The Southern Ocean in the Earth System

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ABSTRACT. Southern Ocean processes influence climate and biogeochemical cycles on global scales. The Southern Ocean connects the ocean basins and links the shallow and deep limbs of the overturning circulation, a global-scale system of ocean currents that determines how much heat and carbon the ocean can store. The upwelling of deep waters releases carbon and returns nutrients that support biological productivity in the surface ocean; the compensating sinking of surface waters into the ocean interior sequesters carbon and heat and renews oxygen levels. The capacity of the ocean to moderate the pace of climate change is therefore controlled strongly by the circulation of the Southern Ocean. The future of the Antarctic ice sheet, and hence sea level rise, is increasingly understood to be determined by the rate at which the relatively warm ocean can melt floating glacial ice around the margin of Antarctica. Given the significance of the Southern Ocean to the Earth system, any change in the region would have impacts that extend well beyond the high southern latitudes. Recent studies suggest change is underway: the Southern Ocean is warming and freshening throughout most of the ocean depth; major currents are shifting to the south, causing regional changes in sea level and the distribution of organisms and supplying additional heat to melt ice around the rim of Antarctica; and the future of the Southern Ocean carbon sink is a topic of vigorous debate. Many of these discoveries are the result of the concerted multidisciplinary effort during the International Polar Year, which has provided an unprecedented view of the status of the Southern Ocean, a baseline for assessing change, and a demonstration of the feasibility, value, and timeliness of a Southern Ocean Observing System. The sustained observations of the Southern Ocean provided by such an observing system are essential to provide the knowledge needed to inform policy decisions and wise stewardship of the region.

THE ROLE OF THE SOUTHERN OCEAN IN THE EARTH SYSTEM

For many years, studies of the Southern Ocean were somewhat neglected by the Antarctic science community. The "real" Antarctic science took place on the continent itself; the rough ocean crossing was the uncomfortable prelude and postscript to a season of excitement in the last great wilderness on Earth. However, growing recognition of the global influence of Southern Ocean processes has heightened interest in oceanographic studies of the region.

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Southern Ocean oceanography, in fact, got off to an early start, and many important oceanographic discoveries had been made even before the continent itself was discovered. James Cook noted the strange fact that water temperatures increased with depth in some parts of the region, counter to the tendency everywhere else they had made measurements. James Clark Ross noticed that his ship was consistently set to the east and inferred there was a strong west-to-east flow circling Antarctica, a current system we now know as the Antarctic Circumpolar Current (ACC). Many later Antarctic explorers made measurements in the surrounding ocean, and those measurements provide a baseline to which comparisons of recent measurements are made to detect changes in the Southern Ocean.

The definition of the Southern Ocean is somewhat fuzzy and varies from author to author. From an oceanographic perspective, it makes most sense to consider the Southern Ocean as encompassing those waters that surround Antarctica and participate in the circumpolar circulation around the continent. These waters have physical, chemical, and biological distributions that distinguish them from waters at lower latitudes but that vary only slowly along the path of the flow around Antarctica. Here we define the Southern Ocean to include waters between the Antarctic continent and the Subtropical Front, an oceanographic feature that marks the transition between warm and salty subtropical waters and cooler, fresher waters to the south (Deacon, 1937, 1982). The latitude of the Subtropical Front varies with longitude, but generally lies between 35°S and 45°S (Orsi et al., 1995). The purpose of this paper is to provide an overview of recent progress in understanding how the circulation of the Southern Ocean influences the Earth system. Further background on the history of Southern Ocean exploration and the results of earlier work can be found in Deacon (1982) and Nowlin and Klinck (1986).

The profound influence of the Southern Ocean on the rest of globe can ultimately be traced to the unique continental geometry at high southern latitudes (Rintoul et al., 2001). The Drake Passage is the only latitude band where ocean waters circle the Earth. The lack of continental boundaries means that a circumpolar flow can connect the ocean basins and transfer climate anomalies between them (Figure 1). A dynamical consequence of the lack of land boundaries is that there can be no net north-south flow above the height of the shallowest bathymetry (north-south flows are possible, but must average to zero); this dynamical barrier to north-south exchange of heat contributes to the present glacial climate of the Antarctic continent. The ACC is the largest current in the world ocean, carrying roughly 135–147 $\times 10^6$ m^3 s^{-1} of water around Antarctica (Cunningham et al., 2003; Rintoul and Sokolov, 2001). The absence of land masses in the latitude band of the Drake Passage also means that the dynamics of the ACC differ from those of low-latitude currents, with small-scale eddies playing a prominent role.

The strong eastward flow of the ACC is in dynamical balance with density layers that shoal steeply to the south. Waters found at depths greater than 3,000 m north of the current can reach the sea surface near Antarctica. In this sense, the Southern Ocean provides a window to the deep sea. Where these dense waters outcrop at the sea surface, the exchange of heat and moisture between the ocean and the atmosphere acts to transform water from one density class to another. The net result is an overturning circulation consisting of two cells (Figure 2): deep water that upwells near Antarctica is converted to denser Antarctic Bottom Water that sinks to great depth and ventilates the abyssal ocean; deep water that upwells farther north is converted by warming, precipitation, and melt of sea ice to less-dense waters that ventilate the intermediate layers of the Southern Hemisphere oceans (Speer et al., 2000).

