Workshop on Modeling the Southern Ocean Ecosystem

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I.   Executive Summary

A workshop was convened 16-18 January 1995 to discuss modeling of the Southern Ocean ecosystem. Attendees included both modelers and sea-going oceanographers as well as representatives of both the Joint Global Ocean Flux Study (JGOFS) and Global Ocean Ecosystem Dynamics Experiment (GLOBEC). Both physical and biological oceanographers participated because of the strong links between physical forcing and biological processes in the Southern Ocean. Since this region is critical to global climate and biogeochemistry and because of the immense logistical difficulties in conducting field programs in the Southern Ocean, strong links must be developed and maintained between the modeling and observational communities.

Most numerical models of the upper ocean ecosystem are based on coupled partial differential equations with growth, loss, interaction, and diffusion terms. The basic model has been used in oceanography for many decades, although there have been many enhancements such as size classes, complex grazing and nutrient uptake terms, sophisticated mixed layer models, etc. As these models have grown in complexity, there are more adjustable parameters that must be estimated and more uncertainty about the exact forms of the parameterizations. Simple changes in parameters can have dramatic effects on model behavior. Several studies are investigating methods to reduce the number of parameters to those that capture most of the possible model behaviors.

As ocean models move towards a closer coupling with observations through data assimilation, it becomes essential that we know far more about the various parameters and functional forms than simply their mean and variance. Assimilation models require that we characterize the temporal and spatial variability of these parameters in order to fill in the gaps in time and space. This is a daunting task. For example, we know decorrelation scales of phytoplankton biomass in only a few locations in the world ocean; little is known about the decorrelation scales of phytoplankton growth rates.

Numerical models, including data assimilation models, also require experimental design and sampling strategies directed towards the specific questions being addressed. Much of the field data that have been used to provide model parameters and functional forms was gathered to solve specific scientific questions and hypotheses that are not always related to the questions being addressed by the model. For example, models of the relationship between chlorophyll concentration and diffuse attenuation may be based on field measurements from tropical waters, and it is not appropriate to apply such functional forms in models of high latitude processes.

The Southern Ocean will be the site of major field campaigns for both JGOFS and GLOBEC. There is still great uncertainty about the regulation of primary productivity in the Southern Ocean; iron limitation, grazing, and light limitation have been invoked. Near the ice edge, processes are even more complicated. Existing coupled biological/physical models must contend with a wide range of processes, many of which (such as iron limitation) have not yet been incorporated into existing models.

Given the expanse of the Southern Ocean and its isolation, field programs are by necessity both limited and costly. The upcoming JGOFS and GLOBEC Southern Ocean projects represent a unique opportunity to collect data on Southern Ocean biogeochemistry and ecological processes. Campaigns by other countries, including the United Kingdom, Australia, France, Germany, Japan, and South Africa, will also provide important data sets along with long-term studies such as the Palmer Long Term Ecological Research (LTER) program. It is unlikely we will be able to assemble these resources again. Given the predicted sensitivity of the Southern Ocean to climate change (and the resulting feedbacks), we must improve our ability to make predictions about the functioning of the Southern Ocean with only limited data sets in the future.

Physical forcing is particularly intense in the Southern Ocean. Strong wind forcing, large seasonal (and interannual) variations in ice cover, and mesoscale eddies are some of the processes that play critical roles in Southern Ocean dynamics. Weak stratification (relative to waters at lower latitudes) gives rise to short dynamical scales. The internal radius of deformation decreases towards the south, ranging from 20 km to 8 km. Bottom topography has a much stronger effect on the flow than at mid-latitudes because weak stratification allows bottom disturbances to penetrate to the surface. Coupled with the smaller dynamical scale, this means that small topographic

features can have large-scale dynamical effects. This physical environment has strong links with biological processes that must be accounted for in both our field and modeling programs.

The focus of the workshop was an assessment of our present state of knowledge from both observations and models. We assessed where our greatest uncertainties lie and where small improvements in observation strategies and models would result in large increases in understanding. We estimated the time and space scales over which we can make useful predictions about the Southern Ocean. As part of this assessment, we explored the needs of the observational community in terms of models. We also sought to outline the type of measurement program that would lead to significantly improved models.

The workshop developed the following recommendations.

Increase accessibility to numerical models by observationalists

As observations become more sophisticated in terms of both the processes that can be measured and the scales that can be resolved (both microscales and global scales), models have assumed new importance as a framework within which data may be interpreted. Moreover, the increasing focus on studies of coupled biological/physical processes and the need for scientific research to focus on the prediction of ecosystem response to climate change has also elevated the role of numerical modeling. Thus the complexity of both models and observations require a much closer interaction between those who build and operate models and those who collect and analyze data.

1. Encourage Southern Ocean JGOFS and GLOBEC activities that have both a modeling and a field component
2. Develop a variety of models focusing on specific processes or hypotheses but with clearly defined interfaces and documented assumptions so that other researchers can understand and evaluate the models
3. Archive output of numerical models much as field and satellite observations are archived and distributed
4. Encourage the development of models that are structured as a set of testable hypotheses that can be addressed by appropriately designed sampling strategies

Improve modeling capabilities in advance of Southern Ocean field studies for use in designing sampling programs and analyzing data

Emerging research areas, such as data assimilation and nested models, would benefit by expanded research in advance of the JGOFS and GLOBEC field programs. Various diagnostic techniques, such as estimating advective fluxes, could be used to design specific sampling strategies at the Southern Ocean station sites.

1. Encourage modelers to work with researchers participating in the Southern Ocean JGOFS and GLOBEC field studies
2. Encourage development of data assimilation techniques for biogeochemical modeling
3. Continue development of embedded or nested models which incorporate high resolution models within lower resolution models
4. Use models to simulate advective fluxes around planned Southern Ocean stations and compare with observations as part of model diagnostics

Improve observing capabilities to take advantage of and test numerical models

Present models point towards the need for better estimates of rate parameters as well as more detailed information on size and functional classes in the plankton community. Improvements in data assimilation techniques will require better estimates of the error fields associated with the assimilated data sets. Efforts should be placed towards the development of low-cost sensors to extend the scales that can be observed.

1. Evaluate present JGOFS core observations in context of the needs of existing numerical models
2. Develop models that resolve critical time and space scales as identified in field measurements
3. Collect information on size and functional groups
4. Quantify error covariances for data fields that are assimilated into models

5. Continue to encourage the development of new automated and low-cost sensors to extend sampling coverage of the Southern Ocean

Establish a regular program to further the development of coupled physical/biogeochemical models

Models of the Southern Ocean ecosystem must resolve complex physical dynamics as well as complicated chemical and biological interactions. Because of the nature of the circulation in this vast region of the ocean, these models must have high spatial resolution as well. Our overall goal should be the development of a closer alliance between models (which will always be gross simplifications of reality) and observations (which will always provide a biased and undersampled view of reality). We should continue activities that strengthen the links between these two complementary ways of looking at a complex system.

1. Regularly assess the state of our knowledge and modeling capabilities
2. Support annual workshops where models can be run and evaluated by both modelers and observationalists

II.   Scientific Background

A.   JGOFS Southern Ocean Plans

1.   Overview of JGOFS Goals

The Joint Global Ocean Flux Study, which began over a decade ago, is designed to study biogeochemical processes in the ocean and their role in climate change. The International Science Plan (JGOFS Report No. 5, SCOR, 1990) has set forth two goals:

1. To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.
2. To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

To meet these goals, U.S. JGOFS has developed an approach based on large-scale surveys, time series stations, process studies, modeling, and data management. The large-scale surveys are designed to provide a basin-scale to global-scale view of biogeochemical properties on seasonal time scales. Critical properties include surface pigment, primary production CO_2, and export fluxes. The time series stations will provide long-term, consistent observations to study seasonal variability of biogeochemical processes at a few sites. An improved mechanistic understanding of crucial biogeochemical processes is the objective of the process studies. These campaigns are conducted in critical regions of the ocean for a limited duration. Modeling activities will synthesize these data sets to provide a diagnostic understanding of ocean biogeochemistry as well as eventual use in predictive studies of the ocean's response to climate change. Lastly, these data sets and models will be maintained and managed so that future researchers can have confidence in the quality of the data as well as to facilitate data sharing and intercomparison.

In the area of ocean biogeochemistry, there is a dilemma of linking the smaller scale processes typically observed by biological oceanographers with the larger scale patterns measured by geochemists. In the Joint Global Ocean Flux Study (JGOFS), the time series stations at Bermuda and Hawaii (Michaels et al., 1994; Karl et al., 1996) show little coherence between the level and variability of primary productivity and downward flux of organic carbon in the mid-ocean. Part of this discrepancy may result from the different time and space scales of the processes controlling primary productivity and the vertical fluxes of organic material. Although the buffering capacity of the ocean is enormous given the large inorganic carbon pool (e.g., Siegenthaler and Sarmiento, 1993), there is considerable short-term variability in its effects on the global carbon cycle (Keeling et al., 1995).

2.   The Southern Ocean JGOFS Process Study

Planning for the U.S. JGOFS studies in the Southern Ocean began in 1990, in parallel with international efforts (U.S. JGOFS Report 16; SCOR/JGOFS Report 10). The U.S. planning effort culminated in a science plan and an implementation plan (U.S. JGOFS Report 17; U.S. JGOFS

Southern Ocean Implementation Plan, May 1995). This section provides a brief review of this program now known as the Antarctic Environment Southern Ocean Process Study (AESOPS).

The Southern Ocean poleward of 30^0 S accounts for roughly 20% of the surface area of the world ocean. Circulation is dominated by the Antarctic Circumpolar Current (ACC) which has the largest volume transport of any major current (approximately 130 Sverdrups). Much of the ventilation of the deep ocean takes place in the Southern Ocean. Through air/sea exchange and sea ice formation, upper ocean waters sink and renew deep and intermediate waters of the world ocean. Furthermore, these deep waters derive their physical, chemical, and biological characteristics through processes occurring in the upper waters of the Southern Ocean.

The strong seasonal advance and retreat of sea ice plays a critical role in the physical and biological dynamics of the Southern Ocean. The maximum extent is about 20×10^6 km^2 and the minimum is about 4×10^6 km^2. The ice edge behaves much like an ocean frontal system, albeit one that migrates several hundred kilometers north and south during the year. It strongly affects biological productivity as well as ocean circulation. The ice edge supports high concentrations of marine life, including higher trophic levels.

Field measurements of ΔpCO_2 suggest that the Southern Ocean is a net sink of atmospheric CO_2 (Takahashi et al., 1993). However, models (e.g., Tans et al., 1990) support the view that the Southern Ocean is essentially neutral with respect to the uptake and release of CO_2. As the circulation is characterized by zones of divergence and convergence, we expect the patterns of uptake and release to be complex. Thus, it has proven to be extremely difficult to constrain the net CO_2 flux to anything more precise than -3 to +1 GT C y^{-1}.

Recent field work at the Polar Front (de Baar et al., 1995; Turner and Owens, 1995) reveals strong uptake of CO_2, consistent with biological uptake. Increased chlorophyll and iron concentrations in the Polar Front may be linked (de Baar et al., 1995), but the source of the enriched iron concentrations is not apparent. de Baar et al. (1995) suggest that iron may be acquired as the ACC crosses shallow topographic features, but the time required for diffusion of such bottom material is too long to support the observed patterns.

The control of primary productivity in the Southern Ocean remains an enigma because of the persistent high nutrient, low chlorophyll concentrations south of the Polar Front. Various processes have been suggested from light limitation (Mitchell et al., 1991, Nelson and Smith, 1991) to iron limitation (Martin et al., 1990; Lizotte and Sullivan, 1992). These processes are not necessarily mutually exclusive. Considerable attention has been placed on trace metal limitation, and although the results are compelling, there remain some troublesome points. For example, chlorophyll concentrations increase with iron addition, but productivity is not necessarily enhanced. Bottle experiments reveal a 3-5 day lag time before the iron-enriched samples begin to deviate from the control samples. Some experiments show a strong size-selective response to iron fertilization while others do not.

The next step in understanding the Southern Ocean's role in the carbon cycle is to quantify the link between productivity and downward carbon flux. Most sediment trap programs have measured high particle flux rates only during limited time periods or in restricted locations (Honjo, 1990; DeMaster et al., 1992). The measured fluxes only represent about 10% of annual productivity. However, about 50% of the productivity is supported by nitrate ("new production"), and this is potentially available for export (Smith and Sakshaug, 1990). In other regions of the world ocean, high f-numbers are associated with high total productivity. The discrepancy between measured sediment fluxes and the apparent production that is available for export is difficult to reconcile. As with the measurements of ΔpCO_2, one likely explanation is that our sampling is inadequate, and critical regions and scales are not being sampled. However, if the magnitudes of these estimates of particle flux and new production are correct, this suggests that 1) there is considerable vertical export of organic matter from the euphotic zone via pathways other than gravitational sinking or, 2) the nitrogen-based estimates of new production significantly overestimate the amount of potential production available for export.

Much as with the physical dynamics of the Antarctic Circumpolar Current, JGOFS research to date suggest that mesoscale dynamics play a more important role in regulating horizontal and vertical

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exchange than expected. More emphasis will be given to sampling designs that can account for these processes over long time periods.

The linkage between the physical dynamics and biogeochemical processes must be better understood if we are to make significant progress on the next challenge of climate research; how will the ocean respond to climate change? Much remains to be learned about how these two components of the ocean system operate separately, but we must design a strategy to link these two components together. The feedbacks between the physical system and the biogeochemical system are complex, and it has become apparent that mesoscale processes and intense, short-lived events play a critical role in this coupling.

The net effect of these processes is a high level of sensitivity to climate change. Changes in atmospheric forcing (winds as they affect mixing, latent heat flux as it affects sea ice formation, etc.) will have a significant impact on Southern Ocean circulation. For example, changes in the freshwater balance might be one outcome of climate change. Given that the weak stratification of the Southern Ocean is largely determined by salinity, such changes would affect the mixing regime and possibly ecosystem structure and productivity. Our ability to predict these feedbacks rests on understanding the critical processes at the appropriate time and space scales, development of numerical models that adequately represent these processes, and production of data sets with which to force and test the models.

3. Specific Southern Ocean Objectives

Several objectives have been developed for AESOPS. These include:

1. To constrain the fluxes of carbon in the Southern Ocean and to place them in the context of the global carbon cycle
2. To identify the factors and processes that regulate the magnitude and variability of primary productivity and the fate of biogenic materials,
3. To determine how the Southern Ocean has responded to past climate change,
4. To develop coupled physical biogeochemical models of the Southern Ocean that can reproduce past and present carbon clues.

The Southern Ocean may be viewed as a set of concentric rings that divide the region into four distinct zones. These zones have distinctive biogeochemical properties, and the zones are thought to be relatively continuous entities. The original JGOFS Implementation Plan discusses these four regions and science activities, which include

1. The frontal regions including the Subtropical Convergence, the Subantarctic Front, and the Polar Front,
2. The permanently open ocean zone between the Polar Front and the equatorward limit of the ice edge,
3. Deep water regions with seasonal ice cover,
4. The continental shelf/slope system.

Although these regions encompass the broad spectrum of ecosystems in the Southern Ocean, the AESOPS plan now includes studies of only the Ross Sea and the Antarctic Polar Frontal Zone (APFZ) at 60°S, 170°W. This approach will provide a unique opportunity to develop a mechanistic understanding of the processes occurring in the Southern Ocean. The elements of the program include process study cruises to investigate coupled biogeochemical and physical processes, long-term deployments of physical, chemical, and biological instrumentation, satellite observations, and numerical models.

B. GLOBEC Southern Ocean Plans

1. Overall GLOBEC Science Goals

The overall goal of the Global Ocean Ecosystems Dynamics (GLOBEC) program is "to understand how physical processes influence marine ecosystem dynamics in order to predict the response of the ecosystem and the stability of its food web to climate change." The linkages between the planktonic stages of marine life and physical forces are likely vulnerable to changes associated with variations in climate. For example, long-term shifts in the amount of seasonal sea ice formed

around the Antarctic continent will affect physical mixing which in turn will influence primary productivity. These changes in food abundance will affect the entire food web.

The U.S. GLOBEC program has identified the following specific objectives (U.S. GLOBEC Report No. 12):

1. To determine physical influences and biophysical interactions in planktonic communities
2. To understand the dynamics of zooplankton (i.e., holoplankton, meroplankton, and icthyplankton) and their interactions with both lower and higher trophic levels
3. To identify probable changes in living marine resources resulting from climate change.

To accomplish these objectives, U.S. GLOBEC has identified several marine ecosystems types for detailed process studies. The studies will focus on describing the basic characteristics of each system, including variability of populations and their environment, quantify biological and physical rates, characterize the sensitivity of the ecosystem to climate forcing, and determine the critical global change processes. For each system, GLOBEC will design a monitoring system that will link modeling and observations. At present, U.S. GLOBEC has conducted studies at Georges Bank, and is just beginning studies of the Southern Ocean. Upcoming studies include the California Current as well as critical regions of the open ocean.

2. Science Issues

Discussions at the initial workshop held in June 1991 highlighted the importance of the annual formation and retreat of pack ice in influencing the structure and function of the Antarctic marine food web. Observations that include the austral winter and extend over several ice cycles were given high priority as components of a Southern Ocean GLOBEC program. In particular, the need for seasonal observations of the abundance and distribution of Antarctic krill (*Euphausia superba*) and the salp (*Salpa thompsoni*), which were identified at the workshop as key target species, was noted. Other suggested target species included a commercially harvested fish species (e.g., *Champsocephalus gunnari*), a non-harvested holopelagic fish species (e.g., *Pleurogramma antarctica*) and a non-harvested nearshore fish species (e.g., *Notothenia neglecta*). The workshop discussions also focused attention on the importance of top predators in the Antarctic marine ecosystem. Hence, several penguin species (e.g., Adelie and Chinstrap penguins), the crab eater seal, and the Antarctic fur seal were recognized to be very important and recommendations were made to include these as key species. Benthic communities were also considered to be an important component of an Antarctic GLOBEC program and recommendations were made to include as target species bivalves, echinoderms and crustaceans that have both pelagic and benthic larval stages.

The Southern Ocean workshop convened in 1993 as part of International GLOBEC had as its objective defining the key science question for a Southern Ocean GLOBEC program. These questions were designed to provide a basis from which to develop elements of research programs and to select core study sites. Southern Ocean GLOBEC is focused on understanding population dynamics of certain key species and how these are affected by physical (environmental) variability. Hence, the first part of the workshop focused on narrowing the species of interest. The key zooplankton species were identified as: *Euphausia superba*, *Calanoides acutus* and *Metridia gerlachei*. *Salpa thompsoni* was recognized also as an important species since it tends to dominate in years and/or locations when *Euphausia superba* is scarce. The primary target species for the top predator component were defined in terms of the degree of association with ice cover or the ice edge, the degree of dependence on krill, the availability of data from existing and historical studies and the feasibility of study. These species are: Crabeater seal, Adelie penguin, snow petrel, Antarctic petrel, fish, and squid.

The key questions for the zooplankton component of a Southern Ocean GLOBEC program are focused on factors influencing ecological cycles:

- zooplankton overwintering strategies
- seasonal and geographical variations in the distribution of Southern Ocean key zooplankton species, especially in relation to the physics of the environment
- factors affecting successful reproduction
- factors relating to larval survival and recruitment to the adult population

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- the distribution of Southern Ocean zooplankton in relation to the distribution of food biomass and reproduction.

Similarly, the key science questions for the top predator component of a Southern Ocean GLOBEC program are focused on:

- effects of variability in the physical and biological environments on predator population dynamics
- the role of ice in affecting foraging performance, reproductive success and survival of top predators
- krill variability and its allocation between several top predator species
- the effect of predator foraging activities on altering the distribution and abundance of krill
- the nature of the functional relationships between krill availability and performance and survival of its predators.

The key science questions for zooplankton and top predators require that a Southern Ocean GLOBEC program study the population dynamics of a variety of organisms that range from small copepods to large seals. Modeling is recognized as an important component of all GLOBEC programs. Many of the important scientific questions identified for Southern Ocean GLOBEC require modeling approaches or input from model simulations. It was suggested that many of these questions be examined within the context of a conceptual model that would be developed for the Antarctic prior to the development of a field program. The conceptual model would also provide a framework for the field program. There are also unique features of the Antarctic ecosystem (sea ice, krill swarming) that need to be included in models. The primary recommendations are that:

- a conceptual model of the Antarctic physical environment and marine food web be developed
- GLOBEC International should sponsor a workshop on observation, theory and modeling of krill swarms
- existing circulation, ice and biological models of the Southern Ocean be evaluated for use as a point of departure for future modeling efforts
- models of krill allocation (as a key species) among various predator species be developed.

