MONITORING AND UNDERSTANDING SOUTHERN OCEAN VARIABILITY AND ITS IMPACT ON CLIMATE: A STRATEGY FOR SUSTAINED OBSERVATIONS

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ABSTRACT *The Southern Ocean profoundly influences regional and global climate. Several unique features of the Southern Ocean contribute to this climate 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 is also remote, and the environment is hostile. As a consequence, historical data is scarce and hypotheses regarding the climate impact of Southern Ocean processes have been difficult to formulate and test. For these reasons, design and implementation of an observing system for the Southern Ocean is a formidable challenge. However, recent advances in understanding and instrumentation mean that it is now feasible to obtain the sustained observations needed to describe and understand the Southern Ocean processes responsible for climate variability.*

1. INTRODUCTION

Appreciation of the extent to which the Earth's climate is variable is increasing rapidly. The substantial social, economic and political impacts of climate variability are also becoming clear. Yet our understanding of the physical mechanisms driving the variability, and our ability to attribute observed changes to natural climate processes or to human influence, remain primitive. As a result, we are not well-positioned to either minimize the adverse effects or capitalize on opportunities of a variable climate. Progress in understanding and modelling the climate system has been slowed in large part because of a lack of observations. Measurements are particularly sparse in the Southern Ocean.

As described in Section 2, Southern Ocean processes have a profound impact on regional and global climate. Sustained observations of the mid- and high-latitude oceans of the southern hemisphere are essential to describe and understand the physical processes responsible for climate variability, a primary objective of CLIVAR. Southern Ocean measurements are also required for GOOS and GODAE. To obtain sustained observations in such a remote and harsh region is difficult. However, recent advances in technology and in understanding mean that it is now feasible to design a practical Southern Ocean observing system which can provide the observations needed by CLIVAR, GOOS and GODAE. Specific recommendations for the Southern Ocean observing system are summarized in Section 3.

The purpose of this paper is to make the scientific case for sustained observations in the Southern Ocean. We focus, in particular, on recent advances of direct relevance to the justification and design of a Southern Ocean observing system. In this sense, this paper is an update of the scientific background found in the CLIVAR Science and Implementation plans. While satellite observations are of particular importance in the poorly-observed Southern Ocean, here we address the need for in situ ocean measurements. Issues related to observations of Antarctic sea ice are covered in the paper by Cattle et al. (this volume).

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2. CONNECTIONS BETWEEN THE SOUTHERN OCEAN AND CLIMATE

2.1 Southern Ocean influence on mean ocean circulation and climate

The mean circulation and stratification of the global ocean depends strongly on Southern Ocean processes. The Antarctic Circumpolar Current (ACC) is the primary means by which water, heat and other properties are exchanged between the ocean basins. This unique 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 latitude shoal dramatically across the ACC. Where these layers outcrop, intense air-sea-ice interactions drive water mass transformations (Fig. 1). By converting upwelled deep water into new intermediate and bottom water, the Southern Ocean ventilates a large fraction of the world ocean, and thus regulates the ocean's capacity to store heat and carbon.

While existing observations have been sufficient to establish the influence of the Southern Ocean on the mean state of the global ocean and climate, the extent to which Southern Ocean processes respond to or drive climate variability has been less clear. Recent studies, based on both observations and models, provide new insight into these interactions.

