Collaborative Proposal - AnSlope: Cross-slope exchanges at the Antarctic Slope Front

I INTRODUCTION

During the last few decades we have refined our knowledge of the stratification and circulation of the Southern Ocean continental shelf and adjacent deep ocean. At the same time, our appreciation of the global and climatic importance of water mass exchanges and the associated heat and freshwater fluxes linking these two regimes has been significantly enhanced. What has eluded us so far, however, is the identification and quantification of key rate-setting control mechanisms. We believe that oceanographic technology, ship support, numerical modeling skills and computational speed have now matured to the point where a program focused on Antarctic cross-slope exchange can substantially improve our understanding of these rates and processes.

The most obvious cross-slope exchange is the export of cold, dense Shelf Water and its mixing and descent into the adjacent deep ocean. This outflow provides the kernel for Antarctic Bottom Water (AABW) formation. Onshore transport of relatively warm and saline deep water and surface water and ice exchange across the shelf break close the mass and thermohaline budgets of the shelf regime. Processes with a wide range of scales (Fig. 1) may be involved in cross-slope exchanges of water masses and their properties. Acting in concert with sea-air-ice interactions, these processes govern the characteristics and quantity of the freezing point Shelf Water and the attributes of the globally important AABW. However, knowing that Shelf Water is a parent of the AABW does not explain how, when, where or in what volume it enters the abyssal ocean.

A frontal region referred to as the Antarctic Slope Front (ASF) occurs near the upper portion of the continental slope around much of the perimeter of Antarctica. It is characterized by relatively large subsurface cross-slope thermohaline and density gradients, and separates a relatively thick layer of low-density Antarctic Surface Water to the south from the denser, relatively warm and salty water of the deep ocean regime. In shelf regions containing relatively denser near-freezing Shelf Water at the bottom, a characteristic V-shaped form develops in the cross-slope density fields. The steep isopycnal slopes associated with the ASF are indicative of the relatively swift westward, surface-intensified baroclinic flow of the Slope Current. There may also be a barotropic component with maximum currents also near the shelf break [*Heywood et al.*, 1998]. The Slope Current is located over the irregular topography of the upper continental slope, which is often incised with deep canyons connected to large reservoirs of Shelf Water inshore. The behavior of the ASF near canyons is poorly understood, as is the influence of the interaction between the front and topography on cross-slope exchanges.

A major climate-related research question can thus be posed: *What is the role of the Antarctic Slope Front and continental slope morphology in the exchanges of mass, heat, and freshwater between the shelf and oceanic regimes, in particular those leading to outflows of dense water into intermediate and deep layers of the adjacent deep basins and world ocean circulation?* Because shelf/deep water interactions around Antarctica are closely tied to global ocean overturning, it is important that we develop the ability to adequately parameterize the relevant processes in global climate models. This **AnSlope** proposal[1], the 4th in a series of projects under the SCOR affiliated iAnZone[2] program, addresses these unresolved issues. We aim to obtain the measurements necessary to understand this important regime, and to facilitate development of models capable of depicting the structure and nature of cross-slope exchanges.

Since we cannot investigate the total length of the ASF (~18,000 km), a site must be selected in which exchange is significant yet typifies processes that are important over the length of the front. The largest inputs of dense Shelf Water into the deep ocean are believed to occur in the western Weddell Sea and the western Ross Sea, making these sites obvious candidates for our study. Of these, we have chosen the Ross Sea (Fig. 2) because of significant logistic and other advantages over a western Weddell Sea site. The

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[1] AnSlope Steering Committee: Glen Gawarkiewicz, Arnold Gordon, Alex Orsi & Laurie Padman.

[2] Previous AnZone projects: Ice Station Weddell (1992; *Gordon et al.* [1993]); AnZone flux experiment (1994; *McPhee et al*. [1996]) and Dovetail (1997; *Muench* [1998]).

western shelf/slope regime of the Ross Sea is generally ice-free during the summer months [*Gloersen et al.*, 1992; http://nsidc.org/NSIDC/CATALOG/ENTRIES/G00799.html], facilitating mooring work, the use of Lagrangian technology, and the rapid sampling of thermohaline and tracer fields at small scales over large areas. The Ross Sea bathymetry is better surveyed than other segments of the continental margins, and its shelf region has a substantial database against which new measurements can be compared. In addition, the Italian Antarctic program in the Ross Sea and the German BRIOS modeling effort (see p. C-10) provide value-added collaborations and data sets. Australian and US work downstream (Adelie coast), and the bracketing WOCE sections provide a larger-scale context within which results from **AnSlope** can be interpreted.

In the present proposal, our primary concern is the export of dense Shelf Water. But this may be viewed as the end product of a sequence of dynamical and thermodynamical processes that begin with the transport of Circumpolar Deep Water (CDW) onto the continental shelf, followed by its modification by mixing, surface fluxes and interaction with the ice shelves. The large-scale circulation pattern of the Ross and Weddell gyres (Fig. 2) is accompanied by net onshore and offshore flows at certain locations of the shelf break. We have chosen to focus on the northwestern Ross Sea, where earlier measurements have revealed the saltiest cross-slope exchanges, including shoreward intrusions of 'warm' modified CDW within our larger survey area (Fig. 2).

II BACKGROUND

[A] Observations

Segments of the Antarctic continental margin that generate new AABW display a V-shaped density structure (Fig. 1) near the ASF [*Gill*, 1973; *Jacobs*, 1991]. This is associated with Shelf Water (near freezing, with S>34.5) being present on its southern side [*Whitworth et al.*, 1998]. Shelf Water that descends across the shelf break encounters and mixes with on-shelf flowing modified CDW (Fig. 3) near the ASF. The influx of modified CDW is particularly well developed in the Ross Sea and may be concentrated along the western flanks of submarine banks [*Hofmann and Klinck*, 1998]. Over the shelf, isopycnals (and isohalines) shoal toward the west, where the bulk of the higher salinity (S>34.80) Shelf Water is found. Significant decadal variability in the volume of this saltiest bottom layer has been reported along the southern Ross Ice Shelf [*Jacobs and Giulivi*, 1998].

The distributions and properties of shelf and bottom water in the western Ross Sea [*Jacobs et al.*, 1970; *Locarnini*, 1994] suggest that Shelf Water tends to follow major outflow paths along the Drygalski and Joides troughs, with a minor path along the Glomar Challenger Trough (Fig. 2). Shelf Water as cold as -1.9 ^{o}C and as salty as 34.85 has been observed at the 550 m sill of the Drygalski Trough, which is slightly deeper than the Joides Trough sill. A year-long record of the current at 500 m (~30 m above the seabed) from an instrument deployed near the sill of Drygalski Trough (Mooring C in Fig. 2) revealed a mean northwest flow ~16 cm/s [*Jaeger et al.*, 1996]. West of Cape Adare, the downslope and northwest influence of this Shelf Water is clearly revealed on bottom maps as a tongue of cold, high-salinity, high-oxygen water [*Gordon and Tchernia*, 1972]. The lowest temperatures (<-0.5 ^{o}C) and highest oxygen concentrations (O_2 > 5.6 ml/l) are found at the base of the continental slope. Fresher Shelf Water (34.5<S <34.8) covers the bottom layer of the eastern Ross Sea continental shelf, and appears in the western Ross Sea between the inflowing modified CDW and the saltiest (S > 34.80) bottom layer.

Closely-spaced synoptic stations over the outer shelf/upper slope of the Ross Sea are rather sparse compared with the number of similar high-quality stations over the continental shelf. West of Pennell Bank, vertical sections with sampling adequate to resolve the gradients of the ASF are available only near 178° E and 172° E (Figs. 3 a, b). The section at 178^{o} E extends offshore from the sill of the Joides Trough along a submarine canyon; the 172^{o} E section is located just west of the Drygalski Trough sill. The ASF is marked by the sharp subsurface density gradient between stations 8-6 (178^{o} E) and 89-88 (172^{o} E), at water depths between 1000 and 1500 m. In both sections a V-shaped density field is centered approximately along the 800-m isobath, and filled with a thickened layer of less dense (<28.05) Antarctic Surface Water. Density gradients associated with this structure render a geostrophic shear between 20 and 40 cm/s in the upper 800 m. The relatively strong westward baroclinic flow of the Slope Current over the upper slope is consistent with the inferred flow patterns on horizontal property maps.

The upstream section (178^{o} E) has relatively warmer and saltier deep water, a more pronounced poleward intrusion of modified CDW across the Slope Front, and CDW at the seabed near station 6. At the bottom on stations 2 and 3, AABW (deep ocean water denser than 28.27) may have been advected from a source region upstream. In contrast, the 172°E section shows newly-formed (CFC-12 > 0.5 pmol/kg) bottom water denser than 28.30 along the entire slope, indicating a probable outflow from the Drygalski Trough.

Stations 9 at 178° E and 91 at 172° E (Fig. 3) appear to illustrate another aspect of bottom water formation, i.e., the mixing of modified deep water with Shelf Water near the continental shelf break [*Gill* 1973; *Foster and Carmack*, 1976]. Since both the Shelf and Deep Water at 172° E are more saline than at 35° W in the Weddell Sea, new AABW in this sector of the Ross Sea is saltier than new AABW in the Weddell Sea. Bottom water with characteristics similar to those measured at station 91 is also produced in the eastern Ross Sea, off the Adelie Coast, and at other locations [*Jacobs et al*., 1970; *Gordon and Tchernia*, 1972; *Rintoul*, 1998; *Jacobs and Georgi*, 1977]. We thus expect that much of what we learn about processes at the ASF and AABW production in the western Ross Sea will be relevant to other regions around Antarctica.

Outflows of new deep and bottom waters from the western continental shelf of the Ross Sea influence the global ocean [*Orsi and Bullister*, 1996]. A northward-flowing western boundary current carries ventilated AABW from the Ross Sea along the Victoria-Oates Land coast, and continues into the Indian sector of the Southern Ocean. This export of new AABW to the Australian-Antarctic Basin may be one reason that region shows higher mean CFC concentration than the two adjacent Antarctic basins [*Orsi et al*., 1999]. Most new AABW sinking over the eastern Ross Sea continental slope is likely to be injected northward along the eastern flank of Pennell and Iselin banks into the abyssal layer of the Southeast Pacific Basin [*Gordon*, 1966], from where its further northward influence may be limited by the large-scale bathymetry.

[B] Dynamics of Cross-Frontal Exchange over the Antarctic Slope

Factors that affect the dynamics of possible exchange processes near the ASF in the proposed study area include the following:

1) *Ambient stratification is relatively weak*. The density difference between the surface mixed layer and 700 m depth over the outer continental shelf and the upper slope is 0.2-0.3 kg/m^3. Thus, topographic control of the flow field is expected to be important away from the front, with mean flows primarily oriented along f/H contours. However, this constraint is broken in regions where there are strong lateral shears [e.g., *Williams et al*., 2000], which may be the case within the ASF. Within the front, however, the cross-frontal density gradients and the horizontal and vertical velocity shear are not well known. There may be geostrophic shears of 20-40 cm/s between the surface and 800 m depth (Fig. 3), as well as a barotropic component that is unknown. Strong lateral shears favor the growth of unstable frontal waves [e.g., *Lozier et al*., 2000].

2) *Rugged topography within the region imposes length scales on possible cross-isobath flows*. The shelf edge topography likely contains many canyons and ridges with characteristic length scales that vary from less than, to comparable to, the internal Rossby radius (~9 km). Flow across regions of strongly curved topography may generate eddies, meanders, and other mesoscale features that could be important dynamical mechanisms for triggering pulses of dense Shelf Water and CDW across the shelf break. The length scales of these topographically related processes might differ from the length scales that we would anticipate due to frontal instabilities or offshore eddy forcing along a straight shelf/slope. We hypothesize that topographic features may also be important in determining specific locations along the shelf break where the offshore flux of dense Shelf Water is large.

3) *Tidal and other high-frequency processes are frequently energetic near the shelf break*. Measured tidal currents at Mooring C (Fig. 2) frequently exceed 40 cm/s. Numerical models suggest that spring tidal currents over the upper slope can exceed 100 cm/s [*Padman et al*., 2001a]. Other motions, including weather-band and near-resonant topographic vorticity waves, and wind-forced near-inertial motion, contribute a significant fraction of the cross-slope velocity variance at the Antarctic shelf break. These processes represent energy sources for benthic stirring, baroclinic motion (and thus internal ocean mixing) and affect the sea-ice cover (see ESR section for more details). However, the primary features of these motions that need to be considered in models are: (a) their short length scales, O(10-100 km); (b) the

energetics of these motions can change with seasonal variability in "mean" flow and stratification, the latter being coupled to the tidal field via nonlinear tidal rectification [*Ou*, *2000*]; and (c) dependence of weather-band and near-inertial currents on atmospheric forcing and sea ice cover. Items (b) and (c) imply a likely strong seasonal variability that will be monitored by moorings and assessed by comparisons of summer and late-winter cruise data.

4) *Augmented cross-slope advection of the dense plume water by nonlinear equation of state effects (thermobaricity and cabbeling*). Most of the cross-slope advection is periodic or episodic; the typical instantaneous cross-slope velocity greatly exceeds the time-averaged value (see point 3, above). These oscillatory flows can, however, produce net cross-slope fluxes through the nonlinearity of the equation of state. As cold, dense Shelf Water is advected downslope, thermobaric effects become significant at some depth over the slope. When this happens, the plume density anomaly relative to the background can continue to increase, so fueling the plume's further descent [*Gill*, 1973]. The potential for this process to occur depends on the typical cross-slope advective length scale, relative to the bottom slope. Cabbeling can occur either as isopycnal mixing at the front, or through diapycnal mixing in the weak stratification above the benthic plume. A cabbeling-stable environment can be pushed to instability by the thermobaric effect with sufficient depression of the water mass [*Foster*, 1994], which might occur even with barotropic across-slope flow [*Padman et al*., 1992].

5) *Other processes likely to be important in the downslope evolution of the dense water.* Some processes are well known, including entrainment of the overlying water [*Price and Baringer, 1994*], the detrainment via bottom Ekman transport [*Baines and Condie*, 1998], layering within the plume [*Gordon,* 1998], which causes it to peel off at different neutral levels. One fast process that has not been explored to any extent is the effect of bottom torque on the vorticity balance, which would cause a rapid thinning of the plume, with possible emergence of multiple cores, as indeed exhibited by the observed plume.

III PROGRAM GOAL AND OBJECTIVES

Our primary goal is to: *identify the principal physical processes governing the transfer of dense Shelf Water into intermediate and deep layers of the adjacent deep ocean, and the compensatory poleward flow of open ocean waters across the shelf break.* The specific objectives are:

[A] Determine the Slope Front's mean structure and the principal scales of variability (spatial from ~1 km to ~100 km, and temporal from tidal to seasonal), and estimate the role of the Front on cross-slope exchanges and mixing of adjacent water masses;

[B] Determine the influence of slope topography (canyons, proximity to a continental boundary, isobath divergence/convergence) on frontal location and outflow of dense Shelf Water;

[C] Establish the role of frontal instabilities, benthic boundary layer transports, tides and other oscillatory processes on cross-slope advection and fluxes; and

[D] Assess the effect of diapycnal mixing (shear-driven and double-diffusive), lateral mixing identified through intrusions, and nonlinearities in the equation of state (thermobaricity and cabbeling) on the rate of descent and fate of outflowing, near-freezing Shelf Water.

IV PROGRAM APPROACH

AnSlope has been structured as follows. A core proposal (this collaborative proposal) requests funding for the components considered central to meeting AnSlope objectives, primarily through acquisition of a set of coordinated measurements over the outer continental shelf and upper slope of the western Ross Sea. The core elements are: moorings; CTD/ADCP and CTD-based microstructure; tracers; and basic tidal modeling. “Enhancement” proposals, to be submitted this year and in 2002, request support for benthic float measurements to be added to the **AnSlope** cruises, and for additional modeling studies. Cruise time will be made available if the observational enhancement is funded. The enhancement elements will be extremely valuable to our overall effort, and the full exploitation of **AnSlope** data sets will depend on the support for enhancement proposals. The Italian CLIMA program in the Ross Sea (page C-10) provides a valued international enhancement for the **AnSlope** observational component. The German BRIOS-2 coupled ice-ocean GCM program provides the large-scale modeling complement to the US **AnSlope** process-driven studies.

