The Southern Ocean Observing System:
Initial Science and Implementation Strategy

Draft for review and community comment

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Executive Summary

The Southern Ocean provides the principal connection between the Earth’s ocean basins and between the upper and lower layers of the global ocean circulation. As a result, the Southern Ocean strongly influences climate patterns and the cycling of carbon and nutrients. Changes in the Southern Ocean would therefore have global ramifications.

Limited observations suggest the Southern Ocean is indeed changing: the region is warming more rapidly than the global ocean average; salinity changes driven by changes in precipitation and ice melt have been observed in both the upper and abyssal ocean; the uptake of carbon by the Southern Ocean has slowed the rate of climate change but increased the acidity of the ocean; and Southern Ocean ecosystems are reacting to changes in the physical and chemical environment.

However, the short and incomplete nature of existing time series makes the causes and consequences of observed changes difficult to assess. Sustained, multidisciplinary observations are required to detect, interpret and respond to change.

The Southern Ocean Observing System (SOOS) is motivated by the need to address six key challenges in Southern Ocean science:

1. The role of the Southern Ocean in the planet’s heat and freshwater balance
2. The stability of the Southern Ocean overturning circulation
3. The role of the ocean in the stability of the Antarctic ice sheet and its contribution to sea-level rise
4. The future and consequences of Southern Ocean carbon uptake
5. The future of Antarctic sea ice
6. The impacts of global change on Southern Ocean ecosystems

There is an urgent and compelling need to make progress in each of these areas to inform decision-makers confronted with the challenges of climate change, sea-level rise, ocean acidification, and the sustainable management of marine resources. To deliver this information, sustained observations of the physical, biogeochemical and biological state of the Southern Ocean are critical.

The lack of historical observations has slowed progress in understanding the Southern Ocean and its connections to the rest of the Earth system. However, advances in technology and knowledge mean that it is now possible to design and implement a sustained, feasible and cost-effective observing system for this remote environment.

Users of the SOOS will include the research community, managers of marine resources, policy makers, local planners, shipping operators, Antarctic tourism operators, weather and climate forecasters, and educators. A number of international organisations, including the International Oceanographic Commission of UNESCO, the World Meteorological Organisation and the Scientific Committee on Antarctic Research, have noted the need for sustained observations of the Southern Ocean and supported the development of the SOOS.

This document outlines the scientific rationale and strategy for the SOOS; identifies the variables to be observed; presents a draft plan for an integrated multi-disciplinary
observing system for the Southern Ocean; and identifies the next steps required for implementation.
1. Introduction

1.1 The Southern Ocean and its role in the Earth System

As a result of the unique geography of the Southern Ocean, the region has a profound influence on the global ocean circulation and the Earth’s climate. The absence of land barriers in the latitude band of Drake Passage allows a circumpolar current to exist. The Antarctic Circumpolar Current (ACC) is the largest current in the world ocean and, by connecting the ocean basins, exerts a major influence on global climate. The existence of the ACC tends to restrict the poleward transport of heat, in contrast to the northern hemisphere where currents transport heat directly to high latitudes. The strong north-south tilt of density surfaces associated with the eastward flow of the ACC exposes the deep layers of the ocean to the atmosphere at high southern latitudes. Wind and buoyancy forcing at these isopycnal outcrops transfers water between density layers, and connects the deep global ocean to the surface layers. In this way, the Southern Ocean controls the connection between the deep and upper layers of the global overturning circulation and thereby regulates the capacity of the ocean to store and transport heat, carbon and other properties that influence climate and global biogeochemical cycles (e.g. Rintoul et al., 2001).

The upwelling branch of the overturning circulation in the Southern Ocean returns carbon and nutrients to the surface layer, while the downwelling branches transport heat, carbon and other properties into the ocean interior. The balance between upwelling and outgassing versus subduction of carbon into the ocean interior determines the strength of the Southern Ocean sink of CO$_2$. This balance depends on the wind forcing and eddy dynamics of the ACC. The Southern Ocean contributes more to the ocean storage of the excess heat and carbon added to the Earth-atmosphere system by human activities than any other latitudinal band (Levitus et al., 2005; Sabine et al., 2004). About 40% of the total global ocean inventory of anthropogenic carbon dioxide is found south of 30°S (Sabine et al., 2004). Export of nutrients by the upper limb of the overturning circulation ultimately supports 75% of the global ocean primary production north of 30°S (Sarmiento et al., 2004).

Climate and sea-level rise are influenced strongly by ocean-cryosphere interactions in the Southern Ocean. Changes in sea ice extent or volume result in changes in the Earth’s albedo, oceanic water mass formation rates, air-sea exchange of gases such as carbon dioxide, and affect oceanic organisms from microbes to whales in terms of physiological changes and changes to their habitats. Melting of floating glacial ice by warm ocean waters influences the high latitude freshwater budget and stratification and may affect the stability of the Antarctic ice sheet and the rate at which glacial ice flows to the sea.

Given the influence of the Southern Ocean, any changes in the region would have global 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 will drive further warming by
reducing the ice-albedo feedback. Models suggest that the ability of the Southern
Ocean to absorb carbon dioxide will decline as climate change progresses, providing
another positive feedback (Sarmiento et al., 2004; Le Queré et al., 2007). Turner et
al. (2009a) provide a comprehensive review of the role of Antarctica and the Southern
Ocean in the global system and the potential sensitivity to change (see also Mayewski
et al., 2009, and Convey et al, 2009).

Here we adopt the standard oceanographic definition of the Southern Ocean as the
waters between the Subtropical Front and the Antarctic continent. This is a broader
definition than used in some policy contexts, but reflects the circumpolar continuity of
the waters of this oceanic domain, and the strong scientific connections between them.

1.2 Observed changes in the Southern Ocean

Changes in the physical and biogeochemical state of the Southern Ocean are already
underway. The circumpolar Southern Ocean is warming more rapidly, and to greater
depth, than the rest of the global ocean (Gille, 2002; 2008). The upper layers of the
Southern Ocean have freshened as the result of increases in precipitation and the
melting of floating glacial ice (Curry et al. 2003; Boyer et al., 2005; Böning et al.,
2008). Freshening of Antarctic Bottom Water (AABW) in the Indian and Pacific
regions of the Southern Ocean may also reflect an increase in basal melting of floating
glacial ice (Jacobs, 2004; 2006; Aoki et al., 2005; Rintoul, 2007), with increased
melt linked to increased heat flux from the ocean (Shepherd et al, 2004; Rignot et al.,
2008). Widespread warming of AABW has been observed (Zenk and Morozov, 2007;
Johnson and Doney, 2006); this is believed to be due to a combination of changes in
formation properties, and changes in export processes driven by climate variability
(Meredith et al., 2008).

Since 1992, the satellite altimeter record shows an overall increase in sea level and
strong regional trends linked to shifts in fronts of the ACC (Sokolov and Rintoul,
2009a,b). The average circumpolar extent of sea ice shows a small but significant
increase during the satellite era (post-1978) (Comiso and Nishio, 2008), due primarily
to large increases in the Ross Sea sector that are nearly compensated by large
decreases west of the Antarctic Peninsula (where rates of decrease rival those seen in
the Arctic; Stammerjohn et al., 2008). The regional trends in sea ice extent have been
linked to changing meridional winds associated with the strengthening trend of the
Southern Annular Mode (Turner et al., 2009). While some coupled models suggest
that the overall extent could increase as melt water increases stratification and
insulates the surface layer from warmer deeper water (Zhang, 2007), the IPCC 4AR
models suggest sea ice is likely to decline by about 30% by 2100 (Bracegirdle et al.,
2008). Turner et al. (2009b) suggest that the recent increase in Antarctic sea ice
extent is linked to the depletion of stratospheric ozone and that significant declines in
sea ice are likely in the future as ozone levels recover and the impact of increasing
greenhouse gases is more strongly felt. Models also suggest that sea ice thickness will
decline more rapidly than ice extent, but there are no observations with which to
assess whether sea ice thickness has changed.

The uptake of CO₂ by the ocean is changing the ocean’s chemical balance by
increasing the total inorganic carbon concentration, increasing the acidity and altering
the carbon speciation (Vazquez-Rodriguez et al., 2009). Because of the temperature
dependence of the saturation state of calcium carbonate, the cold waters in the polar
regions will be the first to cross the aragonite under-saturation threshold (Orr et al.,
2005; McNeil and Matear, 2008). There is some evidence that the changes are already
causing a reduction in calcification of the shells of some organisms (Moy et al.,
2009). A common planktonic response to increased CO$_2$ is an increase in primary
productivity under higher CO$_2$ (e.g. Tortell et al., 2008) with changes to the
elementary stoichiometry (e.g. Bellerby et al., 2008). Subsequent changes in the
quantity and nutritional quality of primary production will have consequences for
secondary production, food web carbon and energy flows and biogeochemical
cycling. The response of the Southern Ocean food web to changes in ocean chemistry
remain largely unknown.

The Southern Ocean harbours unique and distinct ecosystems as a result of its
isolation and extreme environment (e.g. Laws, 1985). Phytoplankton biomass is
generally low, despite high concentrations of macronutrients, often ascribed to the
lack of the micronutrient iron (Holm–Hansen et al. 2004a,b; Korb & Whitehouse
2004; Korb et al. 2005; Blain et al. 2007). The Southern Ocean food web is
characterized by a keystone species, Antarctic krill (Euphausia superba), which
supports large populations of higher predators (Murphy et al 2007). This relative
dependence on a single species and the uniqueness of the Southern Ocean food webs
and biogeochemical cycles make the system vulnerable to climate variability and
change. There is evidence of changes in other components of the Southern Ocean
food web, from phytoplankton to penguins and seals (Fraser et al., 1992; Loeb et al.,
1997; Reid and Croxall, 2001; Fraser and Hofmann 2003; Weimerskirch et al., 2003;
Murphy et al., 2007; McClintock et al., 2008). However, most biological and
ecological time series are short, incomplete and limited to a particular location,
making it difficult to assess and interpret long-term trends. Often the physical and
chemical measurements needed to link ecosystem variability to environmental
variability do not exist. Possible synergistic interactions between harvesting of
Southern Ocean resources and climate change are largely unknown and may alter
assessments of the sustainability of these activities.

1.3 The need for a sustained Southern Ocean Observing System

The recent advances summarised above underscore the importance of the Southern
Ocean in the Earth system. Improved understanding of the links between Southern
Ocean processes, global climate, biogeochemical cycles and marine productivity will
be critical for society to respond effectively to the challenges of climate change, sea-
level rise, ocean acidification and the sustainable use of marine resources. In
particular, it is critical to understand how the Southern Ocean system will respond to
changes in climate and other natural and human forcing and the potential for
feedbacks. To achieve this enhanced understanding, sustained multi-disciplinary
observations are essential.

Research programmes over the past 15 years have demonstrated that sustained
observations of the Southern Ocean are feasible. For example, repeat hydrographic
sections have been used to quantify the evolving ocean inventory of heat and carbon,
to demonstrate that changes are occurring throughout the full depth of the Southern
Ocean, and to provide a platform for a wide suite of interdisciplinary observations. Satellites are providing circumpolar, year-round coverage of physical and biological variables and sea ice properties. Moorings are providing time series information on velocities and water properties in critical regions. The development of autonomous profiling floats (Argo) now allows broad-scale, year-round measurements of the interior of the Southern Ocean (to 2 km depth) to be made for the first time. The ocean beneath the sea ice, inaccessible with traditional platforms, is being measured with special polar profiling floats and miniaturised oceanographic sensors attached to marine mammals. Ocean gliders now offer the possibility of making real-time multidisciplinary measurements of the upper 1000 m of the water column, and have recently been deployed for the first time in the Antarctic. Measurements of biological distributions and processes using net tows, continuous plankton recorders, and acoustics are providing new insights into the coupling of physical, biogeochemical and ecological processes. Autonomous underwater vehicles are providing new insight into the ocean deep beneath ice shelves.

These developments are a striking success, and go far beyond what could have been envisioned just a decade ago (Rintoul et al., 2002). In particular, the emphasis then was on maintaining the traditional hydrographic, high-density Expendable Bathythermographs (XBTs), and mooring arrays, and a call for Argo, with its focus on the upper ocean heat budget, to include the Southern Ocean. The fruits of this effort can now be seen in terms of upper ocean salinity observations by Argo and marine mammals that reveal an enhanced freshwater cycle (e.g. Durack and Wijffels, 2010), with important changes occurring in the Southern Ocean.

While existing tools allow the backbone of the SOOS to be established, new technologies are needed in some areas before the observing system is complete. This is particularly true for biogeochemistry and biology, where there are as yet no platforms to provide broad-scale measurements of key variables in a cost-effective manner. Efforts are underway to develop sensors that extend the capability of Argo floats, animal platforms, gliders, moorings and ships of opportunity and these developments will be particularly important in the poorly observed Southern Ocean. The increase in tourism and fisheries in the Southern Ocean opens up new possibilities for observations to be collected as part of the Voluntary Observing Ship Programme (VOS). The SOOS will be a test bed for these instruments and provide the complementary data sets needed for their interpretation.

The capability to model and simulate Southern Ocean processes has also improved dramatically in recent years. Increasingly, models are an integral element of ocean observing systems. Models are needed to interpolate between sparse observations, to integrate diverse observations into consistent estimates of the state of the ocean, to detect the significance of variations in time scales beyond the duration of observations, to infer aspects of the ocean circulation that are not directly observable (e.g. vertical velocity), to integrate circulation and biological observations and to conduct quantitative observing system design studies. In atmospheric science, the wide availability of high quality atmospheric reanalyses has led to dramatic advances in understanding. Ocean science is at the beginning of a similar revolution, with the first global state estimates only recently produced. It is likely that in the future ocean scientists, like their atmospheric counterparts, will rely heavily on ocean analyses produced by combining data and dynamics rather than on the results of individual
observations, cruises or experiments. These ocean state estimates, in turn, depend on access to sustained, broad-scale observations.

1.4 A Vision for a Southern Ocean Observing System

An integrated observing system for the Southern Ocean has been advocated for at least a decade (e.g. Rintoul et al., 1999; Summerhayes, 2004, 2007; Sarukhanian and Frolov, 2004; Summerhayes et al., 2007). This was explored at a workshop in Hobart in 2006, instigated by the Partnership for Observations of the Global Ocean (POGO), the Census for Antarctic Marine Life (CAML), SCAR and SCOR. At the meeting and in subsequent discussions with the broader community there has been strong support for a SOOS. Three further meetings organised by SCAR and SCOR with the support of CAML, the Global Ocean Observing System (GOOS), the World Climate Research Programme (WCRP), POGO and NOAA have been held. As input to these meetings, a survey was conducted of researchers and research users to identify the top priorities for the SOOS. The SCAR/SCOR Expert Group on Oceanography and the CLIVAR/CliC/SCAR Southern Ocean Region Implementation Panel have taken the lead in producing the SOOS strategy, though views have been solicited from as wide a range of interested parties as possible.

