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Monitoring and Understanding Southern Ocean Variability and its Impact on Climate: A Strategy for Sustained Observations

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Abstract – *The Southern Ocean influences regional and global climate in profound ways, and several unique features of the Southern Ocean contribute to this influence: the zonally unbounded nature of the circumpolar ocean, the fact that deep and intermediate layers in the ocean interior are exposed to direct atmospheric forcing there, and the presence of a vast extent of seasonally varying sea ice. The Southern Ocean environment is also remote and hostile. As a consequence, historical data are scarce and hypotheses regarding the climate impact of Southern Ocean processes have been difficult to formulate and test. Design and implementation of an observing system for the Southern Ocean is therefore a formidable challenge. By building on recent scientific and technological advances, however, we can now define and obtain the sustained observations needed to understand the role of the Southern Ocean in climate change and variability.*

A program of coordinated Southern Ocean climate studies is proposed. These experiments will focus on the shallow and deep overturning cells, interbasin exchange, and low-frequency variability of the coupled system. Sustained observations are essential to describe the variability of each of these phenomena, as well as to understand the physical mechanisms driving the variability and to assess sensitivity to future change.

The paper concludes with specific recommendations for an initial Southern Ocean observing system which includes profiling floats (Argo), repeat hydrographic or tracer sections, repeat XBT lines, moored arrays in key locations, and the use of remote sensing technologies – for winds, sea surface height, sea surface temperature, and sea ice.

Introduction

The unique geometry of the Southern Ocean—the absence of land barriers in the latitude band of Drake Passage—exerts a profound influence on the mean stratification and overturning circulation of the global ocean (Gill and Bryan, 1971; Cox, 1989; Toggweiler and Samuels, 1998; Samelson, 1999; Vallis, 2000; Rintoul et al., 2001). The Antarctic Circumpolar Current (ACC) is the primary means by which water, heat and other properties are exchanged between the ocean basins. This circumpolar connection permits a global-scale overturning (thermohaline) circulation to exist (Fig. 1), and allows the transport of anomalies between basins. Density layers found from intermediate to abyssal depths at lower latitudes shoal dramatically across the ACC. Where these layers outcrop, intense ocean–atmosphere–ice interactions drive water mass transformations. By converting upwelled deep water into new intermediate and bottom water (Fig. 1), the Southern Ocean ventilates a large fraction of the world ocean, and thus regulates the ocean's capacity to store heat and carbon. Given the importance of the Southern Ocean in the climate system, sustained observations of the mid- and high-latitude oceans of the

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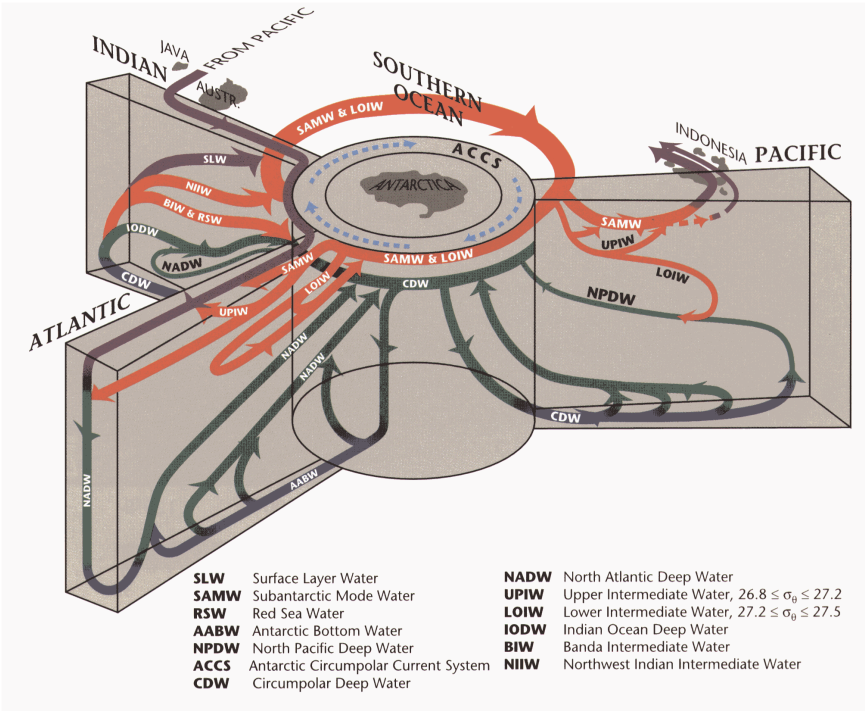

Figure 1. A schematic of the three-dimensional flow between ocean basins. The figure illustrates the two key roles the Southern Ocean plays in the global overturning circulation: (1) the circumpolar link connects the ocean basins, and (2) water mass formation transforms deep water to intermediate and bottom water (from Schmitz, 1996).

Southern Hemisphere are essential to describe and understand the physical processes responsible for climate variability and change, a primary objective of CLIVAR.

The first aim of this paper is to make the scientific case for sustained observations in the Southern Ocean. Even a decade ago, so little was known about the Southern Ocean region that we could not say what was really needed to be measured on a sustained basis, nor did we have the tools to make sustained measurements in such a remote region. Recent scientific advances have provided new insights into the links between the Southern Ocean and climate that guide the design of an observing system. At the same time, technological advances mean that observations of the important fields can now be made on a sustained basis in a cost-effective manner.

The second aim of the paper is to present an outline of a Southern Ocean observing system for climate. Each component of the observing system contributes to a number of scientific goals. To avoid repetition, specific recommendations are presented together at the end of the paper.

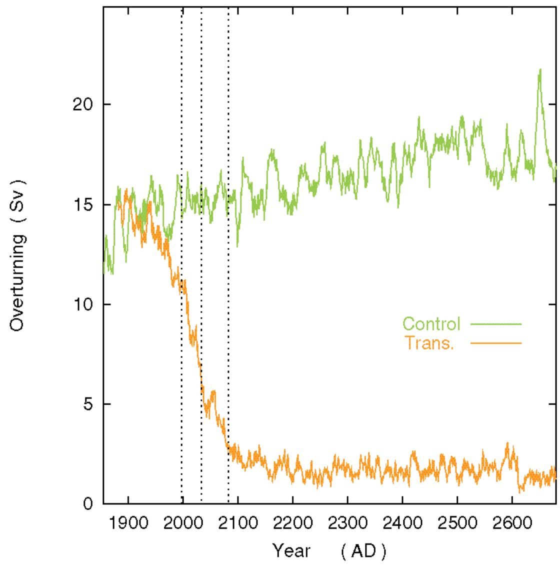

Figure 2. Transport of Antarctic bottom water in Sv (1 Sv = 10^6 m^3 s^{-1}) through 1250 m depth from the control run with no anthropogenic greenhouse gas forcing (green line) and the transient run with greenhouse gas forcing (orange line). The collapse of AABW formation is caused by an increase in stratification at high latitude due to an increase in precipitation, increase in temperature, and decrease in sea-ice formation in the climate change run. From Hirst (1999).

To limit the scope of the paper to a manageable size, we focus here on *in situ* observations of the physical climate system. Satellite observations are of particular importance in such a poorly observed region. Here we highlight a number of remote sensing issues specific to the Southern Ocean, and refer readers to other chapters in this volume which discuss each of the specific satellite sensors in detail. Interactions between the ocean, sea ice, and glacial ice are central to an understanding of how the Southern Ocean influences climate, but cannot be covered in detail here; the justification and requirements for sustained observations in the Antarctic sea ice zone are covered in more depth in Cattle et al. (1999) and Drinkwater et al. (1999). Tracer observations also play a particularly important role in the Southern Ocean, and readers are referred to Fine et al. (this volume) for a more complete discussion.

Connections between the Southern Ocean and climate

Sensitivity of high latitude stratification to climate change

The ocean stratification at high southern latitudes is delicately poised, and is stabilized by low salinity in the upper ocean. This marginal stability is sensitive to freshwater flux changes of either sign. For example, one of the more robust projections from simple theory as well as coupled models is that in a warmer world the hydrological cycle will become more intense—evaporation will increase at mid-latitudes, and rainfall will increase at higher latitudes. An increase in the net freshwater flux will increase the upper ocean stratification at high latitudes. Climate models suggest that the impact of such changes is dramatic, particularly in the Southern Ocean (Manabe and Stouffer, 1994; Hirst, 1999). The sinking of dense water in both hemispheres slows or ceases altogether in response to the presence of a cap of fresh surface water, reducing the heat transported by the thermohaline circulation. The formation of Antarctic Bottom Water (AABW) does not recover through an extended integration at elevated levels of CO2, and the deep ocean remains stagnant (Fig. 2, Hirst, 1999). Ocean uptake of carbon is also reduced (Sarmiento et al., 1998; Matear and Hirst, 1999).