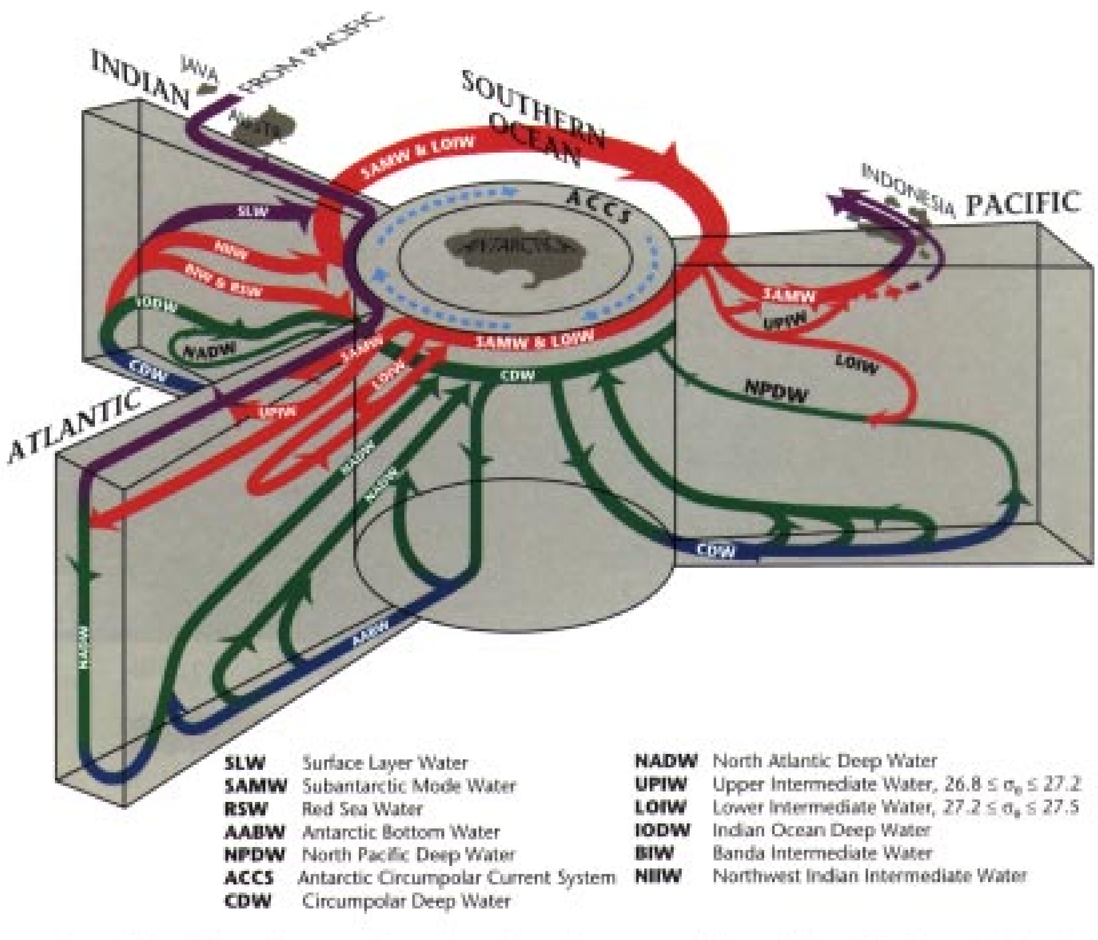

Fig. 1: A schematic of the three-dimensional flow between ocean basins. The figure illustrates the two key roles the Southern Ocean plays in the global overturning circulation: 1) the circumpolar link connects the ocean basins, and 2) water mass formation transforms deep water to intermediate and bottom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

2.2 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 low latitude, and rainfall will increase at higher latitude. An increase in the net freshwater flux will increase the upper ocean stratification at high latitudes. Climate models suggest the impact of such changes is dramatic, particularly in the Southern Ocean (Manabe and Stouffer, 1994; Sarmiento et al., 1998; Hirst, 1999; Matear and 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. Ocean uptake of carbon is also reduced. The formation of AABW does not recover through an extended integration at elevated levels of CO2, and the deep ocean remains stagnant (Fig. 2, Hirst, 1999).

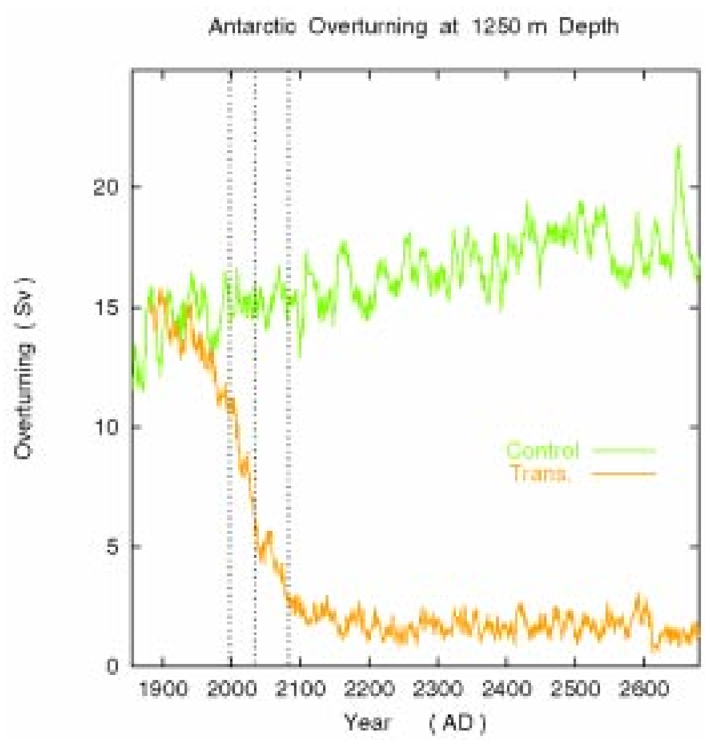

Fig. 2: Transport of Antarctic bottom water in Sv (1 Sv = 10^6 m^3 s^{-1}) through 1250 m depth from the control run with no anthropogenic greenhouse gas forcing (green line) and the transient run with greenhouse gas forcing (orange line). The collapse of AABW formation is caused by an increase in stratification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

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 representation 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 mode," where the fresh cap is sufficient to maintain stability, to a "thermal mode," causing open ocean deep convection as seen in the Weddell polynya of the 1970's (Gordon, 1982; Gordon, 1991a). The polynya results in enhanced heat exchange between ocean and 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.

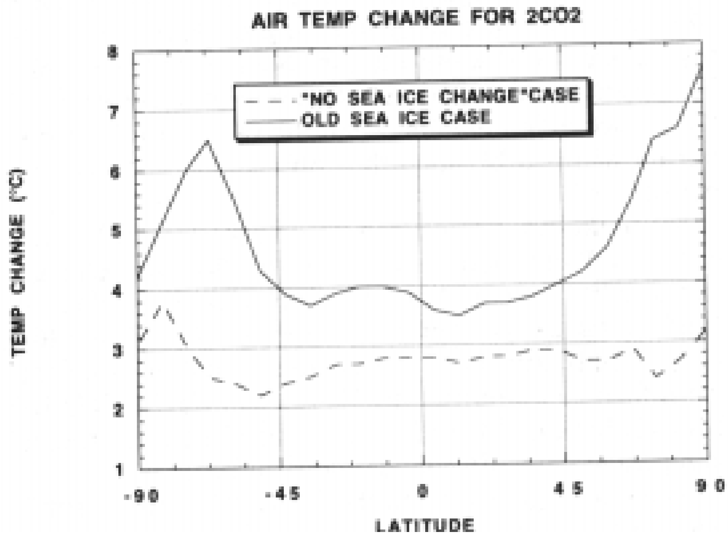

Fig. 3: Annual average surface air temperature change due to $2XCO_2$ in two GCM runs. When sea ice is not permitted to change (dashed line), there is little high-amplitude amplification of the warming, and the warming is reduced even at low latitudes. The total sea ice contribution to the global average warming is 37% in this GCM. (Rind et al., 1995).

