

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

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Workshop Steering Committee Members:

Curtis Deutsch  
Eileen Hofmann\*  
Taka Ito  
Nicole Lovenduski  
Joellen Russell  
Jorge Sarmiento\*  
Walker Smith\*  
Peter Strutton

\*Corresponding authors

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## Executive Summary

This Southern Ocean Carbon, Ecosystems, and Biogeochemistry (SOCEB) Science Plan reports the results 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<sub>2</sub>, 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<sub>2</sub>, 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
  - responses of ecosystems and biogeochemical cycles to climate change
  - uptake of anthropogenic CO<sub>2</sub>
  - responses 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.

## 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<sub>2</sub>) 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<sub>2</sub>. 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 quantified. Increases in the upwelling rate of natural CO<sub>2</sub>, driven by wind stress changes and/or changes in stratification, have been proposed as a principal cause of the increase in atmospheric CO<sub>2</sub> 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; Le Quéré 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<sub>2</sub>. 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<sub>2</sub> from the atmosphere to the ocean. The fraction of primary production that is exported depends on the structure of the phytoplankton and zooplankton communities, which in turn are

influenced by changes in food web structure, mixed layer depth, irradiance, and micronutrient (e.g. 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 in 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
  - responses of ecosystems and biogeochemical cycles to climate change
  - uptake of anthropogenic CO<sub>2</sub>
  - responses 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 Biogeochemistry (SOCEB) research program. These ideas were based on results and advances in understanding made in the Southern Ocean studies undertaken as part of the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) programs. The highlights from these programs are reviewed in the next section and this is followed by a description of the Scoping Workshop approach and an introduction to the proposed SOCEB program.

## Accomplishments of Southern Ocean JGOFS and GLOBEC

In the past two decades the U.S. has developed and conducted a number of large programs in the Southern Ocean. Among them are the Southern Ocean JGOFS (US JGOFS, or AESOPS; Smith et al., 2000; Anderson and Smith, 2001; Smith and Anderson, 2003) and the Southern GLOBEC program (SO GLOBEC; Hofmann et al., 2004, 2008). Both were driven by broad community consensus and within an international framework of research, and both represented substantial advances in our knowledge of specific regional systems and of processes that are critical to biogeochemical cycles and food webs in the Southern Ocean. Brief discussions and highlights from these programs follow.

### Southern Ocean JGOFS

The Southern Ocean JGOFS project was (and still is) the largest coordinated oceanographic program conducted in Antarctic waters. The purpose of the project was to better constrain the fluxes of carbon in the Southern Ocean, to identify the factors and processes that regulate the magnitude and variability of productivity and flux, and to gain an understanding in order to model past and present carbon fluxes in order to predict their response to future global changes. It involved 13 independent cruises to two research areas, five deep-water moorings with current meters and sediment traps, and a series of rate process cruises to investigate the processes involved in controlling carbon fluxes. Additionally, modeling studies were completed both before and after the field effort. Two regions were intensively sampled: the southern Ross Sea and the Antarctic Polar Front in the Pacific sector. Cruises involved both icebreakers and UNOLS vessels. The results were published in a variety of journals and broadly disseminated, and the data were used by numerous non-JGOFS investigators in additional publications and analyses. The major findings of the experiment included the following:

- The seasonal progression of phytoplankton growth (and coupling to both grazers and secondary producers) is characterized by a unimodal peak, which controls many of the ecosystem processes and biogeochemical cycles;
- Carbon export was temporally delayed after the production maximum and reflected both the accumulation of biomass in the surface layer and processes responsible for the flux, such as aggregation and grazer-mediated export;
- Summer growth of the entire phytoplankton assemblage as well as individual species in the Ross Sea is strongly regulated by iron concentrations and fluxes;

- Nutrient drawdown in the Polar front region is regulated by sea-ice melt, which creates a strongly stratified layer and optimal conditions for phytoplankton growth. This area of enhanced phytoplankton growth moves with the ice retreat; areas of stability have a short-lived bloom due to iron limitation;
- Vertical fluxes in the Polar Front region were substantial, and the composition of the material exhibited substantial temporal variations; and
- Surface layer biotic composition has a significant impact on the quantity and quality of material exported to depth.

The data from the U.S. JGOFS program provides a baseline of carbon dynamics on which to build further, more detailed investigations into biogeochemical and ecosystem carbon fluxes.

### **Southern Ocean GLOBEC**

The SO GLOBEC program took a broad view of the Antarctic marine ecosystem that included studies of the habitat, prey, predators, and competitors of Antarctic krill, as well as studies specifically focused on Antarctic krill biology and physiology. Overwintering strategies were highlighted as an important and largely unknown component of the Antarctic ecosystem. The U.S. SO GLOBEC program field studies focused in the western Antarctic Peninsula (WAP) region. The field studies consisted of 11 cruises, mostly in the austral fall and winter, and two year-long current meter array deployments. The U.S. field studies include an extensive top predator component which involved passive acoustic arrays for tracking cetaceans and deployment of satellite tags on marine mammals and penguins. Additional SO GLOBEC field studies were undertaken by the Australia Antarctic Division (east Antarctica), the British Antarctic Survey (South Georgia), the Alfred Wegener Institute for Polar and Marine Research (WAP and Lazarev Sea), and the Korean Antarctic Program (Bransfield Strait). These programs used complementary techniques, thereby allowing comparative analyses. Circulation, ecosystem, and coupled modeling studies were undertaken before and during the SO GLOBEC field studies and are continuing as part of the synthesis phase of the program.

The extensive multidisciplinary data sets acquired as a result of the SO GLOBEC studies have provided important new insights into the workings of Antarctic marine ecosystems. Highlights from the U.S. SO GLOBEC program are:

- The role of Circumpolar Deep Water in determining heat, salt, and nutrient fluxes, and in structuring biological production and habitat along the WAP, was defined.
- The Antarctic Peninsula coastal current was described for the first time.
- Seasonal upper water column variability was described using hydrographic data collected by instrumented seals, demonstrating the importance of marine mammals as data collectors.
- Variability in winter sea ice concentration and extent results in important difference in nutrient fluxes and chlorophyll distributions in the following austral summer, which affect Antarctic krill growth and reproduction.
- Antarctic krill use a variety of mechanisms to survive the austral winter that include body shrinkage, reduced metabolism, ingestion of sea ice algae, carnivory, and combustion of lipid stores.
- Significant advances were made in understanding relationships between predators, from fish to seals, to habitat and prey distribution.



- The first winter observations of predator condition, distribution and habitat use were made and highlighted the importance of crabeater seals as winter krill predators.
- Cetacean presence in the austral winter was documented using a passive acoustic array and surveys.