The Southern Ocean overturning circulation has a number of significant implications for the Earth system. The sinking of water from the surface of the Southern Ocean carries oxygen, heat, and carbon dioxide into the ocean interior. These water masses then spread throughout much of the ocean. In this way, the Southern Ocean renews the oxygen levels in the deep ocean and sets the capacity of the Southern Hemisphere oceans to store heat and carbon. When we talk about global warming over the last 50 years, we really mean ocean warming: more than 85% of the total increase in heat stored by the Earth system has gone into warming the ocean, with much smaller amounts of energy going into warming the atmosphere and land surface or into melting of ice (Levitus et al., 2005). The overturning circulation efficiently transports heat from the surface into the ocean interior, and as a result, the warming of the Southern Ocean extends far below the sea surface. Integrated around the globe, the Southern Ocean stores more of the excess heat trapped by the Earth system than any other latitude band. The Southern Ocean also absorbs a large amount of the carbon dioxide released by human activities, with about 40% of the total ocean inventory of anthropogenic CO_2 found south of 30°S (Figure 3; Sabine et al., 2004). The accumulation of anthropogenic CO_2 on the northern side of the Southern Ocean reflects the efficiency with which the upper cell of the overturning circulation transfers water from the surface, where the ocean absorbs CO_2 from the atmosphere, to the interior of

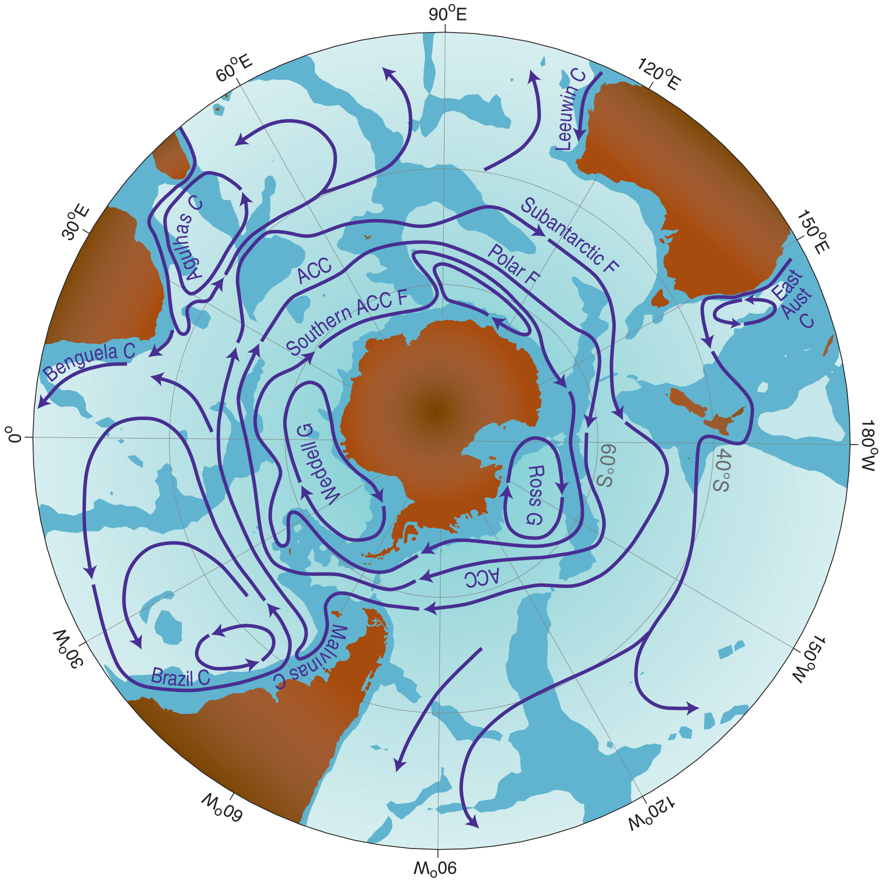

FIGURE 1. A schematic representation of the current systems in the Southern Ocean. The Antarctic Circumpolar Current (ACC) flows from west to east around Antarctica in two major branches, the Polar Front and Subantarctic Front. Clockwise gyres fill the deep basins between the Antarctic continent and the ACC. Adapted from Rintoul et al. (2001).

the ocean. Cooling and sinking of subtropical waters also contribute to the high inventory of anthropogenic CO_2 in this region.

The Southern Ocean overturning also has implications for the biology and chemistry of the global ocean. The upwelling of deep water returns nutrients to the surface ocean, where they can be used by phytoplankton. In model simulations, if the export of nutrients by the Southern Ocean overturning circulation is set to zero, the primary production in the rest of the ocean is reduced by 75% (Sarmiento et al., 2004). Deep water is also very rich in carbon; when deep water upwells, carbon is lost to the atmosphere (Le Quéré et al., 2007). The sinking of intermediate and bottom waters, on the other hand, tends to remove anthropogenic carbon dioxide from the atmosphere and sequester it in the ocean. The balance between the upwelling and downwelling limbs of the Southern Ocean overturning circulation plays a large part in determining how much carbon dioxide is absorbed and stored by the ocean. Biological production also plays a role in sequestering carbon as organic material sinks from the surface ocean and decomposes in the deep sea.

Climate and sea level rise are influenced strongly by interactions between the Southern Ocean and the cryosphere. Freezing of the ocean surface in winter forms sea ice covering about 16 million km^2, larger than the area of the Antarctic continent itself (Figure 4). Changes in sea ice extent or volume in the future may result in changes in the Earth's albedo, oceanic water mass formation rates, and air-sea exchange of gases such as carbon dioxide and affect the habitat of oceanic organisms from microbes to whales. Melting of floating glacial ice by ocean waters

