Project summary

Proposed work and intellectual merit (Criterion 1). Antarctic Intermediate Water (AAIW) is a low salinity, high oxygen and low potential vorticity (thick) water mass that fills almost all of the southern hemisphere and the tropical oceans at about 800 to 1000 m depth. As the densest of the circumpolar Subantarctic Mode Waters (SAMW), AAIW is formed as a thick, outcropping mixed layer in the southeastern Pacific just north of the Subantarctic Front (SAF). SAMW and AAIW formation have a major impact on the oceanic sink for anthropogenic CO_2, whose largest uncertainty is at intermediate depths. AAIW has a major role in southern hemisphere freshwater transport and as such, can impact global-scale ocean overturning processes. AAIW is the only intermediate-depth, large-scale water mass that has not been studied at its winter source, despite general knowledge of the location of the source region for several decades. This proposal is part of a multi-institutional effort to ***characterize the processes responsible for the formation of Antarctic Intermediate water (AAIW) in the southeast Pacific***. Results from this region will be relevant to SAMW formation in other regions. The plan is to study (1) northward Ekman advection of Antarctic Circumpolar Current surface waters across the SAF, (2) convection driven by local air-sea fluxes, and (3) northward subduction of AAIW across the northern front bounding the deep mixing region.

The proposal includes a winter hydrographic survey of the AAIW outcropping region and the fronts that bound it. Also proposed is a summer survey following the winter survey to study the evolution, restratification, and dispersal of the previous winter's waters. The surveys proposed here are one part of a multifaceted approach to address this difficult question. This work will be coordinated with other U.S. and international studies involving carbon component and chlorofluorocarbon measurements, moorings, acoustic and profiling floats, and more limited hydrography in the study region (for mooring deployments). Here we cover the following components: CTD, salinity, oxygen, nutrients, XCTD, ADCP, LADCP, and shipboard meteorological measurements.

Broader Impacts (Criterion 2). *Infrastructure:* The high-quality data set with comprehensive coverage in winter and summer will fill an important and large gap in global ocean observations for physical processes that impact long-term climate change. The surveys will also serve as a means for making late winter carbon and CFC observations that will impact understanding of ocean carbon uptake. *Education:* 1 graduate student and 1 postdoc. *International education*: Work with Chilean and European Union graduate students, at no cost to this proposal. Talley taught a summer course at U. Concepcion in 2002 and advised a U. Copenhagen graduate student (Chilean nationality) for four months in 2002. The proposed work will strengthen collaboration between U.S. and Chilean scientists.

Project Description

This proposal is one of several that will bring together investigators from various U.S. and international institutions to ***characterize the processes responsible for the formation of Antarctic Intermediate Water (AAIW) in the southeast Pacific***. As a representative of the general class of Subantarctic Mode Waters (SAMW), study of the AAIW formation process will also inform our understanding of mechanisms, mass, chemical, and buoyancy budgets for all of the SAMWs.

The *broader impacts* of our proposed study include this understanding of the processes that maintain the extensive region of deep mixed layers in the southern hemisphere. These are tied to questions of the overall dynamics of the Antarctic Circumpolar Current (ACC), including importantly the fate of the large wind-driven northward transport (Ekman transport) across the ACC. Knowledge will be gained for improved modeling of an important ocean ventilation process that can impact long-term climate change and carbon dioxide uptake, graduate student study, and collaboration with scientists and their students from Chile, Canada and Germany.

1. Introduction and objectives. Thick mixed layers dominate the upper ocean in the southern hemisphere, directly north of the Antarctic Circumpolar Current (ACC). These mixed layers are known collectively as "Subantarctic Mode Water" (SAMW) (McCartney, 1977). The mixed layer depths range from about 200-300 meters in the Atlantic and western Indian sectors to greater than 500 meters in the eastern Indian and across the Pacific sectors (Fig. 1a) (Talley, 1999a; Hanawa and Talley, 2001). The only other open ocean region with similarly thick mixed layers is the subpolar North Atlantic.

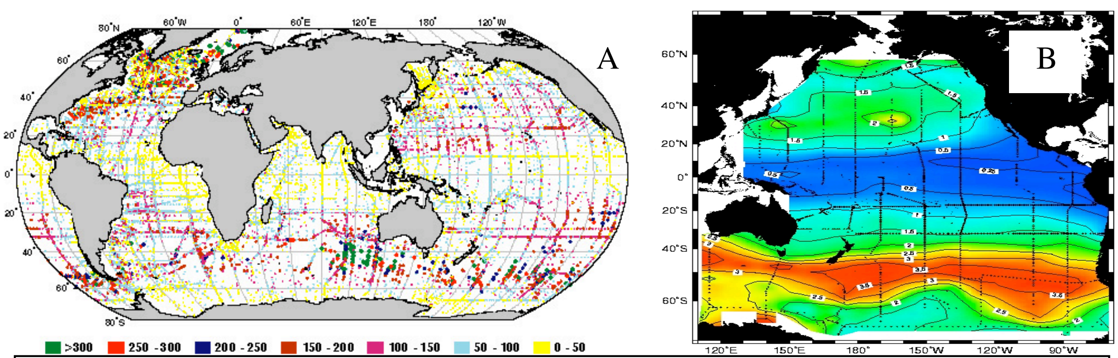

Fig. 1. (a) Proxy of late winter mixed layer depth (m) (95% oxygen saturation horizon), from Talley (1999a). This underestimates SAMW thicknesses somewhat. (b) CFC column inventory (μmol m^{-2}) in 1993.

The SAMW mixed layers, like other mode waters such as Subtropical Mode Waters, are closely associated with the warm side of the Subantarctic Front (SAF), which is the northernmost current core of the ACC. The SAF spirals southward from a northernmost point at the Falkland/Brazil Current confluence east of South America, to a southernmost point in the southeastern Pacific where it enters Drake Passage. The SAMW mixed layers follow this gentle southward spiral (Fig. 2). The thickest, densest, coldest, and freshest SAMW is located in the southeastern Pacific, just before the entrance to Drake Passage. This freshest, densest SAMW is the only source of Antarctic Intermediate Water (AAIW) for the world ocean, with modification in Drake Passage and the Falkland loop for the Atlantic/Indian type of AAIW (McCartney, 1977; England et al., 1993; Talley, 1996; Hanawa and Talley, 2001).

AAIW is the low salinity water mass that fills almost all of the southern hemisphere and the tropical oceans at about 800 to 1000 m depth (Fig. 3). The AAIW salinity minimum is at 31.6-31.9σ_1 (27.0 to 27.3σ_θ). In the South Pacific and South Atlantic, AAIW is also marked by an oxygen maximum and potential vorticity minimum in the vertical. The global source of AAIW in the southeast Pacific and southwest Atlantic is marked by these same extrema (salt, oxygen, potential vorticity) along isopycnals: lowest salinity, highest oxygen and lowest potential vorticity. (Northward Ekman transport across the SAF is often indicated schematically as the AAIW, but actually feeds into the thick SAMW surface layers, based on analysis of WOCE meridional sections. Only in the southeast Pacific does it directly feed the AAIW. These opposing views are discussed in section 2.)

AAIW subducts northward from its surface SAMW source into the South Pacific subtropical gyre where it is the densest water in the thermocline (McCartney, 1982; deSzoeke, 1987). This northward path is also evident in Reid's (1997) circulations. The AAIW then moves into the tropical Pacific, where the salinity minimum erodes to a higher density, and then into the North Pacific where it lies well beneath the locally-ventilated thermocline.

A portion of the AAIW also passes eastward from the SE Pacific surface source through Drake Passage, into the South Atlantic. Surface and lateral mixing modify its properties en route. From the Falkland-Brazil Current confluence, it mixes into the South Atlantic and Indian subtropical gyres, well below the densest locally subducted waters (Talley, 1996; Suga and Talley, 1995). It spreads into the tropics in both oceans. In the Atlantic it is part of the northward transport of warm waters that feed North Atlantic Deep Water formation (Tsuchiya, 1989; Tsuchiya et al., 1994). Transport estimates for these two exports (Pacific and Atlantic) of AAIW are about equal, for a rough total of 10-25 Sv (Schmitz, 1995; Sloyan and Rintoul, 2001).

As a relatively fresh water mass with a relatively large, although not well-quantified formation rate, AAIW impacts global freshwater budgets, and thus may figure in millenial and longer climate variability through its impact on NADW (e.g. Rahmstorf, 1996; Keeling and Stephens, 2001). Freshening of Pacific AAIW over the past decades (Wong et al., 1999) may be associated with anthropogenic climate change (Banks et al., 2000). As the base of the thermocline in the Pacific, AAIW affects tropical stratification and thus may affect very long-term (paleo) variations in El Nino/Southern Oscillation (e.g. Fedorov and Philander, 2001; Hendy and Kennett, 2000).

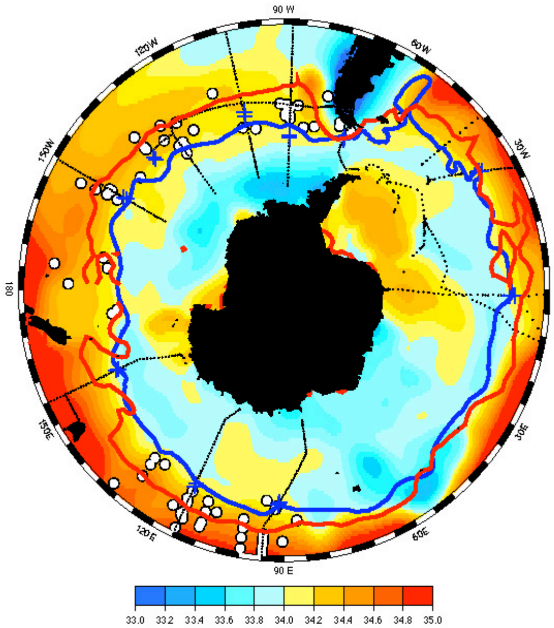

Fig. 2. SAMW formation region. Color: austral winter salinity (Levitus climatology). Blue curve: SAF from Orsi (pers. comm.). Large blue +: SAF based on WOCE hydrographic sections. Red curve: zero wind stress curl. White dots: mixed layers deeper than 300 m, from Fig. 1a. AAIW formation is associated with SAMWs in the southeast Pacific.