These model results need to be viewed with caution, given known weaknesses in present climate models (e.g. weak high-latitude stratification in the control run (Gnanadesikan, 1999a) and inadequate representations of intermediate and bottom water formation). Nevertheless, they illustrate the potential sensitivity of global climate and future atmospheric CO2 concentrations to Southern Ocean processes.

The high latitude Southern Ocean is also sensitive to changes of freshwater flux of the opposite sign. Decreases in freshwater flux can shift the system from the present 'haline control', where the fresh cap is sufficient to maintain stability, to an open ocean 'thermal mode', causing deep convection, as seen in the Weddell polynya of the 1970s (Gordon, 1982; Gordon, 1991a). The polynya results in enhanced heat exchange between the ocean and the atmosphere, driving substantial cooling in the ocean and changes to the atmospheric circulation of the Southern Hemisphere (Glowienka-Hense, 1995).

A system of negative feedbacks involving ice, ocean and atmosphere contributions to the freshwater balance likely accounts for the relative stability of the present configuration, but these processes are not well understood (Martinson, 1990; Gordon and Huber, 1990; Martinson, 1993). The global response of climate models to increasing atmospheric CO2 is extremely sensitive to changes in Antarctic sea ice (Fig. 3; Rind et al., 1995, 1997), so progress in understanding these feedbacks is critical. Sustained observations (and modelling studies) contributing to a more complete understanding of the freshwater budget and its sensitivity to change are high priority.

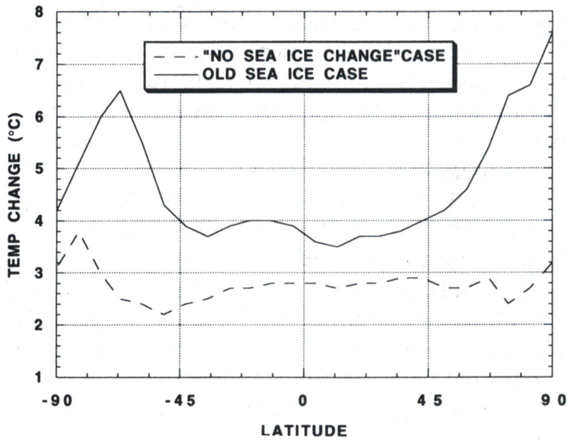

Figure 3. Annual average surface air temperature change due to 2 x CO_2 in two GCM runs. When sea ice is not permitted to change (dashed line), there is little high-amplitude amplification of the warming, and the warming is reduced even at low latitudes. The total sea-ice contribution to the global average warming is 37% in this GCM. (Rind et al., 1995).

Global overturning circulation

A number of recent studies have highlighted the Southern Ocean's role in the global overturning circulation. In particular, North Atlantic Deep Water (NADW) exported from the Atlantic must somewhere be converted to less-dense intermediate water which flows north in that basin to close the overturning cell (Rintoul, 1991). The traditional view is that this water mass conversion is accomplished by uniform upwelling of deep water into the thermocline (e.g. Stommel and Arons, 1960). However, the few direct observations of mixing in the ocean thermocline that exist show values an order of magnitude too small to support the required upwelling (e.g. Ledwell et al., 1993). Recent modelling (Döös and Coward, 1997; Toggweiler and Samuels, 1998; Webb and Suginohara, 2001) and observational studies (Sloyan and Rintoul, 2000a,b; Gnanadesikan, 1999b; Speer et al., 2000) suggest that the required water mass transformation is accomplished by ocean–atmosphere–ice interactions where the deep water layers outcrop in the Southern Ocean. Circumpolar deep water upwells south of the

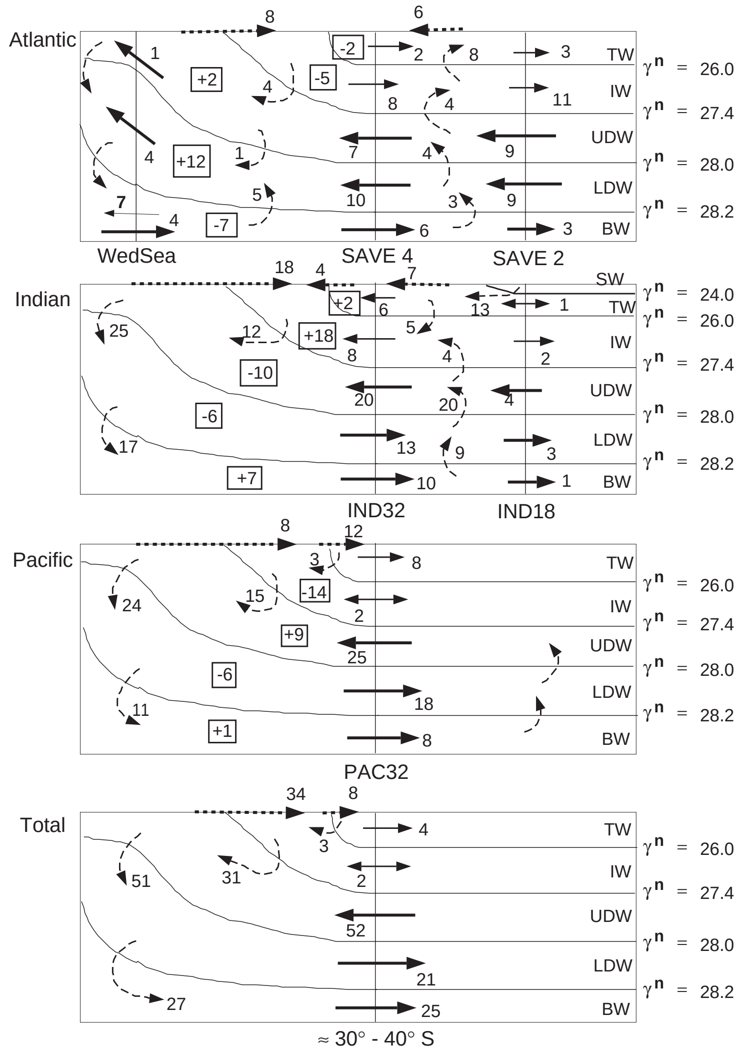

Figure 4. A schematic 5-layer summary of the overturning circulation in each ocean basin, and the zonal sum. The transports are in Sverdrups (1 Sv = 106 m3 s-1). The bold dashed line near the surface is the transformation driven by air–sea buoyancy fluxes; dashed lines in the interior represent mixing/entrainment; boxed numbers show the net convergence in each Southern Ocean sector due to meridional and diapycnal fluxes (+'ve means more water enters the layer in this sector, and is balanced by zonal divergence of the ACC). Layers are defined by neutral density surfaces (labels on right hand side). The figure illustrates the importance of Southern Ocean air–sea buoyancy fluxes and diapycnal mixing in the global overturning circulation. (From the inverse model of Sloyan and Rintoul, 2000a).

Antarctic Circumpolar Current (ACC), is warmed and freshened as it is driven north in the Ekman layer; and ultimately sinks again to form Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) (Fig. 4).

The illustrations of the Southern Ocean overturning circulation in Figures 1 and 4 have changed little from those produced by Sverdrup and Deacon in the 1930s. What is new is the ability to quantify the lateral and diapycnal fluxes involved in the overturning. Figure 5 shows a schematic five-layer summary of the overturning circulation in each ocean basin from an inverse model which explicitly accounts for water mass transformation by air–sea fluxes and includes a new parameterization for diapycnal fluxes in the ocean interior (Sloyan and Rintoul, 2001a). The overturning cells in the Southern Hemisphere are vigorous (e.g. more than twice the transport of the global NADW cell) and largely isolated from the overlying thermocline waters. Conversion of about 30 Sv of upwelled deep water to lighter intermediate water driven by the gain of heat and fresh water from the atmosphere is a key link in the overturning. Diapycnal mixing is also a large term where layers outcrop at high latitude, in the abyss at low latitudes, and in eddy-rich regions.

Water mass transformations driven by air–sea exchange in the Southern Ocean permit a vigorous global overturning circulation to exist, despite weak mixing in the ocean interior. This fact has implications for the mechanism and time scale of variability in the overturning (and hence climate). If the overturning is closed through interior diffusive mixing, the upwelling branch of the cell occupies the full volume of the ocean beneath the thermocline, and is likely to be steady on long time scales (i.e. no direct link between deep mixing and changes in surface forcing). If the overturning is closed through an advective response to air–sea interaction at high southern latitudes, then the response to a change in forcing may be rapid. These results suggest that the global overturning circulation, a key focus of CLIVAR, cannot be understood without observations of the Southern Ocean. In particular, hydrographic sections with tracers are needed to define closed volumes for inverse studies, accurate air–sea fluxes are needed to estimate water mass transformations, and efforts to determine the magnitude and distribution of diapycnal mixing must be encouraged. (As noted above, specific recommendations are deferred to the end of the paper.)