[A] Observational Approach

We expect the cross-slope transport of shelf and deep-ocean water mass properties to be highly variable, and almost certainly intermittent, in time and space. Probable major time scales of variability range from tidal to seasonal (and beyond), the latter including the ASF's response to strong seasonality in wind stress and thermohaline forcing, both modulated by changes in ice cover and upper ocean stratification. We propose a 12 to 14 month-long field study, with time series measurements from moored instrumentation for the entire period complemented by high spatial resolution measurements of the thermohaline, tracer, and velocity fields during three cruises, in austral summer 2002/03, late winter 2003, and summer 2003/04. Moorings, and comparisons between late winter and summer cruise data, will provide information on seasonal variability; moorings and analyses of variability within individual cruises will help resolve the higher frequency processes of interest. While our hydrographic survey will cover the western half of the Ross Sea continental margin, specific experiments and monitoring components of our program will take place at the western end of the continental slope, where a deep canyon appears to be a major conduit for Shelf Water export (Fig. 2, 3).

1. **Core Observational Components (see specific 5-page sections for amplification):**

(i) Swath mapping of bathymetry: We will devote the ship time required for such mapping during the XBT survey prior to mooring deployment.

(ii) Meteorology**:** Conditions at the field site during the experiment duration will be obtained from the NCAR/Penn-State 30 km "MM5" (http://www.mmm.ucar.edu/mm5/) global climate prediction model. Measured weather data will be obtained from the ship during the cruises (total of 125 day on site), and from vessels transiting to McMurdo Station. We will request that the US Antarctic vessels contribute weather data directly to the Global Telecommunications System (GTS), which is the gateway for global meteorological data to enter the weather prediction models.

(iii) Moored current meters; Orsi, Whitworth (TAMU), Pillsbury (OSU)*:* One year of direct current and temperature measurements will characterize the horizontal and vertical flow structure of the Antarctic Slope Current, its most important time-varying components from tidal to seasonal scales, and allow an assessment of the eddy components of cross-slope fluxes of heat, freshwater and momentum. The current meter array (Fig. 4) is designed to track the front's location over time. To maximize chances of achieving complete, contemporaneous coverage during the most critical period of intensive measurements (CTD, ADCP, tracers), the array will be deployed prior to the CTD/tracer surveys, and recovered and redeployed at the end of the summer cruise of 2002-03. This combination of data will provide the context for data returned from the year-long deployment. This component addresses objectives [A], [B], and [C].

(iv) CTD/ADCP; Gordon, Jacobs, Visbeck (LDEO): This component, providing high resolution measurements of the stratification and velocity shear fields of the outer shelf, slope and intervening fronts, enables study of vertical coherence of these fields under varied bathymetric conditions; detects exchanges of water masses between the shelf and slope regimes, including plumes; and investigates the role of cabbeling and thermobaric effects. Special attention will be paid to the benthic spatial scales, particularly within the confines of submarine canyons. The combined use of hull-mounted and lowered ADCP allows accurate estimates of the width of frontal jets; provides first order estimates of tidal velocities; obtains full ocean depth velocity profiles and accurate estimates of near-bottom flow. Removal of tides will be done with a regional model and assimilated bottom pressure and currents from the moorings (see "Modeling Approach"). This component addresses objectives [A], [B] and [D].

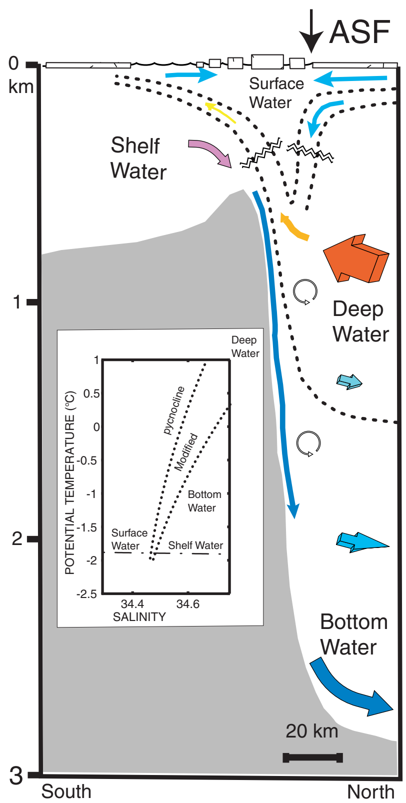

Figure 1: Schematic basin-averaged section of cross-slope exchanges at the Antarctic Slope Front (ASF), principal water mass names are placed on θ–S space (inset). Dotted lines represent neutral density surfaces; dash-doted line is the sea surface freezing point.

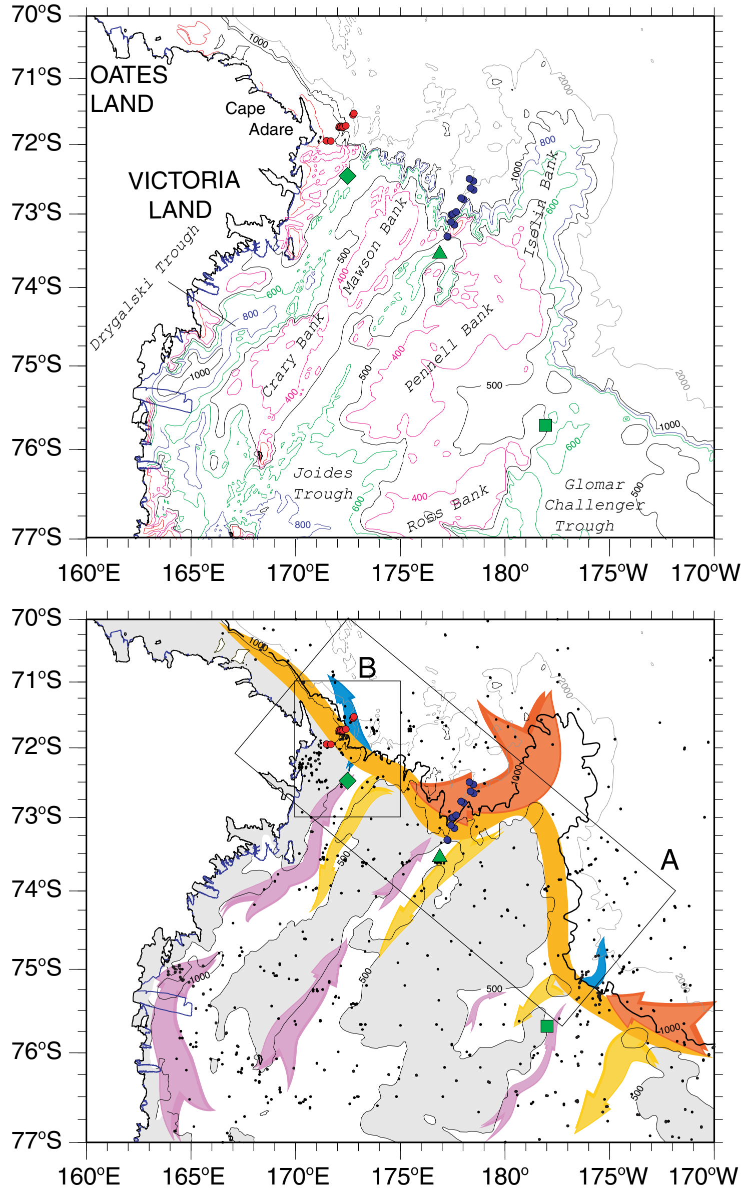

Figure 2: Top: place names. Bottom: arrows represent the schematic flow pattern of Deep Water (red), modified Deep Water (orange along the Front, yellow farther inshore), Shelf Water (purple), and new AABW (blue); box A [B] indicates AnSlope hydrographic/ADCP/tracer [moorings/Lagrangian] elements. Sections located near 172°E [178°E] are indicate by the red [blue] circles. Mooring C, JGOFS/AESOPS-6, and CLIMA site H mooring locations are indicated by the green diamond, triangle, and square, respectively; locations of historical hydrographic data base are shown as black dots. Bathymetry is from GEBCO 1997 CDs.

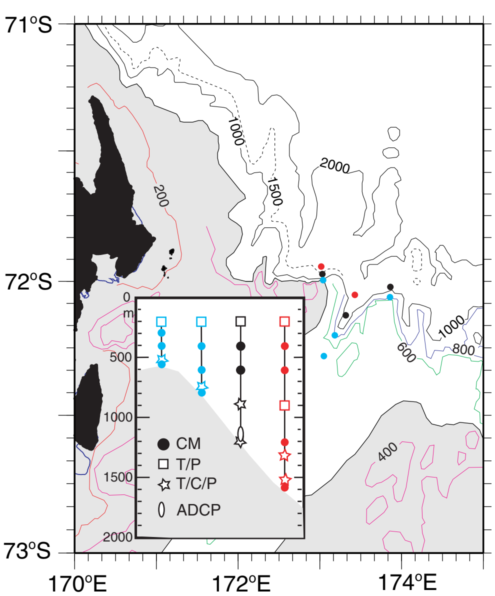

Figure 4: location of current-meter moorings around the Drygalski canyon.

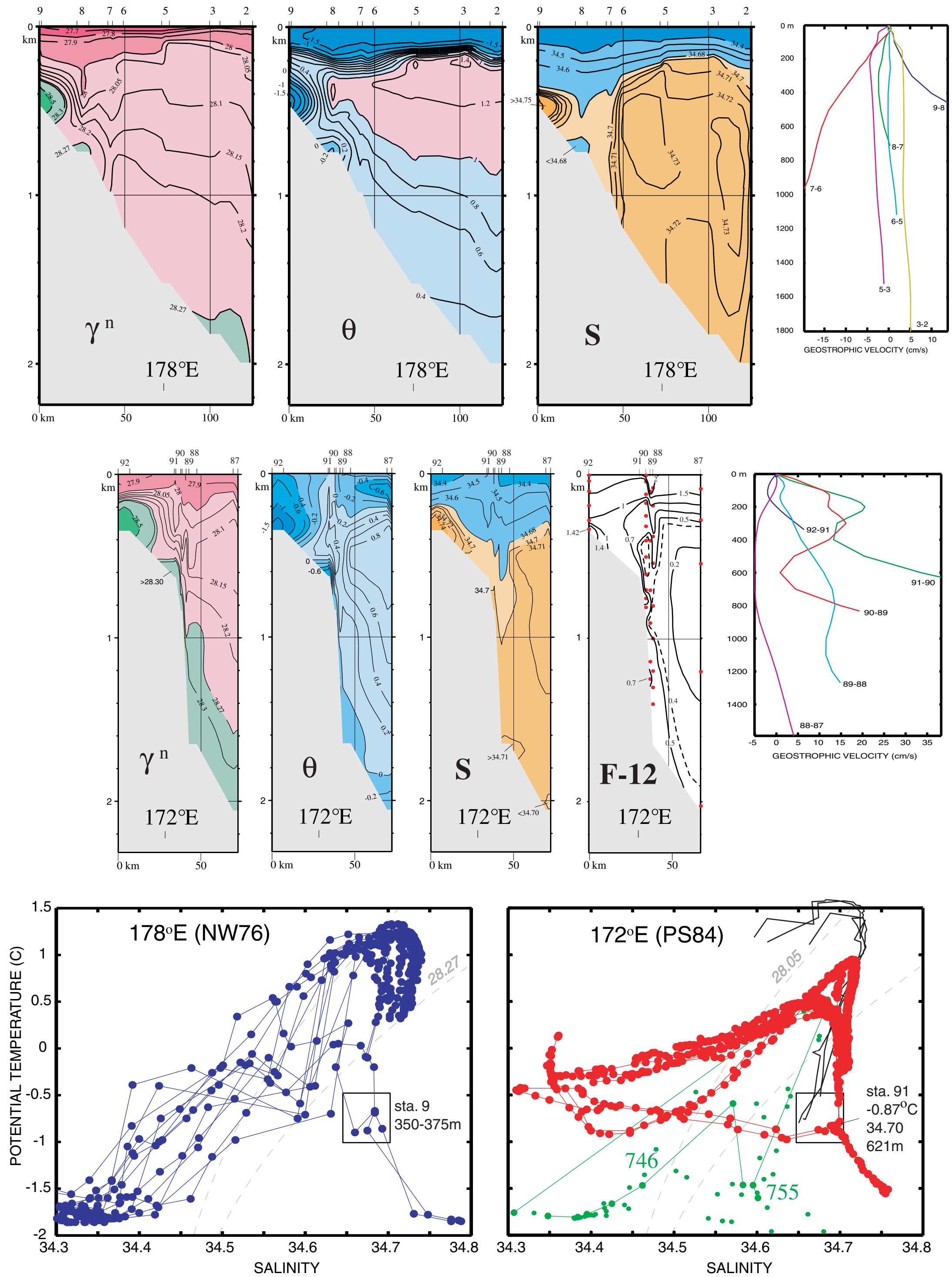

Figure 3: Vertical sections of neutral density (kg/m^3), potential temperature (^{o}C)and salinity for CTD stations (down and up casts) on two slope sections in the western Ross Sea, at 178^{o}E (top) and 172^{o}E (middle). CFC-12 distribution is also shown for the 172^{o}E section. Rightmost panels show geostrophic shear relative to the sea surface for adjacent CTD down casts. Bottom: T-S diagrams for section casts. In the 172^{o}E diagram, green dots (curves) are for stations at a 35^{o}W section (R/V Polarstern 1986) just west of the Filchner Depression; and black curves are for stations in the eastern Ross Sea (sta 82 of Northwind cruise 77 of 1977), off the Adelie Coast (sta 27 of WOCE cruise SR3 of 1992) and the Amery Basin (sta 242 of Conrad cruise 17 of 1974). Gray dashed lines indicate the traces of neutral density surfaces with 28.05 and 28.27 kg/m^3, bounding CDW and MCDW in the Ross Sea.

***(v) Microstructure on CTD; Padman, Muench (ESR)*:** A microstructure package will be mounted on the CTD rosette to obtain direct estimates of the diapycnal diffusivity, K_v, and to identify the primary instability processes driving vertical turbulent fluxes. This instrument has a depth range of ~2000 m and so can sample into the benthic dense plume out to the central slope. This work addresses objectives [A] and [D].

***(vi) CFC and stable isotope tracers; Smethie, Schlosser (LDEO)*:** CFCs, isotopes of oxygen and helium, and tritium will be measured on the Coarse and Fine Scale Resolution surveys. Shelf Water is well ventilated and contains high CFC concentrations and low He-3 concentrations. Opposite characteristics are found in the CDW upwelling across the slope. Sharp contrasts in tracer concentrations and ratios (CFC-113:CFC-11, CFC:tritium) are observed between Shelf Water types that form underneath the Ice Shelf or over the continental shelf. CFC, He-3 and hydrographic data are used to map spreading pathways and to determine exchange and mixing history across the ASF; δO-18 and total helium data will determine the location of the sources of outflowing Shelf Water types; ratios will determine residence times. **AnSlope** CFC measurements will provide critical information on the controlling processes for surface and Shelf Water chemistry, such as the extent to which they are in equilibrium with the atmosphere. This component addresses objectives [A], [B] and [D].

2. Observational Enhancement Component:

Benthic floats; Hebert, Prater (URI): Acoustically-tracked bottom-following floats will be deployed to examine the Lagrangian pathways, evolution and dynamics of the dense water across the slope. Aided by an acoustic altimeter, the floats remain within a predetermined height above the bottom (approx. 30 m) and within the dense water plume by adjusting their volume (density), which is recorded. Thus, the temporal (Lagrangian) evolution of the temperature, salinity and density of the dense water will be known. During the first summer cruise, 50 floats will be parked on the bottom near the shallowest mooring. The floats will self-release at one-week intervals, and all will surface during the austral summer season. These Lagrangian data will complement the Eulerian measurements of the moorings and the integrative-Lagrangian results of the natural tracer measurements by providing a new perspective of the dense water plume dynamics. The benthic floats will address objectives [B], [C] and [D].

3. Field Schedule, 3 Cruises (seasons are "austral"):

***Summer 2002/03 (50 day cruise)*:**

Rapid Survey: Several XBT and hull ADCP transects (no stations) are made within Box B (Fig. 2) to provide a first look at the stratification and shear. XBTs will be T-7 (depth range ~750 m) in the ASF and T-5 (~1500 m) over deeper segments of the slope. Swath mapping of the canyon area (Fig. 4) is conducted to guide mooring site selection. The short term mooring array is deployed.

Coarse Scale (10 km spacing) Survey: An array of CTD/ADCP/tracer stations is obtained at nominally 10 km spacing in Box A (Fig. 2), resolving stratification and shear features over a wider range of bathymetric forms. The array extends east to CLIMA site H (Fig. 2) and just west of the mooring array.

Fine Scale (5-10 km spacing) Survey: An array of CTD/ADCP/tracer stations (Fig. 6) is obtained at spacing near the Rossby radius within the confines and adjacent environs of the submarine canyon where the **AnSlope** moorings were deployed (Box B, Fig. 2). The short-term moorings are recovered and the year-long moorings are deployed.