Results from the SO GLOBEC studies are providing new conceptual understanding of how Southern Ocean marine ecosystems work, which in turn is the basis for the ongoing synthesis, modeling, and integration studies. These studies provide a baseline for ecosystem processes that can be used to develop more extensive studies of Southern Ocean food webs and feedbacks to biogeochemical cycles.

### 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> levels. The rationale comes from the need for projections of: 1) future concentrations of atmospheric CO<sub>2</sub> 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<sub>2</sub> 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 Southern Ocean 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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 responses 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 interannual 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 Antarctic Circumpolar Current 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 further shift in warm, maritime climate southward towards the WAP. 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°S (Gille, 2002, 2008). However, the response of the Southern Ocean to SAM and wind forcing is not consistent or uniform on a circumpolar scale.

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<sub>2</sub> 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 specific physical oceanographic studies are not proposed 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 the physical oceanographic and meteorological communities.

### **Ecosystem Structure and Productivity**

Despite the harsh environment, current Southern Ocean ecosystems are very productive. Because of the convective vertical exchange with the deep ocean, macronutrients rarely 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 (Smith and Comiso, 2008). These rates sustain large populations of Antarctic krill, other zooplankton species, fish, squid, and gelatinous zooplankton, 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  $\sim 2\text{-}4 \text{ PgCyr}^{-1}$  (south of  $50^\circ\text{S}$ ), 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 cetaceans. 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 on these linkages are only now being addressed.

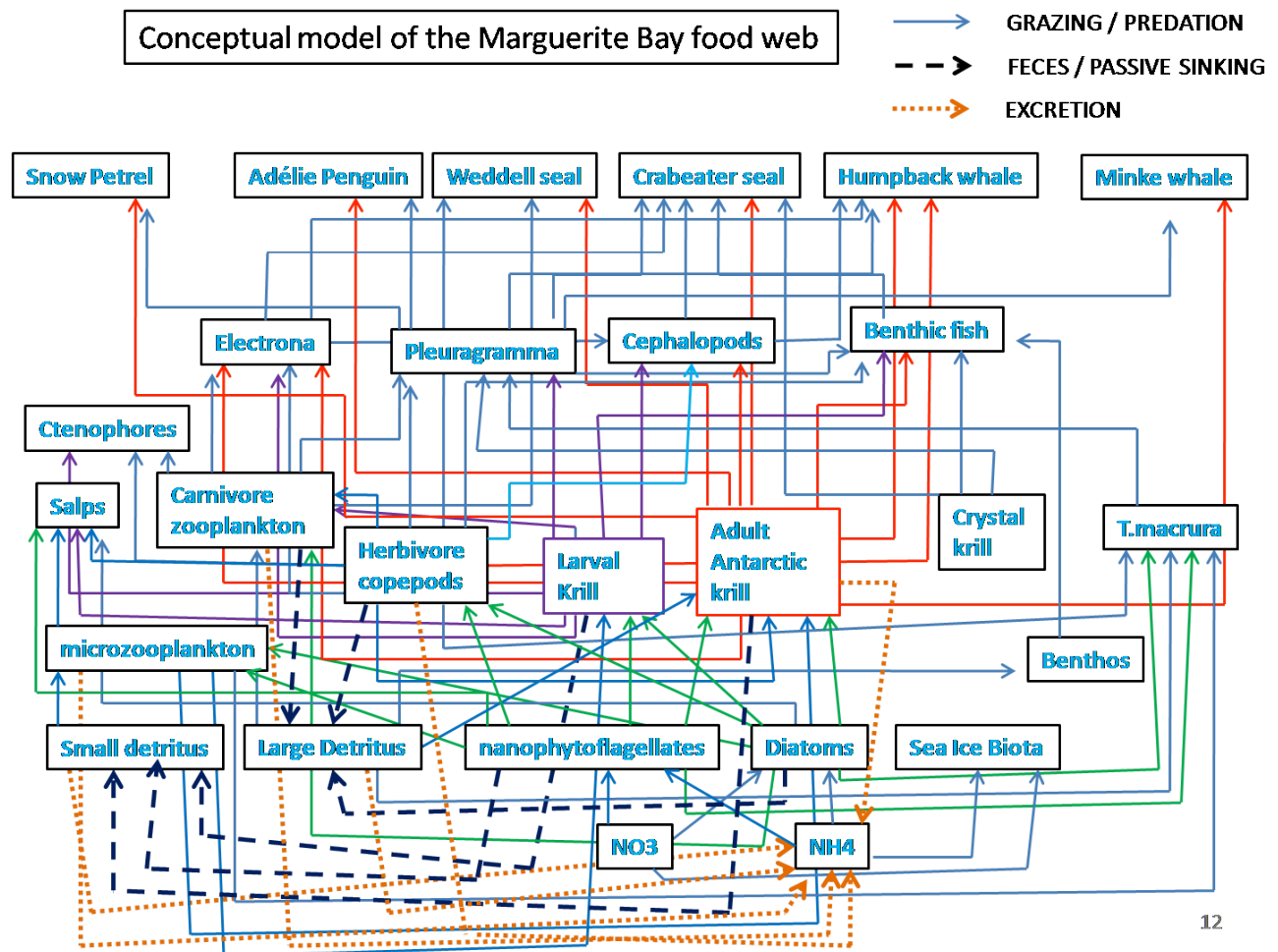


Figure 1. Conceptual model of a coastal Antarctic food web (Ballerini et al., in prep.).

Over long time scales, variations in net ecosystem production of organic matter are critical to the air–sea balance of CO<sub>2</sub> 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 et al., 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 is 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<sup>-1</sup>, 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 sea ice retreated southward along the Antarctic Peninsula, 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 WAP 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 WAP 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 et al., 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 as a key component in Antarctic food webs (Nicol, 2006), has declined significantly in the past century (Atkinson et al., 2004) and has been replaced by other zooplankton species, such as salps (e.g. *Salpi thompsoni*). Adélie penguin (*Pygoscelis adeliae*) populations along the WAP 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<sub>2</sub> (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<sub>2</sub> 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 dissolved organic carbon?
- 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). Also, the sensitivity of ecosystems and carbon fluxes to varying supply of micronutrients is unknown. Studies designed to assess this sensitivity should be carried out in conjunction with studies of the sources of micronutrients and of the sensitivity of these sources to changing environmental conditions (e.g. Gabric et al., 2010). Presently, fundamental factors that remain unknown include (1) the relative importance of dust, upwelling and continental margin sources of micronutrients, and (2) the response of the Southern Ocean ecosystem to varying supply of different micronutrients, including iron, zinc and cobalt, each of which may limit different taxa under certain conditions.