Subantarctic Mode Water and Antarctic Intermediate Water

Changes observed in the temperature and salinity of intermediate waters (AAIW/SAMW) (Fig. 6)

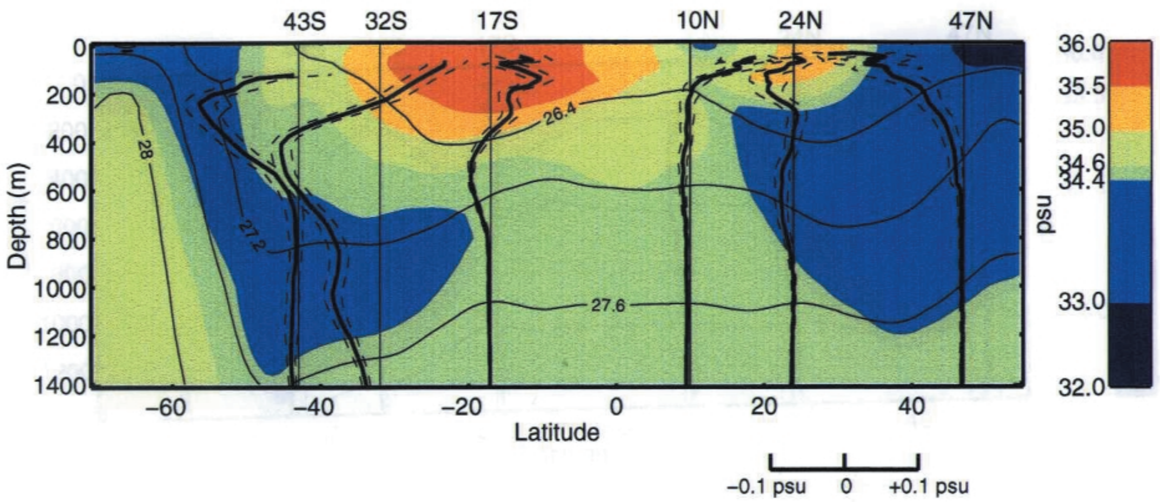

Figure 5. Change in salinity of intermediate waters observed in the Pacific Ocean between the 1960s and 1990s (from Wong et al., 1999). The tongues of low salinity intermediate water spread from the sea surface at high latitude, where intermediate water is formed, toward the equator beneath the subtropical gyres. The intermediate water enters the interior along isopycnals (thin solid lines). Bold lines at particular latitudes show the vertical profile of the change in salinity between sections occupied a few decades apart. A consistent pattern of fresher intermediate water and saltier water in upper layers of the subtropical gyres is seen in both hemispheres, broadly consistent with an increase in vigor of the hydrological cycle as projected by climate models.

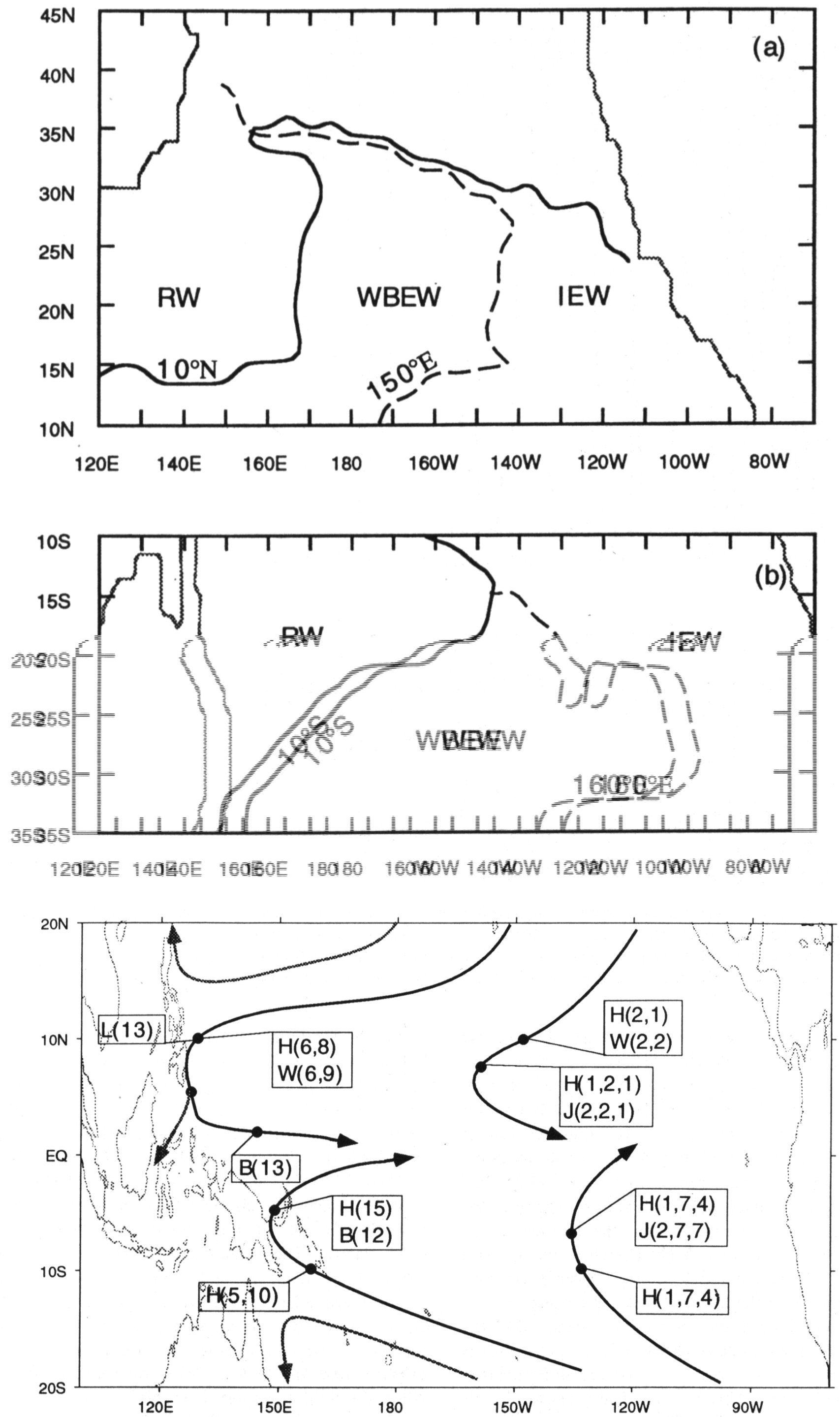

Figure 6. An illustration of the relative contributions of northern and southern hemisphere water to the equatorial Pacific in the NCEP model (from Huang and Liu, 1999). (a,b) Circulation regimes revealed by tracking particles (RW = recirculation regime, no exchange with equator; WBEW = exchange window through which particles reach equator by passing through low-latitude western boundary currents; IEW = exchange window through which particles can reach equator in the interior of the basin. Note that the exchange windows extend across more of the basin and reach higher latitudes in the South Pacific. (c) Transport summary based on the model results of Huang and Liu (labelled H); and the observational results from Wijffels (1993) (W), Johnson and McPhaden (1999) (J), and Butt and Lindstrom (1994) (B). Both models and observations agree that the Southern Hemisphere supplies most of the water reaching the equatorial Pacific thermocline.

suggest the upper limb of the overturning circulation may already be responding to the polar freshening projected by climate models (see observations reported in Johnson and Orsi, 1997; Wong et al., 1999; Bindoff and McDougall, 2000). These models suggest that the signal of anthropogenic climate change will be most easily detected in the mode waters of the Southern Hemisphere (Banks et al., 2000). These layers the upper limb of the overturning circulation may already be responding to the polar freshening projected by climate models (see observations reported in Johnson and Orsi, 1997; Wong et al., ventilate the lower thermocline of the Southern Hemisphere subtropical gyres (McCartney, 1982) and carry low salinity water northward to close the freshwater budget (Tsuchiya, 1989; Gordon, 1991b). Changes in the properties of AAIW and SAMW may therefore feedback on the hydrological cycle and the heat storage capacity of the subtropical gyres (Gordon, 1991b). Moreover, because the signal of anomalous surface forcing is transmitted to the interior ocean by subduction of AAIW and SAMW, these water masses are natural buffers of climate change. Existing estimates of change in Southern Ocean water masses need to be treated with some caution, since differences between data taken decades apart in time may alias variability on other time scales. To determine how and why the interior ocean is changing, additional repeat measurements from ships and profiling floats are needed.