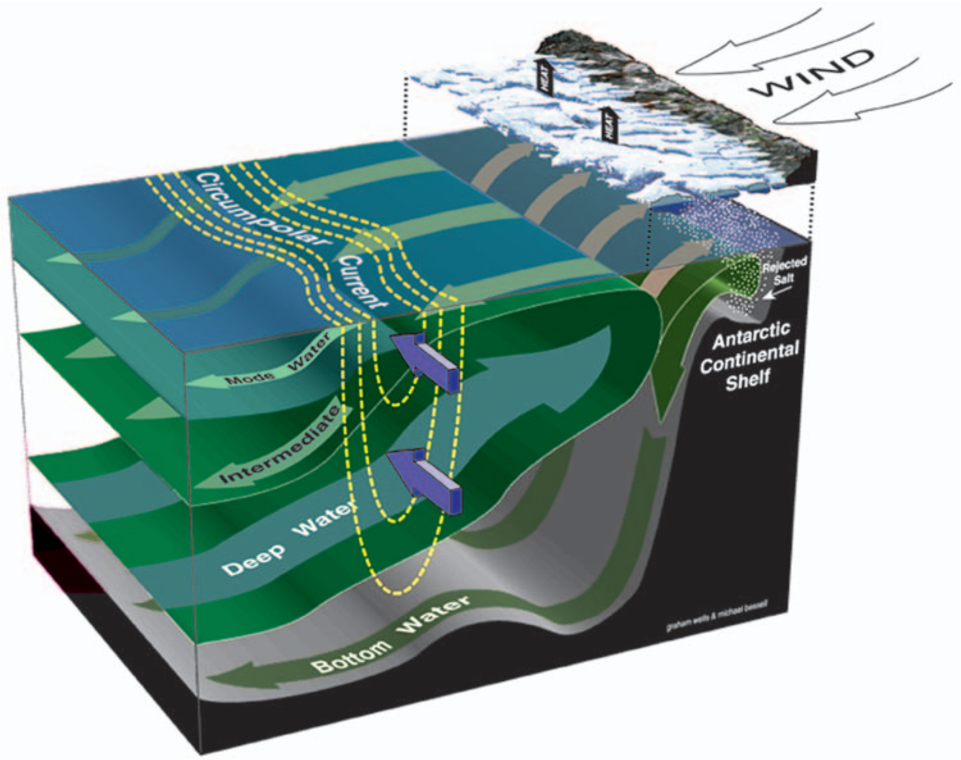

FIGURE 2. A schematic representation of the Southern Ocean overturning circulation. The figure shows the two cells contributing to the overturning: deep water upwelling to the surface of the Southern Ocean either moves toward Antarctica and sinks to form dense Antarctic Bottom Water or moves north and ultimately sinks to depths of 500–1,500 m on the northern flank of the ACC. From Rintoul (2000); used with permission.

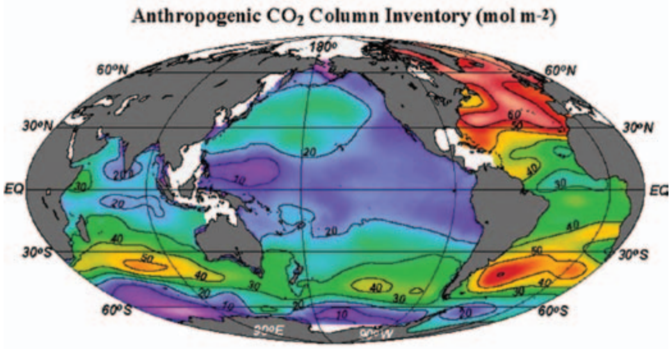

FIGURE 3. The inventory of anthropogenic carbon dioxide in the ocean. High values (shown in yellow and red) are located in regions where water masses sink from the sea surface to the interior of the ocean, in the North Atlantic and between 30°S and 50°S in the Southern Hemisphere oceans. From Sabine et al. (2004); used with permission.

at temperatures above the local freezing point influences the high-latitude freshwater budget and stratification and affects the mass balance of the Antarctic ice sheet and the rate at which glacial ice flows into the sea (Rignot et al., 2004).

The Southern Ocean therefore has a significant influence on global climate, biogeochemical cycles, biological productivity, and the Antarctic ice sheet. By connecting the ocean basins, the Southern Ocean allows a global-scale overturning circulation to exist. This system of alternating flows in the shallow and deep ocean transports heat and carbon efficiently around the Earth and establishes mean climate patterns. The uptake and storage of heat and carbon by the Southern Ocean act to slow the rate of atmospheric warming caused by increases in greenhouse gases. The Southern Ocean also connects the deep and shallow layers of the ocean, providing a return path for nutrients and maintaining global ocean productivity at levels that