***Winter Conditions 2003 (65 day cruise)*:**

The CTD/ADCP/tracer station grid is reoccupied to provide a view of the Slope Front when the region is covered by sea ice and the seasonally integrated buoyancy forcing has peaked. Seasonal changes in the ASF thermohaline characteristics and Slope Current transports are expected as the shelf regime responds to strong winter forcing from surface buoyancy fluxes and wind stress. Observations of the ASF after the integrated effect of winter has occurred, but before the summer stratification sets in, have never been made in this sector. Access by the *NB Palmer* should be feasible at least by October, i.e., prior to the expected establishment of summer stratification.

Summer 2003/04 (50 day cruise):

The CTD/ADCP (no tracers) grid similar to that carried out in 2002/03 is repeated, first the fine resolution survey (Box B) then the coarse survey (Box A). Moorings are recovered.

[B] Modeling Approach

The environment presents a challenging modeling task. While the ultimate goal for Antarctic frontal modeling is an integrated prognostic model capable of predicting cross-slope fluxes of heat, salt, and momentum around Antarctica, the prudent approach to the problem is to initially break the effort into manageable components that can be tested and refined in comparisons with the AnSlope data set. The organization of the modeling component is as follows. Basic modeling of tides is included in this core proposal (Padman). Process modeling of cross-frontal exchange and downslope descent of dense water is covered by an enhancement proposal (Ou) to be submitted concurrently with this core proposal. Mesoscale modeling of frontal dynamics including frontal instabilities and interactions with topography will be covered by a proposal to be submitted in June 2002 (Gawarkiewicz and Chapman, WHOI). Also in June 2002, a proposal will be submitted to model vertical structure (boundary layer dynamics and baroclinicity) of tidal currents, and vorticity wave (diurnal tidal, and weather-band) sensitivity to background stratification and mean flow (Padman, ESR). The one-year delay in the WHOI and main ESR modeling efforts is due to other grant commitments for these investigators. The German BRIOS-2 large-scale model (see p. C-10) will provide boundary conditions for the process models and a test environment for flux parameterizations developed from the US AnSlope process models.

The rationale for this organization of modeling effort is explained in the cover letter. We have taken the approach, in this resubmission of **AnSlope**, that acquisition and interpretation of data (guided by existing theoretical knowledge and numerical capabilities) are the primary tools for a study of cross-slope exchange processes. We adopt this view since so few data presently exist to clearly guide modeling efforts, which thus will be offered as enhancement proposals that can take advantage of **AnSlope** data. The only exception is the tidal modeling, which is included in the core proposal because tides are expected to be very energetic and spatially complex near the shelf break, and so must be removed to reveal the critical non-tidal signals in the hull-mounted and lowered ADCP records across the ASF. We regard all other modeling components as essential elements in the full exploitation of the **AnSlope** data. However, there is only a limited scope for feedback from the proposed modeling to field operations, and so we provide other modeling as enhancement proposals. There are three fundamental roles for the modeling component of this work.

(i) Tide modeling: Data assimilation tidal modeling will be used to improve the description of tides along the entire shelf break of the Ross Sea, but specifically in the **AnSlope** region. Non-assimilative, depth-integrated models perform poorly at modeling the amplitude and phase variability of the dominant diurnal tides [*Robertson et al*., 1998; *Padman and Kottmeier*, 2000]. Semidiurnal tides are complicated by proximity to the critical latitude for M_2 (~74.5^o S) so that wind-forced near-inertial motion and M_2 tides cannot be separated in data. Improving our model skill, for the primary goal of tidal current removal from current meter and ADCP/LADCP records, will be achieved by assimilation of the mooring array data (bottom pressure and currents) and the hull-mounted ADCP. More details are provided in ESR's 5-page section. Work funded by this core proposal will predict only the barotropic component of tides, but an estimate of baroclinic contamination can be made from the data, and vertical variation of tidal currents will be addressed in an enhancement modeling proposal to be submitted in 2002 (Padman).

(ii) Refinement of Frontal Models: **AnSlope** observations will provide fundamental characteristics of the ASF that will be crucial to successful modeling of cross-slope exchange processes. The observed width of the front, maximum along-slope currents, mean vertical velocity shears, and other frontal quantities will define the parameter space to be examined in the modeling studies. Among the important questions to resolve are: the seasonality of the cross-slope fluxes and how it relates to possible seasonal changes in the ASF structure; the role of Slope Current variability in forcing pulses of dense shelf water across the shelfbreak; the importance of Ekman dynamics in the cross-slope transport of dense water; and the role of high-frequency processes (tidal, near-inertial, weather-band and instability-band) in modulating mixing of the dense shelf plume and the overlying stratified waters including the seasonal pycnocline.

(iii) Testing process model results in large-scale models: The German BRIOS-2 large-scale model (see V-B below) will provide boundary conditions for the US process-oriented modeling efforts, and will provide a modeling environment for testing flux parameterizations inspired by US **AnSlope** measurements and modeling. First, the various process model efforts will be brought together into one model that is effective at predicting cross-slope exchange rates in the **AnSlope** study area. Second, essential features of the combined model will be identified and parameterized for testing in BRIOS-2. Finally, BRIOS-2 can be used to identify other potential sites of significant cross-slope exchange around Antarctica, and provide feedback to the process modeling effort.

V INTERNATIONAL LINKS

[A] Italy: The multidisciplinary Italian CLIMA program has studied various aspects of the Ross Sea continental shelf for the past decade, with a strong focus on the Terra Nova Bay (TNB) region [*Spezie and Manzella,* 1999]. Future plans include measurements and modeling of outflow processes on the Antarctic continental slope. In 1997-98 current meter moorings were deployed in TNB and at site H (Fig. 2) and mesoscale surveys carried out there and near Cape Adare. Hydrographic measurements were made in TNB and in the two shelf-break areas noted above in Jan/Feb 2001, along with tracer sampling by a collaborating US group (P. Schlosser and W. Smethie, LDEO). All the moorings were recovered and redeployed. In 2001-02 the moorings will be turned around, and in 2002-04 continued work is anticipated in conjunction with **AnSlope**. CLIMA will host the 2nd Int'l Conference on Oceanography of the Ross Sea in October 2001, along with the 7th SCOR/iAnZone meeting, both providing venues for international coordination of Ross Sea research. The lead PI for the CLIMA Program is G. Spezie, IUN, Naples.

[B] GERMANY: Knowledge of the basin-scale fields including the iceshelf cavities enhances our understanding of the mesoscale processes along the Antarctic continental slope. A coupled ice-ocean GCM focused on the Weddell Sea (BRIOS-2, *Timmermann et al*. [2001]) with zonal and meridional resolutions of 1.5^{o} and 1.5cos(latitude)° has been applied to the circumpolar domain extending from 82^{o} S to 50^{o} S (http://e-net.awi-bremerhaven.de/Modelling/BRIOS/). The model uses *Smith and Sandwell* [1997] bottom topography, SAC (Special Analysis Center, Hamburg) hydrographic data for initialization and boundary restoring, and NCEP/ECMWF products for atmospheric forcing. Preliminary results reveal that the model reproduces the Southern Ocean gyre circulation, water mass characteristics, sea ice distribution, and the inter- annual variability of each. BRIOS will provide boundary conditions for the US **AnSlope** process models and serve as a test-bed for parameterizations of cross-slope exchanges in large-scale models. German studies will focus on the Ross Gyre, its interaction with the ACC, influence on the modification of Shelf Water, impact on deep and bottom water formation, and sensitivity to short-term perturbations. The lead PI in this work is H. Hellmer, Alfred-Wegener-Institut, Bremerhaven.

VI PROGRAM AND DATA MANAGEMENT

Program organization and management of **AnSlope** will be overseen by a 4-member steering committee, (footnote 1, p. 1). A. Gordon is the primary point of contact. LDEO will serve as lead institution, provide coordination of field work, and maintain a web site for program coordination and dissemination of data and results. **AnSlope** is the 4th project of the SCOR affiliated **iAnZone** program (see footnote 2, p. 1; **iAnZone** website: http://www.ldeo.columbia.edu/physocean/ianzone/). A workshop will be held at LDEO in the summer 2004, about 5 months after the end of **AnSlope**'s field phase. The objective of this workshop is to coordinate all preliminary analyses of **AnSlope** measurements to be presented at the Western AGU Meeting in San Francisco in December 2004. Both meetings will offer **AnSlope** investigators with the opportunity to collectively review the observational and model data and coordinate the final synthesis phase of the program. Post cruise coordination at the international level will be pursued as part of **iAnZone**, at a meeting tentatively planned for Hobart in 2004 or early 2005.

VII PROGRAM COMPONENTS - OBSERVATIONAL

[A] Moored Current Meter Array (A. Orsi, T. Whitworth, TAMU)

This component of **AnSlope** will make the first long-term (O(1 year)) current measurements of the Slope Current with an array of moored current meters designed to characterize its mean spatial structure and dominant scales of variability. The proposed will:

- monitor the mesoscale variability of the Slope Current during the fine-scale CTD survey;
- provide estimates of the barotropic velocity as the constant of integration for the thermal wind component obtained from CTD measurements of the density field;
- provide estimates of the mean velocity and variability of the Slope Current;
- provide estimates of the mean and eddy fluxes of the shelf and deep ocean water masses.

The few existing synoptic sections across the Antarctic Slope Front suggest that it is a very narrow feature locked to the bathymetry. Typically, it is a sharp subsurface temperature gradient found near the 1000-m to 1500-m isobaths, but there has never been a systematic survey of the Front to determine its spatial and temporal scales. We have no idea what the Front might look like a few kilometers upstream or downstream of a section, or at the same section in the following week. The fine-scale CTD survey proposed here will provide good short-term estimates of the Front's width and location relative to the underlying bathymetry, but because even a rapid survey takes several days to conduct, this picture will be quasi-synoptic at best — a collection of snapshots of the Front and its associated current. Contemporaneous velocity and temperature measurements from the moored array will put individual CTD crossings of the Front into temporal context.

Until recently, the only estimates of the speeds within the Front have been indirect, based on the density field and a presumed level of known motion. Such estimates, in a region known to be highly barotropic, are subject to large uncertainties. We know of two crossings of the Front during the World Ocean Circulation Experiment (WOCE) where geostrophic speeds have been referenced to contemporaneous hull-mounted ADCP current measurements. Near 17° W the total transport associated with the Slope Current is about 13 Sv, between stations 3 and 9 in WOCE line A23 [*Heywood, et al.*, 1998], a four-fold increase over the baroclinic transport of 3 Sv relative to the bottom. At 53° E, the Slope Current has a relative transport of 1.8 Sv and an adjusted transport of 15 Sv between WOCE S4I stations 35 and 38 [*Orsi et al.*, 1998]. These data suggest that the transport may be at least four times as great as indicated by indirect estimates. The current meters will provide the integration constants needed to convert relative geostrophic currents into absolute currents during the fine-scale CTD surveys, and will continue to characterize the current at coarser resolution (the mooring separation distance) for a year. Although the moored array will not be able to detect changes in the Front's width with the same precision as the CTD surveys, the continuous current and temperature measurements will allow us to detect temporal differences in the character of the front and in its velocity structure that ultimately can be related to differences in seasonal stratification, ice cover, and winds.

We have no direct long-term information about the lateral meandering scale of the Slope Current, but it would be extraordinary if it didn't meander at all. The shelfbreak jet in the Middle Atlantic Bight is similar in width to the Slope Current and varies in position on the order of 10-20 km [*Houghton et al.*, 1988]. A number of current meters have been placed in the Antarctic Coastal Current (which we would call the Slope Current) near 20° W in the southeastern Weddell Sea. *Fahrbach et al.* [1994] show several temperature records from moorings on the shelf and slope, which reveal large fluctuations that last from a few days to a few weeks. To us these records suggest a meandering current that alternately exposes the instruments to cold water from the shelf region to the south and warmer Modified Circumpolar Deep Water (MCDW) from the north. Year-long current measurements from the moored array will allow an estimate of the extent and frequency of cross-slope excursions of the Antarctic Slope Front, enabling us to determine how "locked" it is to a particular isobath.

An inferred time-scale for the meandering of the Slope Front was measured accidentally at a bottom-moored pressure recorder on the 1000-m isobath of the continental slope near the Greenwich Meridian. Fig. 5 shows a temperature plot from this instrument. As expected at this location, the record is dominated by temperatures characteristic of the local MCDW; during three quarters of the record length temperatures were greater than 0°C and the overall mean was 0.12°C. However, there are several cold episodes (8% of record) with temperatures well below -1°C, seven of which lasted for at least a week and one for a whole month. The mooring measured conductivity as well as temperature, and the inset shows the scatter plot of the record's individual θ-S pairs, along with traces of three CTD stations occupied during the WOCE ANTX expedition about 60 km from the pressure gauge. The θ-S plots demonstrate that the cold events do not represent the descent of new Antarctic Bottom Water (indeed, there is no dense Shelf Water in this sector of the Weddell Sea to form bottom water), but Antarctic Surface Water. The likeliest explanation for surface water reaching a depth of 1000 m is a northward excursion of the Slope Front, which carries a thick layer of surface water farther offshore than usual. The time-scales and lateral extent of Antarctic Slope Front meanders will provide information about potential forcing mechanisms for the mesoscale motions (e.g. wind forcing, topographic waves). Synoptic wind data will be available from the ship, McMurdo Station and Automated Weather Stations over the study area, the European Centre for Medium-Range Weather Forecasts and The Australian Bureau of Meteorology.

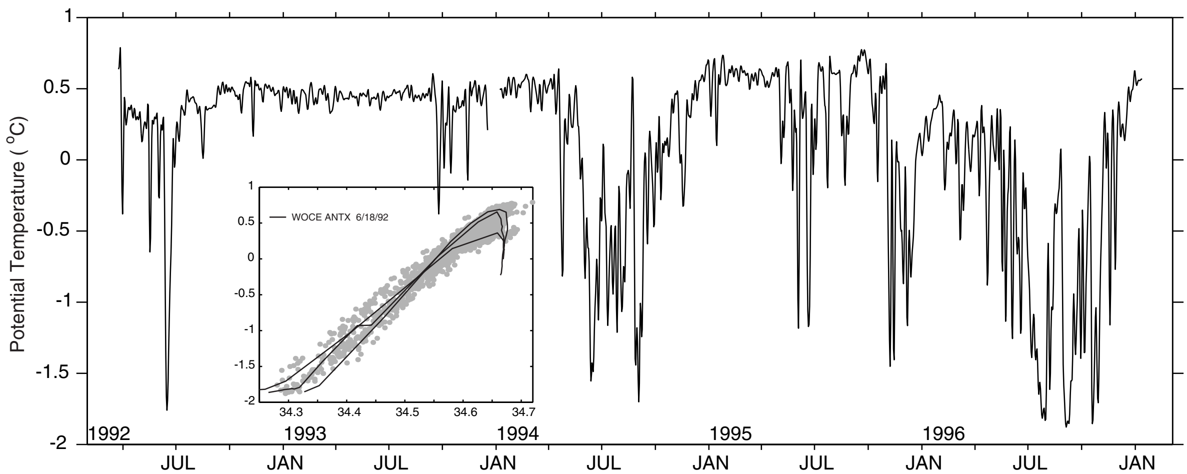

Figure 5: Long-term record of potential temperature from a Bottom Pressure Recorder (BPR) deployed at the 1000-m isobath of the continental slope off SANAE station; the inset shows the record's potential temperature vs salinity scatter, and three traces of CTD stations (WOCEANTX) occupied 60 km from the BPR.

Characterizing the Current's mesoscale-to-seasonal variability and monitoring the water mass stratification at the Front are essential to estimate instability mechanisms that may lead to cross-slope exchanges and near-boundary convection. Long-term measurements at the Mid Atlantic Bight shelf-break jet [*Aikman et al.*, 1988] revealed that seasonal fluctuations in the Front's density gradient and overall current velocities were sensitive to changes in the strength of the wind forcing. Similar fluctuations were also noticed in the surface intensification of the mean westward flow. At the Antarctic Slope Front we still need to determine what mechanisms make the Slope Current unstable, and how often that happens.

As shown in the background section, there is a thin lens of Shelf Water lying near the shelf break of the western Ross Sea, e.g. at the bottom 100 m of station 9 in the 178° E section. We do not know how this Shelf Water traverses the continental slope to enter the deep ocean offshore as new Antarctic Bottom Water, or how it mixes with less dense waters above during its descent. It is likely that the sharp horizontal density gradient of the Antarctic Slope Front and its associated westward current play a role in the export of Shelf Water. When the Shelf Water extends northward far enough to be adjacent to the Front, there is probably a steady infusion of Shelf Water into the westward flow, where it subsequently sinks with modified characteristics. Another possible outflow mechanism is more episodic: an offshore excursion of the Slope Front might permit a direct flow of the resident Shelf Water onto deeper portions of the continental slope, potentially introducing a large volume of Shelf Water to the open ocean in one event. Conversely, periods during which the Front is near the shelf break might block the outflow of Shelf Water, but enhance the inflow of modified Deep Water onto the shelf. Frontal fluctuations may be more pronounced and longer-lasting across canyons, which may be directly connected to the voluminous inshore reservoirs of Shelf Water.