Antarctic Bottom Water

Some of the deep water which upwells in the Southern Ocean is converted to denser Antarctic Bottom Water (AABW), which is exported from the Southern Ocean to cool and ventilate the abyssal layers of the world ocean (Figs 1 and 4). A variety of AABW types are formed in different regions and at different densities; in terms of ventilating the abyssal ocean, the lighter varieties which are not confined within deep basins play a particularly important role. The transport of the deep or bottom water cell is significantly larger than the overturning associated with formation of North Atlantic Deep Water (Fig. 5; Schmitz, 1995; Sloyan and Rintoul, 2001a). However, the fact that a still unknown number of relatively small sources contribute to the overall bottom water production rate makes it difficult to connect the variability of individual sources to the global overturning rate (Fahrbach et al., 2001). On time scales of ≈50 years and longer, changes in AABW formation will change the abyssal stratification and biogeochemical distributions at lower latitudes. The formation of dense water south of the ACC in part determines the meridional density gradient across the current, and hence its transport (Gent et al., 2001): variations in AABW formation may be linked to changes in the interbasin exchange of heat and other properties. Changes observed in the formation and export of AABW serve as a diagnostic of changes in ocean–atmosphere–ice interactions at high latitude (Coles et al., 1996; Hogg and Zenk, 1997; Fahrbach et al., 1998).

Vigorous ocean–atmosphere–ice interactions on the continental shelf, particularly in coastal polynyas, drive the formation of AABW (Gordon, 1998; Rintoul, 1998), but the details are not completely understood. Because AABW formation depends on a variety of processes operating at small spatial scales at sites which are logistically challenging, direct measurements of AABW formation rates are difficult to make on a sustained basis. One strategy used successfully in the World Ocean Circulation Experiment (WOCE) is to monitor the outflow of dense water at some distance from the formation regions using repeat sections and moored current meters (Fahrach et al., 1994a, 1995, 2001). A powerful alternative strategy is to use tracer inventories (e.g. CFCs) to constrain the total formation rate of AABW (Orsi et al., 1999).

As mentioned above, models suggest the formation of AABW may be sensitive to changes in fresh water flux, but the processes are not well enough understood to assess the realism of these projections. Observations confirm a link between variations in AABW formation and in the freshwater budget due to changes in sea ice export from the formation area (Fahrbach et al., 2001; Harms et al., 2001); continental sources of fresh water (ice shelves, icebergs) also play a role (e.g. Fahrbach et al., 1994b). Broecker et al. (1999) highlight a discrepancy between AABW formation estimates derived from different tracers and interpret this as evidence for a three-fold decrease in the formation rate of AABW in the 20th century. New CFC inventory estimates for the less dense classes of AABW, on the other hand, show significant ventilation of these lighter layers (Orsi et al., 2001, ms. submitted to *J. Geophys. Res.*). This result brings the estimates based on CFCs and other tracers more or less into agreement, supporting a steady rate of AABW formation over the last millennium (Orsi et al., 2001). In any case, the issue remains a topic of debate. Observations of the terms in the freshwater budget in the ice-covered and open ocean are needed to assess the sensitivity of AABW formation to changes in forcing.

Variability of interbasin exchange of heat and other properties

A zonally coherent increase in transport of the ACC, with no anomalous divergence of heat, water masses or other properties, might by itself be expected to have little impact on climate. However, because the heat transport by the ACC is large, even small percentage changes in heat transport may result in significant divergence. Results from Southern Ocean WOCE suggest the interbasin exchange of heat varies significantly from year to year at some locations. For example, the heat flux entering the Pacific south of Australia varied by 0.6×10^{15} W (relative to 0°C) between 1991 and 1996 (Rintoul and Sokolov, 2001). The large-scale significance of this heat flux variability is difficult to interpret in the absence of other observations. Changes in baroclinic heat transport south of Australia could be balanced by local or basin-scale storage, by changes in the heat carried by the ACC at other locations, by changes in meridional heat flux in the Indian and Pacific basins, by changes in air–sea heat flux, or by changes in barotropic flow. Given that the observed variability is significant relative to the meridional heat transport in neighboring basins, it is important that the Southern Ocean observing system provides the measurements needed to assess its impact (see 'A Southern Ocean climate observing system' for a discussion of the measurements required).

The transport of individual water masses changes around the circumpolar path of the ACC. For example, more intermediate water enters the Atlantic through Drake Passage than exits south of Africa, the difference made up by export of NADW (Rintoul, 1991). South of Australia, more SAMW enters the Pacific than leaves through Drake Passage; the inflow of SAMW balances the outflow of water through the Indonesian passages (Sloyan and Rintoul, 2001b). If changes in air–sea forcing drive changes in water mass formation, the transport of anomalous water masses will carry the signature of the forcing anomaly into neighbouring basins where it may affect the climate there. For example, repeat sections south of Australia show that while transport of deep layers (denser than SAMW) is steady (varying by <2 Sv), SAMW transport varies from 4 to 16 Sv (Rintoul and Sokolov, 2001). Once again, results from a single section are difficult to interpret. Transport measurements at other chokepoints (Drake Passage, the Indonesian passages) are needed, as are broadly distributed profiling floats and satellite altimetry to measure the transient storage.

Measurements of ACC property transports constrain basin-scale budgets of heat and fresh water (e.g. Georgi and Toole, 1982; Rintoul and Sokolov, 2001). Direct estimates of heat and freshwater transports from oceanographic observations are generally more accurate than any alternative method presently available (e.g. integration of air–sea fluxes estimated from bulk formulae, or estimated as a residual from atmospheric models and satellite measurements; Bryden and Imawaki, 2001; Wijffels, 2001). The indirect estimates are particularly uncertain at high southern latitudes where the air–sea fluxes are poorly known, the bulk formulae may be in error, and the atmospheric reanalyses are not well constrained by observations. Budget studies using transport and storage observations in the Southern Ocean are an important tool for improving our knowledge of the exchange of heat and fresh water between ocean and atmosphere.

Antarctic Circumpolar Wave

The coupled pattern of ocean, atmosphere and sea ice anomalies known as the Antarctic Circumpolar Wave (ACW; White and Peterson, 1996) depends on the slow oceanic teleconnection provided by the circumpolar flow of the ACC. The mechanism maintaining the ACW anomalies in the face of dissipation remains a topic of debate. Hypotheses for the ACW include forcing by ENSO-related atmospheric teleconnections (Peterson and White, 1998), and feedbacks between ocean heat content and anomalies of wind stress and Ekman heat transport (White et al., 1998); a coupled instability of the atmosphere–ocean system 'local' to the Southern Ocean (Qiu and Jin, 1997; Goodman and Marshall, 1999); or a passive ocean response to stochastic atmospheric forcing (Weisseet al., 1999), to fluxes from atmospheric reanalyses (Bonekamp et al., 1999), or to standing patterns in the atmosphere (Christoph et al., 1998). With longer-term surface records, it is becoming clear that the nature and strength of the ACW signal varies with time (e.g. Simmonds, 2002), but the physical mechanisms driving the variability are unknown. For example, knowledge of the phase relationships between anomalies in different media (ice, atmosphere, surface and subsurface ocean) over a number of ACW periods would permit testing of the proposed mechanisms. Observations of the vertical structure of the ocean anomalies associated with the ACW are needed to test competing hypotheses: vertical coherence is expected in a simple dynamical framework, while its absence would point to a forced or damped response.

Recent studies suggest the ACW has a substantial impact on regional climate variability. For example, White and Cherry (1998) and White (2000) have shown that rainfall in New Zealand and southern Australia is more strongly correlated with the ACW than with ENSO, and suggest this link may provide some predictive skill at lead-times out to a year. To exploit this potential predictability, it is essential to understand the underlying dynamics, and their sensitivity to changes in stratification or forcing. Changes in upper ocean stratification can alter the nature of atmosphere–ocean modes responsible for low-frequency climate variability (e.g. the usually close link between the strength of deep convection in the Labrador Sea and the NAO breaks down in the presence of a fresh surface layer (Curry et al., 1998)). The lack of observations means that we cannot yet document salinity anomalies in the Southern Ocean like those observed to propagate around the North Atlantic, but the potential exists for modulation of coherent patterns of Southern Ocean variability, such as the Antarctic Circumpolar Wave.

Interannual to multidecadal variability of the Southern Hemisphere atmosphere

Numerous studies have documented interannual and longer period variability in the dominant modes of the Southern Hemisphere atmospheric circulation (e.g. Rogers and van Loon, 1982; Hurrel and van Loon, 1994; Allan et al., 1995; Karoly et al., 1996; Garreaud and Battisti, 1999; Mo, 2000). For example, the semi-annual oscillation explains more than half the mean annual variance of sea level pressure over large areas of the Southern Hemisphere (van Loon, 1972). It is a coupled ocean–atmosphere phenomenon that results from phase differences in the annual cycle of temperature between the ocean-dominated midlatitudes and the continent-dominated higher latitudes. A marked decrease in amplitude of the semi-annual oscillation after 1979 (Hurrel and van Loon, 1994) has been linked to changes in the annual cycle of SST near 50°S (Meehl et al., 1998b). The importance of dynamical coupling between ocean, atmosphere and sea ice is underscored by the fact that coupled models with a non-dynamic mixed layer ocean do not reproduce the variability observed at mid- to high-latitudes of the Southern Hemisphere and seen in fully coupled models (Meehl, 1991; Manabe and Stouffer, 1996; Simmonds and Walland, 1998).