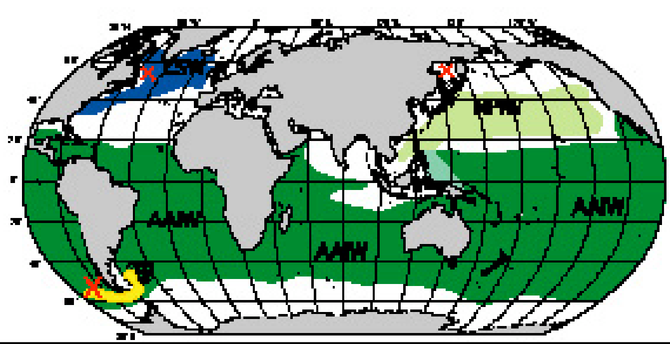

Fig. 3. AAIW salinity minimum (dark green). Red Xs - formation regions of the low salinity intermediate water masses (after Talley, 1999a). Yellow: general region of major AAIW transformation.

SAMWs affect vertical carbon distributions and carbon cycling in the oceans: the global zonal bands between 40-50°S have the largest total accumulation of anthropogenic CO_2 and highest CFC column inventory (Fig. 1b) in the oceans. SAMWs and AAIW also provide one of the most important pathways for moving anthropogenic tracers into the ocean interior (Fine, 1993; Fine et al., 2001; Sabine et al., 2002). The largest uncertainties in the current approaches for estimating anthropogenic CO_2 in the oceans are at intermediate depths. Understanding the AAIW formation processes in the southeastern Pacific will improve our understanding of the oceanic sink for anthropogenic CO_2 (Sabine and Feely, 2001).

Despite these large-scale influences of AAIW and the knowledge for 25 years that AAIW is formed in the southeastern Pacific, AAIW is the only intermediate water that is almost completely unstudied at its winter source. Zero order questions exist about the SAMW and AAIW formation mechanisms. Its formation rate has not been quantified. Therefore, the central goal of our proposed work is to ***characterize the formation process of the thick SAMW mixed layers and AAIW in the southeastern Pacific***. The two potential major formation mechanisms are *(1) northward advection of dense ACC surface waters across the SAF (Ekman advection and eddy transport)* and *(2) convection driven by local air-sea fluxes* acting on waters from both the subtropical gyre (SAMWs lying to the west of the AAIW region) and on the cross-frontally advected waters. We will test these two hypotheses, including the possibility that both are operative. To accomplish this main goal, we will:

1) Map, in winter, the locations, properties and circulation of well-mixed SAMW layers that are the source of AAIW;
2) Characterize the regional processes that create southeast Pacific SAMW (Antarctic Intermediate Water), specifically the relative importance of local air-sea fluxes and winds, the Subantarctic Front (SAF), and cross-SAF exchange through Ekman transport and eddy shedding;
3) Inventory the water properties in the AAIW formation region during the ensuing summer, to study its restratification and beginnings of export.

As a second goal, we will also ***quantify formation, import and export rates***. Cooperation with other programs will improve the estimates from our synoptic surveys. As our contribution, we will:

4) Produce three-dimensional velocity fields in the broad synoptic survey region, including estimates of inflow and outflow transports in the region north of the SAF, estimate the Ekman flux that actually crosses the SAF, and define the properties of waters that should be included in the SAMW/AAIW budget.

To address these broad objectives, we propose an austral winter and follow-on austral summer survey of the AAIW formation region in 2004-2005 (Fig. 4). Associated, separate programs, include: proposed velocity and moored profiler time series (WHOI and URI), Drake Passage ADCP/XBT repeat programs (Chereskin), Drake Passage repeat hydrographic sections (Southampton Oceanography Center), 43°S repeat hydrographic sections (U. Chile), and full implementation of global observing systems facilitated by our cruises to this remote region (ARGO and surface drifters). Our approach to these four objectives is detailed in section 3.

2. Background.

Our main question is the mechanism that creates and modifies the thick mixed layers (SAMW) in the southeast Pacific that are the principal source of AAIW. The heart of our proposed work are the winter and summer surveys, mapping the locations of thick, relatively unstratified layers, the penetration depth of ventilation signatures (e.g. oxygen), and the distribution of complex upper ocean structures associated with cross-SAF transport either by Ekman or eddies. Evaluating these data, in the context of forcing and larger-scale data sets, we will assess the relative importance of cross-SAF transport, subtropical gyre inflow (upstream SAMW inflow to the SE Pacific), and local air-sea flux (schematic in Fig. 7).

These issues are closely tied to those of circumpolar current dynamics - that is, the fate of the northward Ekman transport, whether mixed into the surface SAMW layer or injected isopycnally to below the SAMW layer, or balanced locally by some other type of transport, the importance of eddy fluxes, and the role of these overturns and fluxes in global heat and freshwater transports (i.e. the geometry of variously proposed "Deacon" cells and their larger-scale impact).

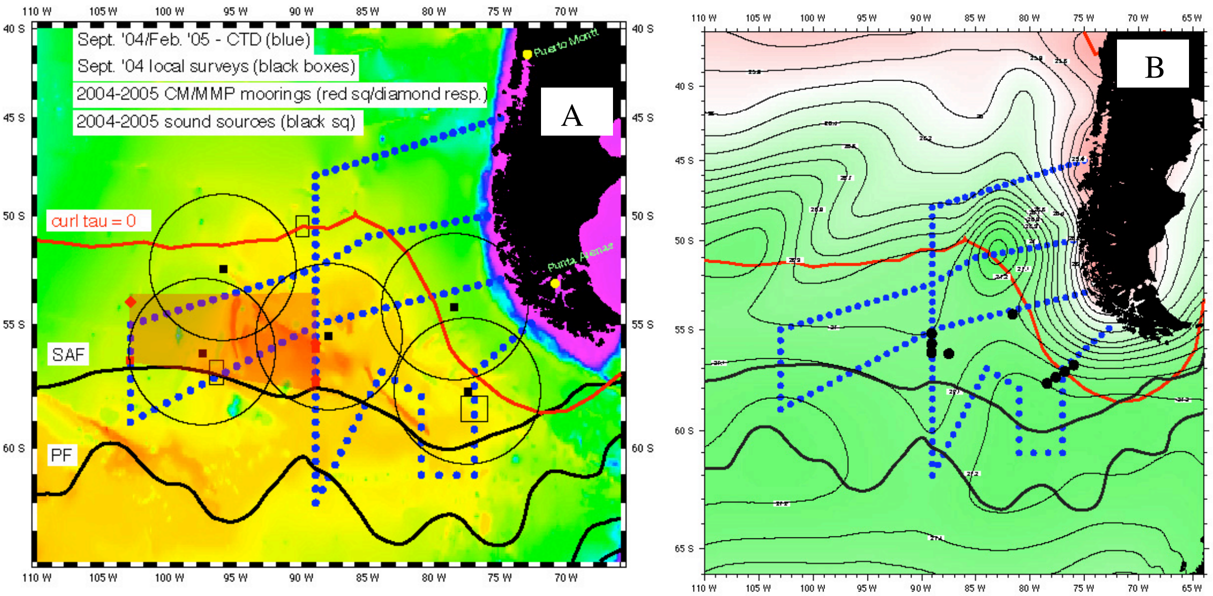

Fig. 4. Proposed hydrographic surveys in (a) September-October, 2004, with etopo5 bathymetry. Blue dots: CTD/rosette stations. Open black squares are intensively-sampled regions, using XCTDs at < 5 nm spacing: convection patch (site depending on basic survey and information obtained just before the survey), SAF survey, and SAMWF survey. Red diamonds: WHOI moored profilers. Red squares: WHOI moorings. Black squares: URI sound sources. Large black circles: RAFOS insonification regions. Transparent red block: WHOI/URI float deployment region. Approximately 45 ARGO floats and 30 surface drifters from the Global Drifter Program will also be deployed from the cruises. Heavy red curve: zero wind stress curl. Heavy black curves: Orsi Subantarctic and Polar Fronts.
(b) February-March, 2005, with Levitus winter surface potential density (based on little data away from the coasts). Blue: same stations. Black dots - well-mixed layers in winter, 1980 and summer, 1993. The actual SAF location was approximately the same (Orsi) location as shown in the figure.

How do we know where to look for AAIW formation? An excellent, general recent review of these issues is in Rintoul et al. (2001). AAIW forms adjacent to the SAF. (Defining "adjacent" is an objective of our proposed winter survey.) Because of its circumpolar salinity minimum and the westerly winds, it was often presumed that the AAIW source is the low salinity surface water crossing the SAF all around Antarctica through Ekman transport. However, as described in section 1, isopycnal distributions of salinity, oxygen, and potential vorticity, and also models (e.g. England et al., 1993), show the most extreme AAIW properties (highest oxygen indicating most recent ventilation, lowest salinity and lowest potential vorticity) in the southeastern Pacific, northern Drake Passage and west of the Falkland Current (McCartney, 1977; Talley, 1996; Rintoul et al. 2001) (yellow in Fig. 3). Therefore, our proposal is to study the SAMW in the southeast Pacific, at the source of these extrema and hence AAIW.

Outcropped AAIW in the SE Pacific is a layer of about 400-500 m thickness of low salinity, high oxygen saturation and high anthropogenic CO_2. Salinity is lowest at the sea surface (Fig. 5). (The subsurface salinity minimum indicating AAIW and the SAF is weak or absent.) The thickest observed layers in previous surveys (black dots in Fig. 4b) are about 100-200 km north of the SAF, in a low eddy kinetic energy region (Fig. 6). Sampling has not been complete enough to define the full region of thickest layers. The stations between these thick layers and the SAF have complicated vertical structure (20-50 meter layers plus much shorter vertical scales), suggesting mixing, probably of surface waters crossing the SAF (Ekman transport) and/or due to eddies.