3.   Site Selection and Implementation

During the initial Southern Ocean GLOBEC workshop in 1991, considerable attention was given to the selection of research sites for a Southern Ocean GLOBEC program. Characteristics that were considered to be important for potential sites included the existence of identifiable populations of the key target species, reliable sea ice cover, and accessibility by ships and from shore-based laboratories. One region that meets these criteria is the area that extends west of the Antarctic Peninsula to the eastern portion of the Bellingshausen Sea. Other areas that were also discussed as potential sites were the southeastern Weddell Sea, the northern part of the Atlantic sector of the Southern Ocean, the Ross Sea and the Indian Ocean.

During the implementation meeting in June 1994, it was decided that Southern Ocean GLOBEC would consist of two major field studies, each a minimum of six months duration. The summer study will focus on foraging and recruitment; the winter study will focus on overwintering strategies. These field studies will take place in three areas: (1) the Antarctic Peninsula region, (2) eastern Weddell Sea, and (3) the Indian Ocean sector (Figure 1). The sampling strategy in each region will consist of two elements: a synoptic, mesoscale Time-Series Survey in an area of about 40,000 km^2, and Process Studies aimed at understanding phenomena and mechanisms of crucial importance within the survey area. These two elements would alternate at 2-week intervals, providing a continuous research effort over a minimum period of 6 months. A series of standardized measurements will be employed, allowing for comparison of results both within and among the three study sites. A variety of new technologies will be employed for sampling and analysis.

Modeling studies are to be initiated, prior to the advent of field programs, in three key areas: the development of (1) a conceptual model of the ecosystem, (2) circulation models, and (3) biological models. Regarding circulation, mixed-layer and sea-ice models are required, with emphasis on site specific models. Biological models of trophic transfer and krill swarming are particularly needed. Data assimilation methods should be developed.

It is anticipated that modeling studies will begin in 1995, well in advance of field studies, which are anticipated to begin no later than 1997. In fact, the U.S. National Science Foundation-Office of Polar Programs has recently issued an announcement of opportunity for modeling studies in support of Southern Ocean GLOBEC field initiatives. Detailed logistic and scientific plans will be made in a series of three Regional Planning Meetings, one for each study site, held in 1995.

III. Critical Measurements for Modeling the Southern Ocean

A. Fundamental Processes

It is axiomatic (though often overlooked) that modelers cannot model what they do not understand. Our success in creating models that capture the essence of Southern Ocean biogeochemistry depends critically on how successful the process studies are in elucidating the mechanisms that control primary productivity and export in the Southern Ocean. It is important that these questions be answered empirically, else there will be no important insights for modelers to capture.

In the other two high nutrient, low chlorophyll (HNLC) areas, studies of the size-dependent response of phytoplankton to iron addition (Price et al., 1994) and of the relation of ammonium uptake to nitrate uptake (Wheeler and Kokkinakis, 1990; Price et al., 1994) have provided valuable insight into the micronutrient contribution to the HNLC condition (Armstrong, unpub. ms.). Grazing control of phytoplankton size class and taxa (e.g., diatoms versus *Phaeocystis*) is also certain to be important (Banse, 1991; Frost and Franzen, 1992; Armstrong, 1994; Price et al., 1994) with individual algal size cases and taxa being controlled by predation while the overall biomass of the system is controlled by nutrients. In the Southern Ocean, the process will be complicated by the interplay of grazing by krill and salps. Deep convective mixing (Mitchell et al., 1991) and other physical processes will almost certainly be important. It is of course possible that the relative importance of these mechanisms will differ regionally in the Southern Ocean. For example, Helbling et al. (1991) showed no response to iron addition south of the Polar Front but a substantial (5-fold) response to iron addition within the ACC.

This multiplicity of possible mechanisms contributing to the HNLC condition must be critically examined to ensure a successful modeling effort. From a modeling perspective, it is therefore critical that empirical studies of these topics be coordinated with a sharp focus towards answering these fundamental questions.

B. Critical Parameters Must Be Measured

Successful modeling of Southern Ocean biogeochemistry requires measurements of as many critical rate processes as possible, ideally on a size-and-taxon specific basis. There is often a mismatch between the quantities measured by field programs and those required for biogeochemical models. This can be illustrated by a cursory comparison of the JGOFS core measurements versus the model parameters and variables for a simple ecosystem model. Table 1 lists the JGOFS core measurements as well as the variables in the 7-compartment ocean ecosystem model developed by Fasham et al. (1990). In many cases, the model requires data that are not measured by JGOFS such as specific growth rates. This disparity between the observational and numerical views arises for several reasons.

JGOFS Core Measurements (General Categories)	Fasham Model Variables and Parameters with an Analog to JGOFS Core	Fasham Model Variables and Parameters with No Analog to JGOFS Core
Meteorological variables	Cloudiness, PAR	
Temperature		Cross-thermocline mixing rate
Salinity		
Dissolved oxygen		
Photic zone depth	Light attenuation due to chlorophyll	
Beam transmission	Light attenuation due to water	
NO_3	Nitrate	Half-sat. rate for nutrient uptake
NO_2		
$NO_3 + NO_2$		
NH_4	Ammonium	NH_4 inhibition
Urea	Labile DON	NH_4/DON uptake ratio
Phosphate		
SiO_2		
Alkalinity		
TCO_2		
pCO_2		
POC		
PON		
DOC		
Chlorophyll		
Bacterial abundance	Bacterial abundance	Bacterial maximum growth rate
Cyanobacteria abundance		Bacterial specific excretion rate
Bacterial production		Bacterial half-sat. rate for uptake
Phytoplankton abundance	Phytoplankton abundance	Initial slope of the P/I curve
Primary production by ^{14}C		Phytoplankton exudation fraction
Primary production by O_2		Phytoplankton maximum growth rate
New production by ^{15}N		Phytoplankton specific mortality rate
Mesozooplankton abundance	Zooplankton abundance	Zooplankton maximum growth rate
Mesozooplankton grazing	Zooplankton half-sat. rate for ingestion	Zooplankton specific mortality rate
Mesozooplankton egestion	Zooplankton specific excretion rate	Zooplankton assimilation efficiency
Microzooplankton abundance		Detrital fraction of zooplankton mortality
Microzooplankton grazing		Ammonium fraction of zooplankton excretion
Sediment trap quantities	Detritus	Detrital breakdown rate
		Detrital sinking rate

Table 1 Comparison of JGOFS Core measurements with variables and parameters that are used in the ecosystem model of Fasham et al. (1990)

Time evolving models by necessity focus much attention on rates of processes (e.g., phytoplankton growth, grazing) while a large fraction of the available field data involves measurements of biological standing stocks. In part, this is due to the inherent difficulty of constraining transformation rates in the ocean, but the result is that the magnitude of key processes must be either extrapolated from laboratory work or inferred from small net changes in standing stocks. The issue of model-data comparison is further complicated by the fact that the model representation of a particular variable may be only a close cousin of the actual measured quantity. A primary example of this is the difference between observed photosynthetic assimilation rates (mg C/mg Chl/day) and modeled phytoplankton specific growth rates (mg C/mg C/day). The two quantities are linked via the phytoplankton Chl:C ratio, which is often not measured due to time and/or expense. In addition to rate measurements, models typically require the specification of a set of functional responses; for example how do phytoplankton growth and zooplankton grazing rates vary, respectively, with nutrient and prey abundance? Although culture experiments can guide the form of the model parameterizations, the appropriate parameter values for a particular region may be unknown. Deducing the functional relationships from field data may involve a range of conditions beyond that naturally observed, thus requiring small volume manipulation experiments at sea. Finally, model closure often forces modelers to include terms, such as phytoplankton mortality, that either lack a strong biological basis or are an amalgamation of a variety of processes.

In general, these terms are unconstrained by observations and are set by "tuning" the model to observations. Unfortunately, as was recently demonstrated for zooplankton mortality (Steele and Henderson, 1992), the treatment of these closure terms can dramatically alter the behavior of an ecosystem model.

If JGOFS sets as an objective the development of data assimilation models, then in addition to collecting information on key processes, it must also ensure that the sampling strategy is adequate to meet the requirements for assimilation. Lawson et al. (1995; 1996) discuss the performance of the adjoint method to recover model parameters as applied to data from the Bermuda Atlantic Time Series (BATS) station. Their conclusions bear strongly on this report. First, measurement of rate parameters is essential as these are a fundamental aspect of the dynamics of the ecosystem. Second, many of the bulk measurements collected by JGOFS (such as phytoplankton chlorophyll) are not produced directly by the numerical model. Thus information relating variables such as phytoplankton nitrogen to chlorophyll would be valuable. Third, sampling should be frequent enough to ensure that there remains adequate correlation between successive measurements, otherwise the assimilation process will fail. Lastly, the assimilation process is more robust if all variables are sampled at the appropriate critical frequency, which may differ for each variable.

IV.   Modeling Approaches

A.   Modeling Philosophy

The ability of a model to accurately forecast or hindcast is a complicated function of the accuracy of the model, and the accuracy, detail and type of data used to formulate, calibrate and initialize the model. Regardless of the accuracy of a model's prediction, however, we can never know if the model is "valid" in the sense that it is a true representation of the system being modeled (Oreskes et al., 1994). An accurate prediction does not necessarily mean that the model is correct; neither does a bad prediction or hindcast necessarily invalidate the model. Evidence can be gathered to corroborate a model. However, this evidence does not confirm a model's veracity; rather, it supports the model's probability of being accurate. The most trustworthy models, then, are those that have withstood multiple tests using independent data under a variety of conditions. These models can then be extrapolated beyond available data to give reasonable predictions or hindcasts.

The degree to which a model can be used for prediction depends on the type of question being asked, and the local temporal and spatial decorrelation scales of the processes being modeled. Predictions regarding the statistics of a process may be quite accurate long into the future. Predictions regarding the details of local dynamics will rapidly become inaccurate as boundary conditions influence the interior dynamics, and errors in initial conditions cause divergence of the modeled and measured processes. A model that can accurately predict from one data set to the next is an extremely useful tool, as it can then be used to explore details of the dynamics underlying changes in the state variables between the data sets. Using models in this interpolative mode is one of the great strengths of coupled modeling and field programs. The model can be used to quantify processes that were logistically impossible to sample in the field.

Defining the accuracy of the model is a difficult task. Ideally, the model should be tested with a data set independent of the one used to formulate and calibrate it. In practice, this is seldom possible. In any case, performance criteria must be defined for the model; an acceptable model must reproduce the available data within specified errors. Care must be taken to test the fit of all state variables, even those that are not the focus of the study. Does the model sacrifice realistic behavior of one state variable in order to accurately reproduce another state variable? It is essential to include sanity checks at all stages of the modeling. Such checks should be developed in collaboration with observationalists.

A model that accurately predicts the statistical behavior of a system becomes a useful tool for the design of sampling programs. Such a model can be used to infer decorrelation time and length scales which can then be used to plan the frequency and density of sampling. An ideal sampling scheme will sample more frequently than the decorrelation time, and more dense than the decorrelation length scale. Typically three to five samples per decorrelation scale are adequate. The processes governing local decorrelation scales are often complex, and may be driven by non-

local forcings. Models are invaluable tools for obtaining estimates of local decorrelation scales, given appropriate knowledge of boundary conditions. Statistical estimates of forcings and boundary conditions are often appropriate to obtain statistical estimates of decorrelation scales.

B.   Time and Space Scales

The range of processes and components in oceanic ecosystems is daunting, and new observing techniques are constantly revealing new complexity. Even simple ideas of heterotrophs and autotrophs cannot be distinguished unambiguously in many cases as species cross these boundaries. The functional complexity of the ecosystem is further confounded by the broad range of temporal and spatial scales associated with these processes (Denman and Powell, 1984; Mackas et al., 1985). Because of the nonlinear interactions that dominate ecosystems, one cannot simply ignore processes at scales smaller than the scales of interest (Denman and Powell, 1984). For example, the characteristic scales of variability in the environment may drive the response scales of phytoplankton physiology over evolutionary time scales (Harris, 1986; Abbott, 1993).

The observed richness and complexity of the natural world results in a tension between modelers who try to retain only the critical elements of the system in order to develop a manageable and understandable model and observationalists who insist that such sparse models are missing essential processes. The tension between model robustness and model richness will never be resolved, and the balance point between these two forces will depend on the goals of the model.

C.   Compact Representations of Ecosystem Components

An ideal (unaggregated) model would predict abundances of all species, as well as size and stage distributions of species with complex life histories; it would also predict geographically, seasonally, and historically which species and life stages should occur where. Given the current (and future) impossibility of constructing and calibrating such a model, various aggregate representations of ecosystem components have been devised. Below we list several approaches that incorporate increasing degrees of aggregation. It is not clear which of these will prove most useful; indeed, different strategies may be needed for different questions. We suggest that sampling should be done keeping all levels of aggregation in mind. In particular, we suggest that size-fractionated samples be taken wherever possible to support models with higher degrees of aggregation.

Two goals of aggregation are to reduce dynamical complexity (numbers of state variables) and the number of independent parameters that must be estimated. The simplest and most straightforward approach to aggregation is exemplified in the report of Totterdell et al. (1993), where discrete "synthetic" species (Lehman et al., 1975) are constructed to exemplify representative functional groups of organisms. Totterdell et al. (1993) suggest, for example, that a robust ocean ecosystem model would need to contain roughly six categories of phytoplankton (representing diatoms, coccolithophorids, nitrogen fixers, picoplankton, phytoflagellates, and dinoflagellates). The first three are included so that their roles in geochemical cycles other than the carbon cycle can be represented (silica for diatoms; carbonate, and hence alkalinity, for coccolithophorids). The other three are needed "to correctly model the seasonal pattern of the carbon and nitrogen fluxes, taking into account processes such as grazing, sinking, etc." (Totterdell et al., 1993). To this list were added four types of zooplankton (zooflagellates, microzooplankton, mesozooplankton, and salps) that had different grazing strategies and/or sinking rates of fecal material; these groups could be split or combined in certain ways depending on modeling requirements. Bacteria, detritus, dissolved organic matter, and mineral nutrients were then added to complete the model.

Two major problems with this approach were identified (Totterdell et al., 1993). (1) These models are complicated enough to have complex dynamical behaviors that are difficult to understand in terms of system structure and parameterization, and (2) parameter values may be difficult to estimate, since each of these groups is a "synthetic" species (Lehman et al., 1975) whose characteristic parameter values may vary seasonally and/or geographically. Even so, this approach represents an enormous simplification of the actual biological and geochemical complexity.

One extension of this approach would be to represent zooplankton functionality in terms of a single entity that could switch among phytoplankton prey types as they change in relative abundance (Fasham et al., 1990; Totterdell et al., 1993). This procedure diminishes dynamical

complexity by requiring fewer zooplankton state variables; however the switching mechanism itself adds complexity and increases the difficulty of parameter estimation. Other objections to this approach are found in Totterdell et al. (1993).

Within the multispecies context, it may be possible to reduce the number of independent parameters that must be estimated by making certain assumptions about the structure of parameter space. Moloney and Field (1991), for example, exploited allometric (power law) relations in rate constants (e.g., growth rates, sinking rates) among species of different sizes to reduce the number of independent parameters. Their approach allows an important axis of variability (size) to be included in models, allowing different size classes to appear in different situations, while adding a minimal number of parameters. However, these models are still dynamically complex, since they can contain large numbers of phytoplankton and zooplankton size classes; this dynamical complexity can lead in turn to a large range of possible dynamical behaviors and steady-state endpoints with only minor changes in food web structure (Armstrong et al., 1994). In addition, the basic size-structured model no longer contains biogeochemically diverse taxa; the needed diversity could be added either by constructing additional size-lineages for geochemically important taxa (with an attendant increase in dynamical complexity) or by parameterizing their effects (e.g., Maier-Reimer, 1993).

Building on the above considerations, Hurtt and Armstrong (1996) have proposed the further simplification that densities of individuals in successive size classes should conform to the pattern observed empirically by Raimbault et al. (1988) and by Chisholm (1992): that to a good approximation there is equal (maximum) chlorophyll biomass in equal logarithmic size classes, and that biomass is added by adding successively larger size classes rather than by adding biomass within existing size classes. This approach allowed them to define summary growth, death, and sinking rates for the entire size spectrum; total phytoplankton biomass is then represented by a single state variable, dramatically reducing dynamical complexity. The resulting model has only four compartments (nitrate, ammonium, phytoplankton, and a "recycling" compartment), yet produces excellent fits to simultaneous time series of nitrate, chlorophyll, and productivity from the JGOFS BATS program. As in the explicit multiple-chains approach, geochemical diversity could be added either by adding extra state variables or by parameterizing the needed effects.

At present it is not clear which of these approaches is best, or whether each is best in some domain. While the estimation of physiological size-specific growth parameters is probably not feasible in the field, it is important to know whether patterns such as that proposed by Chisholm (1992) hold generally, and what the taxonomic correlates of these patterns might be. Characterizing phytoplankton biomass simultaneously by size and taxonomic composition (dictated by geochemical differences) would indicate whether patterns such as Chisholm's apply to the Southern Ocean; if they do, it may be possible to reduce dramatically both the dynamical complexity and the number of parameters to be estimated in constructing a predictive model of the Southern Ocean.

A different approach has been suggested by Flierl and Davis (1996) who propose using empirical orthogonal functions (EOF) as a basis for reducing the complexity of coupled biological/physical models. Underlying this approach is the assumption that there is a finite (and presumably small) number of modes of biological variability that characterize most of the important processes in the system. The EOFs are used to identify a basis set that is now small enough to be linked to a complex physical model.

Flierl and Davis (1996) apply this approach to a complex model of copepod population dynamics, and it worked successfully in several physical models. They identify two potential limitations to this approach. First, the details of the forcing may affect the mode reduction process. For example, rapid changes in forcing may require retention of more modes. In EOF analysis, nonlinear processes greatly complicate the procedure. In some cases, the reconstructed fields may not be positive definite. The second limitation is also common to EOF analysis in general; the EOFs often do not have a clear biological meaning. Although the EOF approach shows promise, it clearly needs much more research.

D.   Embedding/nesting of models

Model embedding makes use of two numerical models; one applied to a sub-domain of the other. This sub-domain is the region of study. The larger domain is included in the modeling study

because the influence of the region is perceived to be important to the evolution of the flow in the smaller domain. Typically, the large-domain model is run at lower resolution or may have simplified physics. Within the sub-domain, the resolution is chosen to resolve the phenomena of interest. The primary motivation behind the embedding approach is to reduce the computational cost. A recent study made use of this approach to study eddies in the Atlantic (Spall, 1991). The results of global scale models might also be used analogously, though most mathematicians probably regard embedded models as interactive.

To date, model embedding has been limited to physical models and our discussion reflects this fact. However, the biological analogs are obvious. For the purposes of Southern Ocean modeling, there are a few cases in which an embedding approach might be of use. One is in a study of the eddy dynamics of the ACC and the other a study of Weddell Sea processes.

Consider first the case of eddy dynamics in the ACC. To provide the large scale flow, a $0.25°$ (roughly 30 km) primitive equation model might be used. Forced by winds, and perhaps by surface heat flux, a passable representation of the ACC is possible. This would then provide an eddy-resolving regional model with $0.025°$ resolution (3 km) with the boundary conditions representative of the ACC. This model could be 300 km on a side. The large-domain model would have 122,500 grid points and the regional model would have 10,000 grid points. Assuming that both models have the same vertical discretization, the computational costs would be roughly evenly divided between each component. Resolving the entire Southern Ocean at 3 km would be 1000 times the computational cost of the large-scale model or 500 times the cost of the embedded-model strategy. Clearly, this is the difference between a numerical experiment that can be conducted and one that will not be possible for many years.

This large advantage comes at a cost. The fundamental limitation of the embedding strategy is the transfer of eddy energy between the large scale and the regional models. For this example problem, the focus of the regional model is on the eddy processes and associated eddy fluxes. A 3 km resolution model is chosen because we are interested in processes occurring at 30 km and above (roughly 10x the resolution of the model). As the flow enters the regional model at the western end of the domain, there is little or no energy at the eddy scale since the large scale model represent flows at 300 km and larger. The eddy field must be generated within the regional model as the flow carries energy from west to east. This adjustment occurs over a region that may be estimated as the product of the flow velocity and the eddy growth period; 20 cm/s * 5 days = 125 km. This is only an order of magnitude estimate and a range of 60 to 1250 km might provide reasonable bounds on the potential adjustment domain. Using the 125 km estimate, much of our domain (42%) will be taken up by an adjustment of the eddy field. Furthermore, the climatology of the ACC may be different in each model either in structure or position. These physical processes can result in significant eddy diffusion and vertical transport and therefore may be important to chemical and biological processes as well. Careful numerical experiment design will be required to separate the effects of adjustment within the regional model from the signal of ACC eddy dynamics.