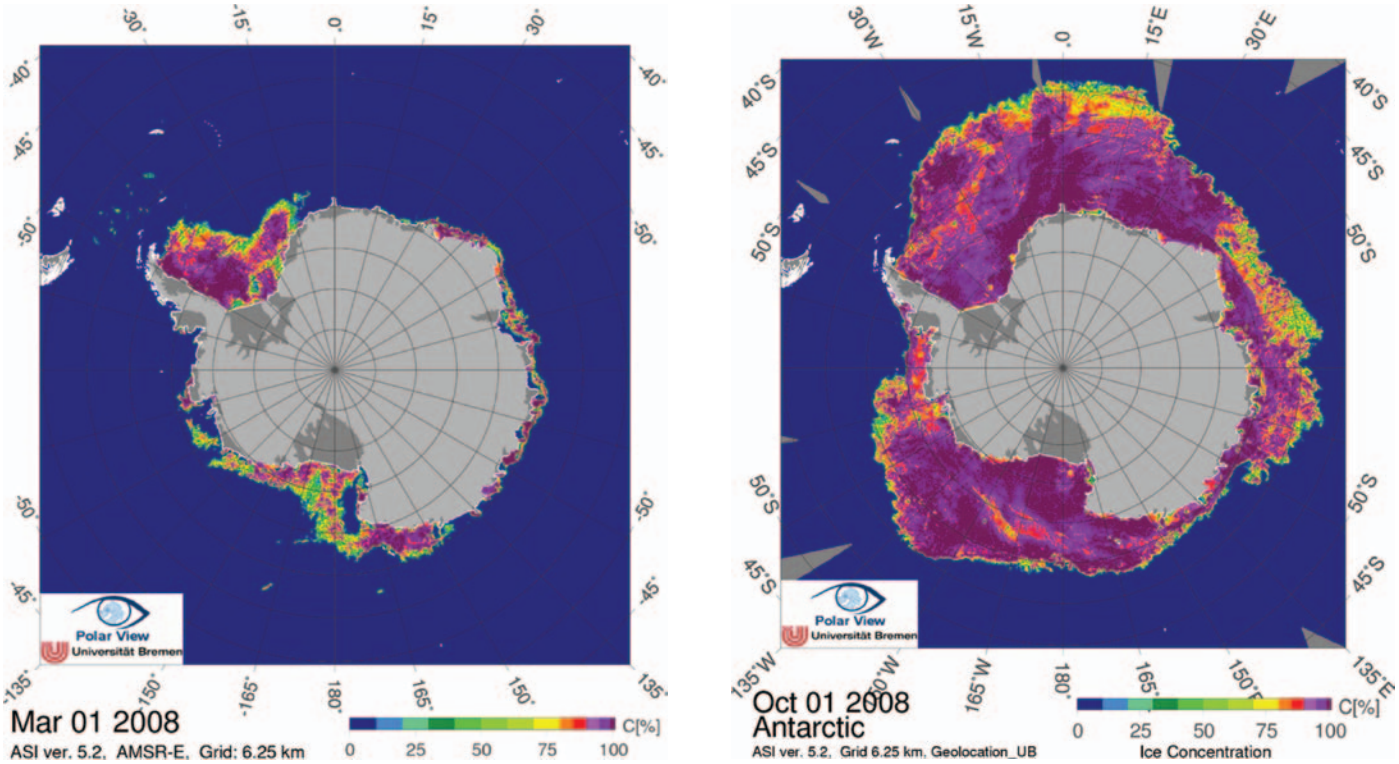

FIGURE 4. (left) Summer (1 March) and (right) winter (1 October) distribution of Antarctic sea ice in 2008. The sea ice extents reaches a maximum value of about 16 million km^2 in winter. From AMSR-E (http://www.iup.uni-bremen.de:8084/amsr/amsre.html).

are much higher than would be the case in the absence of this connection.

EVIDENCE FOR A CHANGING SOUTHERN OCEAN

Given the global influence of the Southern Ocean, any changes in the region would have widespread consequences. In particular, coupling between ocean circulation, sea ice, and biogeochemical cycles can result in positive feedbacks that drive further climate change. Changes to the freshwater balance as a result of changes in sea ice, precipitation, or ocean–ice shelf interaction may influence the strength of the overturning circulation. Reductions in sea ice extent would drive further warming through the ice-albedo feedback. Models suggest that the ability of the Southern Ocean to absorb carbon dioxide will decline with climate change, providing another positive feedback (Sarmiento et al., 2004; Le Quéré et al., 2007).

Changes in the physical and biogeochemical state of the Southern Ocean are, in fact, already underway (Turner et al., 2010). The Southern Ocean is warming (Figure 5) more rapidly than the global ocean average (Gille, 2002, 2008; Böning et al., 2008). The upper layers of the Southern Ocean have freshened as the result of an increase in precipitation and possibly melting of ice (Curry et al., 2003; Jacobs et al., 2002). The dense water that sinks near Antarctica to form the deep branch of the overturning circulation, known as Antarctic Bottom Water (AABW), has become less salty and less dense in recent decades in the Indian and Pacific sectors of the Southern Ocean (Figure 6) (Jacobs, 2004, 2006; Aoki et al., 2005; Rintoul, 2007). The freshening likely reflects an increase in basal melt of floating glacial ice, particularly in the southeast Pacific, with increased melt caused by warmer ocean temperatures (Shepherd et al., 2004; Rignot et al., 2008). Widespread warming of AABW has also been observed (e.g., Johnson and Doney, 2006).

Since 1992, satellite measurements show an overall increase in sea level and strong regional trends linked to shifts in fronts of the ACC (Sokolov and Rintoul, 2009). The sea surface is higher on the equatorward side of the ACC, so a southward shift of the current results in a