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, allow proposing 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<sub>2</sub> in the Southern Ocean. The high dissolved inorganic carbon (DIC) and thus pCO<sub>2</sub> concentrations in the surface waters of the Southern Ocean lead to a very large pre-industrial degassing flux of CO<sub>2</sub> into the atmosphere in this region. The inefficiency of autotrophic plankton in depleting surface nutrients results in higher atmospheric CO<sub>2</sub> than would otherwise occur, and a more efficient removal of those nutrients should lead to a reduction of atmospheric CO<sub>2</sub>. The sensitivity of atmospheric CO<sub>2</sub> 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<sub>2</sub>, 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 because 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<sub>2</sub> partitioning of any major oceanic region in the world.

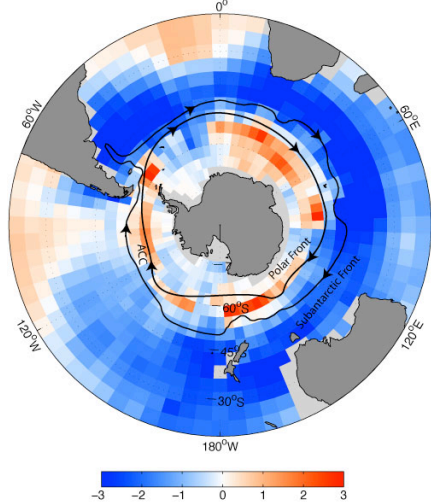


Figure 2. Annual-mean observed sea-air CO<sub>2</sub> flux ( $\text{mol m}^{-2} \text{yr}^{-1}$ ) between the Southern Ocean and the atmosphere (data from Takahashi et al., 2009).

Model studies and observationally-based inverse models making use of the new oceanic DIC and alkalinity data obtained during the World Ocean Circulation Experiment (WOCE) and the JGOFS program show that the Southern Ocean accounts for about 40% of the anthropogenic CO<sub>2</sub> sink. However, observationally based estimates of sea-air CO<sub>2</sub> fluxes indicate that the Southern Ocean is currently a weak sink of atmospheric CO<sub>2</sub> (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<sub>2</sub> 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<sub>2</sub> fluxes, with moderate outgassing in the high latitudes, where upwelling brings waters with high concentrations of respired CO<sub>2</sub> to the surface, being overwhelmed by a large uptake of CO<sub>2</sub> in the mid-latitudes of the Southern Ocean, where solubility effects and biological processes lower surface pCO<sub>2</sub> and draw CO<sub>2</sub> out of the atmosphere (Figures 2,3). In addition, Antarctic shelf waters have very high rates of NPP, and may be a strong CO<sub>2</sub> sink that is not accounted for in model estimates (Arrigo et al., 2008).

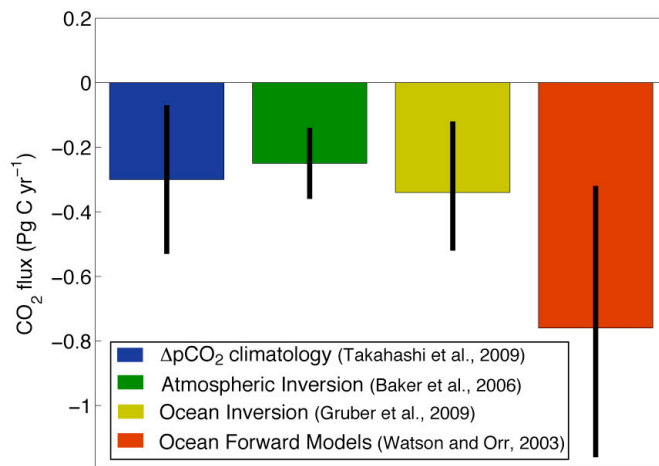


Figure 3. Southern Ocean (<44°S) integrated estimates of air-sea CO<sub>2</sub> flux based on observations, results from the TransCom3 project using interannual inversions of atmospheric CO<sub>2</sub>, an inversion of interior ocean carbon observations using 10 ocean general circulation models and

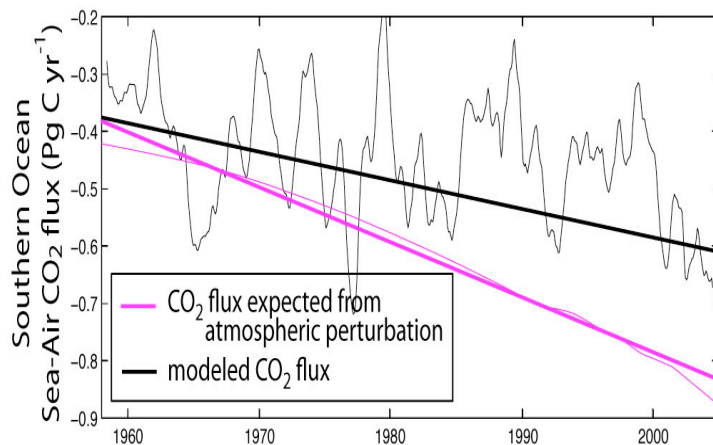
Forward and inverse models of the ocean and atmosphere tend to support the observational data with regard to the sign of the Southern Ocean integrated CO<sub>2</sub> flux, but disagree as to the magnitude of this integrated flux

(Figure 3). For example, the ocean forward models tend to overestimate the sink strength ( $0.8 \text{ Pg C yr}^{-1}$ ), as compared to the other estimates ( $0.3 \text{ Pg C yr}^{-1}$ ; 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.

### Variability and trends

The Southern Ocean sink for atmospheric carbon has not been time invariant. 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  $\text{CO}_2$  sink. Observations and model studies indicate that the Southern Ocean ( $< 30^\circ\text{S}$ ) is a net sink for atmospheric  $\text{CO}_2$  (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 due to changes in wind stress and ocean circulation (Lovenduski et al., 2007; Lenton and Matear, 2007; Verdy et al., 2007; Le Quéré 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  $\text{CO}_2$  flux from this region. Positive phases of the SAM (associated with increased wind stress) coincide with times of anomalous  $\text{CO}_2$  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 transport of carbon-rich waters in association with increased wind stress.



*Figure 4. Spatially-integrated Southern Ocean ( $<30^\circ\text{S}$ ) sea-air  $\text{CO}_2$  flux from a model hindcast forced with a long-term increase in Southern Hemisphere wind stress (black) and expected flux from the atmospheric  $\text{CO}_2$  perturbation with no change in forcing (pink) (data from Lovenduski et al., 2008). Note that there is less uptake of  $\text{CO}_2$  under increased wind stress.*

Oceanic models (Lovenduski et al., 2008), atmospheric data (Le Quéré et al., 2007), and oceanic observations (Metzl, 2009) indicate that the Southern Ocean sink for atmospheric  $\text{CO}_2$  has substantially weakened in the last few decades, relative to the expected sink from rising atmospheric  $\text{CO}_2$  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  $\text{CO}_2$ -rich waters (Figure 5; Le Quéré et al., 2007; Lovenduski et

al., 2008).