A modeling study of the Weddell Sea and the formation of Antarctic water masses might be carried out with the large scale model providing conditions at the outer edge of the sea. A small scale model including nonlinear effects in the equation of state might be used to look at the processes that lead to very cold, salty water leaving the Weddell Sea. Here, the boundary condition provided by the large-scale model will not have as rapid effect upon the interior. In fact, the essence of the study would be to understand the way in which the boundary condition affects the Weddell Sea. We do not expect that the lack of eddies in the large scale model will have a dramatic effect upon the result, primarily because these eddies would not extend onto the shelf to a significant extent.

In summary, model embedding can provide an economical approach to studying systems at high resolution. Some problems are more amenable to this approach than others. Naive use of the boundary conditions from a large scale model will contaminate the regional model results with adjustment processes. Careful numerical experiment design may permit the application of this method to a greater range of problems.

E.   Assimilation

Data assimilation provides a powerful tool with which to link observations and numerical models. Measurements are used to constrain model evolution and a dynamical model is used to produce

complete, gap-free fields that are consistent with the underlying dynamics. This method is well-established in the meteorological community, and it is now becoming a more widely-used approach in physical oceanography. Data assimilation in biogeochemical models is only in its earliest stages of development (Lawson et al., 1995; Lawson et al., 1996). This immaturity is due in part to the complexity of coupled biological/physical processes and to inadequate field observations.

When we try to reconcile models and data, we are constructing fields of currents, temperature, phytoplankton biomass, etc. which nearly fit the data and nearly solve the model equations. Why should we admit that the models might be imperfect?

1. Their external forcing fields may be erroneous either due to errors in the methods used to generate the fields or undersampling of critical scales
2. The dynamics are only approximate and include unresolved scales, simplified parameterizations of critical processes, etc.
3. The numerical model computes a grid value; how should this be related to an observation somewhere in the surrounding cells? How do we close the equations after averaging over cells?

The Kalman filter is an excellent algorithm for sequential assimilation of data into imperfect models. There is a well-recognized method for inserting a best estimate of the covariance of the errors in the dynamics-plus-forcing. Although the sequential aspect is valuable, the price is high. One must compute the full error covariance matrix for the solution. This has made the algorithm prohibitive for large problems.

The adjoint method is usually implemented such that distributed dynamical errors are suppressed. This need not be the case, but including the fields of model errors would make the dimension of the search so long that unpreconditioned searches for a best fit would be prohibitive. By suppressing fields of dynamical errors, one only need search for the best initial fields and a few tuning parameters in the dynamics. However, for a long enough assimilation interval, the initial conditions have insufficient control and the results are poor as the later data have no or incorrect impact on model behavior. Clearly, dynamical errors must be allowed to appear later in the assimilation.

The use of representers allows fields of dynamical errors as well as adjustments to the parameters. It properly preconditions the search by limiting it to the space of observable degrees of freedom. Two concerns have been raised about the representer approach. First, it applies only to linear models, and second, the workload increases dramatically as the data set increases. However, the representer method has been applied iteratively to nonlinear quasi-geostrophic models and three-dimensional, time-dependent primitive equation models. Convergence in both cases was rapid. Concerning the size of the data sets, it is now possible to assimilate very large data sets.

Along with incomplete models, our understanding of the error fields associated with the data sets to be assimilated is also inadequate. In many cases, we have little quantitative knowledge of how biogeochemical fields change on a temporal and spatial basis. This is most apparent with rate measurements such as primary productivity. Abbott et al. (1995) showed that simple bio-optical models that are used to convert instrument measurements into biologically-relevant quantities, such as chlorophyll, can have significant temporal and spatial variability. The variations in the model parameters must be understood before such measurements from drifters and moorings can be assimilated into a model. Characterization of these error fields requires extensive, repetitive measurements at the appropriate scales.

These problems are well-known, yet in our haste to develop coupled models we sometimes ignore other, equally important issues. First, although circulation models are more mature (and the equations of motion are better defined than the equivalent ecological equations), there remain some obvious problems. Circulation models have problems with resolution and parameterizations, just as do coupled models. Forcing fields and initial conditions are no less a problem with purely physical models than with coupled models. Second, our understanding of the physics is still limited. Processes such as fronts, bifurcating jets, and other intermittent events are difficult to express in mathematical form. Third, there remain serious technical challenges in the numerical methods as well. For example, there are issues in variational methods applied to nonsmooth or singular problems (e.g., abrupt switches in parameterized processes, outcroppings

in layered models), least squares methods applied to non-Gaussian processes such as intermittent ocean fields (fronts, spring blooms, etc.), the estimation of error fields in least squares estimators, and preconditioning techniques.

Biogeochemical models need fields of vertical velocity that are produced from circulation models as one example of physical/biological coupling. E. Harrison (pers. comm.) has compared vertical velocities as produced by present circulation models using different wind forcing data sets. The differences in the vertical velocities are as large as the differences between ENSO and non-ENSO conditions. This observation suggests that there still remain serious problems in both the models and in the forcing fields. Coupling biogeochemical models with physical models is not straightforward.

Despite these obstacles, many lessons have been learned from past modeling efforts. It appears that biological models should include at least two types of phytoplankton (a diatom and a smaller form that does not require silica), two types of grazers and two nutrients. One could model iron effects as a regulator of the rate of nitrate uptake, but so far no one has developed an explicit iron cycling model. The food web structure is important to model behavior, especially in terms of grazing and export production. Some differences in light utilization are related to phytoplankton size. Thus simple nutrient-phytoplankton-zooplankton models do not capture all of the essential behavior. New techniques in parameter estimation are being applied to biological models, but such tuning must be viewed with caution since our knowledge of the functional forms that we are trying to fit may be inadequate. The first steps in data assimilation in biogeochemical models show promise and should be pursued (Prunet et al., 1996a, 1996b).

V.   Modeling and Field Measurement Strategies

A.   General Considerations

As JGOFS begins its final process study, it is also beginning a Synthesis and Modeling Program (SMP) that will integrate the JGOFS observations and a suite of numerical models that will capture our knowledge of the oceanic carbon cycle, including the uncertainties in this knowledge. As AESOPS unfolds, it should benefit greatly from the SMP activities, particularly during the analysis phase. In this section, we describe the types of observation and modeling activities that will be especially relevant to SMP. Although GLOBEC has not yet developed an equivalent SMP effort, this discussion should be relevant to it as well.

The types of model studies will depend on the scientific issues that we wish to address. Concerning coupled biological/physical models, most biologists would request information relevant to the horizontal and vertical transport of nutrients and biomass, which would then permit evaluation of the interactions between components (e.g., rate processes). The biological aspects of a coupled model must therefore define the links between components, i.e., the functional forms of the interactions. In addition, we must know how the parameters of the functional forms vary in response to variations in temperature, salinity, depth, etc. What do we need from physics so that the coupled model adequately represents the physical environment in which the biological components function? To first order, the physical aspects of the model should provide the mean and spectrum of variations in horizontal and vertical velocities, and the fluctuations in temperature, salinity, and mixing conditions. Although this appears to be straightforward, considerable scientific thought and understanding is required to quantify the time and space scales that are relevant for the particular model. These scales will depend on the scientific questions under study and will drive the specific components and the functional forms that are included in the model.

To develop these models will require a substantial interaction between the observational and modeling components of JGOFS and GLOBEC. For example, how could measurement and sampling strategies be improved to derive the most return from numerical models? What sorts of measurement programs are needed to improve models and model parameters?

B.   General Issues for JGOFS and GLOBEC

The JGOFS Southern Ocean implementation plan identified several regions in which to address scientific issues. The identified regions were sufficiently distinct that no single coupled model could address all regions. In addition, each region possesses considerable temporal and spatial

variability over a range of scales, thus complicating the interpretation of a data set which must be collected over a limited time and space domain.

Several specific scientific questions that fit within the JGOFS effort include:

- What is the quantitative outgassing of CO_2 to the atmosphere that results from northward transport and warming of Antarctic waters?
- To what extent does the subduction of ΣCO_2 and DOC influence water column carbon flux and air-sea exchange of CO_2?
- What is the contribution to carbon flux of upper ocean remineralization processes and the fluctuations in the pools of POC and DOC?
- To what extent can estimates of vertical advection be incorporated into estimates of the vertical transport of organic material?
- To what extent does the Antarctic continental margin and ice edge advance and retreat influence primary production processes in the Southern Ocean?

These questions require a range of modeling approaches, none of which is presently available "off-the-shelf." One of the major limitations identified was the lack of resolution within the mixed layer by most existing models. It was suggested that most of the JGOFS questions required a higher resolution of FRAM (Fine Resolution Antarctic Model) with a well-defined mixed layer, as well as implementation of a hierarchy of biogeochemical models.

In contrast to the JGOFS scientific plan, the GLOBEC initiative has a greater emphasis on the response of the marine ecosystem to environmental change. Since the GLOBEC plan focuses on the response of populations of marine zooplankton, fish, mammals, and birds, the regional focus is closer to the continent than is the main JGOFS plan. This regional focus results in a different suite of questions and a different range of modeling issues. Several specific modeling problems were identified within this regional focus.

- How can the physical and biological components of ice edge processes be integrated into a coupled model?
- How do complicated physical dynamics, resulting from the topographic shelf edge effects, impact the distributional patterns of regionally aggregated populations?
- To what extent can site-specific life cycles for regional populations be imbedded within coupled models?

These issues would require the construction of regional, high-resolution models that could be nested within larger scale, lower-resolution models. The complexity of the Antarctic food web poses additional problems for incorporating the biological components into coupled models. It was suggested that a hierarchy of food web models of increasing complexity be developed. This is a long-term research problem that is not limited to analyses of the Antarctic food web.

All models suffer from sub-grid scale representations of biological and physical processes. The time and space scales of importance for many of the biological processes, and several of the physical processes, are within this sub-grid scale. This creates serious research issues in the development of coupled models in general.

For many issues, regional models are the appropriate tool. In particular, regional models are especially valuable for the study of specific processes. However, regional models in the Southern Ocean are faced with several challenges, including boundary conditions, model initialization, ice dynamics, coverage of the full seasonal cycle, shelf drainage, and bottom water formation. The Antarctic Circumpolar Current (ACC) presents its own set of challenges in terms of modeling. The weak stratification and high latitude lead to short dynamical scales (Inoue, 1985). In addition to requiring higher resolution in both the vertical and horizontal dimensions, these smaller scales in turn lead to a different mix of processes that must be considered compared to mid and low latitude models. The impacts of ice formation must also be included in circulation models of the ACC.

Another issue concerns the relative merits of the isopycnal layer coordinate system versus the fixed depth (level) coordinate system in providing vertical resolution for biological processes within the upper ocean. While it was concluded that the layer approach is probably more appropriate for the representation of isopycnal transport and diapycnal mixing, most existing coupled models rely on a fixed depth coordinate system. However, new capabilities of isopycnal

models show promise for future Southern Ocean models. In particular, isopycnal models are superior in their abilities to resolve the thermohaline circulation of the ocean.

The term balances from any coupled model must be evaluated. The relative imbalance between terms in the equations of any given model can provide important information on model parameterization as well as key parameters to be measured in the field with better precision.

Finally, it was agreed that the scientific questions must be articulated (as in the program overview statements for JGOFS and GLOBEC), but there needs to be some consideration of how to break these larger questions into achievable components that can be addressed by simple coupled models. This is not a trivial task, but it is essential that the models developed for Southern Ocean studies focus on specific issues rather than try to be all-encompassing. At this point in time, our knowledge of the basic processes is sparse and direct measurements are few. Performance of a single, complex model may be compromised by either inaccurate forcing functions, poor parameter estimation, incorrect model formulation, or simply a lack of observations with which to compare model output.

C.   Specific Issues for Coupled Models

Several European nations have JGOFS process studies underway in the Atlantic sector of the Southern Ocean, and U.S. JGOFS AESOPS in the Pacific sector will take place during 1996-98. The U.S. GLOBEC Southern Ocean program is planned for 1999-2000. After these studies have been completed, it is unlikely that other field programs of this magnitude will be conducted in the Southern Ocean in the foreseeable future. Thus all attempts to advance our understanding of the Southern Ocean system after 2000 will, by default, rely more heavily on remote sensing capabilities, moored instruments and models than on direct observation and experimentation at sea. This situation means that the window of opportunity provided by the JGOFS and GLOBEC field programs of the U.S. and other nations in the Southern Ocean will be of the most lasting scientific value if those programs address questions that:

- pertain to scientific problems that are of significant magnitude at the regional and/or global scale,
- are clearly unanswered at present,
- require direct observation and experimentation at sea to answer them, and
- can help in the future development of models (both physical and biogeochemical) and long-term monitoring strategies that may be able to predict and/or measure responses of the Southern Ocean to any future changes in climatic forcing.

Here we give six scientific questions of that kind and discuss their implications, both for the 1996-98 AESOPS field program and for modeling efforts. Although we have phrased these questions in terms of JGOFS, similar issues could be formulated for GLOBEC. Rather than endorse specific field programs or specific models, we consider general questions that the JGOFS field programs in the Southern Ocean are well positioned to address.

Is the Southern Ocean a net source of CO_2 to the atmosphere or a net sink?   Of what magnitude?

Studies of ΔpCO_2 between the atmosphere and oceanic surface waters have previously indicated the Southern Ocean (defined rather broadly in those studies as the zonal band between 40 and 70°S) to be an area of net CO_2 flux into the ocean, with an estimated magnitude of 2.7 GT C y^{-1} (Takahashi et al., 1986). That flux is approximately equal to the global net uptake of CO_2 by the oceans (ibid.), indicating that CO_2 fluxes are approximately in balance for the rest of the ocean. In other words, the Southern Ocean may dominate the global net uptake of CO_2 by the oceans. That view can be disputed, however, as studies of meridional CO_2 gradients in the atmosphere suggest little or no net uptake of CO_2 by the ocean in the Southern Hemisphere (e.g., Tans et al., 1990). With known areas of net uptake in the vicinity of the Subtropical Convergence (Takahashi et al., 1986), a net Southern Hemisphere flux of approximately zero would imply net outgassing from the waters to the south. The large-scale circulation of the Southern Ocean is characterized by zonal bands of convergence and divergence, suggesting a reasonably complex pattern of alternating sources and sinks, with the result that the overall net balance is difficult to evaluate. The spatial coverage of existing ΔpCO_2 data is not particularly good in the Southern Ocean and seasonal information is almost completely lacking, especially in the Pacific sector. Thus the net

CO_2 flux is difficult to constrain using the available data to no better than -3 to +1 GT C y^{-1}, with negative values denoting uptake.

Implications for field measurements: Field measurements of ΔpCO_2 should be given a high priority within the Southern Ocean JGOFS programs of all nations, and should seek to maximize both spatial (especially meridional) resolution and seasonal coverage. The overall purpose of this work should be to constrain the net CO_2 exchange within much tighter limits than it is now possible to do.

Implications for modeling: It would be helpful to develop satellite-observable proxies for oceanic pCO_2 (based on surface temperature and perhaps ocean color). Once developed, these could be merged with wind data to model CO_2 fluxes after 1998.

Do biological processes matter quantitatively in atmosphere/ocean CO_2 exchange in the Southern Ocean?

The mean primary productivity of open-water areas south of the Antarctic Polar Frontal Zone (APFZ) is only 30 - 40 gC m^{-2}y^{-1} (e.g., Smith et al., 1988), four times lower than that in the Sargasso Sea near Bermuda (Lohrenz et al., 1992; Michaels et al., 1994), and lower than that in any large oceanic area except the permanently ice-covered central Arctic (Smith and Sakshaug, 1990). Productivity is significantly higher in continental-shelf areas near Antarctica (e.g., DeMaster et al., 1992) and may be higher within the APFZ (e.g., Bathmann et al., 1995; Turner and Owens, 1995), but those areas are restricted enough spatially that the average productivity for the region as a whole probably cannot exceed 50 gC m^{-2}y^{-1}. The APFZ and all waters to the south comprise an area of about 4 x 10^7 km^2 (e.g., Comiso et al., 1993), a little more than 10% of the surface area of the ocean. The maximum estimate of primary productivity in the Southern Ocean is thus approximately 50 gC m^{-2} y^{-1} x 4.0 x 10^{13} m^{-2} = 2.0 x 10^{15} gC y^{-1} (2.0 GT C y^{-1}). Exportable "new" production has been estimated in several subsystems of the Southern Ocean to be approximately 50% of total primary productivity, over a wide range of low- to high- productivity conditions (numerous studies, summarized by Smith and Sakshaug, 1990; Nelson, 1992). Thus the estimated maximum carbon flux from the surface layer of the Southern Ocean is on the order of 1 GT C y^{-1}, meaning that the *magnitude* of the biologically driven flux is considerably less than the present *uncertainty* in the net gas exchange.

If the net absorption or release of CO_2 by the Southern Ocean is at present very nearly zero, or if photosynthetic carbon uptake is of major importance in maintaining oceanic undersaturation in those areas of net absorption, then biological pumping mechanisms are quantitatively significant in the regional CO_2 balance. Otherwise they are not. Recent efforts by J. Sarmiento (pers. comm.) combines projected climate changes in the deep circulation of the ocean with models of ocean biogeochemistry. This work suggests that there will be a significant impact on the atmospheric CO_2 content as result of biological activity, especially in the Southern Ocean. This impact is magnified if there is a concurrent change in the structure of the marine ecosystem that impacts biological activity.

Implications for field measurements: Measurements of primary productivity, nutrient uptake rates and biogenic particle flux should be coordinated very closely with those of ΔpCO_2 to evaluate the role of phytoplankton photosynthesis and organic-matter export in the uptake of CO_2 by the ocean. All biological process studies should be conducted in a way that addresses the dominant biological time scale in the Southern Ocean, which is seasonal. Seasonal cycles of primary productivity and biogenic particle flux are more pronounced in the Southern Ocean than in other regions because of the strong seasonality in solar irradiance and, in the southern portion of the system, ice cover (e.g., Smith and Sakshaug, 1990; Fischer et al., 1988). Moreover, the specific growth rates of phytoplankton are lower in the Southern Ocean than in lower-latitude systems (e.g., Wilson et al., 1986), primarily because of low surface-layer temperatures and light limitation. This means that highly transient bloom events lasting one day to several days, which have been observed in low-latitude systems (e.g., Marra et al., 1990), cannot be quantitatively significant in comparison with the seasonal signal and may not develop at all.

Beyond these purely practical considerations, all biological studies should be approached with the understanding that the processes they are evaluating *may or may not* be of major importance in the effort to understand carbon fluxes. A comprehensive biological program should be part of the JGOFS AESOPS, but its central purpose should be to understand the pelagic ecosystem and

biogeochemical cycles of the region. We should seek to understand processes that are significant ecologically (e.g., photosynthesis, nutrient uptake and regeneration, grazing, biogenic particle flux) regardless of whether or not they are major carbon-flux terms. As noted earlier, the work by Sarmiento indicates that the structure of the marine ecosystem will have significant impacts on air/sea exchange of carbon.

Implications for modeling: If biological terms can be neglected, carbon-flux models can be immensely simpler and still have predictive value. Such models would have to consider wind forcing, circulation patterns, gas exchange, inorganic chemical equilibria and very little else. The models would still have to select appropriate temporal and spatial scales of resolution - a non-trivial problem - but they would be inherently simpler and more testable than those that require an ecosystem submodel.

If biologically driven carbon fluxes are important quantitatively, pelagic ecosystem models will have to be incorporated into the carbon-flux models. Ecosystem models should be constructed, whether or not they are incorporated into ocean/atmosphere CO_2 exchange models, and we recommend that such models consider on the order of 20 biotic and abiotic variables including pCO_2, alkalinity, NO_3^+, NH_4^+, $Si(OH)_4$, Fe, O_2, POC (considering suspended and sinking POC separately), DOC, phytoplankton (considering 3-5 functional groups within the phytoplankton) and grazers (considering 3-5 functional groups of grazers). The recommendation for this level of complexity, rather than greater or less complexity, is explained in section III.C of this report.

What controls primary production in the Southern Ocean?

Low phytoplankton biomass and primary productivity are widespread in the waters south of the APFZ in spite of persistently high nutrient concentrations. Thus the Southern Ocean is the largest of the three well documented high-nutrient/low chlorophyll (HNLC) regions of the ocean (the other two being the subarctic and equatorial Pacific; e.g., Cullen, 1991). As is the case in other HNLC areas, hypotheses that seek to explain low productivity in the Southern Ocean center around the irradiance/mixing regime (Mitchell et al., 1991; Nelson and Smith, 1991), iron limitation (Martin et al., 1990) and grazing (e.g., Miller et al., 1991; Frost, 1991). It is unlikely that any single hypothesis can explain the HNLC condition throughout the Southern Ocean because of the spatial heterogeneity and strongly seasonal character of many of the processes (irradiance, vertical mixing, atmospheric dust inputs, formation and melting of pack ice, krill swarms etc.) Moreover, the hypotheses that have been put forward are not mutually exclusive; it is likely for example, that phytoplankton blooms develop in marginal ice zones in response to the combined effects of water-column stabilization and iron enrichment (Martin et al., 1990; Nelson and Smith, 1991). Similar conditions may enhance productivity at the APFZ and other open-water frontal systems, although the direct observational evidence from those systems is less developed at this point.