Observations needed:
To assess the rate and impact of polar freshening, the Southern Ocean observing system must monitor upper ocean stratification, including profiles of both temperature and salinity, on broad spatial scales. Measurements are needed in both the sea ice zone and in the open ocean. Sea surface temperature and salinity measurements are also needed.

2.3 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 NADW into the thermocline (e.g. Stommel and Arons, 1960). However, direct observations of mixing in the ocean interior show values an order of magnitude too small to support the required upwelling (e.g. Ledwell et al., 1993). Recent modelling and observational studies suggest that the required water mass transformation is accomplished by air-sea-ice interactions where the deep water layers outcrop in the Southern Ocean (Doos and Coward, 1997; Toggweiler and Samuels, 1998; Sloyan and Rintoul, 1999; Gnanadesikan, 1999b; Speer et al., 1999). Circumpolar deep water upwells south of the 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).

It appears that the water mass transformations driven by active air-sea-ice 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 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 air-sea interaction at high southern latitudes, then the response to a change in forcing may be rapid.

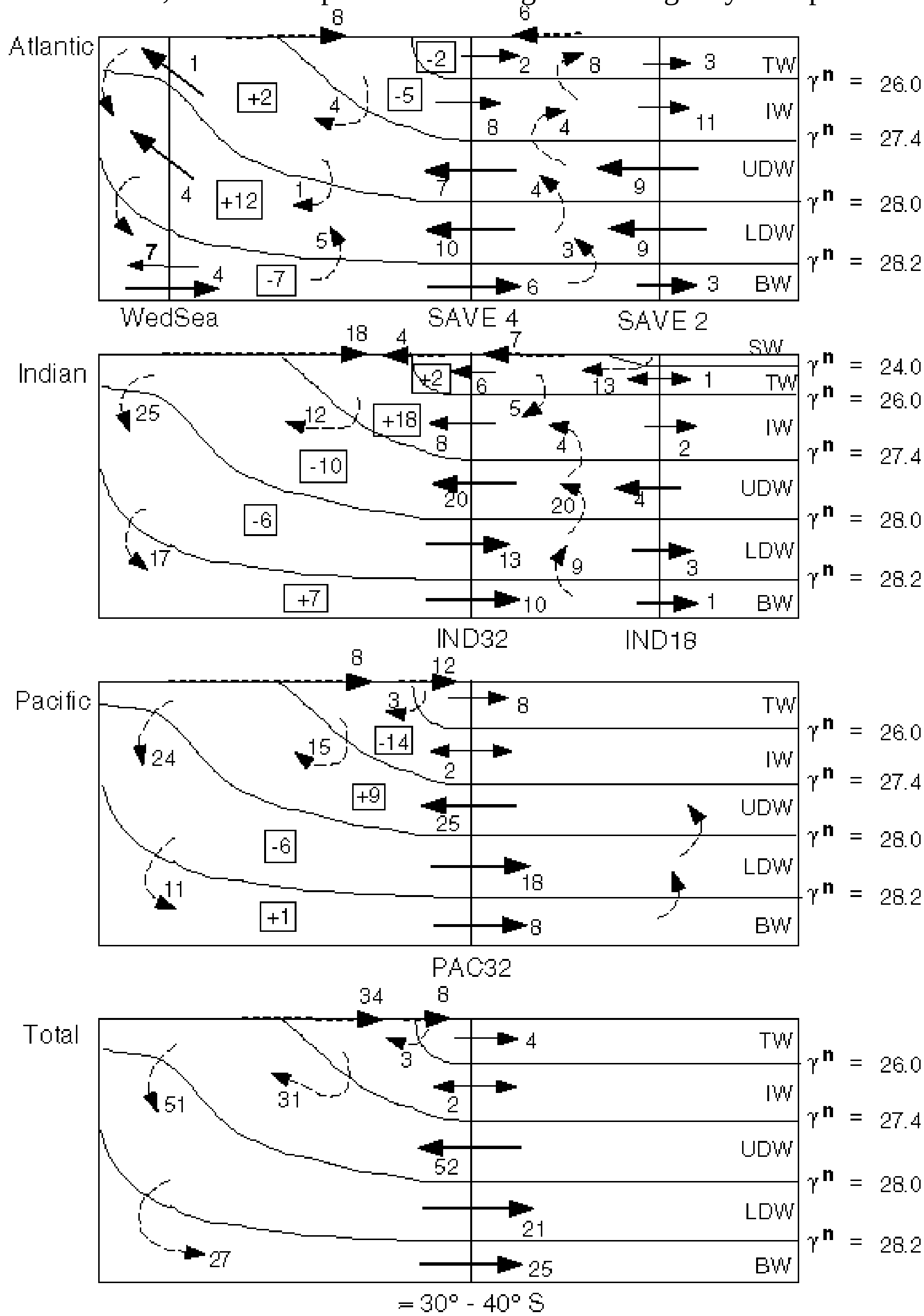

Fig. 4: A schematic 5-layer summary of the overturning circulation in each ocean basin, and the zonal sum. The transports are in Sverdrups (1 Sv = 10^6 m^3 s^{-1}). The bold dashed line near the surface is the transformation driven by air-sea buoyancy fluxes; dashed lines in the interior represent mixing/entrainment; 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 density surfaces (labels on right hand side). From the inverse model of Sloyan and Rintoul (1999). The figure illustrates the importance of Southern Ocean air-sea buoyancy fluxes and diapycnal mixing in the global overturning circulation.