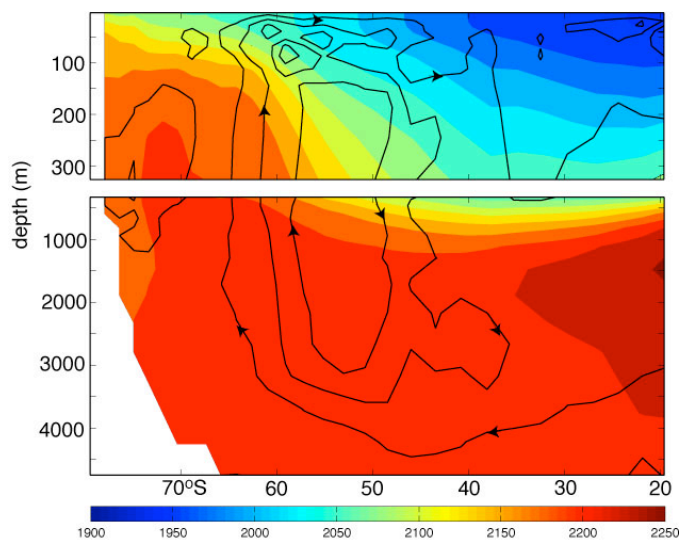


Figure 5. Model estimated trend in meridional overturning stream function ( $0.3 \text{ Sv yr}^{-1}$ ; black contours) from 1979-2004. Colors represent the zonal mean modeled dissolved inorganic carbon concentration ( $\text{mmol m}^{-3}$ ) (data from Lovenduski et al., 2008).

Ice core records show a tight coupling between  $\text{CO}_2$  and climate and previous studies have invoked a control on atmospheric  $\text{CO}_2$  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  $\text{CO}_2$  in the deep ocean, while the latter allows for degassing of  $\text{CO}_2$  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  $\text{CO}_2$  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  $\text{CO}_2$  and silica-rich waters to the surface and creates more diatom production and opal burial.

### Knowledge Gaps and Future Needs

Large differences in simulated Southern Ocean air-sea  $\text{CO}_2$  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  $\text{CO}_2$  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<sub>2</sub>, 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 CO<sub>2</sub> taken up at the surface (and where is it transported)?
- What is the relative importance of the upper and lower cells in the uptake and storage of anthropogenic CO<sub>2</sub>?
- How robust is the evidence for increased CO<sub>2</sub> 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<sub>2</sub> and its interannual variability, and the storage of anthropogenic CO<sub>2</sub> in the ocean.**

### **Implementation objectives**

To reduce the uncertainty in the 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, a number of 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<sub>2</sub>, oxygen) 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 observational efforts to:

- Quantitatively determine the processes that control uptake of CO<sub>2</sub> 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<sub>2</sub>;
- Accurately measure net fluxes of CO<sub>2</sub> from the Southern Ocean.

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

This chapter focuses on the second overarching scientific questions raised in the introduction:

**What will be the future impact of climate change, the CO<sub>2</sub> increase, and human actions on Southern Ocean ecosystems, biogeochemical cycles, and the ocean carbon sink?**

The fundamental issues regarding the future changes of the Southern Ocean ecosystems, biogeochemistry and carbon cycle are addressed here. 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.

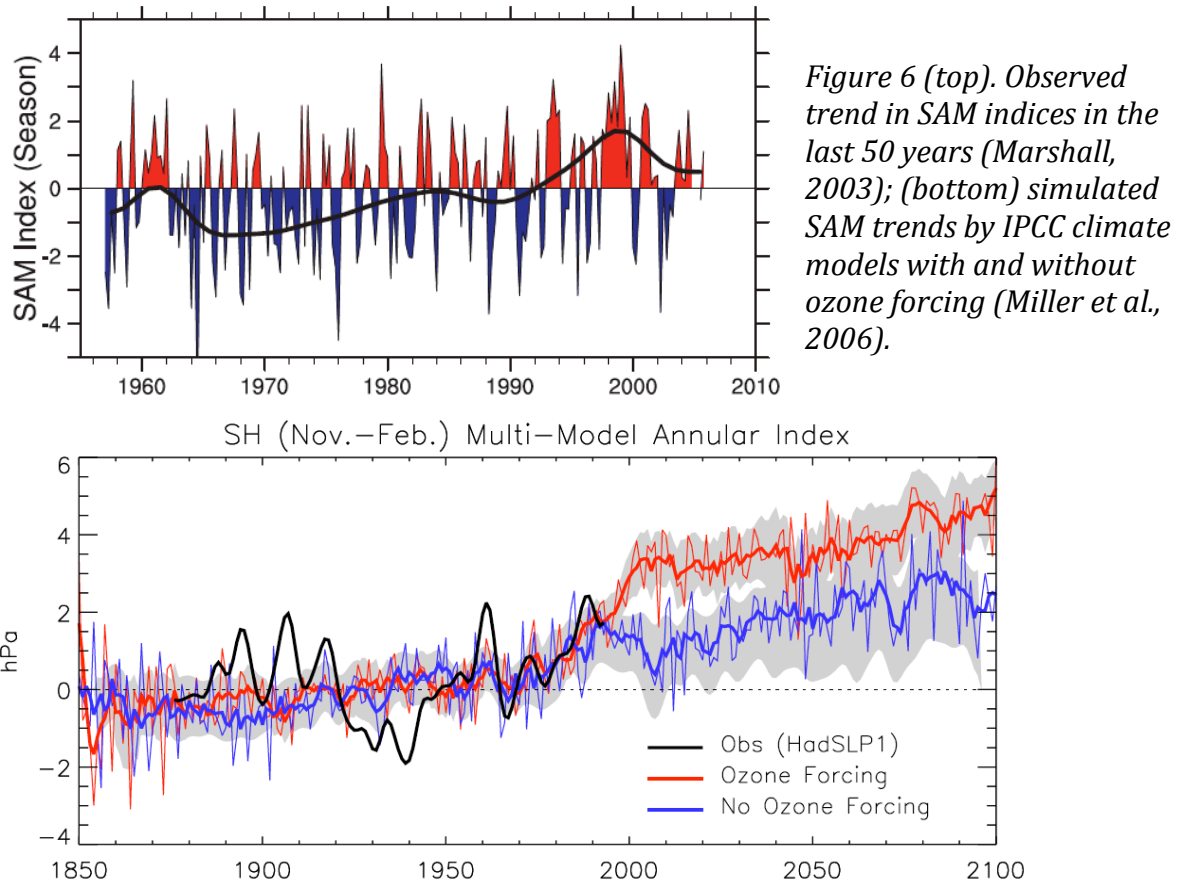
### Potential Drivers for Long-term Change

It is essential to assess and improve our understanding in the potential drivers 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 stronger westerly winds over the Southern Ocean and

with the poleward shift of the maximum westerly winds. Through air-sea interaction, the changing winds will impact the air-sea heat fluxes (Verdy et al., 2007; 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 the Antarctic Circumpolar Current 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.