The community involved in developing the SOOS concept reached broad consensus that a Southern Ocean Observing System must be:

- sustained,
- feasible and cost-effective,
- circumpolar, extending from the Subtropical Front to the Antarctic continent and from the sea surface to the sea floor,
- multi-disciplinary (including physics, biogeochemistry, sea ice, biology, and surface meteorology),
- targeted to address specific scientific challenges,
- integrated with the global ocean and climate observing systems,
- based initially on proven technology but evolving as technology develops,
- integrated with a data management system built on existing structures,
- able to deliver observations and products to a wide range of end-users, and
- built on past, current and future research programmes.

1.5 Purpose and structure of the strategy

The purpose of this Initial Science and Implementation Strategy is to highlight the scientific relevance of the Southern Ocean, articulate the need for sustained observations to address major outstanding scientific challenges, and to provide a roadmap for implementation of the SOOS. Chapter 2 outlines the scientific rationale for sustained observations of the Southern Ocean. Chapter 3 identifies six key challenges for Southern Ocean science, summarises the sustained observations needed to meet them and outlines a draft strategy to obtain the observations. A summary of the current status of Southern Ocean observations and an initial roadmap for implementation of the SOOS is presented in Chapter 4.
2. Rationale for a Southern Ocean Observing System

2.1 Role of the Southern Ocean in climate and global biogeochemical cycles

The Southern Ocean overturning circulation consists primarily of two counter-rotating cells (Figure 1). Deep water formed in the North Atlantic spreads south to the Southern Ocean and is carried east by the ACC. This water spreads poleward (in some cases after first passing through the deep Indian and Pacific basins) and shoals across the ACC, reaching the surface over a range of latitudes and densities. Water upwelling close to Antarctica is converted first by freshening and subsequently by cooling and addition of brine released by sea ice formation to denser AABW, which sinks from the continental shelf to the deep ocean. Slightly less dense deep water upwells at lower latitude, beneath the westerly winds where surface waters are driven north in the Ekman layer. Gain of heat and freshwater in the surface layer converts the upwelled deep water to less dense water that subducts as Antarctic Intermediate Water and Subantarctic Mode Water. The strength of this upper cell of the overturning circulation is controlled by eddy fluxes and air-sea forcing (Figure 2).

Figure 1: A representation of the global overturning circulation, from Lumpkin and Speer (2007). The Southern Ocean connects the ocean basins, through the Antarctic Circumpolar Current, and connects the upper and lower limbs of the global overturning circulation, through water mass transformation.
Figure 2: A sketch of the ACC system showing the zonal flow and the meridional overturning circulation and watermasses. Antarctica is at the left side. The east-west section displays the isopycnal and sea surface tilts in relation to submarine ridges, which are necessary to support the bottom form stress that balances the wind. The curly arrows at the surface indicate the buoyancy flux, the arrows attached to the isopycnals represent turbulent mixing. From Olbers et al. (2004), redrawn from a figure from Speer et al. (2000).

The overturning circulation largely determines the overall exchange rate between the surface layers and the ocean interior, and therefore how much heat and carbon the ocean can store. Much of the increase in heat stored by the ocean is found in the Southern Ocean, where the overturning circulation has transferred heat from the surface to the ocean interior (Figure 3).

Figure 3: Linear trend (1955–2003) of the zonally integrated heat content of the world ocean by one-degree latitude belts for 100-m thick layers. Heat content values are plotted at the midpoint of each 100-m layer. Contour interval is $2 \times 10^{28} \text{ J year}^{-1}$. Levitus et al. (2005).
The overturning circulation also influences the global cycle of carbon and nutrients. Subduction of intermediate water and mode water in the upper cell of the Southern Ocean sequesters \( \text{CO}_2 \) in the ocean interior, so the Southern Ocean as a whole is a significant sink of carbon: the ocean south of 30°S accounts for about 40% of the total oceanic inventory of anthropogenic \( \text{CO}_2 \) (Figure 4). Upwelling of carbon-rich deep water at high latitudes results in outgassing of carbon dioxide to the atmosphere and wind-driven variations in the Southern Ocean overturning therefore drive changes in ocean uptake of \( \text{CO}_2 \) (Le Quéré et al., 2007; Lovenduski et al., 2007; Lenton and Matear, 2007; Verdy et al., 2007; Butler et al., 2007).

**Figure 4:** Column inventory of anthropogenic \( \text{CO}_2 \) in the ocean. High inventories are associated with Deep Water formation in the North Atlantic and Intermediate and Mode Water formation between 30°-50°S. Total inventory of shaded regions is 106±17 Pg C. Sabine et al. (2004).

The upwelling of deep water in the Southern Ocean returns nutrients to the surface ocean at high latitudes. A fraction of the upwelled nutrients is not utilized in the Southern Ocean and is exported to lower latitudes in mode and intermediate waters. The nutrient input supports biological productivity not just in the Southern Ocean but worldwide: model studies suggest that nutrients exported from the Southern Ocean by the upper cell of the overturning support 75% of oceanic primary production north of 30°S (Sarmiento et al. 2004).

However, while evidence for the critical role played by the Southern Ocean in global budgets of heat, freshwater, carbon and nutrients continues to accumulate, many uncertainties remain. Eddy fluxes make a significant contribution to meridional exchange of mass and heat across the Southern Ocean and vertical exchange of momentum (Rintoul et al., 2001), but the extent to which eddy fluxes and Ekman transport compensate each other in the mixed layer is unresolved. Coarse resolution climate models that include parameterisations of eddy processes, rather than resolving them directly, suggest that an increase in winds over the Southern Ocean would result in an increase in the strength of the overturning circulation. However, models that
resolve eddies suggest that the equatorward Ekman transport and poleward eddy transport tend to compensate one another, resulting in a reduced change in the strength of the overturning circulation (e.g. Hallberg and Gnanadesikan, 2006).

Resolving this issue is critical to understanding how changes in forcing may affect the Southern Ocean overturning and the capacity of the ocean to store heat and carbon.

Ocean observations have been interpreted as evidence that the real ocean is closer to the latter case (Böning et al., 2008), but this result requires testing with sustained observations and better understanding of the underlying dynamics.

The possibility that increased freshwater input to the high latitude ocean could cause a slowing of the thermohaline circulation, driving an abrupt change in climate, has attracted considerable interest (Alley et al., 2003). Most attention has focused on the North Atlantic, where a significant decrease in the salinity of North Atlantic Deep Water (NADW) has been observed during the past four decades (e.g. Dickson et al., 2002). (The reversal of this long-term freshening trend in recent years demonstrates the significant influence of decadal variability.) However, the Southern Ocean also makes an important contribution to the global overturning, by connecting the shallow and deep limbs of the overturning circulation and by forming dense waters that make a similar contribution to ventilation of the deep ocean to that made by NADW (e.g. Orsi et al., 2002). Evidence for freshening of the Southern Ocean continues to grow, with freshening observed in the upper ocean (Boyer et al., 2005; Böning et al., 2008), in the Ross Sea (Jacobs et al., 2002; Jacobs and Giulivi, 2010), and in Antarctic Bottom Water (Aoki et al., 2005; Jacobs, 2004, 2006; Rintoul, 2007). Sustained observations of the freshwater budget are needed to assess the likelihood of future changes in the overturning circulation. Model studies further suggest that perturbations of the freshwater and heat balance at high southern latitudes can have rapid and widespread influence on climate and ocean properties, by generating waves that rapidly transmit this climate signal on hemispheric or global scales (e.g. Ivchenko et al., 2004; Richardson et al., 2005; Masuda et al., 2010).

The ACC is the primary means of exchange of mass, heat and freshwater between the ocean basins. Recent advances in observations, models and theory have provided new insights into the dynamics and structure of the current, the role of eddies and topographic interactions, and the dynamical connections between the ACC and the overturning circulation (Rintoul et al., 2001; Olbers et al., 2004; Sokolov and Rintoul, 2007). The sensitivity of the ACC transport to changes in forcing remains a topic of debate. Coarse resolution models, such as those used in the IPCC assessments, tend to suggest that the ACC transport is more sensitive to changes in wind forcing (Fyfe 2006, Fyfe et al., 2007), while models that explicitly resolve eddies show a weaker response (e.g. Hallberg and Gnanadesikan, 2006; Meredith and Hogg, 2006). Long-term observations of ACC transport indicate only a moderate response of ACC transport to changes in the winds (Meredith et al., 2004), whilst observations of the density structure of the ACC also indicate relatively little change in recent decades (Böning et al., 2008). Sustained observations of ACC transport are needed to resolve this question and to quantify basin-scale budgets of heat, freshwater and other properties.

2.2 Sea ice and ice shelves
Antarctic sea ice influences climate and affects the interaction between the ocean and atmosphere in a number of important and complex ways. During winter, the Antarctic sea ice covers approximately $19 \times 10^6$ km$^2$, a larger area than the continent itself, and decreases to 20% of this amount during summer (Figure 5). The ice surface can reflect up to 90% of the incident solar radiation, depending on its thickness and snow cover, while the ice-free open ocean absorbs a similar fraction. Even a relatively thin cover of first year ice with a few centimetres of snow significantly increases the surface albedo of the ocean. A decrease in sea ice extent, on the other hand, reduces the albedo and warms the ocean, providing a positive feedback that drives further melt. The salt released when sea ice forms is also key in dense water production.

Coastal polynyas, where strong katabatic winds drive the ice offshore as rapidly as it forms, are regions of intense air-sea interaction and water mass formation. When sea ice melts, the additional freshwater increases the stability of the surface layer and affects air-sea exchange, water mass formation and the depth of the mixed layer. The formation and melting of sea ice therefore influences the light and nutrient environment experienced by phytoplankton in the sea ice zone. Sea ice also strongly influences air-sea exchange of heat, moisture and gases. The presence of a 10 cm thick layer of sea ice reduces air-sea heat loss by 90%. Changes in sea ice extent have been linked to large swings in atmospheric CO$_2$ between glacial and interglacial periods.

Sea ice is also closely related to biological productivity in the marine ecosystem. It provides a habitat for some species and a platform for others. Microorganisms are trapped in the sea ice structure as it forms, often in higher concentrations than occur in the water column, and then released again when the sea ice melts. During their time within the ice environment, some species thrive while the growth of others is either inhibited or stopped completely. Gradients of temperature and salinity within the ice dictate the living conditions for organisms trapped there while the thickness of snow cover determines the amount of light available. High concentrations of algae are often observed near the bottom of the ice, providing food for krill. Krill is a key component of the food chain and a primary source of food for baleen whales, seals, penguins and other birds. Changes in sea ice extent would therefore be expected to have impacts on the entire Antarctic food chain. For example, declines in sea ice extent have been linked to a reduction in krill biomass and an increase in salps, at least in some regions of Antarctica (Figure 5, Atkinson et al., 2004), and to changes at higher trophic levels (Barbraud et al. 2000).
Sea ice extent and concentration can be measured from a variety of satellite instruments (e.g. Figure 6), and algorithms continue to be improved (e.g. Lubin and Massom, 2006). Sea ice thickness (and volume) is of greater importance for many climate questions (e.g. the high latitude freshwater balance) but is much more challenging to observe. In the Arctic, long time series of ice thickness measurements from upward-looking sonars on submarines have revealed a 1.3 m decrease in mean ice draft in the central Arctic basin (Thorndike et al., 1999) between 1958-76 and 1993-97. The changing ice thickness distribution for the same period has been reported by Yu et al. (2004) and shows substantial losses occurred in ice thicker than 2 m and a significant increase in ice 1-2 m thick. Thickness measurements in the Antarctic are limited to sparse ship observations that have been compiled into a climatology for the period 1980 - 2005 (Worby et al., 2008) and even more sparse measurements from moored instruments (Strass and Fahrbach, 1998; Worby et al., 2001) and in situ drilling (e.g., Wadhams et al., 1987).
Melt of glacial ice, in the form of icebergs or floating ice shelves and glacier tongues, also makes an important contribution to the high latitude freshwater balance. Interest in the basal melt of floating ice has increased with growing evidence that the continental ice sheets can respond rapidly to changes in the floating ice that acts as a “buttress” to inhibit the flow of ice to the sea. For example, the rapid collapse of the Larsen-B ice shelf was followed by a dramatic acceleration of the flow of glaciers feeding the ice shelf (Rignot et al., 2004; Pritchard and Vaughan, 2007). If the ice sheets respond rapidly to changes in the floating ice, present estimates of the rate of future sea level rise may be too conservative (IPCC 4AR). In the Antarctic, warmer ocean temperatures have been linked to an increase in the basal melt rate and the

Figure 6: Minimum (February) and maximum (October) sea ice extent around Antarctica for 2003 from AMSR-E passive microwave data. Courtesy J. Comiso, NASA/Goddard Space Flight Centre, USA.
retreat of grounding lines in Antarctica (Figure 7, Rignot, 2008): a 1°C increase in ocean temperatures increases basal melt rates by ~10 m yr\(^{-1}\) (Rignot and Jacobs, 2002). The dynamic response of the ice sheets will be determined largely by what happens in the ocean, as air temperatures over the Antarctic continent are unlikely to increase enough to cause widespread surface melting, unlike Greenland. Reducing the uncertainty in future estimates of sea level rise requires observations of changes in ocean temperature and circulation and an improved understanding of ocean-ice shelf interaction. Ice shelves are just beginning to be added to climate models, but the ice balance depends strongly on oceanic properties and circulation not well represented in the present state of modelling; hence long-term observations of the ocean near and beneath ice shelves are crucial for model verification and improvement.

Figure 7: Ice velocity of Antarctica colour coded on a logarithmic scale and overlaid on a MODIS mosaic. Circles denote mass loss (red) or gain (blue) of large basins in gigatonnes per year. Drainage basins are black lines extending from the grounding-line flux gates. From Rignot et al., 2008.

### 2.3 Southern Ocean biology and ecology

The Southern Ocean includes some of the most productive and unique marine ecosystems on Earth (Figure 8). These marine ecosystems were heavily exploited in the past. Sustainable management of marine resources requires the ability to distinguish the effects of human exploitation (e.g. harvesting) from the effects of...
climate variability and change (see discussions in Ainley et al., 2005; Nicol et al. 2008). For the Southern Ocean, distinguishing these effects is difficult because of limited observations and understanding of how changes in the physical environment are linked to changes in ecosystem structure or function.

Figure 8: A generalised Southern Ocean food web from the level of krill upwards. Four main size groups of animals (each in a coloured ellipse) are shown. Each animal is shown to scale within each ellipse. Scale bars are present in each ellipse along with a measurement in metres showing how big the bar would be in its natural size. Squid and lantern fish are used for comparing scales between ellipses. Lower orange ellipse: (1) Antarctic krill, (2) lantern fish. Lower middle red ellipse: (2) lantern fish at new scale, (3) Adélie penguin, (4) mackerel icefish, (5) squid. Upper middle green ellipse: (5) squid at new scale, (6) crabeater seal*, (7) white-chinned petrel*, (8) Antarctic fur seal, (9) Patagonian toothfish, (10) leopard seal*, (11) southern elephant seal*, (12) orca* (13) sperm whale*, (14) minke whale*, (15) humpback whale*, (16) southern right whale*, (17) blue whale*. (Source: * indicates illustrations by Brett Jarrett from Shirihai, 200757; Adélie penguin photo – A. Cawthorn; Other photos – A. Constable). From Constable and Doust (2009).