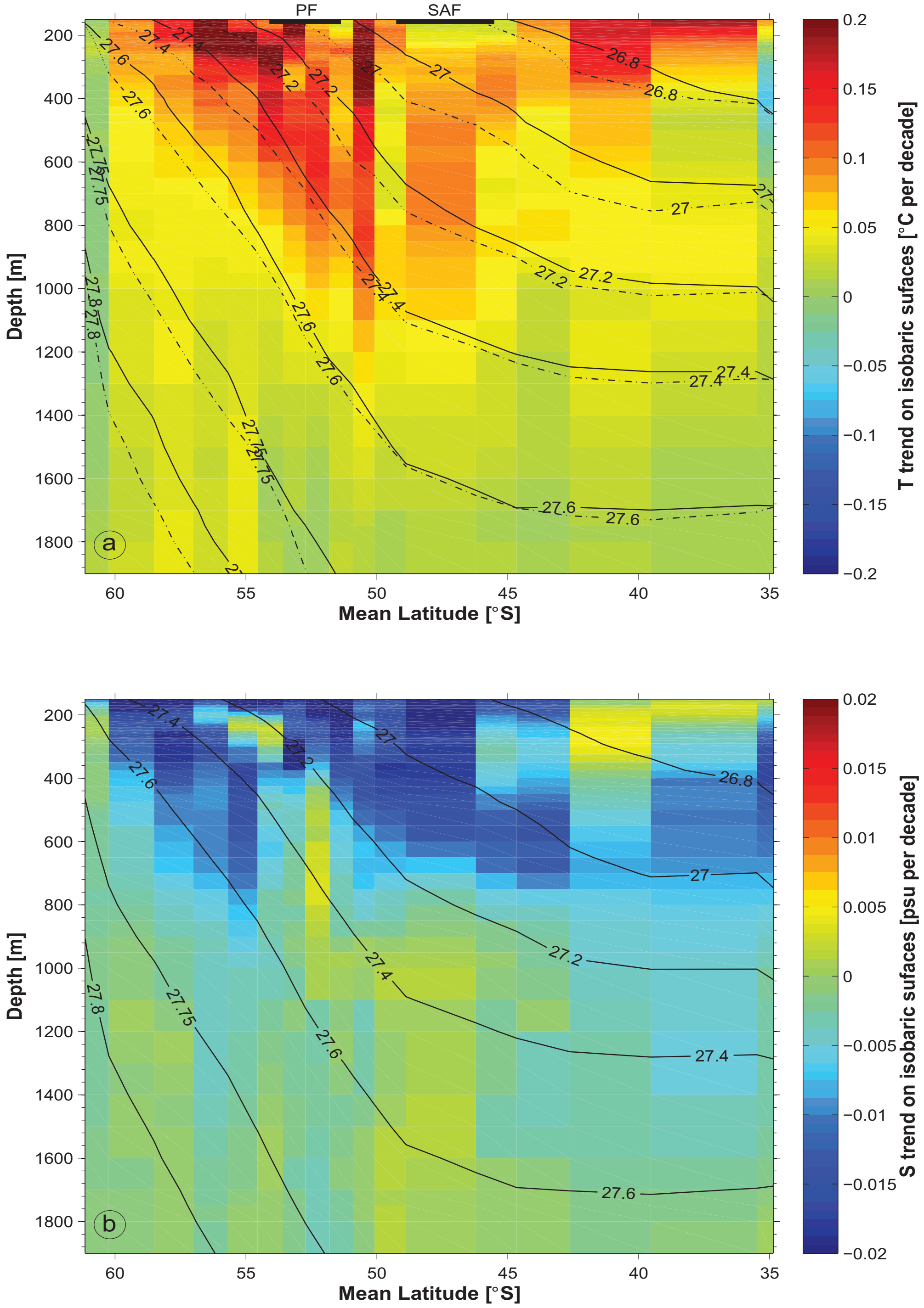

FIGURE 5. Decadal trends in (top) temperature and (bottom) salinity between 35°S and 60°S, estimated by subtracting recent measurements from ships and Argo floats from a long-term mean climatology (color). Differences are taken on surfaces of constant pressure (similar to depth) and along the mean streamlines of the ACC. The black lines on the plot indicate surfaces of constant density anomaly (in kg m^{-3},–1,000). The density surfaces shift south with time, but with little change in slope, indicating the transport of the ACC does not change much with time. From Böning et al. (2008); used with permission.

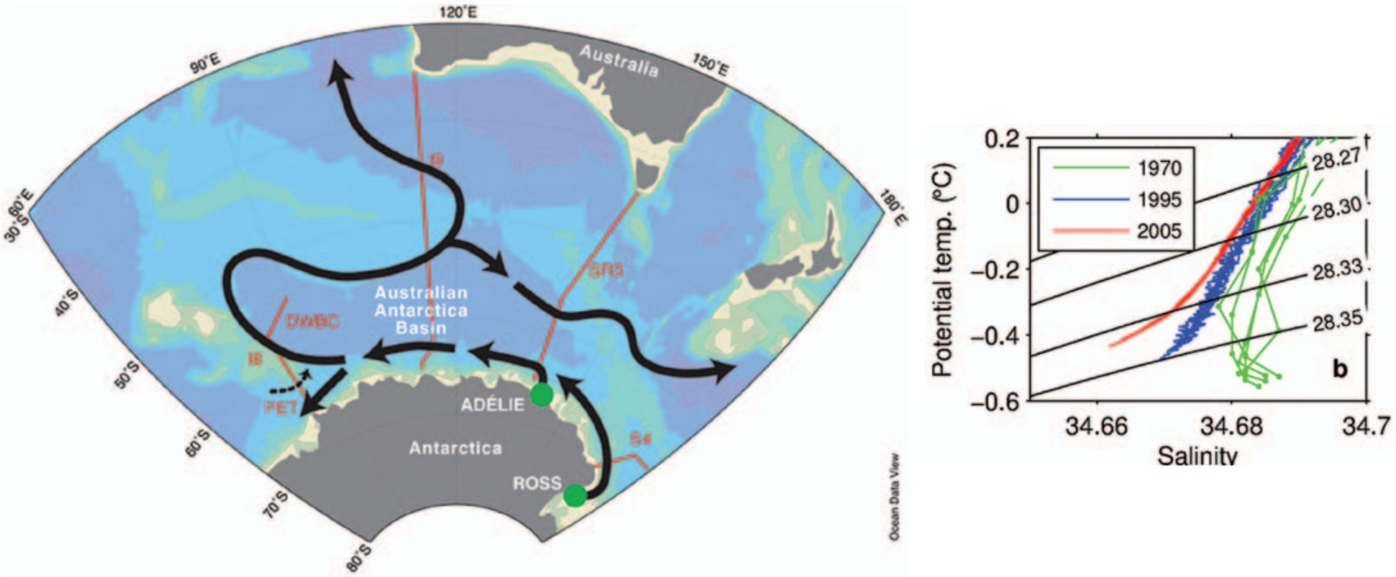

FIGURE 6. Freshening of Antarctic Bottom Water in the Australian Antarctic Basin. (left) Comparison of observations from the early 1970s, mid-1990s, and mid-2000s shows a shift toward less-salty and less-dense bottom water formed in the Indian and Pacific oceans at each of the sections indicated by red lines on the map. (right) An example of the changes in potential temperature and salinity observed near 115°E is also shown. (Potential temperature is the temperature of the water corrected for pressure effects.) The solid black lines indicate surfaces of constant density anomaly. From Rintoul (2007); used with permission.

regional increase in sea level. Changes in the location of ocean currents will also affect the distribution of organisms, and there are some early indications that species are also shifting south (Cubillos et al., 2007).