Multi-decadal variability has been described in a number of atmospheric fields in the Southern Hemisphere. Examples include the strength of the subtropical high (Reason, 2000); rainfall in South Africa (Tyson and Preston-White, 2000) and western Australia (Ansell et al., 2000; Smith et al., 2000); and cyclone characteristics, which have decreased in number but increased in radius and depth between 1970 and 1995 (Simmonds, 2002). The Pacific-South America pattern, the dominant teleconnection linking the tropics and higher latitudes in the Southern Hemisphere, appears in both interannual and multi-decadal frequency bands (Garreaud and Battisti, 1999). Mo (2000) links a decrease in the zonal mode (the leading EOF for 500 hPa seasonal mean height anomalies) to an increase in SST over the southern oceans in recent decades. The physical mechanisms responsible for the observed low-frequency variability remain a topic of active debate. In particular, it is not yet clear how much of the variability is forced by the tropics and how much reflects coupled ocean–atmosphere–ice interactions in the Southern Ocean region.

Much of the recent progress in describing the low-frequency variability in the Southern Hemisphere atmosphere has relied on reanalysis products produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the US National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) (e.g. Garreaud and Battisti, 1999; Mo, 2000; Simmonds, 2002). However, it must be kept in mind that the models are run with prescribed SST and sea ice as lower boundary conditions. Observations of both SST and sea ice were sparse, particularly in the first half of the reanalysis period. The low-frequency variability inferred from the reanalysis products may therefore not accurately reflect the true variability. Future progress is likely to continue to rely heavily on reanalyses; sustained measurements of sea surface temperature, sea level pressure, and sea ice extent are required to ensure the quality of the analyses in the Southern Ocean region.

Centennial variability

Climate models and paleoceanographic records provide some intriguing suggestions of links between the ACC and variability of the global circulation on centennial time scales. Studies using ocean models driven with mixed boundary conditions (i.e. restoring to observations for temperature and a fixed freshwater flux for salinity) suggest that advection of salinity anomalies leads to oscillations of the overturning circulation (and ACC transport) with periods of about 300 years (Mikolajewicz and Maier-Reimer, 1990; Pierce et al., 1995; Drijfhout et al., 1996; Osborn, 1997). The source of the oscillations appears to lie in the Southern Ocean (Pierce et al., 1995; Osborn, 1997). Paleoceanographic proxy records show evidence of cycles with similar time scales (e.g. Leventer et al., 1996; Domack and Mayewski, 1999).

It is well known, however, that models run with mixed boundary conditions may exaggerate the feedback between salinity anomalies and high-latitude convection which is at the heart of these oscillations (e.g. Tziperman et al., 1994). Coupled model results are inconclusive: some show that the salinity feedback is important, others do not. Hence, while models have identified a mechanism by which Southern Ocean salinity anomalies drive global-scale variability on century time scales, further work is required to determine whether such a mechanism is likely in the real ocean. Sustained observations of the stratification of the upper ocean (including salinity) and the terms in the freshwater budget (e.g. air–sea fluxes, sea ice formation and melt, and Ekman fluxes) are required to understand the ocean–atmosphere–ice interactions which are fundamental to these oscillations.

Low latitude influence of Southern Hemisphere subtropical and subantarctic waters

The potential for oceanic advection of heat anomalies to produce delayed negative feedback, and hence oscillations, in the ocean–atmosphere system underlies several recent theories of decadal and interdecadal variability (e.g. Latif and Barnett, 1994, 1996; Gu and Philander, 1997; Sutton and Allen, 1997). The proposed mechanisms differ in important ways, but the fundamental feature linking them is a slow time scale set by ocean advection of anomalies (e.g. Meehl et al., 1998a). Most of these studies have focused on the relatively well measured Northern Hemisphere, where hypotheses are easier to test. But many of the large-scale anomalies which have received attention in the Northern Hemisphere have a signature in the Southern Hemisphere as well (e.g. White and Cayan, 1998). Moreover, water from the Southern Hemisphere dominates the surface and thermocline waters of the equatorial Pacific (Fig. 7) (Lu and McCreary, 1995; Liu and Huang, 1998; White and Cayan, 1998; Huang and Liu, 1999; Johnson and McPhaden, 1999). The tropical Atlantic is also supplied by waters from the south (e.g. Schott et al., 1998). These studies suggest that advection of extratropical Southern Hemisphere anomalies drives decadal and longer period variability in the tropics (Weaver, 1999; Schneider et al., 1999).

The extratropical influence on the tropical Pacific thermocline extends at least as far south as the ACC. For example, the Southern Hemisphere waters which supply the Equatorial Undercurrent (EUC) include SAMW formed on the northern flank of the ACC (e.g. Tsuchiya et al., 1989; Toggweiler et al., 1991; Blanke and Raynaud, 1997; Lu et al., 1998). Anomalies in subduction, circulation, or formation of the water masses which supply the EUC may therefore ultimately influence SST when the EUC shoals in the eastern tropical Pacific. Such extratropical anomalies might arise from changes in the midlatitude westerlies, which in turn are known to respond to changes in tropical SST via atmospheric teleconnections such as the Pacific–South American pattern. Taken together, we have the ingredients for a delayed-action oscillator of the same nature as that proposed by Gu and Philander (1997), but one likely operating on a longer, interdecadal time scale (given the longer path and slower advection speed at these depths). The interdecadal variability mechanism proposed by White and Cayan (1998) is similar in spirit, but relies on out-of-phase SST anomalies in the tropics and Subarctic or Subantarctic Frontal Zones, linked by atmospheric teleconnections. Sustained observations in mid-

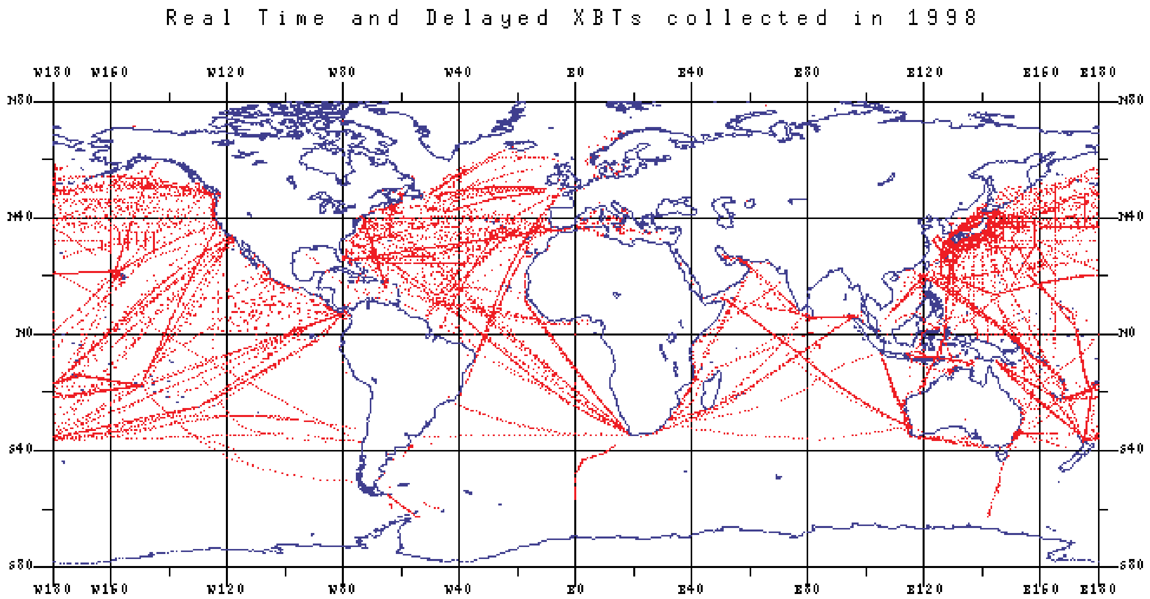

Figure 7. Upper ocean temperature observations obtained by the XBT network in 1998. The sparse coverage in the Southern Ocean is obvious.

and high-latitudes of the Southern Hemisphere oceans are needed to explore how tropical–extratropical exchange modulates ENSO.

A Southern Ocean climate observing system

The existing observational network in the Southern Ocean is completely inadequate to address the scientific issues reviewed above. For example, the distribution of temperature profiles obtained by volunteer observing ships makes it clear that very little of the mid- to high-latitudes of the Southern Hemisphere is sampled on a routine basis (Fig. 8). An enhanced Southern Ocean observing system is essential if we are to monitor and understand climate variability and change. In this section we summarize the sustained observations required in the Southern Ocean.