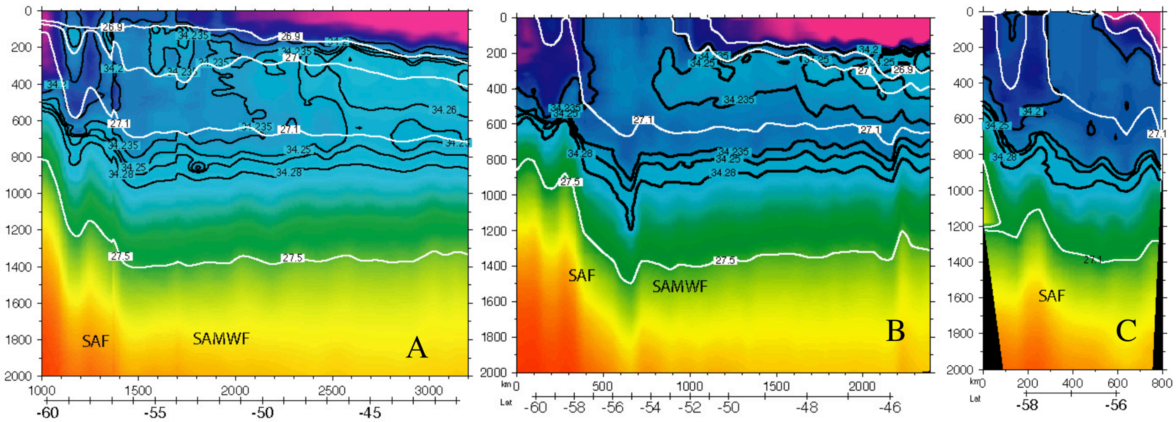

Fig. 5. (a) Salinity (color and black) section at 88°W in the Pacific (WOCE P19) (see Tsuchiya and Talley, 1998). Potential density in white contours. Fronts – SAF and SAMWF.
Salinity on (b) western section up 90°W and into the Chilean coast and (c) eastern (Drake P.) section in austral winter, 1980. (Data source - M. McCartney and D. Georgi)

The SAF, which bounds SAMW/AAIW to the south, is one of the major currents of the world, with surface speeds in excess of 50 cm/sec, high eddy kinetic energy and obvious eddies/meanders (Fig. 6b). The thick AAIW mixed layers in the SE Pacific are bounded to the north by another property front centered at 50°S, apparent even in climatological data (Fig. 4b). We are not aware of a name for this front, and so we call it the SAMW Front (SAMWF). A similar front in the Indian Ocean has been called the South Subtropical Front (Belkin and Gordon, 1996). The SAMWF was well-sampled on WOCE P19 (Tsuchiya and Talley, 1998) and is the southern boundary of the AAIW salinity minimum in the SE Pacific. To enter the South Pacific subtropical gyre, AAIW subducts from the surface layer northward across the SAMWF. The SAMWF, not the SAF, is located at the maximum wind (zero wind stress curl) (Figs. 4, 6).

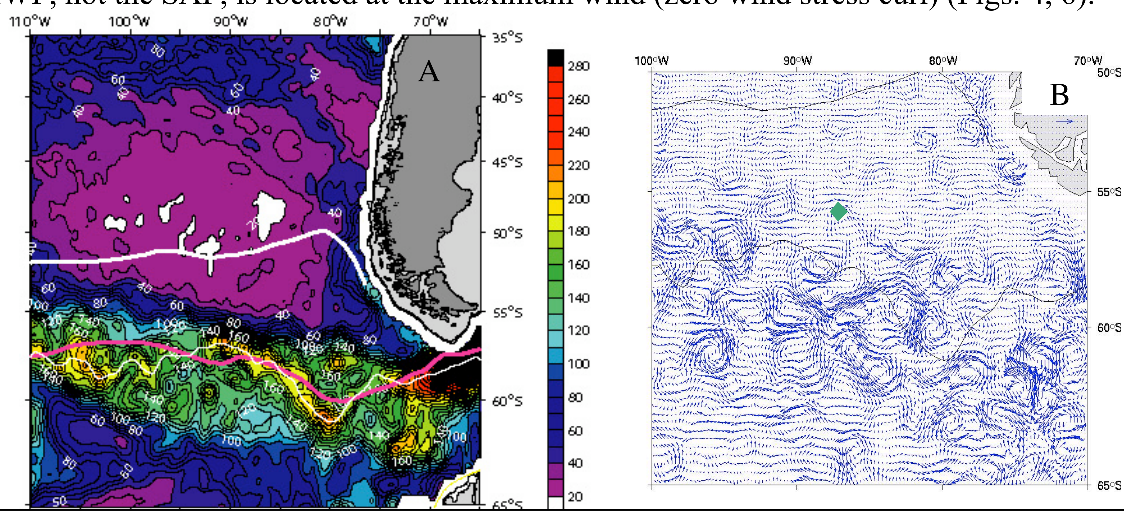

Fig 6. (a) Eddy kinetic energy from Topex/Poseidon, with maximum EKE (thin yellow), Orsi Subantarctic Front from historical hydrographic data (pink), and 0 wind-stress curl (thick white).
(b) Instantaneous geostrophic velocity field from blended Topex/Poseidon, for January, 1993 (during observation of thick mixed layer along 88°W, position marked in green). (T/P analysis by S. Hormazabal.)

What is the source water for AAIW? The candidates are (1) northward Ekman and eddy transports across the SAF, and (2) subtropical gyre input including upstream SAMW (Fig. 7). The total Ekman transport across the SAF is 34 Sv with 7 to 8 Sv in the Pacific. This is a potentially important volume source of AAIW (Sloyan and Rintoul, 2001b), as it feeds the upstream SAMW that becomes AAIW and also feeds AAIW directly in the SE Pacific. If residual circulation models (Karsten et al., 2003) are correct, this might be a gross overestimate of the direct impact of Ekman transport, and the AAIW could come mostly from the subtropical circulations feeding southward into the SAF. The eastward decrease/increase in SAMW temperature/density would come from this continual cross-SAF input of colder, denser surface waters. Rintoul and England (2003) indicate that variations in SAMW properties south of Australia arise from this source.

The McCartney (1977, 1982) paradigm assumes that SAMW comes from the subtropical circulation, with northward loss of SAMWs through typical subtropical subduction (Luyten et al., 1983, deSzoeke, 1987; Huang and Qiu, 1998). In this view, southward flow in the west feeds into the SAMW region, where buoyancy loss through air-sea flux decreases the temperature and increases the density of the thick mixed layer. The thickness of the mixed layer is then ascribed to the very large isopycnal slopes associated with the SAF, which as the northern front of the ACC is one of the stronger currents in the world, with surface velocities of about 50 cm/sec. The Pacific SAMW is also fed from the Indian Ocean SAMW, much of which subducts into the Indian subtropical gyre (e.g. McCartney, 1982; Talley, 1999a; McCarthy and Talley, 1999), but with some passing on to the Pacific (Sloyan and Rintoul, 2001).

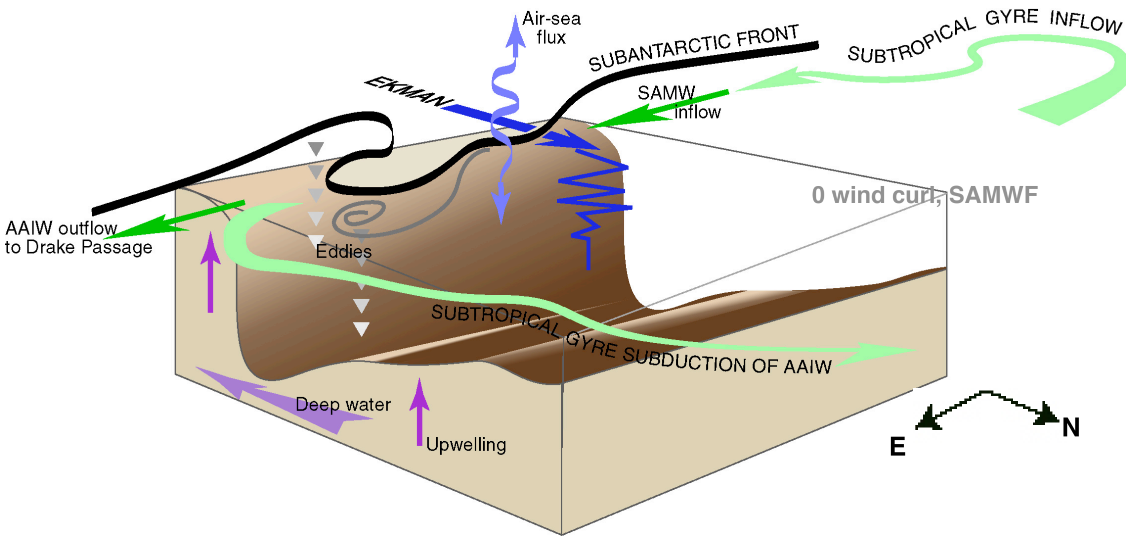

Fig. 7. Schematic of SAMW/AAIW processes, showing: (1) inflow from subtropical gyre and outflow to Drake Passage and subtropical gyre subduction (green), (2) northward Ekman transport at the Subantarctic Front creating intrusions/mixing, fed by upwelling from below and deep flow southward across the front (blue), (3) upwelling driven by Ekman suction north of the SAF (as per all observations - see Fig. 2), preconditioning the region for convection (purple), (4) eddy fluxes across the SAF (gray), (5) air-sea fluxes including heat/salinity balances and also wind stirring (light blue), The shaded brown shape represents the base of the surface layer.

Where does the Ekman transport return, and exactly how does it manifest itself north of the SAF? The first is the subject of numerous studies of the "Deacon cell", dating back decades, also reviewed in Rintoul et al. (2001). The 34 Sv must be balanced by southward transport, which could be (1) geostrophic and below Drake Passage sill depth (e.g. Toggweiler and Samuels, 1993; Warren et al., 1996) or (2) shallow enough that outcrops occur north of Drake Passage (Speer et al., 2000), or (3) at mid-depth, associated with eddy fluxes or eddy viscosity (e.g. Wyrtki, 1960; deSzoeke and Levine, 1981; Speer et al. 2000; Karsten and Marshall, 2002; Karsten et al., 2003; Thomas et al., 2002), Surface buoyancy fluxes (net cooling, net heating, neutral) should provide a major clue to the most likely mechanism for southward flow because the southward flow transforms into the surface Ekman flow. Because winter observations are lacking and the overall flux is nearly neutral, the mechanisms are all plausible. Our own estimate (Talley, 2003; Talley et al., 2003) of the southern ocean overturn based on circulation at 30°S suggests a net deep water flow into the southern ocean that nearly balances bottom water outflow, and thus requires less surface heating than in some treatments, such as Sloyan and Rintoul (2001) or Speer et al. (2001), and more in line with Ganachaud and Wunsch (2000) and Wijffels et al. (2001).