In contrast to the Arctic, where large decreases in sea ice extent and thickness have occurred, the overall extent of Antarctic sea ice has slightly increased in recent decades (the trend is not statistically significant) (Zwally et al., 2002; Parkinson, 2004). However, strong regional changes in sea ice extent and the seasonality of advance and retreat have been recorded in the Pacific sector (Stammerjohn et al., 2008), with substantial impacts on the marine ecosystem (Wilson et al., 2001).

The most dramatic changes observed in recent decades in Antarctica and the Southern Ocean have occurred along the Antarctic Peninsula. The peninsula has warmed more rapidly than anywhere else in the Southern Hemisphere, with the largest warming trend observed at Faraday/Vernadsky station (+0.53°C per decade for the period 1951–2006; the station is located at 65°15′S, 64°16′W). Ocean temperatures have also increased (Meredith and King, 2005), and the extent and duration of the winter sea ice cover have declined in the northern peninsula (Stammerjohn et al., 2008). Significant changes have also taken place in the marine ecosystem. Phytoplankton production has declined in the northern and increased in the southern part of the waters west of the Antarctic Peninsula (Montes-Hugo et al., 2009), as the result of changes in the sea ice regime. Gentoo penguins are extending their range farther south along the peninsula into regions previously dominated by Adelie penguins, and shifts in penguin diets have been observed (Ducklow et al., 2007).

Many of these changes observed in Antarctica and the Southern Ocean in recent decades are likely caused by the changes in winds over this time period (Turner et al., 2010). Changes in winds, in turn, drive changes in ocean circulation and temperature patterns and in the distribution and seasonality of sea ice (Figure 7). The primary mode of variability of the Southern Hemisphere winds is known as the Southern Annular Mode (SAM), which refers to a ring or vortex of winds that circles Antarctica from west to east and reaches from the stratosphere to the sea surface. In recent decades, there has been a tendency for this wind pattern to strengthen and contract closer to the Antarctic continent (Marshall, 2003). The changes observed to date in the SAM wind pattern are likely caused by a reduction in ozone in the stratosphere (Figure 8; Thompson and Solomon, 2002), but climate models suggest that increases in

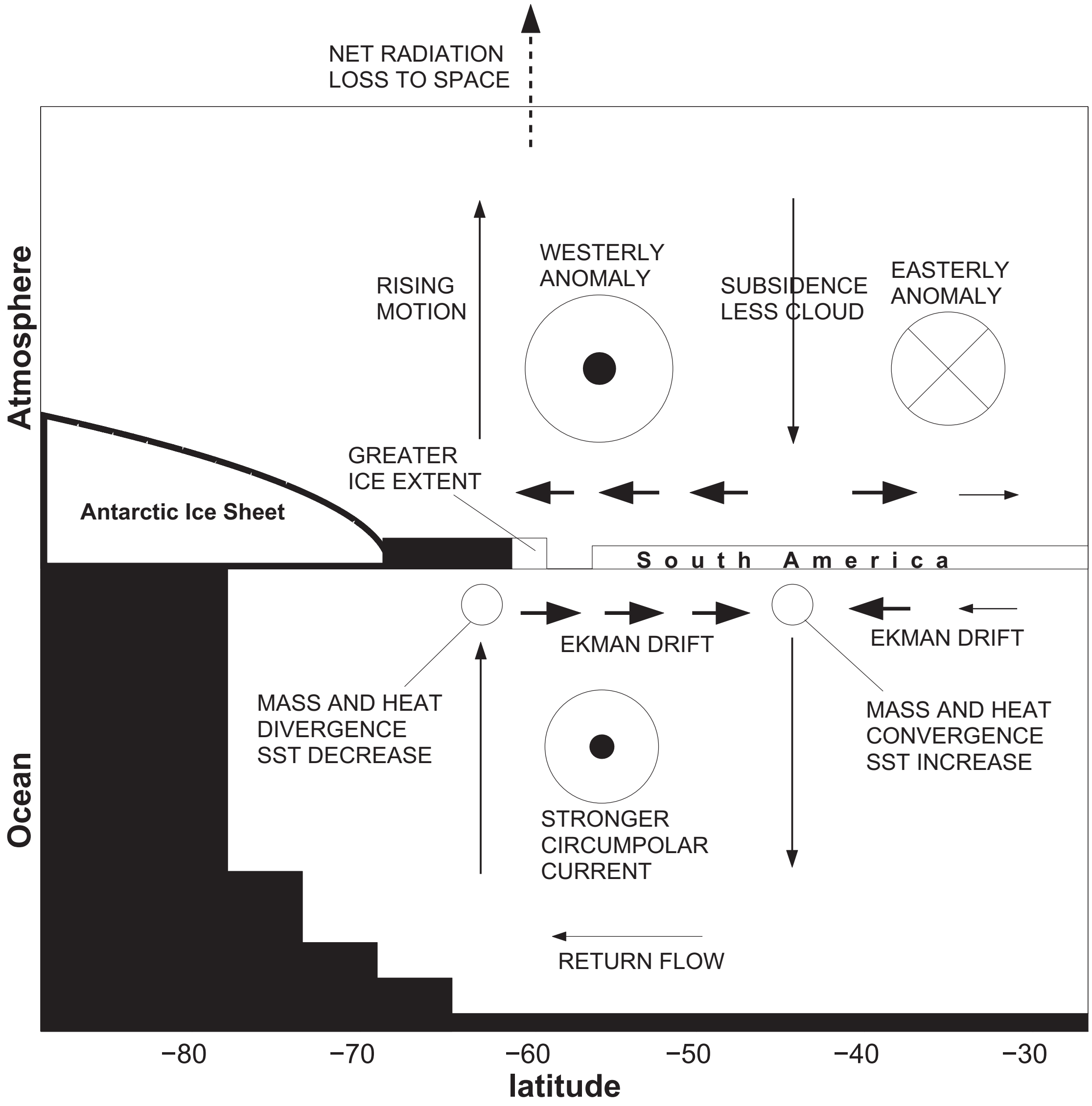

FIGURE 7. A representation of the changes in the atmosphere and ocean associated with variations in the Southern Annular Mode (SAM), the primary mode of variability of the Southern Hemisphere atmosphere. A strengthening of the winds drives stronger upwelling on the southern side of the Southern Ocean and stronger downwelling on the northern side. The stronger winds also tend to drive sea ice farther offshore. From Hall and Visbeck (2002); used with permission.

greenhouse gases will, in the future, drive similar changes in Southern Ocean winds (Schindell et al., 1998).

