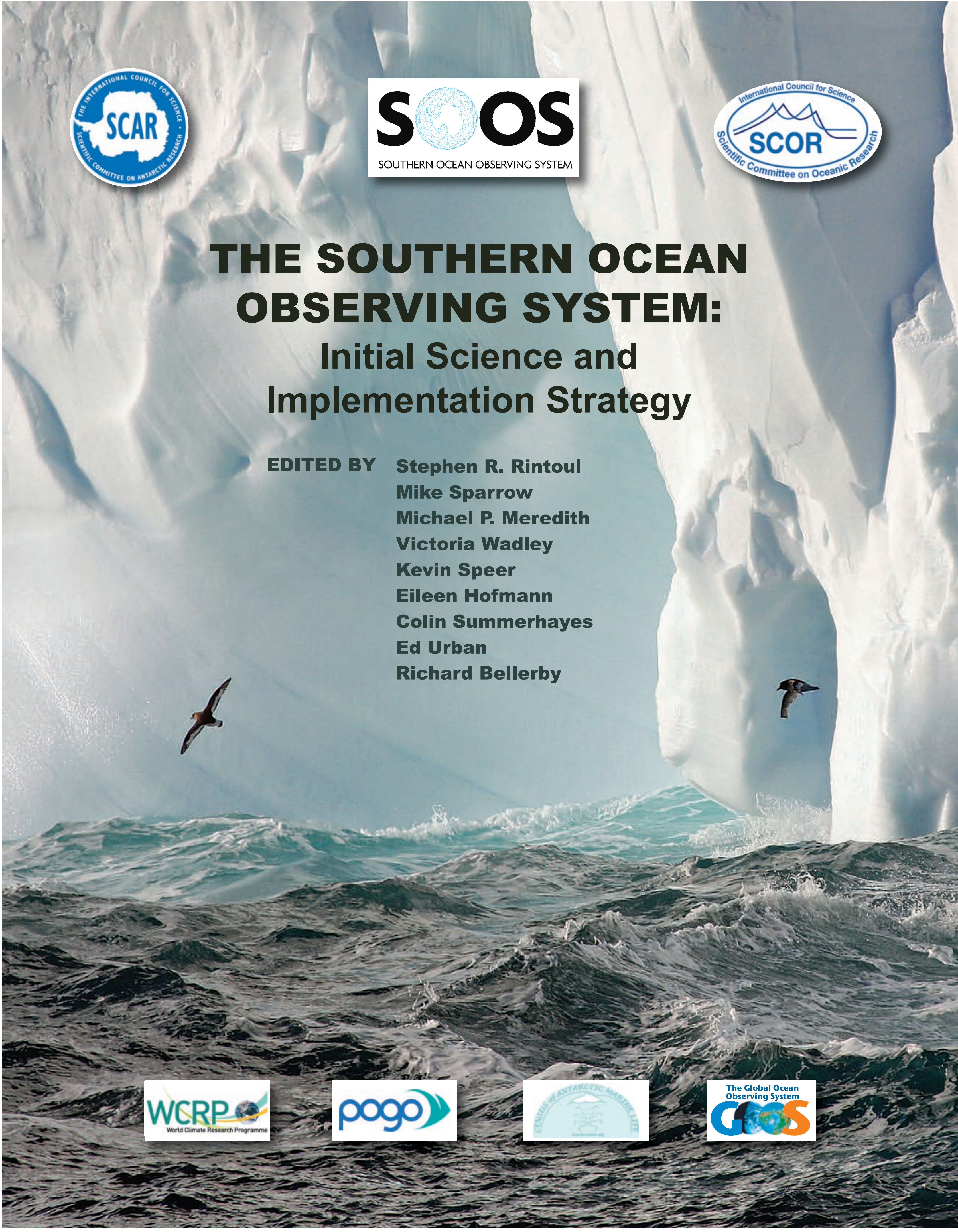

SOUTHERN OCEAN OBSERVING SYSTEM

THE SOUTHERN OCEAN OBSERVING SYSTEM: Initial Science and Implementation Strategy

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**The Editors thank these contributors for conducting formal reviews of this Strategy.*

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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 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 atmospheric climate change but caused basin-wide ocean acidification; 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, multi-disciplinary observations are required to detect, interpret and respond to change.

The Southern Ocean Observing System (SOOS) is needed to address six overarching scientific challenges:

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 need to increase understanding 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 other parts 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, ship operators, Antarctic tourism operators, weather and climate forecasters, and educators. Several international organisations, including the Intergovernmental Oceanographic Commission of UNESCO, the World Meteorological Organisation, the Scientific Committee on Oceanic Research, and the Scientific Committee on Antarctic Research, have noted the compelling 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

The purpose of this introduction is to highlight the significance of the Southern Ocean and the rationale for sustained Southern Ocean observations for a general audience; a more detailed and fully referenced scientific justification for SOOS is provided in Section 2. 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.

1.1 The Global Importance of the Southern Ocean

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 (~56 to 62ºS) 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 in these regions 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.

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 release of CO_2 versus uptake of carbon into the ocean interior determines the strength of the Southern Ocean sink of CO_2. This balance depends mainly 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. About 40% of the total global ocean inventory of anthropogenic carbon dioxide is found south of 30°S, whilst export of nutrients by the upper limb of the overturning circulation ultimately supports 75% of the global ocean primary production north of 30°S.

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, water mass formation rates, and air-sea exchange of gases such as carbon dioxide, and affect oceanic organisms from microbes to whales through 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 will 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 through 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.

1.2 The Southern Ocean is Changing

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 global ocean average. The upper layers of the Southern Ocean have freshened as the result of increases in precipitation and the melting of floating glacial ice. 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, with increased melt linked to increased heat flux from the ocean. Widespread warming of AABW has been observed; this is believed to be due to a combination of changes in formation properties, and changes in export driven by climate variability.

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, though the sensitivity of ACC transport to winds is small. The average circumpolar extent of sea ice shows a small but significant increase during the satellite era (post-1978), 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. The regional trends in sea-ice extent have been linked to changing meridional winds associated with the strengthening trend of the Southern Annular Mode. Models also suggest that sea ice thickness will decline more rapidly than ice extent, but there are no robust long-term observations with which to assess whether sea ice thickness has changed.

The uptake of CO_2 by the ocean is changing the ocean's chemical balance, increasing the acidity and reducing the concentration of carbonate ions. Carbonate ions are used by a variety of calcareous organisms to form shells. As the amount of carbonate ion declines, it becomes more difficult for organisms to produce shells and other hard parts made of calcium carbonate. Because of the temperature dependence of the saturation state of calcium carbonate, cold waters in the polar regions will be the first to become under-saturated. There is evidence that such changes are already causing a reduction in calcification of the shells of some organisms. Increased CO_2 can also influence the quantity and nutritional quality of phytoplankton, with consequences for zooplankton, carbon and energy flows, and biogeochemical cycling. The response of the Southern Ocean food web to changes in ocean chemistry remains largely unknown.

The Southern Ocean harbours unique and distinct ecosystems as a result of its isolation and extreme environment. Phytoplankton biomass is generally low, despite high concentrations of macronutrients, often ascribed to the lack of the micronutrient iron. The Southern Ocean food web is characterised by a keystone species, Antarctic krill (*Euphausia suberba*), which supports large populations of higher predators, and which has declined in abundance. This heavy dependence on a single species and the uniqueness of the Southern Ocean food webs and biogeochemical cycles make the system potentially 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. However, many 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 is needed to inform an effective response 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. Bottom pressure recorders (often enhanced with inverted echo sounders) are routinely monitoring flows of the major current systems at key choke points like Drake Passage, whilst conventional tide gauges at coastal locations are useful in this context and also for a range of other applications, including long-term sea level variability and change studies. 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 multi-disciplinary measurements of the upper 1000 m of the water column, and have recently been deployed for the first time around

Antarctica. 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 exploring 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. In particular, the emphasis then was on maintaining the traditional hydrographic sections, high-density expendable bathythermographs (XBTs), 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, for example, in the first broad-scale measurements of salinity in the upper ocean by Argo and tagged marine mammals, which have revealed an enhanced freshwater cycle and 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-borne instruments, 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 (VOS) Programme. 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 on 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. This was explored at a workshop in Hobart in 2006, instigated by the Partnership for Observation of the Global Oceans (POGO), the Census of 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 a wide range of interested parties.

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, to articulate the need for sustained observations to address major outstanding scientific challenges, and to provide a road-map 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 are presented in Chapter 4.

2. Detailed Background and Rationale

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 latitudes, 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 into the ocean interior 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).

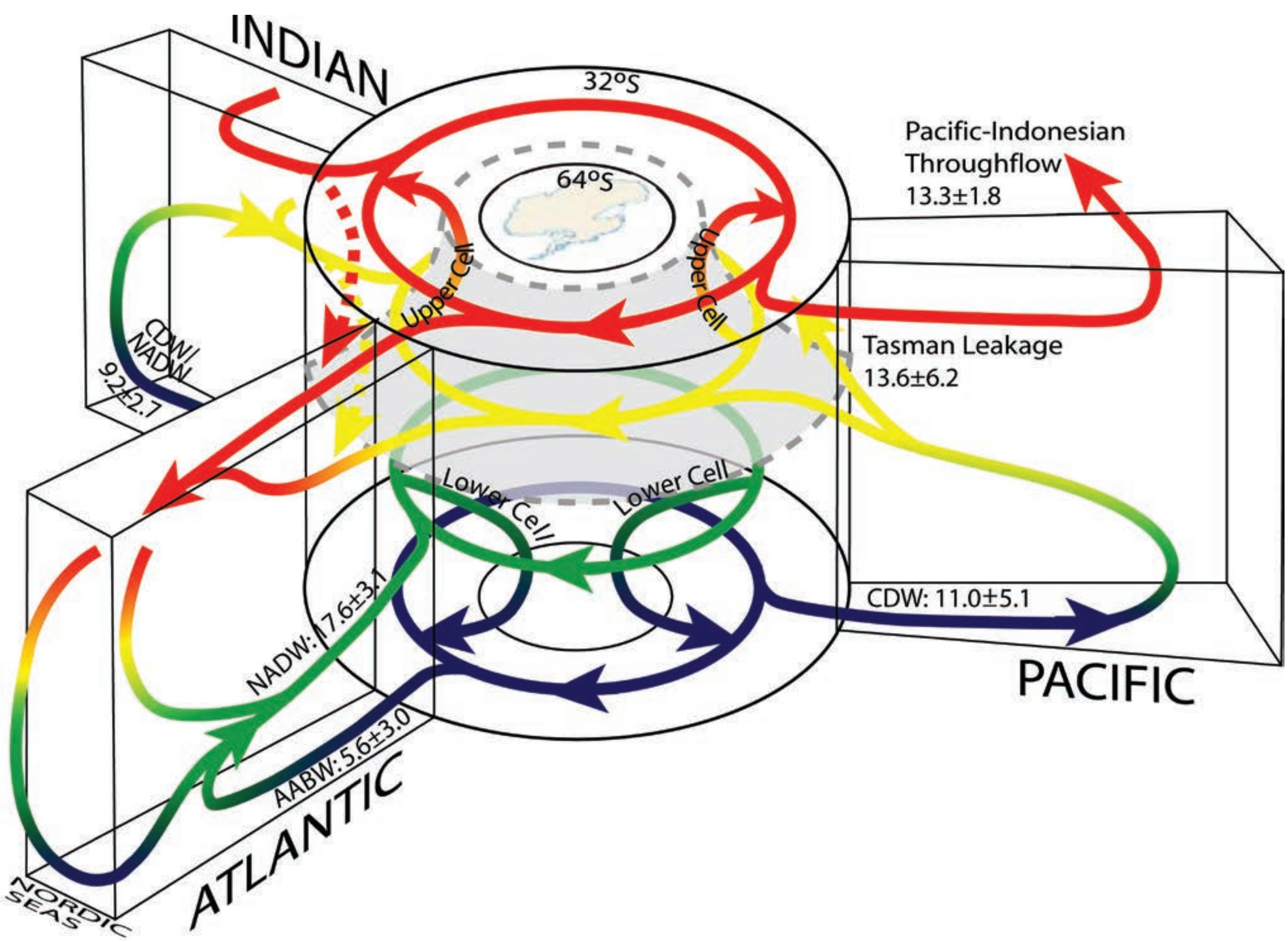

Figure 1: *A representation of the global overturning circulation. The Southern Ocean connects the ocean basins, through the Antarctic Circumpolar Current, and connects the upper and lower limbs of the global overturning circulation, through water mass transformation. From Lumpkin and Speer (2007), Copyright American Meteorological Society. Reprinted with permission.*

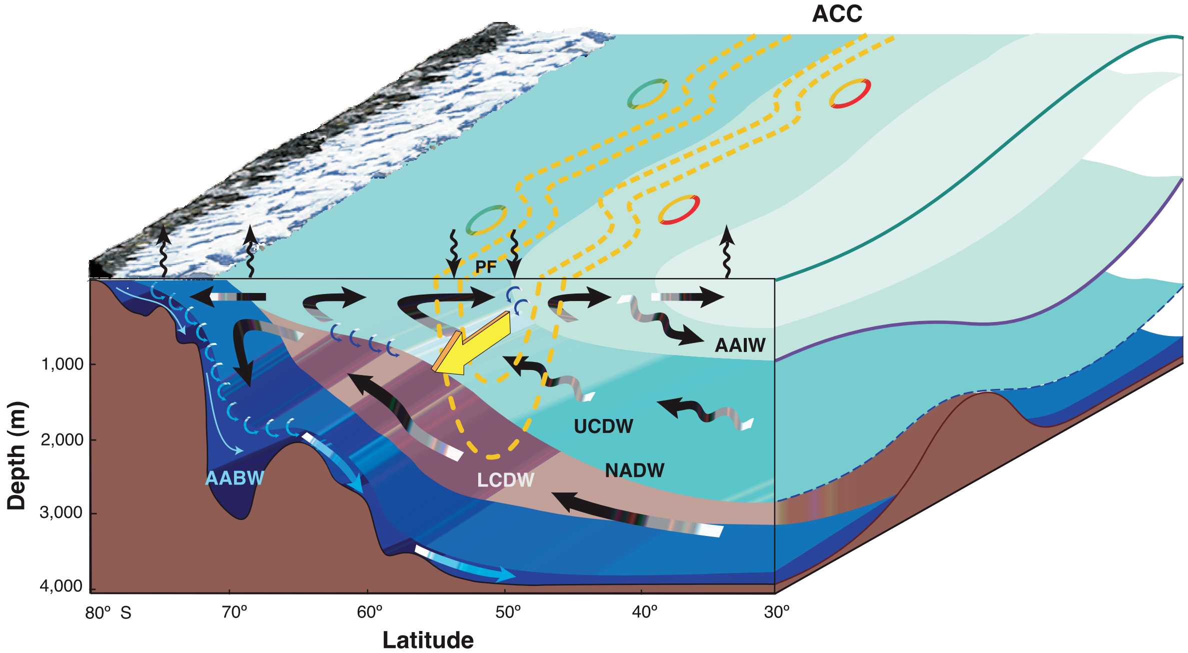

Figure 2: *A sketch of the ACC system showing the eastward flow of the ACC (orange dashed lines), the north-south meridional overturning circulation (black arrows), and the major water masses. Antarctica is at the left side. The east-west section displays the isopycnal and sea surface tilts in relation to submarine ridges; these tilts 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), Copyright American Meteorological Society. Reprinted with permission.*

The overturning circulation largely determines the overall rate and extent of exchange 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).

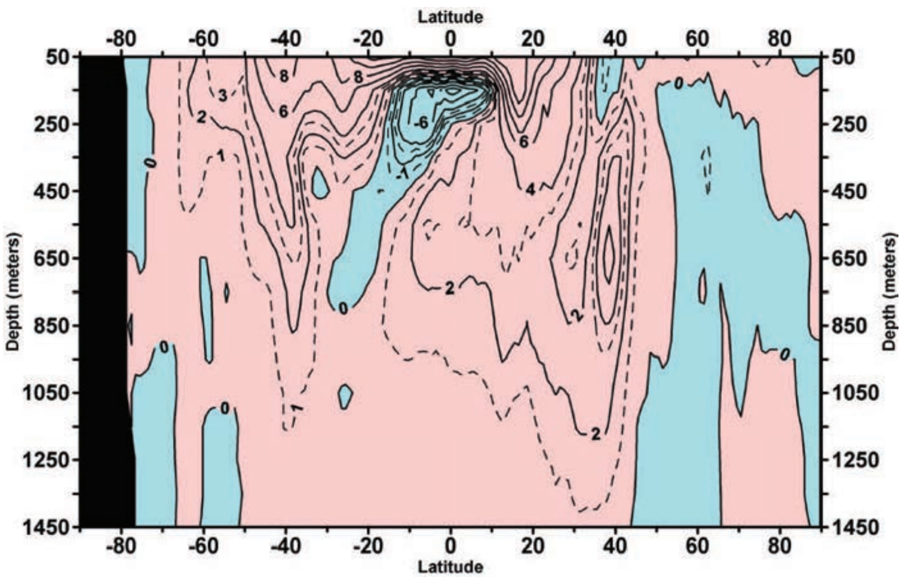

Figure 3: *Linear trend (1955–2003) of the zonally integrated heat content of the world ocean by one-degree latitude belts for 100-m thick layers. Heat content values are plotted at the midpoint of each 100-m layer. Contour interval is 2 x 10^{18} J $year^{-1}$. From Levitus et al. (2005). Used with permission from the American Geophysical Union.*

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 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 CO_2 (Figure 4). Upwelling of carbon-rich deep water at high latitudes tends to cause release of carbon dioxide to the atmosphere and wind-driven variations in the Southern Ocean overturning have been linked to changes in ocean uptake of CO_2 (Butler et al., 2007; Lenton and Matear, 2007; Le Quéré et al., 2007; Lovenduski et al., 2007; Verdy et al., 2007). Changes in the strength of Southern Ocean overturning have climatic implications on a range of timescales, from interannual and decadal up to millennial and beyond; for example, large changes in Southern Ocean air-sea exchange during the Last Glacial Maximum are believed to have been associated with significant changes in the pattern and strength of overturning (e.g. Watson and Naveira Garabato, 2006).

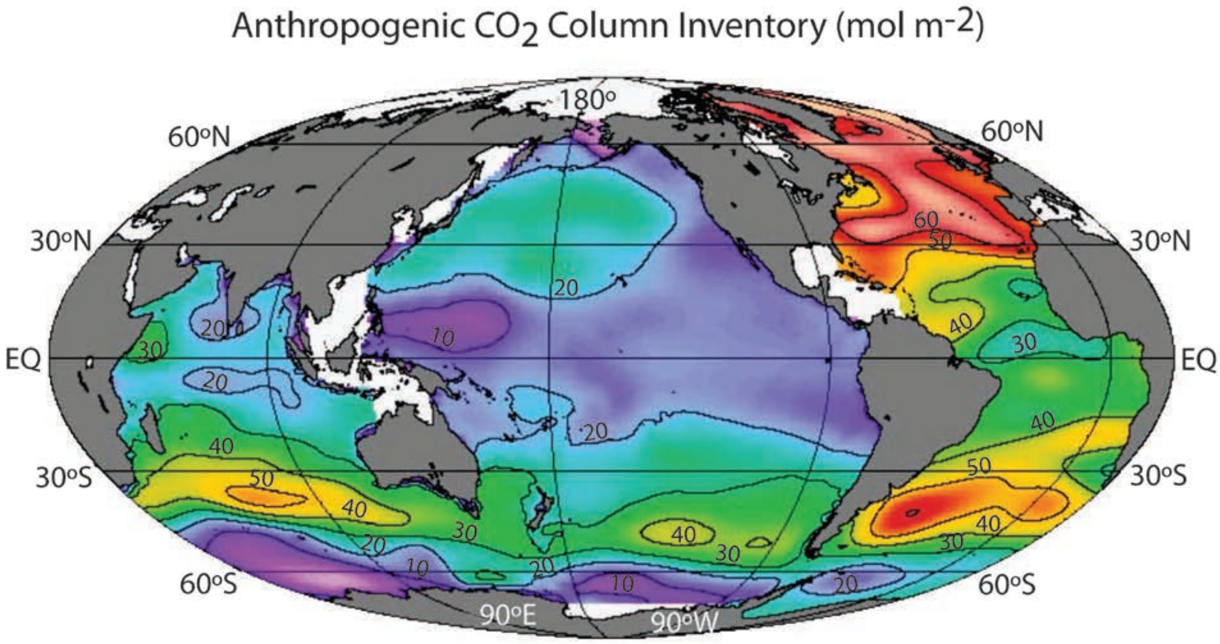

Figure 4: *Column inventory of anthropogenic CO_2 in the ocean. High inventories are associated with deep water formation in the North Atlantic and intermediate and mode water formation between 30° and 50°S. Total inventory of shaded regions is 106±17 Pg C. From Sabine, et al., 2004. The oceanic sink for anthropogenic CO_2. Science 305:367-371. Reprinted with permission from AAAS.*

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 utilised 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).