The Southern Ocean ecosystems are structured broadly by latitude, or rather by the quasi-zonal structure of the ACC (e.g. Treguer and Jacques, 1992; Grant et al., 2006; Figure 9) and by depth. In the silica-limited waters north of the Sub-Antarctic Front,
dinoflagellates, small flagellates, coccolithophores and small zooplankton dominate the plankton community. Diatoms become increasingly dominant to the south in the “high nutrient, low chlorophyll (HNLC)” waters of the ACC, where primary production is believed to be limited by lack of iron. The presence of high productivity areas in the wake of island sources of iron, such as South Georgia, Crozet and Kerguelen, supports this notion. The seasonal sea ice zone is by far the most productive region of the Southern Ocean. In particular, it is the main foraging region for a large number of air-breathing predators (seals, whales, penguins and other birds). The main prey is krill, whose life cycle is strongly associated with sea ice.

Figure 9: Bioregionalisation of the Southern Ocean. Grant et al. (2006)

An observed decline in krill in the southwest Atlantic has been linked to a reduction in sea ice (Atkinson et al., 2004) and is likely to result in a shift in the community structure and associated food webs as they move from krill dominated to non-krill
dominated (Figure 10)(Murphy et al. 2007). In the Western Antarctic Peninsula, ice-dependent Antarctic species (Adélie penguin Pygoscelis adeliae and Weddell seal, Leptonychotes weddellii) are being replaced by open water sub-Antarctic species (Gentoo, P. papua and Chinstrap, P. antarctica penguins, and southern fur, Arctocephalus gazella and elephant, Mirounga leonina, seals) (e.g. Fraser et al. 1992, Fraser & Patterson 1997, Ducklow et al. 2007).

*Figure 5.* a) krill-dominated and b) non-krill dominated food web pathways in the Scotia Sea from Murphy et al. (2007b).

The Southern Ocean ecosystem is generally assumed to be controlled by the supply of nutrients and light that are needed for photosynthesis by primary producers. This bottom-up control suggests that the ecosystem will be sensitive to changes in physical forcing that influence the light and nutrient environment experienced by phytoplankton (e.g. upwelling, mixed layer depth, sea ice). Phytoplankton are integral to determining biogeochemical fluxes and the export of carbon and nutrients from the surface ocean to the deep sea. The efficiency of the biological pump depends on a range of environmental and biological factors, which are in turn affected by climate change. Simultaneous measurements of the physical and chemical forcing, environmental structure, and the biological and ecological responses are required to develop the mechanistic understanding that is required to predict the response of ecosystems and carbon export to climate change. In addition, predators exert controls on ecosystem structure and function (top-down control), which contribute to ecosystem variability (Ainley et al., 2005). Top predators are important for preserving ecosystem structure and function (Rooney et al., 2006), transferring energy between the interacting species of the trophic system. To differentiate between bottom-up and top-down controls, integrated observations of physics and biology across multiple trophic levels are required.
Understanding the response of marine biota to climate forcing is important both for climate and for management of marine resources. Phytoplankton mediate the biogeochemical fluxes of carbon, oxygen and nitrate by transferring carbon and nutrients from the surface ocean to the deep sea. The efficiency of the biological pump depends on a number of factors, each of which is potentially influenced by climate forcing. For example, the fraction of primary production that is exported depends on the species and size class of the phytoplankton and zooplankton communities, which in turn can be influenced by changes in the mixed layer depth and the supply of macro- and micro-nutrients, including iron.

The biological pump also influences the Antarctic benthos, which is rich in biomass on the shelves and rich in species in the deep-sea. However, it is still not known to what degree benthic assemblages reflect temporal processes in the water column or are relatively uncoupled from primary productivity, being an adaptive heritage from past climate cycles. These processes determine the final fate of organic carbon in the ocean. The nearshore benthos is influenced strongly by sea ice processes and scour by icebergs can cause local disturbances (Stark et al., 2005; Smith et al., 2006). Some Antarctic benthic organisms are physiologically adapted to these natural changes, but others have limited ability to adapt to variations in the environment, such as warming (Peck et al., 2006). Conservation and management of marine ecosystems requires that the impact of human activities, such as fishing and waste disposal near research stations, can be distinguished from the impact of climate variability and change. Long-term observations of the forcing and response of the system are needed to provide the knowledge of system behaviour needed to inform managers and decision-makers.

Past research programs have provided knowledge of particular aspects of Southern Ocean ecosystems, such as controls on primary production, the biology and ecology of Antarctic krill, copepod life cycles, and predator foraging and behaviour. More recent research programs like the Global Ocean Ecosystem Dynamics (GLOBEC) programme and the Palmer LTER have attempted to integrate ecological and environmental measurements to provide a more complete view of particular ecosystems, for example the physical and biological factors that contribute to the survival and success of krill populations throughout the year (Hofmann et al. 2004, 2008; Schofield et al., 2010). However, we still lack the mechanistic understanding and modelling tools to predict the ecosystem response to climate variability and change. A critical gap is the lack of sustained, integrated observations that span disciplines and a range of time and space scales.

2.4 Observed Changes in the Southern Ocean

Southern Ocean processes influence climate change and variability, biogeochemical cycles, sea-level rise and marine productivity, as described above. Changes in the Southern Ocean would therefore have significant implications. In this section, we summarize some of the evidence for change in the Southern Ocean and consider projections of future change. A more complete overview of changes in Antarctica and the Southern Ocean is provided by Mayewski et al. (2009), Turner et al. (2009a), Convey et al (2009), and Schofield et al. (2010).

Large-scale changes
The most pronounced change in the Southern Ocean is the circumpolar warming of the Southern Ocean in the region of the ACC in recent decades (Figure 11) (Gille 2002; Gille 2008; Levitus et al. 2005), the rate of which exceeds that of the global ocean as a whole. While the warming is surface-intensified, with magnitudes of more than a tenth of a degree C per decade near the surface, the signal extends to more than 1000 m depth. As a result of this deep-reaching temperature change, more heat has been stored in the Southern Ocean as the Earth warms than in any other latitude band.

Figure 11: Profiles of temperature difference between 1990s temperature profiles and hydrographic data sorted by decade. Differences are computed as 1990s reference temperatures minus historic temperature profiles sorted by decade, using the nearest neighbour method discussed in the text. Here results are presented for summer data (November through March), averaged first by latitude band. [Gille, 2008].

Other physical and chemical properties of the Southern Ocean are also changing (Bindoff et al., 2007). Salinity has decreased in the water masses exported from the Southern Ocean in the upper limb of the overturning circulation (Wong et al., 1999; Curry et al., 2003; Aoki et al., 2005a; Durack and Wijffels, 2010). Antarctic Bottom Water (AABW) has become fresher and less dense in the Indian and Pacific sectors since the late 1960s (Jacobs 2004, 2006; Aoki et al., 2005b; Rintoul, 2007). The freshening of AABW reflects at least in part the strong freshening on the Ross Sea shelf, where salinity has reduced by more than 0.2 since 1950, a decline linked to an increase in glacial melt in the southeast Pacific sector (Jacobs et al., 2002; Jacobs and Giulivi, 2010; Figure 12). Oxygen concentrations have reduced below the base of the
mixed layer, south of the ACC (Aoki et al., 2005a). Long time series from the Weddell Sea do not show a similar trend, and act as a reminder that decadal variability can complicate the interpretation of short and incomplete records.

Figure 12: Freshening of Ross Sea shelf waters between 1960 and 2008. [Jacobs and Giulivi (2010).]

Many of the large-scale and regional changes in the physics and chemistry of the Southern Ocean have been linked to changes in wind forcing, in particular the intensification and southward contraction of the circumpolar westerly winds associated with a positive trend of the Southern Annular Mode (SAM, (Thompson et al. 2000)). Mechanisms linking stronger winds to circumpolar ocean warming include a southward shift in the location of the ACC, increased heat flux into the ocean, and increased mesoscale eddy activity (Fyfe 2006; Fyfe et al. 2007; Gille 2008; Hogg et al. 2008; Meredith and Hogg 2006). The trend in the SAM has been attributed to human activities, including greenhouse gas emission and ozone depletion (e.g. Marshall 2003; Thompson and Solomon 2002; Fyfe et al., 2007). The overall warming of the surface ocean, increase in precipitation and ice melt, and changes in sea ice extent and thickness have also likely contributed to the observed changes. To make further progress in understanding how climate change and variability are driving change in the Southern Ocean, sustained observations of the ocean stratification and circulation are needed.

There is fragmentary evidence of changes in the Southern Ocean ecosystem. The range of the coccolithophorid Emiliania huxleyii has now extended south into the sea-
ice zone within the last decade, possibly in response to global warming (Cubillos et al. 2007; Mohana et al. 2008). Changes in seabird and krill abundance have been noted in particular areas (e.g. Croxall et al. 2002, Atkinson et al. 2004). It is well established that the effect of environmental variability propagates throughout the marine food web with significant impacts (Croxall 1992, Waluda et al. 1999, Forcada et al. 2005, Barbraud and Weimerskirch 2001; Barbraud and Weimerskirch 2006, Jenouvrier et al. 2003; Jenouvrier et al. 2005; Jenouvrier et al. 2006; Weimerskirch et al. 2003) Leaper et al. 2006, Clarke et al. 2007, Barnes & Peck 2008, Murphy et al. 2007, Trathan et al. 2007) and for some systems these changes can be profound and long lasting (e.g. Costa et al. 1989). A number of impressive biological time series exist, such as the Emperor penguin time series at Dumont d’Urville that starts in 1952 (Figure 13, Barbraud and Weimerskirch 2001) and on the western Antarctic peninsula (Figure 14, McClintock, 2008). However, there are usually few observations of change in the physical environment near these colonies, thus we are not currently able to relate changes in predator populations to changes in environmental forcing. A SOOS would provide the oceanographic context needed to better understand the environmental factors responsible for such demographic changes.

**Figure 13.** From Barbraud and Weimerskirch (2001).
Figure 14: Changes in the number of breeding pairs in penguin rookeries near Palmer station, western Antarctic Peninsula. As the amount of sea ice declines, ice-dependent Adélie penguins are declining and being replaced by sub-polar Gentoo penguins. McClintock et al. (2008).

Sea Ice Variability

In contrast to the Arctic, where large decreases in sea ice extent and thickness have occurred, trends in the circumpolar extent of Antarctic sea ice are weak but generally positive (Stammerjohn and Smith, 1997; Watkins and Simmonds, 2000; Yuan and Martinson, 2000; Zwally et al., 2002; Parkinson, 2004; Comiso and Nishio, 2008). Regional changes in sea ice extent and the seasonality of advance and retreat have been recorded in the Pacific sector (Figure 15, Stammerjohn et al., 2008), with substantial impacts on the marine ecosystem (Wilson et al., 2001). Direct observations of sea ice extent are limited to the satellite era. Proxies for sea ice extent based on historical whaling (de la Mare, 1997) and ice core records (Curran et al., 2003) suggest a decline in sea ice extent occurred between the 1950s and 1970s, but these results remain somewhat controversial (e.g. Ackley et al., 2003).
information on changes in sea ice extent in Antarctica are limited, even less is known about changes in sea ice thickness (and therefore volume). In this regard, it is notable that climate models suggest that Arctic sea ice thickness will change more rapidly than extent, with total volume projected to decrease at approximately double the rate of ice thickness (Gregory et al., 2002).

Figure 15: The 1979–2004 trend (days/year) in ice season duration. The black/white contours delimit the 0.01/0.10 significance levels. Within the sea ice zone, gray shading signifies near zero trend. [Stammerjohn et al., 2008]

Carbon Dioxide Uptake and Ocean Acidity

Carbon uptake by the Southern Ocean has acted to reduce atmospheric CO₂ concentrations and thereby to slow the rate of climate change. As a result of the increased burden of CO₂, the surface waters of the Southern Ocean have become more acidic and surface pH has decreased by around 0.1. Ocean acidification is expected to affect a wide range of calcifying organisms, with the impacts felt first in the cold waters of the Southern Ocean due to the temperature dependence of aragonite solubility (Orr et al 2005, Royal Society Report 2005, Hunt et al. 2008, McClintock et al., 2009; Fabry et al., 2009). However, the response to ocean acidification is poorly understood, varies with species, and the response of the ecosystem as a whole almost entirely unknown.
Studies based on inversion of atmospheric carbon dioxide data (Le Quéré et al. 2007) and coarse resolution ocean models (Lovenduski et al., 2007, 2008; Zickfeld et al., 2007; Verdy et al., 2007; Lenton and Matear, 2007) conclude that the positive trend in the SAM has caused a reduction in the ability of the Southern Ocean to absorb CO$_2$. 

In these studies, the poleward shift and intensification of the westerly winds drives enhanced equatorward Ekman transport and therefore enhanced upwelling of deep water rich in dissolved inorganic carbon (DIC) (e.g. Hall and Visbeck, 2002). The increased supply of deep water causes more outgassing of natural carbon dioxide from the deep ocean, decreasing the effectiveness of the Southern Ocean sink of CO$_2$. Warmer surface waters will also dissolve less atmospheric CO$_2$ than will colder waters. The link between increases in the wind field, isopycnal tilt and upwelling in the presence of eddies is not direct, as discussed previously, however changes in DIC and $^{14}$C in high latitude surface waters are consistent with an increase in upwelling (Metzl et al., 2009). The issue is presently a topic of vigorous debate. Resolving the issue is critical to assess the sensitivity of the Southern Ocean carbon sink to climate change and the potential for feedbacks. Observations of the evolving ocean inventory of carbon are needed, as well as further model studies.

Regional Variability

Rapid change has been observed in particular regions of the Southern Ocean. The most notable example of this is the western side of the Antarctic Peninsula, where the atmosphere has warmed more rapidly than anywhere else in the southern hemisphere in recent decades. Here, a wintertime warming in excess of 5ºC over 50 years has been observed (King et al. 2004; Vaughan et al. 2003), with a smaller rate of warming seen in summer. These atmospheric changes are strongly associated with a marked retreat of sea ice extent, warming of the upper ocean and more rapid melt of ice shelves (Meredith and King 2005).