Changes observed in the temperature and salinity of intermediate waters (AAIW/SAMW) (Fig. 5) suggest the upper limb of the overturning circulation may already be responding to the polar freshening projected by climate models (e.g. Bindoff and McDougall, Johnson and Orsi, 1997; Wong et al., 1999). Temporal changes in Southern Ocean water masses are as large as the better documented variability in the northern hemisphere. These layers ventilate the lower thermocline of the southern hemisphere subtropical gyres (McCartney, 1982) and carry low salinity water equatorward to close the freshwater budget (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 a good place to look for evidence of climate change.

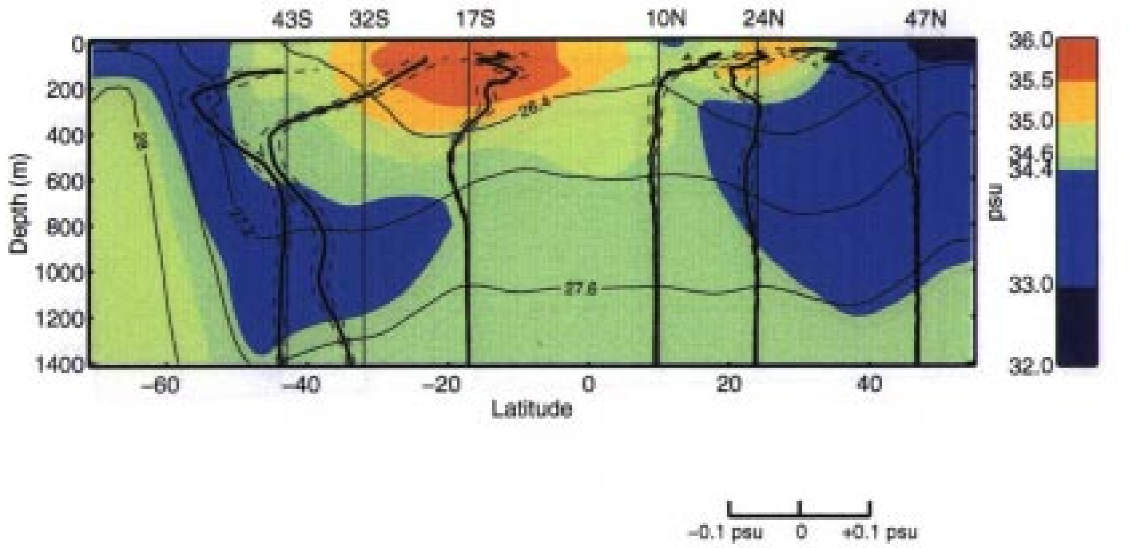

Fig. 5: Change in salinity of intermediate waters observed in the Pacific Ocean between the 1960's and 1990's (from Wong et al., 1999). The salinity section (in color) shows tongues of low salinity intermediate water spreading from the sea surface at high latitude, where intermediate water is formed, 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.

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 (Fig. 1 and 4). Vigorous air-sea-ice interactions on the continental shelf, particularly in coastal polynyas, drive the formation of AABW (Gordon, 1998; Rintoul, 1998), but the details are poorly 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. Orsi et al. (1999) have shown that tracer inventories (e.g. CFCs) provide powerful constraints on the total formation rate of AABW. As mentioned above, models suggest the formation of AABW may be sensitive to changes in freshwater flux, but the processes are not well enough understood to assess the realism of these projections. Broecker et al. (1999) highlight a discrepancy between AABW formation estimates derived from different tracers and interpret this as evidence for a significant decrease in the formation rate of AABW in recent times.

Observations needed:
To evaluate the potential for Southern Ocean processes to modulate the overturning circulation, the observing system needs to monitor changes in transport and properties of water masses which participate in the overturning cells. Broad-scale inventory measurements (of temperature, salinity and tracers) are needed to document patterns of variability. Zonal sections to measure changes in the properties and transport of water masses exchanged between the Southern Ocean and lower latitudes are necessary. An array to monitor AABW at one or more carefully chosen sites will measure variations in the strength and properties of the "lower limb" of the Southern Ocean

overturning. Improved surface flux measurements (heat, freshwater and momentum) are needed to estimate the water mass transformations involved in the overturning.

2.4 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, 1997), 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 either stochastic atmospheric forcing (Weisse et al., 1999), atmospheric reanalyses (Bonekamp et al., 1999), or to standing patterns in the atmosphere (Christoph et al., 1998). The lack of observations makes unravelling the dynamics of the phenomenon difficult. 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. The question is important as each mechanism has different implications for climate variability.