## 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 declining sea ice in the Antarctic Peninsula region and with increasing sea ice in the Ross Sea (Figure 7).

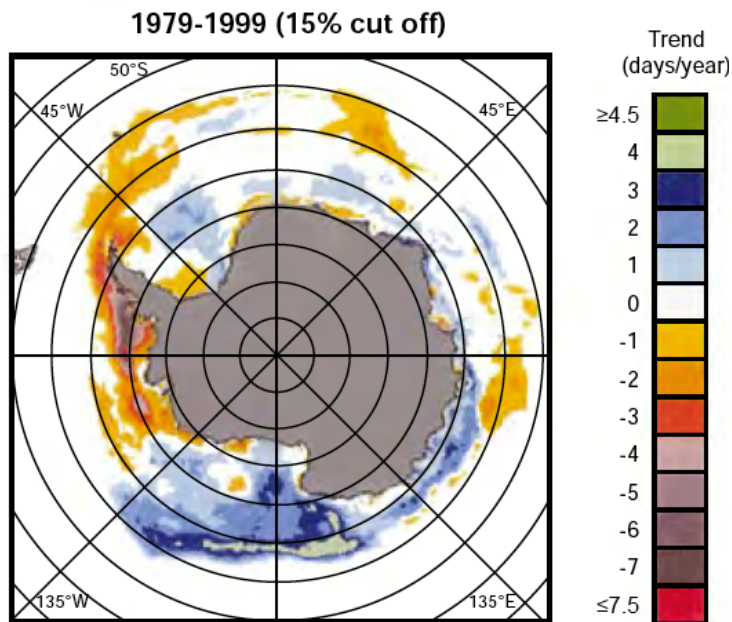


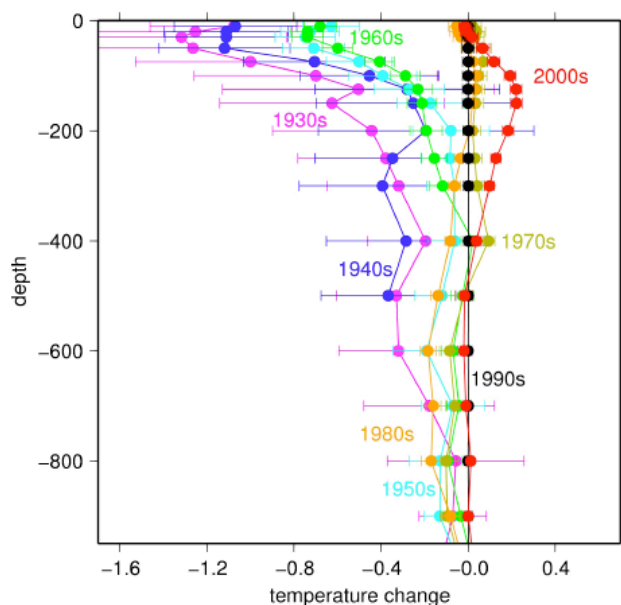
Figure 7. Observed trend in the length of sea ice seasons between 1979 and 1999, indicating longer sea ice seasons in the Ross Sea and shorter sea ice seasons in the Weddell Sea (Parkinson, 2002).

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 sea ice distribution and extent that are associated with future trends in SAM will likely have major impacts 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; Böning et al., 2008; Figure 8). Both warming and freshening tend to increase 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 macronutrients, and the vertical migration of marine organisms. The rate of upwelling

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



also impacts the outgassing of natural carbon (Le Quéré 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.

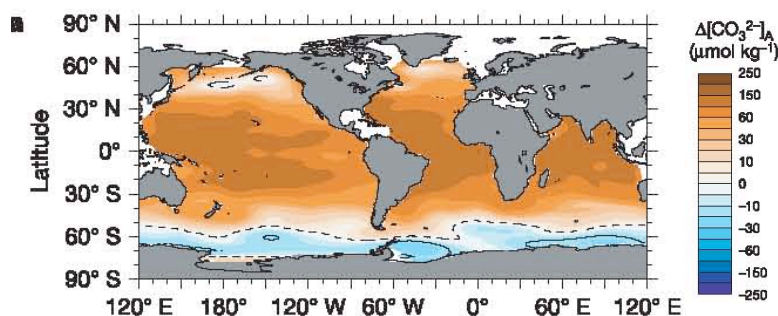


Figure 9. The aragonite saturation state as a function of latitude, emphasizing the extreme vulnerability of the Southern Ocean to ocean acidification (from Orr et al. 2005).

#### 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, current knowledge gaps and future needs that were identified by the Scoping Workshop that are specifically related to improving future projections of the ecosystem, biogeochemistry and carbon cycle of the Southern Ocean are discussed.

### Long-term Change in Ecosystems and Biogeochemical Cycles

#### Knowledge Gaps and Future Needs

Climate change may impact Southern Ocean ecosystems over a wide range of spatial and temporal scales, as well as 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 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. Community-wide efforts and international collaborations are required 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 micro- and macro 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 primary tools for predicting the long-term co-evolution of physical and chemical environments, 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 directed is:

**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 fifth 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<sub>2</sub>.**

**Goal 5: Provide the scientific basis for societal decisions about Southern Ocean ecosystems and contributions to the management of CO<sub>2</sub> and the carbon cycle.**

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

## **Knowledge Gaps and Future Needs**

Response of the Southern Ocean air-sea CO<sub>2</sub> flux to the increasing atmospheric winds has been the subject of intense research (Le Quéré et al., 2007; Lovenduski et al., 2007; Bönning et al., 2008; Le Quéré 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<sub>2</sub> 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 processes, primary productivity, stoichiometric ratios, export efficiency and remineralization.

There are considerable uncertainties in potential impacts of future human activities on 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 projections 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 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, sea ice, biogeochemistry and ecosystem components to synthesize multi-disciplinary 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 sinks. Also, approaches are needed to develop parameterizations of these processes so that critical mesoscale biogeochemical and food web processes can be embedded in global models that simulate sequestration of carbon dioxide.

