A U.S. Southern Ocean Carbon, Ecosystems and Biogeochemistry Science Plan

A report of the Southern Ocean Scoping Workshop sponsored by the Ocean Carbon and Biogeochemistry Program and the NSF Office of Polar Programs

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Executive Summary

This Southern Ocean Carbon, Ecosystems, and Biogeochemisty (SOCEB) Science Plan is derived from a workshop held at Princeton University in June 2009 with support from the National Science Foundation Office of Polar Programs and the Ocean Carbon and Biogeochemistry Program. The workshop was designed to facilitate development of a coordinated US program of scientific research in the Southern Ocean. The research program that emerged was motivated by five overriding scientific concerns:

- The Southern Ocean is responding in measurable ways to the atmospheric increase in CO_2, but the associated mechanisms of response are poorly quantified;
- The Southern Ocean undergoes natural fluctuations in carbon cycling over a wide range of time and space scales, and these will continue to vary in ways that are unknown;
- Predictions of the future behavior of Earth's climate system requires understanding the functioning of the Southern Ocean ecosystems and biogeochemical systems;
- Major changes are occurring in Southern Ocean food webs, which have direct effects on key species and indirect impacts throughout the food web, and the consequences of these for carbon and biogeochemical cycling and overall biological production are unknown;
- Scientific progress over the past decade has enabled a new level of integrated understanding that is directly relevant to critical societal questions associated with the economic and environmental effects of climate change, increasing CO_2, and human impacts on Southern Ocean ecosystems and the carbon cycle.

The framework outlined for a Southern Ocean research program is a strategic and optimal mix of essential components, which include sustained *in situ* observational and monitoring networks, integrated modeling studies, and innovative process studies. The strategy underlying this framework is designed to

- *Identify critical research questions* that will advance understanding of the Southern Ocean carbon cycle and ecosystems and identify long-term goals;
- *Develop new research initiatives* that are feasible, cost-effective, and compelling, to improve the understanding and hence ability to monitor and predict future
    - response of ecosystems and biogeochemical cycles to climate change
    - uptake of anthropogenic CO_2
    - response of the natural carbon cycle to climate change
- *Strengthen the broad research agendas of the agencies and improve international collaboration* through better coordination, focus, conceptual and strategic framework, and articulation of goals.

This SOCEB Science Plan underscores the need for these components to be coordinated, rigorous, and interdisciplinary, as well as providing research that is strategically prioritized to address societal needs. The planned activities will enhance understanding of Southern Ocean biogeochemical cycles, ecosystems, and their interactions and also improve capabilities to anticipate future conditions so that informed management and policy decisions can be made.

This plan represents a merger of two major scientific communities dealing with related research on ocean biogeochemistry and ecosystems. The issues identified for Southern Ocean research in the next decades are such that neither community alone can provide the expertise and insights needed to adequately address them. Combining the biogeochemical and food web research communities will capitalize on scientific synergisms, avoid unnecessary duplication, and make the best use of the limited resources that are available for Southern Ocean research. This will also place U.S. Southern Ocean research at the forefront of international research programs that are addressing similar themes.

Chapter 1: Introduction

Rationale and Background

Carbon and nutrient cycling and food web dynamics in the Southern Ocean south of 40°S, including the Subtropical Front, are regulated by a complex interplay of physical, biological and biogeochemical processes, most of which are not well understood. The Southern Ocean provides a critical link in the large-scale ocean circulation and makes significant contributions to global budgets of heat, carbon, freshwater and nutrients. For example, the Southern Ocean covers a fifth of the global ocean surface area, yet accounts for approximately 40% of the global anthropogenic carbon dioxide (CO_2) uptake (Sabine et al., 2004; Gruber et al., 2009) and upwelling of deep water south of the Polar Front accounts for a substantial fraction of the degassing flux of natural CO_2. Moreover, future climate predictions suggest that the Southern Ocean air-sea heat balance and carbon system account for most of the response of the ocean to global warming, but these predictions are fraught with uncertainty and the greatest disagreements between models is in this region.

That the Southern Ocean has a critical role in the global overturning circulation is accepted, but many uncertainties about this circulation remain, such as the primary pathway for return of deep waters to the surface ocean. Eddy fluxes may be a significant contributor to the meridional exchange of mass and heat, and presumably carbon and nutrients, across the Southern Ocean, and to the vertical exchange of momentum (Rintoul et al., 2001), yet are poorly understood. Increases in the upwelling rate of natural CO_2, driven by wind stress changes and/or changes in stratification, have been proposed as a principal cause of the increase in atmospheric CO_2 that occurred at the end of the last ice age (Anderson et al., 2009). Furthermore, model simulations of the contemporary climate (Russell et al., 2006; LeQuere et al., 2007; Lovenduski et al., 2008) suggest that increased wind stress resulting from global warming and expansion of the ozone hole has increased northward Ekman transport and upwelling, resulting in increased anthropogenic uptake and the degassing of natural CO_2. However, the extent to which eddy fluxes may compensate the Ekman transport in the mixed layer is unresolved, as is the balance between increased carbon uptake and outgassing that result from increased upwelling.

Phytoplankton and microbial communities are the first step in generating the biogeochemical fluxes of carbon, oxygen and nutrients through the biological pump, which ultimately transfers these quantities from the surface ocean to the deep sea. A major characteristic of large portions of the Southern Ocean is that the surface macronutrients are utilized inefficiently due to poorly understood interactions among iron, macronutrient, and light limitation, and physical mixing processes. Indeed, it is the very failure of ecosystems in the Southern Ocean to deplete nutrients that makes these waters the principal source of nutrients to the main thermocline to the north, supporting up to three-quarters of biological production north of 30°S (Sarmiento et al., 2004). Estimates suggest that complete removal of these surface nutrients could remove about 100 Pg C of CO_2 from the atmosphere to the ocean. The fraction of primary production that is exported depends on details of the phytoplankton and zooplankton communities, which in turn are influenced by changes in food web structure, mixed layer depth, and iron and macronutrient supply. Moreover, the effect and importance of connections between the surface mixed layer and deep ocean processes (e.g. Circumpolar Deep Water) on primary production remains unclear. It has also been suggested that changes in winds associated with the Southern Annular Mode (SAM), lead to changes in mixed layer depth and productivity (Sallée et al., 2010), but this remains to be verified.

The supply of nutrients and light needed for photosynthesis by primary producers is generally assumed to control the production of Southern Ocean ecosystems. This bottom-up control implies ecosystem sensitivity to changes in physical forcing that influence the light and nutrient environment experienced by phytoplankton (e.g. upwelling, mixed layer depth, sea ice). However, top-down control exerted by predators is an important contributor to Southern Ocean ecosystem variability (Ainley et al., 2007), and as such the structure of the upper trophic levels potentially impacts biogeochemical cycles. The extent to which this happens is unknown but is critical to understanding the feedbacks between food web and biogeochemical cycling.

The unique and distinctive food web of parts of the Southern Ocean is characterized by dependence on a single species, Antarctic krill (*Euphausia superba*), which supports large populations of higher predators. This dependence on a single species makes the food webs and biogeochemical cycling processes vulnerable to climate variability and change. Changes in the environmental structure that many of the Southern Ocean species depend upon, such as sea ice, are already occurring and having effects. For example, an observed decline in Antarctic krill in the southwestern Atlantic Ocean over the past 50 years has been linked to a reduction in sea ice (Atkinson et al., 2004). The long-term consequences of these environmental and food web changes on Southern Ocean ecosystems and biogeochemical cycling are unknown. Moreover, inadequate spatial and temporal observations make it difficult to separate the effects of global warming from those resulting from historical harvesting of higher trophic levels.

Recognition of the importance of the Southern Ocean to climate change and the need to understand this region to improve projections of the consequences of climate change led to the convening of a Scoping Workshop, with participants from the US and international Southern Ocean research community (Appendix A), to:

- *Identify critical research questions* that will advance understanding of the Southern Ocean carbon cycle and ecosystems and identify long-term goals;
- *Develop new research initiatives* that are feasible, cost-effective, and compelling, to improve the understanding and hence ability to monitor and predict future
    - response of ecosystems and biogeochemical cycles to climate change
    - uptake of anthropogenic CO_2
    - response of the natural carbon cycle to climate change
- *Strengthen the broad research agendas of the agencies and improve international collaboration* through better coordination, focus, conceptual and strategic framework, and articulation of goals.

The ideas that were formulated and discussed at the Scoping Workshop provide the basis for the science plan outlined in the following sections for development of a Southern Ocean Carbon, Ecosystems, and Biogeochemisty (SOCEB) research program.

Workshop Approach

The workshop presentations, working groups, and plenary discussions (Appendix B) were focused around two fundamental science questions:

- What has been and what is the ongoing impact of climate change, the CO_2 increase, and human actions on Southern Ocean ecosystems, biogeochemical cycles, and the ocean carbon sink?
- What will be the future impact of climate change, the CO_2 increase, and human actions on Southern Ocean ecosystems, biogeochemical cycles, and the ocean carbon sink?

The first question focuses on past and present behavior of biogeochemical cycles, including carbon, and ecosystems because understanding this behavior provides powerful clues for understanding the response of ecosystems to climate change and human intervention, and the disposition of carbon released as a result of human activities, the underlying processes in this disposition, and their sensitivity to perturbations. Improved understanding will require targeted development of a sustained and coordinated observational effort of the Southern Ocean, and associated analysis, synthesis, and modeling. Chapter 2 describes the past and present research and results that have bearing on future studies directed at answering this question.

The second question focuses on predicting future concentrations of atmospheric CO_2 and the state of Southern Ocean ecosystems, including the effects of resource exploitation. The study of essential processes in biogeochemical cycles and food webs will be integrated with a rigorous and comprehensive effort to build and test models that project possible changes and responses of these to perturbations in the Southern Ocean, to evaluate and communicate uncertainties in alternative model simulations, and to make these simulations available for public scrutiny and application. Chapter 3 explores the critical scientific issues that are relevant to predicting future impacts.

Proposed SOCEB research program

This Scoping Workshop report outlines the elements of a SOCEB research program (Chapter 4) that takes a long term view of improving and making credible projections of the response of Southern Ocean ecosystems and biogeochemical cycles to climate change and of the role of the Southern Ocean in determining future atmospheric CO_2 levels. The rationale comes from the need for projections of: 1) future concentrations of atmospheric CO_2 to characterize and predict the behavior of the Earth's climate system on decadal to centennial time scales, and 2) responses of Southern Ocean ecosystems to climate change, the CO_2 increase, and human actions. These are required to make informed decisions about policies that will affect the future health of the Southern Ocean environment. Moreover, the scientific community is in a good position to make important progress in this area. But making such progress will require an unprecedented level of coordination among the scientists and government agencies that support this research.