To facilitate a concise discussion of the observational requirements, we group the phenomena described above into four main (somewhat overlapping) research themes:

- The **shallow overturning circulation** refers to upwelling of Circumpolar Deep Water and conversion to SAMW and AAIW. Key issues include formation and circulation of SAMW and AAIW, sensitivity to changes in air–sea fluxes, link to the global overturning associated with NADW formation and export, role in ventilation of the subtropical thermocline, exchange with lower latitudes, and oceanic uptake of heat and anthropogenic CO_2.
- The **deep overturning circulation** refers to upwelling of deep water and conversion to denser AABW. Key issues include stability of the deep overturning circulation (e.g. in response to changes in freshwater flux), rate of AABW formation and sensitivity to change, freshwater balance at high southern latitudes, and sensitivity of low-latitude stratification to changes in AABW formation and export.
- **Interbasin exchange** refers to variability in ACC transport and the exchange between the Southern Ocean and the subtropical gyres, connections between changes in interbasin exchange and basin-scale heat and freshwater budgets, and the propagation of anomalies between basins and their impact on regional climate.
- The **low-frequency variability** theme includes the ACW and other variability of the coupled ocean–atmosphere–ice system in the Southern Ocean region, on time scales from interannual to centennial. Key issues include the relative roles of remote (e.g. tropical) and local forcing, whether the dominant modes of variability reflect coupled dynamics or a forced response, and the impact of Southern Ocean anomalies on regional climate.

Table 1 presents a summary of the fields which need to be measured on a sustained basis in order to address these four research themes. It is clear that there is substantial overlap. For example, all four themes require sustained observations of the upper ocean stratification (T(x,z,t), S(x,z,t)). In general, sustained observations of each of the fields in Table 1 will require a number of platforms and techniques, as shown in Table 2. For example, improved air–sea fluxes over the Southern Ocean, which are essential for each of the four themes, will ultimately be derived from a combination of *in situ* data, satellite measurements, and numerical models (Taylor et al., this volume). Several moored flux reference sites and upgraded VOS measurements are needed to correct biases in satellite and numerical model-derived fluxes and to develop regional tunings of the flux parameterizations; satellites are needed for global observations of surface wind, surface shortwave radiation, and precipitation; and SST and SLP measurements from ships and buoys are needed for assimilation into numerical weather-prediction models. Finally, heat and freshwater transports estimated from hydrographic sections are needed to constrain basin-scale budgets (Bryden and Imawaki, 2001; Wijffels, 2001).

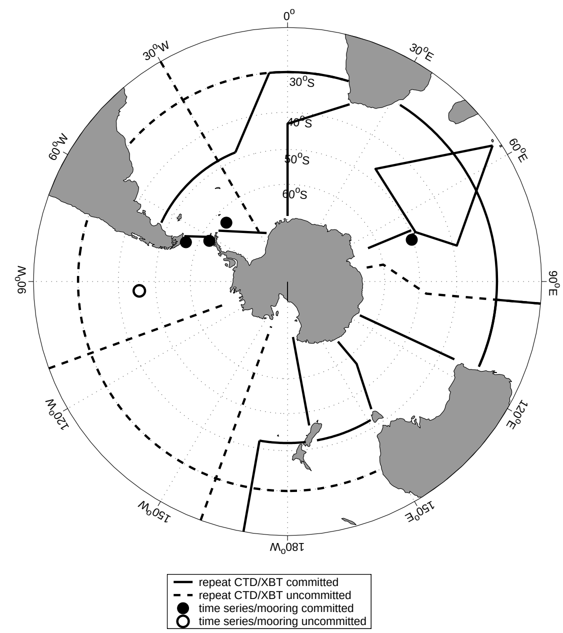

Figure 8. Sustained observations recommended for the Southern Ocean *in situ* observing system. 'Committed' means that an intention to carry out the measurements has been expressed, e.g. in a national plan for CLIVAR/GOOS. Further details are listed in Table 1. Float and drifter sampling is not shown.

Specific recommendations are discussed briefly below, and summarized in Tables 3–5. The Southern Ocean observing system outlined here is a first step. In some cases, quantitative array design studies are required before an optimal sampling program can be defined. Results of the ongoing WOCE synthesis will likely suggest modifications to the plan.

Remote sensing

Global remote sensing issues are discussed in detail in other chapters in this volume, so we have limited our discussion to *in situ* observations. However, it is important to emphasize that remote sensing has a particularly crucial role to play in remote regions like the Southern Ocean, where *in situ* observations will always be sparse. Of particular importance are continuous, high accuracy satellite altimetry from at least two satellites (Mitchum et al., this volume; Le Traon et al., this volume); gravity missions to measure the geoid and permit absolute currents to be inferred from sea surface height (Johannessen et al., this volume); scatterometers to measure surface winds (Millif et al., this volume); infrared and microwave radiometers to measure SST (Reynolds, this volume); and remote sensing of sea ice extent and motion, including active and passive microwave, SAR in specific regions, and improved algorithms (Drinkwater et al., 1999; Cattle et al., 1999).

Remote sensing of the Southern Ocean region encounters some unique challenges. Persistent cloud cover limits the coverage obtained by infrared sensors. A combination of infrared and microwave sensors is therefore required for satellite measurements of SST, and *in situ* measurements for removal of biases are particularly important at high latitudes (Reynolds, this volume). TOPEX/POSEIDON is our most precise altimeter, but its large groundtrack spacing means that much of the mesoscale and frontal variability is undetected at higher latitudes, and the groundtrack does not extend to the Antarctic continent at most longitudes. Combining TOPEX/POSEIDON and ERS altimeters (followed by JASON and ENVISAT on the same groundtrack configurations) provides more complete coverage at high latitudes. There is also the problem of large data dropouts as the satellite approaches the ice, and there is a need to investigate better waveform algorithms and corrections near the critical ocean–sea

Table 1. Fields that must be measured by the Southern Ocean observing system in order to address each of the four general themes identified in the text. (OT = overturning circulation, SAMW = Subantarctic Mode Water, AAIW = Antarctic Intermediate Water, AABW = Antarctic Bottom Water, SO = Southern Ocean, DWBC = Deep Western Boundary Current, ACC = Antarctic Circumpolar Current, SSH = sea surface height, SST = sea surface temperature, SSS = sea surface salinity.)

	Shallow OT + SAMW/AAIW	Deep OT + AABW	Interbasin Exchange	Low-frequency variability
Stratification	X	X	X	X
SO–subtropical exchange	X	X	X	X
Air–sea flux	X	X	X	X
Wind	X	X	X	X
Tracers/CO_2	X	X	X	
ACC transport	X	X	X	X
SSH	X		X	X
SST/SSS	X	X	X	X
DWBC array		X	X	
Sea ice		X		X

Table 2. The combination of platforms and techniques required to provide sustained observations of each of the fields identified in Table 1. Specific recommendations are given in the text and in Figure 9. (OT = overturning circulation, AABW = Antarctic Bottom Water, SO = Southern Ocean, DWBC = Deep Western Boundary Current, ACC = Antarctic Circumpolar Current, SSH = sea surface height, SST = sea surface temperature, SSS = sea surface salinity.)

Fields	Platforms
Stratification T(x,z), S(x,z)	
- z < 2000 m	Argo; repeat hydrography; repeat XBT
- z > 2000 m	Repeat hydrography
SO–subtropical exchange	Argo; repeat hydgrography/tracers; repeat XBT; boundary current moorings; satellite altimetry
Air–sea flux	Flux observatories; improved VOS measurements (e.g. IMET); SLP from drifters for assimilation in NWP models; SST from drifters, satellite, and VOS thermosalinograph
Wind	Satellite scatterometer; improved re-analysis products obtained by assimilating additional SST and SLP data
Tracers/CO2	Repeat hydrography; VOS for pCO2
ACC transport	Repeat hydrography; high density XBT; moored arrays; end-point monitoring; satellite altimetry
SSH	Satellite altimetry and gravity missions (GOCE, GRACE); sea level gauges
SST	Satellite (IR + MW); surface drifters; VOS thermosalinograph; Argo
SSS	Argo; VOS thermosalinograph; repeat hydrography; drifters?; satellite (?)
DWBC transport	Repeat hydrography; current meter moorings across AABW outflow
Sea ice extent/volume	Satellite (various); upward looking echo sounders for ice thickness; ice drifters

ice–continent interface. Tide gauges around the coast of Antarctica are therefore important for extending measurements of sea level to the coast (Mitchum et al., this volume). Remote sensing of sea surface salinity shows some promise for low latitudes (Johannessen et al., this volume). However, the sensitivity decreases rapidly with temperature (e.g. Lagerloef and Delcroix, this volume) and the signals at high latitude are relatively small compared to the tropics, so it is not yet clear that remote sensing of salinity to the required accuracy (0.1 psu) is feasible in the

Southern Ocean. Improved sensors or algorithms for sea-ice extent, concentration, volume and motion are a high priority (Drinkwater et al., 1999).