Changes in sea ice and ocean properties at the western Antarctica Peninsula have had profound ecological consequences. According to Ducklow et al. (2007), “the western Antarctic Peninsula is experiencing the most rapid warming of any marine ecosystem on the planet.” Marine species in this region are typically well adapted to cope with low temperatures, but poorly adapted to cope with changes in temperature. Population and species level losses of some marine organisms can be expected at the western Peninsula in response to a change in ocean temperature of 2ºC (Peck et al. 2004). The observed warming is over half this amount already, in just a few decades, raising the possibility of serious disruption to the marine ecosystem here in the near future. Indeed, some significant shifts in different trophic levels have already been observed in response to the warming (e.g. Ducklow, 2008, McClintock, 2008, and related papers). The region is also a key breeding and nursery ground for Antarctic krill, an important species in the Southern Ocean food web. Atkinson et al. (2004) suggest krill numbers in this region have strongly declined as a result of ocean warming and loss of sea ice. The rapid pace of environmental change, a long record of interdisciplinary observations, and relatively easy logistics make the western Antarctic Peninsula an excellent laboratory for studying the effects of climate change and variability on ecosystem function.
Figure 16 Upper left: surface atmospheric temperature change at Faraday and Rothera stations on the western Antarctic Peninsula. Temperature change here has been the most rapid in the southern hemisphere, with most of the warming concentrated in the winter months. Upper right: coupled to the atmospheric warming (and retreat of sea ice), a strong warming of the upper ocean has occurred in recent decades, which acts as a positive feedback on the climate change, and which has profound implications for the local and regional ecosystems (Meredith and King, 2005). Lower: the climate change at the Peninsula has also profoundly affected the glacial ice field, with the majority of marine-terminating glaciers in retreat, and with retreat rates accelerating in recent years (Cook et al., 2005).

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 IPCC AR4 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., 2005).
The weighted mean model results predict further warming of the air over the Southern Ocean over the next century (Figure 17a), a 25% reduction in sea ice production, and a continued increase in strength of the westerly winds.

Averaging 19 IPCC AR4 model outputs for sea surface temperatures similarly provides a reasonable estimate of future change (Fig 17b, from Wang and Meredith, 2008, reproduced in Turner et al 2009a). The SST changes are smaller than those observed in surface air temperature (Fig 17a) because the heat capacity of the ocean is much larger than that of the atmosphere. Both the air temperatures and the ocean temperatures will affect the sea ice. Close to the coast warming is likely to reach 0.5° to 1.0°C, perhaps rising to 1.25°C in the Amundsen Sea, in summer (Fig 17b). Winter temperatures are likely to be much as they are today, perhaps up to 0.5°C warmer. Bottom water temperatures are likely to change in much the same way over the continental shelf (Turner et al., 2009a).

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 (cf McClintock et al., 2008). With regard to acidification in the Southern Ocean, whilst there is considerable uncertainty surrounding its speed of progression, climate models using a business-as-usual scenario for CO2 emissions (IS92a) predict that the surface waters will become undersaturated with respect to aragonite by 2050, extending through the entire Southern Ocean by 2100 (Orr et al., 2005). As noted by McNeil and Matear (2008), when the seasonality of the carbonate ion concentration is taken into account, the saturation threshold is crossed several decades earlier.

Figure 17a. Predicted trends in surface temperatures over the next 100 years from a weighted average of the IPCC AR4 coupled models. Note the widespread warming of the air over the Southern Ocean, which is strongest in the Weddell and Ross Seas.
owing to the retreat of the sea ice there and the consequent change in albedo. From Bracegirdle et al. (2008).

Figure 17b. Sea surface temperature change between 2000 and 2100 in summer (a) and winter (b). From Wang and Meredith (2008) and Turner et al., 2009a.)
2.5 Informing Decision-makers

In addition to climate effects, human pressures on the Southern Ocean are increasing and will likely continue to do so. Further exploitation of marine resources is likely as more traditional sources of protein decline or increase in cost. Antarctic tourism is a rapidly growing industry and the effects of this industry on the environment requires monitoring and regulation (e.g. Enzenbacher, 1992; Fraser and Patterson, 1997; Frenot et al., 2005). Increased use of the Southern Ocean will increase the need for an effective search and rescue capability, guided by the best available information on ocean conditions. As the number of vessels using the Southern Ocean increases, the risk of an oil spill or other contaminant release also increases, further underscoring the need for timely and accurate information on ocean currents. Geo-engineering solutions (e.g. iron fertilisation of the Southern Ocean; see Watson et al. (2008) and accompanying articles) are being considered as mitigation strategies for CO₂ removal. Increased use of the Southern Ocean will result in greater demand for knowledge to manage resources and to inform decisions by policy makers, industry and the community.

3. Design of a Southern Ocean Observing System

3.1 Key science challenges and the need for sustained observations

Based on the rationale above, six overarching Southern Ocean science challenges can be identified, each of which requires sustained observations to be addressed.

1. The role of the Southern Ocean in the global heat and freshwater balance

Changes in the polar water cycle will have global impacts due to the sensitivity of the overturning circulation and heat transport to changes in freshwater input (Broecker, 1997, Clark et al., 2002). Observations suggest changes in the global water cycle may already be apparent in changes in ocean stratification (e.g. Durack and Wijffels, 2010). The stratification of the Southern Ocean is delicately poised and particularly sensitive to changes in the freshwater balance (Gordon, 1991). Substantial uncertainty remains with regard to the high-latitude contributions to the global water cycle, the sensitivity of the water cycle to climate change and variability, and the impact of changes in the high latitude water cycle on the rest of the globe.

Freshwater fluxes from melting sea ice, sub-ice shelf melting and precipitation are of the same order of magnitude in the Southern Ocean (Hellmer and Timmerman, 2004), and all three components need to be measured. Variables that need to be measured include atmospheric circulation (winds, storms, evaporation, precipitation, moisture flux); the horizontal and vertical circulation of the ocean, including exchange between high and low latitudes and the circulation beneath the sea ice, through the annual cycle; sea ice extent, thickness and distribution; and the contribution of glacial ice (ice shelf melt and iceberg production). New satellites promise synoptic observations of aspects of the freshwater balance, including snow and ice thickness, that can not be
measured at high spatial or temporal resolution using conventional means, but these
new sensors are in critical need of data sets for validation.

2. The stability of the Southern Ocean overturning circulation
Climate models suggest the overturning circulation in both hemispheres is sensitive to
climate change (e.g. IPCC, 2007). Enhanced greenhouse warming is expected to
drive a more vigorous hydrological cycle, with increased precipitation at high
latitudes and increased evaporation at low latitudes. The resulting reduction in
surface salinity reduces the formation of dense water at high northern and southern
latitudes. Paleoclimate records demonstrate that changes in the overturning circulation
have been associated with large and abrupt climate changes in the past (e.g. Clark et
al., 2002). Changes in strength of the Southern Ocean overturning circulation have
been linked to changes in the ocean uptake and release of carbon dioxide, both in the
present day ocean and in association with glacial – interglacial cycles. Sustained
observations of temperature, salinity, stratification and ventilation are needed to detect
changes in the overturning in response to changes in atmospheric forcing. The
observations need to span the entire water column and include carbon, oxygen and
other tracers.

3. The role of the ocean in the stability of the Antarctic ice sheet and its future
correlation to sea-level rise
The largest uncertainty in assessments of future sea-level rise concerns the polar ice
sheets (IPCC, 2007). Recent evidence that the dynamic response of ice sheets to
changes in forcing can be much more rapid than previously believed has added
urgency to this issue. For most of Antarctica (i.e. outside of the Antarctic Peninsula),
air temperatures are projected to remain below the freezing point of ice for centuries.
Basal melting of ice by warm ocean waters will therefore play a primary role in
determining the future behaviour of ice sheets and glaciers buttressed by floating ice
shelves (Rignot, 2008). Sustained observations of ocean temperatures near the ice
shelves are needed to assess basal melt rates, and salinity and stable isotope
measurements are needed to detect the input of meltwater and its impact on ocean
stratification.

4. The future and consequences of Southern Ocean carbon uptake
Climate models suggest the Southern Ocean uptake of carbon dioxide will decrease as
a result of changes in circulation and stratification caused by enhanced greenhouse
warming, providing another potential positive feedback for climate change (Sarmiento
et al., 1998). As discussed above, recent studies have highlighted the sensitivity of
the global carbon cycle to changes in the Southern Ocean. The uptake of carbon by
the ocean results in acidification and changes in carbonate chemistry that will likely
have significant but largely unknown consequences for life in the ocean. Full water
column sections of carbon, oxygen, nutrients and physical variables are needed to
track the evolving inventory of anthropogenic CO₂ and other properties related to the
carbon and biogeochemical cycles. Additional surface observations are needed to
complement the water column measurements to improve the spatial coverage.

5. The future of Antarctic sea ice
Sea ice influences climate through its contribution to the freshwater balance, water
mass formation, albedo, and modulation of air-sea exchange of heat and gases. Sea
ice also provides important habitat for Antarctic organisms including algae, krill,
penguins and seals, and influences productivity in the ocean by supplying iron and
meltwater to influence mixed layer depth and the light environment. While there has
been little change in the total extent of Antarctic sea ice in recent decades, there have
been strong regional trends in ice extent and duration, and models predict a decline in
sea ice extent and volume in the future. A sustained observing system for Antarctic
sea ice will rely heavily on remote sensing from satellites and aircraft, but these
methods are critically dependent on in situ observations for validation and algorithm
development.

6. Impacts of global change on Southern Ocean ecosystems
A better understanding of the impact of global change on Southern Ocean ecosystems
(Clarke et al 2007, Barnes & Peck 2008) is essential to guide conservation and marine
resource management decisions. Our ability to predict changes in marine resources
and biodiversity, to assess ecosystem resilience, and determine feedbacks between
food webs and biogeochemical cycling depends on sustained, integrated observations
of key physical, chemical and biological parameters. High priority variables to
measure include: primary production, distribution and abundance of key species
and/or functional groups, benthic community structure, top predator abundance,
distribution (both geographical and in relation to physical structure) and diet.
Simultaneous measurements of the physical and chemical environment are needed,
including pH, temperature, salinity, mixed layer depth, wind speed and direction,
meteorological conditions, sea ice conditions, currents, and nutrients. Studies of
 predator species can reveal “hot spots” of foraging activity (or Areas of Ecological
Significance (AES)) and changes in foraging and demographic parameters that reflect
changes in lower trophic levels (e.g. zooplankton, fish and squid) that are difficult to
observe directly.

3.2 Building blocks of an integrated Southern Ocean Observing System
Having defined the key overarching science challenges, variables that needed to be
observed on a sustained basis were identified (Table 1). For each variable, multiple
platforms or techniques could be used to deliver the sustained observations (Table 2).
Each of the challenges requires a different mix of observations, but there is substantial
overlap as well. For example, each of the themes depends on sustained observations
of the stratification of the upper ocean (i.e. temperature and salinity as a function of
space and time). A number of platforms and techniques can be used to measure the
upper ocean stratification, including Argo floats, repeat hydrographic sections,
underway measurements, animal-borne sensors, gliders, and ice-tethered platforms.
Similarly, improved understanding of the response of marine ecosystems to
environmental change requires sustained observations of a wide range of physical,
chemical and biological variables. In the following, we discuss each of the “building
blocks” of an integrated observing system in turn, including how the measurement
contributes to SOOS, what sampling is needed, present status and gaps, and
recommendations.
Table 1: A summary of the variables for which sustained measurements are required to address the key scientific challenges. The entries in the list of variables are shorthand for a number of related variables (e.g. “carbon” refers to pCO₂, DIC, POC, PIC, alkalinity).

<table>
<thead>
<tr>
<th>Variables required to be measured</th>
<th>Key science challenges</th>
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<td>Freshwater balance</td>
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<td>mammals</td>
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Table 2: The combination of platforms and techniques needed to provide sustained observations of each of the fields identified in Table 1.

<table>
<thead>
<tr>
<th>Platforms and techniques</th>
<th>repeat hydrography</th>
<th>Argo</th>
<th>underway sampling</th>
<th>moorings</th>
<th>animal sensors</th>
<th>sighting surveys &amp; cameras</th>
<th>C-R</th>
<th>gliders/AUV</th>
<th>ROV &amp; imaging methods</th>
<th>satellite</th>
<th>ice stations</th>
<th>acoustics</th>
<th>trawls/nets</th>
<th>bottom landers/corers</th>
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<td>stratification (T(z),S(z))</td>
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Access to historical data

Given the lack of observations from the Southern Ocean, it is particularly critical that historical data are accessible and their quality assessed. Significant efforts have been made to do this for physical oceanographic data and to a lesser extent with sea ice, chemical and biological data sets. However, much data still resides with the originating investigators, are in formats and media that are not easily accessible, require standardisation to reduce biases, or may have large uncertainties that need to be quantified. Upper trophic level and hydroacoustic data sets are examples of the latter. The compilation of zooplankton net tow data sets (KRILLBASE, Atkinson et al. 2009) provides an example of the value of compiling historical biological data sets in a consistent manner and making the resulting data base easily accessible.

Recommendations: The biogeochemical and ecological data sets (e.g. animal tracking) need to be integrated with historical environmental data (e.g. hydrographic climatologies). Many of these data sets are available via a range of data management
systems. A common data portal is needed to provide access to multi-disciplinary data sets (e.g. SCAR-MarBIN which provides comprehensive biodiversity data). The SOOS needs to ensure that both past and future data sets are accessible and comparable.

**Repeat hydrography**

Repeat hydrographic sections provide the backbone of a multidisciplinary SOOS. Repeat hydrography provides water samples for analysis of properties for which in situ sensors do not exist, the highest precision measurements for analysis of change and for calibration of other sensors, accurate baroclinic transport estimates, a platform for a wide range of ancillary measurements and the only means of sampling the full ocean depth. CLIVAR (the CLimate VARiability and Predictability project of the World Climate Research Programme) and the global carbon survey have re-occupied many of the sections occupied during the World Ocean Circulation Experiment (WOCE). During the International Polar Year (IPY), a near-synoptic circumpolar snapshot of the Southern Ocean was obtained.

**Recommendations:** Figure 18 shows the WOCE/CLIVAR repeat hydrographic lines to be repeated as part of SOOS. This plan is consistent with the programme of global repeat hydrographic sections (Hood et al., 2010). To document the changing inventory of heat, freshwater and carbon dioxide, the sections need to be repeated on a 5 to 7 year time-scale. Annual occupations of the Drake Passage line are needed. The transects should include measurements of physical (e.g. CTD (Conductivity-Temperature-Depth), O$_2$, Shipboard and Lowered Acoustic Doppler Current Profilers (SADCP/LADCP), tracers, oxygen-18, biogeochemistry (e.g. nutrients, trace elements and micronutrients, carbon, isotopic measurements of export flux, dimethyl sulphide (DMS)), and biology (e.g. primary production, pigments, bio-optics, fast repetition rate fluorometer, molecular diversity, biomarkers, targeted trawls, net tows, acoustic).

The sections should extend from north of the ACC to the Antarctic coast, including the sea ice zone and the continental slope and shelf (therefore the high latitude sections need to be sampled using ice-capable vessels). The programme of CTD sections across the Antarctic slope and shelf by research and supply vessels travelling to and from Antarctic bases initiated by the SASSI (Synoptic Antarctic Shelf Slope Interactions) project for IPY should be continued and placed on a more operational basis (Figure 19).
Figure 18: Repeat hydrographic sections to be occupied by SOOS. Symbols indicate the WOCE/CLIVAR designations for each line.