Development of coupled models that simulate future scenarios for climate-ecosystem-carbon cycle interactions 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 their role in the transport of carbon, limiting nutrients and living organisms, potentially nesting important coastal and shelf regions with much higher spatial resolution models to synthesize observations and to predict the long-term evolution of the Southern Ocean carbon cycle. Synthesis of observations and numerical models are needed to constrain current states of the Southern Ocean carbon cycle so that simulations of the future changes in the oceanic carbon sink can be initialized using the best estimates of current carbon cycle. 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 of the Southern Ocean. 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>, 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<sub>2</sub> 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<sub>2</sub> 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 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<sub>2</sub> by the Southern Ocean will continue to increase in response to rising atmospheric CO<sub>2</sub> 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<sub>2</sub> 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 continue to shift towards less dependence on Antarctic krill as climate warms, and energy transfer to higher trophic levels will occur via alternative pathways.

These hypotheses are testable by integration of the program elements described in the sections below. Addressing these hypotheses will require new mechanisms to integrate information on the carbon cycle and coordinate interagency efforts as well as additional funding in critical areas. To provide guidance on integrating the program elements and to indicate potential research directions, four priority research areas, which emerged from the Scoping Workshop presentations and discussions, are summarized in the following section.

## **Program Priorities**

### **Changing Habitats**

The Southern Ocean is changing rapidly, with greatly decreased ice cover in the Amundsen-Bellinghousen sector and significantly increased ice concentrations in the Ross Sea (Comiso and Nishio, 2008). Whereas the net change in the past three decades is insignificant, the regional differences reflect the range of changes that can be expected in the future – particularly the notable decreases, which are predicted to begin to occur in all regions in the next 50 years (Sarmiento et al., 1998). In addition, there are rapid changes in ice distribution through the calving of massive icebergs and the break-up of ice shelves. Examples of such events include the formation and grounding of icebergs in the Ross Sea and the disintegration of the Larson Ice Shelf. Iceberg generation has been shown to alter the circulation of the entire continental shelf (Dinniman et al., 2007) and sea ice distributions (Smith and Comiso, 2008), and to impact ecosystem process from primary production to penguin migration and reproductive success (e.g. Arrigo et al., 2002a; Seibel and Dierssen, 2003; Smith et al., 2006). In a similar manner, ice-shelf disintegration has opened up vast areas to increased irradiance, resulted in increased productivity, and likely altered large-scale circulation patterns (such as deep water formation and associated

surface expressions; Baines, 2009; Thompson and Heywood, 2008). Linkage of ecosystem components and processes is clearly linked to sea ice distribution (Smith et al., 1996; Montes-Hugo et al., 2009), and this strong relationship will continue with future ice distribution changes. Understanding the mechanistic linkages is critical to being able to predict future ecosystem and biogeochemical alterations.

### **Changing Food Web Structures and Feedbacks to Biogeochemical Cycles**

Oceanographers are now aware of the strong linkage between food-web structure and composition and biogeochemical cycles. For example, a strong decline in krill abundance and biomass in the past century has been documented and is associated with increased abundances of salps (Atkinson et al., 2004). Given that the flux of biogenic material from the surface layer as mediated by the two groups is markedly different (e.g. González, 1992; Perissinotto and Pakhomov, 1998), biogeochemical cycles and fluxes also likely have been altered. While the impacts of top predators on biogeochemical cycles is largely undocumented, it can be expected that their changes would also have impacts on biogeochemical cycles, either directly via altered carbon-nutrient fluxes, or indirectly by trophic cascades that generate changes in the entire food web. Additionally, certain functional groups commonly found in the Southern Ocean (e.g. diatoms and haptophytes) have markedly different elemental stoichiometries (e.g. Arrigo et al., 2002b), which in turn is reflected in the composition of material that enters deep water (regardless of the mechanism of export). This in turn can alter the nutrient regeneration ratios in deep water and have impacts far beyond the Southern Ocean. Because there is substantial uncertainty in these relationships, it is essential to quantify the impacts of trophic structure and ecosystem processes on biogeochemical cycles in order to understand future anthropogenic changes on the Southern Ocean.

### **Changing Physical Dynamics**

Interannual variability of the circulation and climate of the Southern Ocean has profound impacts on the ecosystem, biogeochemistry and carbon cycle. Variability of surface wind, sea ice concentrations and distributions, and surface temperature fields reflects the effects of the SAM and El Niño-Southern Oscillation (Comiso and Nishio, 2008; Stammerjohn et al., 2008; Ciasto and Thompson, 2008; Verdy et al., 2007). Multi-decadal warming of the sub-polar thermocline has been observed in hydrographic and float observations (Gille, 2002; Bönning et al., 2008) and may be related to the southward migration of the Antarctic Circumpolar Current fronts in certain regions (Gille, 2008). Subsurface warming is also observed at subtropical latitudes (Roemmich et al., 2007) which may be due to the spin up of the subtropical gyre (Cai et al., 2010). The circulation of the Southern Ocean includes intense mesoscale variability and multiple zonal jets leading to transfer of buoyancy and biogeochemical tracers primarily along constant density surfaces. On interannual timescales it has been hypothesized that the non-linear effect of mesoscale eddies tends to compensate for the effect of wind-driven Ekman flow, where an increase in the westerly wind intensifies the eddy field but causes little change in the ACC transport and associated meridional overturning (Hallberg and Gnanadesikan, 2006; Meredith and Hogg, 2006; Bönning et al., 2008). This process is often referred to as the “eddy saturation”. Thus understanding and quantifying the response of mesoscale eddies to climate variability is

essential for the future projection of the outgassing of natural carbon, as well as the upwelling of nutrients and the uptake of anthropogenic carbon.

### **Exploitation of Marine Resources**

Given that harvests from the natural stocks of the ocean show no increase or slight decreases for a number of decades (FAO, 2007), there is a substantial interest by a number of nations to increase fishing efforts and harvests in the Southern Ocean above those levels that already occur. Direct harvesting of krill in the past two decades has occurred, although levels are modest relative to the estimated system-wide biomass. Harvesting of whales for scientific purposes continues with a controversial and unknown impact on ecosystems and biogeochemical cycles, and perhaps even more importantly, harvesting of Antarctic toothfish (*Dissostichus eleginoides*) is being presently debated, despite a near complete lack of understanding of its impacts on food webs and biogeochemical cycles. Illegal fishing for this valuable resource continues unabated, and some nations (e.g. China) are planning new and massive programs of harvesting in various sectors. Given the poor understanding of the quantitative impacts on higher trophic levels and ecosystem processes on biogeochemical cycles, and in view of the substantial future changes now under discussion, it is imperative that a scientific analysis of these effects be undertaken.

### **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<sub>2</sub> inputs to the atmosphere. Only with accurate predictions of future changes can sound management practices be implemented.