It is hoped that field studies during AESOPS can achieve a reasonably mechanistic understanding of how primary production is controlled in the Southern Ocean. If that effort is successful the biological understanding obtained can provide a basis for modeling the predicted changes in the ecosystem in response to any climate-change scenario, and can indicate which properties of the system can most usefully be monitored from satellites and moored instruments (e.g., mixed-layer depths, light attenuation coefficients, atmospheric dust inputs) to track the control of primary productivity through time.

Implications for field measurements: Field experiments should be directed toward testing specific control hypotheses in several subsystems of the Southern Ocean (e.g., the APFZ, the low-productivity open waters to the south, the coastal waters surrounding Antarctica). A program-level effort should be made to coordinate proposed studies of individual control mechanisms in a way that permits competing and/or complementary hypotheses to be tested in the same areas of the ocean at the same times. It is likely that much of this coordination will have to take place after the individual hypothesis-testing proposals have been submitted, as investigators will normally be unable to know ahead of time what other studies will be proposed by other groups. As is the case for all biological studies in the Southern Ocean, studies of the control of primary production should address the dominant seasonal time scale, and should specifically address the question of whether there are major temporal changes in the controlling mechanisms during the spring and summer.

Implications for modeling: Primary production models, and primary production components of larger models, should be based upon control mechanisms that can be demonstrated at sea. Nutrient-based models, for example, are inapplicable to the Southern Ocean because of the almost universally nutrient-rich conditions that prevail. Models should also be comprehensive enough to reflect the fact that high-productivity events do occur in the Southern Ocean, and that they cannot occur unless *both* the physical environment (e.g., light and vertical mixing) and the chemical environment (e.g., Fe and other micronutrients) are favorable. Models invoking grazer control should take into account the fact that some bloom-forming phytoplankton groups (e.g., diatoms) are readily grazed by particle-selective herbivores and other bloom-forming groups (e.g., *Phaeocystis*) are assiduously avoided by many grazers.

It would also be helpful if algorithms can be developed by which those properties that are shown to be important in controlling primary production can be estimated from remote sensing data (e.g., mixed-layer depths from local wind-stress, solar irradiance from cloud cover, light attenuation coefficients from ocean color, atmospheric dust inputs from large-scale wind patterns). Such algorithms could permit satellite data to be used in monitoring processes known or believed to be of major importance in controlling primary production.

What controls export of organic matter to the deep ocean?

The concept of the "biological pump", (Longhurst and Harrison, 1989) which can in principle pump CO_2 against its concentration gradient from the atmosphere into the deep ocean via the photosynthetic production and vertical transport of organic matter, has been expanded to comprise at least three different pumping mechanisms. These were characterized by Longhurst (1991) as:

> …a *rotary pump* which circulates material in the microplankton food web of the euphotic zone, an *Archimedian pump* by which the flux of fecal and aggregated material occurs continually under gravity, and a *reciprocating pump* by which diel migrants actively carry material down at dawn, to rise again at dusk to feed.

To these we must certainly add a *diffusion pump* by which dissolved and non-sinking particulate organic matter accumulate in the photic zone and are mixed downward (Anderson, 1993).

To date, most sediment trap studies in the Southern Ocean have shown the biogenic particle flux to be highly seasonal, usually restricted to a brief summer period, with integrated annual fluxes that are very low in comparison with those in other oceans (e.g., Fischer et al., 1988; Honjo, 1990). Those fluxes typically represent only about 10% of the annual primary productivity, even though primary productivity is very low by global ocean standards (see above). Thus the Archimedian variant of the biological pump (*sensu* Longhurst, 1991) appears to operate slowly and sporadically in the Southern Ocean. Mid-summer fluxes in spatially restricted areas of high productivity such as the Ross Sea can be enormous (e.g., DeMaster et al., 1992), but the small extent of those areas makes their overall contribution to organic matter export minimal.

Studies of nitrogen uptake by phytoplankton in the Southern Ocean suggest that about 50% of the primary production is supported by nitrate, irrespective of the total primary productivity of a region (Smith and Sakshaug, 1990; Nelson, 1992). Because nitrate is supplied from beneath the euphotic zone and other nitrogenous nutrients (primarily ammonium and urea) are supplied by *in situ* recycling within the euphotic zone (Dugdale and Goering, 1967), the ratio of nitrate uptake to total nitrogen uptake by phytoplankton (the f ratio; Eppley and Peterson, 1979) can be taken as a measure of the fraction of primary production that is potentially available for export to depth. Thus about 50% of the organic matter produced by phytoplankton appears to be potentially available for export in the Southern Ocean, over a wide range of regional primary productivity levels. This finding contrasts sharply with observations in tropical and subtropical systems, where the general pattern is that only areas of high annual primary productivity have f ratios as high as 0.5, with values as low as 0.05 - 0.1 in oligotrophic surface waters (e.g., Eppley and Peterson, 1979).

If the existing data sets on gravitational particle flux and f ratios in the Southern Ocean are both correct in their overall magnitudes, then one of two things must be true. Either:

1. there is considerable vertical export of organic matter from the euphotic zone of the Southern Ocean via pathways other than gravitational settling (e.g., active migration of grazing organisms or downward mixing of dissolved organic material and non-sinking particles), or
2. nitrogen-based f ratios provide large overestimates of the production of potentially exportable organic matter in the Southern Ocean.

The role of biogeochemical processes in the Southern Ocean in the global carbon cycle, and in any apparent net uptake of CO_2 by the ocean at high southern latitudes, cannot be evaluated in even crude quantitative terms until this situation is resolved. We recommend that all national JGOFS experiments in the Southern Ocean place a high priority on achieving a quantitative understanding of the relationship between total organic matter export and primary productivity, and that they explicitly examine the role and quantitative importance of pathways other than gravitational particle flux.

Implications for field measurements: While it will be important to measure the gravitational flux of biogenic particulate matter with sediment traps, and to do everything possible to assure that the sediment trap data provide an accurate measure of the gravitational flux term, it will be of at least equal importance to obtain data that permit estimates of non-gravitational fluxes. Studies of grazing rates, especially those of organisms large enough to undertake significant diel vertical migrations, will be necessary to quantify the "reciprocating pump" as a transport mechanism for organic matter. Similarly, studies of the rate of turbulent mixing near the base of the euphotic zone and detailed measurements of the vertical gradients in dissolved organic matter and suspended (non-sinking) biogenic particulate matter will be necessary to evaluate the downward mixing "diffusion pump" term. Both of these non-gravitational mechanisms may be sharply discontinuous in time (e.g., they may be driven by major events such as storms or the passage of krill swarms). Sampling strategies should take that strong likelihood into account.

Implications for modeling: It would be very useful to determine whether a nitrogen-based f ratio is a valid measure of the potential fraction of primary productivity that can be exported to depth in a system where nitrate is not depleted to potentially limiting concentrations. Qualitative arguments for both alternatives can be presented: On one hand, the strong positive correlation between the nitrogen-based f ratio and total primary productivity in tropical and subtropical systems may be based largely on differences in nitrate availability in the surface layer. This would predict that multiplying f by productivity may be a poor predictor of organic matter export in nitrate-replete systems such as the Southern Ocean. On the other hand, the overall character of the nitrogen cycle in the Southern Ocean is similar to that in other areas; nitrate is regenerated at depth and advected or mixed upward, while ammonium and urea are regenerated within the surface layer. This would predict that the product of f and productivity is closely related to export even in systems where no nutrient is limiting to the phytoplankton. These alternatives may be addressable in quantitative terms by modeling, which if done in advance of field programs may help identify those field data that are most crucial to resolving the question.

Do ice and ice biota influence the system?

Each autumn and winter about 16 million km^2 of the Southern Ocean's surface (about 40% of the waters south of the APFZ and 4% of the global ocean) freezes (e.g., Zwally et al., 1983; Comiso 1991). Each spring and summer, this ice melts . This seasonal advance and retreat of ice in the Southern Ocean is probably the most profound seasonal cycle that occurs in any ocean. An additional about 4 million km^2 of the Southern Ocean is permanently ice covered, primarily in the western Weddell Sea (ibid). Sea ice has been shown or hypothesized to have direct effects on ocean/atmosphere gas and momentum exchange, light penetration and deep water formation (e.g., Gow and Tucker, 1990). In addition to the direct effects of ice on physical and chemical exchange, the seasonal formation and melting of ice have been shown to enhance upper water-column stability, diminish mixed layer depths, and increase primary productivity in spring and summer (Smith and Sakshaug, 1990), with associated increases in the abundances of heterotrophic organisms ranging in size and function from bacteria to seals and seabirds (e.g., Ainley and DeMaster, 1990). Melting sea ice has also been hypothesized to be a quantitatively significant source of iron to surface waters, resulting in enhanced ice-edge productivity (Martin et al., 1990). Any field study of biogeochemical processes in the Southern Ocean would be enormously deficient if it failed to take these effects of sea ice into account, as would any model of the Southern Ocean system.

Sea ice is also itself a habitat for biota. Dense algal layers can form within the ice and at its under surface (e.g., Garrison et al., 1986), and those algal layers provide the apparent food source for dense and diverse communities of microheterotrophs that inhabit interstitial waters within the ice (Garrison, 1991). Direct observations from ROVs have shown that ice-algal layers at and near the under surface of pack ice can be a major winter feeding ground for first-year krill which, unlike adult krill, must feed through the winter (ibid.). Being trapped within the forming sea ice and remaining viable within the ice appears to be an important overwintering strategy for many Antarctic phytoplankton species, several of which are dominant within the ice-edge blooms that develop in the water column as the ice retreats in spring and summer (Wilson et al., 1986). There are thus very significant interactions between the biota of the sea ice and the water column, especially in areas where ice cover is seasonal.

Seasonal pack ice does not advance as far north as the APFZ, but it completely covers the Ross Sea in winter. Thus the effects of ice do not have be considered in field studies or models of the APFZ or other northern parts of the Southern Ocean. However it will be crucial to understanding the Ross Sea and other seasonally ice-covered areas, from both a scientific and a logistical perspective. For example, the presence of sea ice greatly affects the flux of CO_2 between the ocean and atmosphere (Hibler, 1992). In addition to those effects of ice cover that warrant scientific study, the seasonal ice cover severely restricts the ability of ships to get into the Ross Sea in winter and to recover moored instruments in any area of significant ice cover, even in summer.

Implications for field measurements: Biogeochemical studies in the Ross Sea should commence as soon after the first appearance of sunlight and open water as is logistically possible, and should continue until advancing ice makes it necessary for the ship to leave. The first light appears in September, the first open water is generally observed in mid-October, and ice is usually advancing rapidly by late March. Key data sets that can be obtained from moorings while no ship is in the area (e.g., currents, transmissometry, biogenic particle flux) should continue through the winter. Studies of primary productivity, grazing, nutrient removal and regeneration, biogenic particle flux, CO_2 exchange etc. should all take into account both the intense, diatom-dominated phytoplankton blooms that form in the ice-edge zone of the Ross Sea in summer and the *Phaeocystis*-dominated blooms that are now known to develop very rapidly after the first appearance of light and open water in spring.

Implications for modeling: Physical and biogeochemical models of the Ross Sea and other seasonally ice-covered areas should have explicit submodels dealing with the sea-ice system, and should account in a realistic way for each of the known or hypothesized physical, chemical and biological interactions between sea ice (including the seasonal formation/melt cycle) and the water column. Because of the great apparent importance of mesoscale phytoplankton blooms in the export of biogenic material to the deep water column and the sea floor in the Southern Ocean (discussed below), these models should pay particular attention to the mechanisms by which blooms develop near the receding ice edge in spring and summer, and to the biogeochemical consequences of enhanced primary productivity near the ice edge.

What are the sediments telling us?

The APFZ and waters to the south comprise the largest area of modern siliceous sediment accumulation in the world, accounting for at least 50% of the global removal of Si from the ocean (e.g., Tréguer et al., 1995). This accumulation of biogenic - overwhelmingly diatom - material has been taken in the past as evidence of high primary productivity, or at least high diatom productivity, in Southern Ocean surface waters (e.g., Mortlock et al., 1991). However, as discussed above, direct measurements of ^{14}C productivity and satellite images of ocean color combine to indicate that the average primary productivity of the Southern Ocean is < 50 gC m^{-2} y^{-1}, lower than that of any other oceanic region except the permanently ice-covered central Arctic (e.g., Smith and Sakshaug, 1990). This paradoxical situation - rapid, globally significant accumulation of diatomaceous sediments in a region where the annual primary productivity is very nearly the lowest on Earth - leads to two questions:

1. What processes support the formation of major opal deposits in the Southern Ocean? and,

2. When does siliceous sediment accumulation indicate a period of high primary productivity and when does it instead reflect processes similar to those occurring in the modern Southern Ocean?

Studies of the cycling of siliceous and organic matter in the water column and upper sediments of the Ross Sea suggest that differential preservation (i.e. enhanced preservation of opal over organic matter) plays a major role in the formation of opal-rich, organic-poor sediments in that system (DeMaster et al., 1992). However, the Ross Sea is a relatively shallow (300 - 700 m) nearshore area whose annual primary productivity is about 140 gC m^{-2} y^{-1}, about 3 times as high as that of the Southern Ocean as a whole (Smith et al., 1996). So the applicability of findings from the Ross Sea to the rest of the Southern Ocean is questionable. Globally, enhanced opal preservation appears to dominate over high primary productivity as the process responsible for the formation of siliceous sediments, and there is indirect evidence that enhanced preservation results from processes that are peculiar to diatom blooms (Nelson et al., 1995). If correct, and applicable to Southern Ocean deposits, this general trend would imply that the occasional, spatially restricted diatom blooms that are known to occur in the Southern Ocean in summer are the main source of the opal that is transported to the sea floor and preserved. The opal signal in modern sediments appears to be greatest in the APFZ, where surface sediments containing > 95 weight % opal occur in some places (Bareille, 1991). This observation is supported by the fact that significant diatom blooms, composed of species that are abundant in the sediments, have been observed during the European JGOFS studies in the Weddell Sea (e.g., Quéguiner et al., 1995).

The organic-poor character of surface sediments in the APFZ, and throughout the Southern Ocean, indicates that those processes that deliver diatom opal to the sea floor do not also carry significant quantities of organic carbon to the sea floor. However, areas of significant opal export from the surface layer must also be areas of significant carbon export unless the decoupling of the cycles of silica and carbon is virtually complete within the surface layer. That is clearly not the case in the Ross Sea, where sediment-trap data indicate that the C/Si ratio of particles sinking through the 250 m depth horizon is 4 - 5 times as great as the C/Si ratio in the sediments, even though those sediments are at much shallower depths and have considerably greater organic carbon content than those in the APFZ (DeMaster et al., 1992). Thus, those processes delivering opal to the seabed may greatly intensify the transport of organic carbon to the deep ocean in the APFZ, even though the decomposition of that organic material within the deep water column is virtually complete.

The APFZ appears to be an area of significant net uptake of CO_2 by the ocean (e.g., Takahashi et al., 1986). To the extent that biological pumping processes contribute to that uptake, the biogenic particle export indicated by the opal sediments of the APFZ appears to be reflected in the pCO_2 signal. So even though opal sediments may be a poor indicator of total primary productivity they may be a much better indicator of organic matter export and biologically mediated CO_2 uptake by the ocean.

Implications for field measurements: It would be useful to know whether the pelagic decoupling between the cycles of silica and carbon observed in the Ross Sea pertains also to the APFZ, where the largest and most quantitatively important area of modern opal sediment accumulation in the ocean is found. Of more direct importance to the study of carbon cycling would be an assessment of the upper-ocean processes that result in enhanced transport of diatom silica to the seabed and the degree to which organic carbon is carried to the deep ocean by those same processes. On the basis of presently available data from the Ross and Weddell Seas (e.g., DeMaster et al., 1992; Quéguiner et al., 1995), bloom areas – even though spatially restricted and of minor importance in the overall annual primary productivity of the Southern Ocean – may be of great quantitative importance in the vertical export of both siliceous and organic biogenic material.

Implications for modeling: The seabed signal in the APFZ is derived from the production and vertical export of biogenic opal while the biological component of the atmosphere-to-ocean CO_2 flux is driven by the production and export of organic carbon. This difference implies that biogeochemical models of the Southern Ocean should consider the individual dynamics of carbon, nitrogen and silica. To resolve the sediment signal and its relationship to upper-ocean processes the models should also include at least two functionally different categories of

phytoplankton – diatoms and smaller forms that neither take nor require Si. Moreover, such models should be formulated to address the possibility that there are strongly nonlinear relationships between production and export – at least for opal and perhaps for organic matter as well. Models with that degree of flexibility would be of great help in identifying relationships that result in enhanced export of opal and (perhaps) organic matter from surface waters during diatom blooms.

VI.   Recommendations

Increase accessibility to numerical models by observationalists

In the past, modelers and observationalists have often worked in isolation. This sometimes results in models that are not consistent with field measurements in either their formulation or their behavior. Often sampling programs do not resolve the appropriate temporal and spatial scales or they focus on specific processes that are either not parameterized in models or have only secondary or tertiary importance. As observations become more sophisticated in terms of both the processes that can be measured and the scales that can be resolved (both microscales and global scales), models have assumed new importance as a framework within which data may be interpreted. Moreover, the increasing focus on studies of coupled biological/physical processes and the need for scientific research to focus on the prediction of ecosystem response to climate change has also elevated the role of numerical modeling. Thus the complexity of both models and observations require a much closer interaction between those who build and operate models and those who collect and analyze data.

Large-scale coupled biological/physical models are still in a state of infancy. It would be premature to develop a single model of the Southern Ocean as it would not resolve critical physical and biological processes. Rather, efforts should be focused on a variety of models that are limited either in the scales or processes that are resolved. We expect that eventually researchers may wish to link some of these models together; this will require that the underlying assumptions be clearly stated so that inherent contradictions are avoided.

Specific Recommendations

1. Encourage Southern Ocean JGOFS and GLOBEC activities that have both a modeling and a field component
2. Develop a variety of models focusing on specific processes or hypotheses but with clearly defined interfaces and documented assumptions so that other researchers can understand and evaluate the models
3. Archive output of numerical models much as field and satellite observations are archived and distributed
4. Encourage the development of models that are structured as a set of testable hypotheses that can be addressed by appropriately designed sampling strategies

Improve modeling capabilities in advance of Southern Ocean field studies for use in designing sampling programs and analyzing data

Although present models are not capable for developing detailed sampling strategies, they can be used to develop specific hypotheses for the field component of JGOFS and GLOBEC. Emerging research areas, such as data assimilation and nested models, would benefit by expanded research in advance of the JGOFS and GLOBEC field programs. Various diagnostic techniques, such as estimating advective fluxes, could be used to design specific sampling strategies at the Southern Ocean station sites.

Specific Recommendations

1. Encourage modelers to work with researchers participating in Southern Ocean JGOFS and GLOBEC field studies
2. Encourage development of data assimilation techniques for biogeochemical modeling
3. Continue development of embedded or nested models which incorporate high resolution models within lower resolution models
4. Use models to simulate advective fluxes around planned Southern Ocean stations and compare with observations as part of model diagnostics

Improve observing capabilities to take advantage of and test numerical models

Although many observationalists consider them primitive, present models can be used to guide field programs in the types of observations that should be made to improve parameterizations and constrain model behavior. For example, many of the core JGOFS measurements are standing stock observations, yet most of the uncertainties in existing models concern rate parameters. There was a strong consensus that data must be collected on size and functional classes of the ecosystem. Although there is controversy regarding the level of detail that must be included in models, clearly there are profound implications on carbon cycling as the structure of the ecosystem changes. As assimilation techniques improve, it is essential that we develop a scientific basis for our estimates of the error fields associated with the data being assimilated into the models. This may require tedious, closely-spaced observations as these error fields may vary seasonally as well as regionally. Lastly, the Southern Ocean will always be difficult to sample using conventional ship techniques. The JGOFS and GLOBEC programs should draw upon developments in other programs to use low-cost or expendable sensors to increase the scales that can be sampled.

Specific Recommendations

1. Evaluate present JGOFS core observations in context of the needs of existing numerical models
2. Develop models that resolve critical time and space scales as identified in field measurements
3. Collect information on size and functional groups
4. Quantify error covariances for data fields that are assimilated into models
5. Continue to encourage the development of new automated and low-cost sensors to extend sampling coverage of the Southern Ocean

Establish a regular program to further the development of coupled physical/biogeochemical models

Models of the Southern Ocean ecosystem must resolve complex physical dynamics as well as complicated chemical and biological interactions. Because of the nature of the circulation in this vast region of the ocean, these models must have high spatial resolution as well. However, our overall goal should be the development of a closer alliance between models (which will always be gross simplifications of reality) and observations (which will always provide a biased and undersampled view of reality). We should continue activities that strengthen the links between these two complementary ways of looking at a complex system.