In simple older models of the ACC, the dense Ekman transport mixes down into the deep mixed layer. More modern large-scale modeling might mix this water in along isopycnals, which would produce water masses more like the older observationally-based concept of AAIW formation (water sliding down along isopycnals). Actual profiles north of the SAF have very complicated structure in the upper ocean, with none of the intrusions exactly matching surface water south of the SAF. This suggests that at least part of the Ekman transport mixes directly into the surface layer, with mixing starting immediately, similar to subduction observations in other regions (e.g. N. Atlantic, Japan Sea). Some models suggest though that the Ekman transport is returned very close to its source (Thomas et al., 2002) or is balanced by opposing southward flow, yielding a small "residual" circulation (Karsten et al., 2003).

What creates the low stratification in the SAMW north of the SAF? Mixing of the higher density surface waters crossing the SAF is one possibility. Buoyancy loss to the atmosphere, acting on already weak stratification because of the large isopycnal slopes, is a second possibility, but is much less important than in Subtropical Mode Water formation regions of the Gulf Stream/Kuroshio, since air-sea fluxes are small or positive in the SAF region (Trenberth et al., 2001; Speer et al., 2000; Rintoul et al., 2001; Rintoul and England, 2003). Thus preconditioning for convection must be important, and could be due to cross-SAF intrusions or local upwelling.

As it circles Antarctica, the SAF shifts southward and flows through Drake Passage (e.g. Stommel, 1957; Wyrtki, 1960). Stommel's Sverdrup solution implied an upwelling region north of the SAF, although Wyrtki believed instead that the SAF was the axis of maximum westerlies and therefore developed a frictional model of the SAF. While Wyrtki was correct about the dynamics (see Rintoul et al., 2001), Stommel was correct about the upwelling. The SAF lies well south of the maximum westerlies in the Pacific and eastern Indian Oceans (Fig. 2, 4, 6). Thus Ekman transport is divergent most of the year in most of the broad SAMW/AAIW outcropping region. This upwelling could precondition deep mixed layer development, through enhanced vertical mixing and cyclonic structures (Legg et al., 1998). The zonal asymmetry of this upwelling might be related to SAMW thickness asymmetry (Figs. 1, 2).

Surface salinity may also assist in preconditioning since it is actually maximum in the meridional direction in the SAMW formation region (Fig. 2). North of the SAMWF, subduction of the low salinity waters forms the shallow salinity minimum (SSM) of the subtropical gyre (Reid, 1973; Tsuchiya, 1982), with a much smaller impact than the AAIW salinity minimum. The salinity maximum between the SSM and AAIW might be subduction of western Pacific SAMW.

How does AAIW exit the SE Pacific? Reid's (1997) circulation maps for 200 and 500 dbar suggest that the SAMW/AAIW that subducts northward into the subtropical gyre comes from the western part of the proposed sampling region, while the thick surface layers from the eastern part of the region proceed eastward into Drake Passage. (Floats at 1000 m [Davis, 1998] corroborate Reid's 1000 dbar circulation.)

Sloyan and Rintoul find northward AAIW transports of 12, 6 and 6 Sv in the Pacific, Atlantic and Indian. Using the volume of AAIW ventilated with CFCs and the CFC age, Fine et al. (2001) estimated that about 8 Sv of AAIW is exported into the South Pacific from the southeast Pacific formation region. (These do not include southward transports of northern waters, mainly upwelled deep waters.) Thus we are looking at 20-25 Sv of new AAIW, flowing about equally into the Pacific and Atlantic/Indian. Global overturn across 30°S estimated from Reid's (1994, 1997, 2003) circulations shows a warm cell of 9 Sv of subtropical water downwelling into northward flowing water in the AAIW density range (Talley, 2003; Talley et al., 2003). The heat transport is large: -0.7 PW (poleward). Upwelling Upper Circumpolar Water (UCPW) is weak, whereas it dominates AAIW overturn in Sloyan and Rintoul (2001) and Speer et al. (2000). Thus the latter analyses would support a major role for northward Ekman transport across the SAF while the former would support the subtropical/upstream SAMW source for AAIW.

Previous observational experience relevant to SAMW/AAIW formation

Direct observation of water mass formation is difficult because it is sporadic, spatially inhomogeneous, and at small scale, on the order of kilometers. Truly well-mixed layers beneath the surface seasonal pycnocline after winter are exceedingly rare, possibly because some measure of restratification occurs relatively rapidly. Completely vertically mixed layers might also never occur because of earth's rotation and/or rapidly developing instability (Straneo et al., 2002; Legg et al., 1998; Sheremet, personal communication). Eddy processes can change the potential vorticity within the first few months after formation (e.g. Joyce et al., 1998). Convective surface layers lose their undersaturated gas properties within weeks, due to air-sea equilibration and mixing of the very localized and small patches with surrounding saturated waters.

So what can we expect to find? These small mixing structures have been observed and modeled as embedded in larger "convection patches", on the order of 100 km across (Marshall and Schott, 1999). Such convection patches have been observed in the Mediterranean, Labrador, Greenland and Japan Seas. The scale of STMW formation regions, in anticyclonic meanders of the Gulf Stream, is similar (Talley and Raymer, 1982). In the Japan Sea, undersaturated surface oxygen indicated the convection patches (Talley et al., 2003). In our survey we will expect to find at least one of these convection patches, which we will survey intensively.

SAMW/AAIW formation, adjacent to the energetic Subantarctic Front, is similar in many respects to subtropical mode water (STMW) formation next to the Gulf Stream and Kuroshio. An obvious difference is the lack in the AAIW region of the large annual-average surface heat losses in the Gulf Stream and Kuroshio. Another difference is the more zonal geometry of the ACC and SAMW. Gulf Stream and Kuroshio STMWs have been observed and studied for many decades (review in Hanawa and Talley, 2001). The STMW mixed layers outcrop in a narrow region close to the warm, equatorward sides of the currents. Meanders of the currents surround especially active vertical mixing regions. The STMW waters have been tracked back into the currents, and are associated with major buoyancy loss. Basic questions remain, including the importance of Ekman and eddy fluxes across the Gulf Stream/Kuroshio.

Fully unraveling mode water dynamics is daunting, as evidenced in current planning for a U.S. CLIVAR Gulf Stream project, even with all of the years of past observations and modeling. Our proposal for SAMW/AAIW formation will take us to at least the first, and essential, step: basic mapping and description of the late winter mixed layers relative to the SAF and its meanders. An initial mass and salinity budget is also expected. What we have learned from present knowledge of STMW is: the necessity of detailed observations near and across the SAF, and within both cyclonic and anticyclonic SAF meanders, the usefulness of mapping the eddies (which we will do with altimetry and SST), and the necessity of measuring air-sea heat fluxes.

We also know from past observations of the SAF and other salinity/temperature fronts that finestructure intrusions are widespread, and associated with cross-frontal mixing (Joyce, 1977; Toole, 1981). These intrusions are especially pronounced in the upper ocean, and we believe are associated with Ekman transport (our unpublished results from WOCE sections).

The proposed SAMW/AAIW study is also partially informed by studies of convection in the Labrador, Greenland, Mediterranean and Japan Seas. Unlike AAIW, all of these are characterized by convection in a confined region, partially defined by local geometry (coastlines), and subject to massive cold air outbreaks. In the first three, just as for STMWs, decades of observations provided information about where convection might be expected. These non-winter observations were then followed by modest programs of difficult, late winter observations (Clarke and Gascard, 1983; Pickart et al., 2002; Rudels et al, 1989; Medoc Group, 1970). Finally, after sufficient information was gathered, massive, resource-intensive studies, many involving tomography and multiple mooring and meteorological groups, of a scope have been undertaken (e.g. LabSea Group, 1998; Schott et al., 1996; Morawitz et al., 1996). In the Japan Sea, we began with several formation hypotheses, based on air-sea flux observations (Kawamura and Wu, 1998), summer properties (Senjyu and Sudo, 1993), AVHRR SST, ice cover, and scattered profiling floats. Our first broad survey covered the subpolar region in late winter (2000). We located the deep mixing regions (Talley et al., 2003). Based on this, we have conducted small-scale surveys in subsequent winters.

We already know from global mapping of AAIW properties, and from our observations from WOCE P19 (Tsuchiya et al., 1998), and from unpublished winter 1980 observations (McCartney), that the source of AAIW is the SAMW of the southeast Pacific, with modification through Drake Passage. Therefore we already know the general area for observations.

We learn from these previous programs that the next step for AAIW, proposed here, is an intensive late winter survey that fully defines the convection region and its relation to the important dynamical features such as the SAF and another front (defined below). Because the region is so remote, and because a late winter cruise is so difficult, the survey must be comprehensive enough to cover the potentially important processes (Fig. 7):

- Inflow of SAMW from the west, north of the Subantarctic Front (SAF)
- The relatively quiescent flow regime between the SAF and the northern SAMW Front, in the AAIW formation region, feeding the bifurcation and outflow of AAIW to the north (subduction) and east (through Drake Passage)
- Ekman transport of dense surface waters across the SAF, creating finestructure intrusions in the AAIW layer
- Eddy transport of denser waters (up to full water column) northward across the SAF, mixing in polar properties and possibly potential vorticity flux
- Upwelling from below, north of the SAF, preconditioning for deep mixing
- Eddy and streamer creation, preconditioning for mixing
- Buoyancy flux into the atmosphere – cooling, and also local precipitation
- Convection driven by buoyancy flux and possibly Ekman intrusions
- Restratification into summer, capping mixed layers, facilitating subduction

To make the most of such a winter survey, a summer survey tracking mixed layer restratification, isolation, and initial subduction is also proposed.

3. Work plan (winter 2004 and summer 2005 surveys and analysis)

Two intensive hydrographic surveys are proposed: the first in austral winter, 2004 to observe the winter ventilation of AAIW, and the second in austral summer, 2005 to observe its restratification and dispersal. The surveys cover a broad region because they are exploratory and must define all of the regions of relevant deep mixed layers and complex mixing regions near the SAF, and the regional context for these structures - properties within and just south of the SAF and its eddies, and northward to the SAMWF. Previous experience with detecting and defining deep convection regions indicate that such a broad regional study is required, certainly before more localized, repeated studies can be undertaken (based on experience in numerous water mass formation regions, including our Japan Sea experience [Talley et al., 2003].)