Figure 19: Hydrographic sections (lines) and moorings (circles) occupied as contributions to the IPY SASSI program. Many of these lines are near Antarctic bases and could be repeated more regularly as a contribution to the SOOS.
Enhanced Southern Ocean Argo

All of the key science challenges require sustained, broad-scale measurements of the ocean state, measurements that can only be obtained using autonomous platforms such as profiling floats. A sustained commitment to maintenance of a profiling float array in the Southern Ocean is critical. Argo has made a particularly significant contribution to observations of remote areas like the Southern Ocean; already there are more profiles collected from Argo floats than from the entire history of ship-based oceanography in this region. As an example, Figure 20 shows the location of profiles collected south of 30°S during the 24 month IPY period. Floats with oxygen sensors are beginning to be deployed in the Southern Ocean; we can anticipate that with time the capacity to measure additional variables from floats will increase. The float array needs to extend to seasonally ice-covered seas, through the use of ice-capable floats and acoustic tracking of floats.

Recommendations: The first priority is to maintain the Argo network at the nominal Argo density (1 float per 3 degree longitude x 3 degree latitude square, or roughly 970 floats south of 40°S). As seen in Figure 21, there is still some way to go to reach this level of coverage. The extension of the system to sample under sea ice is also important, as some of the most important changes are occurring near the ice shelves and within the sea ice zone. Floats capable of deeper profiling would be of particular value in the Southern Ocean, where significant changes have been observed below 2000 m. Oxygen sensors will provide useful information on ventilation processes and the carbon cycle. Sensors to measure a wider range of biological and chemical parameters (e.g. bio-optics) are needed to relate variations in the physical environment to biogeochemistry and ecosystem processes.

Figure 20: The location of more than 60,000 Argo profiles of temperature and salinity collected during the 24 months of the IPY. Courtesy of Mathieu Balbeoch, JCOMMOPS.
Figure 21: The status of the Argo array in the Southern Ocean, as of May 2010.

Despite the progress in recent years, large regions of the high latitude Southern Ocean remain poorly observed. Courtesy of Mathieu Balbeoch, JCOMMOPS.

Underway sampling from ships

The full hydrographic sections need to be complemented by more frequent underway sampling transects, to reduce aliasing of signals with time-scales shorter than the 5-7 year repeat cycle of the repeat hydrography (the issue of seasonal aliasing remains, as most underway measurements are made between October and March). While underway measurements are generally limited to the surface layer, use of ships of opportunity provide a cost-effective means of collecting a wide range of physical, biogeochemical and biological observations: temperature, salinity, velocity (from ADCP), pCO$_2$, pH, nutrients, fast repetition rate fluorometry (FRRF), plankton (from CPR), phytoplankton pigments, surface meteorology and expendable Bathythermographs and CTDs (XBTs/XCTDs) to provide measurements of upper ocean thermal structure along the ship track, including mixed layer depth (the Japanese Antarctic Research Expeditions (JARE), the French Ocean Indien Service d’Observation (OISO), and Australia-France Astrolabe programs provide an example of what is required). However, few ships at present measure this complete suite of variables. Aerosol sampling from ships is needed to quantify the aeolian input of iron and other trace elements to the Southern Ocean.

Recommendations: The present underway sampling system is shown in Figure 22. There is a need to maintain and expand the fleet of ships making routine measurements of the Southern Ocean and to increase the number of variables measured on each line. Antarctic resupply ships and tourist vessels remain underexploited. Autonomous sampling devices (e.g. Ferry Box) should be installed on additional vessels. Upgrading the surface meteorology measurements made on these vessels is a high priority and will help improve the poorly constrained air-sea flux estimates over the Southern Ocean. A comprehensive review of requirements for monitoring changes to the global ocean-atmosphere carbon flux can be found in Schuster et al (XXX).
Acidification detection system: As the ocean absorbs CO₂ and becomes more acidic, the saturation threshold for aragonite will be crossed first in the cold waters of the polar regions. Sustained observations of both ocean chemistry and the effect of changing ocean chemistry on organisms are required. Feely et al. (2010) outline the requirements for sustained observations to track ocean acidification and its impacts. The repeat hydrography, underway observations, and Argo floats armed with chemical sensors discussed above will provide the primary means of measuring DIC, alkalinity, pCO₂ and pH. Time series measurements from moored sensors should be deployed in key regions.

Recommendations: Establish network and protocols for sampling of calcareous plankton and benthic organisms, to detect effects of changes in acidification and saturation state of the Southern Ocean. This will need to be complemented by simultaneous measurements of pCO₂, alkalinity and pH to determine the saturation state of calcite and aragonite and the depth of the saturation horizon. For critical regions such as the high latitudes and coastal areas, abundances and distributions of key taxa should be tracked with sufficient precision and resolution to detect possible shifts corresponding to observed changes in the geochemical parameters. There is an immediate need for baseline data on calcifying organisms in regions that are projected to become undersaturated with respect to aragonite in the coming decades, such as the Southern Ocean. Rapid, cost-effective technologies for quantifying abundances of targeted organisms should be a central component of any integrated ocean acidification observation network.

Continuous monitoring of key passages and locations
Several key passages and boundary currents in the Southern Ocean are high priorities for sustained observations because of their role in the global-scale ocean circulation (Figure 23). The presence of energetic variability at a range of periods means that
continuous observations from moored arrays are needed in passages and boundary
currents to provide year-round sampling and to help de-alias infrequent repeat
hydrography. Tide gauges and bottom pressure recorders have been shown to provide
a cost effective means of monitoring the variability in the transport of the ACC on
timescales from weeks and months (Hughes et al., 2003) to years (Meredith et al.,
2004). At longer timescales, tide gauge data from the Antarctic coast and Southern
Ocean islands form a critical part of the global sea-level observing system.

Recommendations: High priority regions for sustained moored measurements include
Drake Passage, along the prime meridian (e.g. the Weddell Sea Convection Control
(WECON) and Goodhope programs south of Africa) and the locations of deep
outflows (e.g. the western Weddell Sea and the deep boundary current on the eastern
flank of the Kerguelen Plateau, the Princess Elizabeth trough, and the Ross Sea and
Adélie Land bottom water outflows). The existing array of tide gauges and bottom
pressure sensors needs to be maintained and extended to the western hemisphere. The
Antarctic Slope Front and Antarctic Coastal Current make a significant contribution
to inter-basin exchange and therefore need to be measured on a sustained basis.
Likewise, the Agulhas and Tasmanian limbs of the southern hemisphere “supergyre”
(Speich et al., 2002) provide important inter-basin connections with consequences for
climate and therefore need to be monitored.

Figure 23: Map of proposed moored arrays (red circles) to sample the primary
Antarctic Bottom Water formation and export sites, as part of a coordinated global
array to measure the deep limb of the global overturning circulation. Each of these
sites has been occupied in recent years. The map shows the inventory of
chlorofluorocarbon 11 (CFC-11) in the density layer corresponding to AABW (from
Orsi et al., 1999).
Animal-borne sensors

Oceanographic sensors deployed on birds and mammals can make a significant contribution to a SOOS in two ways: by relating predator movements and behaviour to fine-scale ocean structure (Biuw et al. 2007; Burns et al. 2004), and by providing profiles of temperature and salinity from regions of the Southern Ocean that are difficult to sample by other means (e.g. beneath the winter sea ice; Charrassin et al. 2008, Figure 24; Costa et al. 2008; Nichols et al., 2008). The animals also often provide high resolution transects across the Southern ocean frontal zones (e.g. Boehme et al., 2008). Because the tags can also monitor changes in body condition of the animals (e.g. Biuw et al. 2007), they can provide a link to changes in the animal’s resource acquisition and impacts of observed and modelled oceanographic change on populations of top predators.

Recommendations: Maintain the network of seal tag deployments established during IPY (Figure 25), to provide information on seal foraging behaviour and its relationship to environmental variability and on the in situ oceanographic conditions in the open ocean and in the sea ice zone in winter (see Boehme et al., 2008, Nicholls et al., 2008). (See also the section on “Ecological monitoring via top predators” below.)

**Table 3. Summary of the possible species, age/sex classes and locations for CTD SLDR deployments as part of SOOS.** These have been chosen to provide optimal spatial and temporal coverage, guided by experience during the IPY and earlier tagging programs.

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<th>Southern Elephant seals</th>
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**Figure 24.** Temperature field at 500 m during 2004–2005 from the Coriolis database and from the merged Coriolis and elephant seal databases. Mean front positions during the same period derived from Coriolis (A) or Coriolis and seal temperature field at 500m (B) (thick lines), and from altimetry (thin lines in A and B). Plotted fronts are the southern boundary of the ACC (Bdy), southern branch of the southern ACC front, and central branches of the Polar Front (PF) and the Subantarctic Front (SAF). Note the increased level of detail in the combined plots. (From Charrassin et al. 2008; front names follow Orsi et al., 1999 and Sokolov and Rintoul, 2007).

**Figure 25.** Surface temperature and location of 67,904 CTD profiles collected by seals during the Marine Mammals Exploring the Oceans Pole to Pole (MEOP) program during IPY.

**Sea ice observations**

Measurements of both the extent (period, seasonality) and thickness (volume) of sea ice are needed to understand the role of Antarctica in the climate system. A variety of satellite instruments provide continuous, circumpolar observations of sea ice extent, with varying spatial resolution. Measuring sea ice volume, however, remains a significant challenge. Recent advances in radar and laser altimetry may be the key to providing information on sea ice thickness, however Antarctic sea ice poses a number of challenges that have yet to be overcome. In particular, most Antarctic sea ice is
relatively thin and therefore has a relatively small freeboard measurement, making altimetry methods more difficult. The widespread formation of snow ice through surface flooding and refreezing also complicates altimetry measurements.

**Recommendations:** A variety of tools will be needed to meet the challenge of providing sustained measurements of sea ice thickness and extent: AUVs and fixed-point moorings with ice-profiling sonars, acoustically-tracked floats with ice thickness sensors, ship-board observations including ice drift stations, remote sensing and data- assimilating models. The most critical observations to make are those that can be used to validate remote sensing measurements, as satellites provide the only means to sample sea ice over broad areas. A circumpolar “snapshot” of Antarctic sea ice thickness fields should be obtained as soon as possible to provide a baseline against which future change can be assessed. Regional-scale ice and snow thickness data should be obtained using a range of techniques including AUVs which measure ice draft from an upward looking sonar, and airborne techniques such as laser and radar altimetry and electromagnetic induction. Ideally “ice-edge to coast” transects in different seasons, and targeting regions with varying conditions, would provide the necessary information on regional and temporal changes in conditions as assessed by the Antarctic Sea Ice Processes and Climate (ASPeCt) programme (Figure 26, Worby et al., 2008). In situ measurements of ice and snow thickness properties, particularly density, are also essential for interpreting these data. The AUV programme will also collect oceanographic and biological data as well as ice thickness (e.g. salinity, temperature, currents, sonar for biology). Time series of ice thickness from fixed-point moorings are needed to complement the spatial sampling from the AUV programme as well as more systematic collection of Antarctic sea ice thickness measurements, including ASPeCt observations and IceCam, from additional research, supply and tourist vessels. Recovery of historical Antarctic sea ice thickness data from individual investigators is essential for establishing a longer baseline of observations and a data portal has been established at the Australian Antarctic Data Centre for this purpose and for archiving all other data on Antarctic sea ice properties ((http://data.aad.gov.au/aadc/seaice).

**Figure 26:** Annual mean sea ice thickness derived from ASPeCt ship observations (Worby et al., 2008). Units are metres.
Surface drifters: Additional surface drifters are required to provide better coverage of sea-level pressure (SLP) and sea surface temperature (SST) for input to numerical weather prediction (NWP) models, and hence improve the quality of the air-sea fluxes provided by the models; to provide SST measurements for removal of biases in satellite products; and to measure velocity and temperature in the ocean mixed layer and so provide insight into the surface ocean heat budget (e.g. Moisan and Niiler, 1998) and circulation (e.g. Niiler and Maximenko, 2003).

Recommendations: Maintain surface drifter sampling in the Southern Ocean to at least the density of the global requirement of 1250 drifters worldwide or at least 2-3 drifters per 10 degree box (Zhang et al., 2006) (Figure 27).

Figure 27: Status of the global surface drifter array in May 2010 (top) and the equivalent buoy density (EBD) for January–March 2010 produced by NOAA. Yellow and red squares indicate regions where observations from ships and drifters fall below the required density. Note the lack of drifter data close to the Antarctic coast (but see Figure 28).
Enhanced sea ice drifter array

Our understanding of the intense and highly variable ocean-ice-atmosphere interactions taking place in the Antarctic sea ice zone is poor due to the lack of observations. Numerical weather predictions south of 60°S suffer from a lack of surface pressure observations from the Sea Ice Zone (SIZ); as a consequence, flux products derived from reanalyses of the numerical weather prediction (NWP) models are also uncertain. An example of the coverage of drifters deployed by the International Program for Antarctic Buoys is shown in Figure 28. At present, few ice drifters are being deployed.

Recommendations: The target is for circum-Antarctic buoys spaced every 500 to 1000 km in the zonal and meridional directions, consistent with the typical length scale of variations in sea-level pressure and air temperature. A smaller number of “mass balance buoys” is needed to measure ice and snow thickness, providing crucial ground-truth for new satellite sensors. Dense clusters of buoys need to be deployed in some locations for detailed studies of ice dynamics and deformation. Further work is required to define these requirements.

Figure 28: The complete record of Ice drifter trajectories from the International Program for Antarctic Buoys (IPAB), compiled over a number of years. The relatively dense sampling in the Weddell Sea and off East Antarctica indicates the efforts of the German and Australian sea ice programs in recent decades. The buoy drifts illustrate the circulation of the subpolar gyres and the overall divergent drift to the north, indicating that repeated seeding of floats is required to maintain coverage.
Ocean circulation under sea ice

With few exceptions (e.g. Nichols et al., 2008) the ocean circulation and structure beneath the Antarctic sea ice remains largely unknown. New technologies now allow ocean currents and stratification beneath the sea ice to be observed for the first time. The strategy for sub-ice observations in the Antarctic will rely heavily on technology being developed for the Arctic: acoustic tracking of floats and gliders, acoustic communication links, ice-tethered profilers and listening/telemetry/sound source stations, ice thickness measurements from floats, animal-borne sensors, and upward-looking sonar and current meter moorings. However, the challenges are significantly greater in the Antarctic. The area of the Antarctic sea ice pack is much greater than that of the Arctic; many areas are more remote; and the divergence and strong seasonality of the sea ice pack makes ice-tethered stations more difficult to maintain. Therefore, in the Antarctic efforts will need to focus on one or more “well-measured” regions or basins.

Recommendations: Maintain the array of sound sources and acoustically-tracked floats established in the Weddell Gyre during the IPY (Figure 29). Establish a similar system in the Ross Sea Gyre. Expand the deployment of ice-capable floats (e.g. the Polar Profiler) and Ice Tethered Profilers in the Antarctic sea ice zone. Maintain and enhance the deployment of sensors on animals that forage in the sea ice zone.
Figure 29: Array of sound sources being used to track profiling floats in the Weddell Sea during the IPY (upper plot) and temperature and velocity field derived from profiling float data (E. Farhbach, pers. comm.). These measurements need to be sustained to extend the global array of profiling floats to the ocean beneath the sea ice. A similar array is needed to sample the Ross gyre.