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 (e.g. Toggweiler and Samuels, 1998). 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). Ocean observations have been interpreted as evidence that the real ocean is closer to the latter case (Böning et al., 2008), but the issue remains a topic of active debate. 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.

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) was observed between 1965 and 2000 (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 contribution to ventilation of the deep ocean similar 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., 2005b; 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). There are also indications that MWP-1a (melt water pulse 1a), which is believed to have been a prominent feature of the last deglaciation around 20,000 years ago, originated from the Antarctic Ice Sheet. MWP-1a is believed to have led to a sea-level rise of ~20 meters in less than 500 years (Weaver et al., 2003).

The ACC is the primary means of exchange of mass, heat and freshwater among the ocean basins (Figure 1). 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 several important and complex ways. During winter, Antarctic sea ice covers approximately 19 x 10^6 km^2, a larger area than the continent itself, and decreases to 20% of this amount during summer (Figure 5). Sea ice 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 transfer by 90%. 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, contributing to cooling. A decrease in sea-ice extent, on the other hand, reduces the albedo and warms the ocean, driving further melt. Thus sea ice provides a strong positive feedback effect on climate. The salt released when sea ice forms is also key to dense bottom 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. Changes in sea ice extent have been linked to large swings in atmospheric CO_2 between glacial and interglacial periods (Stephens and Keeling, 2000).

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 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 6, Atkinson et al., 2004), and to changes at higher trophic levels (Barbraud et al., 2000)

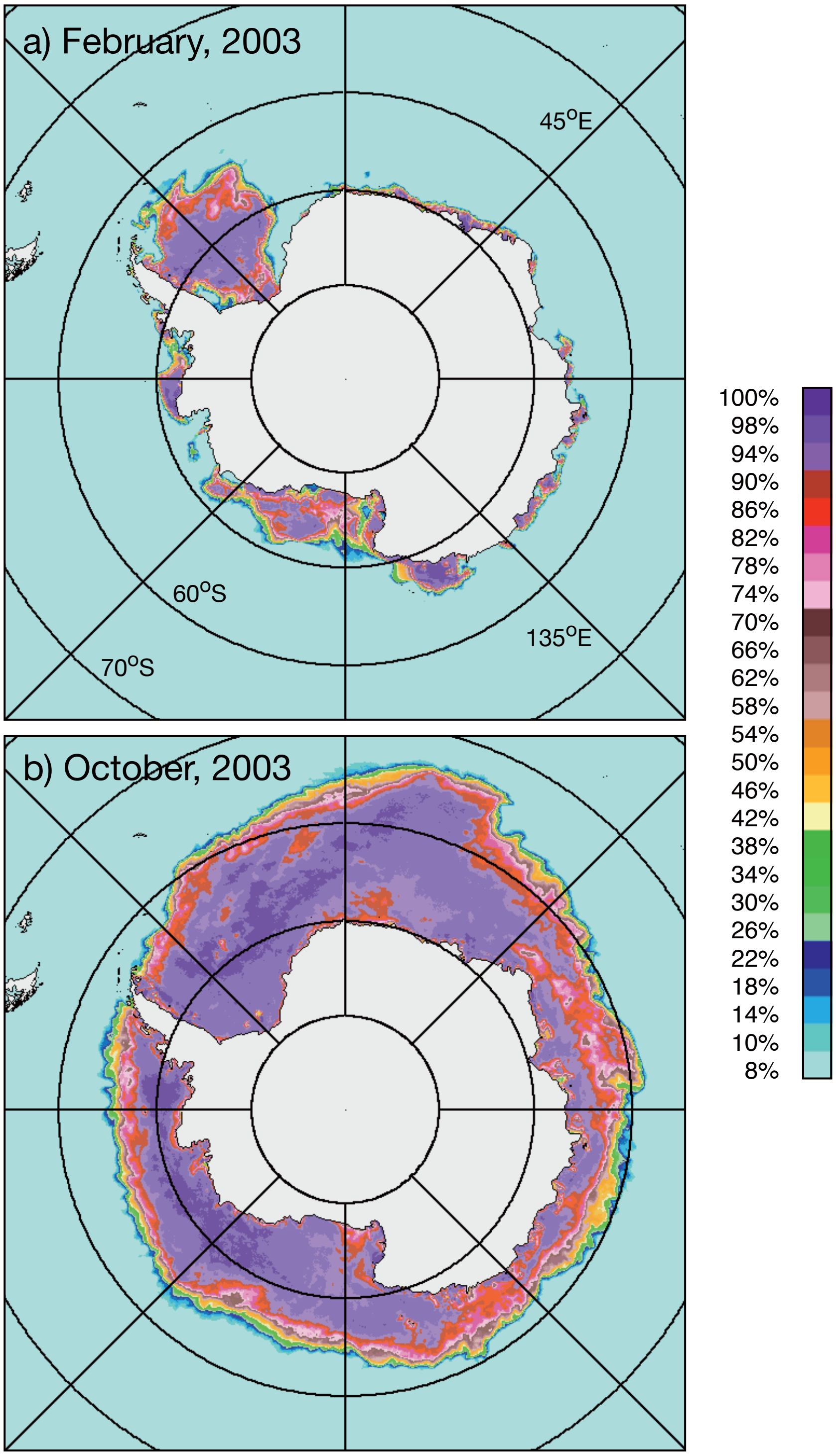

Figure 5: *Minimum (February) and maximum (October) sea-ice extent around Antarctica for 2003 from AMSR-E passive microwave data. Courtesy J. Comiso, NASA/Goddard Space Flight Centre, USA.*

Sea ice extent and concentration can be measured from a variety of satellite instruments (e.g. Figure 5), and algorithms to derive ice properties from raw satellite measurements 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 (Rothrock et al., 1999) between 1958-1976 and 1993-1997. 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. These have been compiled into a climatology for the period 1980–2005 (Worby et al., 2008). A few measurements also exist from moored instruments (Strass and Fahrbach, 1998; Worby et al., 2001) and *in situ* drilling (e.g. Wadhams et al., 1987).

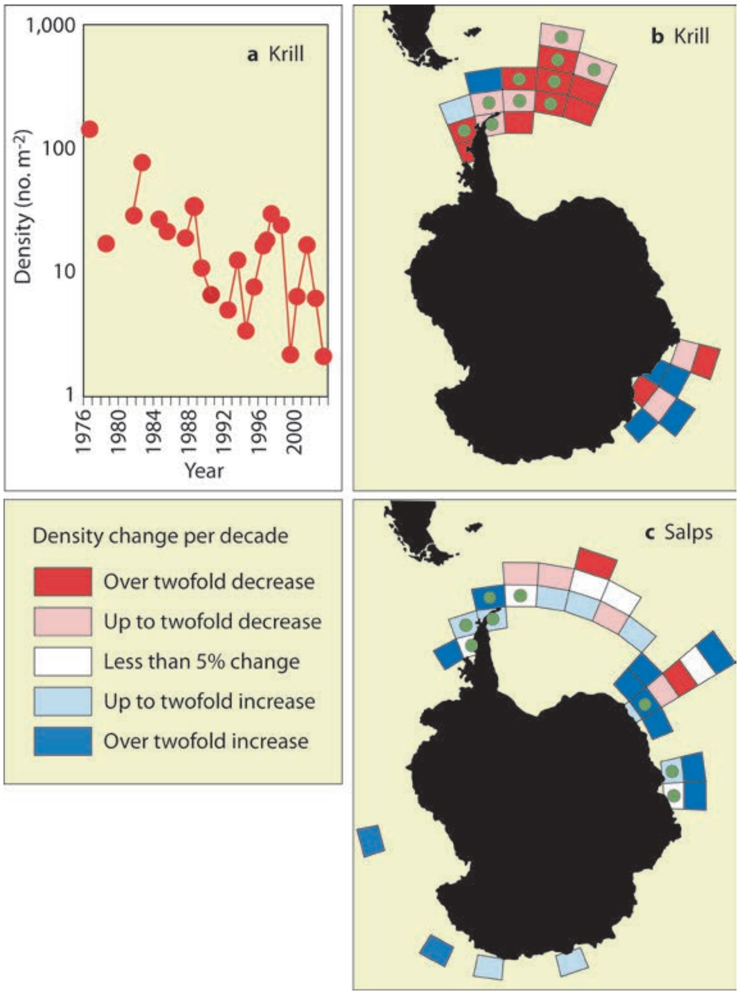

Figure 6: *Temporal change of krill and salps. (a) Krill density in the SW Atlantic sector (4,948 stations in years with >50 stations). Temporal trends include (b) post-1976 krill data from scientific trawls; (c) 1926–2003 circumpolar salp data south of the southern boundary of the Antarctic Circumpolar Current. Reprinted by permission from Macmillan Publishers Ltd: Nature (Atkinson A, Siegel V, Pakhomov E, Rothery P (2004) Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature 432:100-103.), copyright (2004).*

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 shelves has increased with growing evidence that the continental ice sheets can respond rapidly to changes in the floating ice shelves 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 area (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, 2007). Warmer ocean temperatures have been linked to an increase in the basal melt rate and the retreat of grounding lines in Antarctica (Figure 7, Rignot et al., 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 present models; hence long-term observations of the ocean near and beneath ice shelves are crucial for testing and improving models.

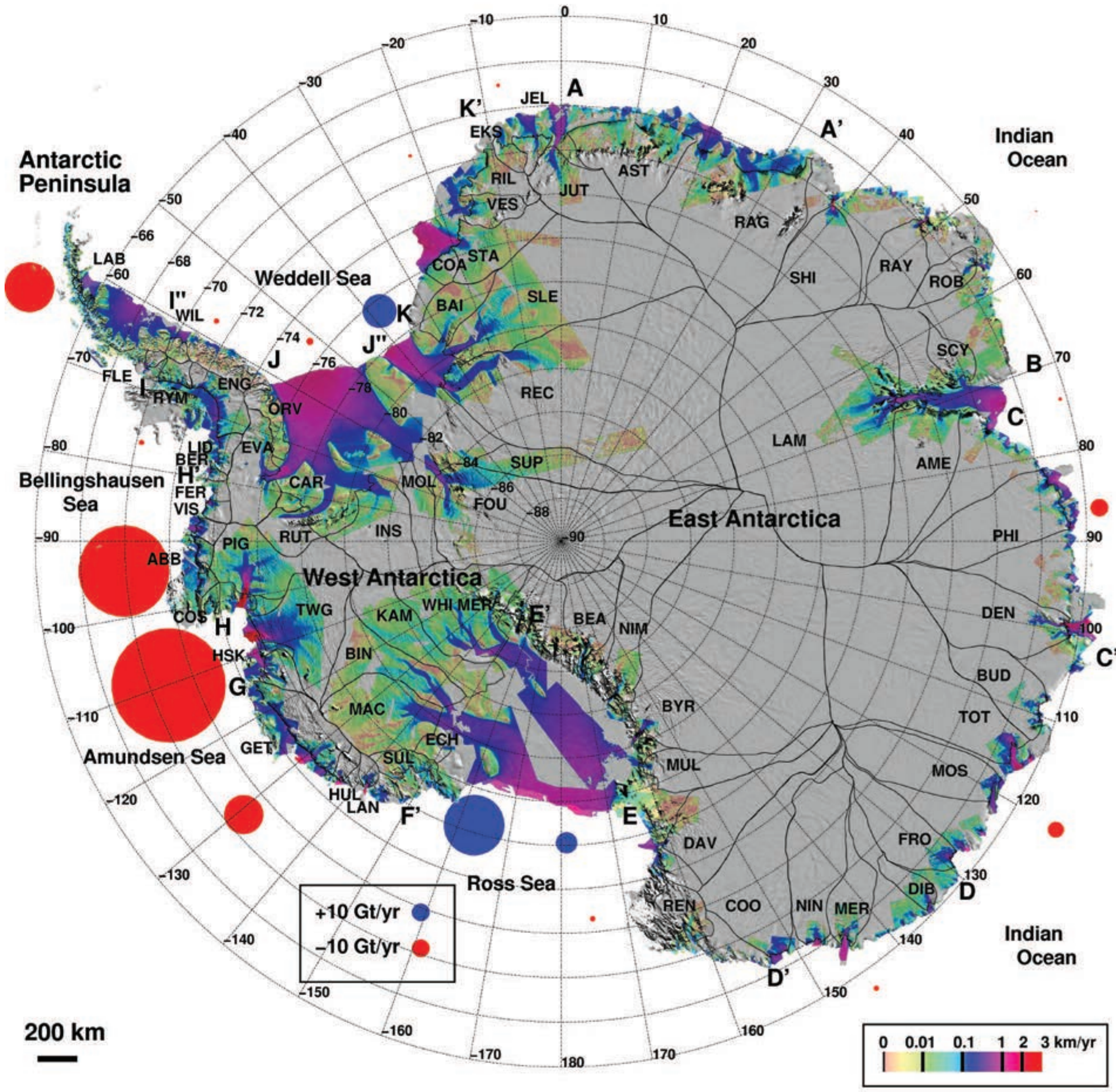

Figure 7: *Ice velocity of Antarctica, colour coded on a logarithmic scale. Circles denote mass loss (red) or gain (blue) of large basins in gigatonnes per year. Drainage basins are black lines extending from the grounding-line flux gates. Reprinted by permission from Macmillan Publishers Ltd: Nature Geosciences (Rignot, E. et al., 2008. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nature Geoscience 1:106-110), copyright (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), which have been 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). In the Southern Ocean, distinguishing these effects is difficult because of limited observations and understanding of how changes in the physical and biogeochemical environments are linked to changes in ecosystem structure and function.

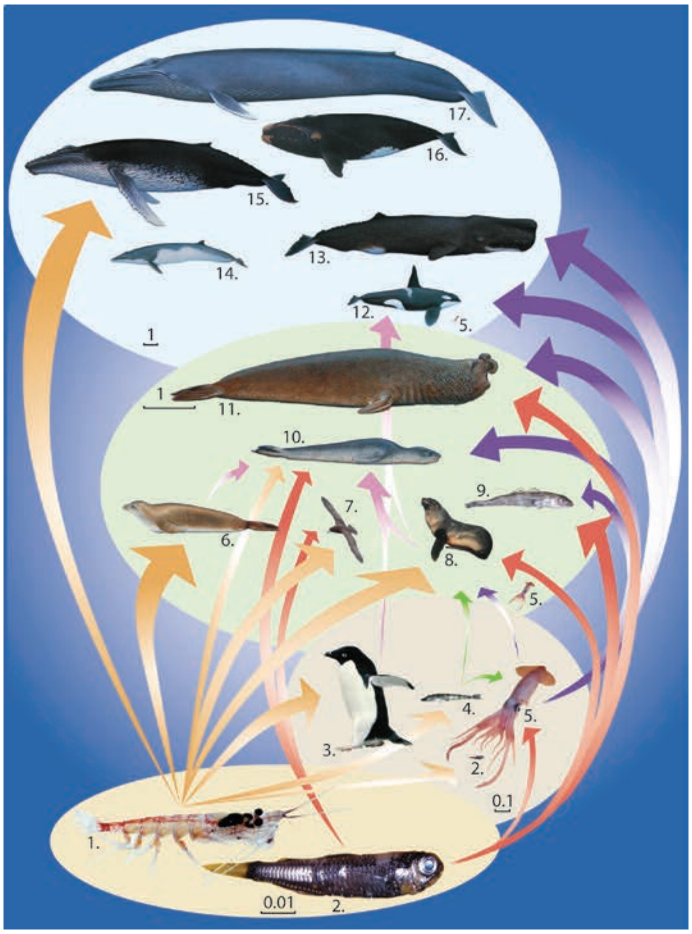

Figure 8: *A generalised Southern Ocean food web from the level of krill upwards. Four main size groups of animals (each in a coloured ellipse) are shown. Each animal is shown to scale within each ellipse. Scale bars are present in each ellipse along with a measurement in metres showing how big the bar 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*. Top blue ellipse: (5) squid at new scale, (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, 2007; Adélie penguin photo – A. Cawthorn; Other photos – A. Constable). From Constable and Doust (2009).*

The Southern Ocean ecosystems are structured broadly by latitude, or more precisely, by the quasi-zonal structure of the ACC (e.g. Treguer and Jacques, 1992; Grant et al., 2006; Griffiths et al., 2009; Figure 9) and by depth. In the silica-limited waters north of the Subantarctic 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.

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., 2007b). In the Western Antarctic Peninsula, ice-dependent Antarctic species (Adélie penguin, *Pygoscelis adeliae* and Weddell seal, *Leptonychotes weddellii*) are being replaced by open water subantarctic 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 and Patterson, 1997; Ducklow et al., 2007; McClintock et al, 2008, 2010).

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 needed to assess the impacts of 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, 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.