Although the fact that the Southern Ocean absorbs large amounts of anthropogenic carbon dioxide is a positive in the sense of slowing the rate of climate change, the additional carbon dioxide is also changing the chemistry of the ocean in ways that are likely to affect marine life. The uptake of CO_2 by the ocean is increasing the total inorganic carbon concentration, increasing the acidity, and reducing the amount of carbonate ion (Vazquez-Rodriguez et al., 2009). Because of the temperature dependence of the saturation state of aragonite (a form of calcium carbonate used by many organisms to make shells or other hard structures), the saturation threshold will be crossed first in the polar regions (Orr et al., 2005; McNeil and Matear, 2008). Indeed, there is some evidence that the changes are already causing a reduction in calcification of the shells of some organisms (Moy et al., 2009). Changes

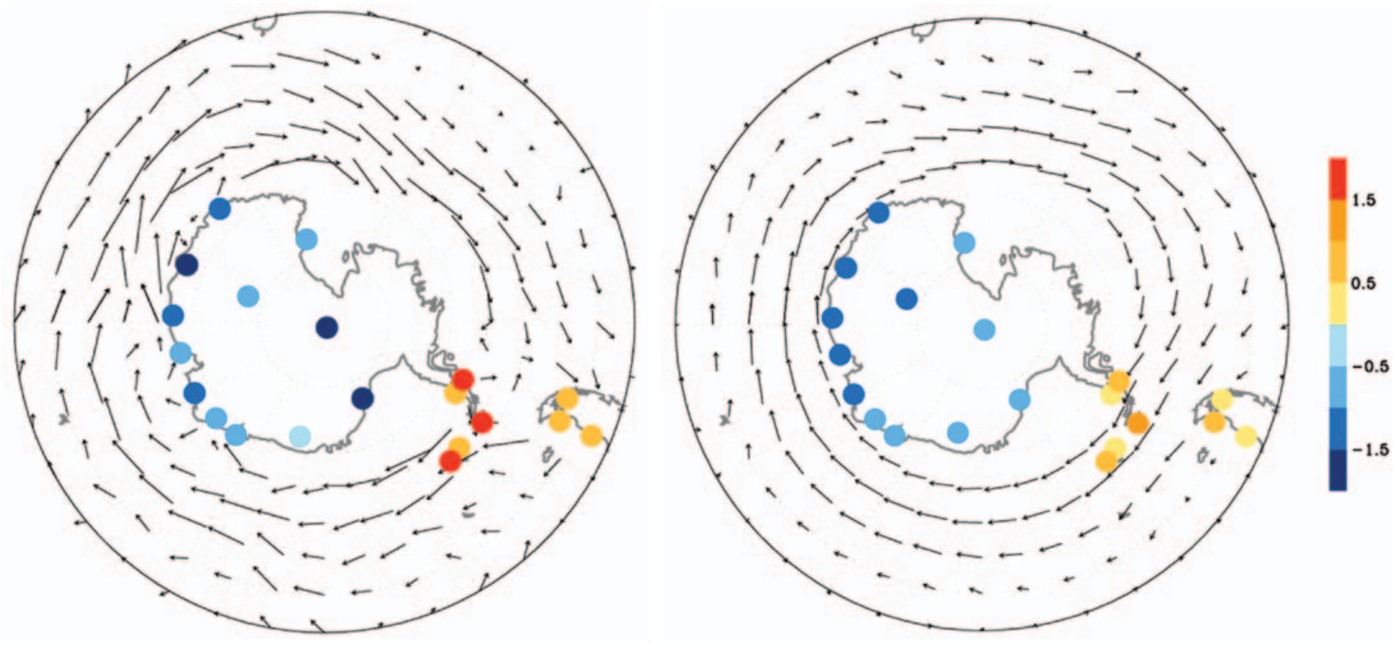

FIGURE 8. (left) Observed trends in surface wind over the Southern Ocean (arrows) and surface air temperature at Antarctic stations (colored dots) and (right) the part of the pattern that is congruent with the Southern Annular Mode. The wind data are from the NCAR/NCEP Reanalysis, for the period 1979–2000. From Thompson and Solomon (2002); used with permission.

in the quantity and nutritional quality of primary production will have consequences for secondary production, food web carbon and energy flows, and biogeochemical cycling, but the impact of changes in ocean chemistry on the Southern Ocean food web is largely unknown.

PROJECTIONS OF FUTURE CHANGE

Predicting future change in the Southern Ocean is particularly challenging. Small-scale phenomena like ocean eddies, which are unresolved by climate models, play a particularly important role in the Southern Ocean. Observations are scarce for testing of ocean models and for developing improved parameterisations. Existing models often do not perform well in the Southern Ocean. For example, an ocean carbon model intercomparison study found that the models diverged most dramatically in the Southern Ocean, primarily because of differences in how the models simulated the stratification and circulation (Orr et al., 2005).

Faced with a set of divergent model projections, one approach is to form a “weighted average” of a number of models, in which higher weight is placed on results from models that do a better job of simulating high-latitude climate (Bracegirdle et al., 2008). Using output from a large number of climate models used in the Intergovernmental Panel on Climate Change (IPCC) assessment reports, the weighted-mean model results predict further warming of the Southern Ocean over the next century, a 25% reduction in sea ice production, and a continued increase in strength of the westerly winds.