Southern Ocean Argo

Broadly distributed profiles of temperature and salinity are required to meet every scientific issue raised in the above discussion. The only feasible way to obtain such measurements in a remote region like the Southern Ocean is with profiling floats. The velocity information provided by the floats will help constrain estimates of transport within the Southern Ocean, and between the Southern Ocean and the subtropical gyres (e.g. Wijffels et al., 2001). (See Argo Science Team (this volume) for a more complete discussion of Argo.)

At the nominal resolution of Argo (1 float per 3° longitude x 3° latitude square), roughly 970 floats are needed south of 40°S. Quantitative array design studies need to be carried out to determine the optimal sampling and deployment strategy. High-priority areas for initial deployments are likely to include the southeast Pacific (including SAMW/AAIW formation regions, and the areas of high variability in sea level pressure and SST at higher latitude), the central and eastern Indian sector where mode and intermediate water enter the subtropics, areas of deep water upwelling south of the ACC and within the ACC itself.

Year-round profiles of temperature and salinity in the seasonal sea-ice zone would be of great value, given the lack of observations and the potential for ocean–atmosphere–ice interactions there to feedback on climate. Sea ice presents obvious difficulties for profiling floats, but it is believed these can be overcome (e.g. stop the profile before reaching the surface when ice is present, store profiles until in open water, use acoustics to track floats in high-priority areas with persistent ice cover). The Weddell gyre is a particularly high priority.

Repeat hydrographic sections

Profiling floats cannot monitor transport changes; transport monitoring requires high density sampling along a well-defined cruise track, preferably from land to land. Repeat hydrography is also the only way to obtain temperature, salinity, carbon and tracer measurements throughout the full water depth. (See Gould et al., this volume, for a more complete discussion of the role of repeat hydrography in the ocean observing system.) Acoustic Doppler current profilers (ADCPs) with accurate heading (e.g. from 3D GPS) on Antarctic research and supply ships are needed to obtain routine measurements of absolute currents; such measurements are particularly important in the Southern Ocean where the stratification is weak and the barotropic currents may be strong.

- *Chokepoint sections:* High-priority lines are those occupied by WOCE across the three Southern Ocean 'chokepoints' and across the Weddell gyre (WOCE lines SR1-4), to monitor the exchange between basins. (Repeating the WOCE chokepoint sections is also desirable to continue an established time series and because the lines were sited in locations that were logistically feasible). At least annual sampling at one line is needed to avoid aliasing of interannual signals such as the ACW, with Drake Passage the best choice. Experience from WOCE suggests less frequent CTD repeats at the other chokepoints may be sufficient (every 5–7 years), provided that repeat XBT lines are carried out along the same track to avoid aliasing.
- *Zonal lines:* Sections across each of the midlatitude Southern Hemisphere basins near 30–40°S are needed to measure changes in temperature, salinity and tracer inventories, and to monitor long-term changes in meridional fluxes and the overturning circulation. These infrequent (every 5–7 years) full-depth sections should be complemented with higher-frequency XBT lines to avoid aliasing. Two alternative lines are shown in the Atlantic and Pacific basins. Either one (or both) of the lines would satisfy the primary requirement for a zonal line across each subtropical basin.
- *Additional sections:* To measure changes in water mass inventories, additional infrequent repeat sections are required at other locations. High-priority lines are those with a history of prior occupation, which cross important circulation paths (Atlantic: 30°W; Pacific: 110°W, 170°W; Indian: 55°E, 90°E, 115°E, between French bases in central Indian basin).

Tracer measurements

The fact that the Southern Ocean is a source of water masses which ventilate a large fraction of the world ocean, is potentially sensitive to climate change, and is a significant sink of atmospheric CO_2 makes the region a particularly high priority for tracer measurements. As described in detail by Fine et al. (this volume), transient tracer concentrations (and their ratios) can be used to quantify water mass formation, subduction and spreading rates; to constrain estimates of mixing; to quantify the oceanic uptake of CO_2; and to provide data sets for testing of numerical models. Because the transient tracer signal in the ocean interior is evolving with time, changes observed between repeated surveys can be used to quantify the rate of spreading of climate signals from the sea surface into the ocean interior. Stable isotopes (^{18}O, ^{3}He) are particularly useful for estimating the contribution of glacial melt in the freshwater balance. Changes in convection patterns as a result of changes in the surface freshwater budget will be reflected in changes in oxygen concentrations, as well as other gases such as the CFCs. Nutrient measurements, particularly silica, provide useful constraints on the large-scale flow (e.g. Robbins and Toole, 1997). Tracers should be measured on each of the repeat hydrography lines on a 5–7 year cycle, including CFCs, carbon tetrachloride, stable isotopes at high latitude, and new compounds, as technology evolves.

Repeat high density XBT sections

The repeat hydrographic sections across the chokepoint sections and the zonal lines across the subtropical basins should be paired with more frequent (quarterly) repeat high-density XBT lines to avoid aliasing of signals with time scales less than 5–7 years. A similar recommendation was made by a recent review of the global XBT network (see Smith et al., this volume, for a more complete discussion of the role of XBT sections in the observing system). One of the main uses of the XBT sections is to monitor changes in heat storage and upper ocean stratification. In addition, the 'stability' of the temperature–salinity relationship can be exploited to determine baroclinic transport variability from repeat XBT sections in the Southern Ocean (e.g. Rintoul et al., 2001).

Surface drifters

Additional surface drifters are required to provide better coverage of sea level pressure and SST for input to numerical weather prediction (NWP) models, and hence improve the quality of the air–sea fluxes provided by the models; provide SST measurements for removal of biases in satellite products; 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, when feasible, measure sea surface salinity. The sampling required for each of these goals is somewhat different. For example, the NWP requirement for SST is a measurement on a spatial scale of 100 km, time scale of 1 day, with an accuracy of 0.5 K (WMO World Weather Watch 4th Long Term Plan, 1996–2005); to correct biases in AVHRR (Advanced Very High Resolution Radiometer) measurements of SST, the global requirement is for one *in situ* measurement per 5° square, on a time scale of several days, with an accuracy of 0.1 K is needed (OOSDP, 1995); denser sampling is required in the data-sparse Southern Ocean (Reynolds et al., this volume). The Drifting Buoy Coordination Panel is encouraged to provide recommendations for upgrades of the drifting buoy network to satisfy these diverse aims.

Thermosalinographs on supply/research ships

Given the importance of salinity in determining the stratification at high latitude, measurements of sea surface salinity (SSS) are particularly important in the Southern Ocean. Well-calibrated thermosalinographs on Antarctic supply and research ships would help fill the present data void with regard to SST and SSS, complementing the observations made by floats, drifters, repeat sections, and satellites. Morrow and Chaigneau (2001, ms. submitted to *J. Geophys. Res.*), for example, have used repeat thermosalinograph measurements from an Antarctic supply ship to show that the Levitus climatology significantly misrepresents the seasonal cycle of surface salinity. Models driven with this climatology, which is too salty in winter and too fresh in summer, will in turn misrepresent the near-surface stratification, water mass formation, and ventilation processes. For SST, hull contact sensors should be installed on all Antarctic research or resupply vessels.

Mooring array to monitor AABW outflow

To monitor the lower limb of the Southern Ocean overturning circulation, mooring arrays to measure the transport and properties of AABW are needed. The Weddell Sea is the primary source of bottom water, and measurements there show evidence of significant changes in temperature and salinity in recent decades. The northwest corner of the basin provides a useful place to monitor the outflow from the Weddell Sea into the world ocean. A continuation of US and German efforts to monitor bottom water export in this location is a high priority. Repeat tracer surveys downstream from the source regions are also required to monitor changes in AABW formation and export.

Continuous measurements from a fixed location complement the Lagrangian measurements from profiling floats (e.g. Send et al., this volume). Ship-based time series stations are particularly valuable because a range of properties can be monitored, but they are difficult to maintain in remote regions. The continuation of the French station in deep water 60 nm southwest of Kerguelen (KERFIX/CLIOKER; Jeandel et al., 1998) is a high priority. Moorings with profiling or discrete measurements of temperature and salinity in water mass formation regions are needed. High priorities include the southeast Pacific and Indian oceans and AABW formation sites. Pairs of similar moorings can be used to monitor baroclinic transport across basins and through passages (Send et al., this volume). Further design studies are needed to determine the viability of end-point monitoring of transports across 30°S in each basin and across the chokepoint sections.