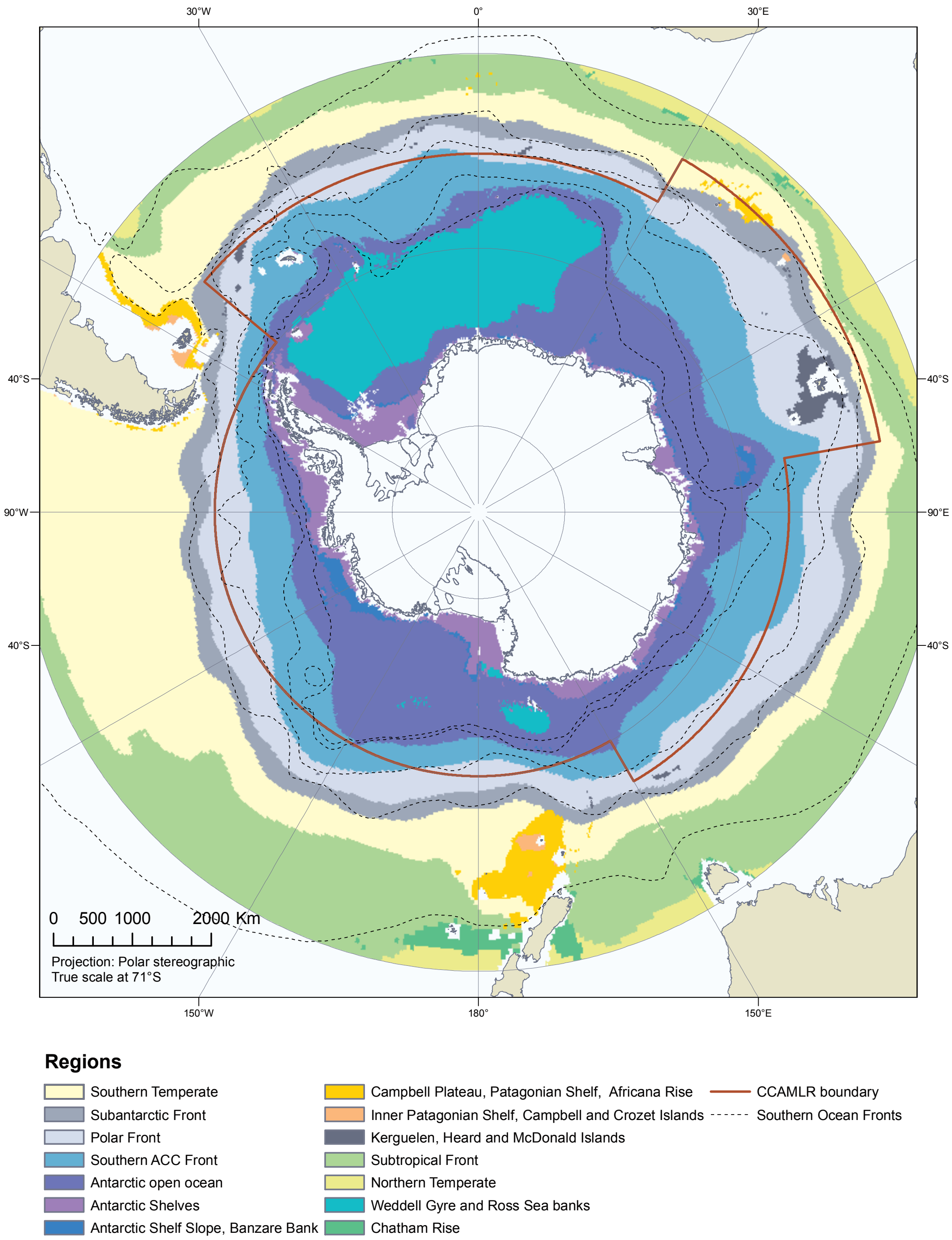

Figure 9: *Bioregionalization of the Southern Ocean (from Grant et al., 2006).*

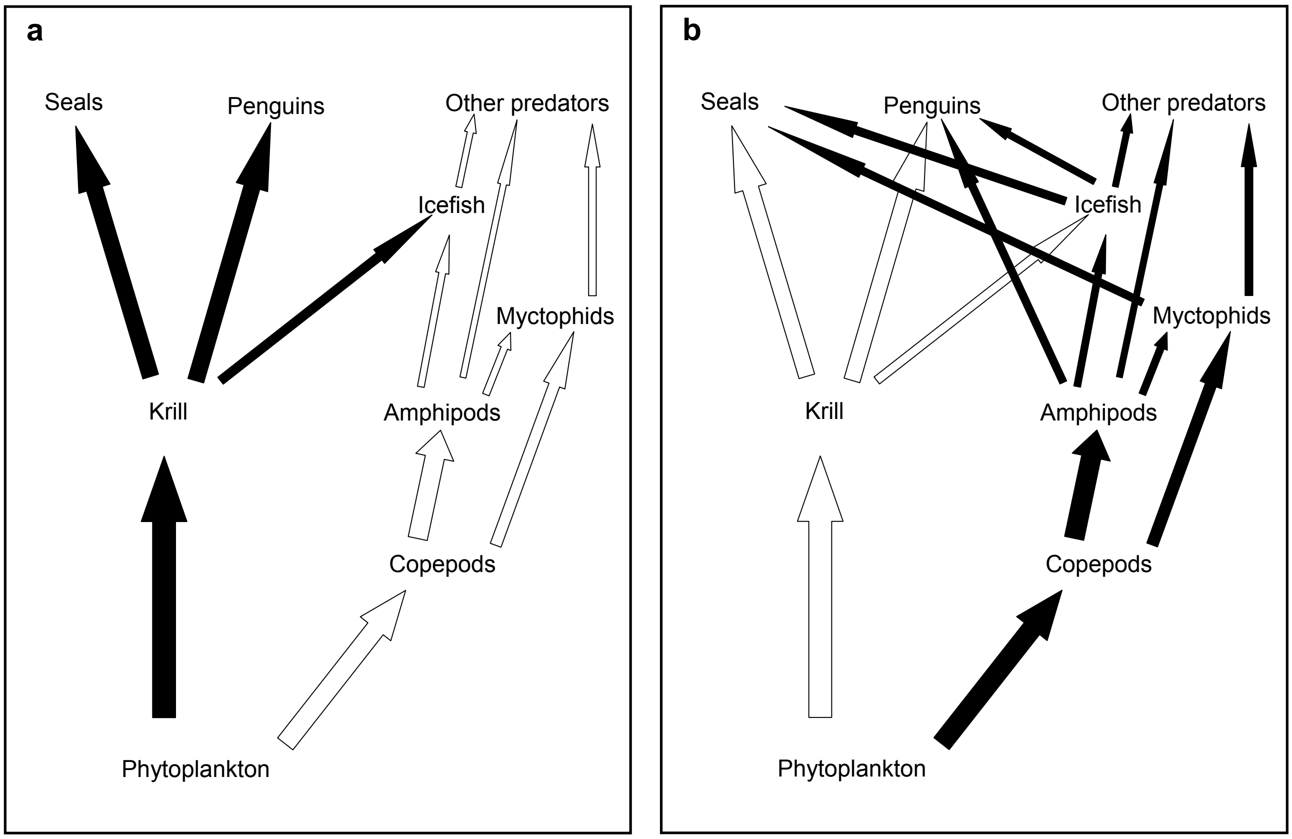

Figure 10: *Alternative pathways in part of the Scotia Sea foodweb. (a) represents years when krill are abundant and (b) indicates years when krill are scarce. Black arrows indicate major trophic pathways. From Murphy et al. 2007b. Spatial and temporal operation of the Scotia Sea ecosystem: a review of large-scale links in a krill centered food web. Philosophical Transactions of the Royal Society B, 362:113-148. Used with permission from the Royal Society (UK) and E. Murphy*

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 several 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 (e.g. Brandt et al., 2007). 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). Nevertheless, care must be taken in extrapolating from laboratory experiments to the open sea, recognising that several Antarctic species survive well in waters around South Georgia that can be 3°C warmer (Turner et al., 2009a). 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 required to inform managers and decision-makers.

Past research programmes 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 programmes like the Global Ocean Ecosystem Dynamics (GLOBEC) project and the Palmer Long-Term Ecological Research programme 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). There are numerous other examples from other sectors of the Southern Ocean; however, we still lack the mechanistic understanding and modelling tools to predict ecosystem responses to climate variability and change on regional and circumpolar scales. Critical gaps are the lack of sustained, integrated observations that span disciplines and a range of time and space scales, and a unified framework in which to synthesise diverse observations and model results.

2.4 Observed Changes in the Southern Ocean

Southern Ocean processes influence weather, 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 for society. In this section, we summarise 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 in the region of the ACC in recent decades (Figure 11) (Gille, 2002, 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.

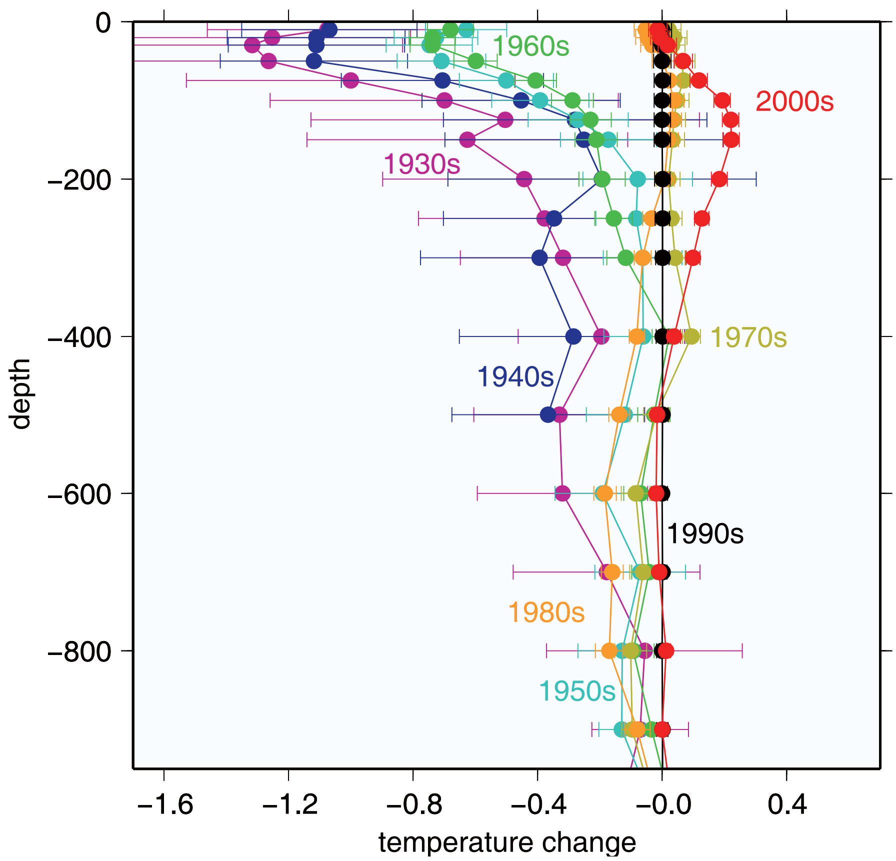

Figure 11: *Profiles of temperature difference between 1990s temperature profiles and hydrographic data sorted by decade. Differences are computed as 1990s reference temperatures minus historic temperature profiles sorted by decade, using the nearest neighbour method. Here results are presented for summer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

Other physical and chemical properties of the Southern Ocean are also changing (Bindoff et al., 2007). Long-term monitoring of sea surface salinity south of Australia shows a net decrease in sea surface salinity during the 1990s in the Antarctic Zone, linked to increased precipitation over the same period (Morrow et al., 2008). 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 1960, 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 decreased 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.

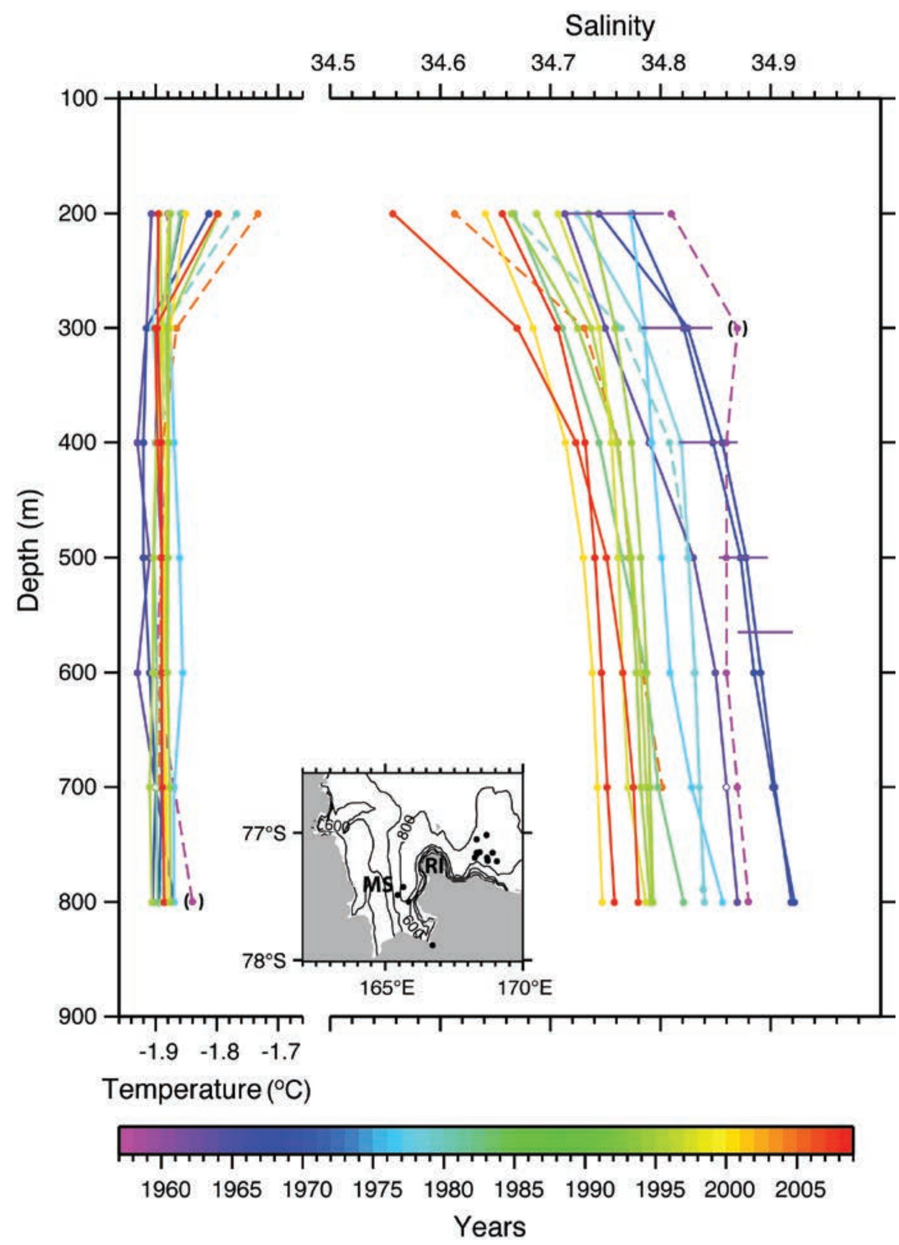

Figure 12: *Freshening of Ross Sea shelf waters between 1960 and 2008 (from Jacobs and Giulivi 2010). Copyright American Meteorological Society. Reprinted with permission.*

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 are ultimately coupled to the atmospheric forcing, but we are still far from understanding all the links between the observed physical changes.

There is fragmentary evidence of changes in the Southern Ocean ecosystem (Smetacek and Nicol, 2005). The range of the coccolithophorid *Emiliania huxleyii* has extended south into the sea-ice zone within the last decade, possibly in response to global warming (Cubillos et al., 2007; Mohan et al., 2008). Changes in seabird and krill abundance have been noted in particular areas (e.g. Naganobu et al., 1999, Croxall et al., 2002; Atkinson et al., 2004). To quantify changes in population levels of top predators, the distribution across the entire geographic range of the species should be considered. In this context, changes in the local geographical distribution, for example, in breeding colonies of penguins, is potentially misleading. The distribution of seabirds and marine mammals follows the ecological differences (food availability) related to hydrology: water masses and pack-ice, and fronts and ice edge, including eddies (Joiris, 1991, 2000; McClintock et al., 2008, 2010; Bost et al., 2009).

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; Barbraud and Weimerskirch, 2001; Jenouvrier et al., 2003; Weimerskirch et al., 2003; Forcada et al., 2005; Jenouvrier, 2005; Barbraud and Weimerskirch, 2006; Jenouvrier et al., 2006; Leaper et al., 2006; Clarke et al., 2007; Barnes and Peck, 2008) 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 started in 1952 (Figure 13, Barbraud and Weimerskirch, 2001) and on the western Antarctic Peninsula (Figure 14, McClintock et al., 2008). However, there are often few observations of change in the physical environment near these colonies, making it difficult to relate changes in predator populations to changes in environmental forcing. SOOS will provide the oceanographic context needed to better understand the environmental factors responsible for such demographic changes.

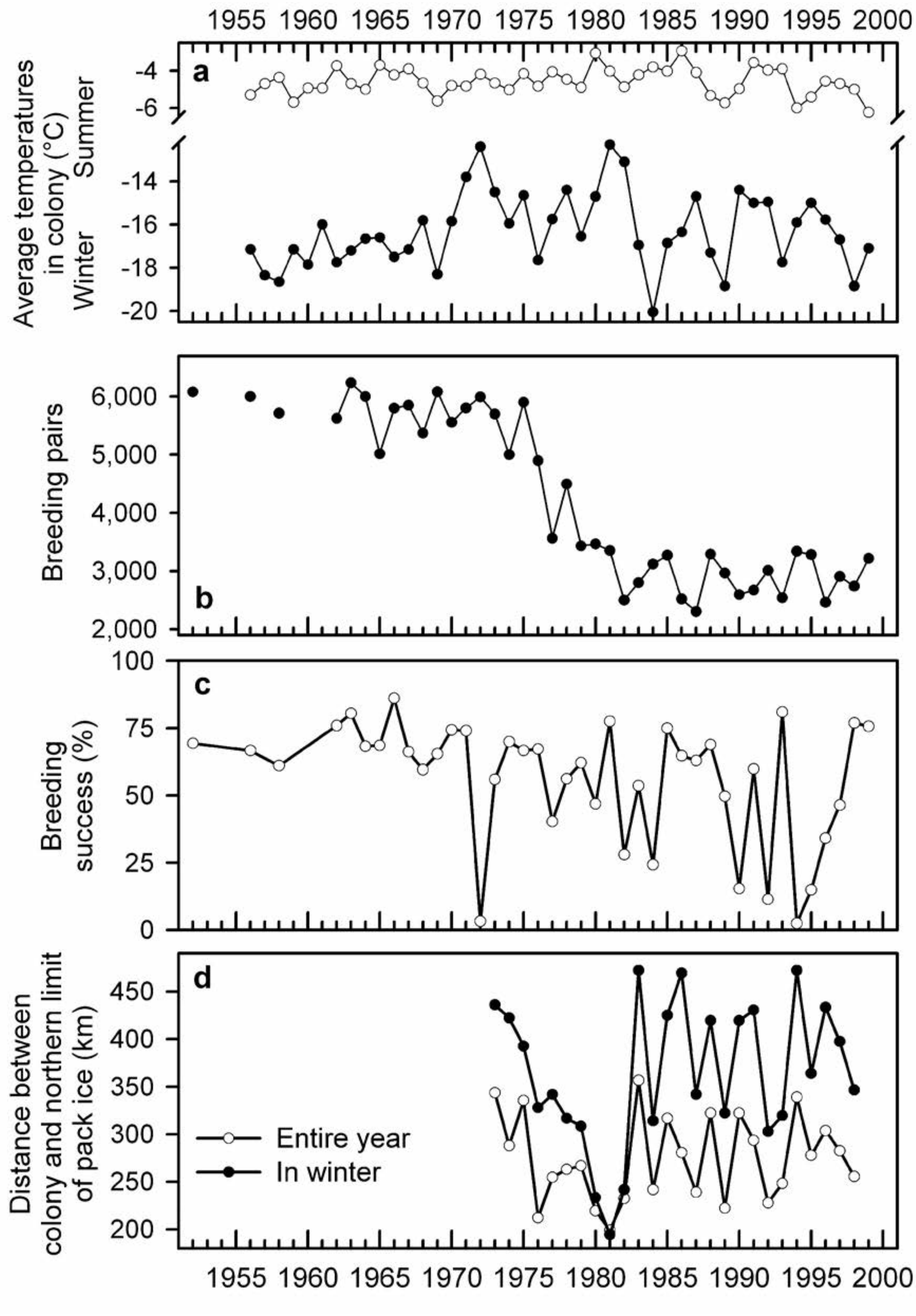

Figure 13: *Climate and population changes. (a) Summer and winter average temperatures recorded at Dumont D'Urville meteorological station (1956-1999). (b) Number of breeding pairs of emperor penguins at Pointe Géologie archipelago, Terre Adélie (1952-1999). (c) Change over time in breeding success (number of chicks fledged divided by number of eggs laid). (d) Changes over time (1973-1999) in the average distance between the penguin colony and the northern extent of the pack ice. From Barbraud and Weimerskirch (2001). Reprinted by permission from Macmillan Publishers Ltd: Nature (Barbraud, C., and H. Weimerskirch. 2001. Emperor penguins and climate change. Nature 411:183-186), copyright (2001).*

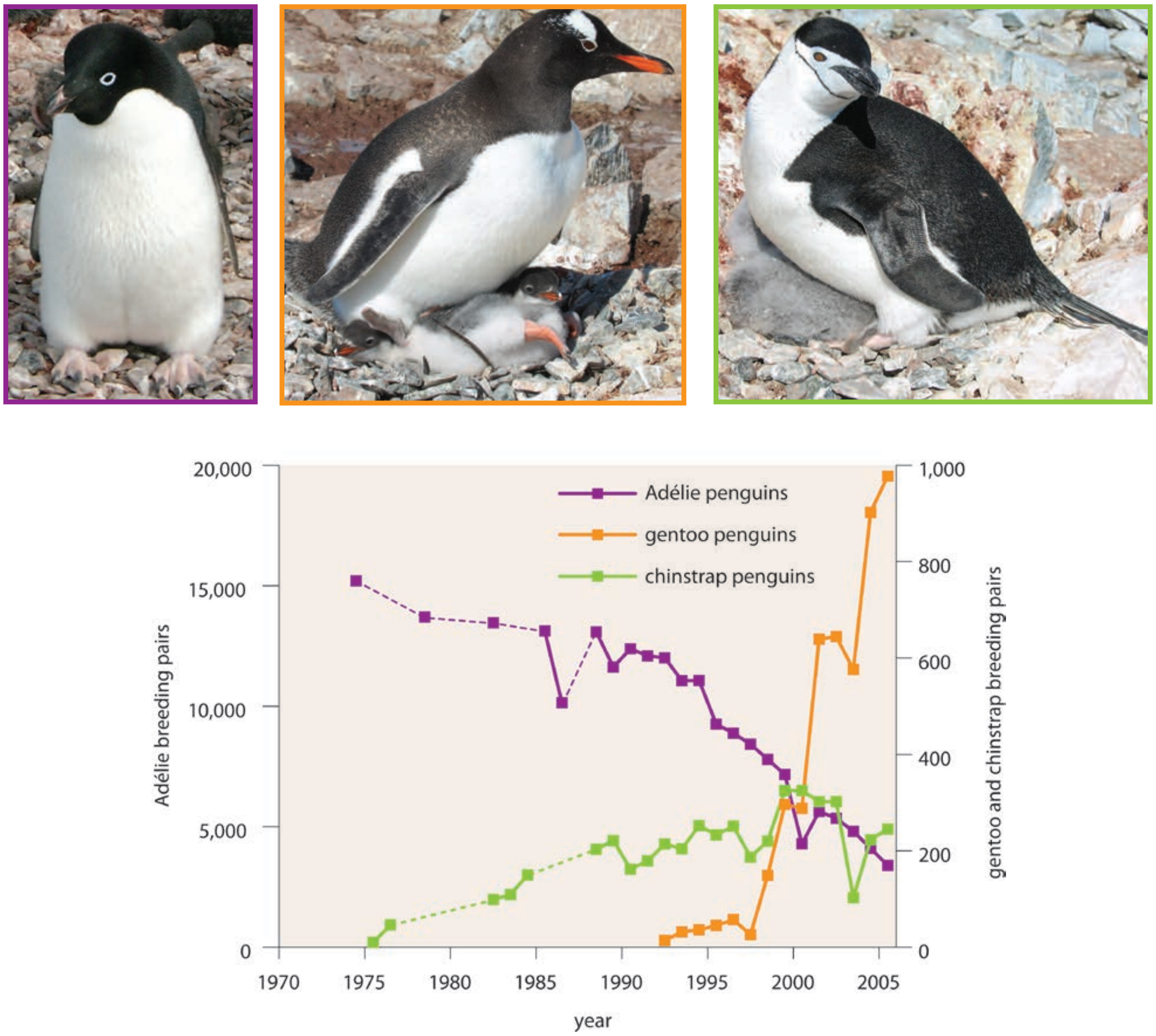

Figure 14: *Changes in the number of breeding pairs in penguin rookeries near Palmer station, western Antarctic Peninsula. As the amount of sea ice declines, ice-dependent Adélie penguins are declining and being replaced by sub-polar Gentoo penguins. Permission to re-use figure from McClintock et al. (2008) granted by American Scientist.*

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; Venegas et al., 2001; 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 primarily restricted 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 that a decline in sea ice extent occurred between the 1950s and 1970s, but these results remain somewhat controversial (e.g. Ackley et al., 2003). While 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 extent (Gregory et al., 2002).