Sea level: Tide gauges on the Antarctic continent contribute to monitoring of the Antarctic Circumpolar Current (e.g. Hughes et al., 2003; Meredith et al., 2004) as well as sea level, by contributing to the Global Sea Level Observing System (GLOSS, Figure 30). Three stations on the Antarctic Continent and several from islands and extreme southern points of continents are currently contributing in near-real time to the system in the Southern Ocean.

Recommendations: Maintain and expand the Southern Ocean GLOSS network, including increasing the number of stations reporting in real time. Install coastal tide gauges in the data-sparse Amunsen Sea sector.

Figure 30: Status of the Global Sea Level Observing System (GLOSS) in October 2009. Green dots = "Operational" stations for which the latest data is 2005 or later; yellow = "Probably operational" stations for which the latest data is within the period 1995-2004; orange = "Historical" stations for which the latest data is earlier than 1995; red = Stations for which no PSMSL data exist.

Basal melting and freezing
Basal melting and freezing on the undersides of floating ice shelves exert significant influences on the ocean close to the Antarctic margin. These processes impact strongly on shelf water characteristics and the dense precursors of AABW in locations such as the southern Weddell and Ross Seas (e.g. Nicholls and Jenkins, 1993; Nicholls and Makinson, 1998). Freshening of AABW observed in the Indian and Pacific Sectors of the Southern Ocean has been attributed to enhanced basal melt (Jacobs et al., 2002; Jacobs, 2004, 2006; Rintoul, 2007). In West Antarctica, a marked deflation of parts of the ice sheet has been observed, ascribed to increased ocean temperatures impacting strongly on the ice shelves (e.g. Shepherd et al. 2004; Jenkins et al., 2010). However, despite their importance, ocean circulation and properties under shelf ice has been measured in only very few locations. Recent measurements beneath the Pine Island Glacier using the AUV Autosub are an exciting development, but sustained measurements are also needed, to track the impacts of ocean climate
changes on the ice shelves, and the subsequent feedbacks.

Recommendations: Deploy and maintain oceanographic moorings beneath the Antarctic ice shelves in key strategic locations using hot water drilling technology (Figure 31). Coordinate work with the geological science community, where appropriate, to take advantage of drilling expeditions being conducted for studies of sediments and the sub-seabed. Establish moored arrays and repeat hydrographic sections near the ice front of key ice shelves to monitor inflow and outflow from the sub-ice cavity.

Figure 31: White circles indicate location of current or planned drill holes through ice shelves, allowing sampling of underlying ocean waters.

Enhanced meteorological observations
An enhanced atmospheric observing system is needed to improve Antarctic and southern hemisphere weather forecasts. The enhanced observations should include additional automatic weather stations and remote profilers, sea level pressure observations from ice and ocean drifters, and aircraft (manned and un-manned). Climate research benefits from improved weather forecasts in the increased accuracy of the flux products derived from Numerical Weather Prediction model reanalyses. The air-sea fluxes of heat and moisture are poorly known at high southern latitudes, making it difficult to diagnose the interactions between atmosphere, ocean and sea ice that lie at the heart of climate variability and change.

Recommendations: State-of-the-art meteorological sensors (e.g. Improved Meteorology (IMET) systems) should be installed on additional Antarctic research, supply and tourist ships to provide validation data for the next generation of flux
products from reanalyses and satellites. Deployment of surface flux reference stations is a significant technical challenge in the strong current, high wind and sea state environment typical of the Southern Ocean, but is required to provide a data set to test flux products derived from satellite data and reanalyses. The recently deployed air-sea flux mooring in the Subantarctic Zone south of Tasmania is an important development (Figure 32); similar moorings are being planned for higher latitudes south of Australia, in the southeast Pacific, in the Argentine Basin, and in the Agulhas Return Current region.

Figure 32: Air-sea flux mooring deployed at 47°S, 140°E south of Tasmania as part of Australia’s Integrated Marine Observing System (IMOS). This is the first air-sea flux mooring so far deployed in the Southern Ocean and will be used to assess the quality of air-sea flux products derived from satellites and reanalysis products. [Source: http://imos.org.au]

Phytoplankton, primary production and microbial processes

Sustained observations of biomass, primary production and species distributions of phytoplankton and protozoa are needed to relate environmental variability (including sea ice) to biological activity. Ocean colour satellites are critical as they provide the only circumpolar view of biological activity in the Southern Ocean. In situ measurements are needed to refine algorithms used to interpret the satellite data, to relate surface chlorophyll to column-integrated production and for analysis of additional pigments and phytoplankton community composition.

Recommendations: Chlorophyll fluorescence, fast repetition rate fluorometry (FRRF), transmissometry, ocean colour and pigment analyses are needed on a larger suite of underway vessels (research, supply and tourist ships) supplemented by regular sampling for microscopic identification of species. These observations should also be made in the upper ocean on each of the repeat hydrographic transects; fluorescence is now being measured with seal tags as well. Such measurements should follow recommended procedures for calibration/validation of ocean colour by remote sensing (see below). Phytoplankton assemblages should be identified as closely as possible to species level and primary production rates measured using conventional $^{14}$C techniques, or using oxygen electrodes, during repeat transects by science vessels. Total particulates should be measured by transmissometry and/or underway flow cytometry. Unlike fluorometry, this measurement is not subject to photoinhibition and
includes stocks of phytoplankton, protozoa, bacteria and detritus (i.e. the food available for grazers), complementing the other measurements. These data will enable the use of remote sensing data to quantify CO$_2$ fluxes and ecological responses to change at basin scales.

Zooplankton and micronekton

Mid-trophic level organisms (zooplankton, fish and squid) play a critical role in Southern Ocean ecosystems by transferring biomass and energy from primary producers to predators. However, despite their huge biomass and function in ecosystems and biogeochemical cycling, these organisms are poorly observed. They may also be particularly sensitive and vulnerable to climate change. Global warming will affect sea ice patterns and plankton distributions. Increased UV levels, ocean acidification, geographic shifts in species composition, invasive plankton species, pollution and harvesting impacts may also drive changes in mid-trophic levels with implications for both carbon cycling and top predators. Zooplankton sampling has in the past largely been carried out as part of focused, short-term experiments and has generally focused on distribution and abundance. Existing long-term sampling programs include the Japanese Antarctic Research Expedition (JARE) annual Norpac plankton net sampling, the US Antarctic Marine Living Resources (AMLR) program, the Palmer LTER (Waters and Smith, 1992), the British Antarctic Survey monitoring programme and the SCAR Southern Ocean Continuous Plankton Recorder (SO-CPR Survey, Figure 33). Gaps include a lack of winter data, lack of sampling in the sea ice zone, lack of data from the Pacific, and a lack of sampling at depths greater than 200 m. The CPR, the primary tool used for broad-scale sampling of zooplankton, samples the top 20 m.

Acoustic approaches have great potential for sampling of mid-trophic levels (Figure 34). The contribution that automated acoustic systems can make to the sustained observing system is summarised in Handegaard et al. (2010). Systems are being designed suitable for deployment on ships, moorings and drifting platforms.

Recommendations: Maintain and expand the CPR survey, in particular to fill gaps in the Pacific and Atlantic sectors and in winter. Use results from regional studies to design a zooplankton sampling plan that combines the broad spatial and temporal coverage of the CPR with other techniques (net tows, acoustics) to fill gaps and assess potential biases (e.g. summer sampling, CPR limited to top 20 m). Expand the use of automated acoustic techniques to sample the mid-trophic levels (Handegaard et al., 2010).
Figure 33: Location of CPR tows completed between 1991 and 2008.

Figure 34. Demonstration of basin scale distribution and abundance of mid-trophic organisms provided by calibrated ships of opportunity (fishing vessels) over multi-year time frame using well established standardized technologies and methodologies (Fig. 4 from Kloser et al., 2009). These basin scale snapshots provide information for ecosystem model parameterization, data assimilation and as an ecological indicator.
of change in the deep scattering layer over basin scales. Implementation of this
method is very cost effective and forms a component of the necessary global coverage.

Ecological monitoring via Top Predators

Observations of the distribution and abundance of top predators (fish, penguins, sea
birds, seals and whales) can provide indications of changes in the ecosystem as a
whole. Long-term ecological monitoring programmes have been established at a few
sites around Antarctica, including the Long Term Ecological Research (LTER) site on
the western Antarctic Peninsula. The Commission for the Conservation of Antarctic
Marine Living Resources (CCAMLR) also monitors land-breeding marine predators
(seals, penguins and seabirds) at a number of sites under the CCAMLR Ecosystem
Monitoring Programme (CEMP). The CEMP sites are located in three Integrated
Study Regions in the South Shetland Islands, South Georgia and Prydz Bay (Agnew,
1997). Although CEMP was established to monitor fisheries impacts, the long term
time series are now also providing insights into ecosystem processes (e.g. Ballerini et
Shetland Islands offers an excellent example of a long term time series where ship
based oceanographic measurements have been made every year since 1986 along with
colony based measurements of the population status and foraging behaviour of fur
seals and penguins since 1998. Through these programs and others studies, significant
changes in penguin populations have been observed in some regions (e.g. Ducklow et
al., 2008; Weimerskirch et al., 2003), particularly on the western peninsula where the
most dramatic environmental changes have been observed in recent decades.

However, monitoring of top predators is limited in many parts of Antarctica.
Enhanced development and application of platforms, technologies and survey
methods will be crucial to establishing a broader network of monitoring for top
predators. Furthermore, in many cases there is a lack of simultaneous physical and
biogeochemical data, and information on lower trophic levels, to allow the causes of
observed changes in higher trophic levels to be determined.

The Tagging of Pacific Pelagics Programme (TOPP) (Block et al., 2002), is an
excellent example of the type of integrated multi-species tracking programme that
could be achieved under SOOS (see http://www.topp.org/). The power of such an
approach is that combining at-sea movements of many individuals from multiple
species enables identification of regions and marine features that are of most
importance to the community of predators (i.e. ecologically significant areas, or
ESAs). Different species employ different foraging and breeding strategies; by using
a number of species, different aspects of the Southern Ocean environment can be
monitored. Equally importantly, when this is conducted over a multi-year time frame,
the dynamics of the system can be quantified.

Table 4. List of species used to observe Ecologically Significant Areas. For each
species the important ecological characteristics are listed as well as the most
appropriate method of tracking.

<table>
<thead>
<tr>
<th>Species</th>
<th>Prey</th>
<th>Habitat</th>
<th>Max. dive depth (m)</th>
<th>Device*</th>
</tr>
</thead>
</table>

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### Table: Southern Elephant Seal, Adélie Penguin, Emperor Penguin, Antarctic Petrel, Antarctic Fulmar, Snow Petrel, Cape Petrel, Short-tailed Shearwater, Weddell Seal

<table>
<thead>
<tr>
<th>Species</th>
<th>Diet</th>
<th>Habitat</th>
<th>GLS 1900</th>
<th>Device Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern elephant seal †</td>
<td>squid, fish</td>
<td>pelagic</td>
<td>1900</td>
<td>CTD</td>
</tr>
<tr>
<td>Adélie Penguin †</td>
<td>krill, squid, fish</td>
<td>pack ice</td>
<td>160</td>
<td>GLS</td>
</tr>
<tr>
<td>Emperor Penguin †</td>
<td>krill, squid, fish</td>
<td>fast ice</td>
<td>600</td>
<td>GLS</td>
</tr>
<tr>
<td>Antarctic Petrel †</td>
<td>krill, amphipods, fish</td>
<td>pelagic</td>
<td>5</td>
<td>GLS</td>
</tr>
<tr>
<td>Antarctic Fulmar</td>
<td>krill, amphipods, fish</td>
<td>pelagic</td>
<td>5</td>
<td>GLS</td>
</tr>
<tr>
<td>Snow Petrel</td>
<td>krill, squid, fish</td>
<td>pelagic</td>
<td>5</td>
<td>GLS</td>
</tr>
<tr>
<td>Cape Petrel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-tailed shearwater (summer only)</td>
<td>krill, fish (?)</td>
<td>pelagic</td>
<td>50</td>
<td>GLS</td>
</tr>
<tr>
<td>Weddell seal †</td>
<td>fish</td>
<td>fast ice</td>
<td>900</td>
<td>Argos</td>
</tr>
</tbody>
</table>

*Device types include Conductivity-Temperature-Depth recorders (CTD), Argos PTTs (Argos) and light temperature loggers (GLS).

†Denotes core species which will be studied at multiple locations.

### Recommendations:

Establish and maintain multi-species tracking studies of key Antarctic predators to identify areas of ecological significance. Maintain existing long-term monitoring programs and extend monitoring to regions where little activity currently occurs. Assess the benefit of enhancing the physical and biogeochemical observing system in the vicinity of long-term monitoring sites to add value to ecological time series. Surveys of crab eater seal populations every 5 years should be conducted in regions where a baseline exists, to detect changes in abundance.

### Benthos:

The benthos is an important but generally poorly understood component of the Antarctic marine ecosystem and biodiversity. Antarctic benthic communities show high levels of endemism, gigantism, slow growth, longevity, late maturity, and adaptive radiations that generated considerable biodiversity in some taxa (Clarke & Johnston, 2003). Studies of these communities are therefore relevant to understanding the effect of global changes in the marine environment. Recent studies suggest some benthic organisms may be particularly sensitive to environmental changes (e.g. Peck et al., 2006) and to human disturbance (Stark et al., 2003). The effects of ocean acidification will be felt first in the cold, sub-surface waters in polar regions and therefore may have a significant impact on the benthos. Sustained observations of the distribution, abundance and diversity of benthic organisms are needed to determine the sensitivity of the benthic communities to climate and other changes. This information is particularly important to inform conservation and management decisions.
**Recommendations:** A number of recent programmes provide good examples of the integrated multidisciplinary benthic studies required (Snape et al. 2001, Stark et al. 2003, Clarke et al. 2008, Montone & Weber in press; Sicinski et al. submitted, Smith et al. 2008, Brandt et al. 2004, Brandt et al. 2007; Gutt 2007, Gutt et al. 2007). These studies have used a variety of tools, including benthic landers with sediment traps and time-lapse photography and physical sensors; seafloor video surveys; coring; and targeted trawling. Sustained benthic observatories using these approaches should be established at a number of locations around Antarctica, including regions of rapid change (the Antarctic peninsula), areas where future change is expected (the Amundsen and Bellingshausen Seas), and more stable environments (East Antarctica). Sampling sites should be representative of the Antarctic shelf, continental slope and deep-sea. The biological observations need to be integrated with changes in the physical and chemical environment.

**Remote sensing:** Remote sensing has a particularly crucial role to play in remote regions like the Southern Ocean, where in situ observations will always be sparse. However because of the electromagnetic opacity of the seawater, satellite data are restricted to near-surface properties – such as skin temperature, surface elevation, ocean colour, and surface roughness. Satellite data have the unique advantage of showing the “big picture” of the large-scale ocean circulation while at the same time providing the “regional details” necessary to capture the very energetic mesoscale eddies.