An important result from the Scoping Workshop was recognition that a research program that will improve understanding and knowledge and lead to credible predictions of the response of Southern Ocean ecosystems and biogeochemical cycles to climate change requires a coordinated and interdisciplinary strategy. This will allow the relevant interactions and feedbacks to be incorporated so that the role of the Southern Ocean in determining future atmospheric CO_2 levels, given realistic emission and climate scenarios, can be quantified. The research program must also yield better understanding of past changes in Southern Ocean ecosystems and biogeochemical cycles, which will allow development of realistic projections of future states of these systems. The research strategy articulated in this Science Plan will strengthen the scientific foundation for management decisions in numerous areas of great public interest.

Chapter 2: The past and present Southern Ocean Carbon, Ecosystems and Biogeochemistry

Chapter 1 introduced the two overarching scientific questions that the SOCEB is designed to address. This chapter focuses on the first of these questions:

> **What has been and what is the ongoing impact of climate change, the CO_2 increase, and human actions on Southern Ocean ecosystems, biogeochemical cycles, and the ocean carbon sink?**

Carbon cycle and ecosystem research relating to climate change in the Southern Ocean fundamentally concerns three large scientific issues analogous to those that apply to other components of the global earth system. The first of these is the natural partitioning of carbon and behavior of ecosystems in the Southern Ocean, how this affects the pre-industrial air-sea flux of CO_2 and how the carbon partitioning and flux and the ecosystems are affected by climate variability and change. The second scientific issue is the contribution of the Southern Ocean to the oceanic uptake of net anthropogenic carbon emissions resulting from the combined effect of fossil fuel emissions and land use change minus the land carbon sink, and how the associated changes in ocean chemistry such as the CO_2 concentration increase and acidification affect ocean ecosystems and the carbon fluxes. The third scientific issue is how direct human activities in the Southern Ocean such as harvesting alter oceanic ecosystems and how such changes may feed back to the carbon fluxes. Overlying all of these scientific issues is the Southern Ocean circulation, mixing, and climate response, which provides the fundamental framework for understanding the carbon, biogeochemistry, and ecosystem processes, their variability and their response to climate change.

The following three sections summarize recent progress and major unknowns in (1) the physical state and climate sensitivity, (2) ecosystem structure and productivity and (3) biogeochemistry and carbon cycle, in the Southern Ocean. Each section concludes with a proposed major near term research initiative that will address the major unknowns.

Ocean Circulation and Climate

Due to its physical geography, the Southern Ocean is a major conduit for exchange of water properties between ocean basins, and between the surface ocean and the abyss. The Antarctic Circumpolar Current system driven by mid-latitude surface westerly winds accounts for large fluxes of heat, nutrients, and carbon in the climate system. At the same time, it effectively isolates the polar ocean from lower latitudes, giving rise to the coldest temperatures in the World's ocean, deep surface mixed layers, and a large area of seasonal sea ice. These physical characteristics have profound impacts on Southern Ocean biogeochemical cycles and ecosystems.

Variations in the position and intensity of the Southern Hemisphere jet stream, associated with the SAM can drive large changes in the circulation of the Southern Ocean. For example, Meredith et al. (2004) showed that inter-annual variability in ocean transport through Drake Passage is forced by variability in the SAM. Ocean general circulation models are also sensitive to this change in forcing, and indicate that the SAM drives variability in both the ACC transport and strength of the meridional overturning/Deacon cell (Hall and Visbeck, 2002).

The SAM index has become more positive in recent decades (Hall and Visbeck, 2002) and is projected to continue to become more positive in the future (IPCC, 2007), resulting in a shift in warm, maritime climate southward towards the West Antarctic Peninsula. This shift may in turn have moved the location of large-scale fronts to the south (Sokolov and Rintoul, 2003; Oke and England, 2004), with the net result being an increase in the heat content of the waters south of 40^0S (Gille, 2002, 2008).

In addition to the variability induced by changes in SAM, substantial ENSO-related variability occurs in the Southern Ocean (Parkinson, 2004; Yuan, 2004). The teleconnections introduce atmospheric temperature changes throughout the Southern Ocean, which in turn influences sea ice. During El Niño events more heat is transferred southward in the Amundsen-Bellingshausen sector (ABS) and less in the Weddell sector; conversely, during La Niña events, less heat is transferred in the ABS, but more to the Weddell.

Finally, like other high-latitude regions, the Southern Ocean is expected to undergo a long-term decrease in surface buoyancy fluxes due to surface warming and freshening. The degree to which these stratifying influences will counteract the shift toward stronger westerlies that enhance upwelling remains a source of major uncertainty.

Knowledge Gaps and Future Needs

It is critically important that we understand the mechanisms and magnitude of Southern Ocean changes in winds, sea ice, and buoyancy fluxes, as they have direct consequences for the future atmospheric CO_2 concentration. Such a goal is not restricted to the Southern Ocean, but the unique oceanographic and ecological interactions there make the problem both more difficult as well as more imperative. The role of changing physical forcing and the ecological and oceanographic changes it will induce must be pursued in the context of a greater understanding of the natural variability of the region. While we do not propose specific physical oceanographic studies as part of SOCEB, it will of course not be possible to achieve a clear understanding of biogeochemical and ecological processes and their changes over time without a close coordination with our physical oceanographic colleagues.

Ecosystem Structure and Productivity

Despite the harsh environment, Southern Ocean ecosystems are very productive. Because of the convective vertical exchange with the deep ocean, macronutrients do not limit the productivity of phytoplankton. However, the cold temperatures, short season of adequate light, and the scarce supply of trace metal nutrients combine to maintain very low plankton population growth rates (Tremblay and Smith 2007). Nevertheless, on a regional basis, primary productivity can be quite large, especially in the seas along coastal Antarctica, and in areas undergoing sea ice retreat. These rates sustain large populations of Antarctic krill and salps, which in turn support a wide array of marine birds and mammals.

With the advent of satellite ocean color sensors, and algorithms for estimating primary productivity, the total annual production estimates have begun to converge on a range of ~2-4 PgCyr^{-1} (south of 50°S), consistent with estimates of productivity in upper trophic levels. Production rates are highest on the continental shelf in the Ross and Weddell Seas, although the vast open ocean area north of the Marginal Ice Zone accounts for the majority of integrated Southern Ocean photosynthesis. The dominant phytoplankton groups are diatoms and prymnesiophytes, which have different impacts on organic matter export. The massive populations of Antarctic krill provide a crucial link between primary producers and several of the oceans top predators including blue whales. Indeed, trophic linkages in the Southern Ocean are as complex as temperate and tropical systems (Figure 1), and the impacts of climate change and human impacts are only now being addressed.

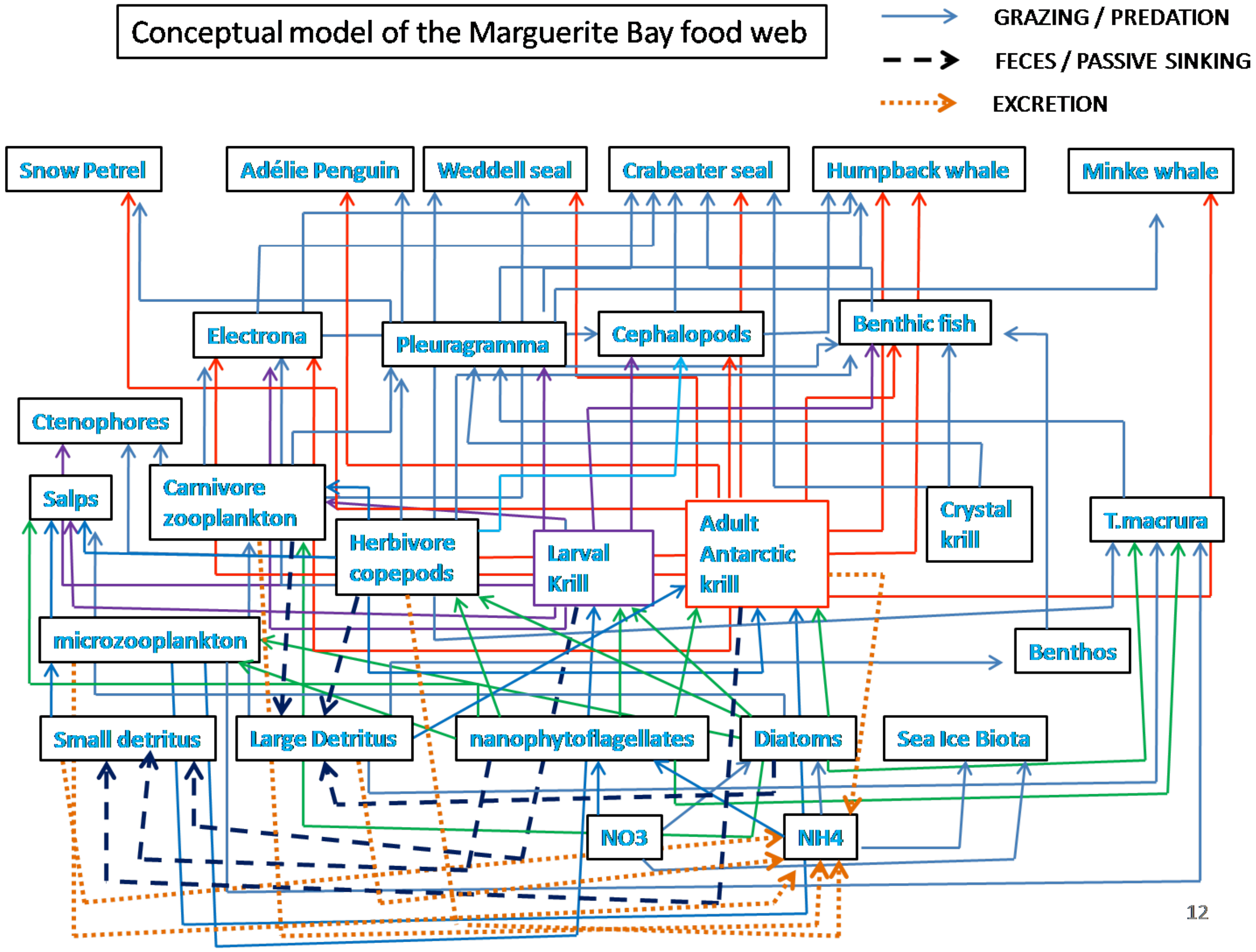

Figure 1. Conceptual model of a coastal Antarctic food web (Ballerini et al., in prep.).

Over long time scales, variations in net ecosystem production of organic matter is critical to the air–sea balance of CO_2 in the Southern Ocean, as well as to the productivity of low latitude oceans that ultimately receive the unused nutrients from Southern Ocean surface waters via Subantarctic intermediate and mode waters (Sarmiento, 2004). There is considerable uncertainty about the variations in export from the surface layer. Although the importance of the export efficiency is clearly known (Buesseler and Boyd, 2003; Lutz et al., 2007), the factors that govern the fraction of net primary production (NPP) that gets exported remain poorly known. Comparison among twelve models that predict export in the Southern Ocean showed an order of magnitude difference (Najjar et al., 2007), suggesting that our understanding of the determinants of export flux remain poorly constrained. An inverse modeling approach suggests that the overall export flux in the Southern Ocean south of 30°S is ~2 Pg yr^{-1}, but substantial regional variations were found (Schlitzer, 2002).