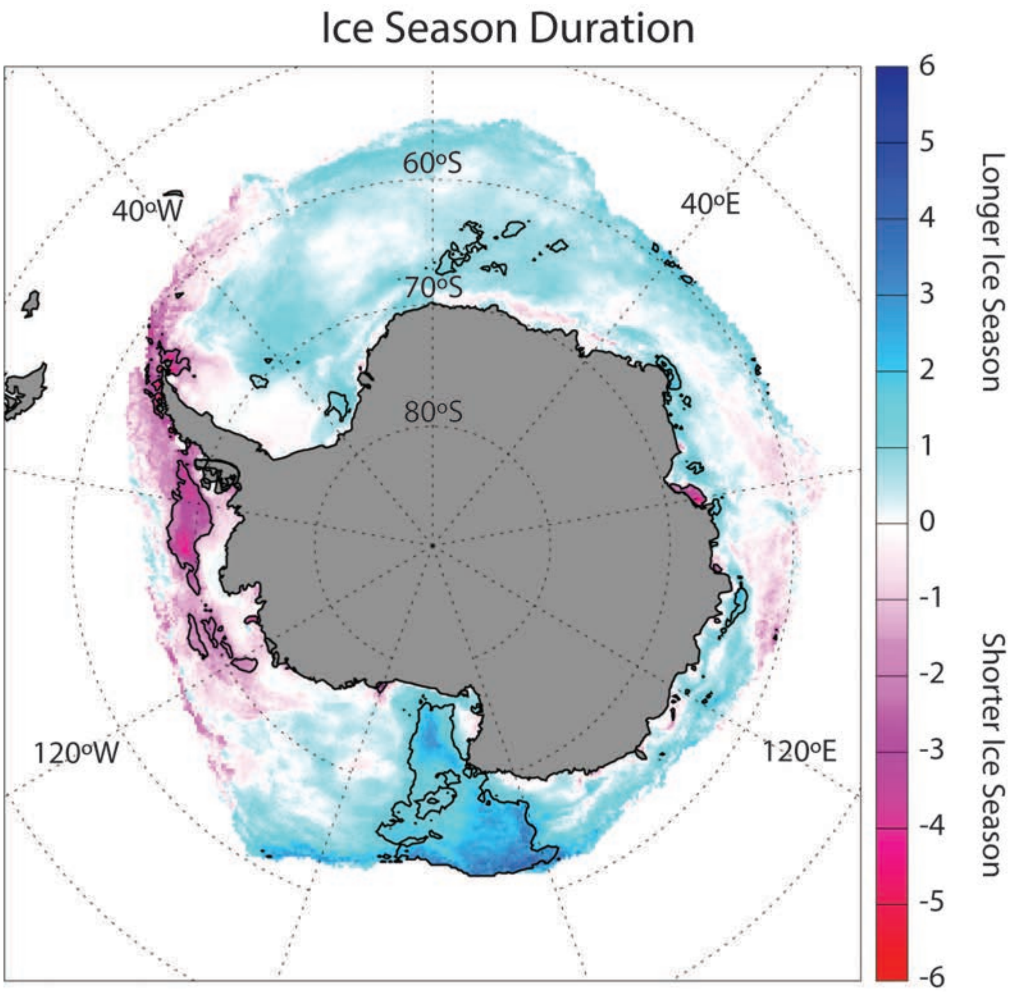

Figure 15: *The 1979–2004 trend (days/year) in ice season duration. The black/white contours delimit the 0.01/0.10 significance levels. Within the sea ice zone, gray shading signifies near zero trend. [Stammerjohn et al., 2008]. Used with permission from the American Geophysical Union.*

Carbon Dioxide Uptake and Ocean Acidification

Uptake of anthropogenic carbon by the Southern Ocean (e.g., Sabine et al., 2004; Hauck et al., 2010) has acted to reduce the rate of increase in atmospheric CO_2 concentration and thereby to slow the rate of climate change. As a result of the increased burden of CO_2, the pH of Southern Ocean surface waters has decreased by about 0.l, corresponding to a 30% increase in acidity, and the carbonate ion concentration has decreased. Ocean acidification is expected to affect a wide range of calcifying organisms, with the aragonite saturation threshold crossed first in the cold polar oceans (e.g. Orr et al., 2005; Royal Society, 2005; Hunt et al., 2008; Fabry et al., 2009; McNeil et al., 2010). The impact of ocean acidification on marine organisms is poorly understood and likely to vary between species; the impact on the Southern Ocean ecosystem as a whole is even less well understood.

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 (Vaughan et al., 2003; King et al., 2004), 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 Antarctic Peninsula have had profound ecological consequences (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 has been more than half this amount already, in just a few decades, raising the possibility of serious disruption to the marine ecosystem 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 et al., 2008; and related papers). The region is also a key breeding and nursery ground for Antarctic krill. 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.

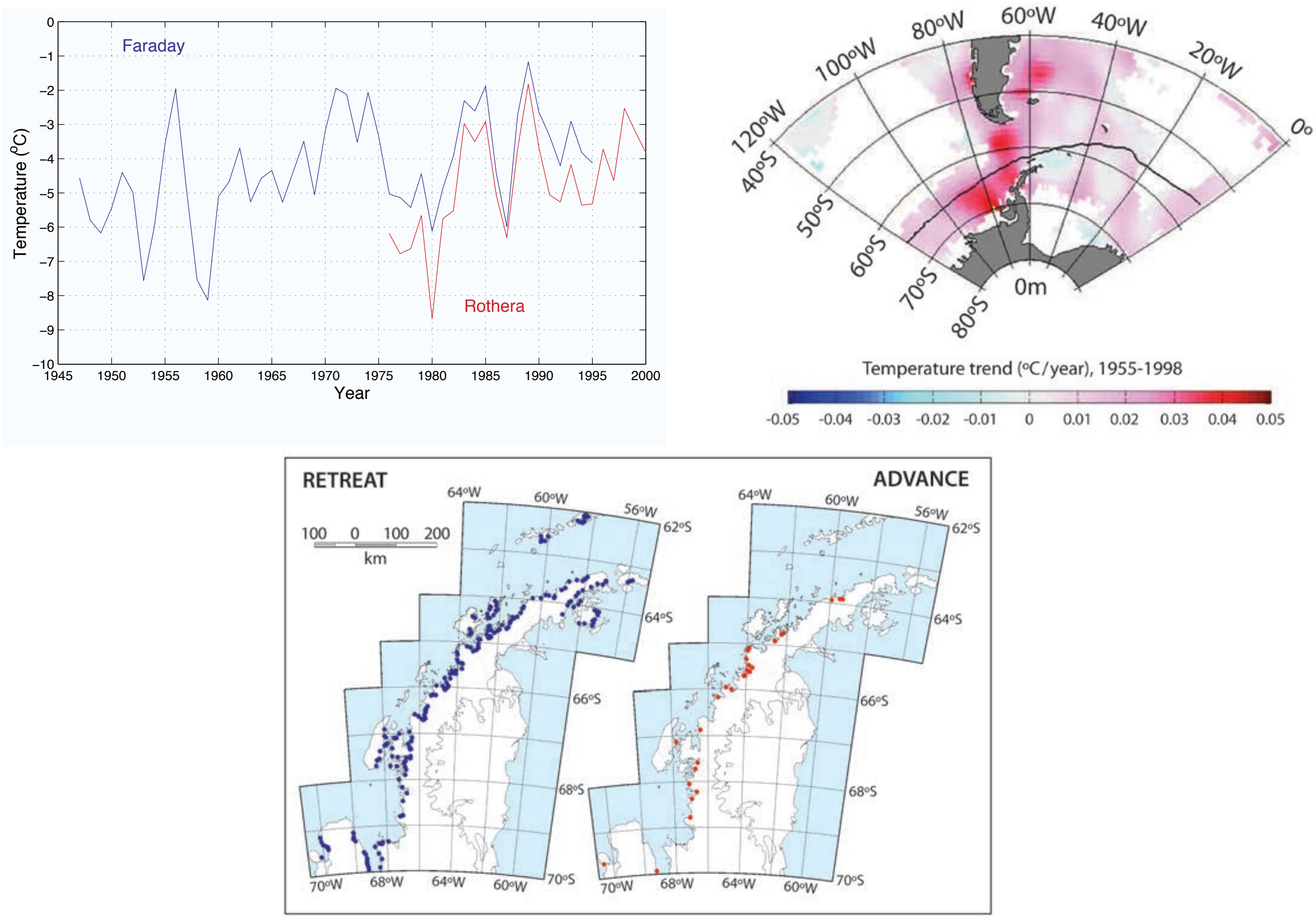

Figure 16 (upper left): *Surface atmospheric temperature change at Faraday and Rothera stations on the western Antarctic Peninsula. Temperature change here has been the most rapid in the Southern Hemisphere, with most of the warming concentrated in the winter months. Source: M. Meredith, BAS.* **Upper 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). Used with permission from the American Geophysical Union.* **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). From Cook, A.J., A.J. Fox, D.G. Vaughan, and J.G. Ferrigno, 2005. Retreating Glacier Fronts on the Antarctic Peninsula over the Past Half-Century. Science 308:541-544. doi:10.1126/science.1104235. Reprinted with permission from AAAS.*

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 perform better at simulating high-latitude climate (Bracegirdle et al., 2008). 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, Turner et al., 2009a). The SST changes are much 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 (compare with 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 CO_2 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). When the seasonality of the surface ocean carbonate ion concentration is taken into account, the aragonite saturation threshold is crossed several decades earlier in winter and delayed in summer (McNeil and Matear, 2008; McNeil et al., 2010),

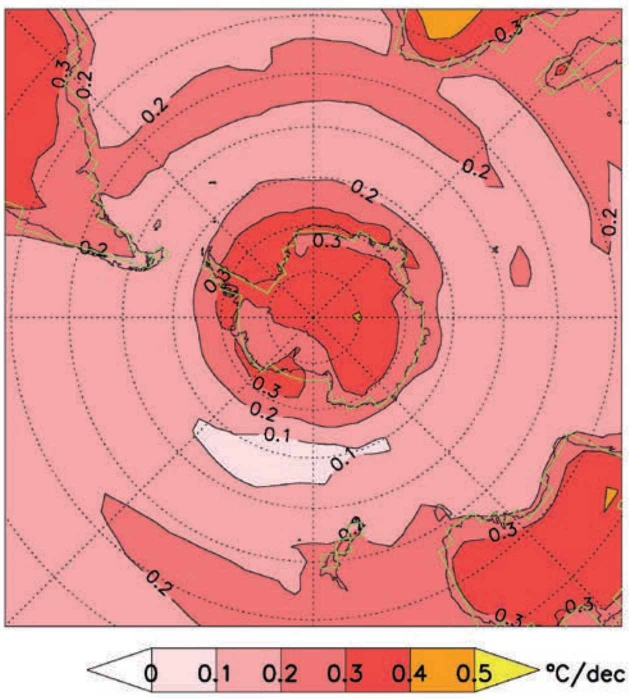

Figure 17a: *Predicted trends in surface temperatures over the next 100 years from a weighted average of the IPCC AR4 coupled models. Note the widespread warming of the air over the Southern Ocean, which is strongest in the Weddell and Ross Seas owing to the retreat of the sea ice there and the consequent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

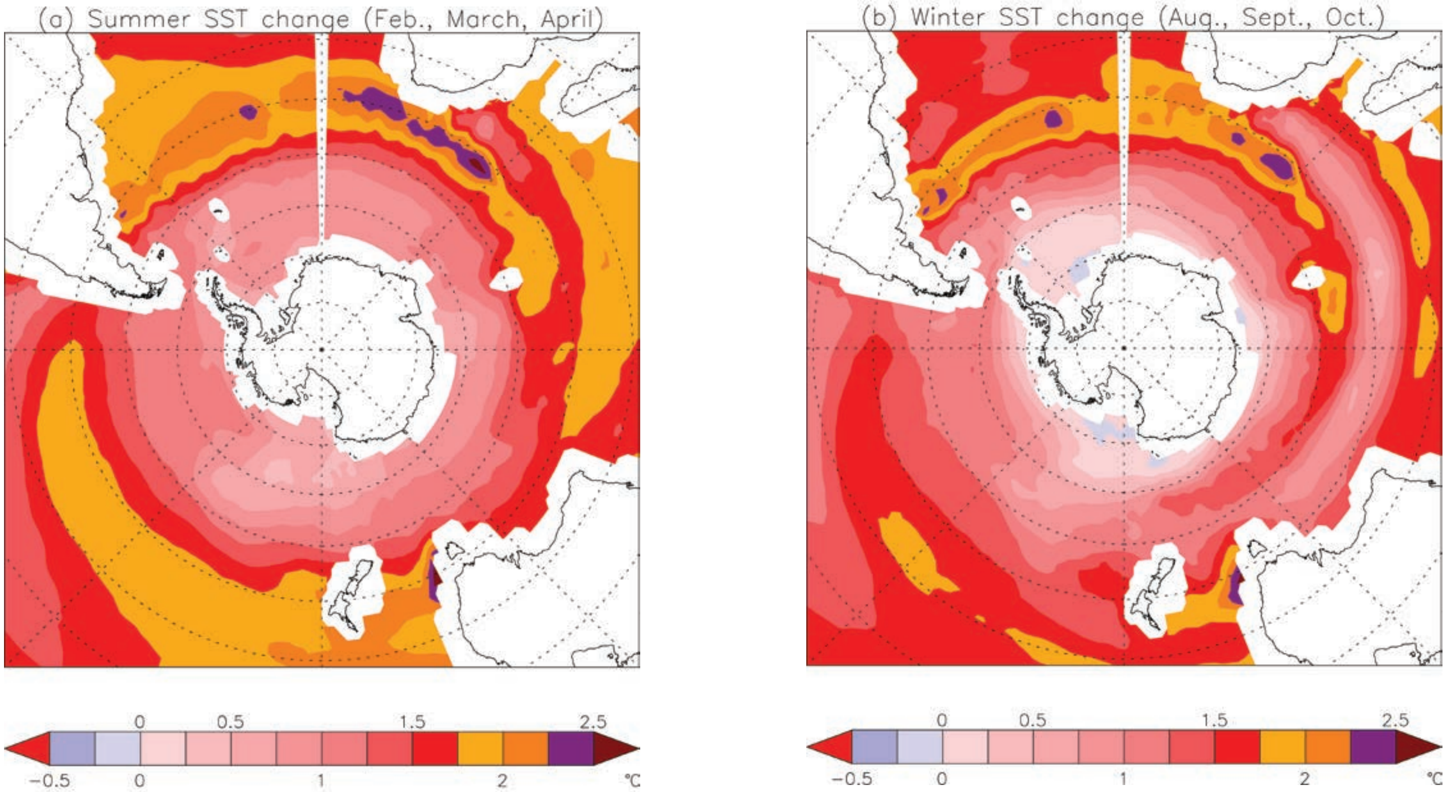

Figure 17b: *Predicted sea surface temperature change between 2000 and 2100 in summer (a) and winter (b). From Turner et al. (2009a).*

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 CO_2 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 scientific community.

3. Design of a Southern Ocean Observing System

3.1 Key Science Challenges and the Need for Sustained Observations

Based on the scientific rationale and gaps in understanding outlined in Section 2, six overarching Southern Ocean science challenges were identified. Sustained observations are essential to meet each of these challenges.

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 that 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 remainder 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, 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 cannot 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 the Northern and Southern 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. Palaeoclimate 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). Southern Ocean overturning is thought to exert a strong control on global productivity and CO_2 (Marinov et al., 2006), and 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 need to include carbon, oxygen and other tracers.

3. The role of the ocean in the stability of the Antarctic Ice Sheet and its future contribution 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 (Rignot et al., 2011). 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 et al., 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

As discussed above, recent studies have highlighted the sensitivity of the global carbon cycle to changes in the Southern Ocean. 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). More surface carbon observations are needed to improve the spatial coverage to reduce the uncertainty in estimates of the air-sea flux of CO_2. However, the Southern Ocean will remain a large conduit for the uptake and global distribution of anthropogenic carbon to the global oceans (Tjiputra et al., 2010). Full water column sections of carbon, oxygen, nutrients and physical variables are needed to track the evolving inventory of anthropogenic CO_2 and other properties related to the carbon and biogeochemical cycles. The uptake of carbon by the ocean results in acidification and changes in carbonate chemistry that will likely have significant consequences for biological and biogeochemical processes in the ocean.