Recent studies show the ACW has a substantial impact on regional climate variability. For example, White and Cherry (1998) and White (1999) have shown that rainfall in New Zealand and southern Australia is more strongly influenced by the ACW than by 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. For example, 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 cap (Curry et al., 1998)). The lack of observations means that we cannot 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.

Observations needed:

To further explore the nature of the ACW and its impact on climate, the following observations are required: broad-scale measurements of upper ocean temperature and salinity; improved surface fluxes over the Southern Ocean; observations of sea surface temperature, salinity, and height; sea ice extent; and repeat sections in a few key locations to measure heat and volume transport anomalies associated with the ACW.

2.5 Variability of interbasin exchange of heat and other properties

A zonally coherent acceleration or deceleration of the ACC, with no anomalous divergence of heat, water masses or other properties, would likely have little impact on climate. However, because the heat transport of the ACC is large, even small percentage changes in heat transport may result in significant divergence. Is there evidence for changes in ACC heat transport? 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, 1999). 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 might be balanced by storage, either local or basin-scale; by zonal divergence of the ACC (although measurements at Drake Passage suggest this is not the case); by meridional divergence in the Indian and Pacific basins; by changes in air-sea heat flux; or by changes in barotropic flow. In any case, given that the observed variability is significant relative to the meridional heat transport in each basin, it is important the Southern Ocean observing system provides the measurements needed to assess its impact.

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 Subantarctic Mode Water (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, 1999). 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 neighboring 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. Once again, results from a single section are difficult to interpret. Were the changes observed south of Australia balanced by transport changes at the other chokepoints, storage within the Pacific, or by changes in the Indonesian throughflow?

Measurements of ACC property transports constrain basin-scale budgets of heat and freshwater (e.g. Georgi and Toole, 1982; Rintoul and Sokolov, 1999). 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. 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 freshwater between ocean and atmosphere.

Observations needed:

Transport measurements at the Southern Ocean chokepoints and across the southern hemisphere basins, and basin-scale observations of T(z) and S(z), are needed to monitor and interpret ACC variability.

2.6 Centennial variability

Climate models and paleoceanographic records provide some intriguing suggestions of links between the ACC and variability of the global circulation on century time-scales. Studies using ocean models driven with mixed boundary conditions 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. Coupled model results are inconclusive: some show the salinity feedback is important, others do not. So 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. One requirement is a better understanding of the air-sea-ice interactions which are fundamental to these oscillations.

Observations needed:

Broad-scale measurements of upper ocean stratification; monitoring of anomalies of sea surface temperature and salinity; and improved estimates of air-sea fluxes.

2.7 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. 6) (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).

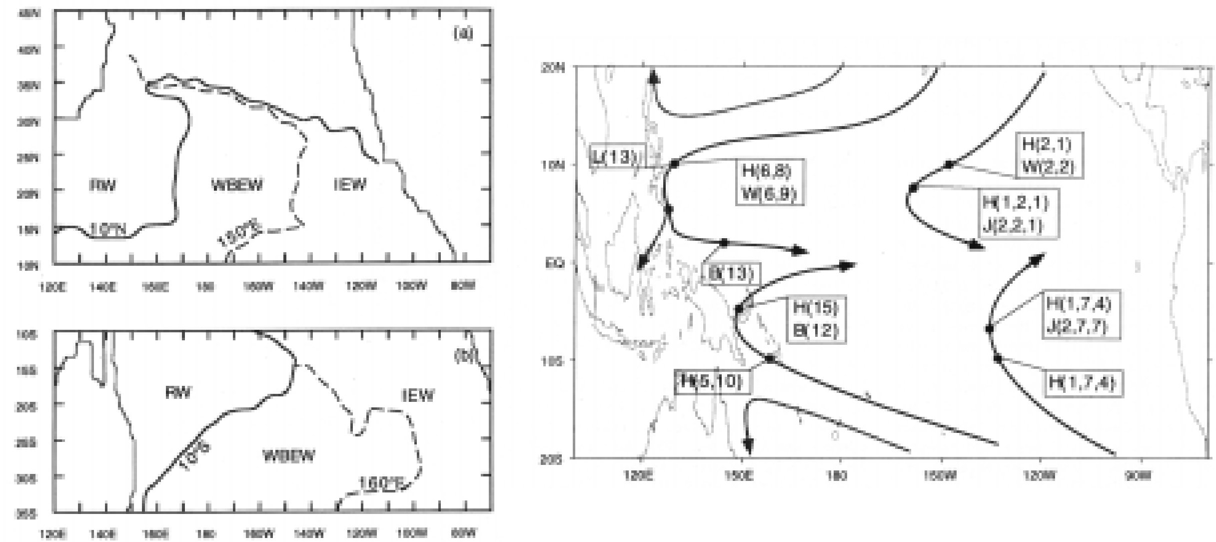

Fig. 6 An illustration of the relative contributions of northern and southern hemisphere water to the equatorial Pacific in the NCEP model (from Huang and Liu, 1999). Left panels: circulation regimes revealed by tracking particles (RW = recirculation regime, no exchange with equator; WBEW = exchange 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. Right panel: 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.

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 Southern Ocean water masses which supply the EUC may therefore ultimately influence SST when the EUC shoals in the eastern tropical Pacific. Such extra-tropical anomalies might arise from changes in the mid-latitude westerlies, which in turn are known to respond to changes in tropical SST via atmospheric teleconnections like the Pacific South Amerian (PSA) 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/Subantarctic Frontal Zones, linked by atmospheric teleconnections. Sustained observations in mid- and high-latitudes of the southern hemisphere oceans are needed to explore how tropical-extratropical exchange modulates ENSO.