Variability and trends

A variety of studies have begun to elucidate the large-scale changes in the Southern Ocean ecosystems. The Antarctic Peninsula region has been shown to be among the most rapidly warming regions in the world (Vaughan et al., 2004), and coincident with this atmospheric warming ice concentrations have decreased, which in turn affect the distribution of numerous species within the food web (Ducklow et al., 2007). Montes-Hugo et al. (2009) found that as the ice retreated southward along the Antarctic Peninsula that the winds increased, and the energy transferred to the ocean resulted in increased vertical mixing, which then altered the biomass and size distribution of phytoplankton. Conversely, in regions farther south, chlorophyll increased significantly. Thus a clear indication of climate change on ecosystems and biogeochemical cycles has been demonstrated.

The variability in large-scale atmospheric and oceanographic forcing in the Southern Ocean gives rise to substantial variations in food web processes. Interannual variations in phytoplankton biomass and productivity have been demonstrated throughout the Southern Ocean (Arrigo et al., 2004; Prézelin et al., 2004; Smith et al., 2006; Smith and Comiso, 2008; Arrigo et al., 2008). Much of this variability is related to large-scale physical forcing, but the detailed mechanisms remain unclear. Arrigo et al. (2008) concluded that 30% of the variation in primary production is attributable to SAM. Interannual variability in annual production was most closely tied to changes in sea ice cover, although changes in sea surface temperature also played a role. Large interannual variations in flux also were observed in the Antarctic Peninsula region (Ducklow et al., 2007), which did not have an obvious relationship to changes in phytoplankton abundance, size or zooplankton composition, or to the changes in physical forcing described by Montes-Hugo et al. (2009). However, seasonal and interannual variability in phytoplankton production and relative abundance of species in western Antarctic Peninsula waters has been related to the presence of Circumpolar Deep Water and the frequency at which this water mass intrudes onto the continental shelf (Prézelin et al., 2000, 2004).

Based on nearly a decade of satellite data, annual primary production in the Southern Ocean appears to have had no trend (Arrigo, 2008). However among individual taxa, there are a number of established temporal trends. Substantial changes (including modification of regional distributions) in nearly all components of the food web have been observed (e.g., Ross et al., 2008; Brierley and Kingsford, 2009; Montes-Hugo et al., 2009). Antarctic krill biomass, considered to be a key component in Antarctic food webs (Nicol, 2006) has declined significantly in the past century (Atkinson et al., 2004) and have been replaced by salps. Adélie penguin (*Pygoscelis adeliae*) populations along the western Antarctic Peninsula have declined sharply over several decades, and they have been replaced by Chinstrap penguins (*Pygoscelis antarcticus*) (Emslie et al., 1998; Ducklow et al., 2007).

In addition to the impact of changes in the physical environment, projections of changes in the acidity of the Southern Ocean due to the uptake of anthropogenic CO_2 (Orr et al., 2005; Fabry et al., 2009) suggest that the Southern Ocean will be among the first regions to become undersaturated in aragonite. Indeed, Fabry et al. (2009) refer to polar systems as, "bellweathers for global ocean acidification". Future increases in oceanic CO_2 will exert substantial impacts on not only calcareous organisms that are presently extant (e.g., pteropods, a critical grazer in polar coastal and oceanic regions; Smith et al., 2007; cold-water corals, bivalves), but also on the cascade of impacted trophic interactions as well as interactions within the functional groups of a single trophic level (e.g., phytoplankton: Tortell et al., 2008; Feng et al., 2010). Such modifications of food webs and ecosystems have been shown to be of great importance in other systems, but we presently are poorly prepared to predict the large-scale effects of ocean acidification in the Southern Ocean.

Knowledge Gaps and Future Needs

Despite the clear linkages of biological processes to physical oceanographic dynamics, our understanding of the physical-biological coupling remains primitive. An increased understanding of these interactions is essential to an accurate prediction of the effects of future climate change. Defining and quantifying the response of marine ecosystems and biogeochemical cycles to variability and trends in the climate remains as a key question for Southern Ocean research. Answering this broad question requires addressing critical knowledge gaps in the mechanisms that link the physical state of the Southern Ocean to the structure and function of its ecosystems and to the global carbon and biogeochemical cycles. The critical knowledge gaps identified by the Scoping Workshop were:

- What is the mean taxonomic composition of the plankton communities, both autotrophs and heterotrophs?
- How do iron and light interact to influence plankton growth rates and stoichiometry?
- What controls the fraction of primary production that is exported to depth?
- What is the influence of temperature on rates of key biological processes, including bacterial production and DOC?
- How will acidification impact plankton calcification, physiology, and ecosystem function?
- What are the implications of population shifts among upper trophic levels for nutrient and carbon cycles?

Each of the critical knowledge gap questions cannot be presently addressed because of a lack of data on key components of each process. For example, while variations in ecosystem structure and function are partially known, the linkages, temporal scales of change, and dynamics of each trophic level remain poorly constrained. Similarly, it is uncertain how the ocean will respond to enhanced winds, and a number of responses have been suggested from modeling and theoretical studies (e.g., increased upwelling: Anderson et al., 2008; increased cascade of energy from the large- to mesoscale; insensitivity to wind changes: Bönning et al., 2008).

The importance of these questions with their huge consequences for ocean ecology, biogeochemical cycling, and the ocean carbon sink, together with the development of new measurement techniques, data interpretation methods, and improved models, have placed us in a position to be able to propose a major near term research initiative with the following goal:

Goal 1: Quantify and understand the impacts of climate change and interannual variability on Southern Ocean ecosystem productivity and structure

Biogeochemistry and the Carbon Cycle

A defining characteristic of the biogeochemical cycles of Southern Ocean waters is the lack of utilization of nutrients in the euphotic zone by autotrophic plankton. Model simulations and observational analyses suggest that the nutrients that feed northward into the Subantarctic Mode Waters (SAMW) supply the perhaps three-quarters of the biological production north of 30°S and that because these waters tend to be silica poor, they lead to lower diatom production levels than might otherwise be expected (Sarmiento et al., 2004).

The failure of organisms to consume nutrients at the surface of the ocean has major consequences for the air-sea flux of CO_2 in the Southern Ocean. The high dissolved inorganic carbon (DIC) and thus pCO_2 concentrations in the surface waters of the Southern Ocean lead to a very large pre-industrial degassing flux of CO_2 into the atmosphere in this region. The inefficiency of autotrophic plankton in depleting surface nutrients results in higher atmospheric CO_2 than would otherwise occur, and a more efficient removal of those nutrients should lead to a reduction of atmospheric CO_2. The sensitivity of atmospheric CO2 to nutrient depletion however, depends strongly on the region (Marinov et al., 2006). Nutrient depletion in the SAMW and Antarctic Intermediate Water (AAIW) formation regions has very little effect on the air-sea balance of CO_2 since most of these nutrients are eventually consumed downstream in the upper conveyor belt to the north of the Southern Ocean. By contrast, nutrient depletion in the bottom water formation regions has a large effect on the atmosphere since it involves nutrients that remain sequestered in the deep ocean for their entire trajectory, thus never having a chance to come to the surface where biological processes can remove them along with an associated burden of carbon from the atmosphere. Surface nutrient depletion in this region thus has by far the largest effect on the oceanic remineralized nutrient inventory and thus air-sea CO_2 partitioning of any major oceanic region in the world.

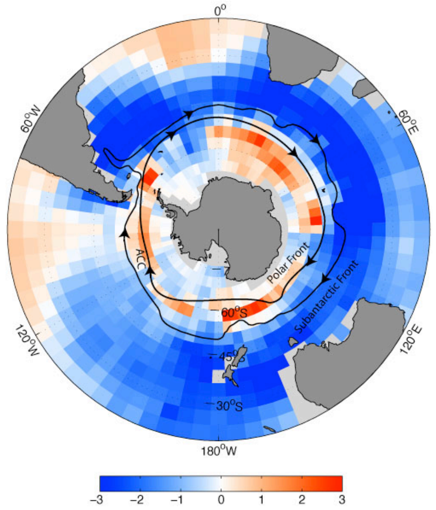

Figure 2. Annual-mean observed sea-air CO_2 flux (mol m^{-2} yr^{-1}) between the Southern Ocean and the atmosphere (data from Takahashi et al., 2009).

Model studies and observationally based inverse models making use of the vast amount of new oceanic DIC and alkalinity data obtained during the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) show that the Southern Ocean accounts for about 40% of the anthropogenic CO_2 sink. However, observationally based estimates of sea-air CO_2 fluxes indicate that the Southern Ocean is currently a weak sink of atmospheric CO_2 (Takahashi et al., 2009). This small sink results from the balance between two large numbers, one being the uptake of anthropogenic carbon, and the other being a smaller natural, i.e., pre-industrial, CO_2 source to the atmosphere due to upwelling of deep waters which have high DIC and nutrients due to the biological pump. There is a delicate regional balance of CO_2 fluxes, with moderate outgassing in the high latitudes, where upwelling brings waters with high concentrations of respired CO_2 to the surface, being overwhelmed by a large uptake of CO_2 in the mid-latitudes of the Southern Ocean, where solubility effects and biological processes lower surface pCO_2 and draw CO_2 out of the atmosphere (Figures 2,3). In addition, Antarctic shelf waters have very high rates of NPP, and may be a strong CO_2 sink that is not accounted for in model estimates (Arrigo et al., 2008).

Forward and inverse models of the ocean and atmosphere tend to support the observational data with regard to the sign of the Southern Ocean integrated CO_2 flux, but disagree as to the magnitude of this integrated flux (Figure 3). For example, the ocean forward models tend to overestimate the sink strength (0.8 Pg C yr^{-1}), as compared to the other estimates (0.3 Pg C yr^{-1}; Gruber et al., 2009). In addition, there is still quite a bit of uncertainty surrounding the magnitude of these fluxes using each of the various methods (Figure 3), and there are large regional differences in the fluxes from method to method.

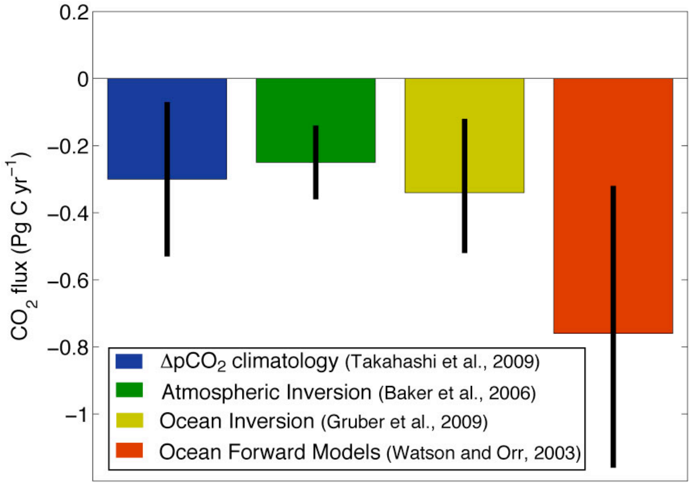

Figure 3. Southern Ocean (<44°S) integrated estimates of sea-air CO_2 flux based on observations, results from the TransCom3 project using interannual inversions of atmospheric CO_2, an inversion of interior ocean carbon observations using 10 ocean general circulation models, and results from the 13 ocean models that participated in the second phase of the OCCMPP (data from Gruber et al. (2009).