Where do we expect to find SAMW associated with new AAIW? We have only limited prior knowledge of the specifics. Well-mixed layers or remnants of them, with AAIW properties, have been found spread over the SE Pacific, but concentrated about 150 km north of the SAF (Fig. 4b). The winter 1980 survey near Drake Passage (Fig. 5b) showed homogenized layers of local SAMW/AAIW properties to 380-500 m depth, with the deepest layers along 88^{o}W and about 100 km north of the SAF. The WOCE P19 summer (Jan./Mar.) sections at 54^{o}S and 88^{o}W showed high oxygen saturation at one station to 500 m depth (Fig. 4b, 6b), and relatively unstratified layers to 350 m in a broad region of nearly flat dynamic topography, with major capping by seasonal warming above, and some restratification (smoothing) from below. All of the meridional WOCE sections around Antarctica showed the thickest SAMW remnant mixed layers similarly close to, but slightly separated from the Subantarctic Front. The relation of deep mixed layers to SAF eddies (Fig. 4b, 6) and definition of the boundaries of the region of deep mixed layers is unknown. The structure and size of deeply mixed patches is unknown.

Therefore our survey must distinguish the relative importance of various regions for deep mixing: near the SAF, both up and downstream, and within and outside SAF meanders, and in the broad region defined by WOCE P19. Hence the hydrographic station coverage is of a large area, but with deep-reaching underway ADCP and embedded intensive XCTD surveys to study the deeply-mixed upper ocean and the structure of the major fronts (SAF and northern outcropping front). The underway measurements and XCTDs resolve the Rossby deformation radius, required since eddies are a central candidate process for cross-SAF mixing and also localization of convection. The broad surveys cover the SAF and the region of deep mixed layers between the SAF and the northern front (section 2). There are numerous crossings of the SAF. Numerous crossings of the broad Chilean coastal region cover export pathways to the north, and will define the eastern limit of the deep mixed layers.

Ancillary data sets are central to our analysis - AMSR SST, Topex/Poseidon altimetry, quikscat winds, ARGO floats, global ocean drifters and NCEP/ECMWF/NOGAPS atmospheric analyses. The RAFOS and profiling float work proposed by WHOI and URI provides a fully complementary view of the region's processes.

(a) ***Winter (September/October) 2004 survey (Fig. 4a).*** This survey covers the broad region of expected AAIW formation and nearby export during winter. It includes up to 160 hydrographic stations to the ocean bottom, with 30 nm spacing, with CTD/O2/LADCP and full chemistry (salinity, oxygen, nutrients, total CO2, alkalinity, CFC-11, CFC-12). The carbon and CFC measurements are proposed separately to NSF chemical oceanography (Fine, Sabine and Dickson). Underway measurements include 1000-m deep ADCP coverage (requiring specific UNOLS vessels), surface pCO_2 and pN_2O (O. Ulloa, U. Concepcion), underway thermosalinograph and oxygen, and high quality shipboard meteorology.

The actual cruise plan will be modified just prior to the cruise using information gathered from profiling floats, AMSR SST, T/P altimetry, Seawifs Ocean Color, and NCEP/NOGAPS atmospheric fields. Additional intensive frontal (SAF and SAMWF) survey work will be carried out using XCTDs. We will survey at least one convection patch thoroughly with a mix of 1500 m and deep CTDO2 stations.

Profiling floats for ARGO (45 for the U.S. and Canada, deployed at ARGO density), surface drifters with SST and atmospheric pressure (30 throughout the region), and the second seeding of WHOI/URI floats (red transparent box in Fig. 4a) will be deployed.

At 10 knots, the planned survey would take 41 days. Weather time (winter conditions) is included in the form of both the reduced ship speed (2 days) and the addition of 4 days, for a total of 47 days. 6 crossings of the Subantarctic Front and 4 crossings of the SAMW Front on into the Chilean coast are included, to look for evidence of winter convection and intrusions across the Subantarctic Front. One crossing of the Polar Front is included to characterize upper ocean waters that feed across the Subantarctic Front and to measure the winter carbon system in the strongest upwelling regime, associated with the Polar Front (Sabine et al., 2002). This is also a region of high sensitivity in some coupled climate models (Weaver, personal communication).

(b) ***Summer (February/March) 2005 (Fig. 4).*** This survey will cover the same region as the winter survey, and will study the fate of the winter waters observed during the previous September/October. CTD sampling duplicates the winter plan, to provide coverage of the whole of the region. Only 2 days of weather time are included, for a total of 43 days at sea. The convection patch sampled intensively in the winter will be resampled (with possible adjustment in location due to advection, based on floats), to observe restratification of the mixed layer. An intensive SAF XCTD survey is planned since the cross-frontal processes should continue throughout the year. The intensive SAMWF survey should be of additional importance as a local study of subduction of the AAIW northward after summer capping. The hydrographic instrumentation is identical to the winter cruise. Additional IOS/Canada profiling floats will be deployed (third year deployment). The cruise plan will be adjusted based on information from the profiling floats deployed during the preceding year as well as satellite information.

(c) ***Methods.***

CTD, salinity, oxygen and nutrient measurements will be carried out by the UCSD/SIO Oceanographic Data Facility (ODF), to reference quality standards (Joyce and Corry, 1994 a,b).

High quality measurements are required to distinguish different water masses, to estimate geostrophic shears, and to enable comparisons on isopycnal surfaces within a data set, and also to allow comparison with other data sets from this and companion programs, nearby regions, and from other years. CTD/LADCP stations will extend to the bottom because transports are being calculated, and require consistent deep referencing. Moreover, it will be useful to estimate diapycnal mixing rates, or at least Richardson number, and possible enhancement in the strong vertical shear and lateral property gradients of the ACC. Given the unlikelihood of another intensive winter survey of this region, top-to-bottom observations are proposed.

We require CTD data corrected with pressure and temperature laboratory calibrations and with salinities and oxygens corrected against bottle samples. The nutrient data (2004-2005 cruises) also provide valuable information on circulation and mixing. CTD oxygen probe data processing is required. ODF will supply experienced seagoing technicians to provide these services. The budget for ODF shipboard acquisition is handled through NSFs Oceanographic Technical Services Program, instead of being supported by the Physical Oceanography Program, and is not charged to our science budget (recent NSF policy). Although ODF will deliver scientifically usable data at sea, we require fully processed and documented data to complete our work, and for submission to the archive. These shore data processing services are required by NSF to be part of the proposed science budget (a self-contained item under "Other").

LADCP/ADCP velocity measurements will be used to map the circulation, estimate the total shear, calculate the full potential vorticity (PV), and assist with mixing estimates. It is critical in this area of deep wintertime convection to profile the currents below the mixed layer, into the geostrophic interior. Shipboard and lowered ADCP measurements will provide complementary information on the current structure. Donohue et al. (2001) recently showed that shipboard and lowered ADCP measurements in the Southern Ocean are able to detect nonzero bottom velocities below the core jets of the ACC.

The lowered ADCP (RDI 150 kHz broadband) will provide a full depth profile of current at the resolution of the CTD stations, yielding a detailed view of the current and current shear at the locations of the float deployments. We expect barotropic tidal velocities in this region of order 0-3 cm s^{-1}, small compared to the large tidal currents of Antarctic marginal seas (Robertson, 1998). The tide will be estimated and removed from the measured currents using the OSU TPXO model (Egbert et al, 1994). Additionally, the CTD/LADCP measurements used together with parameterizations of turbulent dissipation (Polzin et al, 1995; Polzin et al, 1997) will be useful in characterizing mixing in the region of float deployments, upstream of Drake Passage.

The shipboard ADCP provides the best horizontal spatial sampling. This is particularly important due to the small Rossby radius. We have requested a ship with dual-frequency sonar, either the Revelle Doppler sonar (50/140 kHz) or equivalent, e.g. RDI 38 kHz phased array and 150 kHz narrow band. Dual sonars will allow us to profile to 800-1000 m (below the mixed layer, which can reach to greater than 500 m here) with 16m resolution while the high frequency sonar will provide 8m resolution in the surface layer. Attitude measurements (pitch, roll, heading) are critical for accurate absolute currents and for accurate horizontal shears in the PV calculation. The low frequency sonar should prove useful in geostrophic referencing because the extended range reaches below the mixed layer into the geostrophic interior by several hundred meters. The barotropic nature of the current, excellent horizontal resolution of the SADCP, and the multiple longitudes sampled by our cruise track will more strongly constrain the geostrophic reference (Chereskin and Trunnell, 1996) than was possible with the sparse sectional WOCE data available to Donohue et al. (2001).

ADCP/LADCP processing will follow methods developed in WOCE.

Underway thermosalinograph with oxygen sensor (Seabird). Because frontal intrusion and subduction processes are potentially important and because convection is inherently small scale, better spatial resolution is required than is possible with deep CTD stations. The reference quality underway instrument will measure the short scales of T/S variation and detect surface undersaturation of oxygen and its lateral scale, associated with deep mixing (Talley et al., 2003). Regular calibration of salinity and oxygen will be carried out.

XCTDs. These will be used to yield an average 5 nm profile separation across the SAF and the SAMWF. (Seasoar does not profile deep enough to capture the AAIW mixed layer, and in any case yields about the same profile separation at normal steaming speeds.) If an underway CTD is fully developed prior to any of our surveys (e.g. D. Rudnick, SIO), we will switch from XCTDs to the underway instrument. For the summer survey, if a profiling glider is available, we will replace the intensive local XCTD surveys with a glider/ship survey. On the winter cruise, when underway T/S, oxygen, pCO_2 and XCTDs suggest active or recent convection, we will adjust the station plan to capture the water properties, currents (with SADCP) and spatial scale (vertical and horizontal) of the convected region. With limited shiptime, we will not respond to every such patch, but we plan to cover at least one patch thoroughly, as in a winter Labrador Sea Water formation experiment (Lab Sea Group, 1998; Spall and Pickart, 2001).