Observations needed:

A combination of systematic broad-scale measurements in the southern hemisphere basins, improved surface fluxes where water masses form, and model studies, are needed.

2.8 Variability of the southern hemisphere atmospheric circulation

Numerous studies have documented interannual and longer period variability in the major spatial and temporal patterns 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). For example, the semi-annual oscillation (SAO) explains more than half the mean annual variance of sea level pressure over large areas of the southern hemisphere (van Loon, 1972). The SAO is a coupled ocean-atmosphere phenomenon which results from phase differences in the annual cycle of temperature between the ocean-dominated mid-latitudes and the continent-dominated higher latitudes. A marked decrease in amplitude of the SAO after 1979 (Hurrel and van Loon, 1994) has been linked to changes in the annual cycle of SST near 50S (Meehl et al., 1998b). The importance of dynamical coupling between ocean and atmosphere is underscored by the fact that coupled models with a non-dynamic mixed layer ocean do not reproduce the variability at mid- to high-latitudes of the southern hemisphere seen in full coupled models (Manabe and Stouffer, 1996; Meehl, 1991). Long integrations with coupled models suggest air-sea-ice interactions at these latitudes drive low-frequency variability of the SAO (Simmonds and Walland, 1998). Many other southern hemisphere atmospheric circulation features have been shown to vary on long time-scales (e.g. oscillations of the Trans Polar Index with a period of about 120 years (Villalba et al., 1997); interdecadal modulation of the impact of ENSO on Australian rainfall (Power et al., 1999)), but the dynamics driving the variability are not clear. Whatever the mechanism, these low frequency variations in the atmospheric circulation have a significant impact on regional climate (e.g. Pittock, 1984; Nichols and Lowery, 1992; Allan and Haylock, 1993) and so are important to understand.

Observations needed:

To explore connections between ocean dynamics and atmospheric variability, measurements of upper ocean temperature and salinity are needed, as well as drifters measuring sea surface temperature and sea level pressure (to improve atmospheric analyses and remove bias from satellite products).

2.9 Impact of southern hemisphere observations on development of models and data assimilation systems

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 part in setting the mean stratification of the 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.

With regard to data assimilation, experiments like GODAE will depend heavily on the global coverage provided by altimetry. But existing techniques for using altimetry to constrain subsurface ocean properties have been developed for lower latitudes, and are unlikely to succeed in the Southern Ocean, where 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.

2.10 Summary of required in situ observations

An enhanced Southern Ocean in situ observing system is needed to describe and understand the physical processes responsible for climate variability (Fig. 7). In general terms, sustained observations of the following variables are required: temperature and salinity profiles on broad spatial scales; ACC property transport; sea surface temperature, salinity, and sea level pressure; full-depth profiles of T, S and tracers at key sites; and exchange between the Southern Ocean and lower latitudes.

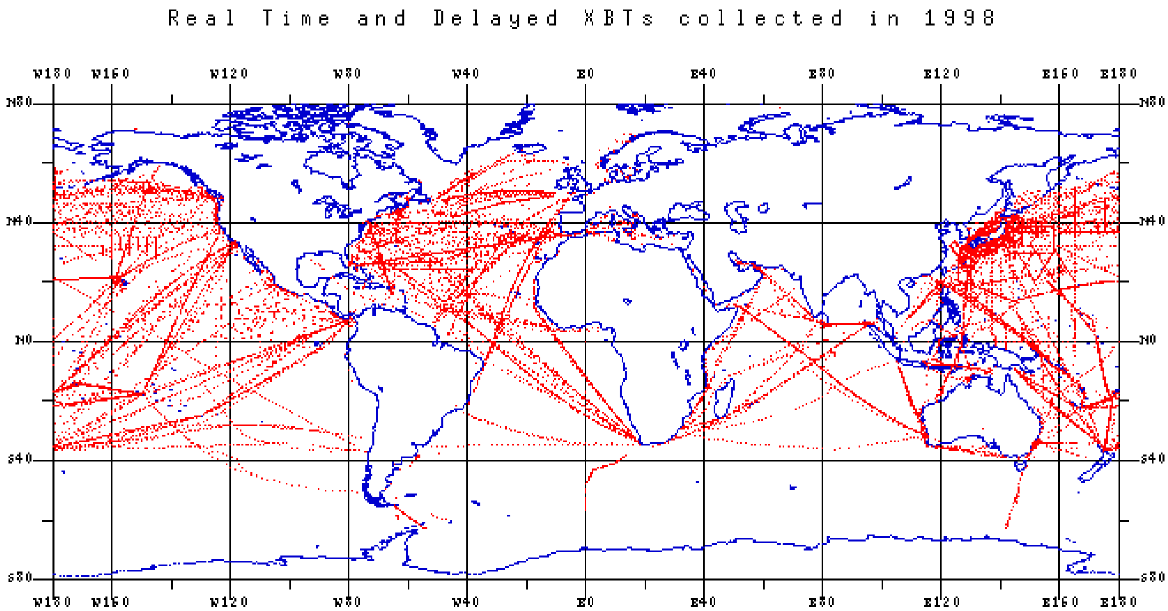

Fig 7: Upper ocean temperature observations obtained by the XBT network in 1998. The sparse coverage in the Southern Ocean is obvious.