Temporal variability in the Slope Current velocity structure may have a significant influence on the production of new Antarctic Bottom Water. The narrow, highly sheared thermohaline gradients at the "V" are likely sites for vigorous mixing of all ingredients required to form deep and bottom waters. Preliminary analysis of yearlong current measurements in the benthic layer just downstream from the Filchner Trough (FRISP/ROPEX, [*Fahrbach*, 2000]) shows variability over a broad range of time-scales, but the lack of concurrent measurements in the overlying Antarctic Slope Front precludes relating the two. Contemporaneous long-term current and thermohaline measurements of both the Antarctic Slope Front velocity structure and the benthic layer offshore of the Drygalski Trough will provide such opportunity.

There are a number of statistical parameters that can be estimated from long-term current and temperature records. We anticipate providing estimates of the eddy heat and momentum fluxes across the Antarctic Slope Front on a shear coordinate frame to better isolate frontal meanders from true mesoscale rings, determining the distribution of eddy kinetic and potential energy at the slope Current, and determining the power spectra of low pass data.

a) Array design

The array we propose is shown in Fig. 4. It consists of nine moorings arranged in three groups. The primary array of four moorings is located in the offshore extension of Drygalski Trough, extending from depths less than 600 m to the 1600-m isobath on the continental slope. This array is centered on the 1200-m isobath, where historical data suggest the Antarctic Slope Front is usually located. These moorings are in the place we consider the likeliest to be in the outflow path of descending Shelf Water mixtures, and will also provide the best resolution for estimating the location of the front. The eastern two-mooring array will provide upstream meander-scale information on the front. It will provide current, temperature and salinity data on the waters carried within the Slope Front upstream of the primary array. The western three-mooring array, in addition to providing meander-scale data, constitutes the "after outflow" picture of the Antarctic Slope Front. The downstream temperature, salinity and velocity characteristics of any outflow of dense water from Drygalski Trough will be detected here.

Moorings are located along the 800-m, 1200-m and 1600-m isobaths, which in this region, are less than 10 km apart—close enough to resolve the expected width of the Antarctic Slope Front. The three groups of mooring are separated about 15 to 20 km from each other, allowing the resolution of meander scales between 15 and 60 km.

b) Instrumentation

The current meters proposed are Aanderaa RCM4s with solid state recording devices. Each of the 28 Aanderaas will measure current speed, direction and temperature at half-hour intervals. Previous deployments of Aanderaas equipped with conductivity sensors have revealed a flaw in the sensor fitting that has resulted in instrument flooding and data loss. Conductivity data will be recorded on Seabird MicroCat T/C/P recorders. Additional MicroCat T/P recorders will be used to provide increased resolution of the thermal field.

The most pronounced density and thermohaline gradients in the Antarctic Slope Front are between 400 and 600 m (see Fig. 3), so all moorings will be instrumented with current meters at these depths. Likewise, all moorings will monitor currents, temperature and conductivity as close to the bottom as possible. The 1200-m mooring at the primary array will be equipped with a bottom-mounted, upward-looking ADCP to provide high-resolution information on the velocity structure of the benthic layer.

Additional instruments will improve the vertical resolution along the expected path of outflow of new deep waters. The two deepest moorings located at 1600 m in the principal and western arrays, will monitor currents and temperature from a current meter at 1200 m, and temperature from a T/P recorder at 800 m. All 1200-m and 1600-m moorings will have T/C/P recorders at 900 m and 1400 m.

To characterize the near surface circulation during the short-term deployment, all four moorings in the principal array will measure temperature from P/T recorders at 200 m. These instruments will be placed above a weak line to minimize the potential for damage from icebergs.

A separate Bottom Pressure Recorder (BPR) will be deployed for the duration of the deployment cruise at about 550 m near the Drygalski sill, to provide high-quality tide data.

c) Timing

Past experience has shown that the most valuable data provided by moored instruments is when other measurements (e.g. CTD grids) are being made—specifically during deployment and recovery cruises. Long-term moorings in the Antarctic are, however, always risky. Even careful planning and the unsurpassed record of the OSU buoy group for high-latitude mooring work cannot eliminate the possibility of multiple instrument failures or iceberg collisions. We have chosen to recover the array at the end of the deployment cruise, extract the data, and redeploy it for subsequent recovery the following austral summer. The recovery and redeployment insures that data return will be high for the contemporaneous CTD and current measurements. Analysis of each data set will be complemented by the other, and allow better planning for the CTD surveys on the winter cruise and the CTD work scheduled for the mooring recovery cruise.

d) Results of Prior NSF Support

Deep Western Boundary Currents in the Southwestern Pacific Ocean

co-PIs: T. Whitworth III and W. D. Nowlin, Jr.

OCE-8917338, $700,000 (4/1/90-3/31/96)

Summary: The objective of this study was to characterize the mean flow and spatial and temporal variability of the deep western boundary current in the South Pacific that carries Antarctic waters northward to supply the abyssal layers of the entire Pacific. The analysis involved CTD and tracer data from three cruises and time series from an array of 60 current meters on 20 moorings for a 20-month period. Results are presented in:

Whitworth, T., B. A. Warren, W. D. Nowlin, Jr., S. B. Rutz, R. D. Pillsbury, and M. I. Moore, 1999, On the deep western-boundary current in the Southwest Pacific Basin, Prog. In Oceanogr. 43, 1-54.

WOCE-Synthesis Southern Ocean Atlas

co-PIs: A. H. Orsi and T. Whitworth III

OCE 9811481, $400,000 (11/1/98-10/31/2002)

Summary: This ongoing project will present the results of all WOCE cruises in the Southern Ocean, and create a quality-controlled Southern Ocean data set of historical stations to characterize the large-scale circulation in terms of tracer patterns. A fully interactive online atlas will be available at the end of this project. Vertical sections; isopycnal, core, level, and bottom maps; dynamic topographies; mean property profiles and other climatological representations of the data are among the atlas data products. Preliminary results are presented in:

Whitworth, T., and A. H. Orsi, 2000, The WOCE Southern Ocean Database, 2000 U.S. WOCE Implementation Report Number 12, U.S. WOCE Office, 11-12.

[B] Moored Current Meter Array (D. Pillsbury, OSU)

a) Work Statement

The field work proposed here is part of a group proposal involving Oregon State University, Lamont-Doherty, and Texas A&M University. The following is a short description of the mooring component which will be carried out by the OSU Buoy Group as part of the Anslope Program.

The deployment plan, description of the intended logistics including supporting international activities, scientific responsibilities, timetable, figures and references are in the attached proposals by principal investigators Arnold Gordon and Tom Whitworth.

Oregon State University will be responsible for the design, construction, installation, and recovery of the current meter moorings proposed for use in this study. OSU will calibrate the current meters before and after installation, prepare the acoustic releases, construct the moorings, and ship all of the equipment to and from the experiment. OSU will recover the moorings, reduce the data using all pre-and post calibrations, produce data report to be distributed via CDrom. OSU will submit the data to the National Oceanographic Data Center and will also archive the data locally.

The AnSlope experiment requires 9 current meter moorings equipped with a total of 29 current meters. Included on the moorings will be six SeaBird temperature/pressure recorders and 13 conductivity/temperature/pressure recorders. An ADCP will be on one of the moorings and a bottom pressure recorder mooring will be provided. All moorings will be deployed for the duration of the first cruise, recovered at the end of that cruise and redeployed for about 12 months. Initial deployment is scheduled for the Antarctic field season of 2002 - 2003, with final recovery 12 months later.

b) Results from Prior NSF Support

R. Dale Pillsbury

Project Title: "The Samoan Passage Experiment - Abyssal Transport from the South Pacific to the North Pacific Ocean: WOCE Moored Array PCM11"

NSF Award: OCE-9496015

OSU Amount as subcontracts from Dan Rudnick at University of Washington and Scripps: $467,990

Period of Support January 1, 1992 - March 31, 1995

The Samoan Passage experiment was designed to determine the northward transport of abyssal water through the Samoan Passage (10°S, 170°W). Six subsurface moorings were deployed in September 1992 and recovered in February 1994. A total of 27 current meters were attached, each measuring horizontal current and temperature, with the upper two meters on each mooring measuring pressure. All instrumentation was recovered. With some minor exceptions the data return was excellent.

The data have been reduced and a data report produced. The data are at the WOCE Current Meter Data Assembly Center and have been transmitted to NODC.

Project Title: "Transport and Variability of the Deep Western Boundary Systems at 20°S in the Indian Ocean"

NSF Award: OCE-9413177

Amount: $1,525,000

Period of Support: June 1, 1994 - May 31, 1999

This experiment is the last in a planned series of three to determine the structure and variability of deep western boundary flows in the Atlantic, Pacific and Indian Oceans. The boundary flows in the southern hemisphere of each ocean basin were chosen for study because the source for these flows is nearby producing good signals. Additional scientific goals were site and basin dependent. All three experiments concentrate on the temporal and spatial variability of the deep western boundary currents.

Data reports have been completed for the first two of the experiments, and the data are in the database at the WOCE Current Meter Data Assembly Center.

The third experiment in the Indian Ocean has been recovered. Ninteen of the twenty moorings installed were recovered during a cruise in January-February 1997. Current meter processing is complete and data have been supplied to the participating investigators. Public release of these data will adhere to WOCE guidelines.

[C] CTD/ADCP (A. Gordon, S. Jacobs, M. Visbeck - LDEO)

a) Introduction

The CTD/ADCP component of **AnSlope** will provide high resolution synoptic snapshots of the temperature, salinity (density), oxygen and velocity fields over the varied bottom morphology of the outer continental shelf and slope of the Ross Sea. Observations using XBTs, CTD-O_2 with a lowered ADCP and hull-mounted ADCP will be made during two (50 day) austral summer cruises [2002/03 and 2003/04] and during the 65 day October and November 2003 cruise when the winter conditions will be measured.

The objectives of the CTD/ADCP program are to:

- Resolve the summer and winter water mass distributions and their spatial and seasonal scales of variability, including the form and position of the ASF over the outer shelf and slope of the western Ross Sea;
- Study coherence of the thermohaline field to the vertical and lateral shear under varied conditions of bottom topography and density stratification ;
- Identify the position and characteristics of the primary mass, heat, freshwater and dissolved oxygen exchanges between the shelf and slope regimes, including surface water, dense plumes and on-shelf intrusions;
- Investigate the role of cabbeling and thermobaric effects on vertical and cross frontal exchange processes;
- Provide the environmental framework for the associated tracer, mooring, drifter and modeling **AnSlope** components.

The CTD/LADCP component contributes to several **AnSlope** objectives: [A], [B] and [D].

Tentative XBT and CTD/ADCP tracks for the two summer cruises and for the winter conditions 2003 cruise are shown in Figure 6. The schedule of the observations and relationship to mooring and float operations are described in section IV-A. The actual CTD/ADCP station array tracks will be adjusted to the initial XBT survey results, which will provide the initial views of the ASF position and structure. Iceberg distribution may also be a factor [*Keys et al*., 1990] and sea ice conditions will influence the winter cruise tracks. The track may be extended shoreward or seaward depending on the position and form of the ASF and of water mass indicators of cross front exchange such as shelf water export. Stations are spaced at 5 to 10 kilometers in the mooring area (Box B Fig. 2) and average 10 km apart over the large scale survey region (Box A Fig 2). The larger scale survey will provide water mass and shear information upstream and downstream of the intensive study area (Box B) and will extend the US **AnSlope** data set eastward to the Italian CLIMA program site H mooring (Fig. 2).

The CTD/ADCP program will provide spatial scale information to complement the mooring time series. The initial XBT and bottom topography survey will aid in the selection of mooring sites (Orsi, Whitworth and Pillsbury component). A combination of predominantly T-7 (750 m) and a small number of T-5 (1500 m) XBT probes will be used to ensure deep sampling where needed, with the ship slowing as needed for the T-5 drops. Water samples will be obtained for monitoring CTD and rosette performance and in support of the tracer components (Smethie and Schlosser).

b) Water Masses (CTD-O2)

The temperature and salinity of a water parcel are set at the sea surface through coupling with the atmosphere, and additionally in polar regions through interactions with sea ice and glacial ice. Dissolved oxygen, a product of the sea surface fluxes and primary productivity, provides an important third end-member for further resolution of the water mass composition and origin. The closely linked tracer chemistry will provide additional quantitative information on water mass time scales and glacial meltwater components. The CTD-O_2 data characterize the water mass spatial scales and associated gradients, or fronts. Temperature, salinity, and pressure define the dynamically relevant density field and associated geostrophic shear. Referencing such data to ADCP measurements, in turn constrained by the

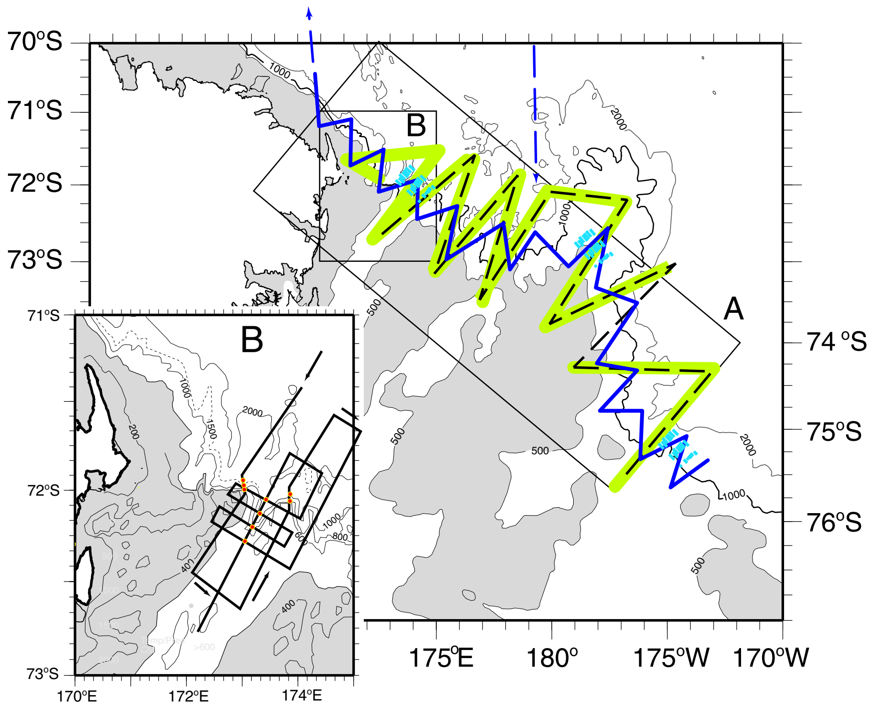

Figure 6. Tentative cruise tracks for the two summer (green) and one winter conditions cruise (blue). Region A encompasses the coarse scale survey region, in which XBT (first summer cruise only, dashed line) and CTD/ ADCP stations will be occupied at a nominal spacing of 10km. High-intensity winter conditions surveys are indicated as light blue hatched areas. Region B covers the fine scale survey region, in which the benthic floats and moorings will be deployed. Nominal station spacing in B will be 5 km.

tidal modeling and time-series mooring data, improves estimates of the absolute geostrophic currents and water mass transports. Water mass information provides the basis for understanding the circulation, mixing, and identification of processes that govern heat and freshwater fluxes. Such data facilitate interpretation of the time series observations provided by the moored instrumentation and allow for more effective modeling. Water mass distribution is an integrated product of circulation and mixing across a wide range of scales, which exchange deep and near- surface water properties across fronts, on and off the continental shelf, and to and from the deep ocean.

c) Hull and Lowered ADCP

The hull mounted and lowered ADCP velocity data will be used to characterize the slope front dynamical regimes. Both systems use acoustic Doppler current profilers (ADCPs). Their sampling is complementary.

The hull mounted ADCP has proven to give good upper ocean velocity profiles on station and underway in ice-free waters with up to moderate sea state conditions. The vertical range is a function of the environmental acoustic conditions and typically restricted to 150-200 m. Thus we can expect to resolve the current structure of the mixed layer and surface frictional boundary (Ekman) layer. One of the great advantages of the hull-mounted system is that it inherently gives velocity "time series". In regions with coherent tidal flows the hull mounted ADCP data can provide first order estimates of tidal velocities. However, tides will need to be removed from the ADCP/LADCP records to provide clean views of frontal velocity structure: this will be done using a regional tidal model in which bottom pressure and currents from the moorings have been assimilated (Padman /Muench Component).