#### ***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. Trends and variations within food webs are now being described, and understanding the linkages of large-scale processes on regional ecosystems and biogeochemical cycles is just beginning. Understanding the magnitude and causes of this variability in the Southern Ocean is a key to understanding the impacts of global climate change.



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

Program Element	Deliverable	Description
<b>ATMOSPHERIC MONITORING</b>		
1. <b>Airborne CO<sub>2</sub> Observation Program</b>	Three-dimensional and temporal distributions of CO <sub>2</sub> 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. <b>Regional atmospheric CO<sub>2</sub> Monitoring Network</b>	Enhanced space/time data for CO <sub>2</sub> 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 <sub>2</sub> , O <sub>2</sub> /N <sub>2</sub> , and related tracers in the Southern Ocean, emphasizing continental and remote marine locations; vertical profiles at selected locations as specified in element 2.
<b>OCEAN OBSERVATIONS</b>		
3. <b>Remote sensing</b>	Continuous satellite observations of Ocean color, SST, sea ice, wind fields, clouds, altimetry, and CO <sub>2</sub>	Satellite observations of oceanic and atmospheric variables.
4. <b>Large scale Ocean Surveys</b>	Ocean-atmosphere fluxes of momentum, heat and freshwater, basin-scale net uptake of anthropogenic CO <sub>2</sub> , and interpretation of seasonal variances, micronutrient supply, atmosphere-ocean-biology interactions, continuous plankton surveys, top predator surveys (e.g. marine mammals and sea birds)	Analysis of ongoing CLIVAR survey data; Develop and deploy time-series and drifting buoys and automated towed vertical samplers for CO <sub>2</sub> and related parameters (DIC, DOM, POM, alkalinity, O <sub>2</sub> , nutrients, <sup>13</sup> CO <sub>2</sub> , <sup>14</sup> CO <sub>2</sub> , T, S) and tracers of ocean circulation (CFCs, <sup>14</sup> C, <sup>3</sup> H/ <sup>3</sup> He), reduce cost per measurement, increase data flow
5. <b>Regional Observational Experiments</b>	Regional determinations of fluxes and concentrations of CO <sub>2</sub> , greenhouse gases, pollutants, ocean-atmosphere fluxes of momentum, heat and freshwater, micronutrient supply, food web interactions from plankton to top predators	Coordinated airborne, ship, and terrestrial experiments integrated with model development and testing
6. <b>Time Series Observations</b>	Long-term ocean biological, biogeochemical, and flux data for major biomes, micronutrient supply	Continued observations at the WAP 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. <b>Ocean Process Studies and Manipulations</b>	Define effects of CO <sub>2</sub> , acidification, temperature changes, circulation, Aeolian deposition, and ice melt on ocean biology and oceanic uptake of CO <sub>2</sub> , micronutrient supply	Physical and biological studies of dispersion of anthropogenic CO <sub>2</sub> and controls on new production/uptake; Ocean manipulation experiments (~2/yr duration) to examine hypotheses such as the role of iron in ecosystem production
8. <b>Ocean Float Observations</b>	Define ocean circulation, detection of particulate organic carbon, provide particulate inorganic carbon profiles, oxygen and nutrient concentrations	Deployment of carbon sensor enhanced profiling Argo-style floats in ensembles throughout the Southern Ocean and Sub-Antarctic waters, provides intercalibrated sensors and allows statistical treatments of data, long-term deployments will provide seasonal and interannual variability
<b>MODELING AND SYNTHESIS</b>		
9. <b>Model Development</b>	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

<b>10. Model Integration</b>	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
<b>11. Model Intercomparison</b>	Identify robust model features and responses; identify key deficiencies and biases	Model-model and Model-data intercomparison projects
<b>12. Complimentary Modeling Studies</b>	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
<b>13. Improving Predictive Capabilities</b>	Better predict changes in the carbon-climate system to guide future observations and policy	Development of Earth System Models that predict CO <sub>2</sub> and climate interactively

### ***Major program elements and activities***

To understand the processes underlying ecosystem and ocean change, the natural changes that occur within regions must be clearly described and quantified. 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 WAP, Ross Sea, Amundsen Sea and Marguerite Bay. These areas have the great advantage of having *de facto* time series of both oceanographic 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. Increasing the breadth of existing regional programs is an area where progress can be made in the 3-5 year time frame and provides a natural linkage to ongoing national programs and international organizations such as the Commission for Conservation of Antarctic Living Marine Resources (CCAMLR). This could be done by inclusion of autonomous measurements systems (e.g. gliders, floats), moorings, and more extensive suites of measurements (see section below on Program Capability Needs).

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

The Southern Ocean is the site for extensive fluxes of CO<sub>2</sub> 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<sub>2</sub> vary significantly depending on the data and analytical approach used (e.g. inverse model analysis of CO<sub>2</sub> data from atmospheric surface stations, changes over time of global CO<sub>2</sub>, O<sub>2</sub>, <sup>13</sup>CO<sub>2</sub>/<sup>12</sup>CO<sub>2</sub>,

measurement based estimates of the air-sea CO<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> 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***

Large-scale 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 for each survey, as well as a rigorous intercomparison of methods. Process studies are needed in each of the regions to quantify the rates and critical roles of biological controls of these fluxes. Furthermore, such studies must encompass all meteorological conditions, and as a result, will require the use of evolving technologies such as CO<sub>2</sub>-measuring buoys and autonomous vehicles, floats, and gliders (Table 1). The data will need to be incorporated into models to trace the time evolution of the inorganic carbon budget. Models can help predict the critical locations of CO<sub>2</sub> fluxes, and a program that is designed to assess the fluxes over a number of years to encompass a full range of atmospheric and oceanographic conditions is needed.

### ***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 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, increased harvesting of Southern Ocean fisheries resources may initiate a series of trophic cascades, the consequences of which are impossible to predict at present. 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<sub>2</sub>) 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 immediately, 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.

### **Program Implementation – Elements and Approach**

Past experience with large, 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, multidisciplinary 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.

The establishment of an office for Southern Ocean research was considered to be important for the development of the SOCEB program. A central project office will ensure that coordination and implementation occurs at the program component, national and international levels. The international nature of Antarctic science makes it unusual in terms of its needs for science coordination. Experiences with JGOFS and SO GLOBEC showed the importance of an office devoted to the program, even with an efficient and functioning International Project Office. The establishment of project offices for regional programs under the umbrella of larger programs, such as the Integrating Climate and Ecosystem Dynamics (ICED) program, which is part of the Integrated Marine Biogeochemical and Ecosystem Research (IMBER) program, supports the assertion that such offices are important. In the case of IMBER programs, the regional project offices work closely with the larger program IPO, but still retain the identity of the regional program. This is the model that will be followed in SOCEB.

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 agencies and through input from the wider scientific community. Experiences in the 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.