Variability and trends

The Southern Ocean sink for atmospheric carbon has not been constant over time. Recent literature suggests that short and long-term variations in the position and intensity of the Southern Hemisphere westerly winds have created changes in Southern Ocean circulation. This in turn has created inter-annual variability, decadal trends, and long-term changes in the Southern Ocean CO_2 sink. Observations and model studies indicate that the Southern Ocean (< 30°S) is a net sink for atmospheric CO_2 (Takahashi et al., 2009; Gruber et al., 2009) but recent literature suggests that this sink is variable and has weakened over the past few decades, owing to changes in wind stress and ocean circulation (Lovenduski et al., 2007; Lenton et al., 2007; Verdy et al., 2007; LeQuere et al., 2007; Lovenduski et al., 2008; Metzl, 2009).

Ocean circulation and biogeochemical models have indicated that the SAM is also associated with inter-annual variability in the sea-air CO_2 flux from this region. Positive phases of the SAM (associated with increased wind stress) coincide with times of anomalous CO_2 outgassing from the Southern Ocean (Lovenduski et al., 2007; Lenton and Matear, 2007; Verdy et al., 2007). These studies suggest that the mechanism driving this outgassing is the anomalous upwelling and Ekman tranport of carbon rich waters in association with increased wind stress.

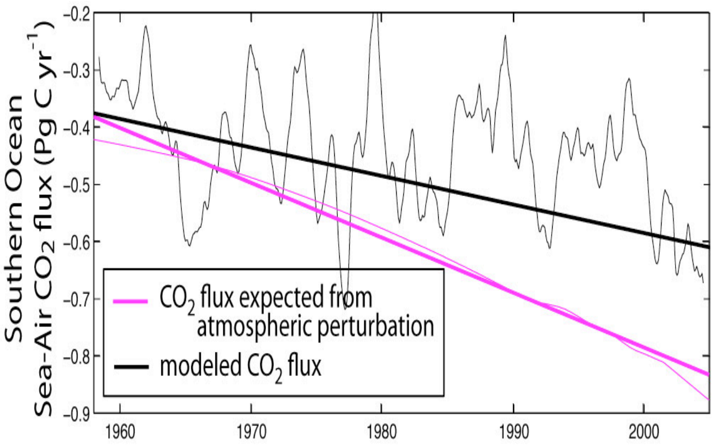

Figure 4. Spatially-integrated Southern Ocean (<30°S) sea-air CO_2 flux from a model hindcast forced with a long-term increase in Southern Hemisphere wind stress (black) and expected flux from the atmospheric CO_2 perturbation with no change in forcing (pink) (data from Lovenduski et al., 2008). Note that there is less uptake of CO_2 under increased wind stress

Oceanic models (Lovenduski et al., 2008), atmospheric data (LeQuere et al., 2007), and oceanic observations (Metzl, 2009) indicate that the Southern Ocean sink for atmospheric CO_2 has substantially weakened in the last few decades, relative to the expected sink from rising atmospheric CO_2 and fixed physical climate (Figure 4). It has been suggested that the primary cause of the sink reduction is a trend in the position and intensity of the Southern Hemisphere westerly winds and the subsequent increase in the upwelling and equatorward transport of CO_2-rich waters (Figure 5; LeQuere et al., 2007; Lovenduski et al., 2008).

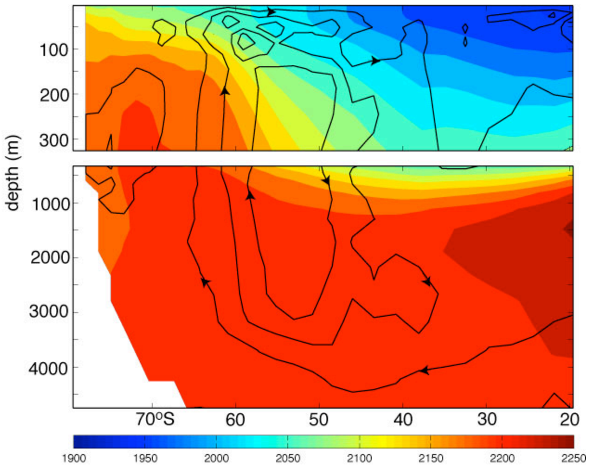

Figure 5. Model estimated trend in meridional overturning stream function (0.3 Sv yr^{-1}; black contours) from 1979-2004. Colors represent the zonal mean modeled dissolved inorganic carbon concentration (mmol m^{-3}) (data from Lovenduski et al., 2008).

Ice core records show a tight coupling between CO_2 and climate and previous studies have invoked a control on atmospheric CO_2 by varying rates of upwelling in the Southern Ocean. Toggweiler et al. (2006) suggest that cold glacial climates have equatorward shifted westerlies, while warm interglacial climates have poleward shifted westerlies. The former allows for reduced ventilation and an accumulation of respired CO_2 in the deep ocean, while the latter allows for degassing respired CO_2 into the atmosphere through upwelling in the Southern Ocean.

Recent observational evidence also indicates that upwelling in the Southern Ocean is a primary mechanism driving increases in atmospheric CO_2 at the end of the ice ages. Anderson et al. (2009) suggested that increased upwelling in the Southern Ocean occurred during deglaciations by relating opal flux in Southern Ocean sediments to nutrient supply and upwelling. They suggest that deglaciation is associated with enhanced upwelling in the high latitude Southern Ocean, which brings CO_2 and silicia-rich waters to the surface and creates more diatom production and opal burial.

Knowledge Gaps and Future Needs

Large differences in simulated Southern Ocean sea-air CO_2 flux estimates stem from the representation of physical and biological processes. Ocean physical models tend to produce dissimilar ocean circulation features because their individual model architecture, physical parameterizations, and surface forcing are widely divergent. This leads to large differences in advection and diffusion that act on both the dynamical and passive tracers, and creates a very large spread in the modeled CO_2 fluxes, particularly in the Southern Ocean (Doney et al., 2004; Orr et al., 2002). Furthermore, the physical circulation and tracer uptake in these models is highly affected by the representation of subgrid-scale processes (Lachkar et al., 2007).

The biological components of the large-scale carbon fluxes are poorly constrained by observations for key parameterizations of plankton growth and stoichiometry, export efficiency and remineralization. Surface nutrient concentrations are an important diagnostic for the role of the Southern Ocean in determining the air-sea partitioning of natural CO_2, but are also poorly known from direct observations (Ito et al., 2004). The knowledge gaps identified at the Scoping Workshop which need addressing to develop high resolution models of the Southern Ocean carbon cycle are:

- What is the fate of anthropogenic CO2 taken up at the surface (where is it transported)?
- What is the relative importance of the upper and lower cells in the uptake and storage of anthropogenic CO_2?
- How robust is the evidence for increased CO_2 outgassing in recent decades?
- How variable are preformed nutrients and oxygen?
- What factors control the depth at which exported carbon gets respired?

The recognition of these limiting knowledge gaps lead to the recommendation for a second research initiative with the goal:

Goal 2: Quantify and understand the contribution of the Southern Ocean to the air-sea balance of CO_2 and its interannual variability, and the storage of anthropogenic CO_2 in the ocean.

Implementation objectives

To reduce the uncertainty in our predictive capability of the Southern Ocean, a number of concerted, multidisciplinary studies are essential; furthermore, given the rate of change in polar systems, it is imperative that these programs be initiated as soon as possible. To that end, the following potential projects are listed as priority needs for understanding the impacts of climate change on the carbon budget, biogeochemical cycles, and ecosystems of the Southern Ocean:

Southern Ocean biogeochemical cycles and ecosystems cannot be studied regionally, given the large interactions among regions, and the importance of these transports (e.g., larval and krill advection). To that end, it is imperative to develop a **circumpolar, interdisciplinary approach** which will provide a framework for understanding climate interactions in the Southern Ocean, and its implications for ecosystem functioning and impacts on biogeochemical cycles. As part of that effort, **circumpolar (remote) instrumentation** that will include large-scale surveys and monitoring, internationally coordinated field efforts, and focused process studies in key regions are needed to ascertain the expected impacts of climate change.

There presently are conflicting interpretations concerning the historical response of the ocean to changing winds over the Antarctic Circumpolar Current, and how future changes will alter the oceanography of the Southern Ocean. Coincident with that, there is considerable uncertainty on how nutrient utilization and the associated biogeochemical cycles will be changed. In view of this uncertainty, a program is needed to monitor system-wide changes in critical environmental variables such as mixed layer depths, upwelling velocities, air-sea exchanges of gases, and nutrient utilization; in addition, models to adequately parameterize these processes need to be developed and embedded in global models that accurately represent mesoscale processes, as well as the impacts of altered functional groups on ecosystem processes. Such a goal would require **interdisciplinary, international programs** in a variety of key locations which are sustained over long (e.g., decadal) time scales to assess both climate change and natural variability. The use of remote platforms and process studies is required to constrain the models.

Future observational efforts should provide adequate sampling of both physical (e.g. upwelling, mixed layer depth) and biogeochemical (e.g. nutrient utilization, pCO_2, O_2) parameters in the Southern Ocean on large spatial and temporal scales. This will greatly aid in determining the processes controlling the spatial and temporal distribution of carbon and provide early detection for changes in the Southern Ocean.

Future modeling efforts need to address the problems plaguing earlier studies, namely the effect of model resolution and parameterization choices on physical processes in the Southern Ocean and the accurate representation of species composition and the sensitivity of nutrient utilization to changing physical and chemical environment. Experimental studies should constrain these problems, so that models can be used to make predictions of changes in Southern Ocean carbon and the underlying processes. This will require sustained observation efforts to:

- Quantitatively determine the processes that control uptake of CO_2 by the Southern Ocean and the temporal and spatial distribution of that uptake
- Provide early detection of shifts in the Southern Ocean carbon cycle function that may lead to rapid release or uptake of CO_2.
- Accurately measure net fluxes of CO_2 from the Southern Ocean

Chapter 3: Projecting the future Southern Ocean Carbon, Ecosystems and Biogeochemistry

This chapter focuses on the second of the overarching scientific questions raised in the introduction, namely

> **What will be the future impact of climate change, the CO_2 increase, and human actions on Southern Ocean ecosystems, biogeochemical cycles, and the ocean carbon sink?**

We address here the fundamental issues regarding the future changes of the Southern Ocean ecosystems, biogeochemistry and carbon cycle. The atmosphere overlying the Southern Ocean has been undergoing significant multi-decadal climate change characterized by the positive trend of the SAM , which may be driven by ozone depletion and global warming (Marshall, 2003; Miller et al., 2006; Thompson and Solomon, 2002). Understanding the evolving Southern Ocean carbon cycle poses challenges to the scientific community to better understand and quantify climate sensitivities of biogeochemical cycles and associated ecosystem structure, and the future of physical and biogeochemical dynamics of ocean carbon uptake and storage.