Underway hull mounted systems also provide high spatial resolution which will allow us to obtain upper ocean velocity transects when crossing the shelf break front and give a detailed description of the width of the high velocity bands associated with the density front. Note that the density fronts extend to depths below the range of shipboard ADCPs and in those regions the lowered ADCP (LADCP) will be of primary importance.

The LADCP will give top to bottom velocity profiles at each hydrographic station. One or two ADCPs will be mounted on the CTD frame to measure the velocity relative to the CTD motion. The individual ranges are short (100-170 m), but with care they can collectively give a full ocean depth profile [*Fischer and Visbeck*, 1993; *Firing*, 1998; *Visbeck* 2001]. Near bottom the LADCP directly measures the otherwise unknown CTD velocity and allows us to obtain absolute velocity profiles within 200 m of the sea floor.

This is one of the few ways to directly observe dense plume over/outflow dynamics.

LADCP velocity profiles can also give useful information about 100 m wave length vertical velocity shear. *Polzin et al.* [1997] have related those LADCP measured velocity shear data to internal wave energy and hence diapycnal mixing rates. Their theory is only strictly valid for open ocean conditions and wave-wave interactions might be more complex near the continental shelf.

The combination of hull mounted and lowered ADCP provides a powerful tool to study several aspects of the velocity field in the slope front regime. These velocity data will provide a benchmark for the tidal, process and regional scale circulation models planned in the context of this experiment.

d) Proposed Cruises

(1) Summer 2002/03 and 2003/2004 Cruises

A 50 day cruise is proposed in each of the austral summers of 2002/03 and 2003/04 to define the water mass, ASF and velocity fields over the western Ross Sea continental margin during the ice free season.

During the first summer (2002/03) cruise a simultaneous swath mapping and XBT survey is planned to help select the exact mooring positions in the western Ross Sea (Fig. 4), where major export of Shelf Water is expected. The moorings and floats will then be deployed. A high resolution CTD/ADCP survey within the mooring region follows the course scale (Box A, Fig. 2) XBT and CTD/ADCP survey. Within the fine scale survey region sections across the Drygalski Canyon and parallel to the Canyon axis are planned, with crossing of the tentative mooring positions (Fig. 4, 6). The CTD/ADCP sections will extend further on the shelf and over the deep ocean than the mooring array in order to better define the shelf and slope water masses occupying the mouth of the Drygalski Trough and seaward of Drygalski Canyon. The high resolution survey with a station spacing of about 5 to 10 km will provide a spatially coherent data set, mapping the three dimensional aspect of the slope front region and associated water mass and benthic layer scales.

The large scale survey will have a station spacing of about 10 km along 11 cross ASF sections. The sections average 50 km spacing west of Iselin Bank (closer to the **AnSlope** moorings), and 100 km east of Iselin Bank. The eastern section will be adjusted to cross the mooring H of the Italian CLIMA program (once the exact site is selected). The actual track will depend on the bathymetry and features in the water column. Swath mapping is desirable if only at a few sites along the hydrographic sections shown in Fig .6 as an aid in interpreting benthic layer stratification and velocity profiles. The sections will allow study of the evolution of the slope water masses (including bottom water products) and structure of the ASF as one progresses with the mean flow (east to west) along the Ross Sea margin across the **AnSlope** mooring array to Cape Adare, the western end of the Ross Sea. The CTD and ADCP measurements will allow comparison of the bottom water and ASF signature to the varied topographic forms and shelf water mass accessibility encountered along the Ross Sea margin. The data set will give the spatial context for the mooring array and regional scale models.

During the austral summer 2003/2004 we will repeat both the large and small scale CTD/ADCP survey. In addition, we have budgeted for ship time to survey small scale features at higher resolution and/or try to resolve part of the short term variability by repeating one of the sections within box B a few times. Finally all moorings will be recovered and more floats released.

Estimated Schedule of the summer cruises: Transit from Lytleton, NZ to the work area and return is estimated to be 14 days. The XBT survey, swath mapping, mooring deployment and CTD/ADCP survey of the fine-scale region box B (Figure 6) will require 12 days. The combined XBT and CTD/ADCP coverage of the coarse-scale area will require 24 days, for a total cruise length of 50 days. On the 2002/03 cruise no XBT work is to be done, but time is needed for the additional observations noted above.

(2) Winter Conditions, 2003 Cruise

We hypothesize that substantially more and perhaps quite different information about the ASF and its associated sinking and upwelling regimes can be obtained by investigating the seasonal variability of this region. Negative buoyancy forcing coincident with winter sea ice formation recharges the high-salinity shelf water reservoir south of the ASF [*Jacobs and Giulivi*, 1999]. In late winter the lateral density contrasts are thus likely to be greater at locations where plumes and bottom boundary layers form, and the locations and energetics of exchanges between the shelf and deep ocean regions may be altered. In addition, multi-decadal changes appear to have altered the properties of this reservoir, which could impact the nature and/or volume of newly ventilated bottom water injected into the deep ocean [*Jacobs and Giulivi,* 1998]. Upwelling of modified Circumpolar Deep Water (CDW) into the near-surface layers has been observed near the ASF in summer, and may be enhanced at times when shelf water export is higher. This upwelling supplies heat and salt to the ASF and shelf regions, potentially reducing sea ice thickness. As the 'exhaling' half of the deep ocean ventilation cycle, upwelling is critical to the carbon and nutrient budgets of the upper ocean, and may also influence the characteristics of newly-formed bottom water

Destruction of the summer surface stratification followed by periods of strong surface forcing will increase deep winter mixing beneath the ice and its many leads. Areas of lower ice concentration occur near the ASF, and at some locations a V-shaped 'river' extends deep into the water column in early summer [*Gill,* 1973]. Because salinization of this region could short-circuit the shelf regime, directly causing deep convection, it is important to determine the winter stability of water columns near the ASF. The use of tracers like chlorofluorocarbon (CFC) to assess the rate of bottom water formation [*Orsi et al.,* 1999] also raises important questions about equilibration rates at the sea surface, and mixing ratios between shelf and other water masses. Shelf waters obtain their salient characteristics mainly during winter under the sea ice, leads and polynyas, but are rarely observed on the slope in summer. This implies rapid mixing near the ASF, with proto-bottom water plumes containing large volumes of 'old' CDW. Late winter is probably the best time to determine how well 'newly ventilated' water has equilibrated with the atmosphere, and how much surface, shelf, slope and deep water is contained in boundary layers as they evolve down canyon and along the slope.

Because of the greater difficulty of working in the pack, shorter (~50 km) sections centered on the ASF would be planned for the winter conditions cruise (Fig. 6). Prior data indicate the ASF is narrow and strongly tied to the bathymetry over the upper continental slope (500-1500 m), and that water properties change slowly with distance away from the front [*Jacobs*, 1991]. A 50 km band should thus be wide enough to encompass the ASF and any eddies that may form near the shelf break. The ship track would be extended into deeper water or onto the shelf to follow features of particular interest, and enroute to and from the study area. Three high-resolution study areas would be included, one near the bottom-moored array (Fig. 4) and another where the ASF overrides Iselin bank, as indicated by the orange band in Fig. 2. A third would be located where 'Ice Shelf Water' has been observed near the shelf break and on the upper slope [*Jacobs et al*., 1985]. This third sector is similar to the Filchner Trough in the Weddell Sea, and the probable source of a lower-salinity benthic layer that feeds the deeper recesses of the SE Pacific Basin [*Gordon,* 1966].

Most off-shelf transport of fresh water via sea ice occurs in winter, and its volume may be closely related to the salinity of the shelf water that provides the dense end member for bottom water generation. Since this project will focus on the shelf break at a location of rapid northward sea ice drift, it offers potential opportunities to, e.g., assess ice transport off the shelf, obtain related *in situ* meteorological data, and observe some of the seasonal biological aspects of this physically dynamic region. We would thus welcome synergistic projects [e.g., as in *Ainley et al*., 1998] that can be accommodated without substantial dedicated ship time.

e) Results from Prior NSF Support

Arnold L. Gordon and B. Huber OPP 95-28807. Award Title: "Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL)" Grant Period: 3/97-2/01 Total award: $633,838

As part of the international DOVETAIL Program, 97 CTD with Lowered Acoustic Doppler Current Profiler (LADCP) and tracer stations were obtained from the N. B. Palmer (cruise 97-5) from 31 July to 8 September 1997 in the southern Scotia Sea and northern Weddell Sea. The data characterize the physical and chemical properties of the dense water outflow from the Weddell Sea, Weddell-Scotia Confluence and Weddell overflow into the Scotia Sea and provides a snap-shot of the velocity field at the time of the CTD stations. When analyzed in concert with the 1992 ISW data, the DOVETAIL data reveal newly resolved details of the benthic layer and Weddell Scotia Confluence Deep Water.

Publications: *Gordon, et al.* [2000], *Gordon, et al.* [2001]

A DOVETAIL web site has been established for background information, research results, and final data distribution (http://www.ldeo.columbia.edu/physocean/proj_Dove.html). Data have been archived at NODC under accession number 9900243.

R. Fairbanks and **S. Jacobs** OPP 99-09374, "Shelf and Bottom Water Formation near East Antarctic Polynyas and Glaciers", 09/01/00 - 08/31/01, $163,811. Acquisition of oceanographic data on cruise NB Palmer 00-8, work that was successfully completed during a 36-day Hobart to Hobart cruise from 20 Dec 00 to 25 Jan 01. The focus was on the Mertz Polynya region, where our Australian collaborators had obtained winter measurements in Aug-Sep 1999. More than 160 CTD/LADCP/rosette casts were made over the continental shelf and slope, with water sampling for dissolved oxygen, oxygen isotopes, nutrients and chlorofluorocarbons. These data will clearly be important in providing the summer connection for the winter experiment there, and for documenting the substantial temporal changes in water properties, possibly related to upstream processes in the Ross Sea. The shelf region east of the historically elongated Mertz Glacier Tongue is currently a veritable iceberg graveyard, with thousands of small bergs and recent major calvings from the Ninnis Glacier Tongue anchored by fast ice, bottom shoals and by a huge piece of the Ross Ice Shelf that broke away in 1987. In addition, several crosssings of the continental slope and shelf break will provide heretofore unavailable details about the broader, more diffuse ASF in that sector.

S. Jacobs and H. Hellmer OPP 94-18151, "Oceanography of the Amundsen and Bellingshausen Seas", 7/1/95-6/30/98, $359,271. The focus of this work was to gain a better understanding of the ocean circulation in the coastal SE Pacific sector and to extend time-series measurements in the southern Ross Sea. More than 450 CTD/rosette stations were occupied from the southwest Ross Sea to the Antarctic Peninsula, on cruises of the NB Palmer and USCGC Polar Sea, entraining related geochemical, glaciological and biological projects. Findings include the discovery of a record-high basal melt rate beneath Pine Island Glacier, the documentation of a weaker slope front upstream from the Ross Sea, and a long-term trend superimposed on large interannual variability in Ross shelf water salinity.

S. Jacobs and M. Visbeck OPP 97-25024 "Circumpolar Deep Water and the West Antarctic Ice Sheet" 03/01/98-02/28/02. Field work was delayed until the third year of this project, as the NB Palmer had previously been committed to other work. CTD-O/LADCP/rosette casts were made at 124 sites over the continental shelf and slope, from McMurdo Sound to the eastern Amundsen Sea, with water sampling for dissolved oxygen, oxygen isotopes, and chlorofluorocarbons. This was a collaborative expedition with geologists and glaciologists from the Univ. of Maine, with a strong focus on swath-mapping the sea floor of the Amundsen continental shelf. It was also an atypically heavy ice year, and vast fields of faast ice prevented planned measurements and moorings near the fronts of the Pine Island and Thwaites Glaciers. As a result, efforts were concentrated near the fronts of the Getz Ice Shelf and in defining the position of the shelf break and deep water access to the continental shelf.

Data reduction and analyses are continuing for these projects; results to date appear in *Ainley et al* [1998], *Giulivi and Jacobs* [1997], *Giulivi et a.l* [1999], *Hellmer et al.* [1998], *Hohmann et al.* [2001a], *Jacobs et al.* [1996], *Jacobs and Giulivi* [1998, 1999], *Jenkins et al* [1997], *Keys et al* [1998] and *Vaughan et al* [2001].

[D] Turbulence Measurements and Tidal Modeling (L. Padman, R. Muench – ESR)

a) Background

ESR's contribution to **AnSlope** directly addresses Specific Objectives [C] and [D] (page C-4), by modeling tidal currents, and obtaining the measurements necessary to assess the role of various small-scale processes on diapycnal and lateral fluxes. By providing the modeling needed to detide hydrographic and velocity measurements from the ship surveys, we also contribute to [A], the assessment of the Slope Front's mean structure and length scales of variability. These goals are addressed by: (1) high-resolution, depth-integrated tide modeling using assimilation of bottom pressure and current meter data (TAMU/OSU moorings) and hull-mounted ADCP records; (2) microstructure profiling (*T* and *C*) with a turbulence package added to the CTD rosette; and (3) oversight of acquisition and analysis of current profiles from the vessel-mounted acoustic Doppler current profiler (ADCP). A separate proposal will be submitted in May 2002 to request support for 3-D modeling of depth-dependent tidal currents resulting from baroclinicity and boundary stresses. The 3-D modeling will include studies of the influence on tidal currents of varying stratification and nonlinear coupling with mean and low (subtidal) frequency flows.

In the following subsections we review tides in the **AnSlope** study area, then very briefly summarize our interest in the finescale and microscale processes that contribute to vertical and lateral fluxes.

(1) Tides (and weather-band shelf waves)

A brief overview of ESR's studies of Antarctic tides, focused on the Ross Sea, can be found at our web site, http://www.esr.org/antarctic/rossseatides.html. More material is available in a downloadable copy of a poster presented at the 2001 Gordon Research Conference in Polar Marine Sciences: go to http://www.esr.org/antarctic/grc2001.html. Tides are the most energetic ocean process along the NW Ross Sea shelf break. Spring tidal currents at Mooring C [*Jaeger et al*., 1996], which is about 50 km inshore of the shelf break and within the **AnSlope** study area, are ~50 cm/s, and can exceed 100 cm/s over the upper slope (Fig. 7, below), based on model studies. Paths of ice-mounted drifters in this region also show significant diurnal energy [*M. Jeffries and N. Kozlenko*, UAF, pers. comm., 2000]. Mean diurnal-band ice drift speeds of ~20 cm/s are found at the shelf break near 177^{o}E, which lies <u>between</u> the two cores of strongest predicted tides (Fig. 7). From these studies we expect that tidal currents will dominate benthic stirring rates, and might also act as a source of turbulent kinetic energy and mixing for the stratified mid-water column (between the benthic and surface mixed layers, and including the upper edge of the dense plume of shelf-derived water). Cross-slope advection of the dense plume flow by tides may contribute to the onset of thermobaricity (see below). Strong tide-forced periodic divergence of the ice cover increases the winter heat loss through pack ice over the ASF [*Padman and Kottmeier*, 2000].

Tidal currents are also a source of "noise" in the measurements that **AnSlope** will use to describe the mean structure and principal scales of variability of the ASF. If the peak current speed is 50 cm/s, the typical tide-induced displacement of a feature from its mean position is *O*(10) km, greater than the expected scales of cross-slope variation in the ASF hydrographic and velocity fields. Thus, to form a picture of the mean cross-front structure of the ASF from CTD/LADCP/tracer data requires that we somehow account for tidal displacement during the time intervals between stations. Even in the rapid transects with ADCP and XBT only (no stations), where the ASF's location might be regarded as essentially "frozen", observed frontal velocity structure will be contaminated (possibly overwhelmed) by tidal currents. Thus, tide removal is essential to reveal the flow components that are directly related to frontal dynamics. The expected short spatial scales of tidal current variability (see below) implies that empirical corrections based on moored current meter data will not be sufficient to detide the ship-based survey data.

Most tidal kinetic energy along the Ross Sea shelf break is associated with diurnal-band topographic vorticity waves (TVWs), which are well known from analyses of moorings in many high-latitude locations. *Middleton et al*. [1982; 1987] provide comprehensive descriptions of TVW properties (weather-band, and diurnal tidal) in a baro<u>tropic</u> ocean. *Cummins et al*. [2000] demonstrated the importance of stratification on TVW dispersion properties along the coast of Vancouver Island. From these studies we note that diurnal tidal TVWs in high-latitude oceans (weak but possibly non-negligible stratification) have the following properties:

- they are strongly constrained to the shelf break;
- they have short spatial scales: cross-slope variation and along-slope wavelength are comparable to slope width; and
- their dispersion properties and processes of energy dissipation are sensitive to bathymetric variability and roughness, stratification, and mean flow and other low-frequency variability.