Specific Recommendations

1. Regularly assess the state of our knowledge and modeling capabilities
2. Support annual workshops where models can be run and evaluated by both modelers and observationalists

VII.   References

Abbott, M.R. 1993. Phytoplankton patchiness: Ecological implications and observation methods. In: *Patch Dynamics* (S.A. Levin, T.M. Powell, and J.H. Steele, eds.) Springer-Verlag, New York, 37-49.

Abbott, M.R., K.H. Brink, C.R. Booth, D. Blasco, C.O. Davis, M.S. Swenson, and L.A. Codispoti,. 1995. Scales of variability in bio-optical properties as observed from near-surface drifters in the California Current. *J. Geophys. Res.* 100: 13,345-13,367.

Ainley, D.G. and D.P. DeMaster. 1990. The upper trophic levels in polar marine ecosystems. In: *Polar Oceanography Part B. Chemistry Biology and Geology* (W.O. Smith, Jr., ed.) Academic Press, New York, 599-630.

Anderson, R.F. 1993. U.S. Joint Global Ocean Flux Study: Southern Ocean Science Plan. U.S. JGOFS Planning & Coordination Office, Woods Hole, 67pp.

Armstrong, R.A. 1994. Grazing limitation and nutrient limitation in marine ecosystems: Steady-state solutions of an ecosystem model with multiple food chains. *Limnol. Oceanogr.* 39: 597-608.

Armstrong, R., S. Bollens, B. Frost, M. Landry, M. Landsteiner, and J. Moisan. 1994. Food webs. In: *Biological/physical modeling of upper ocean processes* (C.S. Davis and J.H. Steele, eds.) Woods Hole Oceanographic Institution Technical Report WHOI-94-32, Woods Hole, MA, 25-35.

Banse, K. 1991. Rates of phytoplankton cell division in the field and in iron-enrichment experiments. *Limnol. Oceanogr.* 36: 1886-1898.

Bareille, G. 1991. Flux sedimentaires: Paleoproductivité et paleocirculation de l'Ocean Austral au cours des 150,000 dernieres années. Ph.D. Dissertation. Univ. de Bordeaux I. 259 pp.

Bathmann, U.V., R. Scharek and C.D. Dubischar. 1996. Chlorophyll and phytoplankton species distribution in the Atlantic sector of the Southern Ocean in spring. *Deep-Sea Res.* in press.

Chisholm, S.W. 1992. Phytoplankton size. In: *Primary Productivity and Biogeochemical Cycles in the Sea*, (P.G. Falkowski and A.D. Woodhead, eds.) Plenum Press, New York, 213-237.

Comiso, J.C. 1991. Satellite remote sensing of the polar oceans. *J. Mar. Sys.* 2: 395-434.

Comiso, J.C., C.R. McClain, C.W. Sullivan, J.P. Ryan and C.L. Leonard. 1993. Coastal zone color scanner pigment concentrations in the Southern Ocean and relationship to geophysical surface features. *J. Geophys. Res.* 98: 2,419-2,451.

Cullen, J.J. 1991. Hypotheses to explain high-nutrient conditions in the open sea. *Limnol. Oceanogr.* 36: 1578-1599.

Denman, K.L., and T.M. Powell. 1984. Effects of physical processes on planktonic ecosystems in the coastal ocean. *Oceanogr. Mar. Biol. Ann. Rev.* 22: 125-168.

de Baar, H.J.W., J.T.M. de Jong, D.C.E. Bakker, B.M. Löscher, C. Veth, U. Bathmann, and V. Smetacek. 1995. Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. *Nature* 373: 412-415.

DeMaster, D.J., R.B. Dunbar, L.I. Gordon, A.R. Leventer, J.M. Morrison, D.M. Nelson, C.A. Nittrouer and W.O. Smith, Jr. 1992. The cycling and accumulation of organic matter and biogenic silica in high-latitude environments: The Ross Sea. *Oceanography* 5: 146-153

Dugdale, R. C. and J. J. Goering. 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnol. Oceanogr.* 12:196-206.

Eppley, R.W. and B.J. Peterson. 1979. Particulate organic matter flux and organic new production in the deep ocean. *Nature* 282: 677-680.

Fasham, M.J.R., H.W. Ducklow, and S.M. McKelvie. 1990. A nitrogen-based model of plankton dynamics in the oceanic mixed layer. *J. Mar. Res.* 48: 591-639.

Fischer, G., D. Fuetterer, R. Gersonde, S. Honjo, D.R. Ostermann and G. Wefer. 1988. Seasonal variability of particle flux in the Weddell Sea and its relation to ice cover. *Nature* 335: 426-428.

Flierl, G.R., and C.S. Davis. 1996. Reduction of complexity in biological/physical models. *J. Mar. Res.,* in press.

Frost, B.W. 1991. The role of grazing in nutrient-rich areas of the open sea. *Limnol. Oceanogr.* 36: 1616-1630.

Frost, B.W., and N.C. Franzen. 1992. Grazing and iron limitation in the control of phytoplankton stock and nutrient concentration; a chemostat analog of the Pacific equatorial upwelling zone. *Mar. Ecol. Prog. Series* 83: 291-303.

Garrison, D.L. 1991. Antarctic sea ice biota. *Amer. Zool.* 31: 17-33.

Garrison, D.L., C.W. Sullivan and S.F. Ackley. 1986. Sea ice microbial communities in Antarctica. *BioScience* 36: 243-250.

Gow, A.J. and W.B. Tucker, III, 1990. Sea ice in polar regions. In: *Polar Oceanography Part A. Physical Science* (W.O. Smith, Jr., ed.) Academic Press, New York, 47-122.

Harris, G.P. 1986. *Phytoplankton Ecology: Structure, Function, and Fluctuation.* Chapman and Hall, New York, 384 pp.

Helbling, E.W., V. Viallafañe, and O. Holm-Hansen. 1991. Effect of iron on productivity and size distribution of Antarctic phytoplankton. *Limnol. Oceanogr.* 36: 1879-1885.

Hibler, W.D., III. 1992. The role of sea ice dynamics in modeling CO_2 increases. In: *Climate Processes and Climate Sensitivity*, (J. Hansen et al., eds.). Geophys. Mono., 29, 238.

Honjo, S. 1990. Particle fluxes and modern sedimentation in the polar oceans. In: *Polar Oceanography, Part B. Chemistry Biology and Geology* (W.O. Smith, Jr., ed.). Academic Press, San Diego, 687- 739.

Hurtt, G.C., and R.A. Armstrong. 1996. A pelagic ecosystem model calibrated with BATS data. *Deep-Sea Res.* 43: 653-683.

Inoue, M. 1985. Modal decomposition of the low-frequency currents and baroclinic instability at Drake Passage. *J. Phys. Oceanogr.* 15: 1157-1181.

Karl, D.M., J.R. Christian, J.E. Dore, D.V. Hebel, R.M. Letelier, L.M. Tupas, and C.D. Winn. 1996. Seasonal and interannual variability in primary production and particulate flux at Station ALOHA, *Deep-Sea Res.* 43: 539-568.

Keeling, C.D, T.P. Whorf, M. Wahlen, and J. van der Plicht. 1995. Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. *Nature* 375: 666-670.

Lawson, L.M., Y.H. Spitz, E.E. Hofmann, and R.B. Long. 1995. A data assimilation technique applied to a predator-prey model. *Bull. Math. Biology* 57: 593-617.

Lawson, L.M., E.E. Hofmann, and Y.H. Spitz. 1996. Time series sampling and data assimilation in a simple marine ecosystem model. *Deep-Sea Res.* 43: 625-651.

Lehman, J.T., D.B. Botkin, and G.E. Likens. 1975. The assumptions and rationales of a computer model of phytoplankton population dynamics. *Limnol. Oceanogr.* 20: 343-364.

Lizotte, M.P., and C.W. Sullivan. 1992. Biochemical composition and photosynthate distribution in sea ice microalgae of McMurdo Sound, Antarctica: evidence for nutrient stress during the spring bloom. *Ant Science* 4: 23-30.

Lohrenz, S.E., G.A. Knauer, V.L. Asper, M. Tuel, A.F. Michaels and A.H. Knap. 1992. Seasonal variability in primary production and particle flux in the northwestern Sargasso Sea U.S. JGOFS Bermuda Atlantic Time-series Study. *Deep-Sea Res.* 39: 1373-1391.

Longhurst, A.R. 1991. Role of the marine biota in the global carbon cycle. *Limnol Oceanogr.* 36: 1507-1526.

Longhurst, A.R. and W.G. Harrison. 1989. The biological pump: Profiles of plankton production and consumption in the upper ocean. *Progr. Oceanogr.* 22: 47-123.

Mackas, D.L., K.L. Denman, and M.R. Abbott. 1985. Plankton patchiness: Biology in the physical vernacular. *Bull. Mar. Science* 37: 652-674.

Maier-Reimer, E. 1993. Geochemical cycles in an ocean general circulation model. Preindustrial tracer distributions. *Global Biogeochem. Cycles* 7: 645-677.

Marra, J., R. R. Bidigare and T. D. Dickey. 1990. Nutrients and mixing, chlorophyll and phytoplankton growth. *Deep-Sea Res.* 37: 127-143.

Martin, J.H., S.E. Fitzwater and R.M. Gordon. 1990. Iron deficiency limits phytoplankton growth in Antarctic waters. *Global Biogeochem. Cycles.* 4: 5-12.

Michaels, A.F., N.R. Bates, K.O. Buesseler, C.A. Carlson and A.H. Knap. 1994. Carbon-cycle imbalances in the Sargasso Sea. *Nature* 372: 537-540.

Miller, C.B., B.W. Frost, P.A. Wheeler, M.R. Landry, N. Welschmeyer and T.M. Powell. 1991. Ecological dynamics of the subarctic Pacific, a possibly iron-limited ecosystem. *Limnol. Oceanogr.* 36: 1600-1615.

Mitchell, B.G., E.A. Brody, O. Holm-Hansen, C. McClain and J.K.B. Bishop. 1991. Light limitation of phytoplankton biomass and macronutrient limitation in the Southern Ocean. *Limnol. Oceanogr.* 36: 1662- 1677.

Moloney, C.L., and J.G. Field. 1991. The size-based dynamics of plankton food webs. I. A simulation model of carbon and nitrogen flows. *J. Plankton Res.* 13:1003-1038.

Mortlock, R.A., C.D. Charles, P.N. Froelich, M.A. Zibello, J. Saltzman, J.D. Hays and L.H. Burckle. 1991. Evidence for lower productivity in the Antarctic Ocean during the last glaciation. *Nature* 351: 220-223.

Nelson, D.M. 1992. Biogeochemical cycles of organic and siliceous matter in the Southern Ocean. In: *Oceanografia in Antartide* (V.A. Gallardo, O. Ferreti and H.I. Moyano, eds.) ENEA-Progetto Antartide, Italia/Centro EULA, Universidad de Concepción, Chile, 9-21.

Nelson, D.M. and W.O. Smith, Jr. 1991. Sverdrup revisited: Critical depths, maximum chlorophyll levels and the control of Southern Ocean productivity by the irradiance-mixing regime. *Limnol. Oceanogr.* 36: 1650-1661.

Nelson, D.M., P. Tréguer, M.A. Brzezinski, A. Leynaert, and B. Quéguiner. 1995. Production and dissolution of biogenic silica in the ocean: Revised global estimates, comparison with regional data and relationship to biogenic sedimentation. *Global Biogeochem. Cycles* 9: 359-372.

Oreskes, N., K. Schrader-Frechette, and K. Belitz. 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263: 641-646.

Price, N.M., B.A. Ahner, and F.M.M. Morel. 1994. The equatorial Pacific Ocean: grazer-controller phytoplankton populations in an iron-limited ecosystem. *Limnol. Oceanogr.* 39: 520-534.

Prunet, P., J.-F. Minster, D. Ruiz-Pino, and I. Dadou. 1996a. Assimilation of surface data in a one-dimensional physical-biogeochemical model of the surface ocean, 1, Method and preliminary results. *Global Biogeochem. Cycles* 10: 111-138.

Prunet, P., J.-F. Minster, V. Echevin, and I. Dadou. 1996b. Assimilation of surface data in a one-dimnesional physical-biogeochemical model of the surface ocean, 2, Adjusting a simple trophic model to chlorophyll, temperature, nitrate, and pCO_2 data, *Global Biogeochem. Cycles* 10: 139-158.

Quéguiner, B., P. Tréguer, I. Peeken and R. Scharek. 1996. Biogeochemical dynamics and the silicon cycle in the Atlantic sector of the Southern Ocean during austral spring, 1992. *Deep-Sea Res.* , in press.

Raimbault, P., M. Rodier, and J. Taupier-Letage. 1988. Size fraction of phytoplankton in the Ligurian Sea and the Algerian Basin (Mediterranean Sea): Size distribution versus total concentration. *Marine Microbial Food Webs* 3:1-7.

Siegenthaler, U., and J.L. Sarmiento. 1993. Atmospheric carbon dioxide and the ocean, *Science* 365: 119-125.

Smith, W.O., Jr., N.K. Keene and J.C. Comiso. 1988. Interannual variability in estimated primary productivity of the Antarctic marginal ice zone. In: *Antarctic Ocean and Resources Variability* (D. Sahrhage, editor), Springer-Verlag, Berlin, pp. 131-139.

Smith, W.O., Jr. and E. Sakshaug. 1990. Polar Phytoplankton. In: *Polar Oceanography Part B. Chemistry Biology and Geology* (W.O. Smith, Jr., ed.) Academic Press, New York, 477-525.

Smith, W.O., Jr., D.M. Nelson, G.R. DiTullio, and A.R. Levanter. 1996. Temporal and spatial patterns in the Ross Sea: Phytoplankton biomass, elemental composition, productivity and growth rates. *J. Geophys. Res.* 101: 18,455-18,465.

Spall, M.A. 1991. A diagnostic study of the wind- and buoyancy-driven North Atlantic circulation. *J. Geophys. Res.* 96: 18,509-18,518.

Steele, J.H., and E.W. Henderson. 1992. The role of predation in plankton models*. J. Plankton Res.,* 14: 157-172.

Takahashi, T., J. Goddard, S.C. Sutherland, D.W. Chipman and C.C. Breeze. 1986. Seasonal and geographic variability of carbon dioxide sink/source terms in the oceanic areas: Observations in the North and Equatorial Pacific Ocean 1984-1988 and global summary. Final Technical Report to the Department of Energy, Lamont-Doherty Geological Observatory, Palisades, NY, 66 pp.

Takahashi, T., J. Olafsson, J.G. Goddard, D.W. Chipman, and S.C. Sutherland. 1993. Seasonal variation of CO_2 and nutrients in the high-latitude surface oceans: A comparative study, *Global Biogeochem. Cycles* 7: 843-878.

Tans, P.P., I.Y. Fung and T. Takahashi. 1990. Observational constraints on the global CO_2 budget. *Science* 247: 1431-1438.

Totterdell, I.J., R.A. Armstrong, H. Drange, J.S. Parslow, T.M. Powell, and A.H. Taylor. 1993. Trophic resolution. In: *Towards a Model of Ocean Biogeochemical Processes*, (G.T. Evans and M.J.R. Fasham, eds.) Springer-Verlag, New York, 71-92.

Tréguer, P., D.M. Nelson, A.J. Van Bennekom, D.J. DeMaster, A. Leynaert and B. Quéguiner. 1995. The silica balance in the world ocean: A re-estimate. *Science* 268: 375-379.

Turner, D.R. and N.J.P. Owens. 1995. A biogeochemical study in the Bellingshausen Sea: Overview of the STERNA 1992 expedition. *Deep-Sea Res.* 42: 907-932.

Wheeler, P.A., and S.A. Kokkinakis. 1990. Ammonium recycling limits nitrate use in the oceanic subarctic Pacific. *Limnol. Oceanogr.* 35: 1267-1278.

Wilson, D.L., W.O. Smith, Jr. and D.M. Nelson. 1986. Phytoplankton bloom dynamics of the western Ross Sea ice edge. I. Primary productivity and species-specific production. *Deep-Sea Res.* 33: 1375-1377.

Zwally, H.J., J.C. Comiso, C.L. Parkinson, W.J. Campbell, F.D. Carsey and P. Gloersen. 1983. *Antarctic Sea Ice 1973-1976: Satellite Passive-Microwave Observations.* National Aeronautics and Space Administration Special Publication #459, Washington, DC, 206 pp.

Appendix 1.   A Sampling of Models of Southern Ocean Processes

Ice/mixed layer models

Hibler, W. D., III. 1979. A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.* 9: 815-846.

Lemke, P. 1987. A coupled one-dimensional sea ice-ocean model. *J. Geophys. Res.* 92: 13,164-13,172.

Lemke, P., W. B. Owens and W. D. Hibler, III. 1990. A coupled sea ice-mixed layer-pycnocline model for the Weddell Sea. *J. Geophys. Res.* 95: 9513-9525.

Owens, W. B. and P. Lemke. 1990. Sensitivity studies with a sea ice-mixed layer-pycnocline model in the Weddell Sea. *J. Geophys. Res.* 95: 9527-9538.

Stossel, A. and P. Lemke. 1990. Coupled sea ice-mixed layer simulations for the Southern Ocean. *J. Geophys. Res.* 95: 9539-9555.

Wind stress climatology

Trenberth, K.E., J.G. Olson and W.G. Large. 1989. A global ocean wind stress climatology based on ECMWF analyses, NCAR Technical Note, NCAR/TN-338+STR, 93 pp.

Trenberth, K.E., W.G. Large and J.G. Olson. 1990. The mean annual cycle in the global ocean wind stress. *J. Phys. Oceanogr.* 20: 1742-1760.

Hydrographic atlases

Olbers, D., V. Gouretski, G. Seiss and J. Schroter. 1992. Hydrographic Atlas of the Southern Ocean, Alfred Wegener Institute, Bremerhaven, Germany, 17 pp., 82 plates.

FRAM model

FRAM Group. 1991. An eddy-resolving model of the Southern Ocean, *EOS Trans. Amer. Geophys. Union* 169: 174-175.

Webb, D. J., P. D. Killworth, A. Coward and S. Thompson. 1991. The FRAM Atlas of the Southern Ocean, Natural Environmental Research Council, Swindon, U.K., 67 pp.

Global PE models

Bryan, K. 1969. A numerical method for the study of the circulation of the World Ocean. *J. Comp. Phys.* 4: 347-376. [GFDL model]

Semtner, A. J., Jr. 1974. An oceanic general circulation model with bottom topography, Numerical Simulation of Weather and Climate, Technical Report No. 9, Department of Meteorology, University of California, Los Angeles, 99 pp.

Semtner, A. J., Jr. and R. M. Chervin. 1988. A simulation of the global ocean circulation with resolved eddies. *J. Geophys. Res.* 93: 15,502-15,522.

Semtner, A. J., Jr. and R. M. Chervin. 1992. Ocean general circulation from a global eddy-resolving model. *J. Geophys. Res.* 97: 5493-5550.

Regional PE models

Haidvogel, D. B., J. L. Wilkin and R. Young. 1991. A semi-spectral primitive equation circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. *J. Comp. Phys.* 94: 151-185. [SPEM]

Blumberg, A.F. and G.L. Mellor. 1987. A description of a three-dimensional coastal ocean circulation model. In: *Three Dimensional Coastal Ocean Models*, Vol. 4, (N. Heaps, ed.) American Geophysical Union, Washington, DC, 208pp. [Princeton Ocean Model]

Layer PE

Bleck, R. and L.T. Smith. 1990. A wind-driven isopycnic coordinate model of the north and equatorial Atlantic Ocean. I. Model development and supporting experiments. *J. Geophys. Res.* 95: 3272-3285.

Oberhuber, J.M. 1993. Simulation of the Atlantic circulation with a coupled sea ice - mixed layer - isopycnal general circulation model. Part I. Model description. *J. Phys. Oceanogr.* 23: 808-829.

Mixed layer models

Martin, P.J. 1985. Simulations of the mixed layer at OWS November and Papa with several models. *J. Geophys. Res.* 90: 903-916.

Large, W.G., J.C. McWilliams, and S.C. Doney. 1994. Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Rev. Geophys.* 32: 363-403.

Appendix 2.   Background Papers

Modeling the Southern Ocean Ecosystem: Overview of physical processes

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Introduction

Most processes affecting oceanic ecosystems occur in the upper few hundred meters of the water column, even in the Southern Ocean where the water tends to be very clear. However, it is possible in some cases that more of the water column is important. For example, negatively buoyant planktonic eggs and larvae or organisms that have a resting stage (or diapause) can sink to considerable depths. This overview will focus mainly, but not exclusively, on near surface physical processes that influence the Southern Ocean ecosystem.