Direct measurements of air–sea fluxes in the Southern Ocean are particularly scarce, although the technology now exists to make such measurements in remote regions. A few surface moorings to measure such fluxes are needed to validate analysis products from meteorological agencies (Taylor et al., this volume). Further study is required to define the optimal number and location of flux reference sites. The minimal requirement is likely to be three sites: one north of the ACC where SAMW is formed and exported in the downwelling limb of the shallow overturning cell; one south of the ACC where deep water upwells and is transformed by air–sea fluxes; and one within the ACC, to resolve interactions between the current and atmospheric forcing. The flux moorings should be deployed in the open ocean, but not necessarily in the middle of ocean basins, so that logistics of deployment and maintenance are as straightforward as possible.

ACC transport monitoring

While earlier studies emphasized the barotropic variability of the ACC (e.g. Whitworth, 1983; Whitworth and Peterson, 1985), WOCE experience suggests that the baroclinic and barotropic flows both contribute to the variability of the ACC (e.g. Cunningham, 2001; Rintoul and Sokolov, 2001; Rintoul et al., 2001). Monitoring of the baroclinic flow requires a combination of approaches. Repeat hydrography provides the most complete and accurate measurements of baroclinic transport (as well as full-depth measurements of water properties and tracers), but is generally infrequent (annual at best). Repeat high-density XBT sections can be made more frequently, and transport over a substantial fraction of the water column (e.g. the upper 2500 m) can be inferred from XBTs with an error of a few per cent using empirical relationships between baroclinic transport streamfunction and upper ocean temperature (e.g. Rintoul et al., 2001), at least in some locations. A similar approach can be used to infer baroclinic transport from sea surface height, permitting continuous measurements of transport from satellite altimetry. These approaches are in their infancy and require further refinement and testing. In addition, moorings with profiling or discrete measurements of temperature and salinity can be used to monitor baroclinic transport; profiles of temperature and salinity (hence baroclinic transport) can also be inferred from inverted echo sounder measurements in the Southern Ocean (Watts et al., 2001; Sun and Watts, 2001). Further design studies and a pilot deployment of such moorings in Drake Passage are recommended to test this approach before instrumenting each of the chokepoint sections.

Monitoring the barotropic flow is even more challenging. Variability of the net barotropic flow can be inferred from measurements of bottom pressure (e.g. Whitworth and Peterson, 1985; Meredith, et al., 1996). To determine the mean barotropic flow, the pressure gauges must be 'levelled' using (laterally coherent) measurements of absolute velocity at some depth. ADCP measurements on repeat hydrographic sections between the gauges will constrain the absolute velocity, but will probably not be sufficiently accurate on their own. A coherent array of moored current meters across the wide chokepoint sections is probably not feasible given likely resources (even the relatively narrow Drake Passage is more than

700 km wide). Direct measurement of the absolute transport of the ACC thus remains a formidable challenge, particularly on a sustained basis. Future progress is likely to come from a variety of *in situ* and remote measurements combined with dynamics in the form of inverse and forward models. The recommendations in Tables 3–5 reflect this approach.

Modelling and data assimilation

The observations required to address these scientific issues will be of great benefit for testing models and for data assimilation. The variability captured by an ocean model depends on its mean state; if the mean state is not realistic, the model will not respond to changes in forcing in a realistic manner. A realistic mean state, in turn, requires adequate representation of the formation and circulation of water masses. Because the water masses formed in the Southern Ocean play such an important role in setting the mean stratification of the World Ocean, model realism is particularly crucial in this region. More observations from the Southern Ocean are needed to provide relevant benchmarks for testing model performance. For example, tracer measurements (e.g. CFCs) have been used to test the ability of models to reproduce the upper-ocean stratification, subduction and subsequent spreading of water masses (England, 1995; England and Hirst, 1997; England and Maier-Reimer, 2001). Other benchmarks of particular relevance to the Southern Ocean include seasonality of mixed-layer depth, stratification (T(z), S(z)), heat and freshwater transports and their components (Ekman, geostrophic, and eddy fluxes), and water mass formation and spreading rates.

With regard to data assimilation, programs like GODAE will depend heavily on the global coverage provided by altimetry. However, existing techniques for using altimetry to constrain subsurface ocean properties have generally been developed for lower latitudes, and different techniques will likely need to be developed for the Southern Ocean, where the stratification is weak the currents are deep-reaching, and salinity plays such an important role. Broad-scale temperature and salinity profiles in the mid- to high-latitude Southern Hemisphere, such as will be provided by Argo, are crucial for the success of a global data-assimilation system.

Relationship to other programs

The proposed observations are directly relevant to scientific questions which extend beyond the Southern Ocean (Principal Research Area D5) to other sub-programs and Principal Research Areas of CLIVAR. While the Southern Ocean

Table 3. Recommended repeat hydrography, with countries committed or interested in occupying the lines. Tracer measurements are generally not done on every occupation for those lines occupied more frequently than every 5 years. (CTD = conductivity, temperature, depth (pressure), ADCP = acoustic Doppler current profiler, TSG = thermosalinograph).

Section	WOCE#	Frequency	Variables	Country
Atlantic:				
Drake Passage	SR1	annual	CTD, ADCP, TSG, tracers	UK, Chile
Weddell Sea	SR4	5–7 years	CTD, ADCP, TSG, tracers	Germany
≈30–40S Atlantic	A11/A12	5–7 years	CTD, ADCP, TSG, tracers	UK
0E Atlantic	SR2	3–5 years	CTD, ADCP, TSG, tracers	Germany
30W Atlantic	A23	5–7 years	CTD, ADCP, TSG, tracers	
Indian:				
30S Indian	I5	5–7 years	CTD, ADCP, TSG, tracers	UK; Australia (eastern)
Central Indian		biannual	CTD, ADCP, TSG, tracers	France
115E	I9	5–7 years	CTD, ADCP, TSG, tracers	Australia
140E	SR3	5–7 years	CTD, ADCP, TSG, tracers	Australia
Pacific:				
170W Pacific	P15	5–7 years	CTD, ADCP, TSG, tracers	
110W Pacific	P18	5–7 years	CTD, ADCP, TSG, tracers	
32–43S Pacific	P6/P7	5–7 years	CTD, ADCP, TSG, tracers	

Table 4. Repeat XBT lines, with commitments or expressions of interest where applicable. SOOP # refers to the line designation by the Ship of Opportunity Program (SOOP).

Section	WOCE/ SOOP #	Frequency	Variables	Country
Drake Passage	SR1/AX22	>4x per austral summer	XBT, ADCP, TSG	USA, UK
0E	SR2/AX25			Germany (occasional)
30S Atlantic	A10/AX18			
30S Indian	I5/IX16,21			USA?
110E	≈I9	1x per austral summer	XBT, TSG	Japan
Austr (115E,30S) to Prydz Bay 80E, 65S)	none	1x per year	XBT, ADCP	China, USA
140E	SR3/IX28	6x per austral summer	XBT, TSG	Aust, France, USA
30S Pacific	P6/PX50			USA, Chile
	PX34	4x per year	XBT	Australia
150E	P11A	1x per austral summer	XBT, TSG	Japan
170W	P14	2–4x per austral summer	XBT	Italy

Table 5. Time series stations or moorings with commitments or expressions of interest.

Location	Type	Frequency	Country
Drake Passage	Deep pressure gauges	continuous	UK
Drake Passage (north)	Profiling CTD mooring	continuous	UK
Weddell Sea	Moorings + CTD	continuous	Brazil, Germany, USA
Greenwich meridian	Current meters, temperature and salinity sensors, upward looking echo sounders, deep pressure gauges	continuous	Germany
Kerguelen	CTD, biogeochemistry	monthly	France
Southeast Pacific (Subantarctic Zone)	Flux reference site; current meters; T, S sensors biogeochemistry?		
South of ACC	Flux reference site		
In ACC zone	Flux reference site		

component of CLIVAR must be closely integrated with the Climate and the Cryosphere program of the World Climate Research Programme, many aspects of the Southern Ocean of most relevance to climate are features of the open, non-ice covered sea, and must remain a central priority of CLIVAR.

Final remarks

The Southern Ocean is not only remote from shipping routes, it is also distant from densely populated land masses. There is a risk, therefore, that the Southern Hemisphere oceans will be poorly sampled by the ocean observing system, simply because they are far away, rather than through a carefully argued scientific case that they are of little relevance to CLIVAR, GOOS and GODAE. The studies described here suggest, on the contrary, that Southern Ocean processes exert a profound influence on regional and global climate, and therefore sustained observations of the Southern Ocean are essential if these programs are to achieve their goals. By exploiting new technologies and building on insights gained from recent observations and modelling studies, it is now feasible to obtain these observations, despite the formidable logistical challenges. The strawman Southern Ocean observing system proposed here is a first step towards understanding how global climate depends on southern hemisphere ocean, atmosphere and ice dynamics.

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