The ongoing climate change in the southern hemisphere allows development of the hypothesis that significant change in ocean circulation, biogeochemical cycles and ecosystem in the Southern Ocean may occur in the coming decades. This chapter first summarizes the current state of the knowledge about future projections of the Southern Ocean carbon, ecosystems and biogeochemistry obtained from discussions and presentations at the Scoping Workshop that focused on potential physical, biological and chemical drivers for the long-term climate change and alteration of biogeochemical cycles and ecosystem processes of the Southern Ocean. Next, current knowledge gaps and future needs for the community to improve understanding and quantification of climate sensitivities of physical and biogeochemical dynamics and marine ecosystems are identified.

Potential drivers for the long term change

It is essential to assess and improve our understanding in the potential drives for the long-term climate of the Southern Ocean. Even though our ability to predict future climate is limited, the Scoping Workshop identified five major perturbations that are likely to play important roles as discussed below.

1. Positive trend in SAM: increasing wind forcing

Climate variability of the extratropical southern hemisphere is characterized by the SAM. A significant multi-decadal trend of SAM has been observed (Figure 6) which may be in part driven by ozone depletion and global warming and that this trend is likely to continue for the next several decades (Thompson and Solomon, 2002; Miller et al., 2006). Positive indices of SAM are associated with the stronger westerly wind over the Southern Ocean and with the poleward shift of the maximum westerly wind. Through air-sea interaction, the changing winds will impact on the air-sea heat fluxes (Verdy et al., 2006; Ciasto and Thompson, 2008) and the wind-driven Ekman currents (Hall and Visbeck, 2002; Fyfe and Saenko, 2006). However, its long-term implication to the Antarctic Circumpolar Current system is not yet clearly understood. Compilation of hydrographic and float observations from the last several decades (Bönning et al., 2008) indicate that the density surfaces have not yet changed significantly suggesting that baroclinic transport of ACC has remained the same for the same time period. The response of ocean circulation to the increasing wind stress is likely to be complex, involving interplays between wind-driven Ekman flow, ocean eddies and density structures.

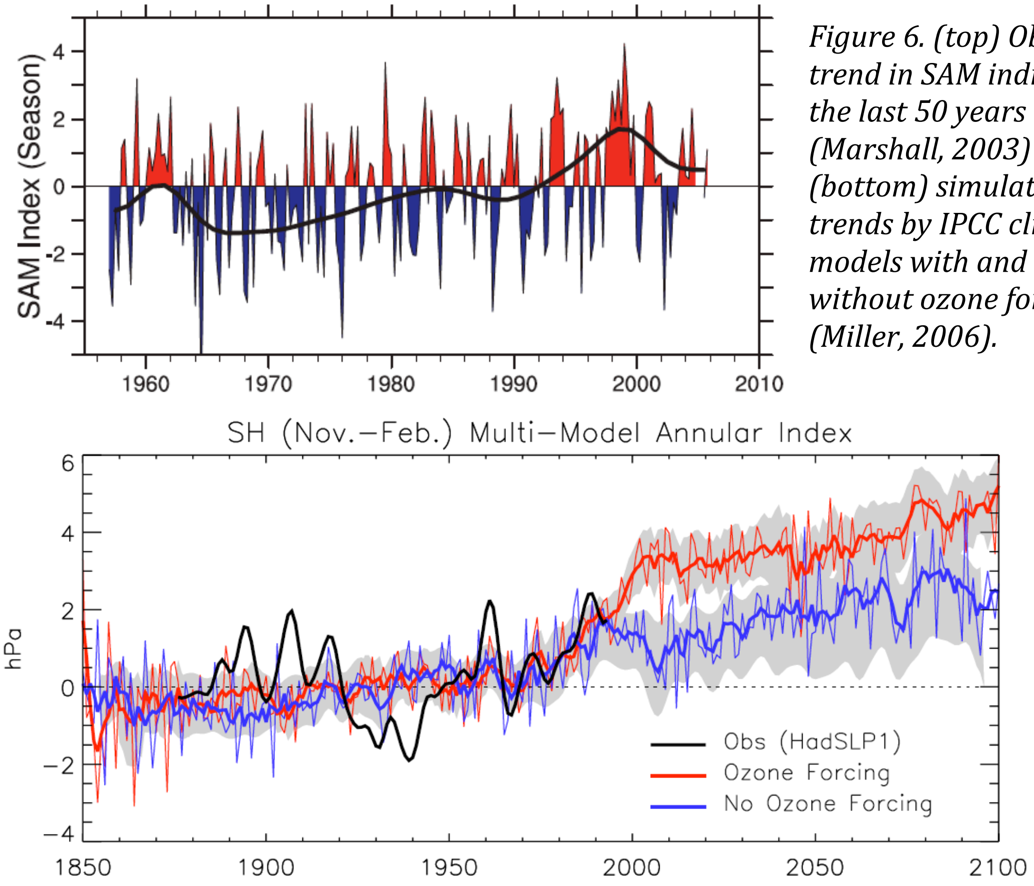

Figure 6. (top) Observed trend in SAM indices in the last 50 years (Marshall, 2003) and (bottom) simulated SAM trends by IPCC climate models with and without ozone forcing (Miller, 2006).

2. Changing sea ice distribution

Associated with the positive trend in the SAM, dramatic alteration of sea ice distribution has been observed (Parkinson, 2002) which will likely to continue impacting on the Antarctic ecosystem. The positive trend in SAM is associated with the declining sea ice in the Antarctic Peninsula and with the increasing sea ice in the Ross Sea (Figure 7).

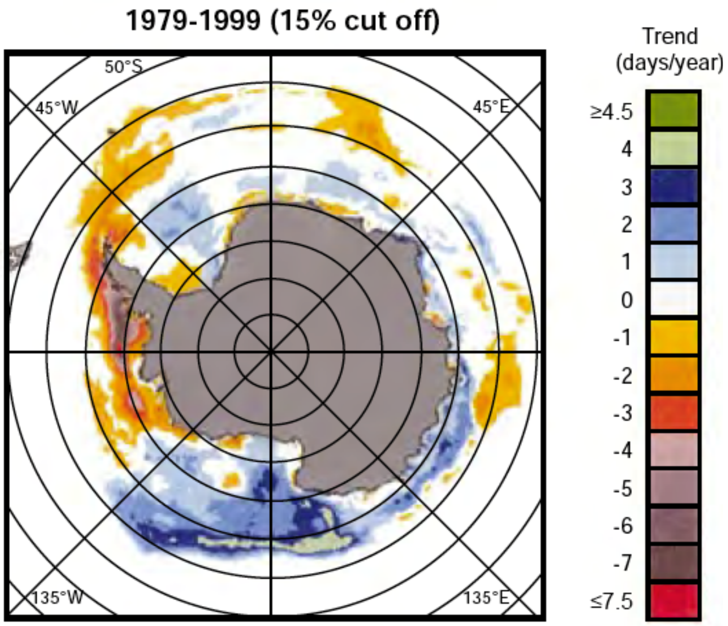

Figure 7. Observed trend in the length of sea ice seasons between 1979 and 1999, indicating longer sea ice seasons in the Ross Sea and shorter sea ice seasons in the Weddell Sea (Parkinson, 2002).

The distribution of sea ice plays a fundamental role in the feeding patterns, foraging behavior and reproductive cycles of a wide range of species), the large-scale changes in the sea ice associated with future trends in SAM will likely to cause major impact on the marine ecosystem. Furthermore, the sea ice distribution impacts the exchange of heat, freshwater, carbon dioxide and other gases between the ocean and atmosphere.

3. Ocean warming and stratification

Hydrographic and float observations show evidence of the warming and freshening of the Southern Ocean (Gille, 2002; Bönning et al., 2008; Figure 8). Both warming and freshening tends to increase the upper ocean stratification, and this trend is likely to continue as the warming of the atmosphere continues. Changes in the upper ocean stratification can have profound impacts on the biogeochemistry and ecosystem processes through the mixed layer depth, the upwelling and cycling of micro and macro-nutrients, and the vertical migration of marine organisms. The rate of upwelling also impact on the outgassing of

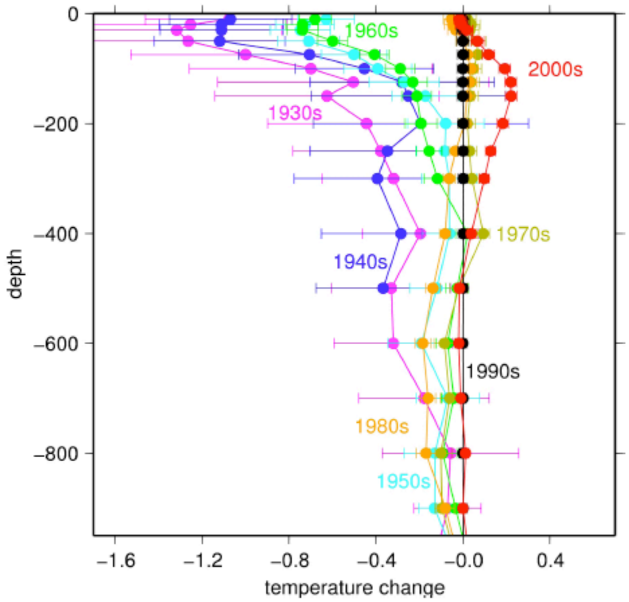

Figure 8. Observed decadal changes in the upper ocean temperature profile in the Southern Ocean from 1930s to 2000s (Böning et al., 2008).

natural carbon (Le Quere et al., 2007; Lovenduski et al., 2007), and the sequestration of anthropogenic carbon dioxide (Sarmiento et al., 1998; Lovenduski and Ito, 2009).

4. Ocean acidification

Absorption of anthropogenic carbon dioxide into the ocean causes seawater to become more acidic. The effect of ocean acidification is pronounced in the cold polar waters, and accumulation of anthropogenic carbon in the Southern Ocean will decrease the saturation state of calcium carbonate particles (Figure 9; Feely et al., 2004). Acidification of the Southern Ocean is likely to impact on several key biogeochemical processes including plankton community structures, and nutrient and alkalinity cycles, formation of calcium carbonate particles, and ballasting of organic carbon in the sinking particulate fluxes.

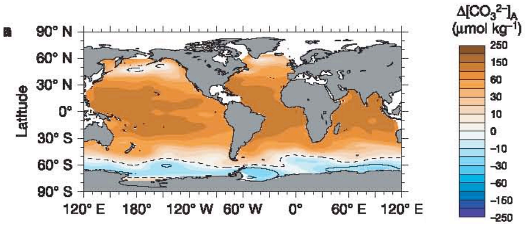

Figure 9. The aragonite saturation state as a function of latitude, emphasizing the extreme vulnerability of the Southern Ocean to ocean acidification (from Orr et al. 2005).