The purpose of this overview is to review physical processes in the Southern Ocean that affect the ecosystem. Given the surface intensified nature of oceanic ecosystem, the bulk of the overview will consider physics near the ocean surface. However, the Southern Ocean is weakly stratified so some physical processes influence the whole water column. Additionally, dynamics will be different in the shallow coastal areas as compared to the deep ocean so it is necessary to discuss these two general regions separately. It is quite likely that the nature of the ecosystem over the continental shelves is different from that in the open ocean so this division of the subject seems natural.

The most obvious surface physical structure is the mixed layer that is driven by wind mixing and density convection. These layers are thicker in the winter and, in the Southern Ocean, can be 100 to 600 m thick. During the warmer months, surface warming and freshwater from melting ice create one or more stratified seasonal mixed layers of 10 to 50 m thick (which is more typical of mixed layers in non-polar regions of the World Ocean). The deepest mixed layers seem to occur in the Weddell sea, while open ocean and coastal areas have winter mixed layers of 100 to 200 m or so. The reasons for these regional differences have to do with the water stratification and the atmospheric forcing.

A less obvious general feature of the Southern Ocean is that thermodynamic processes are much more important than at lower latitudes. This statement may be obvious, but much of our modeling experience is with non-polar oceanic systems and we may be misunderstanding or misrepresenting processes in polar environments. One particular feature of polar environments is that water density, at temperatures near freezing, is controlled strongly by salinity and is only weakly influenced by temperature. It is possible, then, for water at depth to be warmer than that above it. For example, winter mixing creates near-freezing water down to 100 m or so which is capped in the summer by warmer water. Organisms can then experience relatively warm surface water (2°C), cold subsurface water (less than -1.5°C) and deeper water as warm as 1°C. Given the large Q_{10} of biological processes in the polar regions, this may represent the extreme range for the temperature tolerance of some organisms and it can be experienced during daily vertical migration. The temperature structure may also create ecologically desirable depth zones for some organisms. The focus of these comments is on temperature with the assumption that salinity variations do not have a similar effect on ecological processes. The truth of this assumption is not known (to me, in any case).

Sea ice is a clearly perceived feature of the Antarctic environment and it is well known to have a strong influence on thermodynamic exchange across the ocean surface. It also provides a mechanism to create dense water by releasing salt during freezing or to create stratified surface layers through melting. Ice freezing in one place and melting in another produces a salt flux which

may be much larger than the surface precipitation- evaporation imbalance. A less obvious, perhaps, effect of ice is to create a habitat or a transport mechanism for some organisms (for example, krill).

Observations of marine ecosystems in the Southern Ocean are very difficult because of the large size of the system and its remoteness. Satellite based observations have been very helpful in other parts of the ocean; they are less so in the Southern Ocean because of the persistent cloud cover and the high latitude (some satellites are limited in the latitude coverage). One can obtain good information on ice concentration, surface elevation and wind stress from sensors that are not strongly affected by clouds. There is considerable difficulty in using either infrared or visible band instruments that are completely blocked by clouds. The presence of ice may have an effect on altimeter measurements because of the change in reflection characteristics. The scatterometer (which estimates wind stress) will be rendered useless by ice cover since the instrument depends on capillary waves on the ocean surface. The effect of partial ice cover on the performance of either instrument is not known to me.

All physical models need information about fluxes (momentum, heat, freshwater) at the ocean surface. The Southern Ocean is deficient in ship traffic so climatologies based on ship reports are poor compared to similar estimates for other parts of the ocean. Some attempts have been made to use atmospheric circulation models from global weather centers (for example, the European Centre for Medium Range Weather Forecasting) to estimate ocean-atmosphere exchange for the Southern Ocean (D. Olbers, personal comm. referring to unpublished work by A. Stossel). These estimates of forcing have the benefit of being available 2 to 4 times per day, but the quality of the estimates have not been verified extensively.

In general, there is a mismatch in scales between biological and physical processes and this difference manifests itself in the different character of models for these systems. Many biological organisms in the ocean occur as small patches with vertical extents of a few meters and horizontal extents of a few tens of meters. These scales are much smaller than can be represented by circulation models at the present time. There will need to be some sort of "sub-grid scale" parameterization to represent the biological processes in the current family of ocean circulation models. On the other hand, the length scales in oceanic flow are known to be 1 km or larger (except for internal waves, vertical convection and turbulence). Therefore, it may be possible to limit the resolution of the circulation model and put computational resources into a fine grid to consider patch level biological processes. Careful thought is required when combining physical and biological models.

Large Scale Dynamical Processes

Large scale dynamical processes are those that operate on the scale of the whole Southern Ocean. Most of the study of this scale has focused on the dynamics of the Antarctic Circumpolar Current (ACC) which is now thought to be well understood.

The general dynamical balance in the Southern Ocean is that the flow is forced by the atmospheric westerlies that drive eastward flow (the ACC). Since the flow is driven at the surface, vertical shear develops which is supported by lateral density gradients (thermal wind balance). When the shear is sufficiently large, the flow becomes dynamically unstable (baroclinic instability). The eddies that are created deform the interior density surfaces (makes them lumpy) creating internal form drag that transmits downward the momentum transferred from the surface winds. This instability releases potential energy (reduces the slope of the density surfaces) and in the process transmits dense water towards the equator (poleward heat flux). When the momentum reaches the bottom, form drag (pressure difference across a bottom feature) on the bottom topography removes the momentum to slow the flow. A balance occurs when the bottom form drag balances the surface wind stress (Johnson and Bryden, 1989; Marshall et al. 1993; Olbers, 1994). The transient eddies in this process are a critical part of the downward transmittal of momentum and so must be represented properly (either explicitly in an eddy resolving model or parametrically as some sort of vertical viscous process).

It is important to note that flow paths that circle Antarctica and do not contact continental boundaries or bottom topography (generally the layer from 500 m to 2000 m depth) are required to have transient eddies to transfer momentum downward (dynamics do not allow a geostrophically balanced, zonally averaged, net meridional transport). These eddies produce a

poleward heat flux, but they should also transport other water properties (nutrients, plankton, etc) across the ACC. These fluxes have not been measured to my knowledge.

One important feature of the Southern Ocean is that the water is weakly stratified, compared to stratification at subtropical latitudes. Weak stratification gives rise to a short dynamical scale, the first internal radius of deformation, which ranges from 20 km to 8 km, decreasing to the south (Inoue, 1985). This scale defines the width of jets and the size of mesoscale eddies and has a considerable impact on sampling and numerical modeling. In general, both model grids and sampling are at scales that are larger than this dynamical scale which produces aliasing in observations and bad behavior in numerical models. The weak stratification has the further effect that flow disturbance at the bottom of the ocean penetrate to the surface so the ACC is much more strongly affected by bottom topography than flow in mid-latitudes. Additionally, the small dynamical scale means that smaller features in the bottom topography can have large-scale dynamical effects and must be included in circulation models.

One final comment on the eddies is that they can create a convergence of momentum that produces narrow, meandering jets (Eliason-Palm flux). Treguier and Panetta (1994) use a model to show that two jets can be created for a broad region of wind forcing like the Southern Ocean, but the two jets they model are separated by 50 internal radii instead of 5 internal radii which is observed in the ACC. Altimetry can be used to verify the location and size of the ACC jet cores without having to use a geoid (Gille, 1994). The newly released geoid from the US Navy should make these analyses of altimetric observations easier.

Regions of strong eddies seem to be confined to limited geographical regions and to the area between the Subantarctic Front and the Polar Front (Nerem et al. 1994). Polar Frontal zone should be packed with eddies and the effect of this strong stirring on the ecosystem is not clear. Eddies may not have a strong influence on the ecology of the area since they provide stirring but not sources and sinks (transport into or out of the region. Recall that the effect of the eddies is to cause a convergence of momentum and it should be accompanied by convergence of other properties.). Is this true? This region of the ACC is clearly biologically active as evidenced by extensive diatomaceous (siliceous) sediments observed under the mean position of the ACC.

Models of the large scale circulation have been generally successful, but the major test has been the total transport through Drake Passage which was measured for 14 months (1979-80). Both FRAM and Semtner-Chervin models calculate transports for the ACC (190-200 Sv) that are larger than measured values (130 Sv) in spite of realistic forcing. Why?

Large scale circulation models do not represent well processes near the continental slopes. Small scale (1-5 km) bottom features also are shown to be important (small gaps in mid-ocean ridges are important for guiding flow or providing flow path for abyssal water). These small features of topography can have dynamical and thermodynamical effects but are not well represented in these models because of the grid box nature of the model and the (relatively) large values of grid spacing.

Dynamical Processes Near Continents

A general feature of the continental shelves around Antarctica is that they tend to be somewhat deep (200 to 500 m) with very rugged bathymetry. The depth is likely related to the continental depression due to ice loads or due to glacial scraping. A side feature of ice loading is that the shelves often deepen onshore creating shallow containers in which dense water can collect. The rugged bottom topography is due to the very low runoff from the continent that limits the delivery of continental sediments to the near-shore oceanic areas. In lower latitude systems, sediments fill in the low spots to create smoother bathymetry. Because of weak stratification, the circulation on the shelf is likely to be strongly controlled by the rugged bottom topography. As in the large scale dynamics, the dynamical scale can be 10 km or less, which means that small scale bathymetry can be quite important to the dynamics of the coastal environment.

Most of the work on Antarctic shelves has either been general surveys or has focused on the processes that create dense bottom water. There are relatively few studies of general circulation along any section of the shelf that makes this topic an open area of study. This lack of observations means that we do not know the relative importance of wind and thermodynamic forcing on these shelves. Furthermore, we do not know the magnitude or character of tidal

currents nor do we know about the general circulation directions. The weak stratification and deep mixed layers mean that geostrophic calculations of flow are of limited use. It is very likely that there are strong seasonal differences in physical processes because of ice. We can be guided by a number of mature studies of the Arctic Ocean, but the two systems are rather different so one can not just import ideas without careful consideration.

Continental shelf circulation is generally forced both locally and remotely. Local forcing occurs through wind (mainly) and surface thermohaline (less important) forcing. Additional local forcing occurs at the coast due to fresh water runoff from the continent or at the shelf break if there is a strong coastal current (say, an oceanic boundary current) that is driven by large scale processes. Remote forcing occurs because waves propagate along continental shelf and slope which bring information, after some time delay, about flow variations far removed from the region of interest. Since these waves propagate with the coast to the left (looking in the propagation direction in the Southern Hemisphere), the direction of influence for a region is easily determined.

Surface fluxes over Antarctic shelves are poorly known because of the limited number of coastal stations and the small number of ships that transit the area. Information from coastal weather stations must be used with care due to the tall mountains that are common around Antarctica. Some effort is being made to place automated weather stations away from the coast on low islands. These stations will be a great help, but it will take a while for a useful network to be put in place. Another option for estimating surface fluxes to the ocean is through global atmospheric circulation models. However, the quality of these estimates over the continental shelf has not been checked.

A second interesting feature of Antarctic shelves is that, except near the Weddell Sea, the southern part of the ACC flows along the shelf break. The bulk of the water in this flow is Circumpolar Deep Water (CDW, basically North Atlantic Deep Water which has been absorbed into the deep levels of the ACC) which is relatively warm (around 2°C), oxygen poor and nutrient rich. Because of the tilt of density surfaces in the ACC, this water mass occurs at about the depth of the shelf break at many places around the Antarctic continent. This water is observed to flood the continental shelf, by some dynamical process that has not been identified, bringing with it heat and nutrients. The heat provides a balancing effect for the strong winter cooling and may explain why wide areas of the Antarctic Continent thaw during the summer. For example, this may explain why the central areas of the Antarctic Peninsula are relatively ice free compared to areas in the Weddell Sea at the same latitude (separated by the relatively narrow Peninsula mountain range). This import of warm, salty water onto the shelves creates a relatively persistent temperature structure with cold (-1.5°C) water at the bottom of the mixed layer (100 m) and water as warm as 1.5°C below. This layer of deep, warm water may be very important for many biological processes.

A further effect of this import of CDW is that nutrients are brought onto the shelf and this may have some bearing on the observations of relatively high nutrient concentrations, even in the summer (although other processes may explain this excess, such as light limitation, micro-nutrient limitation, top-down control of primary production, etc.).

Ice is a critical element in the coastal environment because of its influence on exchanges with the atmosphere and because of the role that it plays in the thermodynamics of the coastal environment. Ice coverage is different (different thicknesses and different timing for freezing and thawing) in different regions around the continent due to heating from offshore (import of CDW across the shelf break), because of different heating during the summer (different stratification) or because of ice transport by the circulation. Ice has also been proposed to have an effect on the ecosystem by providing a habitat for some organisms. All of these processes are likely to have different relative importance in different parts of the Antarctic coastal environment.

Timely Questions and Observations

Is the thermodynamic forcing of Antarctic shelves as important as wind forcing? Lower latitude coastal systems are forced at the coast and shelf break, while Antarctic systems are forced everywhere along the surface. What is the effect of strong thermodynamic forcing over shallow water? Is this important? Is it important only along some parts of the coast? What process brings CDW up onto the Antarctic shelves? Possible processes are 1) wind driven upwelling, 2) topographic steering by coastal bathymetry, 3) dynamic instability of alongshore flow at the shelf break, or 4) secondary circulation driven by thermohaline forcing.

Can products calculated from atmospheric forecast models be used to estimate fluxes between the atmosphere and ocean (wind stress, heat and freshwater fluxes) with sufficient precision to be useful in the next generation of models (whether they are mixed layer [z,t], coastal or oceanic)? Do these models work well near the coast or does some sort of regional atmospheric model representing the local land topography and driven by the large scale atmospheric conditions (or some other correction) need to be used to specify correctly the atmospheric fluxes over the coastal areas?

FRAM and Semtner-Chervin models (both of which are based on the model code developed by Kirk Bryan at NOAA-GFDL) have large transports (190-200 Sv) relative to measured values in spite of realistic topography and surface forcing. Why? Possible difficulties could be 1) incorrect surface forcing, 2) need for daily varying surface forcing rather than averaged monthly fluxes, 3) poorly represented bottom topography and bottom slope, 4) poorly represented coastal areas, 5) problems with bottom form drag calculation in areas of steep topography, 6) excess viscosity required to remove small scale numerical errors, or 7) numerical problems using a B-grid model where the internal radius of deformation is resolved by the grid.

Problems focusing on the ACC, especially away from the "choke points" could benefit from a cluster of moorings in the open ocean away from mid-ocean ridges and sea-mounts. The study would look at eddy effects in the free ACC (combined with altimetry and scatterometer observations). Moored biological sensors could address effects of eddies on transport of phytoplankton or nutrients.

References

Gille, S. T., 1994. Mean sea surface height of the Antarctic Circumpolar Current from Geosat data: method and application. J. Geophys. Res., 99, 18,255-18,273.

Inoue, M., 1985. Modal decomposition of the low-frequency currents and baroclinic instability at Drake Passage. J. Phys. Oceanogr., 15, 1157-1181.

Johnson, G. C. and H. L. Bryden, 1989. On the size of the Antarctic Circumpolar Current. Deep-Sea Res., 36, 39-53.

Klinck, J. M., 1992. Effects of wind, density and bathymetry on a one-layer Southern Ocean model. J. Geophys. Res., 97, 20,179-20,189.

Marshall, J., D. Olbers, H. Ross and D. Wolf-Gladrow, 1993. Potential Vorticity Constraints on the dynamics and hydrography of the Southern Ocean. J. Phys. Oceanogr., 23, 465-487.

Nerem, R. S., E. J. Schrama, C. J. Koblinsky and B. D. Beckley, 1994. A preliminary evaluation of ocean topography from the TOPEX/POSEIDON mission. J. Geophys. Res., 99, 24,565-24,583.

Olbers, D., 1994. Is there a direct relation between the zonal wind stress and the poleward heat transport in the Southern Ocean? unpublished manuscript, 12pp.

Stossel, A., P. Lemke and W. B. Owens, 1990. Coupled sea ice-mixed layer simulations for the Southern Ocean. J. Geophys. Res., 95, 9539-9555.

Treguier, A. M. and R. L. Panetta. 1994. Multiple zonal jets in a quasi-geostrophic model to the Antarctic Circumpolar Current. J. Phys. Oceanogr., 24, 2263-2277.

Speculation on the Uncertainties of Biological-Physical Interactions in the Southern Ocean

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The Southern Ocean, here defined as the entire region below the sub-tropical convergence, is a physically heterogeneous region that cannot be characterized simply. For example, it is partially seasonally ice-covered, which greatly influences air-sea interactions and modifies the temporal impacts and nature of vertical mixing processes. It exhibits a vast range of physical properties that vary seasonally (e.g., surface temperature, solar irradiance, wind stress), and hence is highly dynamic. Furthermore, we now are beginning to observe and understand that these large-scale variations also have counterparts on the small- and mesoscale.

Because temperature limits the absolute rates of biological reactions, biological processes in polar regions are expected to be more strongly impacted by physics than temperate or tropical waters. That also implies that the biological effects often can be more difficult to experimentally quantify than in other regions. For example, if phytoplankton doubling times are 0.15 d^{-1} and grazing rates of 0.06 d^{-1}, the resultant growth rate (0.09 d^{-1}) is difficult to measure over appropriate time scales without introducing additional potential error from other experimental artifacts (e.g., adaptation to experimental irradiance field, bottle effects, etc.). Certainly grazing rates via the use of current JGOFS dilution techniques are problematic. Therefore temperature is of primary importance to both modeling efforts and experimentalists, and its effects and problems should never be overlooked.

It also has been observed that the Q10 values at very low temperatures in the Southern Ocean are often extreme. If that finding is a general characteristic of Antarctic organisms, some areas like those seasonally covered by ice, may experience a temperature effect due to solar heating of a shallow surface layer. Such an effect has been suggested previously, but it quantitative influence has never been adequately addressed. Heating of surface layers occurs over broad areas (e.g., the Ross Sea) during the austral summer, and hence any heating effect might have wide impacts. It is also noteworthy that Eppley's (1972) treatment of temperature effects on phytoplankton doubling rates did not include any data below 2°C, and despite its application to colder waters, the strength of the relationship has never been thoroughly tested.

Productivity in the Southern Ocean can be controlled by either irradiance, nutrients, micronutrients (e.g., trace metals), or/and grazing. A variety of authors have provided evidence for specific controls at some points in time and space by each. The following is an incomplete listing of recent papers on each:

Irradiance: Nelson and Smith (1991), Mitchell et al. (1991)

Trace metals: Martin et al. (1991), DiTullio and Smith (in press), Buma et al. (1991)

Grazing: Frost (1991), Mitchell and Holm-Hansen (1991).

It is likely that the limitation of productivity varies temporally and spatially throughout the Southern Ocean, and models cannot assume that only one is operative on all scales.

A detailed whole-ocean investigation using available CZCS data was conducted by Sullivan et al. (1993), and a corollary study was conducted by Comiso et al. (1992). Sullivan et al. (1993) concluded that the pigments surrounding Antarctica were asymmetrically distributed, whereas most geophysical properties (bathymetry, hydrography, wind stress, eddy kinetic energy; see

also McClain et al., 1991) were distributed symmetrically around the continent. One parameter, silicic acid concentration, was more highly correlated with phytoplankton biomass, and it was suggested that low levels limited the growth of diatoms. However, this conclusion was based on early data that suggested that diatoms had high affinity constants for $Si(OH)_4$, and these high constants have not been verified by more recent field work (Nelson and Trégeur, 1992). Sullivan et al. (1993) also suggested that large blooms occurred downflow of continental shelf regions, and hence were areas of substantial iron input into surface waters. Experimental evidence for iron concentration increases is lacking, however. Taken as a whole, the data presented by Sullivan et al. (1993) suggest a system dominated at all scales by "bottom-up" processes.

The detailed correlations between various parameters suggests potential factors influencing phytoplankton growth in the Southern Ocean, but just as often the correlations do not appear to be causal in nature. For example, the Geosat-derived eddy kinetic energies are highly correlated with bottom topography in many locales, which presumably suggests that local upwelling and nutrient injection are occurring which stimulates phytoplankton growth. However, given the high levels of nutrients present initially in many locations, the cause of such a stimulation remains elusive. Furthermore, in other areas the correlation is negative, suggesting increased mixing and decreased phytoplankton growth. There are also areas that have extensive mixing and are correlated with low phytoplankton biomass; conversely, there are areas that are traversed by receding ice edges but have generally elevated phytoplankton biomass. These relationships suggest control via the irradiance/mixing regime over broad spatial scales. Field studies, specifically the British JGOFS work, have failed to demonstrate a close relationship between phytoplankton biomass, meltwater input, and vertical stratification over periods of weeks to months, and their results suggested that for their study area (the Bellingshausen Sea) frontal enhancement of phytoplankton biomass and growth was critical. Studies in the Weddell Sea marginal ice zone also have documented the importance of frontal zones to phytoplankton biomass accumulation.