A particularly important issue is the response of the Southern Ocean overturning circulation to climate change. As discussed above, the overturning circulation influences strongly the ability of the Southern Ocean to absorb heat and carbon dioxide, as well as the supply of nutrients. A key question is how the overturning circulation responds to a change in winds blowing over the Southern Ocean. Coarse-resolution models, like those used to project future changes in response to increasing greenhouse gas concentrations, tend to show that stronger winds mean a stronger overturning circulation (as well as a stronger ACC) and a larger release of carbon dioxide from upwelling deep waters. High-resolution models that resolve the effects of small-scale eddies tend to show that the overturning and ACC transport are less sensitive to wind changes because a change in the eddies acts to compensate the change in wind forcing. Observations of the response to past changes in the winds are so far inconclusive, with atmospheric measurements favoring the former scenario (i.e., the Southern Ocean is becoming less effective at soaking up CO_2; Le Quéré et al., 2007) whereas eddy-resolving ocean model simulations and ocean measurements have been interpreted as evidence of the latter view (Hallberg and Gnanadesikan, 2006; Meredith and Hogg, 2006; Böning et al., 2008). Resolution of this issue will be an important step toward increasing certainty in projections of future climate change.

It is likely that warming and freshening of the surface layer will increase the stratification of the upper ocean, reducing nutrient inputs to the euphotic zone. Biological productivity and ecosystem function are also likely to be affected by a reduction in sea ice. Climate models using a business-as-usual scenario for CO_2 emissions predict that surface waters will become undersaturated with respect to aragonite by 2050, extending through the entire Southern Ocean by 2100 (Orr et al., 2005). When seasonal variations in carbonate ion concentration are taken into account, surface waters become undersaturated for aragonite as early as 2030 (McNeil and Matear, 2008).

A REVOLUTION IN SOUTHERN OCEAN OBSERVATIONS

Understanding of the influence of the Southern Ocean on the Earth system has increased rapidly in recent years. Much of the recent progress has relied on the ongoing revolution in ocean observations: tools are now available that enable scientists to really measure the Southern Ocean for the first time. Autonomous platforms like Argo profiling floats are allowing year-round measurements of remote regions like the Southern Ocean (Figure 9). In the last six years the Argo program has already provided more temperature and salinity profiles than obtained in the entire history of ship-based oceanography in the Southern Hemisphere. A variety of satellite sensors are delivering year-round, regular, circumpolar measurements of key variables, including sea surface temperature, sea ice, wind

FIGURE 9. Distribution of Argo floats as of February 2010. Each float acquires and transmits a vertical profile of temperature and salinity as a function of pressure (equivalent to depth), from 2,000 m to the sea surface, every 10 days. From the JCOMMOPS Web site (http://www.jcommops.org).

stress, ocean color (a measure of phytoplankton biomass), sea surface height, and the mass balance of the Antarctic ice sheet. Deep measurements collected by ships have revealed changes in the ocean inventory of heat, freshwater, and carbon. Sensors mounted on elephant seals and ice-capable floats have provided the first broad-scale profiles of the ocean beneath the sea ice in winter (Klatt et al., 2007; Charrassin et al., 2008). By providing simultaneous observations of seal behaviour and oceanographic conditions, the seal observations have provided new insights into the foraging behaviour and population dynamics of the seals (Biuw et al., 2007).

Many of these achievements have relied on the international cooperation and coordination established by the International Polar Year (IPY) and other programs. A legacy of the IPY is the demonstration that a Southern Ocean Observing System (SOOS) is feasible, cost-effective, needed, and timely. The SOOS will provide the sustained observations needed to detect, interpret, and respond to change in the Southern Ocean. During IPY, the community obtained a circumpolar snapshot of the Southern Ocean that has provided new insights into the coupling between physical, chemical, and biological systems and their sensitivity to change. This was achieved with a level of investment only slightly greater than the "business as usual" support of Southern Ocean science. Key to the achievements of the IPY was broad international support and the focus on multidisciplinary science.

SOUTHERN OCEAN SCIENCE INFORMING POLICY

Southern Ocean science contributes to several dimensions of policy. Perhaps the most important contribution is to educate, to inspire, and to raise awareness of the deep and intimate connection between Antarctica and the Southern Ocean and the rest of the globe. The influence of Antarctica on the Earth system is largely mediated through the surrounding oceans. Changes in the Southern Ocean will have significant implications for the Earth system, through feedbacks involving the overturning circulation, the carbon cycle, and ocean-ice interactions. Observations of the Southern Ocean help define what climate trajectory we are on, are essential for testing models used to make climate projections, and may provide an early warning of impending shifts in the climate system. Models that incorporate a better representation of Southern Ocean processes will deliver more skilful climate projections, providing better information to guide mitigation and adaptation strategies. Knowledge of the response of the Southern Ocean to change will help manage the risks of a changing climate.

Human pressures on the Southern Ocean are increasing and will continue to grow. The growth in Antarctic tourism has implications for the safety of both human lives and the environment (e.g., Enzenbacher, 1992; Fraser and Patterson, 1997; Frenot et al., 2005). Further exploitation of marine resources is likely as more traditional sources of protein decline or increase in cost, either for direct human consumption or as feed for aquaculture. Geoengineering approaches to enhancing carbon sequestration (e.g., iron fertilisation of the Southern Ocean; see Watson et al., 2008, and accompanying articles) are being considered. As the use of the Southern Ocean increases, so will the demand for knowledge required to manage marine resources and to inform decisions by policy makers, industry, and the community. To deliver the understanding of the Southern Ocean on which sound policy depends, a sustained, multidisciplinary Southern Ocean Observing System is essential.

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