Diurnal TVWs are excited in depth-integrated models such as the Circum-Antarctic Tidal Simulation ("CATS") model [*Padman and Kottmeier*, 2000] but their properties are only poorly represented, probably because of the generally poor quality of the Southern Ocean bathymetric data base and the models' ignorance of stratification. For the present requirement to detide ship survey data, a more sophisticated tidal prediction method will be required, and this will be based on data assimilation.

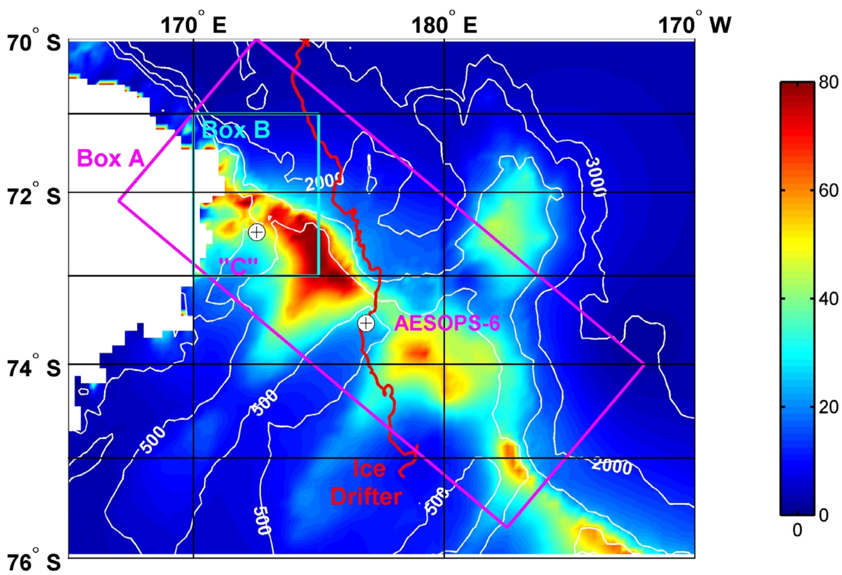

Figure 7: Map of time-mean tidal current speed, $\langle|\mathbf{U}_{tide}|\rangle$ (in cm/s) from CATS00.1 model. The locations of the 2 current meters described in the text (Mooring C [*Jaeger et al.*, 1996] and AESOPS-6) are indicated. Bathymetry is shown as white contours. The modeled value of $\langle|\mathbf{U}_{tide}|\rangle$ agrees quite well with Mooring C data, but significantly overestimates AESOPS-6. Maximum modeled values are >80 cm/s on the shelf break near 72.7°S, 175°E. Maximum tidal current speeds at spring tide may be ~twice these mean values, i.e., up to 1.8 m/s. The drift track of an ice-mounted drifter (see text) is shown.

Currents at Mooring C have a strong spring/neap cycle (~2-week period) as the two dominant diurnal constituents, K_1 and O_1, have similar magnitudes. This cycle adds to the temporal variability of processes such as benthic stirring, which can be expected to show up as spatial variability as mixing products are advected away from the tidal mixing hot spots. The tidal constituents clearly also undergo some nonlinear interactions with topography and/or each other: significant energy is present in constituents that are usually small, including the ~3 cycles/day (cpd) species. The residual currents (i.e., those not accounted for by tidal analyses of the full record) include significant energy in broad bands around 1 and 2 cpd, indicating temporal instability of the constituent amplitudes and/or phases that would be consistent with TVW sensitivity to the slowly-varying environment (changing stratification and mean flow).

The Mooring C data also show significant weather-band energy (currents up to 20 cm/s in the 2-15-day band). These currents may be locally forced, or due to weather-band TVWs propagating to this site from the east as in the Weddell Sea measurements reported by *Middleton et al.* [1982].

(2) Diapycnal Mixing

Understanding the small-scale processes that ultimately cause water mass modification by mixing is a key aspect of **AnSlope** (Specific Objective [D]). The present understanding of ocean mixing in a global sense is that tides and surface stress each provide about half of the total "mechanical" stirring [*Wunsch*, 2000]. However, in specific environments the sources of energy for mixing can be more diverse. Possible sources of energy for mixing in the **AnSlope** study area include: benthic stirring by tidal and other current flow across the seabed; upper-ocean stirring by surface stress and buoyancy forcing; shear instabilities associated with baroclinic tides; lateral (quasi-isopycnal) intrusion dynamics; double-diffusion; and the nonlinear equation-of-state responses, cabbeling ($\alpha(T)$) and thermobaricity ($\alpha(P)$). *Gill* [1973] provides an excellent review of the role of each of these processes in the Antarctic. Other good references for specific processes include *Muench et al*. [1990] and *Robertson et al.* [1995] (double-diffusion); *Fofonoff* [1956] and *Foster* [1972] (cabbeling); and *McPhee* [2000] and *Akimoto* [1999a,b] (thermobaricity). *Joyce* [1977] describes a model for estimating lateral diffusivity from the observed vertical variability of intrusions seen in CTD casts, and this model has provided a reasonable estimate of the decay rate of a Meddy [*Hebert et al*., 1990].

The distillation of this set of studies is that, under the right circumstances, each of these processes can play a significant role in water mass mixing and production. Due to lack of space in this proposal, however, we simply point out that conditions in the NW Ross Sea are conducive to all of these processes. The goal of finestructure/microstructure measurements made by ESR in **AnSlope** will be to identify whether the fluxes of these smaller-scale processes are important relative to simple advective fluxes and mesoscale instabilities that are adequately characterized by frontal dynamics, or perhaps simply "mop up" the hydrographic variability that remains after mesoscale processes create cross-frontal fluxes.

b) Proposed Work

(Task 1) *CTD-based microstructure*. Mixing rates can be estimated in several ways, ranging from studying released dye dispersal [*Ledwell et al*., 1993] to the use of mixing proxies based on internal wave spectral characteristics [*Gregg*, 1989; *Wijesekera et al*., 1993] or measured finescale Richardson number [*Pacanowski and Philander*, 1981; *Muench et al*., 2001b]. Taking into account **AnSlope**'s logistic and budgetary limitations, we have proposed a measurement technique that is a compromise between the high fiscal and logistic cost of an accurate dye release study and the simple internal-wave and shear-based parameterizations. We will provide a CTD-mounted Microstructure Instrumentation Package (CMIP). The CMIP is self-contained (provides its own power and records data internally), and samples at ~1000 Hz. *T* and *C* are resolved to <3 cm vertical scales at very high accuracy. This scale is much smaller than the main Sea-Bird CTD system, which samples at 24 Hz and mechanically filters the small-scale signal as the water is pumped through the conductivity cell. CMIP is built by Rolf Lueck (Victoria, BC), who is a leader in the design and construction of microstructure units for inclusion on moorings, SeaSoar profilers, and autonomous submarines [*Levine and Lueck*, 1999] (see also http://www.soc.soton.ac.uk/OTD/gxg/Autosub IBC talk.pdf and http://www.onr.navy.mil/sci_tech/ocean/info/yerpts/POYE00/POLRG.PDF). The unit is very similar in capability to "MicroSoar" [*Dillon et al*., 2001; http://diana.oce.orst.edu/cmoweb/micro/main.html).

CMIP has sufficient memory to record internally, continuously, for ~3 days, but data will typically be retrieved after every few CTD casts in order to monitor performance. We are investigating the possibility of sending a low-resolution data stream through one of the CTD auxiliary sensor ports to monitor instrument performance in real time. Data will be used to estimate the turbulent dissipation rate (ε) through the Cox number approach (see *Gregg* [1987] for an overview), and through Thorpe reordering [see, e.g., *Dillon and Park*, 1987]. Estimates of ε combined with measurements of the mean stratification of the stirred fluid can be used to estimate diapycnal diffusivity, K_v. As importantly, however, the variability of K_v provides guidance as to the processes that are most important for turbulent mixing. Analyses of structures seen in the high-resolution profiles can be used to identify non-shear-related mixing such as double-diffusive convection [*Robertson et al*., 1995] and water column response to cabbeling and thermobaricity.

(Task 2) *ADCP data acquisition and analysis*: ESR will oversee the collection of ADCP data from the hull-mounted ADCP. The RPSC staff maintains basic data collection on the U.S. Antarctic vessels, with guidance and software/hardware upgrades provided by Eric Firing and Teri Chereskin. ESR's main role is to ensure that the ADCP setup is optimal for **AnSlope**, to collect not only the time-averaged data but also single-ping data. The latter are useful for (a) acoustic backscatter (for tracking layers, e.g., the upper edge of the pycnocline, and biological patchiness) and (b) post-cruise editing (especially useful when the ship is frequently in ice). ESR has the role of ADCP overseer in Southern Ocean GLOBEC, and proposes to continue that role for **AnSlope**.

(Task 3) *Mixing proxies from CTD/ADCP data*: Fine-scale CTD data can reveal the signatures of mixing processes, including large density inversions associated with shear instabilities and the steppy structures associated with double diffusion. Velocity shear measured with an ADCP can be used in combination with CTD-derived hydrographic data as a general guide to mixing in the stratified ocean through parameterizations as discussed in references cited in Task 1, above. Such an approach is inferior to the analysis of the CTD-mounted microstructure unit discussed in Task 1, but does allow for testing the reliability of mixing proxies in other data sets. We propose to analyze the CTD and ADCP data collected during **AnSlope** with these mixing issues in mind, and will assist the LDEO CTD/LADCP team in exploring the reliability of mixing proxies from the combination of CTD-grade hydrography and LADCP.

(Task 4) *Data assimilation barotropic tidal modeling*: Existing Antarctic tidal models are tuned by using data assimilation to "nudge" our dynamical tidal model (CATS) into acceptable compliance with the data. Our Circum-Antarctic Data Assimilation (CADA) model [*Padman et al.,* 2001a] (see also http://www.esr.org/antarctic/cada.html) is a large-scale application of this methodology, which is a fairly standard application of the Oregon State Tidal Inversion Software ("OTIS") package (http://www.oce.orst.edu/po/research/tide/index.html). In CADA, TOPEX/Poseidon (T/P) satellite radar altimetry measurements are the primary constraining data. However, T/P data are only available in ice-free ocean areas north of ~66.2^{o}S, so additional data are needed to constrain tides in the major southern embayments of the Weddell and Ross Seas. We have identified a set of ~40 Antarctic tide gauges south of the T/P domain, including bottom pressure records, coastal tide gauges, and gravimeters and precision GPS measurements on the floating ice shelves. We work closely with several glaciology groups to encourage collection of more GPS tide records, as well as to keep up-to-date on satellite-based sensing of the grounding line of major ice shelves as it affects the tidal predictions under, and adjacent to, the major shelves [*Gray et al*., 2001]. We have recently been investigating the use of tidal current records in an assimilation model of the Weddell Sea, and this method holds significant promise since current meter data are much more common than height data in both the Weddell and Ross Seas.

Prior to the start of **AnSlope**, we will create a data assimilation model of the Ross Sea tides using gravimeter-based tide height [*Williams and Robinson*, 1980; *MacAyeal*, 1984] and current meter data [*Pillsbury and Jacobs*, 1985; *Jaeger et al*., 1996; and other]. A proposed study of ice shelf rifting along the Ross Ice Shelf (RIS) front (to be submitted at the same time as this **AnSlope** proposal) would provide several additional height data points along the RIS front for further model refinement during the first year of **AnSlope**. Much of the tidal energy seen in the **AnSlope** area has previously circulated under the RIS, and so improved data constraints along the RIS front will help our **AnSlope** modeling effort. The Mooring C and AESOPS-6 current records (Fig. 2) are the only records we have near the shelf break, but will also be helpful in the assimilation process. Assimilation studies will continue through the first year of **AnSlope**, allowing us to incorporate the pressure and current measurements from the first TAMU/OSU mooring program (deployed and recovered during Cruise 1). Much of this work involves the application of existing numerical skills. However, it is envisaged that assimilation of at least a subset of the hull-mounted ADCP data will also be necessary to account for variability of tidal current constituents due to changing stratification and mean and subtidal currents. This assimilation of ADCP data is not yet standard. Several issues will need to be addressed, including the effect of spatial correlations in the tidal fields and short sampling time (<1 month of data during one cruise) on the effective accuracy of the solution, and the methods used to account for stratification effects on diurnal TVWs in what is essentially an application of the depth-integrated and linearized momentum equations.

As noted in the previous paragraph, we are aware that a depth-integrated and linearized data assimilation model cannot formally capture some of the tidal current signal seen in the Mooring C and AESOPS-6 current data. This signal includes depth-dependence either as a boundary layer frictional response or baroclinicity, and time-dependence of the diurnal TVW characteristics (and associated harmonics and nonlinear interaction products). For the periods when ADCP data from cruises are available, some nudging of the linearized solution can be performed to improve the model's effectiveness for tide removal from ADCP and LADCP, however this technique does not address the fundamental limitations of such a model, not does it allow extrapolation to periods and areas not covered by the ADCP surveys. An enhancement proposal will be submitted in May 2002 to investigate more sophisticated models of **AnSlope** tides. A hierarchy of models would be developed: (1) 3-D barotropic; (2) quasi-2-D baroclinic "transect" model (see *Holloway* [1996] and *Robertson et al*. [2001]); and fully 3-D baroclinic (see, e.g., *Cummins et al*. [2000] and *Merrifield et al*. [2001]). One contribution to the depth-dependent tidal field will come from critical latitude effects [*Robertson et al*., 2001], however these are directly relevant only to the semidiurnal constituents (primarily M_2), which are weak in the Ross Sea. A more interesting study for our present interests is the possibility that the strong cross-slope currents associated with the diurnal TVWs may trigger significant baroclinic motion even though the fundamental frequency is subinertial and so cannot contribute to the freely propagating internal waves field. It is possible that higher harmonic (~12 h, ~8 h, ~6 h period) internal waves may be generated by nonlinear interactions of the diurnal barotropic tide and abrupt topography [see *Padman et al*., 1991]. An ~8-h tide is apparent in the Mooring C data. The spectral width of the semidiurnal signal in the Mooring C residual ("detided") currents is also consistent with the presence of baroclinic energy, although it might also reflect the temporal variability of the quasi-barotropic fundamental diurnal TVWs. These responses will be obvious in the mooring data, and will be relevant to attempts to completely remove tides from ADCP records, but need to be left to the enhancement tidal modeling study.

c) Results of Prior NSF-Funded Studies

Full references for papers cited here can be found in the main bibliography for this proposal, or at http://www.esr.org/esrpublic.html.). Underlined papers are available in PDF form at http://www.esr.org/esrpapers.html.

L. Padman, *Turbulent Mixing Near the Filchner-Ronne Ice Shelves*, *OPP-9896006, 7/1/97-6/30/00, $285,006*. The 1998 Ronne Polynya Experiment (ROPEX) [*Nicholls et al*., 1998; *Padman et al*., 1998a] obtained about 120 CTD profiles over the southern shelf and slope, many of them in the northern Ronne Depression. Four moorings across the southern shelf break and slope monitored the outflow of dense water from the Filchner Depression from 1/98 to 3/99. ROPEX bathymetry data were used to revise our first Weddell Sea tides model [*Robertson et al.,* 1998]: *Padman et al*. [1998b] found a significant change in mean tidal energy along the southern and western shelf break. We have now developed the "Circum-Antarctic Tidal Simulation" (CATS) [*Padman and Kottmeier*, 2000; *Rignot et al*., 2000], which is already in use by several groups for oceanographic and glaciological studies. ESR tidal studies are described at http://www.esr.org/antarctic/tides.html.

L. Padman, *Heat, Salt, and Momentum Fluxes Through the Pycnocline in the Eastern Weddell Sea: Renewal*, *OPP-9896041, 7/1/97-6/30/99, $125,018*. Using data from the eastern Weddell Sea in austral winter [*McPhee et al*., 1996], we showed the influence of Maud Rise on mesoscale processes, including the distribution of ocean heat flux [*Muench et al*., 2001a]. A paper that describes one heat flux mechanism, cabbeling, is submitted to *JGR* [*Padman et al*., 2001b]. This grant also funded the final year of thesis work of Robin Robertson (PhD, 2/99). From this work, *Robertson et al*. [2001] describes amendments to the Princeton Ocean Model (POM) for use in weakly stratified oceans for tidal studies near critical latitude. Two other papers that discuss the application of the revised POM to the study of baroclinic tide generation near critical latitude in the Weddell Sea have been submitted [*Robertson*, 2001a,b].