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, including CO_2. 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, which influences 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 is essential to guide conservation and marine resource management decisions (Clarke et al., 2007; Barnes and Peck, 2008). 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 environments are needed, including carbonate system variables, 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) 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 need 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 also. 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). Several 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, the sampling that 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. For brevity, the entries in the list of variables are often short-hand for a number of related variables.*

	Key science challenges					
Variables required to be measured	Freshwater balance	Overturning circulation	Ice sheet stability and sea-level rise	Future of sea ice	Carbon and biogeochemistry	Impact on ecosystems
Stratification (T(z),S(z))	■	■	■	■	■	■
Velocity	■	■	■	■	■	■
Tracers	■	■	■		■	■
Inorganic Carbon					■	■
Total alkalinity					■	■
pH					■	■
Nutrients		■			■	■
Oxygen	■	■			■	■
Sea ice	■	■		■	■	■
Wind	■	■		■	■	■
Air-sea flux (heat, FW)	■	■	■	■	■	■
Sea surface height	■	■	■			■
Seabed pressure		■				
Particulates					■	■
Phytoplankton					■	■
Zooplankton					■	■
Benthos					■	■
Fish					■	■
Birds						■
Mammals						■

Table 2: *The combination of platforms and techniques needed to provide sustained observations of each of the fields identified in Table 1.*

	Repeat hydrography	Argo	Underway sampliming	Moorings	Tide gauges	Animal sensors	Sighting surveys and cameras	CPR	Glider/AUV	ROV and imaging methods	Satellite	Ice stations	Acoustics	Trawls/nets	Bottom landers/corers	Drifters
Stratification (T(z),S(z))	■	■		■		■			■			■				
SST, SSS	■		■								■					■
Velocity	■	■		■					■		■		■		■	■
Tracers	■															
CO_2	■		■	■												■
Nutrients	■		■													
pH	■	■	■						■							
Oxygen	■	■		■					■							
Sea ice			■	■							■	■				■
DMS	■		■													
Aerosols			■								■					
Wind	■		■	■							■					
Air-sea flux	■		■	■							■					■
Sea surface height	■	■			■						■					
Seabed pressure			■								■				■	
Particulates	■		■							■						
Phytoplankton	■		■	■		■		■		■	■	■			■	
Zooplankton								■		■			■	■		
Fish						■				■			■	■		
Birds						■	■									
Mammals						■	■									
Predators						■	■									
Benthos			■	■				■	■				■	■	■	

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 (e.g. Key et al., 2010) and biological data sets, for example the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; http://icoads.noaa.gov). However, many data still reside 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 database easily accessible.

Recommendations: The biogeochemical and ecological data sets (e.g. animal tracking) need to be integrated with historical environmental data (e.g. hydrographic and biogeochemical 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., 2009) and sections of the ocean acidification network (Feely 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)), air-sea fluxes and biology (e.g. primary production, pigments, bio-optics, fast repetition rate fluorometer, molecular diversity, biomarkers, targeted trawls, net tows, acoustics). The sections should extend from north of the ACC to the Antarctic coast, including the sea-ice zone and the continental slope and shelf. There is therefore a continued need for ice-capable vessels for the high-latitude sections. 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).

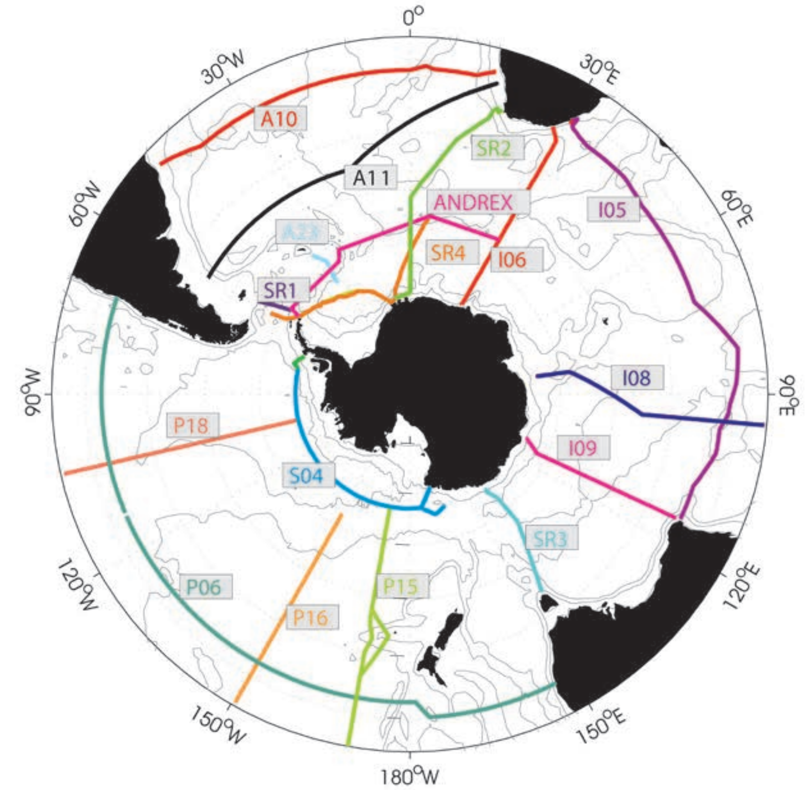

Figure 18: *Repeat hydrographic sections to be occupied by SOOS. Labels indicate the WOCE/CLIVAR designations for each line.*

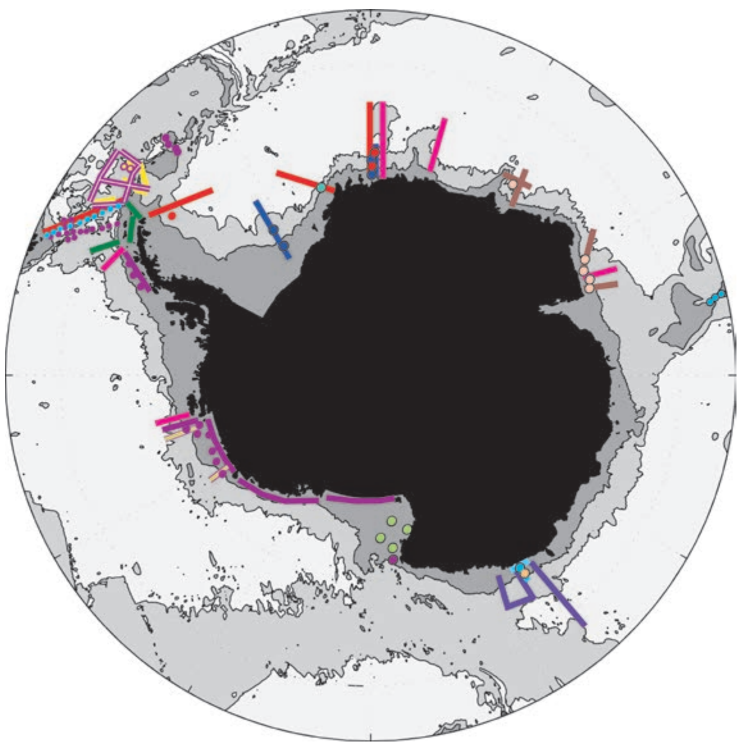

Figure 19: *Hydrographic sections (lines) and moorings (circles) occupied as contributions to the IPY SASSI programme. Many of these lines are near Antarctic bases and could be repeated more regularly as a contribution to the SOOS.*

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, CO_2 system, nutrients) are needed to relate variations in the physical environment to biogeochemistry and ecosystem processes.

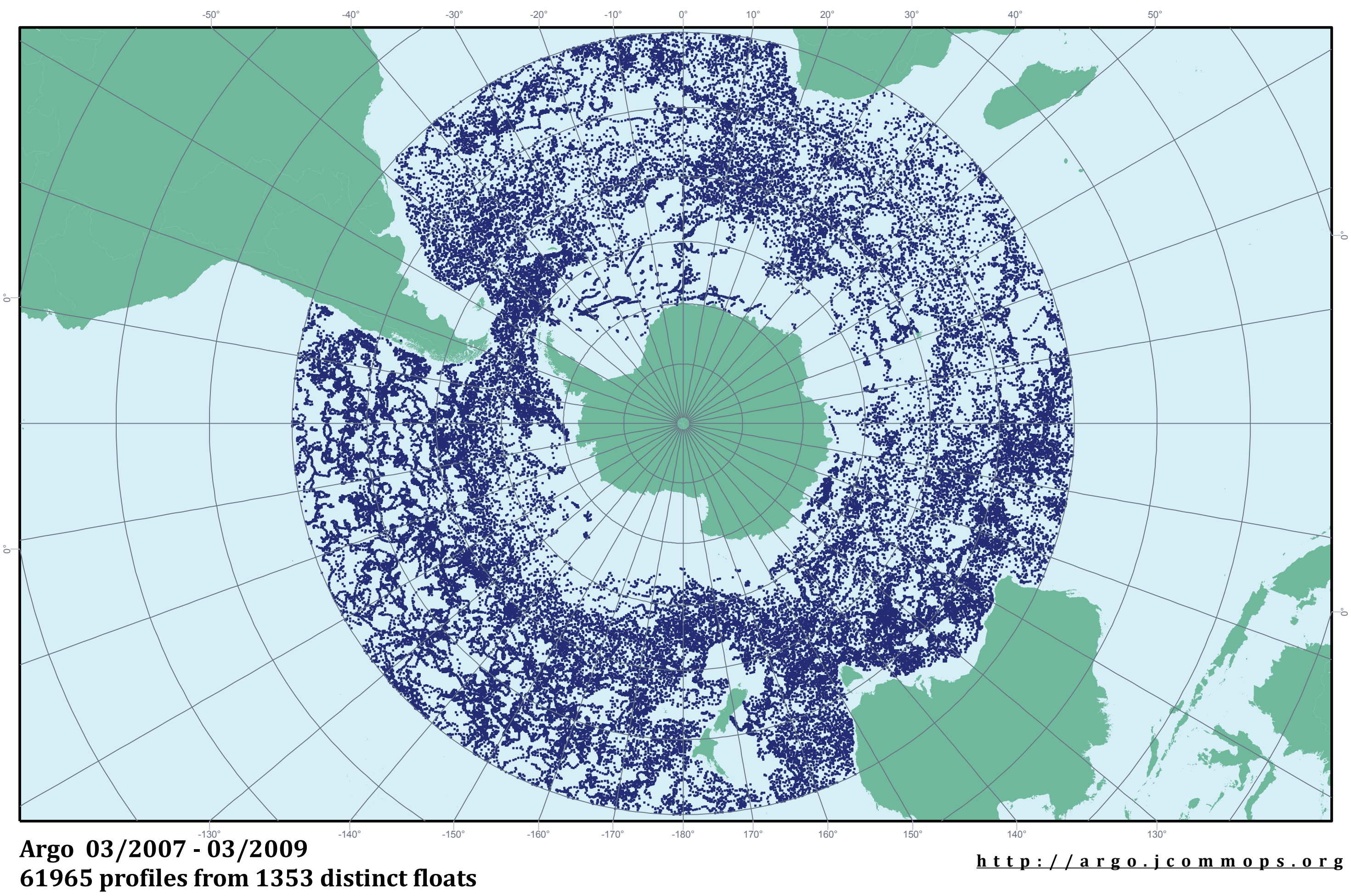

Figure 20: *The location of more than 60,000 Argo profiles of temperature and salinity collected during the 24 months of the IPY. Courtesy of Mathieu Balbeoch, JCOMMOPS.*

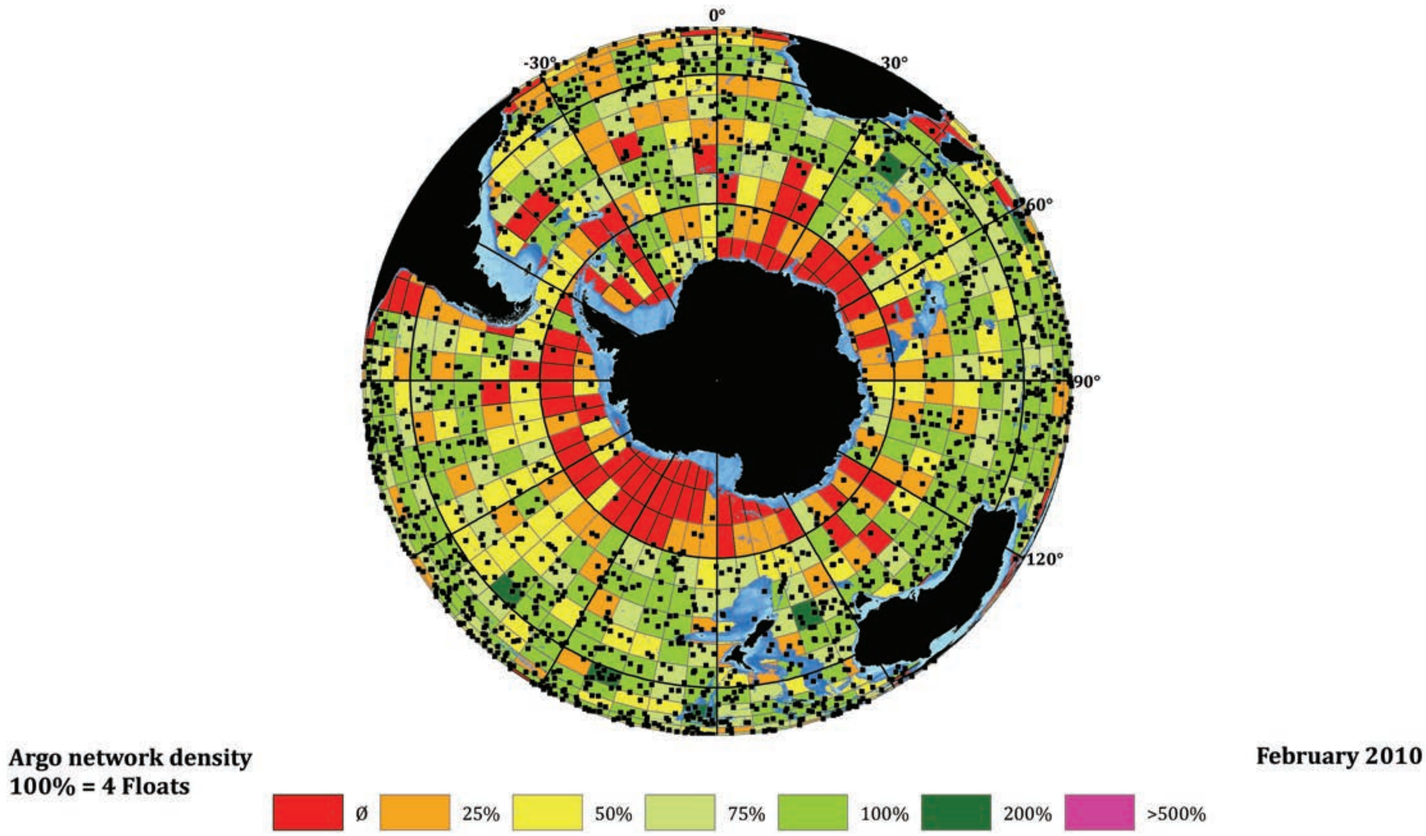

Figure 21: *The status of the Argo array in the Southern Ocean, as of July 2010. Blue colour indicates 0-2000 depth contour. Despite the progress in recent years, large regions of the high-latitude Southern Ocean remain poorly observed, especially close to the Antarctic continent. Courtesy of Mathieu Belbeoch, 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 timescales shorter than the 5- to 7-year repeat cycle of the repeat hydrography. (The issue of seasonal aliasing remains, as most underway measurements are made between October and March; year-round observations from Argo floats help to compensate somewhat for that defect). While underway measurements are generally limited to the surface layer, use of ships of opportunity provides a cost-effective means of collecting a wide range of physical, biogeochemical and biological observations. Such observations include temperature, salinity, velocity (from ADCP), full CO_2 system (pCO_2, pH, total inorganic carbon, total alkalinity), 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 Indian Service d'Observation (OISO), and Australia-France SURVOSTRAL programmes provide examples of what is possible. 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 Monteiro et al. (2010).

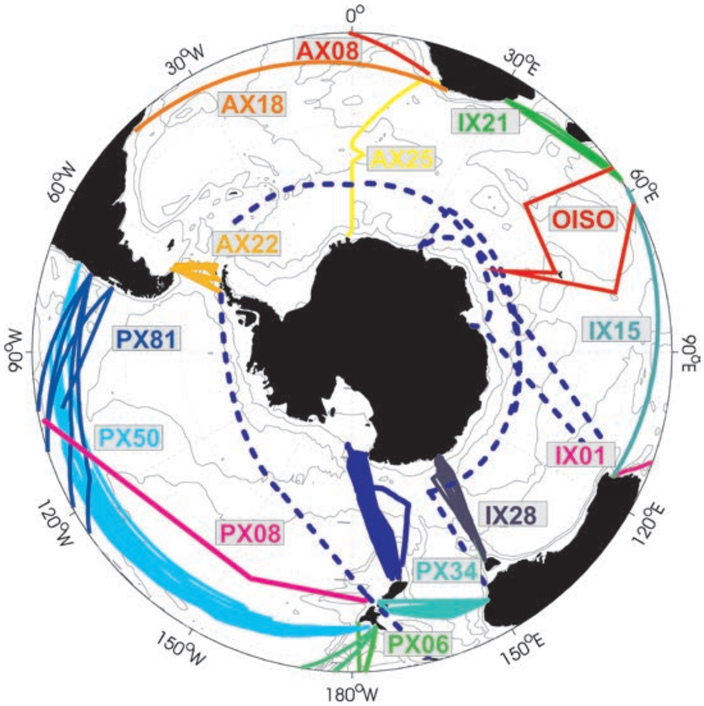

Figure 22: *The existing underway sampling lines in the Southern Ocean that could contribute to SOOS .*

Ocean Acidification Detection System

As the ocean absorbs more CO_2, resulting in ocean acidification, the saturation threshold for aragonite will be crossed first in the high-latitude ocean areas. Sustained observations of both ocean carbon chemistry and the effect of increasing ocean acidification 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 existing and new chemical sensors discussed above will provide the primary means of measuring DIC, alkalinity, pCO_2 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 pCO_2, 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 certain 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) and have the advantage of being able to deliver data via satellite in real time (Woodworth et al., 2006). 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. Transport time series in these key passages can also be extended over nearly two decades using a combination of bottom pressure gauges and/or current meters deployed along altimetric ground tracks. This technique has been used to monitor transport variations over the 1990s and 2000s in key passages (e.g., Rintoul et al., 2002; Meredith et al., 2004; Swart et al., 2008; Provost et al., 2011).

Recommendations: High-priority regions for sustained moored measurements include Drake Passage, along the prime meridian (e.g. the Weddell Sea Convection Control (WECCON) and GoodHope programmes south of Africa) and the locations of deep outflows (e.g. the northern and 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 into the Pacific sector, where present coverage is most sparse. 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.