Meteorology. Measurement of winter air-sea buoyancy fluxes is essential, to determine their importance in deep mixed layer formation (compared with importance of lateral fluxes across the SAF). We therefore require the highest quality shipboard meteorology. A redundant set of sensors is included in the facilities proposal (ODF), because it will not be possible to make repairs to the sensors which are mounted high on the mast during the cruise. For the full winter buoyancy fluxes and context, we will use and compare all available products, including NCEP, ECMWF, and NOGAPS, and Quikscat winds. These wind products will also be used to calculate Ekman transports and convergence/divergence.

Satellite SST, color and altimetry, and results from ***profiling floats*** (ARGO and WHOI) and ***surface drifters*** will be used to map the fronts and major eddies prior to the cruise. Our CTD/XCTD station plan and choice of intensive survey regions will be adjusted based on these. One goal of the winter sampling is to understand the significance of the surface patterns (vertical structure and penetration) and coarsely-sampled ARGO vertical structure, to assist in estimating eddy fluxes and interpreting images from subsequent winters without *in situ* sampling.

(d) Data distribution. All measurements (CTD, salinity, oxygen, nutrients, LADCP, underway ADCP, XCTD, underway $T/S/O_2$, pCO_2 and pN_2O) will be available in near real time, and thus useful for small adjustments in the survey and for initial synthesis. Carbon and CFC measurements (Fine, Sabine and Dickson proposal) will be merged during the cruise as well. Final processed data will be available within six months to two years following the cruise, depending on data type. The final data sets will be delivered to the National Oceanographic Data Center according to NSF policy (two years after collection). Data will be made available to our formal collaborators soon after the cruises.

(e) Data synthesis. The new hydrographic data will be used in many ways in both our own analyses and in future years. At a minimum, they will characterize the winter surface mixed layer properties and evolution into summer, and identify the location of new AAIW/SAMW relative to the dynamical features of the SE Pacific. Future process studies of the region, as well as analysis of broad-scale observing system data, would likely rely heavily on the new winter survey data for siting and interpretation. Our shipboard data sets will be analyzed collaboratively with the profiling floats (ARGO [Freeland, Koblinsky], Sloyan), acoustic floats (Prater, Donohue), moored measurements (Sloyan, Donohue), and other nearby shipboard repeat surveys (Chereskin/Sprintall Drake Passage ADCP/XBT, Roemmich/Sprintall/Talley 32°S XBT, Southampton Oceanography Center Drake Passage repeat hydrography, proposed U. Concepcion 43°S hydrography). This work will be the subject of two PhD theses to be completed under our supervision as well as numerous papers of our own. Berths on the winter survey seem to be especially in demand, suggesting that our many collaborators believe, as do we, that this will be an historic set of measurements. We welcome modeling initiatives that complement our analyses.

Covering the four objectives of section 1, with technical details given in section 3c:

(1) Winter mapping and description of upper ocean. We will identify regions of low stratification and with evidence of recent deep mixing including low surface oxygen saturation, deep layered structures. We will identify regions of complex structure suggesting horizontal

mixing based on complex stratification, velocity shears, and water properties (salinity, temperature, oxygen, nutrients, density ratio, Richardson number). We will estimate the volume of new SAMW/AAIW. We will map the synoptic velocity field from the ADCPs and geostrophic shear. We will map meanders and eddies of the SAF, and map properties between the SAF and Polar Front that might be advected northward across the SAF. (Winter survey, satellite SST, altimetry)

(2) Mechanisms: To distinguish between various hypotheses of deep mixed layer formation, and of the fate of Ekman transport crossing the SAF, we will relate the well-mixed layers and regions with especially complex vertical structure to major dynamical features (SAF, SAMWF, eddies) and air-sea fluxes. Items to be quantified: advection from upstream of SAMW, Ekman transport across the SAF, Ekman divergence, eddy transfers across the SAF, air/sea fluxes.

We will consider the relation between local SAMW properties and upstream SAMW properties and upper ocean properties south of the SAF. We will calculate transports in and out of the sampled region. We will calculate Ekman transports and divergences from various wind products, and consider their annual cycle (context for deep mixing: upwelling or downwelling regions) as well as synoptic transports (cross-SAF fluxes). We will map eddies from satellite information, and their vertical structure from our surveys. We will calculate surface buoyancy flux from shipboard measurements, and will use larger-scale analyses and climatologies for context.

We will look at the relation of the mixed layers to the SAF and the northern edge of the outcropping region (SAMWF), and to finestructure (intrusions) indicating cross-frontal transfers. We will estimate volumetrically the fate of cross-SAF Ekman and eddy fluxes. We will look at mixing as parameterized from ADCP velocity and CTD temperature/salinity. We will relate the synoptically-observed deep mixed layers to time series of upper ocean properties. (Winter and summer hydrographic surveys; satellite SST and altimetry; NCEP, ECMWF, NOGAPS and air/sea fluxes; Quikscat winds; WHOI moored time series; ARGO and other profiling floats, collaborative programs.)

(3) Restratification: We will revisit convection regions, tracked into the summer by profiling floats if possible, and the overall region to study the restratification and hence isolation of the deep mixed layers. We will use large-scale buoyancy fluxes to understand the restratification. We will revisit the SAF and its finestructure to determine if cross-frontal fluxes throughout the year maintain deep mixed layers near the SAF. We will survey the SAMWF to seek information on where AAIW subduction into the Pacific gyre occurs. We will calculate transports of newly-capped waters out of the region (see next). (Summer survey, profiling floats, surface drifters, satellite SST, air/sea flux products, wind products.)

(4) Transports. We will address the large-scale question of how and where AAIW is subducted into the South Pacific subtropical gyre, and the relative transports of AAIW into the Pacific gyre and through Drake Passage into the Atlantic. We will calculate bulk transports (mass, freshwater, salinity, oxygen, temperature) through all sections and especially eastward from upstream of the survey region, eastward downstream into Drake Passage, and northward into the subtropical gyre. We will compare these estimates with those from the many years of repeat ADCP and hydrographic sections in Drake Passage, and with future repeats at 43^{o}S. We will estimate eddy fluxes from surface (satellite) observations, using the hydrographic surveys to estimate their vertical structure and penetration. We will estimate Ekman transports and divergence from winds and relate to the SAF and SAMWF locations. (Winter and summer surveys, satellite SST, Topex/Poseidon altimetry, Quikscat/NCEP/ECMWF/NOGAPS winds, Drake Passage repeat ADCP/XBT sections, Drake Passage repeat hydrography, 43^{o}S repeat hydrography.)

4. Collaborations

(a) U.S. collaborations (some with supplementary letters). (1) R. Fine, C. Sabine and A. Dickson are proposing carbon system and chlorofluorocarbon measurements on our proposed surveys. Their work will be fully integrated with ours. (2) B. Sloyan and M. McCartney (WHOI) and K. Donohue and M. Prater (URI) are proposing time series work in the same region as our hydrographic surveys (Fig. 4a). Their proposal includes three moored profilers, four current meter moorings, a RAFOS float array, PALACE floats at two levels, and two smaller CTD surveys during mooring deployment and recovery. (3) U.S. support for global ocean observing systems, including ARGO and surface drifters, will continue through our proposed survey time. We will deploy 35-45 ARGO floats (1000 meter profiling for T/S) and ~30 surface drifters (with SST and pressure), at the standard global observing density. These data sets will provide profiles and surface properties throughout the broad region, and some measure of surface currents and currents below the SAMW. Deployments for these programs is opportunistic and depends on the existence of shipping in the sampling region. Thus our surveys would be the earliest and possibly only means for complete observing system coverage in this remote region.

We welcome interaction with modelers and with those analyzing SAMW/SAF interactions in other regions around Antarctica. The Princeton GFDL group (Sarmiento/Gnanadeskian and others) in particular is interested in collaboration in evaluating the relative importance of cross-SAF processes versus subtropical inflow/outflow for the SAMW.

(b) International collaborations (supplementary letters). This work was planned in collaboration with (1) Osvaldo Ulloa, Laura Farias, Oscar Pizarro and Wolfgang Schneider of the Programa Regional de Oceanografia Fisica y Clima (PROFC) at U. Concepcion, (2) D. Quadfasel/G. Shaffer at the Danish Center for Earth System Sciences (DCESS), and (3) Howard Freeland (Institute of Ocean Sciences, Sidney, BC, Canada). If this program is funded, we will probably submit a proposal to NSF International Programs for supplementary funding for collaborative work with scientists and students at the U. of Concepcion.

(1) Ulloa and Farias will make the underway pCO_2 and pN_2O observations on our proposed surveys (infrared system of A. Watson for pCO_2; GC built in collaboration with R. Weiss for pN_2O). Hydrographic work associated with our experiment will be carried out by Schneider (43°S, 88°W, 54°S sections, in October 2004). Schneider's graduate student, Rosario Ayuda, will work with PROFC funding for six months at SIO with Talley, who is a member of his thesis committee. His thesis topic is the shallow salinity minimum arising from the low salinity surface water just north of the AAIW formation region. Three or four scientists from U. Concepcion will participate in the cruises.

(2) DCESS, which has cooperated with U. Concepcion, is being disbanded. Quadfasel is moving to U. Hamburg. He will propose new moorings in the AAIW formation region, to begin sometime during our proposed experiment. Moorings (T/S profilers and current meters) currently deployed at 30°S off the Chilean coast may be available for use in the future. S. Hormazabal, a Chilean-nationality graduate student at U. Copenhagen, worked with Talley for four months in 2002 (funding from DCESS). Joint publications are planned from this collaboration. Hormazabal is moving to U. Concepcion after completing his PhD, in late 2003.

(3) Freeland has deployed 6 Canadian ARGO floats in the AAIW formation region using aircraft from Navoceano; all data are available online through ARGO distribution sites). Out-year deployments will be made from our surveys. Freeland and Richard Karsten (Dalhousie) are proposing AAIW studies using the floats and will collaborate with us in general AAIW studies. One scientist from Freeland's group will participate in our winter survey.

(c) Relation of proposed work to climate research programs. Our proposal is to NSF OCE core funding because it is primarily an oceanographic experiment. Our proposed AAIW process experiment does directly address issues in the international CLIVAR implementation plan (http://www.clivar.org), and of specific interest to the newly-formed CLIVAR Southern Ocean panel and the U.S. CLIVAR southern ocean working group.