5. Harvesting of marine biomass

Harvesting of marine biomass due to human activity has profound impacts on the ecosystem structure. Impacts of anthropogenic perturbation in marine ecosystem (e.g. industrial whaling) may propagate through the food web interactions over multi-decadal timescales (Springer et al., 2003), thus interaction across trophic levels including the effects of harvesting by human activity can be a crucial forcing for the long-term evolution of the Southern Ocean ecosystem and the sustainability of marine biomass.

Each of the forcings discussed above has intrinsic uncertainties due to the range of future climate projections and the lack of understanding in physical processes that control ocean currents, stratification and sea ice. This uncertainty then propagates to the long-term change in ecosystem, biogeochemical cycles and carbon cycles. In the following sections, we discuss current knowledge gaps and future needs that were identified in the workshop to be specifically related to improving our future projection in the ecosystem, biogeochemistry and carbon cycle of the Southern Ocean.

Long-term change in ecosystems and biogeochemical cycles

Knowledge Gaps and Future Needs

Climate change may impact the Southern Ocean ecosystem over a wide range of spatial and temporal scales including multiple trophic levels. A knowledge gap exists in linking the environmental changes to the biodiversity, species composition and food web processes. It is crucial to determine the resilience and susceptibility of the ecosystems to the environmental changes and harvesting by human activity. Future changes in ocean currents, stratification, sea ice and harvesting can impact on the primary producers (bottom-up control) as well as predators (top-down control). Perturbations in biomass can occur at multiple trophic levels simultaneously, and their interactions and relative importance to the ecosystem and biogeochemical cycles are not well understood. Effective monitoring programs are crucial in detecting ecosystem changes over inter-annual, decadal and longer timescales. It takes community-wide effort and international collaborations to develop monitoring programs covering the coastal, regional and circumpolar Southern Ocean.

A gap in our understanding exists in linking ecosystem changes to the biogeochemistry. How do rates of nutrient cycling, uptake and export depend on ecosystem structure and food webs? What is the role of higher trophic organisms in mediating the carbon cycle? It is crucial to understand the link between ecosystem and biogeochemical cycling in the context of systematic perturbations in physical environment and harvesting.

Finally, another area of high priority is the development, integration and intercomparison of ocean circulation, biogeochemistry and ecosystem models, which will be a primary tool for predicting the long-term co-evolution of physical and chemical environment, biogeochemical cycles and food webs. It is crucial to improve coupled end-to-end models that include ocean, ice, atmosphere, biogeochemistry, and ecology components possibly including nesting of regional, coastal, and high resolution models into large scale simulations. Models must be tested and calibrated against observations to identify key deficiencies and biases.

The central goal towards which development of an improved understanding of the drivers of long-term change in ecosystems and biogeochemical cycles will be aimed will be to:

Goal 3: Provide greatly improved projections of the impacts of climate change and human activities on Southern Ocean ecosystems and biogeochemical cycles

Long-term change in the Southern Ocean carbon sink

The fourth and final goals of SOCEB science plan are to:

Goal 4: Provide greatly improved projections of the contribution of the Southern Ocean to future atmospheric concentrations of CO_2.
Goal 5: Provide the scientific basis for societal decisions about Southern Ocean ecosystems and contributions to the management of CO_2 and the carbon cycle.

The principal knowledge gaps, future needs, and implementation objectives that are required to fulfill these goals are the following.

Knowledge Gaps and Future Needs

Response of the Southern Ocean sea-air CO_2 flux to the increasing atmospheric winds has been under intense research (Le Quere et al., 2007; Lovenduski et al., 2007; Boning et al., 2008; Le Quere et al., 2008; Lovenduski and Ito, 2009; Ito et al., 2010). Different sensitivity may arise from the representation of physical and biological processes in numerical models. Ocean models tend to produce different ocean circulation features because their individual model architecture, physical parameterizations, and surface forcing are widely divergent. This leads to significantly different ocean transports and creates a very large spread in the modeled CO_2 fluxes, particularly in the Southern Ocean (Doney et al., 2004; Orr et al., 2002). Furthermore, the physical circulation and tracer uptake in these models is highly affected by the representation of subgrid-scale processes (Lachkar et al., 2007). The biological components of the large-scale carbon fluxes are poorly constrained by observations for key parameterizations of food web, primary productivity, stoichiometric ratios, export efficiency and remineralization.

There are considerable uncertainties in potential impact of future human activities in the climate change, ocean acidification and perturbations in marine biomass. Improved understanding and observation of ecosystem structure and biogeochemical cycles can provide scientific basis for societal decisions including future emission of greenhouse gases and harvesting of marine biomass in the Southern Ocean.

Implementation objectives

To improve our predictive capability of the Southern Ocean ecosystems and biogeochemical cycles, concerted, multidisciplinary studies are essential to integrate marine food webs, ecosystems and biogeochemical cycles. Improved scientific understanding can provide useful information for societal decisions regarding the conservation and effective management of marine resources in the Southern Ocean. To this end, the following areas are listed as priority needs for the impacts of climate change on the carbon budget and ecosystems of the Southern Ocean:

- Understanding and quantifying the key processes and feedbacks in determining the response of the carbon cycle to climate variability and human perturbations
- Developing monitoring systems at the circumpolar scale to detect changes in the carbon cycle
- Developing modeling systems that adequately represent interactions and feedbacks in the physical-ecological-biogeochemical processes
- Synthesizing various observations into a unified framework to reduce uncertainties in diagnosis and prediction of the carbon cycle

The future of biogeochemical cycles and ecosystems cannot be studied in isolation from future projection of Antarctic climate, ocean circulation and cryospheric change given that environmental forcing mechanisms (e.g., atmospheric winds, ocean currents, stratification and sea ice) play a crucial role. It is imperative to develop a research program taking multiple disciplinary approaches on physical-ecological-biogeochemical interactions. As part of that effort, characterization of the susceptibility of the ecosystems to the anticipated environmental changes and harvesting is needed for the prediction and protection of marine biomass resources. Deployment of circumpolar instrumentation that will include large-scale surveys and monitoring, internationally coordinated field efforts, and focused process studies are needed to detect and monitor the impacts of ongoing and future climate change.

Future observational efforts should be accompanied with model development and integration that includes ocean, atmosphere, ice, biogeochemistry and ecosystem components to synthesize various observations in a unified framework, which can then be used as a tool to predict the long-term co-evolution of physical and chemical environment, biogeochemical cycles and food webs. Models must be compared to observations to identify key deficiencies and biases. Model-model and model-observation comparisons are crucial so that models can capture relevant processes that may be used for future projections. To reduce the uncertainties in the future behavior of carbon sink of the Southern Ocean, a program is needed to monitor circumpolar-scale changes in critical environmental variables such as mixed layer depths, upwelling, air-sea exchanges of gases, and biological carbon sink. Models are also needed to be developed to parameterize these processes and be embedded in global models that represent mesoscale processes as well as the biogeochemical cycles that are crucial to the sequestration of carbon dioxide.

Developing coupled models to simulate future scenarios for the climate-ecosystem-carbon cycle interaction given current understanding and uncertainties in the physical and chemical environmental change is needed to resolve problems plaguing earlier studies, namely the deficit in scale interactions and the unresolved physical processes and the accurate representation of species composition and the sensitivity of nutrient utilization to changing physical and chemical environment. A new generation of models is needed to adequately represent ocean eddies and its roles in the transport of carbon, limiting nutrients and living organisms, potentially nesting important coastal and shelf regions with much higher spatial resolutions in order to synthesize various observations and to predict the long-term evolution of the Southern Ocean carbon cycle. Synthesis of observations and numerical models to constrain current states of the Southern Ocean carbon cycle is needed such that the future simulations can initialize from the best estimates of current carbon cycle and provide improved predictions of future changes in the oceanic carbon sink. Developing ecosystem and carbon cycle modeling systems is also crucial to support societal decisions for sustainable exploitation for living resources in the Southern Ocean.

Chapter 4. Program Components and Structure

Scientific Program Objectives and Hypotheses

The elements of the SOCEB scientific program are designed to improve scientific knowledge and understanding. To do this, the program is designed around long-term objectives that will result in:

- Development of an observational infrastructure capable of accurately measuring changes in air-sea CO_2 fluxes, carbon storage, nutrient cycling, and environmental structure in the Southern Ocean that interfaces with other programs such as the Southern Ocean Observing System (SOOS).
- Understanding of the biogeochemical, food web, and physical processes that control the temporal trends and spatial distribution of past and current Southern Ocean sources and sinks of carbon and nutrients, and how these might change under future conditions of climate and atmospheric chemistry.
- Determining quantitatively the factors (long term and transient) that regulate the uptake of anthropogenic CO_2 within the Southern Ocean and the net sequestration of this carbon in the Southern Ocean and neighboring regions.
- Development of the ability to predict and interpret changes in the Southern ocean carbon and nutrient cycling in response to climate change and inputs of CO_2, and including changes in the functional aspects of these cycles.
- Development of the ability to predict changes in biogeochemical cycling, food webs and feedbacks and the consequences of these for climate change.

The program that addresses the above objectives must also be able to provide the basis for application of the scientific knowledge and understanding to societal needs. To ensure that this critical component is developed and integrated into a Southern Ocean research program the scoping workshop developed a parallel set of long-term objectives focused on:

- Development of models of the carbon cycle to (1) predict the life times, sustainability and interannual/decadal variability of Southern Ocean carbon fluxes, and (2) provide a scientific basis for evaluating potential management strategies to enhance carbon sequestration.
- Development of the capability for early detection of major shifts in carbon cycle function that may lead to rapid release of CO_2 or other unanticipated phenomena.
- Development of the ability to monitor the efficacy and stability of purposeful carbon sequestration activities.
- Enhancement and development of monitoring systems to allow for early detection of shifts in food web interactions, and biogeochemical cycling that may lead to major shifts and/or perturbations in Southern Ocean ecosystems and CO_2 release or sequestration.
- Development of the frameworks for managing Southern Ocean natural resources and carbon sequestration that provide the basis for informed policy at national and international levels

The potential for near-term progress in achieving the above objectives is demonstrated by four general hypotheses that arose from the presentations, discussion and working groups at the scoping workshop:

1. The oceanic uptake of anthropogenic CO_2 by the Southern Ocean will continue to increase in response to rising atmospheric CO_2 concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology and chemistry.
2. The air-sea flux of natural CO_2 from the Southern Ocean to the atmosphere will increase in response to increased wind stress over the Southern Ocean, but the rate of increase will be modulated by changes in ocean circulation, biology and chemistry.
3. The structure and functioning of the circumpolar Southern Ocean ecosystems will be modified in response to changing sea ice and environmental conditions that accrue from climate warming.
4. Southern Ocean food webs will shift towards less dependence on Antarctic krill as climate warms and hence energy transfer to higher trophic levels will occur via alternative pathways.