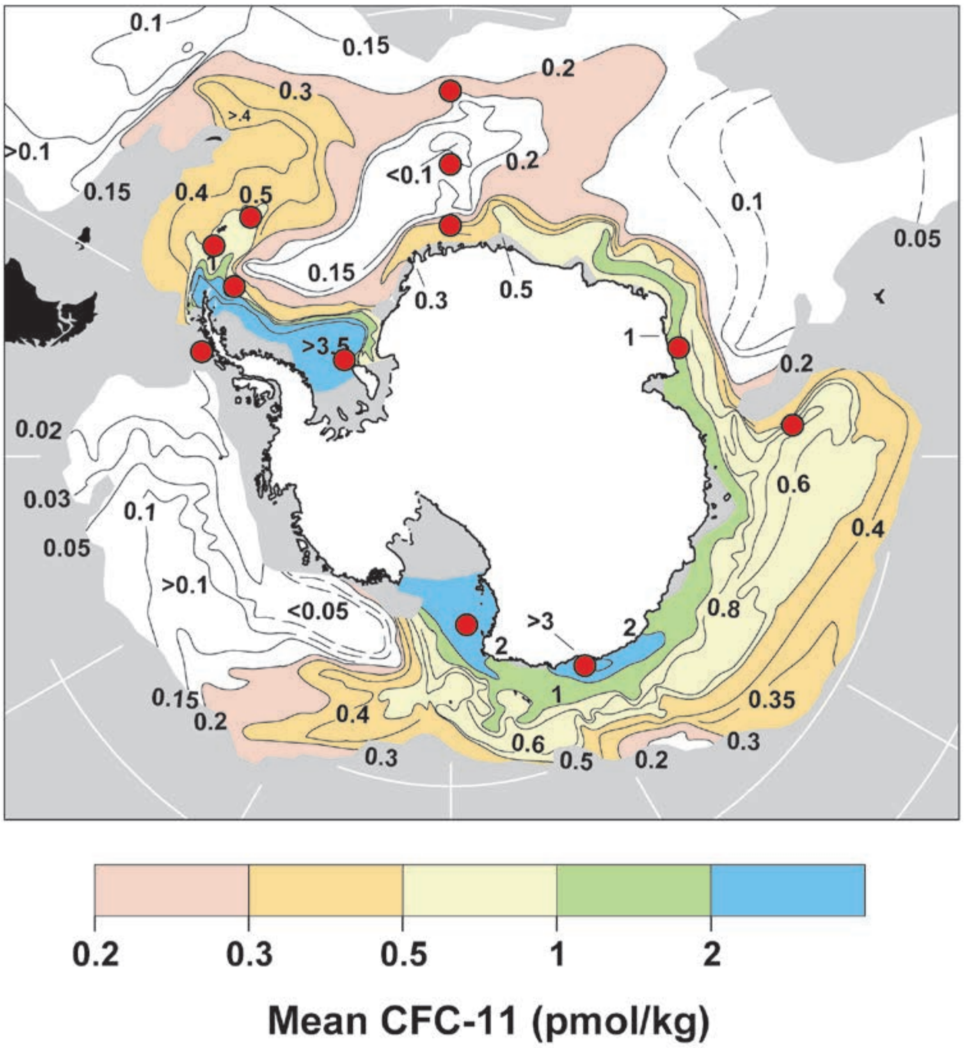

Figure 23: *Map of proposed moored arrays (red circles) to sample the primary Antarctic Bottom Water formation and export sites, as part of a coordinated global array to measure the deep limb of the global overturning circulation. Each of these sites has been occupied in recent years. The map shows the inventory of chlorofluorocarbon 11 (CFC-11) in the density layer corresponding to AABW. Modifed by A. Orsi from figure in Orsi, A.H., G.C. Johnson, and J.L. Bullister. 1999. Circulation, mixing, and production of Antarctic Bottom Water. Progress In Oceanography 43:55-109. Reprinted with permission from Elsevier.*

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 (Burns et al., 2004; Biuw et al., 2007), 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; Nicholls 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 animals' 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). Table 3 suggests deployments of CTD Satellite Relay Data Loggers as part of SOOS. Cross-calibration of the temperature and conductivity sensors with CTD and Argo data should be conducted routinely. (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 Satellite Relay Data Loggers 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 programmes.*

	Weddell Seals			Southern Elephant Seals					
	Adult females			Adult females			Sub-adult males		
Winter Habitat	Inshore fast ice	No. of tags	Possible countries	Winter Ice Edge/ Frontal zones	No. of tags	Possible countries	Antarctic continental shelf	No. of tags	Possible countries
Location/Region	East Antarctica (Davis)	7	Australia	Macquarie Island	10	Australia	Macquarie Island	10	Australia
	East Antarctic (DDU)	7	France	Isles Kerguelen	10	France	Isles Kerguelen	10	France
	WAP	10	USA/UK	Marion Island	10	South Africa	Marion Island	10	South Africa
	Weddell Sea (Drescher Inlet)	10	Germany/UK	South Georgia	10	UK	Bovetoya	10	Norway
	Ross Sea	10	USA/ New Zealand	Elephant Island	10	Brazil	WAP	10	USA/UK
							South Georgia	10	UK

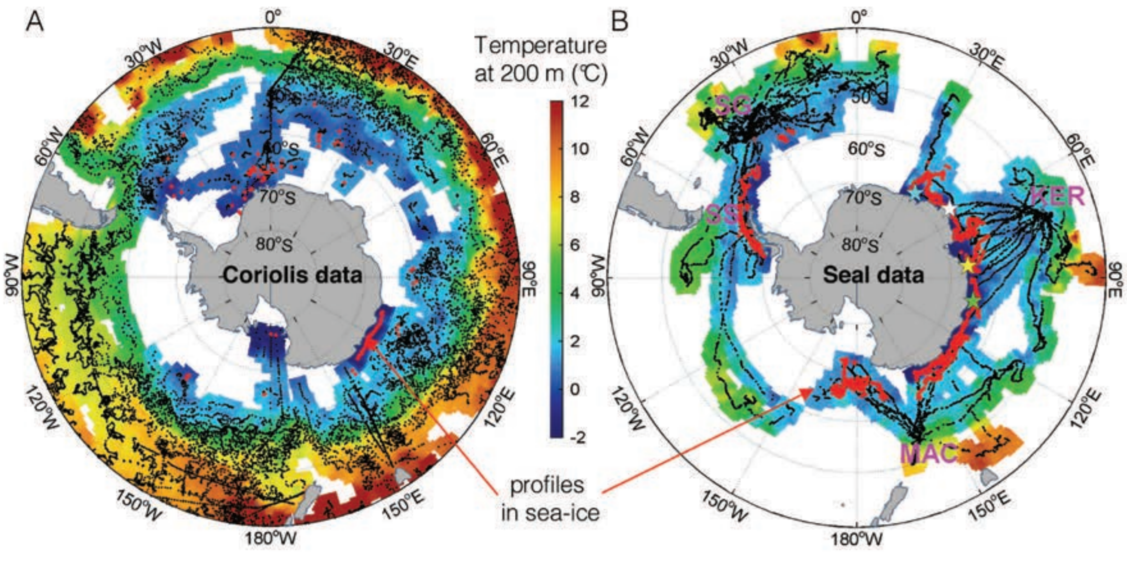

Figure 24: *Circumpolar distribution of hydrographic profiles and temperature at 200 m in the Southern Ocean during 2004–2005. (A) Data from the Coriolis database (Argo floats, XBTs, and research vessels). (B) Data collected by elephant seals equipped with CTD-SRDLs at South Georgia (SG), and South Shetland (SS), Kerguelen, (KER), and Macquarie (MAC) islands. Red points indicate profiles collected in sea ice. Colour stars indicate positions of time series collected in sea ice by four different seals. From Charrassin et al., 2008, Southern Ocean frontal structure and sea-ice formation rates revealed by elephant seals. Proceedings of the National Academy of Sciences 105:11634-11639, doi:10.1073/pnas.0800790105. Copyright (2008) National Academy of Sciences, U.S.A.*

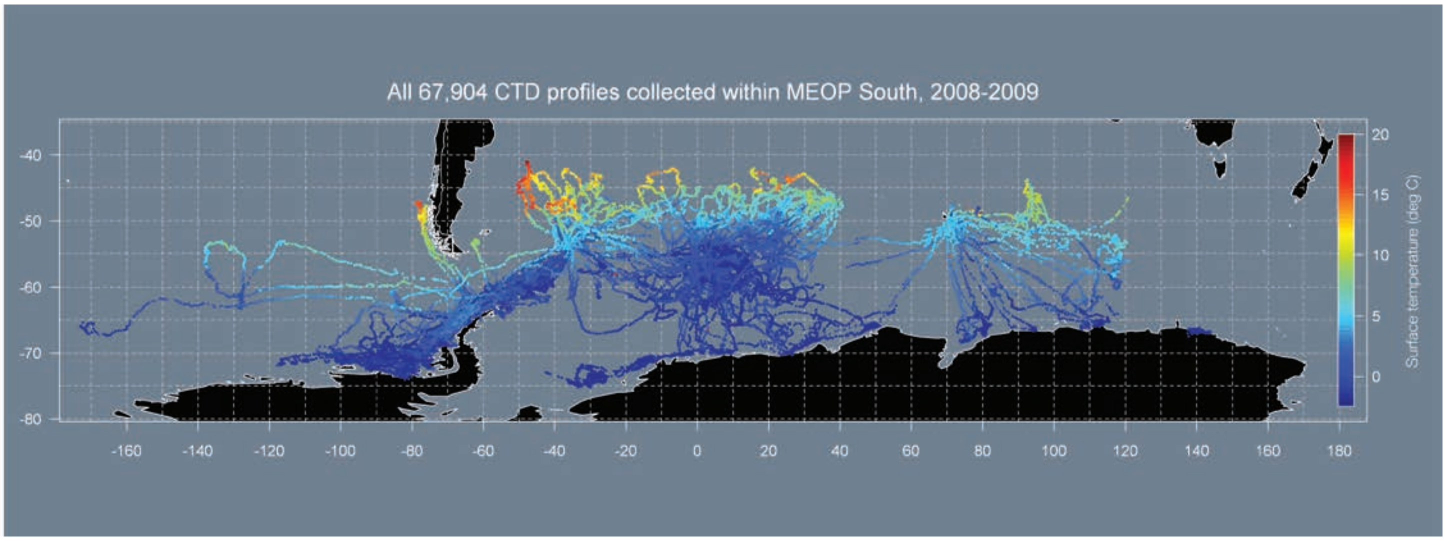

Figure 25: *Surface temperature and location of 67,904 CTD profiles collected by seals during the Marine Mammals Exploring the Oceans Pole to Pole (MEOP) programme during IPY. Data from the MEOP (http://www.meop.info/en/) project. Figure prepared by Martin Biuw, Norwegian Polar Institute, Tromso.*

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. Polar View (http://www.polarview.aq/mapview.php), for example, provides several types of satellite imagery to deliver a comprehensive, detailed and up-to-date picture of sea-ice extent and distribution. 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, 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 sonars, ship-board observations (including ice drift stations and helicopter surveys), remote sensing and data-assimilating models. The most critical observations 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 properties, particularly density, are also essential for interpreting these data. AUVs will also collect oceanographic and biological data (e.g. salinity, temperature, currents, sonar for biology) as well as ice thickness. Time series of ice thickness from fixed-point moorings are needed to complement the spatial sampling from AUVs as well as more systematic collection of Antarctic sea ice thickness measurements, including ASPeCt observations, from additional research, supply and tourist vessels. There is still the need for infrastructure to allow the deployment of marine instrumentation in multi-year sea ice. 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).

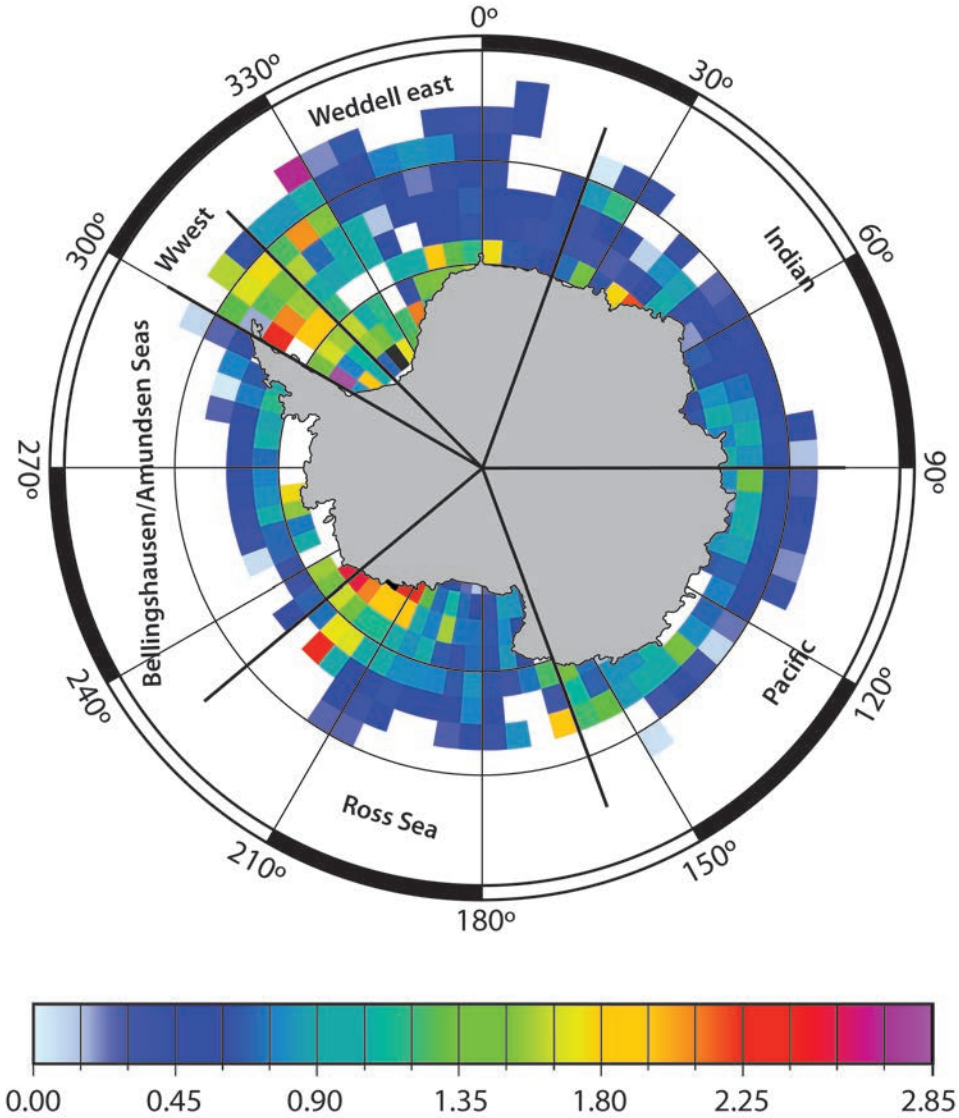

Figure 26: *Annual mean sea ice thickness derived from ASPeCt ship observations (Worby et al., 2008). Units are metres. Used with permission from the American Geophysical Union.*

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 et al., 2003).

Recommendations: Maintain and enhance 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).

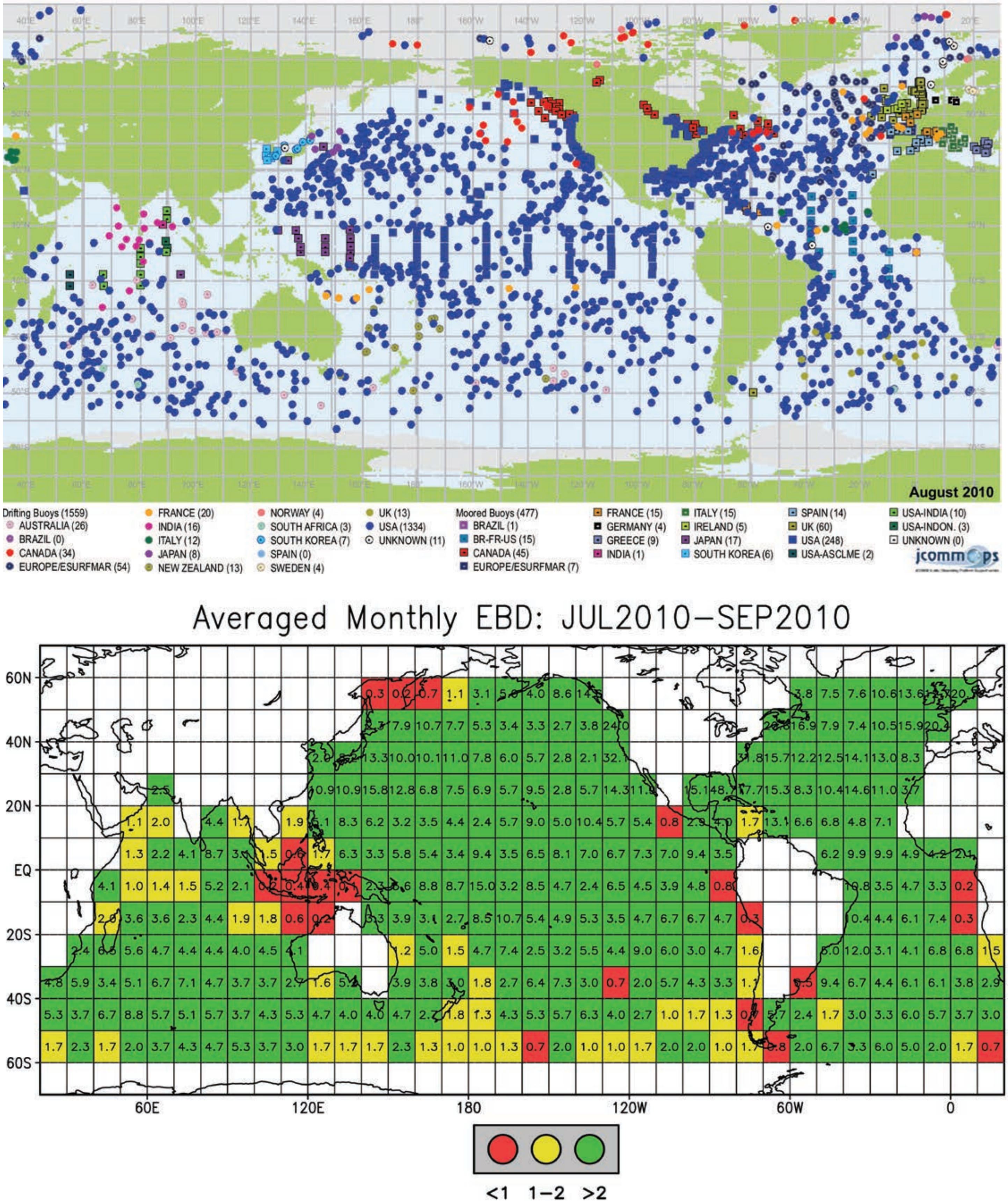

Figure 27: *Status of the global surface drifter array in August 2010 (top) and the equivalent buoy density (EBD) for July – September 2010 produced by NOAA. Yellow and red squares indicate regions where observations from ships and drifters fall below the required density. Note the lack of drifter data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

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. As a consequence, the contributions of increased ice divergence and northward drift, or thermodynamic growth, to the presently observed increase of Antarctic sea-ice extent are unclear. 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 trajectories of drifters deployed by the International Programme for Antarctic Buoys between 1995 and 2002 is shown in Figure 28. At present, few ice drifters are being deployed.

Recommendations: A network of circum-Antarctic buoys should consist of drifters spaced every 500 to 1000 km in the zonal and meridional directions, consistent with the typical correlation 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 and information on ocean heat fluxes. 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.

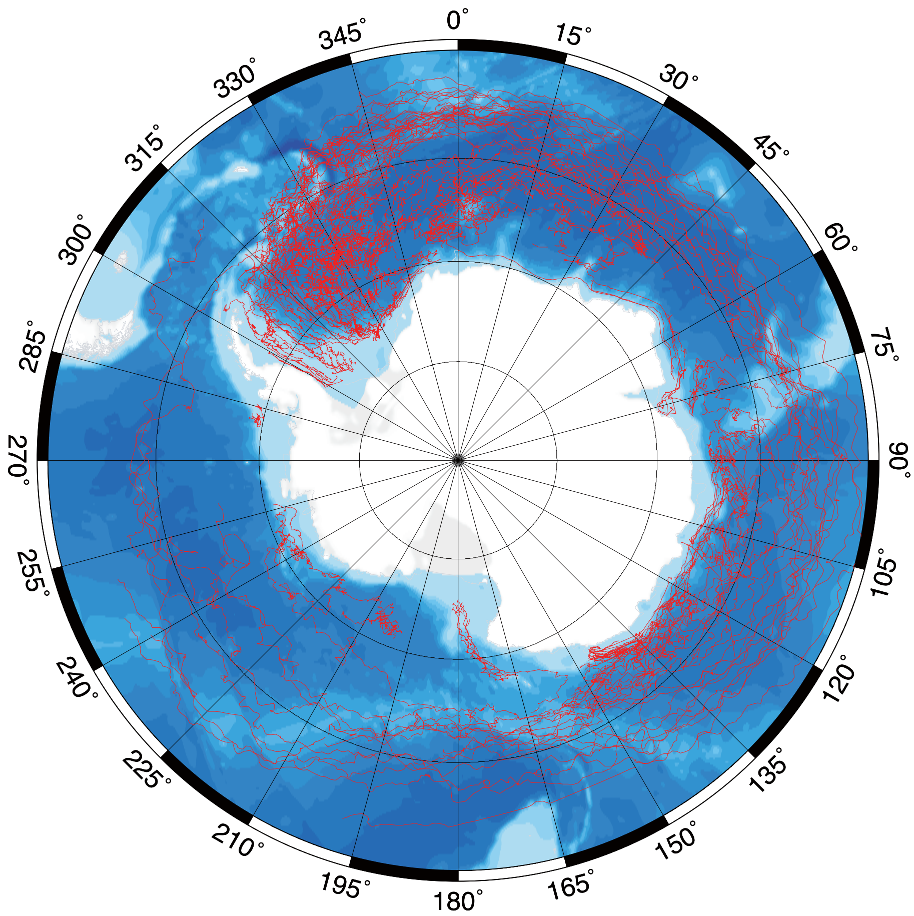

Figure 28: *The complete record of ice drifter trajectories from the International Programme for Antarctic Buoys (IPAB) between 1995 and 2002. The relatively dense sampling in the Weddell Sea and off East Antarctica indicates the efforts of the German and Australian sea ice programmes in recent decades. The buoy drifts illustrate the circulation of the subpolar gyres and the overall divergent drift to the north, indicating that repeated seeding of buoys is required to maintain coverage.*

Ocean Circulation Under Sea Ice

With few exceptions (e.g. Nicholls 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. Satellite measurements have also been used to infer ocean dynamic topography in ice-covered seas (e.g. Kwok and Morrison, 2011). 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 likely 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.