High-precision, continuous satellite altimetry missions (Jason, Envisat, Sentinel), in full synergy with satellite gravity missions (GOCE, GRACE, Mitchum et al., 2001; Le Traon et al., 2001), play a vital role in monitoring surface elevation relative to the geoid, which to a large extent controls the large-scale depth-integrated circulation (Wunsch, 1996). Absolute current velocities can also be inferred from these sea surface height data (Johannessen et al., 2001). Scatterometers enable derivation of surface winds over open seawater (Millif et al., 2001). Infrared and microwave radiometers, including active and passive microwave sensors, measure SST (Reynolds, 2001), sea ice extent and motion (Drinkwater et al, 2001). Ocean colour measurements provide estimates of phytoplankton biomass in surface waters, primary production rates and some indication of community composition.

Satellite ocean colour measurements will be crucial for providing synoptic views of phytoplankton distribution, extending measurements from ships of opportunity, and allowing detection of possible changes in distribution as a result of climate change. It is vital that these measurements should be supported by an active calibration/validation programme that allows remotely sensed ocean colour data to be converted to chlorophyll estimates, and which allows possible changes in biomass to be distinguished from changes in atmospheric interference due to climate change. This will require measurements of surface chlorophyll, hyperspectral incoming radiation and ocean colour, and coloured dissolved organic matter (CDOM) to allow development of improved algorithms. Targeted research cruises will be required to develop models of the relationships between surface colour and subsurface chlorophyll maxima.

Remote sensing of the Southern Ocean region encounters some unique challenges. Persistent cloud cover limits the coverage obtained by infrared and visible band
sensors. Combining data from multiple sensors, such as the Jason and ENVISAT altimeters or the NASA and ESA SST sensor suites, provides more complete coverage at high latitudes. A combination of different types of information, such as infrared and microwave data for measuring SST, is also useful, and in situ measurements for removal of biases are particularly important at high latitudes (Reynolds, 2001). To optimise their orbits to avoid aliasing tides, many of the satellite altimeters are in orbits that do not go poleward of 66 degrees (e.g. Jason). For SST, ocean colour and wind speed, large data or algorithm dropouts occur as the satellite approaches the ice. There is a need to investigate better algorithms and corrections near the critical ocean/sea ice/continent interface in order to extend the sea surface height and wave height measurements close to Antarctica. Tide gauges around the coast of Antarctica are therefore important for extending measurements of sea level to the coast (Mitchum et al., 2001). Agreements for the scientific use of new, higher spatial resolution visible-IR datasets, many of which are currently expensive, would be desirable, particularly as these datasets build up multi-annual coverage. Improved sensors/algorithms for sea ice extent, concentration, volume and motion are a high priority (Drinkwater et al., 2001). The small Rossby radius in polar regions means that satellite remote sensing products need to be produced at a higher resolution than required at lower latitudes, but also means that remotely sensed data are all the more critical for setting hydrographic sections or moorings in the context of the local mesoscale eddy field.

Recommendations: To ensure continuity of satellite data and maintain the quality of data interpretation through in situ validation measurements. The suites of in situ measurements proposed within the SOOS programme naturally provide data for ground-truthing and algorithm improvements for each of the remote sensing data streams mentioned above. In particular, high priority platforms for SOOS include high-precision satellite altimetry missions (Jason, Envisat, Sentinel), in full synergy with satellite gravity missions (GOCE, GRACE); scatterometers for wind stress; microwave and infrared instruments for SST; cryospheric satellites; and ocean colour.

Southern Ocean Climate and Ecosystem Information System: The SOOS vision includes not just the collection of sustained observations, but the delivery of Southern Ocean information to a wide range of users. SOOS will coordinate and provide access to analyses and data syntheses that add value to the raw information. These services might include maps of ocean properties (e.g. ocean heat and salt content, sea ice conditions, or measures of biological productivity) or time series (e.g. changes in pH, sea level, or surface biomass). At present, such products are produced by many groups around the world, but it is difficult and time-consuming to locate and access material from multiple sources, particularly across disciplines.

Recommendations: SOOS should facilitate the development of a system to provide seamless access to a wide range of data products for the Southern Ocean, guided by the needs of research users.

3.3 Complementary research

SOOS has a clear focus on sustained ocean observations. Many other activities, including sustained observations in the atmosphere and cryosphere, process studies,
and modelling, are required to address the science challenges motivating the SOOS. A few examples of research activities that complement the core SOOS mission are noted here.

**Atmospheric trace gas observations:** One of the key questions motivating the SOOS is the sensitivity of the Southern Ocean carbon cycle to climate change. The SOOS observations of ocean carbon need to be complemented by monitoring of the lower atmosphere for a range of gases, including CO$_2$, O$_2$/N$_2$ and related tracers. Both airborne sampling and land-based flask and continuous monitoring stations are required.

**Ice cores from high accumulation rate coastal regions:** The short duration of the instrumental record poses a huge challenge when attempting to understand Southern Hemisphere climate variability and change. Ice cores from high accumulation rate coastal sites will be of immense value in reconstructing a record of past change on time scales from years to millennia (e.g. Curran et al., 2003; Goodwin et al., 2004).

**Sediment cores:** New sediment cores from medium to high accumulation rate regions will help to identify changes in Southern Ocean circulation and structure during the course of past glacial cycles. These cores will provide estimates of past changes in sea ice extent and shifts in ocean fronts, and help to clarify the relationship between changes in the northern and southern hemispheres.

**Process studies:** Some of the key unknowns regarding the role of Antarctica and the Southern Ocean in the global climate system require focused process studies to be resolved. Generally, smaller scale processes associated with submesoscale eddies, internal waves, surface waves etc. are poorly represented in climate models and process studies meant to refine parameterizations are important. In the Southern Ocean context, such processes can exert a control on, for example, mixed layers, upwelling and productivity, the extent of warm water melting the glacial ice, and thus their consequences on the climate system may be large. Exchange of water masses across the Antarctic Slope Front is an important, but poorly understood, process in the formation of dense water on the continental shelf. The complex interactions between the ocean and ice shelves, including melting near the grounding line and formation of marine ice beneath the ice shelf, remain largely unobserved. These interactions are important to the freshwater balance, to water mass transformation, and to the stability of the ice sheets that feed the ice shelves. New technology to explore the ice shelf cavities is now available and expected to provide a significant step forwards. Progress in understanding what physical and biogeochemical processes control the rate of carbon export in the Southern Ocean will require process-oriented field experiments and biogeochemical time series measurements from moorings.

**Ecological process studies.** Regular observations from ships of opportunity will identify different bioregions, characteristic populations and seasonal successions. However certain parameters are not tractable from underway surface measurements, yet are crucial for estimates of food availability and carbon flux, and will require measurements from targeted research cruises if they are to be incorporated in models. These include structure of the deep chlorophyll maximum, diversion of primary production through consumption and respiration in the microbial loop, coupling of phytoplankton production to grazers, and export of carbon and biomass to the deep
Ocean manipulation experiments and mesocosm studies are needed to examine hypotheses such as the role of iron in ecosystem production and to assess the impacts of ocean acidification.

Integration of remotely sensed data from multiple sensors/platforms: Data integration from sensors measuring in similar E-M bands but at different spatial and/or temporal resolution would benefit greatly from the placement of a few automated moorings/ground stations on the ice shelf, above and below the ice/water within the seasonal sea ice zone and in open Southern Ocean waters. Such platforms are currently maintained at lower latitudes, for example at the BATS station and Aqua-Alta in Italy for ocean colour, but not in the high latitude Southern Ocean where ecological and physical conditions often lead to algorithm failure.

4. Status and a roadmap for implementation of SOOS

4.1 SOOS as a legacy of the International Polar Year

Many of the observations identified as “building blocks” of the SOOS in the previous section were completed during the IPY, during which the Southern Ocean was measured in a truly comprehensive way for the first time. IPY measurements spanned the circumpolar extent of the Southern Ocean, from the subtropical front to the Antarctic continental shelf. Most of the WOCE/CLIVAR repeat hydrographic sections were re-occupied, providing a near-synoptic snapshot of the physical and biogeochemical state of the Southern Ocean through the full water depth. Many properties, such as trace elements like iron, were measured throughout the water column for the first time. A similar snapshot, of a more limited set of parameters, took much of a decade to complete during WOCE. Argo floats collected more than 60,000 temperature and salinity profiles during the 24-month IPY period, providing broad-scale, quasi-synoptic, year-round sampling of the upper 2 km of the Southern Ocean. Oceanographic sensors on marine mammals provided a similar number of profiles, including measurements from regions where traditional oceanographic instruments have difficulty sampling, such as the sea ice zone in winter. Moorings provided continuous time-series measurements of dense water overflows and boundary currents, major currents like the Antarctic Circumpolar Current and the Antarctic Slope Front, and coastal sea level. Many new species were discovered and new insights into processes influencing biodiversity and ecosystem structure and function were obtained.

Perhaps most importantly, the IPY activities spanned all disciplines of Southern Ocean science. Southern Ocean IPY demonstrated that an integrated, multi-disciplinary, sustained observing system is feasible and urgently needed to address issues of high relevance to society, including climate change, ocean acidification and the future of the Southern Ocean ecosystem.

4.2 Status of Southern Ocean observations
Commitments have already been made to complete key elements of the SOOS. For example, most of the repeat hydrographic lines will be re-occupied within the next five years, consistent with the SOOS design (GO-SHIP). Several countries have long-standing commitments to monitor Drake Passage with annual full-depth hydrography, more frequent sampling of the upper ocean, and moored instruments. Most of the underway observation network shown in Figure 22 has been in place for more than a decade and is expected to continue. Several moored arrays in the Weddell Sea have been maintained for a decade and are planned to continue. Similar programs are being established in other locations around Antarctica. Plans are well advanced for a comprehensive observing system in the South Atlantic ocean, the South Atlantic Meridional Overturning Circulation (SAMOC) experiment (Figure 35).

Programs like the Argo profiling float array and the MEOP network of tagged seals have helped to revolutionise our ability to observe the Southern Ocean. The science being done with these measurements has already had a significant impact on our understanding of the Southern Ocean. For these reasons, significant effort is being made to ensure these critical data sets are maintained and enhanced in future years. However, there is as yet no firm commitment to long-term sustained funding of these systems.

With regard to biological sampling, the Palmer LTER on the western Antarctic Peninsula has been in operation for 15 years and is expected to continue; the long-term monitoring conducted by the CEMP program also has a long-standing commitment. A number of nations have committed to ongoing CPR transects across the Southern Ocean. The number and breadth of biological measurements being made from ships of opportunity is slowly growing.

**Figure 35:** The draft SAMOC array for the Atlantic sector of the Southern Ocean.
While the list of existing commitments provides some grounds for optimism and a firm foundation on which to build, there is substantial work to be done to secure the resources for a truly sustained and comprehensive observing system in the Southern Ocean. Many of the challenges (e.g. the lack of sustained funding and the need for improved sensors) are common to the global ocean observing system as a whole. Major gaps include:

- sustained funding for most elements of the SOOS
- observations below the sea ice
- biological and biogeochemical sampling in winter and at large scales
- lack of time series data, particularly for biology and biogeochemistry
- inadequate integration of physics, biology and biogeochemistry observations
- sparse sampling of the deep ocean

Almost all elements of the observing system require enhancement to reach the sampling required to address the key scientific challenges. Figure 36 summarises the status of the Southern Ocean observing elements monitored by JCOMMOPS for the month of June 2010, illustrating that substantial gaps remain, particularly in winter.

**Figure 36:** Status of the Southern Ocean observing system for the month of June 2010, for a set of platforms monitored by JCOMMOPS. The ship coverage is more complete in the summer months, but even in that season substantial gaps remain.

### 4.3 Next steps towards implementation

a.) Scientific Coordination

Two panels have shared responsibility for oversight of SOOS during its development stage: the Expert Group on Oceanography co-sponsored by SCAR and SCOR, and
the Southern Ocean Implementation Panel co-sponsored by CLIVAR, CliC and
SCAR. The Expert Group has an explicit focus on integrating across disciplines in
Southern Ocean research, while the CLIVAR/CliC/SCAR panel addresses physical
and biogeochemical aspects of the Southern Ocean climate system. Shared
membership on these two panels has ensured effective coordination between the
panels and across international programs spanning the disciplines of Southern Ocean
research.

As we move towards implementation of SOOS, it is necessary to identify a single
group with lead responsibility for SOOS. The SCAR/SCOR Expert Group, with its
focus on interdisciplinary observations, is the logical choice given the broad scope of
SOOS. The CLIVAR/CliC/SCAR Southern Ocean panel must continue to be closely
involved, particularly in helping to refine the design of the physical and
biogeochemical components of the observing system. A number of other panels and
national and international programs also have an important role to play, as outlined
below.

A program of the scale and complexity of the SOOS requires a Program Office or
Secretariat. The role of the Program Office will be to serve as a central contact point
for SOOS, to monitor progress towards SOOS goals, to facilitate coordination of field
work, to assist in the organisation of workshops and synthesis activities, and to
coordinate a web site and other activities to advertise the aims and achievements of
the SOOS.

b.) Observing system design

For many elements of the SOOS, the optimal sampling plan has not yet been
determined. Quantitative studies of the trade-offs to be made between observing
system elements are needed, using a variety of approaches including formal
Observing System Experiments (OSEs). For each element of the SOOS, a
quantitative target for the number and frequency of observations needs to be defined,
so the progress towards implementation of SOOS can be assessed. For some elements
of SOOS, these requirements have been defined (e.g. repeat hydrography, Argo,
surface drifters, and ice drifters). For others, including many of the biological
parameters, further work is required. This task should be overseen by the
SCAR/SCOR Expert Group on Oceanography, in consultation with others.

c.) New technology
Present tools are not adequate to answer the key science questions motivating SOOS, so SOOS will need to advocate for and adopt new technologies. Examples include the development of new low-power, stable biological and biogeochemical sensors for deployment on a variety of fixed and mobile platforms; long-duration, inexpensive moorings to allow continuous broad-scale sampling; and floats and gliders with expanded capability in terms of depth, range and sensors. These needs are not unique to the Southern Ocean and SOOS will need to be well-integrated with technological developments relevant to the global observing system.

d.) Building of partnerships

As appreciation of the role of the Southern Ocean in global climate, biogeochemical cycles and marine productivity has grown, so has interest from the research community. The number of national and international research programs with a focus on the Southern Ocean has therefore also grown. The success of SOOS will depend on effective integration and coordination of these efforts. The Southern Ocean is a vast and remote domain and the logistical resources available for its study are relatively limited. This places a further imperative on effective coordination of research between nations and across disciplines.