Results from prior NSF support. (Citations included in section D. References)

OCE-9906776 **Circulation studies of the tropical Indian Ocean at 8.5°N and the Indo-Australian Basin; T. K. Chereskin; 9/1/99-8/31/2002 ($360,000).**

Somewhat paradoxically, the Arabian Sea experiences a rapid heat loss during summer when the maximum surface heat flux is directed into the ocean, due primarily to the export of heat via the Ekman transport. Since the Ekman transport is large, carries the warmest water and reverses seasonally, it can potentially reverse the sign of the net seasonal heat transport of the Arabian Sea and the northern Indian Ocean. The Ekman temperature flux is sensitive to assumptions about the Ekman depth, and therefore both the Ekman depth and transport are important issues for the meridional overturning circulation of the Indian Ocean. The Ekman layer temperature calculated from the 8.5°N section across the Arabian Sea in September 1995 was 1.1°C colder than the surface value (Chereskin et al., 2002). The directly measured ageostrophic flows and their associated heat and freshwater fluxes were incorporated into an inverse model for the Arabian Sea that was used to diagnose the heat and freshwater budgets for 8.5°N (Beal et al., 2003). Other major findings are the deep penetration of the Somali Current and Great Whirl (Beal and Chereskin, 2003) and a gyre-scale reversal in the deep circulation in the Somali Basin between June and September (Beal et al., 2000). The main new result from analysis of the I10/IR6 lines is the energetic mesoscale circulation. Our current view of the Throughflow is that it has 3 primary components: a shallow surface Ekman flow, an advection by nonlinear Throughflow eddies, and a mean geostrophic component (Sprintall et al., 2002).

OPP-9816226 **Collaborative research: Shipboard acoustic Doppler current profiling on R/V Nathaniel B. Palmer and R/V Laurence M. Gould; T. K. Chereskin; 1/1/99-12/31/03 ($328,437).** This award supports collection of underway ADCP data from the Antarctic icebreakers. Chereskin's main responsibility is for ADCP data collected from the L. M. Gould, the supply ship for Palmer Station, Antarctica. To-date, about 80 sections have been made across Drake Passage. These section are being used to determine the mean structure and energetics of the jets of the Antarctic Circumpolar Current and to characterize the mesoscale variability. Participation in an ecosystem study of Deception Island, Antarctica was also supported through this grant (Lenn, et al., 2003, Smith et al., 2003).

OCE-9712209 **Pacific circulation based on WOCE observations; Pacific WOCE Hydrographic programme atlas; L. D. Talley; 11/1/1997-9/30/2002 ($410,000).** This supports Pacific WOCE data analysis and the Pacific WHP Atlas (in progress: http://gyre.ucsd.edu/whp_atlas). Global heat transports (Talley, 1999a, 2003) were computed and decomposed into portions associated with shallow, subducting circulation, intermediate water formation and deep water formation, based on Reid's (1994, 1997) velocities. Global meridional overturning streamfunctions were computed (Talley et al., 2003a). Global freshwater transports have been computed, singling out the role of low salinity intermediate waters such as the AAIW (Talley et al., in preparation). A theoretical paper (Talley, 1999b) provides a simple framework for coupled ocean-atmosphere mid-latitude modes and was motivated by the Antarctic Circumpolar Wave and North Pacific mid-latitude decadal modes. Global mode waters, with some information on intermediate waters, were reviewed, with some new perspectives (Hanawa and Talley, 2001). WOCE data synthesis was reviewed (Talley et al., 2001). The roles of cabbeling and double diffusion in altering the density of the NPIW salinity minimum were explored (Talley and Yun, 2001; Yun and Talley, 2003). South Pacific gyre variability was studied using WOCE XBT data from 30°S (McCarthy et al., 1999), revealing large-scale interannual fluctuations of the thermocline and transport associated with variations in Sverdrup transport.

Other current NSF grants are relevant to the proposed AAIW work – a study of dense shelf water formation through brine rejection in the Okhotsk Sea, contributing to new North Pacific Intermediate Water and a study of Japan Sea winter convection and brine rejection.

References

Banks, H. T., R. A. Wood, J. M. Gregory, T. C. Johns and G. S. Jones, 2000. Are observed decadal changes in intermediate water masses a signature of anthropogenic climate change? *Geophys. Res. Lett*., **27**, 2961-2964.

Beal, L. M. and T. K. Chereskin, 2003: The volume transport of the Somali Current during the 1995 southwest monsoon, *Deep Sea-Res. II*, in press.

Beal, L. M., T. K. Chereskin, H. L. Bryden, and A. Ffield, 2003: Variability of water properties, heat and salt fluxes in the Arabian Sea, between the onset and wane of the 1995 southwest monsoon, *Deep Sea-Res. II,* in press.

Beal, L. M., R. L. Molinari, T. K. Chereskin, and P. E. Robbins, 2000: Reversing bottom circulation in the Somali Basin, *Geophys. Res. Lett.,* **27**, 2565--2568.

Belkin, I. M. and A. L. Gordon, 1996. Southern ocean fronts from the Greenwich meridian to Tasmania. *J. Geophys. Res*., **101**, 3675-3696.

Chereskin, T. K. and M. Trunnell, 1996. Correlation scales, objective mapping, and absolute geostrophic flow in the California Current. *J. Geophys. Res.,* **101**, 22619-22629.

Chereskin, T. K., W. D. Wilson, and L. M. Beal, 2002: The Ekman heat and salt transports at 8deg 30’ N in the Arabian Sea during the 1995 southwest monsoon. *Deep-Sea Research II,* **49**, 1211-1230.

Clarke, R.A., and J.C. Gascard, The formation of Labrador Sea Water. Part I: large-scale processes, *J. Phys. Oceanogr*., ***13***, 1764-1778, 1983.

Davis, R. E., 1998. Preliminary results from directly measuring mid-depth circulation in the tropical and South Pacific. *J. Geophys. Res.,* **103**, 24619-24639.

deSzoeke, R. A., 1987: On the wind-driven circulation of the South Pacific Ocean. *J. Phys. Oceanogr.*, **17**, 613-630.

deSzoeke, R. A. and M. D. Levine, 1981. The advective flux of heat by mean geostrophic motions in the southern ocean. *Deep-Sea Res*., **28**, 1057-1085.

Donohue, K., A., E. Firing and S. Chen, 2001. Absolute geostrophic velocity within the Subantarctic Front in the Pacific Ocean. *J. Geophys. Res.* **106**, 19869-19882.

Egbert, G., D., A. F. Bennett, and M. G. Foreman, 1994. TOPEX/POSEIDON tides estimated using a global inverse model, *J. Geophys. Res*., **99**, 24821-24852.

England, M. H., J. S. Godfrey, A. C. Hirst, M. Tomczak, 1993. The mechanism for Antarctic Intermediate Water renewal in a world ocean model. *J. Phys. Oceanogr.*, **23**, 1553-1560.

Fedorov, A.V. and S. G. Philander, 2001: A stability analysis of tropical ocean-atmosphere interactions: Bridging measurements and theory for El Nino. *J. Clim.,* **14**, 3086-3101.

Fine, R.A., 1993: Circulation of Antarctic intermediate water in the Indian Ocean*, Deep-Sea Res.*, **40,** 2021-2042.

Fine, R.A., K.A. Maillet, K.F. Sullivan, and D. Willey, 2001: Circulation and ventilation flux of the Pacific Ocean. *J. Geophys. Res. Oceans*, **106**, 22159-22178.

Hanawa, K. and L. D. Talley, 2001. Mode Waters. Ocean Circulation and Climate, G. Siedler and J. Church (eds), International Geophysics Series, Academic Press, 373-386.

Hendy, I.L., Kennett, J.P., 2000: Dansgaard-Oeschger cycles and the California Current System: Planktonic foraminiferal response to rapid climate change in Santa Barbara Basin, Ocean Drilling Program hole 893A. *Paleoceanography*, **15**, 30-42.

Huang, R,-X; Qiu, B., 1998: The structure of the wind-driven circulation in the subtropical South Pacific ocean. *J. Phys. Oceangr*., **28**, 1173-1186.

Joyce, T. and C. Corry (eds), Requirements for WOCE Hydrographic Programme Data Reporting. WHPO Publication 90-1 Revision 2,WOCE Report 67/91, Woods Hole, Mass., USA, May 1994.

Joyce, T. and C. Corry (eds), WOCE Operations Manual, Volume 3:The Observational Programme, Section 3.1: WOCE Hydrographic Programme, Part3.1.3: WHP Operations and Methods. WHP Office Report WHPO 91-1, WOCE ReportNo. 68/91, Revision 1, Woods Hole, Mass., USA, November 1994.

Joyce, T. M., 1997. A note on the lateral mixing of water masses. *J. Phys. Oceanogr*., **7**, 626-629.

Joyce T. M., J. R. Luyten, A. Kubryakov, F. B. Bahr, and J. S. Pallant, 1998. Meso-to-large-scale structure of subducting water in the subtropical gyre of the eastern North Atlantic Ocean. *J. Phys. Oceanogr*., **28**, 40-61.

Karsten, R., Jones H. and J. Marshall, 2003: The role of eddy transfer in setting the stratification and transport of a Circumpolar Current. *J. Phys. Oceanogr*., in press.

Karsten R. H. and J. Marshall, 2002. Contructing the residual circulation of the ACC from observations. *J. Phys. Oceanogr*., **32**, 3315-3327.
Kawamura, H., and P. Wu, 1998. Formation mechanism of Japan Sea Proper Water in the flux center off Vladivostok, *J. Geophys. Res., **103***, 21611-21622.

Keeling, R. F. and B. B. Stephens, 2001. Antarctic sea ice and the control of Pleistocene climate instability. Paloceanography, **16**, 112-131 and Paleoceanography, **16**, 330-334.

Lab Sea Group, 1998. The Labrador Sea deep convection experiment*. Bull. Amer. Meteor. Soc*., **79**, 2033-2058.

Legg, S., J. McWilliams, and J. Gao, 1998. Localization of deep ocean convection by a mesoscale eddy, *J. Phys. Oceanogr*., **28**, 944–970.