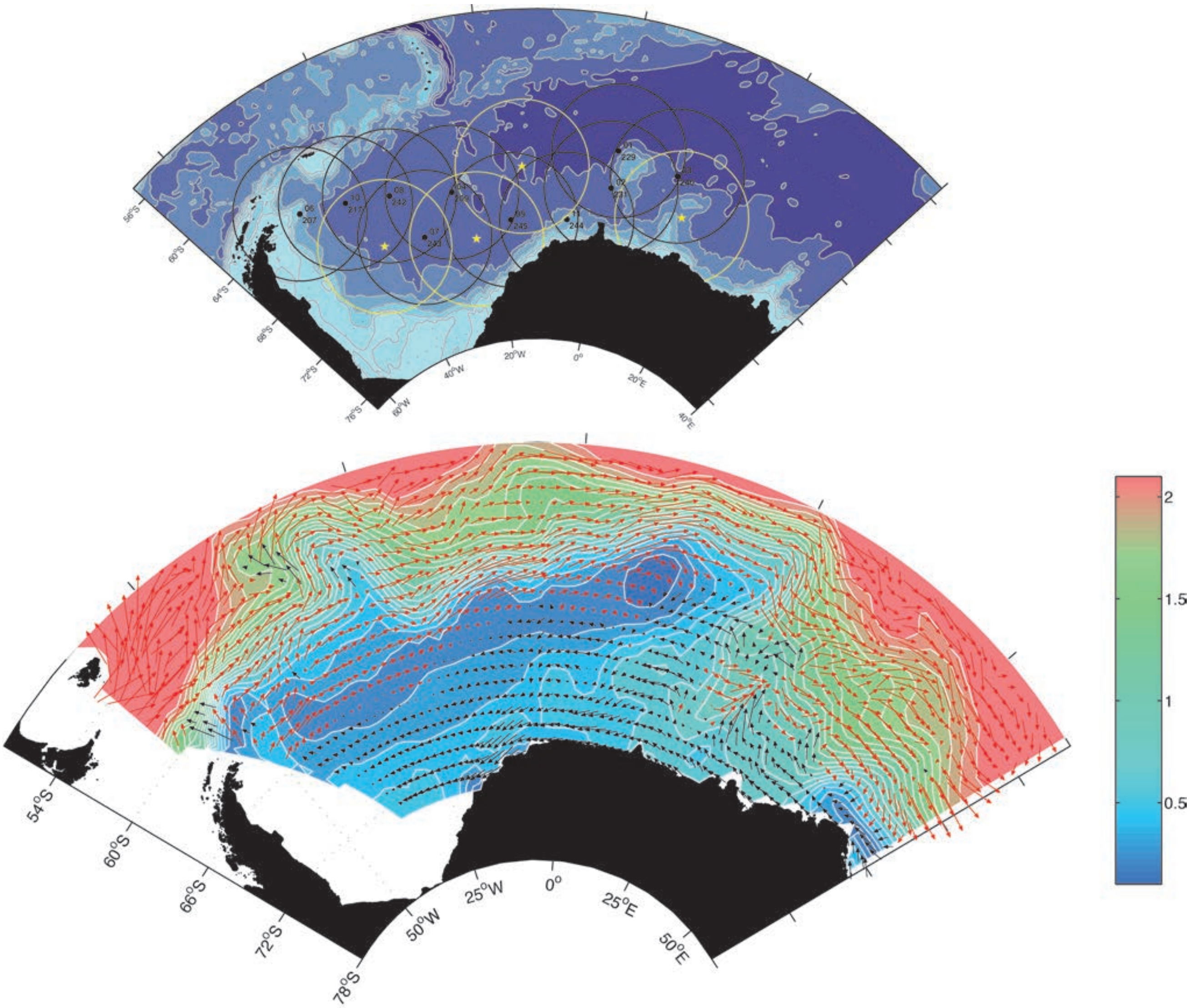

Figure 29: *Array of sound sources being used to track profiling floats in the Weddell Sea during the IPY* **(upper plot)** *and temperature and velocity field derived from profiling float data* **(lower plot)** *(E. Fahrbach, pers. comm.). These measurements need to be sustained to extend the global array of profiling floats to the ocean beneath the sea ice. A similar array is needed to sample the Ross Sea 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. Complementary satellite altimeter-derived sea-surface height data are available, which together with the new GOCE geoid will allow accurate dynamic topography, surface slopes and thus geostrophic currents to be retrieved. Meanwhile, the new capability offered by CryoSat-2 will enable the sea-surface topography to be accurately measured in sea-ice covered areas, and will enable more accurate tidal models to be developed in conjunction with the GLOSS tide-gauge data.

Recommendations: Maintain and expand the Southern Ocean GLOSS network, including increasing the number of stations reporting in real time. Install coastal tide gauges in data-sparse regions, in particular the Amundsen Sea sector. Expand network to include radar tide gauges with precise positioning and levelling with GPS sensors. For coastal tide gauges along the Antarctic continent subject to seasonal ice, pressure sensors and precise positioning with GPS are also necessary.

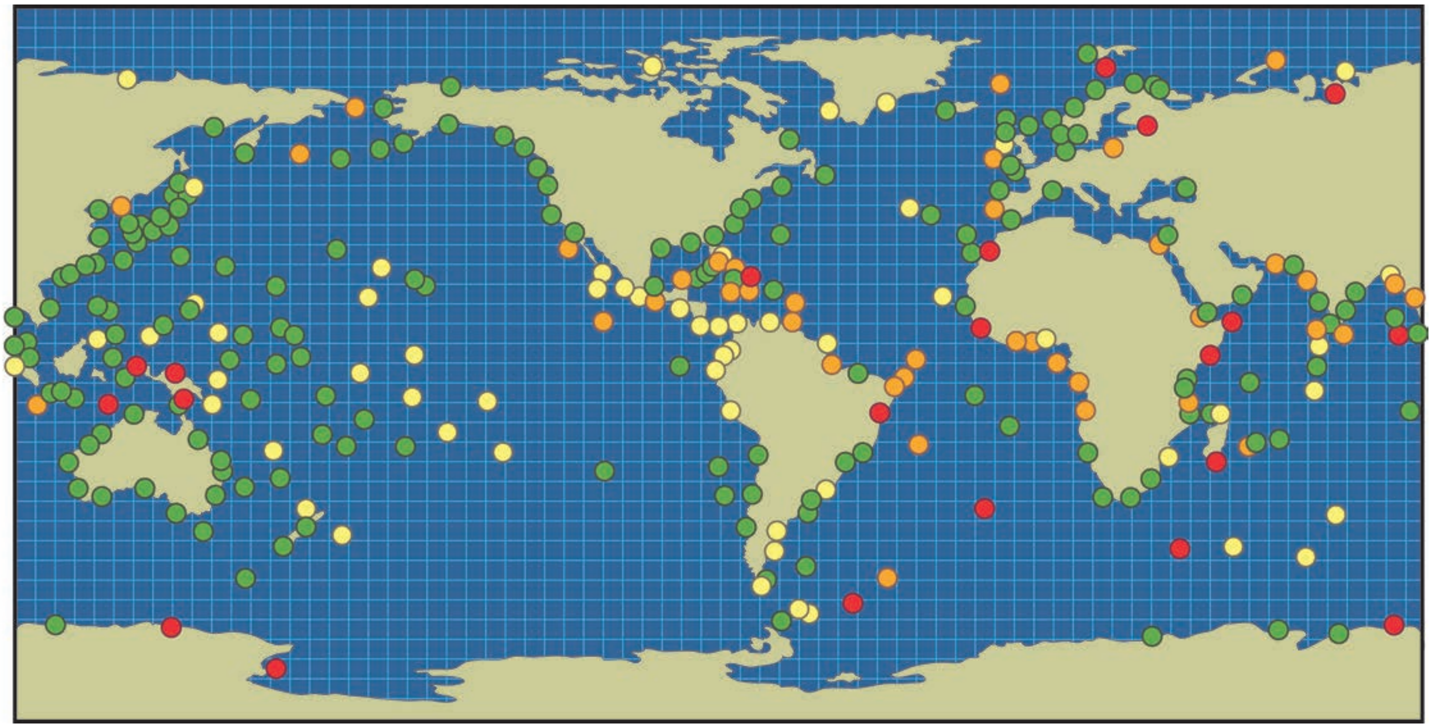

Figure 30: *Status of the Global Sea Level Observing System (GLOSS) in October 2009. Green dots = "Operational" stations for which the latest data is 2005 or later; yellow = "Probably operational" stations for which the latest data are from within the period 1995-2004; orange = "Historical" stations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

Melting and Freezing of Floating Ice Shelves and Glacier Tongues

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 melting the undersides of ice shelves (e.g. Shepherd et al., 2004; Jenkins et al., 2010). Despite the importance of these processes, ocean circulation and properties under shelf ice have been measured in only a very few locations. Recent measurements beneath the Pine Island Glacier using the AUV *Autosub* are an exciting development, but sustained measurements are 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. Use AUVs to provide under-ice surveys in areas of particular significance.

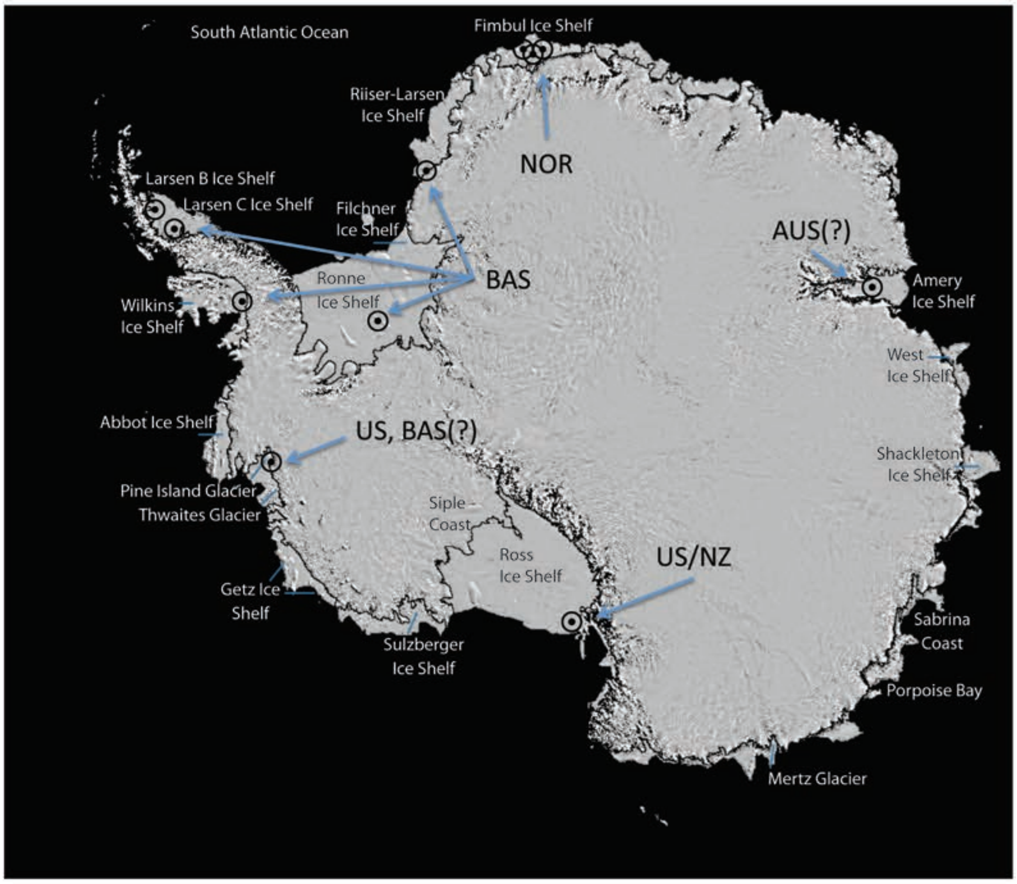

Figure 31: *Circles indicate location of current or planned drill holes through ice shelves, allowing sampling of underlying ocean waters.*

Enhanced Meteorological Observations

An enhanced atmospheric observing system is needed to improve Antarctic and Southern Hemisphere weather forecasts. Better weather forecasts also benefit climate research, as the reanalyses used for climate studies are derived from the systems used for weather prediction. The enhanced observations should include additional automatic weather stations and remote profilers, sea level pressure observations from ice and ocean drifters, more marine meteorological observations from ships, and observations from aircraft (manned and un-manned). 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. Use of ship-launched or land-launched drones for gathering meteorological data over sea ice should be encouraged; suitably equipped with cameras these can also provide valuable data on the dispersed population of sea ice seals, for example, the Ross Seal, about which little is known.

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. Courtesy of Eric Schultz, Australian Bureau of Meteorology.*

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 (e.g., SeaWiFS, MODIS, and MERIS) 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 (e.g. plankton tows, Continuous Plankton Recorder (CPR)) tows) 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.

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 focussed, short-term experiments and has generally focussed on distribution and abundance. Existing long-term sampling programmes include the Japanese Antarctic Research Expedition (JARE) annual Norpac plankton net sampling, the U.S. Antarctic Marine Living Resources (AMLR) programme, 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 Ocean sector, 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 suitable for deployment on ships, moorings and drifting platforms are being designed.

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).

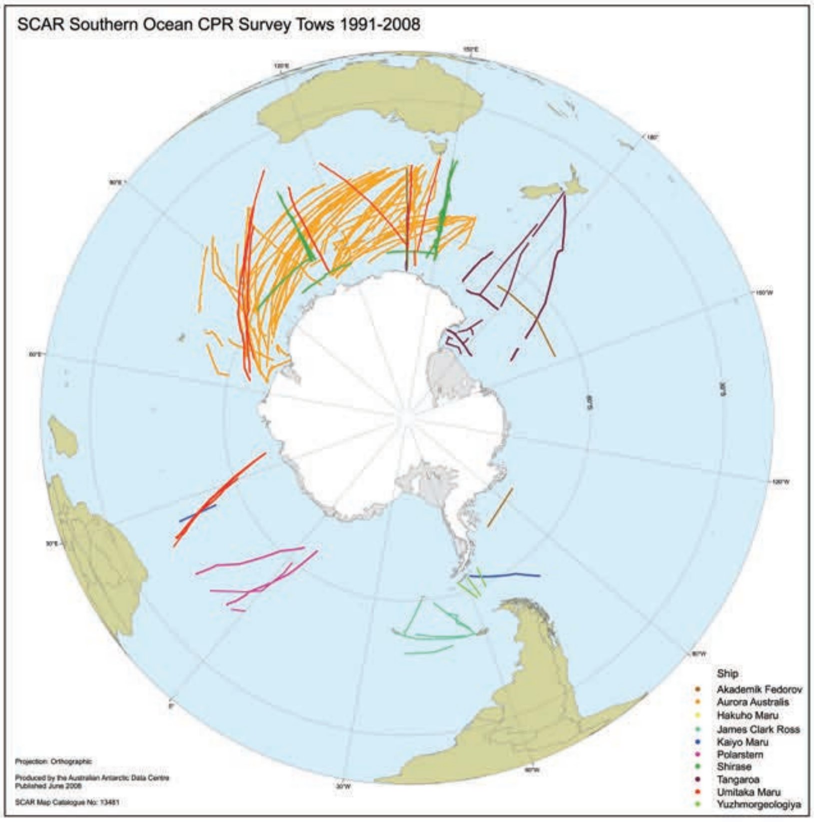

Figure 33: *Location of CPR tows completed between 1991 and 2008. Courtesy of SCAR Continuous Plankton Recorder Expert Group and Graham Hosie*

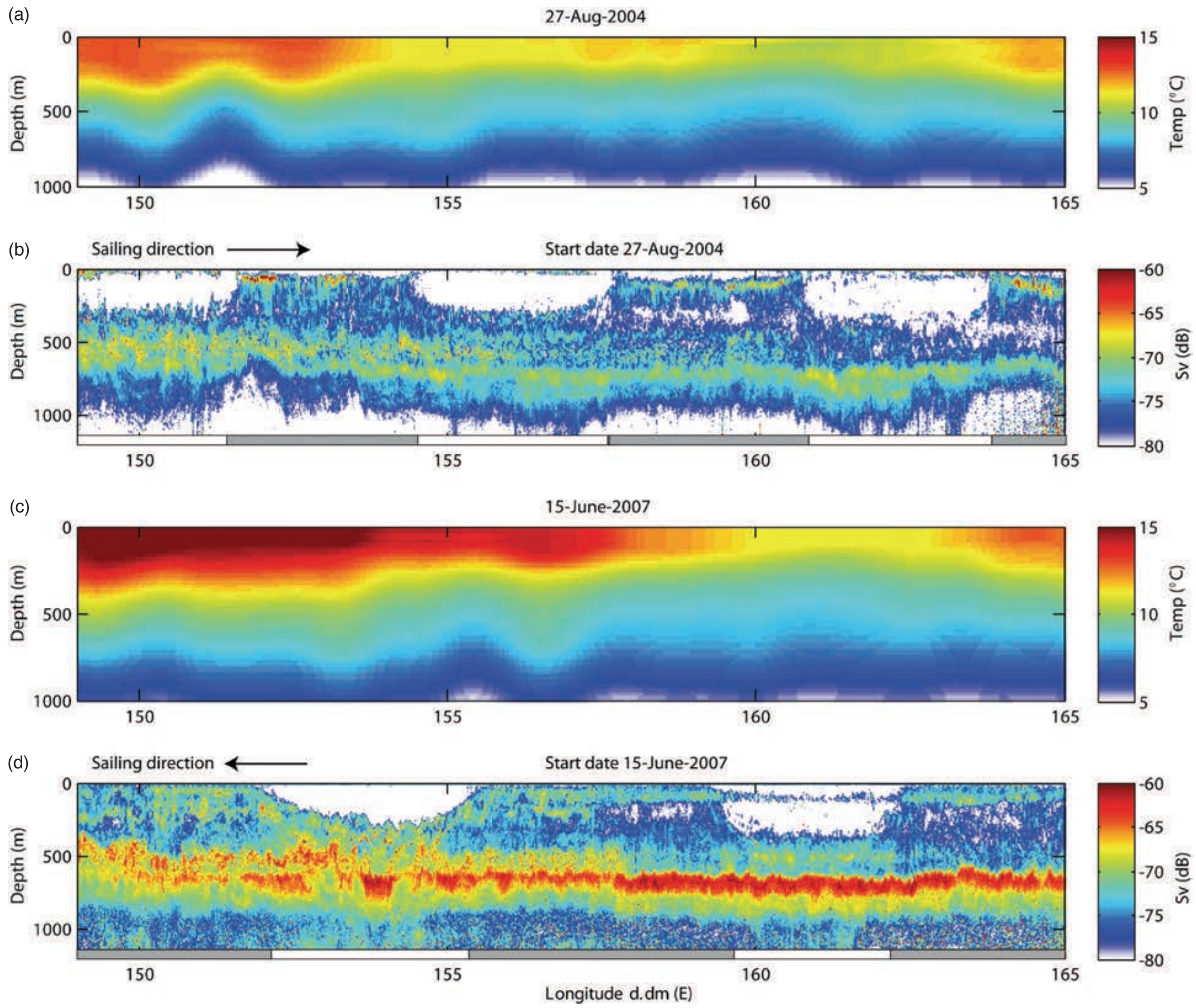

Figure 34: *Demonstration of basin-scale distribution and abundance of mid-trophic organisms provided by calibrated ships of opportunity (fishing vessels) over multi-year time frame using well-established standardised technologies and methodologies (Fig. 5 from Kloser et al., 2009). Distribution of temperature between Tasmania and New Zealand in 2004 (a) and 2007 (c) and acoustic backscatter sampled with a 38 kHz sounder on the same sections (b, 2004; d, 2007). Day/night sampling of transects over three days are indicated by clear and dark bars, respectively. These basin-scale snapshots provide information for ecosystem model parameterisation, 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.*
From Kloser, R.J., et al., Acoustic observations of micronekton fish on the scale of an ocean basin: potential and challenges. ICES Journal of Marine Science*, 2009, 66:998-1006, by permission of Oxford University Press.*

Ecological Monitoring With 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), with observations also made in the Ross Sea. Although CEMP was established to monitor fisheries impacts, the long-term time series are now also providing insights into ecosystem processes (e.g. Emmerson and Southwell, 2008; Ballerini et al., 2009). The U.S. AMLR programme in the South Shetland Islands offers an 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 programmes and other studies, significant changes in penguin populations have been observed in some regions (e.g. Weimerskirch et al., 2003; Ducklow et al., 2007), particularly on the western peninsula, where the most dramatic environmental changes have been observed in recent decades. The Latitudinal Gradient Project operated by New Zealand and others along the Victoria Land coast also collects marine data (Howard-Williams et al., 2010). These efforts tend to be geographically restricted and 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 Predators (TOPP) Programme (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). Different species employ different foraging and breeding strategies; by tagging several different 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 coupled 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.*

Species	Prey	Habitat	Maximum dive depth (m)	Device*
Southern elephant seal†	Squid, fish	pelagic	1900	CTD+Argos
Adélie Penguin †	Krill	pack ice	160	GLS
Emperor Penguin †	Squid, fish	fast ice	600	GLS
Antarctic Petrel †	krill, amphipods, fish	pelagic	5	GLS
Antarctic Fulmar	krill, amphipods, fish	pelagic	5	GLS
Snow Petrel	krill, squid, fish	pelagic	5	GLS
Cape Petrel				
Short-tailed shearwater (summer only)	krill, fish (?)	pelagic	50	GLS
Weddell seal †	Fish	fast ice, pelagic	900	CTD+Argos

*Device types include Conductivity-Temperature-Depth recorders (CTD), Service Argos platform terminal transmitters (PTTs) (Argos) and light-temperature geolocation 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 (Table 4). Maintain existing long-term monitoring programmes and extend monitoring to regions where little monitoring 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 crabeater seal populations every 5 years should be conducted in regions where a baseline exists, to detect changes in abundance. Surveys of pack ice seals can be done effectively from aircraft, including instrumented drones.