***R.D. Muench*,** Moored Current Observation Component of the Ice Station Weddell (ISW) Experiment, OPP-9024828, 6/1/91-5/31/94, $300,000. Results show a northward boundary transport of about 28 x 10^6 m^3 s^{-1} in the western Weddell Sea [*Muench and Gordon*, 1995], about 6 x 10^6 m^3 s^{-1} of which was Weddell Sea Bottom Water. The data also contributed to assessing regional tidal and internal wave fields [*Levine et al*., 1997].

***R.D. Muench**, ADCP and mesoscale current observations in the eastern Weddell Sea; a component of ANZFLUX, OPP-9315019, 6/1/94-9/30/98, $200,000.* Results show that Maud Rise exerts a strong control over ocean heat flux, as well as over local circulation and other ocean conditions [*Muench et al.*, 2001a]. Other work has identified and quantified double diffusive and cabbeling processes in the upper ocean [*Padman et al*., 1996; 2001b].

***R.D. Muench**, Collaborative Research: Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL), OPP-9527667, 6/15/97-5/31/01, $233,220.* This program assesses deep and bottom water flow through the South Scotia Ridge [*Muench*, 1998]. Results show that amplification of tidal currents over banks and shelves significantly impacts upper ocean heat fluxes and water mass modification [*Muench et al.*, 2000; *Muench et al.*, 2001b], and the field data are used to assess results of a circum-Antarctic GCM [*Matano et al.*, 2001]. Primary results are to be published in a special DOVETAIL issue of *Deep-Sea Res. II* of which R. Muench is a Guest Co-Editor.

[E] Tracers: CFC (W. Smethie, LDEO)

a) Background

Chlorofluorocarbons (CFCs) have been used extensively in society for refrigeration and manufacturing/industrial processes, and have been emitted to the atmosphere in significant quantities for the past half-century. Because these compounds cause destruction of ozone in the stratosphere, their concentrations have been carefully monitored in the atmosphere since the late 1970s. From a combination of this monitoring program and records of industrial production, the concentrations in the atmosphere as a function of time are well known (Figure 8). CFCs enter the ocean at the surface by gas exchange and the equilibrium concentration can be accurately calculated from the atmospheric time history and the well-known solubilities [*Warner and Weiss,* 1985; *Bu and Warner*, 1995]. Most of the surface ocean is within a few percent of equilibrium, but in regions where rapid convection occurs or where there is significant ice cover, surface water concentrations are less than the equilibrium value. Differences in the atmosphere time histories of the CFCs have resulted in CFC ratios varying with time (Figure 9) and these ratios are useful indicators of formation times of subsurface water masses. CFC-11, CFC-12 and to a lesser extent CFC-113, have been widely measured in the ocean and used to investigate the spreading and mixing of recently formed subsurface water masses.

b) Previous CFC Work in the Southern Ocean

(1) Southern Ocean

CFCs have been measured on numerous oceanographic programs, including the WOCE program, which provided worldwide coverage. These data clearly show the spreading pathways of deep and bottom water masses formed during the past few decades. For the Southern Ocean, high concentrations are observed in the bottom water around Antarctica revealing sources of bottom water from the Weddell Sea, the Adelie Coast, the Ross Sea and possibly other locations, and high CFC plumes extend northward into the Atlantic, Indian and Pacific oceans [*Orsi and Bullister*, 1996; *Haine et al*, 1998; *Smythe-Wright and Boswell,* 1998; *Meredith et al*., 2000]. The total amount of CFCs in the deep ocean is a direct reflection of the formation rate of the deep water during the past few decades that CFCs entered the ocean. *Orsi et al.* [1999] have used the CFC inventory in the Southern Ocean to estimate the formation rate of Antarctic Bottom Water and *Smethie and Fine* [2001] have used it in the North Atlantic Ocean to estimate the rate of NADW formation. This method has great potential for a number of subsurface water masses, but the CFC concentration in the source water as a function of time, which is a function of processes forming the source water and the well known atmospheric time histories, must be known.

(2) Weddell Sea

CFC measurements were made in the Weddell Sea in the mid-1980s and these measurements showed that recently formed Weddell Sea Bottom Water (WSBW) contained high concentrations of CFCs [*Bullister*, 1989, *Mensch et al*., 1996]. Samples for CFCs and tritium were also taken across the Filchner Depression in front of the Filchner Ice Shelf. Ice Shelf Water (ISW) flowing out from beneath the ice shelf had distinctly different CFC and tritium concentrations than other shelf water masses. The CFC concentrations were lower and the tritium concentrations higher for ISW reflecting the opposite trends in CFC (increasing) and tritium (decreasing) input functions and the isolation time beneath the ice shelf which was estimated to be 14 years from these data [*Mensch et al*., 1996].

CFC measurements were made in the western Weddell Sea along the drift track of the Ice Station Weddell in 1992 and in the northwest Weddell Sea during the DOVETAIL expeditions in 1997 and 1998. Results from these studies are briefly summarized in the Prior Results section.

(3) Ross Sea

The first CFC measurements in the Ross Sea were made in 1984 [*Trumbore et al*., 1991]. Along shelf and cross shelf sections were obtained and one of the cross shelf sections is the 172°E section shown in Figure 3. This section shows low CFC concentration in the Circumpolar Deep Water adjacent to the shelf, high concentration at the shelf break and a bottom maximum along the continental slope. A bottom CFC maximum is also observed to the east on sections normal to the slope at 170° and 176°W [Figures 2 and 3 in *Trumbore et al.*,1991], suggesting outflow of shelf water at multiple locations along the continental shelf. The along shelf section in front of the Ross Ice Shelf shows High Salinity Shelf Water (HSSW) on the western portion of the shelf and Low Salinity Shelf Water (LSSW) on the eastern part of the shelf with similar CFC-12 concentrations of about 1.5 pmol/kg. In the middle of the shelf, HSSW and LSSW are separated from each other by Ice Shelf Water (ISW) flowing from beneath the Ross Ice Shelf and modified Circumpolar Deep Water (mCDW), a mixture of CDW and surface water, flowing onto the continental shelf. The theta, salinity and CFC concentrations indicate that mCDW is a mixture of 60% CDW and 40% surface water and its CFC concentration is less than that for HSSW and LSSW. As is the case for the Weddell Sea, ISW also has a lower CFC concentration than the other shelf water masses. The CFC-12 concentration in ISW is about 1.1 pmol/kg reflecting its isolation beneath the ice shelf. The time the water resided beneath the ice shelf was estimated to be between 5.5 and 7 years by simulating the average CFC concentrations of ISW with a stream tube model and a 1-box model respectively [*Trumbore et al.*, 1991]. Renewal times for HSSW and LSSW with respect to the inflow of Warm Core Water were estimated to be less than 10 years.

The Ross Ice Shelf section was reoccupied in 1994 and, as expected from the above discussion, these data clearly show the contrast in tracer concentrations and tracer ratios between the Ross Sea water masses. Vertical sections of potential temperature, salinity, CFC-11 and the CFC-113:CFC-11 ratio are shown in Figure 10 in which east is to the left and west to the right. The water mass distribution is basically the same *Trumbore et al.* [1991] observed in 1984, except salinity has decreased along the entire section by about 0.05 psu [*Jacobs and Giulivi*, 1998], and the CFC concentrations have increased due to the increasing CFC concentration in the atmosphere between 1984 and 1994 (Figure 8). The lowest CFC concentrations are found in the ISW and mCDW in the center of the continental shelf as was the case in 1984. The coldest ISW ($\theta < -2.0$°C) has higher CFC concentrations and a higher CFC-113:CFC-11 ratio in its eastern half (stations 22-24) than in its western half (stations 28-30) (Figure 10). This suggests two pathways for HSSW, which is the source water for ISW [*Jacobs et al.*, 1985], to flow beneath and exit the cavity beneath the Ross Ice Shelf, a short pathway (eastern half) and a long pathway western half). The shallower mCDW (stations 14-37, $\theta = -1.2$ to -1.6°C, depth=150-300 m) has a similar CFC concentration to ISW, but the CFC-113:CFC-11 ratio is higher. This is the result of Warm Core Water forming by mixing between young well-ventilated surface water and CDW with very low CFC concentrations. This lowers the CFC concentration of surface water but does not affect the CFC-113:CFC-11 ratio. The CFC concentration in LSSW on the eastern part of the shelf appears to be higher than the CFC concentration in HSSW on the western part of the shelf, but the LSSW values are strongly influenced by only two data points with high CFC values and better sampling resolution is needed to determine the concentration in LSSW.

c) Objectives

The objectives of the CFC program are to:

- measure the distribution of CFCs at high spatial resolution for the outer shelf and adjacent continental slope in the **AnSlope** study region;
- identify sites where recently formed high CFC Ross Sea shelf water masses exit the shelf and investigate their transformation as they flow down the continental slope;
- investigate mixing and exchange of water across the Antarctic Slope Front;
- estimate the time the shelf water masses have resided on the shelf before flowing down the slope;
- investigate the water mass structure of the Antarctic Slope Front;
- determine the extent that the Ross Sea shelf water masses are in equilibrium with atmospheric CFC concentrations and gain a better understanding of the processes that control the CFC concentrations in the shelf water masses.

d) Proposed Work

Three cruises will be conducted to the **AnSlope** study site shown in Figure 2, two summer cruises in 2002/2003 and 2003/2004 and one late winter cruise in October 2003. CTD/rosette surveys will be conducted on each of these cruises. During the summer cruises, two surveys will be conducted, one in the small box in Figure 6 with 5 km spacing and one in the large box with 10 km spacing. Because of this very close station spacing and the time constraints for completing the surveys, water samples will be collected on approximately half of the stations. The winter cruise will consist of sections extending from shelf to the slope between the eastern and western ends of the large box with reoccupations of certain summer cruise sections (Figure 6). Water samples will be collected at all of these stations since the pace will be a bit slower due to ice cover. We plan to measure CFCs 11, 12 and 113 on board ship on all water samples collected on the first summer cruise and the winter cruise. In addition samples will be collected for analysis of tritium, helium isotopes, and oxygen isotopes (see Schlosser component) and interpretation of the tracer data will be closely coordinated.

The previous discussion on prior CFC measurements in the Ross Sea demonstrate the contrast in CFC concentrations and ratios between the different shelf water masses that can exit the shelf. Maps of CFCs and ^{3}He (P. Schlosser) will be prepared and used to determine the spreading pathways of recently formed, well-ventilated shelf water masses from the outer shelf to the slope region. The CFC and ^{3}He data will be used in conjunction with the hydrographic data to investigate exchange and mixing of shelf water and Circumpolar Deep Water across the Antarctic Slope Front and flow of this mixture down the continental slope. The sharp contrast in tracer concentrations between the shelf and circumpolar water masses will also aid in determining the structure of the Antarctic Slope Front. Sources of shelf water that flow off the shelf (ISW verses HSSW and LSSW) will be investigated using the CFC data in conjunction with the δ^{18}O and helium concentration data (P. Schlosser). The CFC and tritium data will be used to investigate the time the shelf waters have resided on the shelf before exiting down the slope. These times will be estimated using CFC-113:CFC-11 (Figure 9) and CFC:tritium ratios (Figure 12) and tracer budget calculations for the shelf water masses. The CFC data will also be available for use in the modeling components of this program. A longer term goal of **AnSlope** is to develop a better capability of global ocean circulation models to simulate the high latitude processes that form deep and bottom water around Antarctica. CFCs and other tracers, which are sensitive to the deep water formation rates and exchange and mixing, are now being used in these models, but the boundary condition in the high latitude regions must be understood. The CFC concentrations in shelf waters track the well known concentrations in the atmosphere, but these waters are not in equilibrium with the atmosphere because of extensive ice cover and rapid convection that occurs at some locations. The **AnSlope** CFC measurements will provide much needed information to determine the extent that the shelf waters are in equilibrium with the atmosphere and to understand the processes that control the shelf water concentrations.

The onboard CFC measurements will be available as they are produced to all shipboard scientific parties to aid in planning during the cruises. A preliminary CFC data set will be produced soon after the cruise and will be made available to all **AnSlope** investigators. Final CFC data sets will be completed within a year after each cruise and will be made available to AnSlope investigators as soon as they are completed. These data sets will be archived in national data centers following NSF policy.

e) Links to Other Programs

With support from the NOAA Scripps/Lamont consortium on the Ocean's Role in Climate (CORC), we made CFC measurements on the NBP cruise 00-1 section along the Ross Ice Shelf during the austral summer of 2000. This section is a reoccupation of the section presented in Figure 10. The Italian CLIMA program has been making observations on the inner regions of the Ross shelf focusing on the Terra Nova Bay polynya for the past several years and expanded this program to the shelf break on a cruise in January-February, 2001 (see overview). CFC samples were collected on this cruise in flame sealed glass ampoules by Italian scientists and will be analyzed at Lamont with support from CORC. Data from these two cruises will provide information on the inner shelf water masses and CFC concentrations.

f) Results from Prior Support

OPP 93-17166: Investigation of Deep and Bottom Water Formation in the Western Weddell Sea from

Measurement of CFCs on Samples Collected during the Anzone Project, 2/94-1/97, $141,298.

In 1992 CFC measurements were obtained along the drift track of Ice Station Weddell [*Gordon*, 1998] along the western margin of the Weddell Sea [*Mensch et al*., 1998]. High concentrations were observed in the bottom few hundred meters above the continental slope in newly formed deep water that had recently flowed off the continental shelf. Tritium was also measured and the age of this newly formed water was estimated to be 7±2 years from the CFC-11:tritium ratio, which increases strongly as a function of time because of the opposing trends in the input functions [*Mensch et al.*, 1998]. This age represents primarily the residence time of the water on the continental shelf before entering the deep water since the transit time from the nearby continental shelf is thought to be less than a year.

Publications and Presentations at Meetings

Mensch, M. W.M. Smethie, Jr., P. Schlosser, R. Weppernig, and R. Bayer. 1998. Transient Tracer Observations during the Drift and Recovery of Ice Station Weddell. Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin S. Jacobs and R.F. Weiss eds., Antarctic Research Series 75:241-256.

OPP 95-28806: Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL), 4/97-3/01, $266,923.

An extensive set of CFC measurements were obtained in the northwest Weddell Sea in 1997/98 during the Dovetail project, a detailed study of export of deep water from the Weddell Sea. The CFC and hydrographic data clearly showed the formation of two streams of WSBW in the vicinity of Powell Basin with one stream flowing through Jane Basin and then northward around the South Orkney Plateau and the other flowing eastward along the southern flank of the Endurance Ridge. Ages along the flow path were estimated from the CFC-113:CFC-11 ratio and the fraction of pure shelf water was estimated by comparing the concentrations in the shelf water at the time of outflow to the observed concentrations along the flow path. The age of the Jane Basin branch increases to 5 years north of the South Orkney Plateau with about 30% pure shelf water remaining. The age of the Endurance Ridge branch increases to about 3 years with 50% of pure shelf water remaining. These ages suggest a mean spreading rate of about 1 cm/sec, which includes effects of mixing.

Publications and Presentations at Meetings

Mensch, M., W.M. Smethie, Jr. and P. Schlosser, 1997. Tracer Oceanography in the Weddell Scotia Confluence during NBP 97-5. Submitted to *Antarctic Journal*.

Gordon, A.L. and W.M. Smethie, Jr. 1998. Basin Waters of Bransfield Strait During Dovetail. *Antarctic Journal*, in press.

Gordon, A.L., M. Mensch, Z. Dong, W.M. Smethie, Jr. and J. deBettencourt, 2000. Bransfield Strait deep basin water. *Journal of Geophysical Research*, 105:11337-11346.

Smethie, W.M., Jr., M. Mensch, and W. Roether. 2000. Spreading of deep and bottom water from the northwestern Weddell Sea. European Geophysical Society General Assembly, Nice, France, April 2000.