The case for limitation of phytoplankton biomass and hence production by grazing is less direct. Much of the work has been either through modeling using simple N-P-Z formulations or analogy to other high nutrient, low biomass regions. Few direct experiments have been conducted on the role of microzooplankton in pelagic systems, and experiments using macrozooplankton/krill are difficult to interpret over broader scales due to the heterogeneous distribution of the organisms.

Given the rates of ingestion of particles that have been observed, the potential for grazing limitation exists, but the actual experimental description of such a limitation is lacking.

Satellite information clearly provides the best spatial coverage of the Southern Ocean, but temporal aspects of specific regions remain elusive. This is in large part due to the logistic difficulty of having a ship (or platform) located in one region through a large part or all of the growing season of phytoplankton. Merging different years of data to produce a coherent temporal pattern is often difficult, given the known variations in ice conditions and other physical forcing functions. Indeed, the satellite composites used by Sullivan et al. (1993) are averages over long periods of time, and hence the error associated with any specific location is large.

What we need to know

Much of the Southern Ocean remains poorly sampled. To test specific hypotheses on the limitations of productivity, we need to tightly couple models with field work. The following are brief examples of areas that might integrate modeling and field work:

THE ROLE OF IRON: Given the relatively deep nature of the continental shelf and slope region, how do vertical processes (e.g., mixing) contribute to the resuspension and regeneration of materials and species? Can the sediments of the continental shelf provide iron to supply the requirements of phytoplankton growth during the growing season? A priori the answer is yes, in that iron stimulation does not appear to be operative on shelves, but a coupled biological-physical model that includes the effects of iron might elucidate the role of iron cycling, turnover, vertical mixing, ice input of iron, etc. Conversely, in deeper (off-shelf) regions of restricted aeolian iron input, can vertical processes provide iron to support surface productivity, or would models suggest that productivity is iron limited?

SATELLITE PATTERNS: If the data provided by satellite composites are approximately correct, what causes the differences in phytoplankton biomass among regions with high eddy kinetic energies and those with low EKE's? How can these differences be resolved knowing what we know about mixing/irradiance regimes? Can large-scale models resolve the patterns of phytoplankton biomass?

GRAZING LIMITATION: In regions of the Southern Ocean that remain ice-free and are observed to be characterized by consistently low phytoplankton biomass, can N-P-Z models adequately address the dynamics of such systems? Do the loss terms have to be extensively modified and made more realistic in order to more closely reflect the conditions found in the ocean?

ICE-COVERED REGIONS: Large areas of the Southern Ocean are ice covered and hence are impacted by receding ice edges. However, not all regions are the sites of biomass accumulation as originally suggested. Can models accurately couple ice sub- models to realistic 3D coupled physical-biological models to predict the effect of receding ice edges? Can the effects of winds on the ice be incorporated to produce mesoscale models of coastal polynyas? Finally, because snow has the greatest attenuation of irradiance (relative to water or ice), can stochastic or probabilistic snow fall be incorporated into models of ice-covered regions?

SUB-TROPICAL CONVERGENCE: The sub-tropical convergence is known to be the site of biomass accumulation as well as the removal of silicic acid to low concentrations, but not of nitrate to the same degree. Can models suggest rates of nutrient input and regeneration (and phytoplankton losses) that are necessary to maintain this state over long (many weeks) time periods?

References

Buma, A.G., H. de Baar, R.F. Nolting and A.J. van Bennekom. 1991. Metal enrichment experiments in the Weddell-Scotia seas: Effects of iron and manganese on various plankton communities. Limnol. Oceanogr. 36: 1865-1878.

Comiso, J.C., C.R. McClain, C.W. Sullivan, J.P. Ryan and C.L. Leonard. 1992 coastal zone color scanner pigment concentrations in the Southern Ocean and relationships to geophysical surface features. J. Geophys. Res. 98: 2419-2451.

DiTullio, G.R. and W.O. Smith, Jr. Studies on dimethylsulfide in Antarctic coastal waters. In Proceedings of the Sixth SCAR Symposium on Antarctic Biology (ed. D. Walton), Elsevier (in press).

Eppley, R.W. 1972. Temperature and phytoplankton growth in the sea. Fish. Bull. 70: 1063-1085.

Frost, B.W. 1991. The role of grazing in nutrient-rich areas of the open sea. Limnol. Oceanogr. 36: 1616-1630.

Martin, J.H., R.M. Gordon and S.E. Fitzwater. 1991. The case for iron. Limnol. Oceanogr. 36: 1793-1802.

McClain, C.R., C.J. Koblinsky, J. Firestone, M. Darzi, E. Yeh and B.D. Beckley. 1991. Examining several Southern Ocean data sets. EOS 72: 345,351.

Miller, C.B., B.W. Frost, P.A. Wheeler, M. Landry, N. Welschmeyer and T. Powell. Ecological dynamics in the subarctic Pacific, a possibly iron-limited ecosystem. Limnol. Oceanogr. 36: 1600-1615.

Mitchell, B.G., E. Brody, O. Holm-Hansen, C. McClain and J. Bishop. 1991. Light limitation of phytoplankton biomass and macronutrient utilization in the Southern Ocean. Limnol. Oceanogr. 36: 1662-1677.

Mitchell, B.G. and O. Holm-Hansen. 1991. Observations and modeling of the Antarctic phytoplankton crop in relation to mixing depth. Deep-Sea Res. 38: 981-1008.

Nelson, D.M. and W.O. Smith, Jr. 1991. Sverdrup revisited: critical depths, maximum chlorophyll levels, and the control of Southern Ocean productivity by the irradiance-mixing regime. Limnol. Oceanogr. 36: 1650-1661.

Nelson, D.M. and P. Tréguer. 1992. Role of silicon as a limiting nutrient to Antarctic diatoms: evidence from kinetic studies in the Ross Sea ice-edge zone. Mar. Ecol. Progr. Ser. 80: 255-264.

Sullivan, C.W., K.R. Arrigo, C.R. McClain, J.C. Comiso and J. Firestone. 1993. Distributions of phytoplankton blooms in the Southern Ocean. Science 262: 1832- 1837.

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The Ocean is an extremely complicated system containing many types of physical, chemical and biological processes. Modeling these processes is an arduous task that requires the combined skill of many ocean scientists. Indeed, modeling of the ocean system should be looked upon as a tool for synthesizing those known key processes that play a significant role in the Ocean system as a whole. Over the past decade there has been increased activity in the use of coupled physical-biological models. As an example, the 1994 Woods Hole Program of Summer Study in Geophysical Fluid Dynamics focused on bio-physical models of oceanic population dynamics. With respect to Southern Ocean ecosystem, Michael Sissenwine noted that modeling , "is particularly important for multi-disciplinary, multi-national situations where observations are made and ideas evolve independently. A model is a synthesis of these observations and ideas."

Biological models fall under a wide variety of groups. The discussion for this talk will focus on food web models (Moisan, 1992), size-based models (Moloney and Field, 1991;), structured population models (Hofmann and Ambler, 1988) and trophic/generalized food web models (Fasham et al., 1990).

Similar problems arise in all of these models that not only continue to go unresolved but demand much of the time spent in development of a specific model. These problems will prove to be even more difficult and time consuming as we attempt to adapt these models to fully three-dimensional coupled physical-biogeochemical models. Many of these problems have been explicitly outlined in the proceedings of a NATO Advanced Research Workshop entitled, "Towards a Model of Ocean Biogeochemical Processes" (Evans and Fasham, 1993).

Independent of which type of model is chosen, all of the above models typically consist of a set of coupled partial differential equations that govern the space and time distribution of a non-conservative quantity, and are of the form;

$$\frac{\partial B}{\partial t} + \left(V + V_{biology} \cdot \nabla B\right) - \nabla(K\nabla B) = S \qquad (1)$$

where B is a non-conservative quantity (one of the components in the biogeochemical model); v is the velocity of the fluid, $v_{biology}$ is the vertical sinking rate and/or behavior of the biological components; K is the kinematic eddy diffusivity (which at a minimum should vary with both time and depth); and, S is the source and sink terms for the biogeochemical processes.

Many such systems of equations are in use today in ecosystem modeling. In developing these types of models, the chief task of the biological modeler is: to determine how many of these equations are needed; to determine how each of the model constituents interact with each of the other constituents (i.e. how are they interconnected by processes such as nutrient uptake, grazing, death and remineralization); to determine how to parameterize this flow of material, such

as carbon, nitrogen or some other chemical species; and, finally, to incorporate any behavior processes such as vertical migration or food selection.

The focus of this talk is to see if we can achieve a better, more dynamic, technique for determining how many of these equations are actually needed and what the terms are for S for any given ecosystem. This is currently the key task of the biogeochemical modeler. The impetus for searching for a better technique is due in part to the inability of present day models to adapt to different ecosystems. Indeed, most models must be "reconfigured" for each individual ecosystem modeled. The true test of whether a global biogeochemical model "works" is for it to be able to not only predict the important controlling biological mechanisms [i.e. is the Antarctic iron limited or grazing controlled?], but also predict the productive capacity and food web patterns of that specific ecosystem or biogeographic region. While this of course seems like an impossible task given our current state of model parameter "hardwiring", it is a course of research that offers a new hope in the drive to develop a global biogeochemical model for the Ocean.

Food Webs

We first begin by comparing how natural and model food webs or biogeochemical systems are constructed.

To simplify the discussion and comparison of specific model types, all of these component interactions can be placed into a cascade model format (Cohen and Newman, 1985; Newman and Cohen, 1986), an example of which is shown in Table 1. The source/sink term , S, in equation 1 is calculated by summing the column rates of material inflow and subtracting the row of material outflow for each model constituent. As an aside, this technique for calculating S is also a more pragmatic programming technique since it assures conservation of material flow.

From/To	SiO_4	NO_3	NH_4	DET	LPP	SPP	COP	DOL	EUP
SiO_4					1	1			
NO_3					1	1			
NH_4					1	1			
DET	1		1					1	
LPP				1			1	1	1
SPP				1				1	
COP			1	1					1
DOL			1	1					
EUP			1	1					

Table 1. Example of a cascade model. A "1" denotes a flow of material from one food web component to another. DET = detritus, LPP = large phytoplankton, SPP = small phytoplankton, COP = copepods, DOL = doliolids, and EUP = euphausiids.

The Cascade Model (CM) was first presented by Newman and Cohen (1986) as a way to analyze the many different types of food webs actually observed in nature. If we restructure all of the known actual ecosystem models (not numerical models, but actual descriptive models of known ecosystems), we begin to see similarities in their structure even as the food webs change in complexity. The first observation that should be strongly noted is that the CM matrix is sparse. While the maximum number of possible interactions,

$$I_{max} = N * N \qquad (2)$$

the average number of actual interactions,

$$\bar{I} = 2 * N \qquad (3)$$

This is good news for all modelers who are contemplating whether to increase the number of constituents or "bugs" in their ecosystem model. Several other patterns arise from this matrix when the abiotic interactions of the ecosystem are added to it. These patterns that are observed

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to occur in natural food webs allow us to make more general statements as to how food web constituents interact.

Present work in this area of food chain research has lead to the development of a dynamic food chain model (Cohen et al., 1990), which examines a hybrid model that combines Lotka-Volterra population dynamics with the Cascade Model's food web structure (LVCM). This more dynamical approach to development of food web models has already been incorporated, although not in a stochastic sense, into a size-based food web model (Armstrong, in press).

The need for incorporating food web dynamics into existing biogeochemical models arises from the need to better simulate the effects that species succession can have on nutrient dynamics and the carbon cycle. The models currently in use today do not allow for such time varying food web structures. However, such time varying food web structures have been observed to occur in nature (Schoenly and Cohen, 1991).

Material Flow Rates

Along with food web structure, the rates of flow of material, such as carbon, nitrogen, silicate, etc., is another important area that needs to be addressed in future modeling efforts. Source/Sink terms for these models include nutrient uptake, growth, excretion, egestion, respiration, death, grazing, predation, remineralization and other interactions. As a rule, a more realistic and dynamic model can be created if these rates are calculated using first principles. One issue that I have yet to resolve with myself is whether allometric equations (Moloney and Field, 1989) are as close as we are going to get to such first principle relationships for the biological mediated interactions.

Why not use real measured rates for these interactions? Indeed, field biologists spend incalculable amounts of time collecting such rates. Part of the answer lies in the truth that a measured rate is in fact only the mean value of all the individual rates within a given biological sample from a specific environment.

These measured rates tell us very little about the organism's or population's ability to adapt to changes in their environment. For example, Wood (1992) points out that, "without an estimate of intra-group variation, it is impossible to determine whether or not the differences observed between nominal phytoplankton groups ("species" or otherwise) are any greater than might be observed in a random sample of different members of the same group." In a region like the Antarctic, this point is even stronger due to the paucity of data.

How can these problems be solved? Perhaps we need a more theoretical approach when dealing with biological rates. Are there rules that, like the laws of momentum, allow us to constrain these rates in the biological models? Several biological models have already begun to incorporate these types of rules. As an example, Moisan (1992) incorporated Leibig's "Law of the Minimum" (DeGroot, 1983) into a phytoplankton growth equation that contained three different macronutrients (silicate, nitrate and ammonium). However, these rules are also dependent upon measured variables that again are constrained as constant values in the model.

As an alternative to these types of parameter or even behavior "hardwiring" techniques, Mangel and Clark (1988) present a dynamical approach to modeling biological behavior; and, write that such a modeling approach should follow two hypotheses: "1) That any significant adaptive advantage that is phyletically feasible will tend to be selected; and, 2) Organisms do have some way of getting near to optimal solutions of behavioral problems in situations that they normally encounter." I believe that an optimal dynamic model should allow for such diversity to exist within food web structure, metabolic rates and behavior. The details of this diversity might then help control how each of the members of the food web interacted. As a example, a desirable feature of such a model would be for it to not only allow a silicate-dependent diatom community to dominate wherever the dynamics of the system allow it to; but, also allow other organisms, such as coccolithophores, to flourish within their prospective niches or biogeographic region. If such a more dynamic model was able to simulate present day ocean biogeochemical conditions, it may also be better capable of at least qualitatively simulating (predicting) future changes in the global biogeochemical cycle.

References

Armstrong, R. A., Grazing limitation and nutrient limitation in marine ecosystems: Steady-state solutions of an ecosystem with multiple food chains, Limnol. Oceanogr., 39, 597-608, 1994.

Cohen, J. E. and C. M. Newman, A stochastic theory of community food webs. I. Models and aggregated data, Proc. R. Soc. Lond. B, 224, 153-156, 1985.

Cohen, J. E., T. Luczak, C. M. Newman and Z. -M. Zhou, Stochastic structure and non-linear dynamics of food webs: qualitative stability in a Lotka-Volterra cascade model, Proc. R. Soc. Lond. B., 240, 607-627, 1990.

De Groot, W. T., Modeling the multiple nutrient limitation of algal growth, Ecological Modeling, 18, 99-119, 1983.

Evans, G. T. and M. J. R. Fasham, editors, Towards a Model of Ocean Biogeochemical Processes, NATO ASI Series I: Global Environmental Change, Vol. 10, Springer-Verlag, New York, 350 pages, 1993.

Fasham, M. J. R., Ducklow, H. W. and S. M. McKelvie, A nitrogen-based model of plankton dynamics in the oceanic mixed-layer, J. Mar. Res., 48, 591-639, 1990.

Hofmann, E. E. and J. W. Ambler, Plankton dynamics on the outer southeastern U. S. continental shelf. Part II: A time-dependent biological model, J. Mar. Res., 46, 883-917, 1988.

Mangel, M. and C. W. Clark, Dynamic Modeling in Behavioral Ecology, Princeton University Press, Princeton, NJ, 305 pages, 1988.

Moisan, John R. A Vertical, Time-Dependent Bio-Optical Model. Primary Productivity and Biogeochemical Cycles in the Sea, edited by P. G. Falkowski and A. D. Woodhead, Plenum Press, New York, 522-523, 1992.

Moloney, C. L. and J. G. Field, General allometric equation for rates of nutrient uptake, ingestion, and respiration in plankton organisms, Limnol. Oceanogr., 34, 1290-1299, 1989.

Moloney, C. L. and J. G. Field, The size-based dynamics of plankton food webs, J. Plankton. Res., 13, 1003-1038, 1991.

Newman, C. M. and J. E. Cohen, A stochastic theory of community food webs. IV. Theory of food chain lengths in large food webs, Proc. R. Soc. Lond. B, 228, 355-377, 1986.

Schoenly, K. and J. E. Cohen, Temporal variation in food web structure: 16 empirical cases, Ecol. Monogr., 61, 267-298, 1991.

Large Scale Biological Models

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1.   INTRODUCTION

In Section 2 of this talk I shall review those biological models that have been developed to be generally applicable over large areas, particularly those that have been, or are in the process of being, incorporated in Ocean General Circulation Models (OGCMs). I am restricting the choice to dynamic models (i.e. not those that examine a steady-state), and to Eulerian models. The principal Lagrangian model (Wolf & Woods 1988; Woods & Barkmann 1994) is too computer-intensive to be included in any large physical model, and is best suited to small scale studies.

The impetus to incorporate biological models in OGCMs has come so far from studies of the global carbon cycle, which are primarily interested in the ecosystems in general terms, such as primary production and export flux, rather than in the details of the ecosystems themselves. However, if the biological interactions within the ecosystems are to be modeled and understood more detailed models will be needed. They will also give more confidence that the current extremely simple, carbon-cycle-oriented models are producing good simulations for the right reasons. The most urgently needed improvements in the models, and the measurements that will be required to provide validations and parameter values, are discussed in Section 3.

2.   CURRENT LARGE-SCALE BIOLOGICAL MODELS

The Fasham-Ducklow-McKelvie (1990) model (hereafter FDM90) has been incorporated in several large-scale models. The ecosystem is based on nitrogen, and features seven compartments: nitrate, ammonia, bacteria, phytoplankton, zooplankton, detritus and dissolved organic nitrogen (DON). As important as the variables in a model however are the biological processes represented. In this case the phytoplankton photosynthesize (taking up nitrate and ammonia, but exuding DON) and suffer natural mortality (becoming detritus); the zooplankton graze phytoplankton, bacteria and detritus (producing more detritus as fecal pellets), excrete ammonia and DON and suffer mortality; the bacteria take in ammonia and DON, and excrete ammonia; and detritus sinks and breaks down to DON. The inhibition by ammonia of the uptake of nitrate by phytoplankton is included.

In the original paper this ecosystem existed in a slab mixed layer, the thickness of which was specified over an annual cycle, and biological quantities could be lost from this layer by turbulent mixing, detrainment (in the spring) and sinking (detritus only), while nitrate was resupplied by entrainment (from the end of summer) and by turbulent mixing throughout the year. The zooplankton variable is not specified to be any particular species, and in fact combines aspects of both micro- and mesozooplankton in that it both grazes bacteria (as well as phytoplankton and detritus) and produces fecal pellets (or detrital particles) which have a significant sinking rate. The zooplankton graze on each of their three types of prey with a preference governed by that prey's availability; hence a 'switching' behavior is produced.

The model was tested initially against data from Bermuda Station 'S', and later (Fasham 1993) against data from OWS 'India' (59N, 19W). The comparison of the _-dimensional model at OWS 'India' showed poor agreement unless the function describing zooplankton mortality (including predation by higher organisms) was altered so that there was a lower specific rate in winter. This change enabled more zooplankton to survive the winter and so provided a larger initial population

which was able to respond in time to limit the spring bloom of phytoplankton before the nutrients were depleted.

FDM90 has been embedded in the Princeton OGCM and results published for simulations of the North Atlantic (Sarmiento et al. 1993; Fasham et al. 1993). The model output was compared both with satellite CZCS data and with in situ observations at Bermuda Station 'S' and OWS 'India'. In both of the latter comparisons the biological model over-estimates the phytoplankton concentrations in the spring bloom and under-predicts the summer populations. Also the predicted zooplankton biomass is higher than that observed. These problems relate to the balance between the rates of primary production and grazing, and will be considered again later.

A version of FDM90, with carbon flows coupled to the biology (Anderson 1993) is also being run in the Princeton OGCM, with global coverage, but as yet no results are available. Drange (1994) has independently coupled carbon flows to FDM90, and embedded it in an isopycnic-coordinate OGCM of the North Atlantic. Both this implementation and that in the Princeton OGCM restrict the active biology to the upper levels of the water-column, 180m and 123m respectively. Another interesting study involved embedding FDM90 in a quasi-geostrophic eddy-resolving model (Burren 1993).