### ***Programmatic Needs***

The SOCEB program outlined in this report will require research vessels that are capable of navigating and working in sea ice conditions; furthermore, the proposed regional studies will require platforms that can support process studies and that are capable of long duration efforts. Also, development of partnerships with other nations with Antarctic seagoing capability (e.g. Germany, United Kingdom, Australia, Korea) is a priority, especially in the short term (3-5 years).

Many of the projected changes will occur on the continental shelf and in regions that are difficult to access and are not routinely visited as part of national programs or scientific base resupply routes (e.g. Amundsen Sea). The establishment of autonomous sensor arrays in these regions is a clear need. This will allow continuous measurements at times and in regions that are not accessible. Moreover, these arrays will allow development of seasonal and interannual descriptions of basic processes, such as changes in the surface ocean structure. An additional measurement system that is showing considerable promise for sampling the upper ocean and continental shelf environments is deployment of satellite tags containing CTD sensors on marine mammals. Continued use of this technology and expansion of existing tagging programs has the potential of providing valuable data that are not possible to obtain otherwise. Autonomous gliders are now being tested in Antarctic waters, and continued development of this technology should be a priority; further development of sensors that will provide measurements of carbon and biological processes is essential. Fleets of gliders have the promise of being able to sample large areas in a quasi-synoptic mode.

### ***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 (and should) 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 critical 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 ICED program in the Southern Ocean, which is a regional program of IMBER, a project of the International Geosphere-Biosphere Programme, is a circumpolar ecosystem research program (see IMBER Report No. 2). The developing Southern Ocean Sentinel (Constable and Doust, 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 within the SOCEB program.

In terms of national programs, essential partnerships to be developed are with the Antarctic research programs in Germany, France, Argentina, South Africa, New Zealand, Japan, United Kingdom, and Australia. Each of these countries has a strong Antarctic research program and is investing resources in furthering and strengthening Antarctic physical oceanography, ecological, and biogeochemical research. Other nations are developing strong programs in Southern Ocean research (Korea, China, India) and partnerships with those emerging programs should be encouraged.

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 CCAMLR and the International Whaling Commission (IWC), both governmental organizations with mandates to manage Southern Ocean living resources, 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 achieves success are 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

PARTICIPANT NAME	AFFILIATION
Anne-Carlijn Alderkamp	Stanford University
Eleni Anagnostou	Rutgers University
Robert Anderson	Lamont-Doherty Earth Observatory
Kevin Arrigo	Stanford University
Thomas Arsouze	Lamont-Doherty Earth Observatory
Richard Barber	Duke University
Nina Bednarsek	British Antarctic Survey
Michael Bender	Princeton University
Daniele Bianchi	Princeton University
James Bishop	University of California, Berkeley
Philip Boyd	NIWA/University of Otago, New Zealand
Antonietta Capotondi	University of Colorado/NOAA
Andrew Constable	Antarctic Climate and Ecosystems Coop. Res. Center
Daniel Costa	University of California, Santa Cruz
Kendra Daly	University of South Florida
Curtis Deutsch	UCLA
Michael Dinniman	Old Dominion University
Giacomo DiTullio	Hollings Marine Laboratory, College of Charleston
Scott Doney	Woods Hole Oceanographic Institution
Stephanie Downes	Princeton University
William Drennan	RSMAS, University of Miami
Hugh Ducklow	Marine Biological Laboratory
John Dunne	NOAA GFDL
Olaf Duteil	IFM-GEOMAR
Victor Evrard	University of Hawaii
Victoria Fabry	California State University San Marcos
Kelly Falkner	NSF, Office of Polar Programs
Songmiao Fan	NOAA GFDL
Richard Feely	NOAA PMEL
Ivy Frenger	ETH Zurich
Marjorie Friedrichs	Virginia Institute of Marine Science
Eric Galbraith	Princeton University
Santiago Gasso	UMBC/NASA
Sarah Gille	Scripps Institution of Oceanography
Anand Gnadadesikan	NOAA GFDL
Laura Grange	University of Hawaii
Michael Hiscock	Princeton University
Arno Hammann	Princeton University
Eileen Hofmann	Old Dominion University
Takamitsu Ito	Colorado State University
Li-Qing Jiang	NOAA
Warren Joubert	Princeton University

Robert Key	Princeton University
Samar Khatiwala	Lamont-Doherty Earth Observatory
Josh Kohut	Rutgers University
Adam Kustka	Rutgers University
Eun Young Kwon	Princeton University
Aranzazu Lana	ICM-CSIC, Barcelona, Spain
Veronica Lance	Lamont-Doherty Earth Observatory
Fredric Lipschultz	NASA
Matthew Long	Stanford University
Brice Loose	Lamont-Doherty Earth Observatory
Nicole Lovenduski	Colorado State University
Roberta Marinelli	NSF, Office of Polar Programs
Irina Marinov	University of Pennsylvania
Douglas Martinson	Lamont-Doherty Earth Observatory
Kenneth Mooney	NOAA CPO
John Morrison	University of North Carolina, Wilmington
Ika Neven	University of Groningen
Jill Peloquin	ETH Zurich
Rebecca Pirtle-Levy	North Carolina State University
Helene Planquette	Rutgers University
Keith Rodgers	Princeton University
Anastasia Romanou	NASA GISS
Joellen Russell	University of Arizona
Jorge Sarmiento	Princeton University
Oscar Schofield	Rutgers University
Peter Sedwick	Old Dominion University
Robert Sherrell	Rutgers University
Richard Slater	Princeton University
Walker Smith	Virginia Institute of Marine Sciences
Kevin Speer	Florida State University
Pavica Srsen	University of Hawaii
Colm Sweeney	NOAA ESRL
Taro Takahashi	Lamont-Doherty Earth Observatory
Steven van Heuven	Groningen University
Shanlin Wang	University of California, Irvine
Dieter Wolf-Gladrow	Alfred Wegener Institute



## 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 <sub>2</sub> 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	<p>Breakout Sessions</p> <p>theme: The past and present Southern Ocean carbon cycle</p> <p>1) Quantifying and understanding the cumulative Southern Ocean anthropogenic CO<sub>2</sub> sink and its interannual variability  moderator: Joellen Russell rapporteur: Thomas Arsouze  room: 121</p> <p>2) Quantifying and understanding the natural carbon cycle and its influence on the cumulative air-sea CO<sub>2</sub> flux in the Southern ocean and its interannual variability  moderator: Colm Sweeney rapporteur: Taka Ito  room: 134</p> <p>3) Determining the impacts of climate change on Southern Ocean ecosystems  moderator: Walker Smith rapporteur: Veronica Lance  room: 122</p>
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 <sub>2</sub> 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