These hypotheses are testable by integration of the program elements described below. However, this will require new mechanisms to integrate information on the carbon cycle and coordinate interagency efforts as well as additional funding in critical areas.

Program Goals and Elements

The specific goals, discussed in Chapters 2 and 3, provide a basis for developing the elements of a Southern Ocean research program (Table 1) that will yield results that will address the objectives and test the hypotheses given above. The program elements and activities required by each goal are described below. These will require new mechanisms to integrate information, programmatic coordination at national and international levels, and additional funding in critical areas. Implicit in all of the programs is an element in which the results of the research will be linked to governmental management decisions concerning the regulation of CO_2 inputs to the atmosphere. Only with accurate predictions of future changes can sound management practices be put into place.

GOAL 1*: Quantify and understand the impacts of climate change and interannual variability on Southern Ocean ecosystems and biogeochemical cycles*

In recent years the interannual variability in oceanographic and biological variables for a variety of Southern Ocean subsystems has been clearly documented through field and remote sensing studies of ice, winds, temperature, and chlorophyll. The degree of variability and sensitivity to large-scale forcing has been revealing, but underscores the importance of understanding the processes that drive such pronounced variability. We also are aware of trends and variations within food webs, and are just now beginning to understand the linkages of large-scale processes on regional ecosystems and

Table 1. A list of potential program elements for future research in the Southern Ocean.

Program Element	Deliverable	Description
	ATMOSPHERIC MONITORING	
1. Airborne CO_2 Observation Program	Three-dimensional and temporal distributions of CO_2 and tracers over the Southern Ocean, analyzed to define regional sources/sinks, and constrain atmospheric transport models	Continuous monitoring of atmospheric tracers over entire Southern Ocean in conjunction with the Southern Ocean Observing System (SOOS) and other national/international programs now in place
2. Regional atmospheric CO_2 Monitoring Network	Enhanced space/time data for CO_2 and tracers, defining regional sources/sinks on a global scale, and constraining atmospheric transport models	Increased number (by about a factor of 3) of flask and continuous monitoring stations measuring atmospheric CO_2, O_2/N_2, and related tracers in the Southern Ocean, emphasizing continental and remote marine locations; vertical profiles at selected locations as specified in element 2.
	OCEAN OBSERVATIONS	
3. Remote sensing	Continuous satellite observations of Ocean color, SST, sea ice, wind fields, clouds, altimetry, and CO_2	Satellite observations of oceanic and atmospheric variables.
4. Large scale Ocean Surveys	Ocean-atmosphere fluxes, basin-scale net uptake of anthropogenic CO_2, and interpretation of seasonal variances, atmosphere-ocean-biology interactions, continuous plankton surveys	Analysis of ongoing CLIVAR survey data; Develop and deploy time-series and drifting buoys and automated towed vertical samplers for CO_2 and related parameters (DIC, DOM, POM, alkalinity, O_2, nutrients, $^{13}CO_2$, $^{14}CO_2$, T, S) and tracers of ocean circulation (CFCs, ^{14}C, $^{3}H/^{3}He$), reduce cost per measurement, increase data flow
5. Regional Observational Experiments	Regional determinations of fluxes and concentrations of CO_2, greenhouse gases, pollutants	Coordinated airborne, ship, and terrestrial experiments integrated with model development and testing
6. Time Series Observations	Long-term ocean biological, biogeochemical, and flux data for major biomes.	Continued observations at the West Antarctic peninsula LTER site, development of a new site in the Ross Sea, and development of observational program in 3 sectors of the open ocean in Subantarctic zone, the Polar Front zone, and the Antarctic zone
7. Ocean Process Studies and Manipulations	Define effects of CO_2, acidification, temperature changes, circulation, Aeolian deposition, and ice melt on ocea biology and oceanic uptake of CO_2	Physical and biological studies of dispersion of anthropogenic CO2 and controls on new production/uptake; Ocean manipulation experiments (~2/yr duration) to examine hypotheses such as the role of iron in ecosystem production
	MODELING AND SYNTHESIS	
8. Model Development	Develop and validate models for analysis and synthesis of data	Improved model representations of physical, biogeochemical, and ecological processes in the Southern Ocean on regional and large spatial scales; rigorous, independent comparisons of these models with data
9. Model Integration	Integrate existing models to improve the realism & quantification of Southern Ocean processes	Improved coupled end-to-end models which include ocean, ice, atmosphere, biogeochemistry, and ecology components; nesting of regional, coastal, and high resolution models into large scale simulations
10. Model Intercomparison	Identify robust model features and responses; identify key deficiencies and biases	Model-Model and Model-Data intercomparison projects
11. Complimentary Modeling Studies	Support regional observational experiments, time series observations, and ocean process studies and manipulations with a full range of models	Application of theoretical and numerical models to better understand mechanisms of change at specific Southern Ocean locations
12. Improving	Better predict changes in the	Development of Earth System Models that predict

Predictive Capabilities	carbon-climate system to guide future observations and policy	CO_2 and climate interactively

biogeochemical cycles. Understanding the magnitude and causes of this variability in the Southern Ocean is a key to understanding the impacts of global climate change.

Major program elements and activities

To understand the processes underlying ecosystem and ocean change, we first must clearly quantify the natural changes that occur within regions. As such, a program to monitor the magnitude of interannual variability is urgently needed in a number of key locations in the Antarctic, such as the west Antarctic Peninsula, Ross Sea, Amundsen Sea and Marguerite Bay. These areas have the great advantage of having de facto time series of both oceanographic variables and ecosystem variables (primary productivity, biomass, recruitment, demographics of critical species, etc.), and the time-series analyses of some of these areas have already been initiated. Such programs will need to be extended to include year-round investigations and cover sufficiently long periods (a minimum of 5 years) to encompass the range of variability, and involve the emerging technologies (gliders, floats, profiling moorings) that are now becoming available. New applications of satellite information will also need to be included, and the tools of data assimilation and numerical modeling applied to make predictions of future changes in these systems.

<u>GOAL 2</u>*: Quantify and understand the contribution of the Southern Ocean to the air-sea balance of CO_2 and its interannual variability, and the storage of anthropogenic CO_2 in the ocean, and provide greatly improved projections of the contribution of the Southern Ocean to future atmospheric concentrations of CO_2*

The Southern Ocean is the site for extensive fluxes of CO_2 between the ocean and atmosphere, and there is evidence to suggest that these fluxes are changing significantly in magnitude with time. Current estimates of Southern Ocean uptake of CO_2 vary significantly depending on the data and analytical approach used (e.g., inverse model analysis of CO_2 data from atmospheric surface stations, changes over time of global CO_2 , O_2 , $^{13}CO_2$ /$^{12}CO_2$, measurement based estimates of the air-sea CO_2 flux and dissolved inorganic carbon inventory, and ocean model simulations). A greatly improved understanding of the gas transfer rates in the entire Southern Ocean is needed to adequately understand the region's role in the global carbon cycle and control of atmospheric CO_2. The proposed program is designed to reconcile these estimates to a precision adequate for policy decisions by delivering new types of data; applying new, stringent tests for models and assessments; and providing quantitative understanding of the factors that control sequestration of CO_2 in the ocean and on land. In coordination with other research activities of the SOCEB research program, sound basis for policy debates and decisions will be provided by SOCEB as fully implemented.

Major program elements and activities

As such, large surveys of dissolved gases are needed over a series of transects in the Southern Ocean to compare those distributions to those found in earlier studies. A complete assessment of the total carbon dioxide budget is necessary within each survey, and a rigorous intercomparison of methods as well. Process studies are needed in the regions that are expected to play critical roles in this process. Furthermore, such studies must encompass all meteorological conditions, and as a result, will require the use of evolving technologies such as CO_2-measuring buoys and autonomous vehicles and gliders. The data will need to be incorporated into models to trace the evolution of the inorganic carbon budget through time. Models can help predict the critical locations of CO_2 fluxes, and a program is needed designed to assess the fluxes over a number of years to encompass a full range of atmospheric and oceanographic conditions.

GOAL 3*: Provide greatly improved projections of the impacts of climate change and human influence on Southern Ocean ecosystems and biogeochemical cycles*

Climate change is already impacting the Southern Ocean, and it is projected that such changes will continue unabated for the foreseeable future. Despite a clear understanding of the nature of some climate change issues (e.g., ocean acidification in the Southern Ocean is predicted to have marked impacts on carbonate and iron chemistry, and plankton composition; disappearance of ice is known to cause shifts in the biomass and reproduction of selected apex predators), to date no interdisciplinary studies have been conducted to assess the sensitivity of key processes within ecosystems and biogeochemistry. Furthermore, increasing harvesting of the Southern Ocean fisheries resources may initiate a series of trophic cascades, the consequences that at present are impossible to predict. Given that Antarctic ecosystems are exceptionally vulnerable to large-scale changes and human influence, it is imperative that we understand the nature and complexity of the potential future changes induced by climate change.

Major program elements and activities

Process-oriented field studies are needed to understand the mechanisms responsible for ecosystem changes and to predict future changes. Such process-studies should also incorporate interactive effects among variables (e.g., temperature and CO_2), and investigate all trophic levels utilizing molecular, physiological and ecological approaches. A complete assessment of the critical processes and their susceptibility to climate-human change effects are needed over the entire life history of critical organisms, including winter processes. Modeling programs, especially those expressly addressing the full food web, are needed to address the impacts of climate change and human influence on ecosystems and biogeochemical cycles.

Role of modeling in understanding and predicting critical processes

The goals and overarching questions discussed in the previous sections clearly indicate that SOCEB will require a novel and interactive mixture of sustained observations, long-term monitoring in key locations, survey studies, and process-oriented experiments and projects. Modeling studies provide a mechanism to focus these research efforts, identify gaps in data availability, clarify areas of uncertainty, and determine approaches and strategies for efficient and effective data collection. Sustained observations and monitoring networks will require the use of rapidly evolving technologies, and locations for these efforts can be identified by the use of models. Process-studies remain essential for improving understanding of physical and biological exchanges and interactions, but must be carefully chosen in view of the cost of such intensive efforts. Focused modeling efforts can provide feed-back to investigators conducting field research to allow for adaptive sampling. The highest yield is obtained with modeling studies are iterative and integrated within the whole research program, including field and data analyses.

The SOCEB research program would benefit from compilation, synthesis and integration of existing datasets. Thus, an initial phase of the program, which should begin now, is to invest in modeling studies with a focus on synthesis of existing data to inform decisions about field and observational studies that are developed around the goals and questions articulated at the Scoping Workshop. This activity should include scientists involved in planning field studies, monitoring networks, and process studies. These modeling activities will help identify critical needs and thus result in prioritizing sampling effort.

Modeling studies focused on inter-comparisons of existing Southern Ocean biogeochemical and food web models would be beneficial to furthering development of models that combine processes these processes. This combined modeling approach is new to the Southern Ocean and there are no examples from other parts of the ocean to provide guidance on how this should be done. This is a high priority for SOCEB modeling research.