3. RECOMMENDATIONS FOR SUSTAINED SOUTHERN OCEAN OBSERVATIONS

Obtaining the sustained measurements needed to understand climate variability is a formidable challenge in a region as remote and hostile as the Southern Ocean. However, advances in technology and understanding mean that it is now possible to design a practical in situ observing system to meet this need. A strawman observing system is outlined below and summarized in Fig. 8.

3.1 Southern Ocean Argo

Broad-scale 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 such a remote region 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. An array of profiling floats in the Southern Ocean will have a profound impact on our understanding of climate.

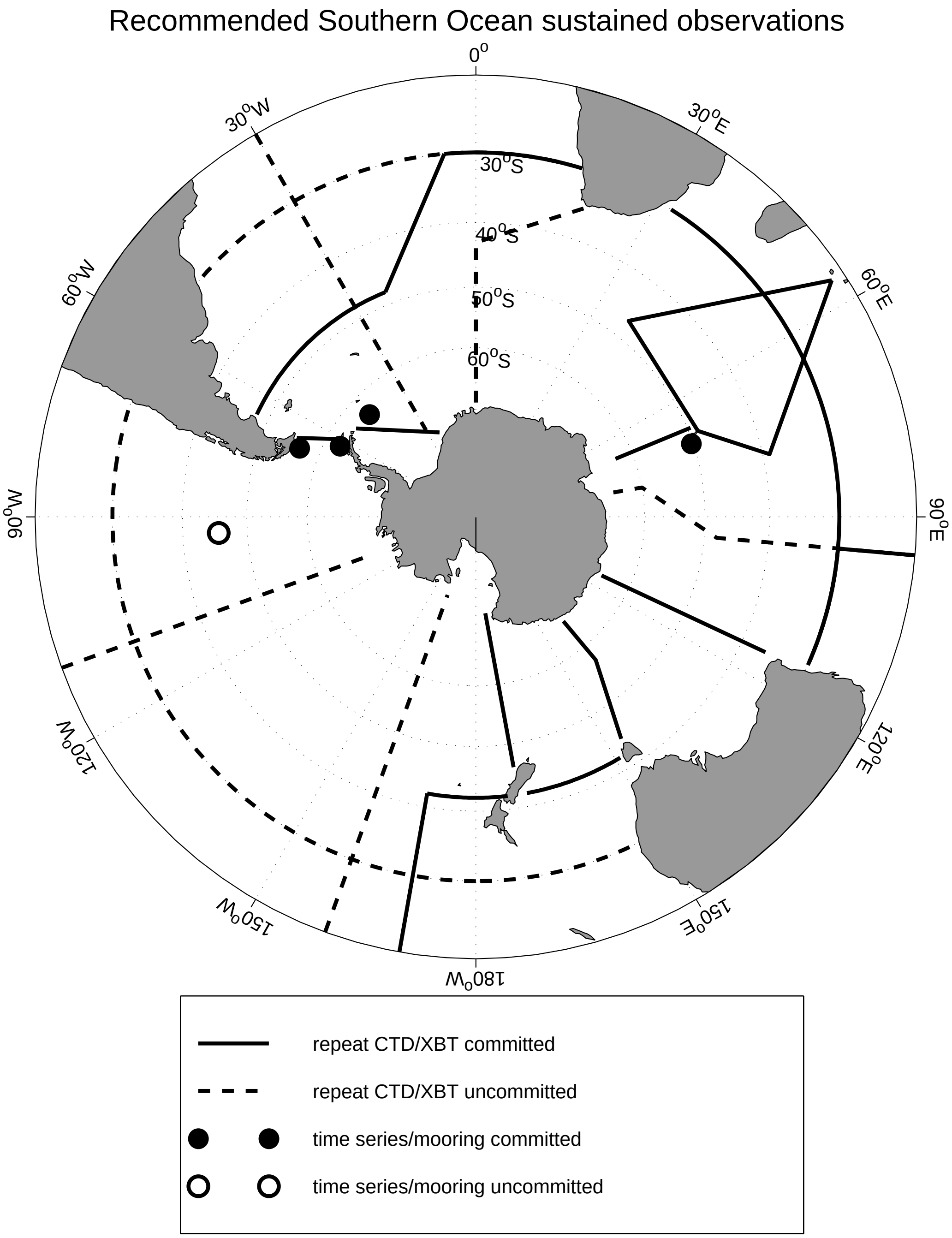

Fig. 8: Sustained observations recommended for the Southern Ocean in situ observing system. "Committed" means that an intention to carry out the measurements has been expressed, e.g. in a national plan for CLIVAR/GOOS. Further details are listed in Table 1. Float and drifter sampling is not shown.

Implementation/Technical issues:

At the nominal resolution of Argo (1 float per 300 x 300 km) roughly 900 floats are needed between 40S and 70S. High priority areas for initial deployments include: the southeast Pacific (including AAIW formation regions, the "exchange windows to the tropics" and the areas of high

variability at higher latitude which may be related to the Pacific-South American (PSA) atmospheric teleconnection); SAMW/AAIW formation/modification region in Drake Passage and the southwest Atlantic; within the poorly-sampled Indian and Pacific sectors, particularly where mode and intermediate water enter the subtropics, or are exchanged between basins; and areas of deep water upwelling south of the ACC.
Year-round profiles of temperature and salinity in the seasonal sea ice zone would be of immense value, given the lack of observations and the potential for air-sea-ice interactions there to drive climate variability. Sea ice presents obvious difficulties for profiling floats, but it is believed these can be overcome (e.g. stop profile before reaching the surface when ice present; store profiles until in open water; in high priority areas with persistent ice cover use acoustics to track floats). The Weddell gyre is a particularly high priority.