Recent initiatives of particular relevance to SOOS include:

• SCAR’s programme on Antarctica and the Global Climate System (AGCS) is a major research programme to investigate the nature of the atmospheric and oceanic linkages between the climate of the Antarctic and the rest of the Earth system, and the mechanisms involved therein. The scientific direction of the project is overseen by the AGCS Steering Committee. The programme makes use of existing deep and shallow ice cores, satellite data, the output of global and regional coupled atmosphere-ocean climate models and in-situ meteorological and oceanic data to understand the means by which signals of tropical and mid-latitude climate variability reach the Antarctic, and high latitude climate signals are exported northwards. AGCS will help define the SOOS requirements for understanding physical climate, and provide a link between the ocean focus of SOOS and climate research in the atmosphere and cryosphere.

• The Southern Ocean Sentinel aims to assess the impacts of climate change on Southern Ocean marine ecosystems. The Sentinel program has a strong emphasis on modelling as well as observations (both process studies and sustained observations). The Southern Ocean Sentinel programme has a significant role to play in refining the design of the ecosystem component of the SOOS.

• Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) is a multidisciplinary circumpolar ecosystem programme. Established by a group of polar scientists from around the world representing a wide range of research areas, ICED will facilitate the scientific coordination and communication required to undertake integrated circumpolar analyses of Southern Ocean ecosystems. Over the next decade, ICED will address the need to increase our understanding of circumpolar ecosystem operation in the context of large-scale climate processes; local-scale ocean physics; biogeochemistry; food web dynamics; and harvesting. ICED is being developed as a joint programme of IMBER and GLOBEC and is closely
linked with EUR–OCEANS. Like the Sentinel programme, ICED can make a major contribution to SOOS by defining and implementing the sustained observations needed to understand Southern Ocean ecosystems and their response to climate and other forcing.

- The Southern Ocean Carbon, Ecosystems and Biogeochemistry (SOCEB) programme under development in the USA is also of direct relevance to SOOS. This initiative recognises that the most pressing issues in Southern Ocean research require much closer integration of the Southern Ocean biogeochemistry and ecosystem research communities. The goals of SOCEB are closely aligned with those of the SOOS plan. The SOCEB community will make a substantial contribution to SOOS by defining the role of sustained observations in addressing critical science questions at the interface of physics, biogeochemistry and ecology.

- The Antarctic Sea ice Processes and Climate (ASPeCt) program has the objectives to determine the spatial and temporal variability of the basic physical properties of sea ice that are important to air-sea interaction and to biological processes within the Antarctic sea-ice zone and to understand the key sea-ice zone processes necessary for improved parameterisation of these processes in coupled models.

e) International context for the SOOS

The SOOS is currently sponsored and/or endorsed by SCAR, SCOR, CAML, GOOS, POGO and WCRP. A SOOS is envisioned to operate in much the same way as a regional component of the Global Ocean Observing System (GOOS). Climate relevant components of the GOOS, and hence SOOS, are implemented by Member States cooperating through the IOC/WMO Joint Commission for Oceanography and Marine Meteorology (JCOMM) and contribute to the Global Climate Observing System (GCOS) and the Global Earth Observing System of Systems (GEOSS). Processes in the Southern Ocean affect climate on the global scale and over a range of time scales. JCOMM is already aiding in the development of SOOS, and at the appropriate time the SOOS supporters will seek formal endorsement by and involvement of JCOMM. Several of the elements of the SOOS are already operating under JCOMM oversight in the Southern Ocean and elsewhere (such as the tide gauge network of GLOSS, the Argo float program, and the International Programme of Antarctic Buoys – IPAB).

The Member States of the Intergovernmental Oceanographic Commission (IOC) of UNESCO, the World Meteorological Organization (WMO) and other relevant bodies, including the Parties to the Antarctic Treaty Consultative Mechanism (for areas south of 60°S), will be asked to formally endorse the SOOS and its network design in order to catalyze the intergovernmental support that is required to achieve a specific set of operational targets and to maintain operations for the long term. The 132 Member States of the Intergovernmental Oceanographic Commission have already resolved to work towards development of a SOOS (Report of the IOC Executive Council XLI, 2008) demonstrating the widespread interest in the SOOS and increasing confidence that the proposed network will be implemented and sustained.

While the Antarctic Treaty itself is concerned mostly with the continent of Antarctica and its ice shelves, its Protocol on Environmental Protection to the Antarctic, which...
entered into force in 1998, encompasses several environmental issues relevant for the Southern Ocean. The SOOS may be in a position to meet a significant portion of requirements of the Protocol, the Convention for the Conservation of Antarctic Marine Living Resources (1982), the Convention for the Conservation of Antarctic Seals (1972), and environmental protection measures in Antarctica and surrounding waters. The development of a SOOS meets the initial requirements of ATCM Resolution 3 (2007), which welcomed and supported “the proposal by SCAR to establish a multi-disciplinary pan-Antarctic observing system, which will, in collaboration with others, coordinate long-term monitoring and sustained observation in the Antarctic”, and which recommended “that the Parties:

1. urge national Antarctic programmes to maintain and extend long-term scientific monitoring and sustained observations of environmental change in the physical, chemical, geological and biological components of the Antarctic environment;
2. contribute to a coordinated Antarctic observing system network initiated during the IPY in cooperation with SCAR, CCAMLR, WMO, GEO and other appropriate international bodies;
3. support long-term monitoring and sustained observations of the Antarctic environment and the associated data management as a primary legacy of the IPY, to enable the detection, and underpin the understanding and forecasting of the impacts of environmental and climate change.”

SOOS is a contribution towards achieving that recommendation.

As stated above, the SOOS will constitute a significant legacy of the IPY. In this context, it is noteworthy that the 60th Session of WMO Executive Council in June 2008 endorsed the idea of an International Polar Decade, in recognition of the rapid rates of change in polar regions and the impact of high latitude change on the rest of the globe. The SOOS would make a major contribution to such an initiative, and (along with an Arctic Ocean Observing System) was called for in the IPY Design Plan.

While widespread support from international agencies and programmes is essential, ultimately much of the funding to support the SOOS will flow from individual nations. It is therefore necessary to build a coalition of national programmes with a strong commitment to the SOOS.

f) Transition to a sustained operational system

Implementing the SOOS implies eventual transition of sustained observations being carried out in the Southern Ocean into an operational data stream that is freely distributed in near real time as the operational Southern Ocean component of the Global Ocean Observing System. As for any regional ocean observing system, a first target is to sustain and expand the existing operational system components, so as to provide near-term tangible achievements, with a high likelihood of success, early in the development of the SOOS.
The Southern Ocean oceanographic research community is, and for many years will continue to be, both the primary provider and primary user of *in situ* ocean data. Thus, incorporating research community products into the observing system, and simultaneously designing the system to help address research community hypotheses, will be absolutely critical in ensuring we can monitor the Southern Ocean for the benefit of all, including operational organizations and their clients. The objective for a SOOS should thus be not to try to fully transition research observations into an operational system, but to better ensure that the wealth of research observations is maintained into the future, is counted as an integral component of the SOOS, and enters the SOOS data system in near real-time, so that the latter draws on all of the best observations being taken, irrespective of whether they are funded on a sustained or research basis.

### 4.4 Data strategy

For the SOOS to succeed, it is critical that a data system be established that ensures that both past and future data sets are accessible and of known quality, consistent with the SCAR Data and Information Management Strategy published in 2009. The SOOS strategy for managing data will be based on the following elements or principles:

1) **Open access to SOOS data**

SOOS will establish a data policy of unrestricted access as soon as feasible after data collection. The data policy will be established based on IPY, IOC and SCAR data policies and national and international legislation. The immediate, free access to Argo data provides a model.

2) **Establish a SOOS data infrastructure**

A SOOS data portal will provide one-stop access to a distributed data archive holding all SOOS related data. The goal is to provide easy access to both historical and future data sets relevant to SOOS. At present, physical and biological data sets are often handled by separate data systems, making interdisciplinary research very difficult. In fact, what is required is a data infrastructure that includes a portal, as well as registries, protocols and standards, services, content, physical hardware and people. The European SeaDataNet project and the Australian Integrated Marine Observing System (IMOS) provide regional examples of the data infrastructure concept. An effective SOOS data infrastructure requires dedicated investment, just as any other component of SOOS infrastructure.

3) **Use existing data centres where possible**

SOOS will use a distributed data system model, where data are quality controlled and archived by data assembly centres. For physical and biogeochemical data, examples of highly effective data centres include the CLIVAR & Carbon Hydrographic Data Office (CCHDO), the thermal data assembly centres, and the Argo data system. For marine biodiversity data, the dataportal SCAR-MarBIN is an open-access repository. Established during the IPY, it houses over 1 million geo-referenced distribution records from 165 datasets. The register of some 16,500 taxa (of which 9,500 are verified species) includes DNA barcodes for 1,500 species. The information is served to the Encyclopaedia of Life, an online resource with an illustrated species on each
page. National Antarctic Data Centres (NADCs) and National Oceanographic Data
Centres (NODCs) will provide building blocks of the SOOS data system.

The SOOS data portal will streamline access to data sets held in the distributed
archives. An important role for the SOOS will be to ensure that it is possible to
identify, access and integrate the physical and biological data relevant for a particular
study, even if the individual data sets are held in different data centres.

Where appropriate data centres do not exist, SOOS will work with established data
centres to seek a solution to host these ‘orphan’ data types. The Polar Information
Commons project of CODATA-IPY-SCADM is exploring novel approaches to tackle
this problem.

4) **Improve access to and quality of historical data**

Given the lack of observations from the Southern Ocean, it is critical that historical
data is accessible and of known quality. Efforts have been made to do this for some
physical oceanographic data (e.g. the Southern Ocean Data Base of Orsi and
Whitworth, 2005), and the recent compilation of zooplankton net tow data sets
(KRILLBASE, Atkinson et al., 2008) demonstrates the value of this approach. SOOS
will aim to foster similar efforts for data sets that have not yet been assembled in this
way and to ensure compatibility and integration between data from different
disciplines.

5) **Foster a culture of good data management practices**

The success of any data system depends ultimately on the willingness of investigators
(and their funders) to take data management seriously. SOOS will aim to foster a
culture where PIs take responsibility for ensuring their data reach data assembly
centres in a timely manner and that metadata records are maintained. The possibility
of appointing a SOOS Data Coordinator in the SOOS Project Office will be explored.
The establishment of data coordinators for individual projects or cruises will be
encouraged.

6) **Establish protocols for data management and data exchange**

The SOOS data portal will also foster agreements on protocols for data collection,
data exchange, quality control and archiving, based on best-practice in individual
disciplines.

4.5 **SOOS in 10 years**

The observations that are feasible now, with existing technology and resources, are
not adequate to address the key science challenges and issues of societal relevance in
the Southern Ocean. Year-round, full-depth, multi-disciplinary monitoring of the
Southern Ocean will remain beyond our reach if we need to rely on existing tools.
New technologies are needed, and many are already under development.
In ten years time, we envision an expanded SOOS that relies heavily on the use of autonomous sampling and includes:

- Profiling floats with additional biogeochemical sensors, depth range and longevity.
- Cost-effective, long-term, moored time series stations, measuring velocity and water properties, and transferring data using data capsule technology and telemetry.
- Gliders used routinely for monitoring key areas and water mass formation areas, including beneath the ice
- Sea ice and snow thickness delivered on a routine basis from satellite sensors, well-calibrated against a decade of \textit{in situ} studies.
- Routine delivery of Southern Ocean state assessments and increasing use of reanalyses in the interpretation of observations.
- Increased capability to observe the Southern Ocean developed in additional countries.
- Development of affordable sensors for biology and biogeochemistry for use on moorings, gliders, marine mammals and floats
- Moored arrays monitoring the major dense water overflows, outflows and shelf waters. Water sampling throughout year for physical and chemical properties from Antarctic bases
- Deployment of chlorophyll a sensors, flow cytometers, and FRRF on floats and AUVs
- Repeat sea ice transects every 30-60 degrees of longitude.
- Comprehensive multi-disciplinary underway sampling of the circumpolar Southern Ocean from an expanded fleet of ships-of-opportunity.

5. Conclusion

The Southern Ocean influences climate, biogeochemical cycles and biological productivity on global scales. Many of the most difficult and pressing issues faced by society – climate change, sea-level rise, ocean acidification, and conservation of marine resources – cannot be addressed effectively without improved understanding of Southern Ocean processes and feedbacks and their sensitivity to change. The most urgent research challenges in the Southern Ocean often span disciplines. A Southern Ocean Observing System is needed to provide the sustained, integrated, multi-disciplinary observations required to meet these challenges.
### Acronyms:

2289  **AABW**  Antarctic Bottom Water  
2290  **AAIW**  Antarctic Intermediate Water  
2291  **ACC**  Antarctic Circumpolar Current  
2292  **ADCP**  Acoustic Doppler Current Profiler  
2293  **AGCS**  Antarctica in the Global Climate System  
2294  **ATCM**  Antarctic Treaty Consultative Meeting  
2295  **AUV**  Autonomous Underwater Vehicle  
2296  **CAML**  Census of Antarctic Marine Life  
2297  **CCAMLR**  Commission for the Conservation of Antarctic Marine Living Resources  
2298  **CCHDO**  CLIVAR Carbon and Hydrographic Data Office  
2299  **CiC**  Climate and the Cryosphere  
2300  **CLIVAR**  Climate Variability and Prediction Program  
2301  **CPR**  Continuous Plankton Recorder  
2302  **CTD**  Conductivity – Temperature – Depth (pressure)  
2303  **GOOS**  Global Ocean Observing System  
2304  **GCS**  Global Climate Observing System  
2305  **GEOSS**  Global Earth Observing System of Systems  
2306  **GLOSS**  Global Sea Level Observing System  
2307  **ICED**  Integrated Climate and Ecosystem Dynamics  
2308  **IMBER**  Integrated Marine Biogeochemistry and Ecosystem Research  
2309  **IMOS**  Integrated Marine Observing System (Australia)  
2310  **IOC**  International Oceanographic Commission  
2311  **IPAB**  International Program for Antarctic Buoy Systems  
2312  **IPY**  International Polar Year  
2313  **JCOMM**  Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology  
2314  **JCOMMOPS**  JCOMM in-situ Observing System Support centre  
2315  **JGOFS**  Joint Global Ocean Flux Study  
2316  **NADC**  National Antarctic Data Centre  
2317  **NOAA**  National Oceanographic and Atmospheric Administration  
2318  **NODC**  National Oceanographic Data Centre  
2319  **POGO**  Partnership for Observations of the Global Ocean  
2320  **SAMW**  Subantarctic Mode Water  
2321  **SASSI**  Synoptic Antarctic Shelf Slope Interaction (IPY project)  
2322  **SCADM**  SCAR Standing Committee on Antarctic Data Management  
2323  **SCAR**  Scientific Committee on Antarctic Research  
2324  **SCAR MarBIN**  SCAR Marine Biodiversity Information Network  
2325  **SCOR**  Scientific Committee on Oceanographic Research  
2326  **SO**  Southern Ocean  
2327  **SOCEB**  Southern Ocean Carbon, Ecosystems and Biogeochemistry  
2328  **WCRP**  World Climate Research Program  
2329  **WMO**  World Meteorological Organisation  
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