Lenn, Y.-D., T. K. Chereskin, and R. C. Glatts, 2003. Seasonal to tidal variability in currents, stratification, and backscatter in an Antarctic ecosystem at Deception Island. *Deep-Sea Res.,* submitted.

Luyten, J. R., J. Pedlosky and H. Stommel, 1983: The ventilated thermocline. *J. Phys. Oceanogr.*, **13**, 292-309.

Marshall, J., and F. Schott, 1999. Open-ocean convection: observations, theory, and models. *Rev. Geophys. 37*, 1-64.

McCarthy, M. C. and L. D. Talley, 1999. Three-dimensional potential vorticity structure in the Indian Ocean. *J. Geophys. Res*., **104**, 13251-13267.

McCarthy, M. C., L. D. Talley and D. Roemmich, 2000: Seasonal to interannual variability from XBT and TOPEX/Poseidon data in the South Pacific subtropical gyre. *J. Geophys. Res.,* **105**, 19535-19550.

McCartney, M. S., 1977: Subantarctic Mode Water. A voyage of Discovery, supplement to *Deep-Sea Res.*, M. Angel, (Ed.), 103-119.

McCartney, M. S., 1982: The subtropical circulation of Mode Waters. *J. Mar. Res.*, **40** (suppl.), 427-464.

MEDOC Group, Observations of formation of deep-water in the Mediterranean Sea, 1969, *Nature**, 227**,* 1037-1040, 1970.

Morawitz, W. M.L., P. J. Sutton, P. F. Worcester, B. D. Cornuelle, J. F. Lynch and R. Pawlowicz, 1996. Three-dimensional observations of a deep convective chimney in the Greeland Sea during winter 1988/89. *J. Physical Oceanogr*., **26**, 2316-2343.

Pickart, R. S., D. J. Torres, R. A. Clarke, 2002. Hydrography of the Labrador Sea during active convection.. *Journal of Physical Oceanography.* **32**, 428-457

Polzin, K., L. J. M. Toole and R. W. Schmitt, 1995. Finescale parameterizations of turbulent dissipation. *J. Phys. Oceanogr*., **25**, 306-328.

Polzin, K., J. M. Toole, J. R. Ledwell, R. W. Schmitt, 1997. Spatial variability off turbulent mixing in the abyssal ocean. *Science*, **276**, 93-96.

Rahmstorf, S., 1996. On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Climate Dyn.,* **12**, 799-811.

Reid. J. L., 1973. The shallow salinity minimum of the Pacific Ocean. *Deep-Sea Res*., **20**. 51-68.

Reid, J. L., 1994. On the total geostrophic circulation of the North Atlantic Ocean: Flow patterns, tracers and transports. Progr. Oceanogr., **33**, 1-92.

Reid, J. L. 1997, On the total geostrophic circulation of the Pacific Ocean: Flow patterns, tracers and transports. *Prog. in Oceanogr.,* **39**, 263-352.

Reid, J. L. 2003, On the total geostrophic circulation of the Indian Ocean: Flow patterns, tracers and transports. *Prog. in Oceanogr.,* in press.

Rintoul, S.R., and J.L. Bullister. 1999: A late winter hydrographic section from Tasmania to Antarctica. *Deep-Sea Res.,* **46**, 1417-1454.

Rintoul S. R. and M. H. England, 2002. Ekman transport dominates local air-sea fluxes in driving variability of subantarctic mode water. *J. of Phys. Oceanography*. **32**, 1308-1321.

Rintoul., S. R., C. W. Hughes and D. Olbers, 2001. The Antarcctic Circumpolar Current System. Ocean Circulation and Climate, G. Siedler and J. Church (eds), International Geophysics Series, Academic Press, 271-302.

Rudels, B., D. Quadfasel, H. Friedrich, and M.-N. Houssais, 1989. Greenland Sea convection in the winter of 1987-1988, *J. Geophys. Res., **94***, 3223-3227.

Sabine, C.L. and R.A. Feely, 2001. Comparison of recent Indian Ocean anthropogenic CO2 estimates with a historical approach, *Global Biogeochemical Cycles*, **15**, 31-42.

Sabine, C.L., R.A. Feely, R.M. Key, J.L. Bullister, F.J. Millero, K. Lee, T.-H. Peng, B. Tilbrook, T. Ono, and C.S. Wong, 2002, Distribution of anthropogenic CO2 in the Pacific Ocean, *Global Biogeochem. Cycles*, Submitted.

Schmitz, W. J., 1995. On the interbasin-scale thermohaline circulation. *Rev. Geophys*., 33, **151-174.**

Schott, F., M. Visbeck, U. Send, J. Fischer, L. Stramma, and Y. Desaubies, 1996. Observations of deep convection in the Gulf of Lions, northern Mediterranean, during the winter of 1991/92, *J. Phys. Oceanogr.,* *26*, **505-524.**

Senjyu, T., and H. Sudo, 1993. Water characteristics and circulation of the upper portion of the Japan Sea proper water, *J. Mar. System **4***, 349-362.

Sloyan, B. M. and S. R. Rintoul, 2001a. The southern ocean limb of the global deep overturning circulation. *J. Phys. Oceanogr.,* **31**, 143-173.

Sloyan, B. M. and S. R. Rintoul., 2001b . Circulation, renewal and modification of Antarctic Mode and Intermediate Water. *J. Phys. Oceanogr*., **31**, 1005-1030.

Smith, K. L., R. C. Glatts, R. J. Baldwin, T. K. Chereskin, H. Ruhl, and V. Lagun, 2003. Weather, ice and snow conditions at Deception Island, Antarctica: long time-series photographic monitoring. *Deep-Sea Res*., submitted.

Spall, M. A. and R. S. Pickart, 2001. Where does dense water sink? A subpolar gyre example. *J. Phys. Oceanogr.,* **31**, 810-826.

Speer, K., S. R. Rintoul and B. Sloyan, 2000. The diabatic Deacon cell. J. Phys. Oceanogr., **30**, 3212-3222.

Sprintall, J., S. Wijffels, T. Chereskin, and N. Bray, 2002: The JADE and WOCE I10/IR6 Throughflow sections in the southeast Indian Ocean, Part 2: Velocity and transports. D*eep-Sea Research II*, **49**,1363-1389.

Straneo, F., M. Kawase, and S.C. Riser, 2002. Idealized Models of Slantwise Convection in a Baroclinic Flow, *J. Phys. Oceanogr., **32***, 558–572.

Suga, T. and L. D. Talley, 1995: Antarctic Intermediate Water circulation in the tropical and subtropical South Atlantic. *J. Geophys. Res.,* **100**, 13,441-13,453.

Talley, L. D., 1996. Antarctic Intermediate Water in the South Atlantic. *The South Atlantic: Present and Past Circulation*, ed. Wefer, Berger, Siedler and Webb, springer, 219-238.

Talley, L. D., 1999a: Some aspects of ocean heat transport by the shallow, intermediate and deep overturning circulations. In Mechanisms of Global Climate Change at Millenial Time Scales, Geophys. Mono. Ser., 112, American Geophysical Union, Clark, Webb and Keigwin, (eds). Pp. 1-22.

Talley, L. D., 1999b: Simple coupled midlatitude climate models. *J. Phys. Oceanogr*., **29**, 2016-2037.

Talley, L. D., 2003: Shallow, intermediate and deep overturning components of the global heat budget. *J. Phys. Oceanogr.,* **33**, 530-560.

Talley, L. D., V. Lobanov, V. Ponomarev, A. Salyuk, P. Tishchenko, I. Zhabin and S. Riser, 2003. Deep convection and brine rejection in the Japan Sea. Geophys. Res. Lett., in press.

Talley, L. D., J. L. Reid and P. E. Robbins, 2003a. Data-based meridional overturning streamfunctions for the global ocean. Submitted to J. Clim.

Talley, L. D., D. Stammer and I. Fukumori, 2001: The WOCE Synthesis. Ocean Circulation and Climate, G. Siedler and J. Church (eds), International Geophysics Series, Academic Press, pp. 525-546.

Talley, L. D. and J.-Y. Yun, 2001. The Role of Cabbeling and Double Diffusion in Setting the Density of the North Pacific Intermediate Water Salinity Minimum. *J. Phys. Oceanogr.,* **31**, 1538-1549.

Thomas, L. N., C. M. Lee and P. B. Rhines, 2002. Ekman frontogenesis: generation of negative potential vorticity, subsequent instability, and application to the subpolar front of the Japan/East Sea. *EOS, Transactions AGU*, **83**, 78.

Toggweiler, J. R. and B. Samuels, 1993. Is the magnitude of the deep outflow from the Atlantic Ocean actually governed by southern hemisphere winds? The Global Carbon Cycle, M. Heimann, Ed., Springer, 303-331.

Toole, J. M., 1981. Intrusion characteristics in the Antarctic Polar Front. *J. Phys. Oceanogr*., **11**, 780-793.

Trenberth, K.E., J. M. Caron and D. P. Stepaniak, 2001. The atmospheric energy budget and implications for surface fluxes and ocean heat transports. *Clim. Dyn*., **17**, 259-276.

Tsuchiya, M., 1982. On the Pacific upper-water circulation. *J. Mar. Res*., **40** (Suppl.,), 777-799.

Tsuchiya,M., 1989. Circulation of the Antarctic Intermediate Water in the North Atlantic Ocean. *J. Mar. Res*., **47**, 747-755.

Tsuchiya, M., L.D. Talley and M.S. McCartney, 1994. Water mass distributions in the western Atlantic: a section from South Georgia Island (54S) northward across the equator. *J. Mar. Res*., **52**, 55-81.

Tsuchiya, M. and L.D. Talley, 1998: A Pacific hydrographic section at 88degW: water property distribution. *J. Geophys. Res.,* **103**, 12899-12918.

Wijffels, SE; Toole, JM; Davis, R., 2001. Revisiting the South Pacific subtropical circulation: A synthesis of World Ocean Circulation Experiment observations along 32 degrees S. *J. Geophys. Res.,* **106,** 19481-19513.

Wong, A., P. S., N. L. Bindoff and J. A. Church, 1999. Large-scale freshening of intermediate waters in the Pacific and Indian oceans. Nature, **400**, 440-443.

Yun, J.-Y. and L. D. Talley, 2003. Cabbeling and the density of the North Pacific Intermediate Water quantified by an inverse method. J. Geophys. Res., in press.