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 and 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 observed 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: Several recent programmes provide good examples of the integrated multi-disciplinary benthic studies required (Snape et al., 2001; Stark et al., 2003; Brandt et al., 2004; Brandt et al., 2007; Gutt, 2007; Gutt et al., 2007; Clarke et al., 2008; Smith et al., 2008). These studies have used a variety of tools, including benthic landers with sediment traps and time-lapse photography, physical and pH 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 key 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 almost entirely 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 and other smaller-scale features.

High-precision, continuous satellite altimetry missions (Jason, Envisat, Sentinel), in full synergy with satellite gravity missions (GOCE, GRACE; Le Traon et al., 2001; Drinkwater et al., 2010), play a vital role in monitoring surface elevation relative to the geoid (Wilson et al., 2010), which to a large extent controls the large-scale depth-integrated circulation. Surface geostrophic current velocities can also be inferred from these sea surface height data, including absolute surface currents (Johannessen et al., 2001; Rio and Hernandez, 2004). Scatterometers enable derivation of surface winds over open seawater and surface Ekman currents (Millif et al., 2001) and derivations of sea-ice characteristics (Drinkwater, 1998). Infrared and microwave radiometers, including active and passive microwave sensors, measure SST, sea-ice extent and motion (Drinkwater et al., 2001; 2010).

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-to-infrared 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: Due to the need for coherent interannual to decadal time series in the Southern Ocean, the continuity of satellite data is crucial. The recent gap in satellite winds due to the demise of Quikscat, with no replacement planned, should be avoided in the future. The quality of satellite data needs to be maintained through precise cross-calibration between a series of satellite missions, continuity of satellite algorithms and corrections, and independent validation with *in situ* data. 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; ocean colour and cryospheric satellites. For the present generation of cryospheric satellites, such as IceSat and Cryosat, we recommend that the data be made available over the continental ice, sea-ice and surrounding ocean for coherent analyses of the ocean-ice interactions. In the future, missions such as SWOT, with swath radar interferometry at 1 km resolution over the global oceans and finer resolution over the continental ice and sea-ice zones, should provide better spatial coverage of the smaller Rossby radius ocean structures, as well as ice topography observations and ice freeboard observations for sea-ice volume estimates.

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.

Bathymetry

Currents are steered by the topography of the ocean floor, and topography is also a primary guide to habitat. A major problem for modelling studies in all of the global oceans, but particularly in the Southern Ocean, is the lack of accurate bathymetric data, particularly over the Antarctic continental slope, shelf and coastal region. Many ships collect bathymetric measurements, but the data are not usually submitted to data centres.

Recommendations: Bathymetric data should be collected by all vessels operating in Antarctic waters and the data submitted to the relevant data centres. These observations need to be integrated with satellite altimetry and gravity observations of ice-free areas. SCAR is supporting the development of a bathymetric chart of the Southern Ocean (under its IBCSO programme) as a contribution to the General Bathymetric Chart of the Oceans (GEBCO), and all agencies funding the acquisition of bathymetric data are urged to submit the data to the U.S. National Geophysical Data Centre to enable its widespread use in such mapping. The requirements for ocean mapping and the collection of bathymetric data are detailed on page 120 onwards in the report of SCOR Working Group 107, on Improved Global Bathymetry, available from the SCOR web site at www.scor-int.org/Publications/WG107Report.pdf

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. Atmospheric measurements should also be performed from ships of opportunity and during repeat hydrographic sections.

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 focussed process studies to be conducted. Smaller scale processes associated with sub-mesoscale eddies, internal waves, surface waves etc. are poorly represented in climate models, and process studies are needed to improve parameterisation of their effects. 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.

Coastal Polynyas

The impact of coastal polynyas on the polar oceans is known to be relevant for both physical and ecological processes; in particular the air–sea heat exchange within a polynya is 1 or 2 orders of magnitude greater than through the surrounding sea ice. The atmospheric and oceanic variability in these areas is not well understood because of the limited *in situ* observations, which are primarily collected during the summer seasons. These areas are typically sites of dense water formation related to the winter surface heat losses as well as net sinks of atmospheric anthropogenic gases (i.e. CO_2). The dense water formation process is likely to be extremely sensitive to the interannual variability of the atmospheric forcing and to the local hydrographic properties, making different amounts of dense water available for bottom water formation processes and for the ventilation of the abyssal oceans. There is a need to maintain and expand observations in coastal polynyas. Traditional techniques (mooring, oceanographic surveys, Automatic Weather Stations), coupled with innovative observations (gliders, floats with biogeochemical sensors, AUV, autonomous sampling devices, drones etc.) and high-resolution remote sensing data provide the best way to monitor such areas.

Ecological Process Studies

Regular observations from ships of opportunity will enable the identification of different bioregions, characteristic populations and seasonal successions. 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 the 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. 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 electromagnetic 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 interface within the seasonal sea-ice zone and in open Southern Ocean waters. Such platforms are currently maintained at lower latitudes, for example at the Bermuda Atlantic Time Series (BATS) station and CNR “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 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, 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 through the GO-SHIP programme (Hood et al., 2009), consistent with the SOOS design. 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 including continuations of the long-term bottom pressure recorder deployments and tide gauge observations. 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 programmes 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).

Programmes like the Argo profiling float array and the Marine Mammals Exploring the Oceans Pole to Pole (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 and how marine mammals use it. 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 and Rothera Time Series (RaTS) programmes also have long-standing commitments. Several 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.

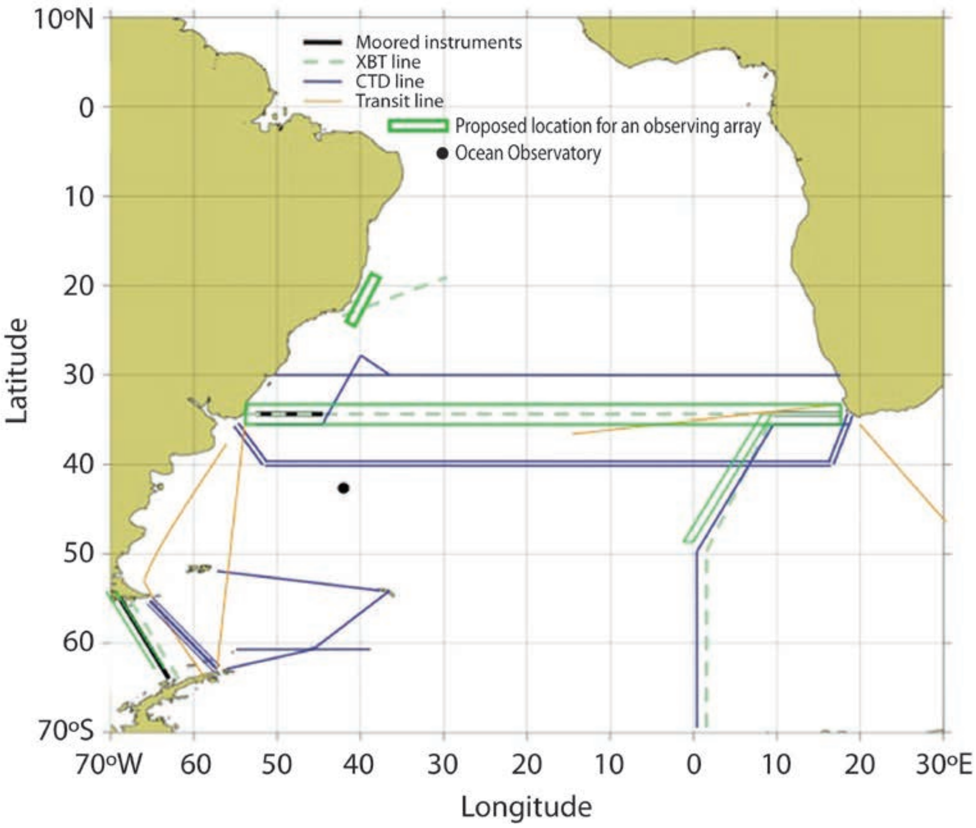

Figure 35: *The SAMOC Array - Current plans for observations in 2010 and 2011. Moored instruments are indicated by a solid black line at: the Drake Passage, Drake (US), off the South American coast, SAM (US/Argentina/Brazil), and off the coast of South Africa, GoodHope (France). Tall moorings are also deployed along the GoodHope line (Gemany). The black circle indicates the location of a planned Ocean Observatory (US). Blue lines indicate CTD sections. Green rectangles indicate the SAMOC-recommended observations: A CTD line nominally at 35°S; a line of moored instruments at the same nominal latitude; enhancement of observations PIES/CPIES along the GoodHope line up to the Subantarctic Front; maintain an optimal distribution of instruments at Drake Passage. Transit lines (Yellow lines) are conducted every year and can be used for Argo float deployments or other observations. From Garzoli et al. (2010) (see http://www.aoml.noaa.gov/phod/SAMOC/SAMOC3_WKSp%20report_9_30.pdf)*

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; and
- adequate access to polar class ships.

Almost all elements of the observing system require enhancement to reach the sampling required to address the key scientific challenges.

4.3 Next Steps Towards Implementation

Scientific Co-ordination

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 groups has ensured effective coordination between the panels and across international programmes 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 and will be reformed to form a SOOS Scientific Steering Committee. 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. Several other panels and national and international programmes also have an important role to play, as outlined below.

A programme of the scale and complexity of the SOOS requires an International Programme Office (IPO). The SOOS IPO will serve as a central contact point for SOOS, monitor progress towards SOOS goals, facilitate coordination of field work, assist in the organisation of workshops and synthesis activities, and coordinate a Web site and other activities to advertise the aims and achievements of the SOOS. The Institute for Marine and Antarctic Studies, University of Tasmania, Australia, has recently established the SOOS IPO, with funding for an Executive Officer for five years. The Australian Antarctic Division is also providing some additional IPO support.

Observing System Design

For many elements of the SOOS, the optimal sampling plan has not yet been determined. Quantitative studies of the compromises to be made between observing system elements are needed, using a variety of approaches, including formal Observing System Simulation Experiments (OSSEs). 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 SOOS Scientific Steering Committee, in consultation with others.

In the case of the global climate module of GOOS, having clear numerical targets for numbers of observing platforms monitoring 'Essential Climate Variables' reported to the United Nations Framework Convention on Climate Change (UNFCCC) has proven extremely useful for brokering multi-governmental support required to sustain the system. Governments have shown themselves willing to sign up to clear, simple numerical implementation targets that are backed up by solid research. To achieve broad intergovernmental support to sustain a SOOS, progress towards SOOS goals should be monitored in a process analogous to that currently employed for the global climate module of GOOS. The newly adopted Framework for Ocean Observations, with its focus on Essential Ocean Variables (EOVs), will enable this process.

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 (including under-ice floats). 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.

Building 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 programmes 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 among 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. 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 programme aims to assess the impacts of climate change on Southern Ocean marine ecosystems. The Sentinel programme 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 research 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 a component of the SCOR/IGBP IMBER project 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, Ecosytems and Biogeochemistry (SOCEB) programme under development in the United States 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) programme 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.
- The SCAR Evolution and Biodiversity in the Antarctic (EBA) programme concerns itself with marine as well as terrestrial biodiversity and was home to the recently completed Census of Antarctic Marine Life (CAML). EBA's marine activities are likely to continue through one or more SCAR programmes, and the possibility exists for a follow-up to CAML's survey of the biota of the Southern Ocean.
- CCAMLR's ongoing marine programmes in support of fisheries activities will continue to be a valuable source of information for SOOS.

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 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 programme, 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 60ºS), 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 2009 Report of the IOC Assembly (IOC, 2009) noted that "One of the most important legacies of the International Polar Year will be its catalytic effect on filling the longstanding polar gaps in the Global Ocean Observing System. Relevant plans outlining how such regional high-latitude systems might be developed include the Sustaining Arctic Observing Networks report (www.arcticobserving.org) and the Southern Ocean

Observing System." On this basis, the Assembly decided to "support multilateral ocean-observing systems in the Arctic and Southern Oceans as regional contributions to GOOS."

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, as well as some of the needs of the Advisory Committee on Albatrosses and Petrels (ACAP). 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 this recommendation.

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.

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 organisations and their clients. The objective for a SOOS should thus not be 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, ICSU, and IOC data policies, and national and international legislation. The immediate, free access to Argo data provides a model.

2. Establish a SOOS data portal

A SOOS data portal will provide one-stop access to distributed data archives holding all SOOS 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. The European SeaDataNet project and the Australian Integrated Marine Observing System (IMOS) provide regional examples of the data portal concept.

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 and Carbon Hydrographic Data Office (CCHDO), the thermal data assembly centres, and the Argo and Global Sea Level Observing System (GLOSS) data systems. For marine biodiversity data, the data portal 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 Ocean Biogeographic Information System (OBIS) and the Global Biodiversity Information Facility (GBIF), as well as to the Encyclopaedia of Life, an online resource with an illustrated page for each species. 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 are accessible and of known quality. Efforts have been made to do this for some physical oceanographic data (e.g. the Southern Ocean database of Orsi and Whitworth, 2005), inorganic carbon and carbon-relevant data (e.g. Key et al., 2010) and the recent compilation of zooplankton net tow data sets (KRILLBASE, Atkinson et al., 2008) which 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 scientists involved in Southern Ocean research 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

The SOOS data portal will also foster agreements on protocols for data collection, 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 can only 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 measurements delivered on a routine basis from satellite sensors, well-calibrated against a decade of *in situ* studies.
- Routine delivery of Southern Ocean state assessments and increasing use of reanalyses in the interpretation of observations.
- 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 the 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.
- Increased capability of additional countries to observe the Southern Ocean.

5. Conclusion

The Southern Ocean influences climate, sea level, biogeochemical cycles and biological productivity on a global scale. 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

AABW	Antarctic Bottom Water
ACAP	Advisory Committee on Albatrosses and Petrels (CCAMLR)
ACC	Antarctic Circumpolar Current
ADCP	Acoustic Doppler Current Profiler
AGCS	Antarctica in the Global Climate System
AMLR	Antarctic Marine Living Resources program (U.S.)
AR4	Assessment Report 4 (IPCC)
ASPeCt	Antarctic Sea Ice Processes and Climate programme
ATCM	Antarctic Treaty Consultative Meeting
AUV	autonomous underwater vehicle
BATS	Bermuda Atlantic Time Series
CAML	Census of Antarctic Marine Life
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCHDO	CLIVAR Carbon and Hydrographic Data Office
CDOM	coloured dissolved organic matter
CEMP	CCAMLR Ecosystem Monitoring Programme
CliC	Climate and the Cryosphere
CLIVAR	Climate Variability and Prediction Programme
CNES	Centre National d'Etudes Spatiales (French Space Agency)
CNR	Consiglio Nazionale delle Ricerche (Italy)
CODATA	Committee on Data for Science and Technology (ICSU)
CPR	Continuous Plankton Recorder
CTD	Conductivity – Temperature – Depth (pressure)
DIC	dissolved inorganic carbon
DMS	dimethyl sulphide
EBA	Evolution and Biodiversity in the Antarctic (SCAR)
ESA	European Space Agency
FRRF	fast repetition rate fluorometry
GBIF	Global Biodiversity Information Facility
GEBCO	General Bathymetric Chart of the Oceans
GEO	Group on Earth Observations
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer (ESA)
GOOS	Global Ocean Observing System
GCOS	Global Climate Observing System
GEOSS	Global Earth Observing System of Systems

GLOSS	Global Sea Level Observing System
GLS	Geolocation Sensors
GRACE	Gravity Recovery And Climate Experiment
HNLC	high-nutrient, low-chlorophyll
IBCSO	International Bathymetric Chart of the Southern Ocean
ICED	Integrated Climate and Ecosystem Dynamics Project
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research project
IMET	Improved Meteorology systems
IMOS	Integrated Marine Observing System (Australia)
IOC	Intergovernmental Oceanographic Commission
IPAB	International Programme for Antarctic Buoys
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
JARE	Japanese Antarctic Research Expeditions
JCOMM	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology
JCOMMOPS	JCOMM in-situ Observing System Support centre
LADCP	Lowered Acoustic Doppler Current Profiler
LTER	Long-Term Ecological Research
MEOP	Marine Mammals Exploring the Oceans Pole to Pole
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NADC	National Antarctic Data Centre
NADW	North Atlantic Deep Water
NASA	National Aeronautics and Space Administration (U.S.)
NOAA	National Oceanographic and Atmospheric Administration (U.S.)
NODC	National Oceanographic Data Centre
NWP	numerical weather prediction
OBIS	Ocean Biogeographic Information System

OISO	Ocean Indian Service d’Observation (France)
OSSE	Observing System Simulation Experiment
POGO	Partnership for Observation of the Global Oceans
PIES	Pressure Inverted Echosounder
PTT	Platform Terminal Transmitter (Service Argos)
ROV	remotely operated vehicle
SADCP	Shipboard Acoustic Doppler Current Profiler
SAM	Southern Annular Mode
SAMOC	South Atlantic Meridional Overturning Circulation experiment
SAMW	Subantarctic Mode Water
SASSI	Synoptic Antarctic Shelf Slope Interaction (IPY project)
SCADM	SCAR Standing Committee on Antarctic Data Management
SCAR	Scientific Committee on Antarctic Research
SCAR MarBIN	SCAR Marine Biodiversity Information Network
SCOR	Scientific Committee on Oceanic Research
SeaWiFS	Sea-viewing Wide Field Sensor
SIZ	sea ice zone
SLP	sea-level pressure
SO	Southern Ocean
SOOS	Southern Ocean Observing System
SOCEB	Southern Ocean Carbon, Ecosystems and Biogeochemistry
SSS	sea surface salinity
SWOT	Surface Water Ocean Topography – NASA/CNES altimeter interfereometry mission – launch planned for 2019.
SST	sea surface temperature
TOPP	Tagging of Pacific Predators programme
UCDW	Upper Circumpolar Deep Water
UNESCO	UN Education, Science and Culture Organisation
UNFCCC	UN Framework Convention on Climate Change
VOS	Volunteer Observing Ships
WAP	West Antarctic Peninsula
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment
XCTD	expendable CTD
XBT	Expendable bathythermographs

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