Program Implementation – Elements and Approach

Past experience with large-scale, multidisciplinary oceanographic research programs has provided invaluable insights into the program elements and approaches that are needed for successful implementation of a program like SOCEB. Discussions at the Scoping Workshop identified elements that were considered to be key to successful implementation of an integrated, multi-disciplinary Southern Ocean research program that is focused on the goals and research priorities described in Chapters 2 and 3. These are described as follows.

Program Integration

The SOCEB research program represents integration of ecosystem, biogeochemical, climate, and human dimensions research. Thus, the program requires an integrated, multidisciplinary approach from the outset and integration across and among these elements needs to be ongoing programmatic priority. To ensure that this integration occurs and that communication is maintained among all project components and international community (see next section), the Scoping Workshop recommended establishment of a SOCEB project office and a science steering committee. It should be noted that the breadth of the proposed SOCEB program requires inputs from a wide range of the science community, many of which have not historically worked together.

A central project office will ensure that coordination and implementation occurs at the program component, national and international levels. A science steering committee provides a structure for discussing and focusing scientific ideas and approaches. Expertise that should be represented on a science steering committee would be determined through discussions with the sponsoring agency and the broad scientific community. Experiences in Southern Ocean JGOFS and GLOBEC programs clearly showed the importance of these programmatic structures, especially for development and coordination of field studies.

Inherent in all aspects of the SOCEB program is the need for communication within all components to enhance the overall project objectives. Thus, an important element of maintaining SOCEB research will be focused workshops that allow program participants to interact and work with one another. These workshops will be especially important for the design and analysis of modeling results and for the design of monitoring, survey and field studies. Also, participants in the SOCEB research program should, from the beginning, plan organized programs of communication, outreach, and education that support the understanding and dissemination of new scientific insights and research results to interested parties in and beyond the scientific community.

Data access and communication

Achieving the goals described in this plan requires open exchange of observations and associated data products, research findings, and model results. Thus, early and continuous investment in information management strategy (observational and model data) is a critical program element to ensure timely provision of data, research findings, and model results; to assimilate/integrate observations and data from different platforms, instruments, and field campaigns; to adhere to appropriate standards, protocols, and guidelines; and to provide metadata critical to the analysis from numerous individual scientists and participating institutions. The continuation of support for any individual or research group involved in SOCEB will depend on the timely and complete availability of data and models generated.

Development of new partnerships

Development of long-term monitoring capability is a critical component of the SOCEB research plan. The instruments and platforms required for this might best be developed through the non-academic extramural research community. The special capabilities and expertise of this community should be developed through partnerships that focus on the design, development, testing, and deployment of measurement systems that could help address the research goals and objectives of the SOCEB research program. This partnership could ensure an appropriate mix of researchers aware of the scientific requirements, and engineers and technicians familiar with system capabilities; and facilitate the exchange of ideas and experience among groups working on the development of systems to meet similar needs. In short, it could create an environment of creative synergy rather than simply duplicate effort. Exploration of the challenges and opportunities of partnerships with the private sector should be an early implementation activity.

The SOCEB research articulated at the Scoping Workshop provides a framework for creative new partnerships among various disciplines and programmatic areas of expertise within the scientific community. This plan represents a merger of two major scientific communities dealing with related research on ocean biogeochemistry and ecosystems. The issues identified for Southern Ocean research in the next decades are such that neither community alone can provide the expertise and insights needed to adequately address them. Combining the biogeochemical and food web research communities will capitalize on scientific synergisms, avoid unnecessary duplication, and make the best use of the limited resources that are available for Southern Ocean research. This will also place U.S. Southern Ocean research at the forefront of international research programs that are addressing similar themes.

Revisions and refinements of existing partnerships between the Office of Polar Programs and the National Oceanic and Atmospheric Administration-funded Antarctic Marine Living Resources (AMLR) program would build on existing capabilities, leverage limited resources, avoid duplication, and produce new opportunities for scientific progress.

Links to international programs

Establishing strong ties to related scientific efforts of other countries and formal international research programs represents a key principle for successful implementation of the SOCEB research program. Research in the Southern Ocean is costly and limited by infrastructure, and fully joining our international partners in collaborative research efforts is the most efficient means of answering the critical scientific questions ahead of us. Such multinational collaboration offers opportunities to leverage resources and take advantage of comparable methodologies and joint projects.

One particularly beneficial approach to international partnerships involves the development and implementation of strong U.S. contributions to established international global change research programs. The SOCEB should establish strong ties to the World Climate Research Program through its Climate Variability and Predictability (CLIVAR) program, which is focused on understanding the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial time-scales. Similarly, the Integrating Climate and Ecosystem Dynamics (ICED) in the Southern Ocean, which is a regional program of the Integrated Marine Biogeochemical and Ecosystem Research (IMBER) project of the International Geosphere-Biosphere Programme, is a circumpolar ecosystem research program (see IMBER Report No. 2). The developing Southern Ocean Sentinel (SOS, 2009) is being planned as an international effort to assess climate change impacts on Southern Ocean ecosystems over the next several decades and as such, provides a long-term structure for furthering research results from the SOCEB program.

The Scientific Committee for Antarctic Research (SCAR) is a non-governmental organization that initiates, promotes, and coordinates Southern Ocean research. It would be important for SOCEB to have connections to SCAR and to have representation on its standing scientific committees. Similarly, development of interactions and connections to the Commission for Conservation of Antarctic Living Marine Resources (CCAMLR) and the International Whaling Commission (IWC), both governmental organizations, with mandates to manage Southern Ocean living recourses, will be critical to dissemination of SOCEB results to management and policy communities.

The sustained measurement and monitoring components of the SOCEB research program can provide substantial and important contributions to the Southern Ocean Observing System (SOOS), which is currently under development. Many of the measurements and data streams that are being considered for the SOOS are similar to what are needed by SOCEB. Hence, early involvement of SOCEB scientists in SOOS working groups and workshops will ensure measurements and data sets that will be important for model development and evaluation and for planning field activities. The SOOS will be interfaced with global observing programs such as the Global Climate Observing System (GCOS) and the Global Ocean Observing System

(GOOS), which will leverage resources (such as space- and ground-based observational platforms), develop and demonstrate new technologies, and allow Southern Ocean observations to be placed in a global, Earth-system context.

SOCEB Program Measures of Success

Specifying measures by which a program can measure success is an important part of the development of any research program. Such an approach is now standard for World Climate Research Programs, such as CLIVAR. For SOCEB a set of success measures will be developed and used to assess program progress from the outset.

Potential success metrics can be established in terms of new resources developed, scientific advances, predictive capability, observational capability, data sets and availability and capacity building. Potential metrics will be developed in each of these areas through discussions with the community and funding agency personnel. The scientific steering committee will have oversight for ensuring that the metrics are met.

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Appendix A - Southern Ocean Scoping Workshop Participants

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Appendix B - Workshop Agenda

Monday, June 8, 2009

Theme: New Frontiers in Observations of Ecosystems, Biogeochemistry, and Climate

8:15-8:45	Continental Breakfast
8:45-9:00	Introduction and Welcome – Jorge Sarmiento
9:00-9:45	"Long-term Warming Trends in the Southern Ocean: Links to Winds and Frontal Migration" - Sarah Gille
9:45-10:30	"Local to global and seasonal to interannual aspects of organic matter utilization in Polar seas" - Hugh Ducklow
10:30-11:00	Coffee Break
11:00-11:45	"Wind driven upwelling in the Southern Ocean and its Impact on atmospheric CO_2 concentrations" - Bob Anderson
11:45-12:00	General Discussion
12:00-1:30	Buffet Lunch
1:30-2:15	"The Upper Cell" - Kevin Speer
2:15-3:00	Breakout Sessions theme: The past and present Southern Ocean carbon cycle 1) Quantifying and understanding the cumulative Southern Ocean anthropogenic CO_2 sink and its interannual variability moderator: Joellen Russell rapporteur: Thomas Arsouze room: 121 2) Quantifying and understanding the natural carbon cycle and its influence on the cumulative air-sea CO_2 flux in the Southern ocean and its interannual variability moderator: Colm Sweeney rapporteur: Taka Ito room: 134 3) Determining the impacts of climate change on Southern Ocean ecosystems moderator: Walker Smith rapporteur: Veronica Lance room: 122
3:00-3:30	Coffee Break
3:30-5:00	Breakout Sessions, continued
5:00-7:00	Workshop Reception, Beer/Wine & Hors d'Oeuvres

Tuesday, June 9

Theme: New Frontiers in Modeling of Ecosystems, Biogeochemistry, and Climate

8:30-9:00	Continental Breakfast
9:00-9:45	"Response of the Southern Ocean to climate variability and trends" - Mike Meredith
9:45-10:30	"Changes in the Southern Ocean CO_2 sink: A large-scale modeling perspective" - Nikki Lovenduski
10:30-11:00	Coffee Break
11:00-11:45	"Simulating Southern Ocean Dynamics in Coupled Climate Models" - Scott Doney
11:45-12:00	General Discussion
12:00-1:30	Buffet Lunch
1:30-2:15	"Spatial and temporal operation of Southern Ocean food webs" - Eileen Hofmann
2:15-3:00	Breakout Sessions theme: Predicting the future Southern Ocean carbon cycle 1) What will it take to provide greatly improved projections of the future response of the Southern Ocean carbon budget? moderator: Jorge Sarmiento rapporteur: Stephanie Downes room: 121 2) What is required to develop the scientific basis for predicting the impacts of climate change on Southern Ocean ecosystems? moderator: Kevin Arrigo rapporteur: Jill Peloquin room: 122
3:00-3:30	Coffee Break
3:30-5:00	Breakout Sessions, continued
7:00-9:00	Workshop Dinner (Prospect House)

Wednesday, June 10

Theme: Interdisciplinary Approaches to Investigating Ecosystem, Biogeochemistry, and Climate Interactions

8:30-9:00	Continental Breakfast
9:00-9:45	"Climate Change and Upper Trophic Level Predators" - Dan Costa
9:45-10:30	"Drivers of temporal and spatial variability in Southern Ocean primary production and export flux" - Philip Boyd
10:30-11:00	Coffee Break
11:00-11:45	"Southern Ocean Food Web Research and Outcomes from the Southern Ocean Sentinel Workshop" - Andrew Constable
11:45-12:00	General Discussion
12:00-1:30	Buffet Lunch
1:30-2:15	"Net community production in the spring and summertime Southern Ocean" - Mike Bender
2:15-3:00	OCB Floats & Gliders Workshop: Southern Ocean breakout group report – Taka Ito
3:00-3:30	Coffee Break
3:30-5:00	Breakout Sessions theme: An integrated Southern Ocean biogeochemistry science research plan Topics TBD based on discussions from Mon and Tues

Thursday, June 11

8:30-9:00	Continental Breakfast
9:00-10:30	Breakout Session Summaries (moderators/rapporteurs), wrap-up, writing assignments
10:30-11:00	Coffee Break
11:00-12:00	Summary, continued
12:00-1:30	Buffet Lunch
1:30	Participants Depart