3.2 Repeat sections (CTD/ADCP/tracer and XBT)

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 deep temperature, salinity, carbon and tracer measurements for monitoring changes in inventory. WOCE experience suggests the "stability" of the temperature-salinity relationship can be exploited to determine baroclinic transport, as well as heat content, variability from repeat XBT sections (e.g. Rintoul and Sokolov, 1999b). Acoustic Doppler current profilers (ADCPs) (either vessel-mounted or lowered) 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 are strong. Present commitments/expressions of interest in repeat CTD and XBT sections are shown in Fig. 8 and Tables 1 and 2.

Implementation/Technical issues:

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), both to continue an established time series, and because the WOCE lines were sited in locations that were logistically feasible and scientifically relevant. At least annual sampling at one line is needed to avoid aliasing of interannual signals like the ACW, with Drake Passage the best choice. Experience from WOCE suggests less frequent CTD repeats at the other chokepoints may be sufficient (once per 3-5 years), provided that repeat XBT lines are carried out along the same track to avoid aliasing.

Zonal lines: Sections across each of the mid-latitude southern hemisphere basins near 30S are needed to measure changes in temperature, salinity and tracer inventories, and to monitor long-term changes in meridional fluxes and the overturning circulation. Ideally these infrequent (once per 5-7 years) full-depth sections would be complemented with higher frequency XBT lines to avoid aliasing.

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: 0W, 30W; Pacific: 100W, 170W; Indian: 55E, 90E, 115E, between French bases in central Indian basin).

3.3 Surface drifters

Given the difficulty of directly observing the air-sea fluxes which drive water mass transformation, we must rely on products derived from atmospheric analyses. Improved observations of SLP and SST from surface drifters are essential to improve the accuracy of these analyses in the Southern Ocean. Drifter measurements of SST are also crucial for removing biases from satellite SST measurements, given the cloudiness of the SO and the lack of ship-based measurements. Drifter measurements of SSS, when feasible, would also be of great value. The trajectories of drifters provide direct measurements of the absolute velocity field in the upper ocean.

***Implementation/Technical issues*:**

A large number of drifters were deployed in the Southern Ocean during WOCE. A small number of drifters are deployed routinely by the meteorological agencies of various nations. The strong zonal flow of the ACC means that repeat seeding along a few meridional lines is an effective way to seed a large area of the Southern Ocean.

3.4 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 here. Well-calibrated thermosalinographs on Antarctic supply and research ships would help fill the present data void with regard to SSS, complementing the observations made by floats, drifters, and repeat sections.

3.5 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.

3.6 Time series stations/moorings

Continuous measurements from a fixed location complement the Lagrangian measurements from profiling floats. Ship-based time series stations are particularly valuable because a range of properties can be monitored, but are difficult to maintain in remote regions. The continuation of the French station near Kerguelen (KERFIX/CLIOKER) is a high priority. Moorings with profiling or discrete measurements of temperature and salinity in water mass formation regions are needed. High priorities include Drake Passage, the southeast Pacific, and AABW formation sites.

Pairs of pressure gauge moorings across passages are needed to monitor ACC transport variability, particularly when combined with other measurements (inverted echo sounders, repeat sections, moored profilers). Present commitments/expressions of interest are shown in Fig. 1 and Table 3.

4. 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 component of CLIVAR must work closely with CLIC, many aspects of the Southern Ocean of most concern to CLIVAR are features of the open, non-ice covered sea, and must remain a central priority of CLIVAR.

5. SUMMARY

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 highlighted 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.

Table 1: Repeat hydrography commitments or expressions of interest.

Section	WOCE#	Frequency	Variables	Country

Drake Passage	SR1	annual	CTD, ADCP, TSG, tracers	U.K., Spain, Chile
Weddell Sea	SR4	3-5 years	CTD, ADCP, TSG, tracers	Germany
40S Atlantic	A11	5-7 years	CTD, ADCP, TSG, tracers	U.K.
0E Atlantic	SR2	5-7 years	CTD, ADCP, TSG, tracers	Germany
30S Indian	I5	5-7 years	CTD, ADCP, TSG, tracers	U.K.; 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
43S Pac (west)	P7	5-7 years	CTD, ADCP, TSG, tracers	Australia, NZ

Table 2: Repeat XBT commitments or expressions of interest.

Section	WOCE #	Frequency	Variables	Country
Drake Passage	SR1	4x / austral summer	XBT, ADCP, TSG	USA
110E	I9	1x / austral summer	XBT, TSG	Japan
140E	SR3	6x / austral summer	XBT, TSG	Aust, France, USA
150E	P11A	1x / austral summer	XBT, TSG	Japan
170W	P14	2-4x / aust. summer	XBT	Italy

Table 3: Time series stations or moorings with commitments/expressions of interest.

Location	Type	Frequency	Country
Drake Passage	deep pressure gauges	continuous	U.K.
Drake Passage (north)	profiling CTD mooring	continuous	U.K.
Kerguelen	CTD, biogeochemistry	monthly	France

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