A more complex version of FDM90 has been developed (Ducklow & Fasham 1992). In this model (DF92), the phytoplankton compartment of FDM90 has been split into separate picoplankton and net phytoplankton compartments, while the original zooplankton compartment has become separate protozoa and mesozooplankton compartments. These additions enabled some representation to be made of the microbial loop, and indeed were made so that the role of bacteria in recycling carbon and nutrients could be examined.

Finally, and with particular interest for this meeting, some work was undertaken to embed FDM90 in a model of the Southern Ocean. The model was a version of the Fine Resolution Antarctic Model (FRAM), but with coarser resolution (1x2° rather than _ x _; hence 'CRAM'). The coarser resolution was required to reduce the computer storage and cpu-time to realistic levels. However, problems were encountered with the climatological forcing used for CRAM (and FRAM) which involved annual-mean quantities for many of the variables. In fact, the only seasonality was provided by the variation of the incident solar radiation. Also the lack of a suitable ice-model, the coarse vertical resolution (20m) in the euphotic zone and the lack of a wind-mixed-layer meant that the project was abandoned after just a few trial runs.

A simpler biological model has been developed by Kurz (1993) for inclusion in the Hamburg HAMMOC3 ocean model. The limiting nutrient is phosphate, and there are also compartments for phytoplankton and zooplankton. The biological processes included are primary production, grazing, natural mortality of phytoplankton and loss from the zooplankton to sinking detritus (due to fecal pellet production and/or higher predation). The biological model is restricted to the mixed-layer, which in the Hamburg model has no seasonal variation. This model has the advantages that it is simple to understand and runs exceedingly fast (the biological time step is one week; the physical time step is one month). It is also an improvement on the previous implicit biology of the Hamburg model. However, particularly in its current implementation, this model is most suitable for long climate runs rather than studying the dynamics of ecosystems.

Taylor, Harbour, Harris, Burkill and Edwards (1993) describe a model (hereafter THHBE93) of the ecosystem in the North Atlantic, based on work by Azam et al. (1983) and Taylor & Joint (1990). This nitrogen-based model includes bacteria, picophytoplankton, heteroflagellates, phytoflagellates, micrograzers (or ciliates), net diatoms and net phytoplankton, as well as silicate, nitrate, ammonium, DOC and detritus. With so many compartments it is obviously impractical to list every biological interaction, but in general the modeled processes are photosynthesis (including uptake of nutrients), grazing (that by mesozooplankton is imposed from measured rates), excretion and remineralization, as well as sinking (diatoms and detritus only). The detailed inclusion of the smaller organisms and their interactions allows a good description of the microbial loop, while having diatoms as a separate variable allows the silicate-limitation of their growth to be included.

The model is compared to the (relatively-detailed) observations made during the North Atlantic Bloom Experiment (NABE) in 1989 and on cruises during the following two years. The area of study covers both areas that exhibit nutrient depletion in the summer (e.g. 47°N, 20°W) and those

which remain nutrient-replete (e.g. 60°N, 20°W), and THHBE93 successfully simulates both types of annual cycle. This model has so far only been run in half-dimensional mode (confined to a mixed layer).

The Hadley Centre for Climate Prediction and Research, part of the U.K. Meteorological Office, have developed a coupled ocean-atmosphere GCM, which can also be run (with suitable climatological forcings) in ocean-only or atmosphere-only mode. Work is nearing completion on a model of the global carbon cycle to be embedded in this coupled OAGCM, and ocean-only runs have been performed with a sub-model describing the marine biology. This model is nitrogen-based (with coupled carbon flows) and has nutrient, phytoplankton, zooplankton and detritus as the variables. The phytoplankton photosynthesize (taking up nutrient) and suffer mortality (becoming detritus); the zooplankton graze on both phytoplankton and detritus, produce fecal pellets (detritus) and suffer mortality due to predation (mainly becoming detritus); while the detritus sinks and is remineralized.

In the current implementation the biology is not restricted to the top couple of hundred meters, though the rate of photosynthesis is set to zero below 180m. A fraction of the detritus can be found sinking at all depths, and zooplankton acting as detritivores can be found to below 400m in the aftermath of a North Atlantic bloom. This model can, with a single parameter set, simulate the low-chlorophyll, high-nutrient ecosystem observed at OWS 'Papa' and in many parts of the Southern Ocean, and also the nutrient-depleting blooms of the North Atlantic, given suitable climatological forcings. This model is particularly constrained by computer storage and cpu-time requirements, as the Hadley Centre coupled OAGCM cannot be run in an 'off-line' mode. Having only one compartment for nutrients, it cannot distinguish new and regenerated production.

There are other models that deserve mention. Hofmann & Ambler (1988) produced a biological model for the US continental shelf featuring detritus, two size-classes of phytoplankton and five stages of the copepod life-cycle (including the egg and the adult stages). This was then embedded in a 2-D physical model (Hofmann 1988). There are also reports that an ecosystem model developed jointly at the Marine Research Centre in Helsinki, Finland and the Marine Research Institute in Tallinn, Estonia has been experimentally incorporated in the OPYC isopycnic code in Hamburg (OPYC circular no. 46, 22nd Dec. '93).

3.   THE FUTURE DEVELOPMENT OF LARGE-SCALE BIOLOGICAL MODELS.

The three biological models that have been run incorporated in OGCMs (FDM90, Kurz's model and that at the Hadley Centre) have been very successful, in fact surprisingly so. Computing restraints have restricted the number of variables representing actual organisms in these models to just three, two and two respectively, and yet something recognizable as the annual cycles observed in different parts of the ocean still results. However, because of the aggregation of the biology into just two or three compartments, there are many parameters that are not well known or that it is not possible to measure - for example the mortality of 'zooplankton' or even the grazing rate of the same. Undeterminable parameters are able to be adjusted (within reasonable limits) to give a good fit to the available data. The value giving the best fit for today's climatological forcings may not be the best for future forcings, so this is an especially dangerous (but often necessary) course to follow in climate prediction experiments. These parameter adjustments are often needed because the data does not exist, and the ecosystems are not understood well enough to produce a detailed model and so suggest parameter values for the more aggregated model.

Also, while the large-scale models developed to date have mainly been intended - at least as incorporated in the OGCMs - to examine the role played by the ocean biology in the global carbon cycle, that will not always be the case. The marine ecosystems are interesting in themselves, and to simulate them in any detail, and understand the interactions, more complex models with better parameterized processes will have to be developed.

3.1.   MICRO-ZOOPLANKTON.

Excessive aggregation forces modelers to use one variable to fulfill two (or more) functions. In the models, fecal pellets which sink (as detritus) are produced by the zooplankton compartment, which is also responsible for such grazing-control of the phytoplankton as is observed. In the real ocean, there is little doubt that fecal pellets are produced by mesozooplankton. However, there is increasingly strong evidence (e.g. Burkill et al. 1993) that most of the grazing of primary

production is by microzooplankton, which have short doubling times. In theory this should please modelers, because the complicated life-cycles and behavioral responses displayed by the mesozooplankton (e.g. vertical migration on a diel or annual cycle) are very difficult to incorporate in a model, and if the important agents for grazing control of phytoplankton are the microzooplankton then our job becomes easier. However, whereas many studies have been made of copepod feeding rates, data on microzooplankton grazing rates are much more scarce. Measurements were made in the Bellingshausen Sea in the austral summer of 1992-3 that indicated that the micro-zooplankton play as pivotal a role in the ecosystem around Antarctica as in the Northeast Atlantic (P. Burkill, pers. comm.).

I see it as crucial, therefore, that extensive measurements are made of microzooplankton biomass and grazing rates in any field program in the Southern Ocean. As yet there are no automated techniques, but that should not be allowed to prevent the measurements being made.

3.2. LATERAL HETEROGENEITY

The large-scale models usually have very coarse resolution; for example the Hadley Centre OGCM has grid points spaced $2.5°$ N-S and $3.75°$ E-W. There is usually no attempt to take account of the patchiness and variability that occurs on scales much less than this. Experimentally determined growth rates for phytoplankton are assumed to be equally valid for the average population in a box several hundred kilometers square. In some cases this may be a good approximation; for example Burren (1993) examined the annual primary production calculated by FDM90 embedded in an eddy-resolving model and found that it differed by just one per cent from that calculated in a coarse-resolution model that did not display any mesoscale variability. However, the time of the predicted bloom was earlier by about a week. More pertinently, the model was run in an area where nutrients were depleted in the summer, and so the primary production should be limited by the available nutrient. In areas that show grazing limitation, the faster growth of the phytoplankton (producing an earlier the earlier bloom) should enable them to "escape" from the grazing control for longer and so show a greater productivity.

The experimental equipment for taking long, continuous and automated readings of chlorophyll in the top 500m of the water column already exists. Laboratories in the U.K., particularly IOSDL and PML, have made extensive use of the SeaSoar for this purpose, so it should be possible to get detailed information on the spatial variability of phytoplankton.

The lateral heterogeneity of the mesozooplankton populations is probably even more important to measure. This should be especially true in the Southern Ocean where Krill swarms can devastate regions of high productivity. Indeed, it may not be possible to model this trophic level accurately by an Eulerian model. Acoustic techniques for measuring large populations of mesozooplankton are now becoming available, and should be used in any Southern Ocean survey.

Lastly, the Bellingshausen Sea surveys along 85 W in the austral summer 1992-3 discovered a 'jet' of extremely high chlorophyll (D. Turner, pers. comm.). It was at about $67°$S-$69°$S, and the chlorophyll values were as high as 5-6 mg-Chl a/m^3. Further west (upstream), the values were 7 mg-Chla/m^3, and it was believed that the jet was carrying biological material advected from a zone of very high productivity further west, possibly near Peter the First Island. The ecosystem to the south of this jet was totally dominated by material detrained from it, at least at the time of the survey, which was over a month after the retreat of the ice. Should we aim to be able to model such locally-important features?

3.3 IRON LIMITATION

It is now clear that there are phytoplankton species in the ocean that are limited by the availability of the micro-nutrient iron. However the impact of iron-limitation on a full ecosystem on time-scales of longer than a few weeks remains to be demonstrated. None of the large-scale biological models feature iron limitation, both because of restrictions on the number of compartments and because of a lack of data. Since the Southern Ocean is one of the main areas claimed to be iron-limited, any experimental evidence on the question could be important.

3.4   ICE MODELS

Satellite imagery has shown strong blooms in regions around Antarctica that have been influenced by ice. Lancelot et al. (1991) modeled the development of an ice edge phytoplankton bloom that had been observed on the European Polarstern Study (EPOS) leg 2. It is also reported that blooms can begin to occur within the ice itself if conditions are suitable, and seed such blooms. Given that the productivity can be very high, it is important that the processes are understood. This is particularly the case if the high-chlorophyll water is then advected into the main ocean, as the Bellingshausen Sea cruises may have observed, and strongly influences the ecosystem there. Murphy et al. (1988) have suggested that the scales of interaction of the Krill with their prey are much smaller in under-ice systems than in the open ocean.

REFERENCES:

Anderson, T.R. 1992. Modeling the influence of food C:N ratio and respiration on growth and nitrogen excretion in marine zooplankton and bacteria. J. Plankton Res., 14, 1645-1671.

Azam, F., T. Fenchal, J.G. Field, J.S. Gray, L.A. Meyer-Reil & F. Thingstad. 1983. The ecological role of water-column microbes in the sea. Mar. Ecol. Prog. Ser., 10, 257-263.

Burkill, P.H., E.S. Edwards, A.W.G. John & M.A. Sleigh. 1993. Microzooplankton and their herbivorous activity in the northeastern Atlantic Ocean. Deep-Sea Res. II, 40, 479-493.

Burren, C.L. 1993. The effect of mesoscale heterogeneity on oceanic primary productivity. Unpublished PhD. thesis, University of Southampton, U.K.

Drange, H. 1994. An Isopycnic Coordinate Carbon Cycle Model for the North Atlantic; and the Possibility of Disposing of Fossil Fuel CO2 in the Ocean. Unpublished PhD. thesis, University of Bergen, Norway. 286pp.

Ducklow, H.W. & M.J.R. Fasham. 1992. Bacteria in the greenhouse: modeling the role of oceanic plankton in the global carbon cycle. In: Mitchell, Ralph (Ed.) "Environmental Microbiology", pp1-31. Wiley-Liss.

Fasham, M.J.R. 1993. Modeling the marine biota. In: Heimann, M. (Ed.) "The Global Carbon Cycle", NATO ASI Series, Vol. I 15, pp457-504. Springer-Verlag.

Fasham, M.J.R., H.W. Ducklow & S.M. McKelvie. 1990. A nitrogen-based model of plankton dynamics in the oceanic mixed layer. J. Mar. Res., 48, 591-639.

Fasham, M.J.R., J.L. Sarmiento, R.D. Slater, H.W. Ducklow & R. Williams. 1993. Ecosystem behavior at Bermuda Station "S" and Ocean Weather Station "India": a general circulation model and observational analysis. Global Biogeochem. Cycles, 7, 379-415.

Hofmann, E.E. 1988. Plankton dynamics on the outer southeastern U.S. continental shelf. Part III: A coupled physical-biological model. J. Mar. Res., 46, 919-946.

Hofmann, E.E. & J.W. Ambler. 1988. Plankton dynamics on the outer southeastern U.S. continental shelf. Part II: A time-dependent biological model. J. Mar. Res., 46, 883-917.

Holling, C.S. 1965. The functional response of predators to prey density and its role in mimicry and population regulation. Mem. Entomol. Soc. Canada, No. 45. (61pp).

Kurz, K.D. 1993. Zur saisonalen Variation des ozeanischen Kohlendioxidpartialdrucks [The seasonal variation of oceanic Pco2]. Examensarbeit Nr. 18, Max-Planck-Institut fur Meteorologie, Germany. 107pp.

Lancelot, C., C. Veth & S. Mathot. 1991. Modeling ice-edge phytoplankton bloom in the Scotia-Weddell sea sector of the Southern Ocean during spring 1988. J. Mar. Syst., 2, 333-346.

Murphy, E.J., J. Morris, J.L. Watkins & J. Priddle. 1988. Scales of interaction between Antarctic krill and the environment. In: Sahrhage, D. (Ed.), 'Antarctic Ocean and Resources Variability', pp120-130. Springer-Verlag.

Sarmiento, J.L., R.D. Slater, M.J.R. Fasham, H.W. Ducklow, J.R. Toggweiler & G.T. Evans. 1993. A seasonal three-dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone. Global Biogeochem. Cycles, 7, 417-450.

Taylor, A.H., D.S. Harbour, R.P. Harris, P.H. Burkill & E.S. Edwards. 1993. Seasonal succession in the pelagic ecosystem of the North Atlantic and the utilization of nitrogen. J. Plankton Res., 15, 875-891.

Taylor, A.H. & I.R. Joint. 1990. A steady-state analysis of the "microbial loop" in stratified systems. Mar. Ecol. Prog. Ser., 59, 1-17.

Wolf, K.U. & J.D. Woods. 1988. Lagrangian simulation of primary production in the physical environment - the deep chlorophyll maximum and nutricline. In: Rothschild, B.J. (Ed.), 'Towards a Theory of Biological-Physical Interactions in the World Ocean', p51. Reidel.

Woods, J. & W. Barkmann. 1994. Simulating plankton ecosystems by the Lagrangian ensemble method. Phil. Trans. R. Soc. Lond. B, 343, 27-31.

Appendix 3.   Meeting Prospectus and Agenda

Modeling the Southern Ocean Ecosystem - Prospectus

Most numerical models of the upper ocean ecosystem are based on coupled partial differential equations with growth, loss, interaction, and diffusion terms. The basic model has been used in oceanography for many decades, although there have been many enhancements such as size classes, complex grazing and nutrient uptake terms, sophisticated mixed layer models, etc. As these models have grown in complexity, there are more adjustable parameters that must be estimated and more uncertainty about the exact forms of the parameterizations. Simple changes in parameters can have dramatic effects on model behavior. Several studies are investigating methods to reduce the number of parameters to those that capture most of the possible model behaviors.

As ocean models move towards a closer coupling with observations through assimilation, it becomes essential that we know far more about the various parameters and functional forms than simply their mean and variance. Assimilation models require that we characterize their temporal and spatial variability in order to fill in the gaps in time and space. This is a daunting task. For example, we know decorrelation scales of phytoplankton biomass in only a few locations in the world ocean; little is known about the decorrelation scales of phytoplankton growth rates.

The Southern Ocean will be the site of major field campaigns for both JGOFS and GLOBEC. There is still great uncertainty about the regulation of primary productivity in the Southern Ocean; iron limitation, grazing, and light limitation have been invoked. Near the ice edge, processes are even more complicated. Existing coupled biological/physical models must contend with a wide range of processes, many of which (such as iron limitation) have not yet been incorporated into existing models.

Given the expanse of the Southern Ocean and its isolation, field programs are by necessity both limited and costly. The upcoming JGOFS GLOBEC Southern Ocean projects represent a unique opportunity to collect data on Southern Ocean biogeochemistry and ecological processes. Campaigns by other countries, including the United Kingdom, Australia, France, Japan, and South Africa, will also provide important data sets along with long-term studies such as LTER. It is unlikely we will be able to assemble these resources again. Given the predicted sensitivity of the Southern Ocean to climate change (and the resulting feedbacks), we must improve our ability to make predictions about the functioning of the Southern Ocean with only limited data sets in the future.

The focus of the workshop will be an assessment of our present state of knowledge from both observations and models. We will assess where are our greatest uncertainties lie and where small improvements in observations and models will result in large increases in understanding. We will estimate the time and space scales over which we can make useful predictions about the Southern Ocean. As part of this assessment, we will explore the needs of the observational community in terms of models. We will also seek to outline the type of measurement program that will lead to significantly improved models.

As a strawman question, I suggest the following to organize our thinking:

"To predict seasonal anomalies in the f-ratio on regional scales in response to changes in atmospheric forcing."

Tuesday, January 17

Cascade Locks C

7:30-8:30	Continental breakfast - fruit, pastries, juices, coffee, etc.
8:30-8:45	Welcome and focus of the workshop - M. Abbott
8:45-9:15	Status of JGOFS Southern Ocean project - R. Anderson
9:15-9:45	LTER results and GLOBEC plans - E. Hofmann
9:45-10:30	Physical processes in the Southern Ocean - J. Klinck
10:30-10:45	Break
10:45-11:30	Biological processes in the Southern Ocean - W. Smith
11:30-12:15	What can be done with data assimilation? - A. Bennett
12:15-1:30	Lunch
1:30-2:15	Examples of assimilation of biological data - E. Hofmann
2:15-3:00	Models of sea ice and ecological processes - K. Arrigo
3:00-3:15	Break
3:15-4:00	Coupled biological/physical models - P. Franks
4:00-4:45	New approaches in biological models - J. Moisan
4:45-5:30	Large-scale biological models - I. Totterdell

Wednesday, January 18

Cascade Locks B
Cascade Locks D (breakout room)

7:30-8:30   Continental breakfast

8:30-9:00   Plenary session to discuss working groups

9:00-12:00   Working groups meet

                Group #1 Field measurements
                    T. Powell (chair) D. Nelson (rapporteur)

                    What types of field measurements should be made during the upcoming
                    JGOFS and GLOBEC programs to improve the quality of our models?

                Group #2 Models

                    K. Denman (chair) T. Cowles (rapporteur)

                    What types of models need to be developed in order to exploit field
                    measurements during JGOFS and beyond?

12:00-1:30   Lunch

1:30-3:00   Working groups meet

3:15-4:00   Group #1 reports to plenary

4:00-4:45   Group #2 reports to plenary

5:30-6:00   Reception

Thursday, January 19

Cascade Locks B
Cascade Locks D (breakout room)

7:30-8:30	Continental breakfast
8:30-10:30	Writing session for both groups
10:30-11:30	Discussion of Group #1 report
11:30-12:30	Discussion of Group #2 report

Attendees

Mark Abbott	Oregon State University
Bob Anderson	LDEO
Rob Armstrong	Princeton
Kevin Arrigo	NASA/GSFC
Andrew Bennett	Oregon State University
Tim Cowles	Oregon State University
Ken Denman	IOS Canada
Scott Doney	NCAR
Glenn Flierl	MIT
Peter Franks	Scripps Institution of Oceanography
David Glover	WHOI
Danny Grunbaum	University of Washington
Eileen Hofmann	Old Dominion University
John Klinck	Old Dominion University
Ricardo Letelier	Oregon State University
John Moisan	Scripps Institution of Oceanography
Dave Nelson	Oregon State University
Angelica Peña	IOS Canada
Tom Powell	University of California, Berkeley
Jim Richman	Oregon State University
Walker Smith	University of Tennessee
Ted Strub	Oregon State University
Ian Totterdell	James Rennell Centre
John Walsh	University of South Florida
Leonard Walstad	University of Maryland