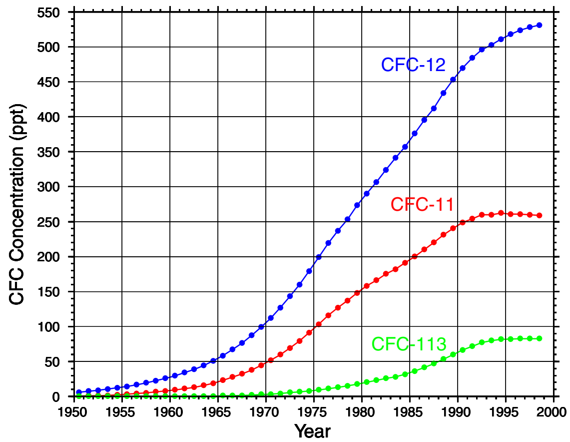

Figure 8. Atmospheric concentrations of CFC-11, CFC-12, and CFC-113 versus time for the Southern Hemisphere [*Walker et al.*, 2000]

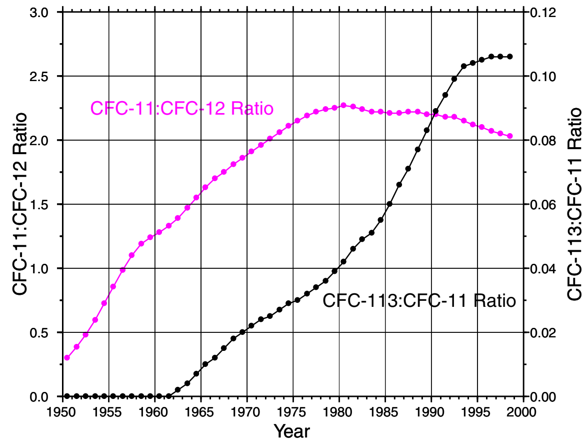

Figure 9. CFC-11:CFC-12 and CFC-113:CFC-11 ratios versus time for water with a temperature of -1.9°C and a salinity of 34 that is in equilibrium with atmospheric CFC concentrations. These ratios were calculated using the data presented in Figure 3 and the CFC solubilities [*Warner and Weiss*, 1985; *Bu and Warner,* 1995].

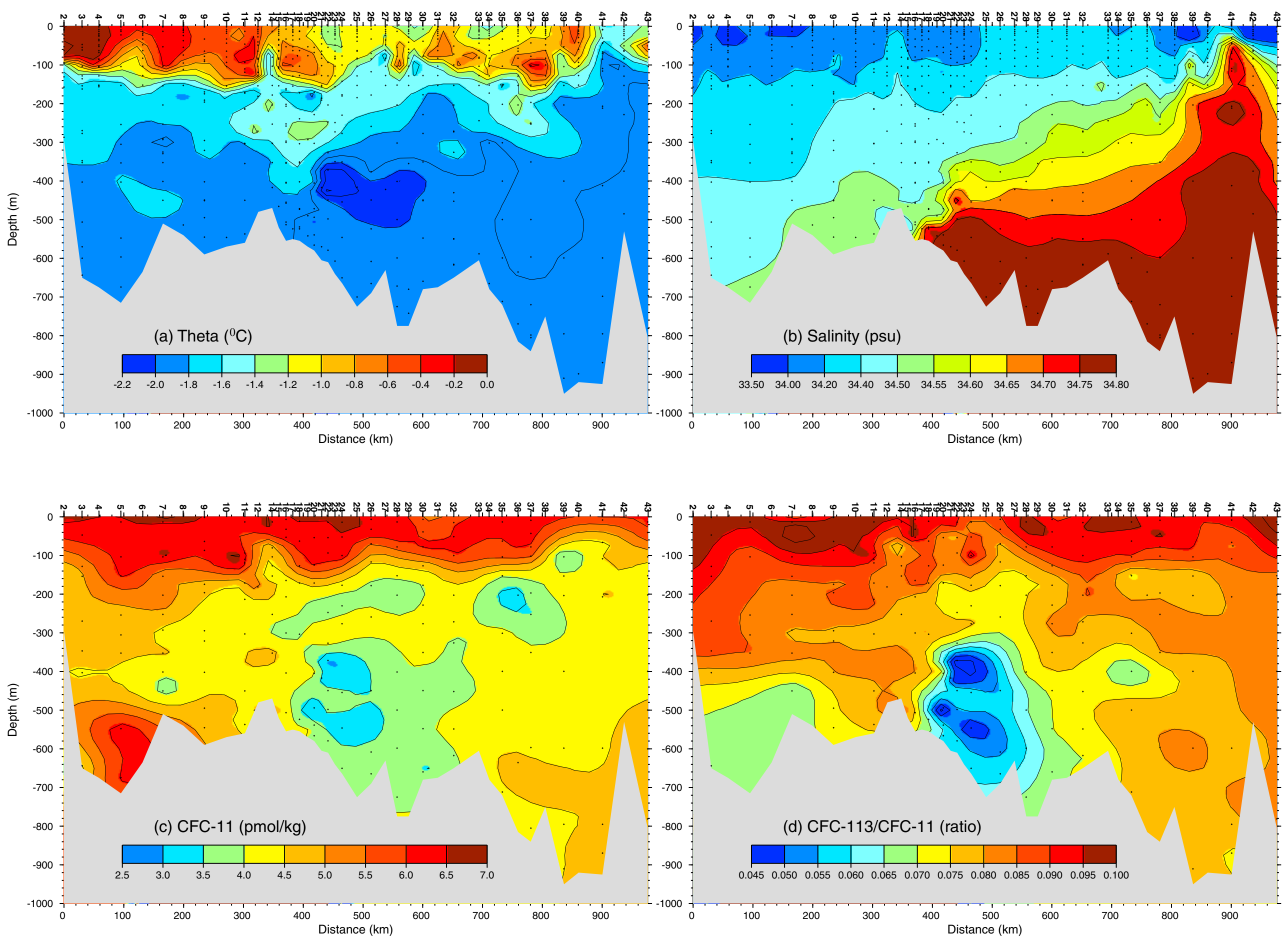

Figure 10. Vertical sections of a) potential temperature, b) salinity, c) CFC-11 and d) the CFC-113:CFC-11 ratio along the front of the Ross Ice Shelf taken in 1994 on NB Palmer cruise 9402.

[F] Tracers: Isotope measurements ($\delta^{18}O$, helium isotopes, neon, and tritium - P. Schlosser, LDEO)

a) Summary

We propose to collect and measure about 600 $\delta^{18}O$, 600 helium isotope and neon, and 150 tritium samples in the framework of the Anslope program. The proposed measurements complement the CFC program proposed by W.M. Smethie and the hydrographic measurements proposed by A. Gordon et al. The data will be used to study (i) the sources of the shelf water contributing to the exchange across the Antarctic Slope Front in the Ross Sea, (ii) the pathways of the waters to the slope front and down the continental slope, and (iii) the mean residence times of the shelf waters. The $\delta^{18}O$ and helium/neon concentration data will be used to determine the sources of the shelf waters that exchange across the slope front (LSSW versus HSSW). The $\delta^{3}He$ data will contribute to the understanding of CDW penetration across the slope front. The tritium data, in combination with CFC data, will be used to estimate the mean residence times of the shelf waters and the transit time of the shelf plumes. The data contribute to overall goals A (cross-slope exchanges and mixing of adjacent water masses), B (outflow of dense Shelf Water), and D (rate of descent and fate of outflowing, near-freezing Shelf Waters) of the Anslope group proposal.

b) Background

Transient and steady-state tracers are used either as regional or global 'dyes' (e.g., CFCs, tritium, tritiogenic or mantle $\delta^{3}He$, $\delta^{18}O$) or as radioactive clocks (e.g., ^{14}C, tritium/^{3}He age). Tracer data add complementary information to 'classical' methods used in Physical Oceanography such as direct current measurements (either Lagrangian or Eulerian) or geostrophic transport calculations.

'Steady-state' tracers

Shelf waters around Antarctica frequently contain significant fractions of glacial meltwater which is characterized by low $\delta^{18}O$ values and high ^{4}He and neon concentrations [Fig. 9; e.g., *Weiss et al.*, 1979, *Jacobs et al.,* 1985, *Schlosser*, 1986, *Schlosser et al*. 1990, *Weppernig and Schlosser*, 1994; *Weppernig et al*., 1996; *Hohmann et al*., 2001a]. The amount of glacial meltwater contained in specific shelf water masses can be used as tracer of these waters. $\delta^{18}O$, ^{4}He and Ne are tools to identify the source waters contributing to the shelf waters that exchange across the slope front in the Ross Sea.

^{3}He is a valuable additional variable for estimates of the fraction of ventilated shelf water contained in the deep and bottom water. ^{3}He is transported into the Weddell and Ross seas via the Antarctic Circumpolar Current and has mean $\delta^{3}He$ values in the WDW/CDW of about 8 to 9% [e.g., *Schlosser et al*., 1987, 1990; *Hohmann et al.,* 2001b]. On the shelves, ^{3}He is lost to the atmosphere by gas exchange. The shelf waters we analyzed to date have mean values close to the solubility equilibrium with the atmosphere ($\delta^{3}He$ values close to -1.8%). ^{3}He is sensitive to the total contribution of shelf water to the deep and bottom water whereas ^{4}He, Ne and $\delta^{18}O$ can be used to quantify the glacial meltwater fraction and to distinguish between specific shelf water masses.

Transient tracers

The strength of transient tracers is their time-dependent delivery to the ocean which can be utilized to study sources, pathways and mean residence times of specific water masses, as well as their interaction with the atmosphere. They are the best proxy signal for studies of the penetration of a climate signal into the interior of the oceans. Tritium is one of the 'dyes' used since the 1960s to study the penetration of surface waters into the interior of the ocean and to delineate their spreading patterns and the related time scales. Additionally, tritium data allow us to estimate the mean residence times of specific water masses, for example shelf waters around Antarctica. This method has been used by *Mensch et al.* [1996] to estimate the mean residence time of ISW underneath the Filchner/Ronne Ice Shelf, as well as the mean residence time of WSW on the shelves of the western Weddell Sea. In this project, we intend to use tritium, together with CFCs (W.M. Smethie), to estimate the mean residence times of the shelf waters in the Ross Sea. These waters, after they exchange across the slope front, feed the plumes on the continental shelves that form deep and bottom waters in the Ross Sea. Estimates of the mean residence times of the shelf waters will be based on simple time-dependent balances [box models; e.g., *Mensch et al.,* 1996], as well as on CFC/tritium ratios [e.g., *Schlosser et al.,* 1991; *Mensch et al*., 1998]. The latter method is based on a significant gradient in the tritium/CFC ratio for roughly the past two decades (Fig. 12) which can be used to determine relative ages of the recently ventilated waters [*Schlosser et al.,* 1991; *Mensch et al*., 1998]. The gradients in the tritium/CFC11 ratios are clearly visible in depth profiles from stations occupied during Ice Station Weddell in the northwestern Weddell Sea (Fig. 11) and during DOVETAIL (unpublished data). The tritium/CFC11 ratios can be converted into transit times of waters from their source regions to specific sampling locations. We plan to use this tool in our evaluation of Anslope data from the continental slope.

c) Previous isotope studies

Starting in the mid-80s, on the basis of the work by *Weiss et al*. [1979] and *Jacobs et al*. [1985], we further developed $\delta^{18}O$ as tracer of shelf water masses in the Southern Ocean. At the same time, we introduced ^4He as additional tracer of glacial meltwater [*Schlosser,* 1986]. The combination of the two tracers and salinity allowed us to estimate the concentration of glacial meltwater in the individual shelf waters around the Weddell Sea, and the melting and refreezing rates underneath the Filchner/Ronne Ice Shelf [*Schlosser et al*., 1990; *Fahrbach et al.*, 1994]. Additionally, we were able to trace ISW formed in the Weddell Sea down the continental slope (to about 2000 meters depth). In a later study we used $\delta^{18}O$ and ^4He to separate ISW and WSW contained in the newly formed deep and bottom waters in the Weddell Sea [*Weppernig et al.,* 1996].

There are much less isotope data available for the Pacific sector of the Southern Ocean. Early work by *Jacobs et al.* [1985] laid the foundation for use of oxygen isotopes in the Ross Sea. Recent helium/neon work in the Amundsen/Bellingshausen Sea showed that neon is an excellent additional tracer of glacial meltwater [Fig. 12; *Hohmann et al*., 2001a]. Unpublished data by Jacobs et al. from the Ross Sea (collected in 1994) confirm the existence of a significant glacial meltwater signal in $\delta^{18}O$. On the basis of the preliminary work we expect to find pronounced tracer signals of glacial meltwater. These signals mark the individual shelf water masses in distinct ways. We will use these signals in the framework of Anslope to determine which shelf waters penetrate to and across the slope front.

Early work of *Weiss et al*. [1979] demonstrated that tritium is a valuable tracer for estimates of deep and bottom water formation rates in the Weddell Sea. Since then, we improved the measurement precision of tritium and applied tritium measurements to the problem of deep water formation [*Bayer and Schlosser,* 1991; *Mensch et al.,* 1996, 1998], as well as the determination of the mean residence times of shelf waters [ISW, WSW; *Mensch et al*., 1996]. In collaboration with W.M. Smethie, we will use tritium and CFC data to determine the pathways and mean residence times of the shelf waters in the Ross Sea. We will also apply the tritium data to study the pathways of the shelf waters down the continental slope.

d) Objectives

The objectives of this component of the Anslope proposal are to create a comprehensive $\delta^{18}O$, helium isotope, neon, and tritium sample set, and use the measurements to:

- Identify the sources of the shelf waters observed south of the slope front. This includes waters formed by exchange with the atmosphere (tritium, δ^3He) as well as by interaction with ice shelves (^4He, Ne, $\delta^{18}O$).
- Study the pathways of these waters to the slope front.
- Study the structure of the slope front and the exchange across the front.
- Estimate the mean time between formation of these waters and exchange across the slope front.
- Determine the origin of the waters that form the plume on the continental slope (after passing the slope front) and their pathway into the deep ocean.
- Provide tracer data sets for the modeling studies (Anslope and other long-term efforts to simulate deep and bottom water formation in the Southern Ocean).

e) Proposed Work

Sample collection

We plan to collect ca. 400 $\delta^{18}O$ and helium isotope/neon samples and ca. 75 tritium samples in the framework of the large scale survey during the first summer cruise. An additional 100 $\delta^{18}O$ and helium isotope/neon samples and 25 tritium samples will be collected in the canyon. During the winter cruise we will collect ca. 100 $\delta^{18}O$ and helium isotope/neon samples, as well as 50 tritium samples in core water masses to elucidate the summer/winter changes in the tracer distributions.

Measurements of tracer samples

The tritium and helium isotope samples will be measured in the L-DEO Noble Gas Laboratory using two separate, dedicated, fully automated mass spectrometric systems (see L-DEO NGL WWW page: http://www.ldeo.columbia.edu/~noblegas; section on instrumentation). Precisions of the tritium, He/Ne concentrations, and $\delta^{3}He$ values will be ±2%, ±0.5%, and ±0.2 to 0.3%, respectively.

The $\delta^{18}O$ samples will be measured in the laboratory of Dr. Richard Fairbanks at L-DEO which can produce about 200 high-quality data per week (precision of $\delta^{18}O$ values: about ±0.02 to 0.03‰).

Link to other programs

The proposed work is coordinated with our participation in the Italian CLIMA project (samples collected with support from the NOAA CORC program; CORC: Consortium on the Oceann's Role in Climate). The samples from this cruise to the Ross Sea (January-February 2001) and from Stan Jacobs's cruise to the Ross Sea and Amundsen/Bellingshausen seas (summer 2000; also collected with NOAA CORC support)) provide good coverage of the inner shelf waters. This information is valuable for understanding of the circulation of the shelf waters that move towards the slope front and are exchanged across it.

f) Results from previous NSF support

DPP-90-25099: 7/1/91 to 6/30/94; Bottom Water Formation and Water/Ice Interaction in the Weddell Sea Studied by O-18 and Helium Isotope Measurements $363,874

As part of the Ice Station Weddell hydrography/tracer program, we collected about 400 helium isotope, 700 $\delta^{18}O$, and 300 tritium samples. Most of these samples were collected on stations along the drift track of the ice camp (early 1992). A small sample set was obtained from stations occupied by the Russian icebreaker AKADEMIK FEDOROV during the ice station deployment cruise.

We observed higher ^{4}He concentrations in the near-bottom waters of the southern part of the ice station drift track than in the northern part [*Weppernig and Schlosser*, 1994; *Weppernig et al*., 1996]. We interpret this pattern as an indication that there are different types of shelf waters contributing to the deep and bottom waters formed in the western Weddell Sea. The bottom waters with high ^{4}He concentrations contain more glacial meltwater than those with low ^{4}He concentrations [helium is added to the water by dissolution of air included in glacial ice during melting at the underside of ice shelves; *Schlosser*, 1986; *Schlosser et al*; 1990]. The $\delta^{18}O$ results are consistent with the helium isotope data but show additional features which would not be visible in the T/S or He isotope data [*Weppernig et al*., 1996]. The main result of the ISW ^{4}He and $\delta^{18}O$ measurements was the separation of ISW-derived from WSW-derived bottom water and the determination of the contribution of ISW to deep bottom water formation. ISW–derived deep and bottom water contributes about 1/3 of the total deep and bottom water formed in the southwestern Weddell Sea [*Weppernig et al.,* 1996].

The tritium results from ISW were used, together with the CFC results, to determine the mean 'age' of the newly formed bottom water found on the slope of the southwestern Weddell Sea [7±2 years*; Mensch et al.,* 1998]. This age is dominated by the age of the shelf water [*Mensch et al*., 1996].

OPP 94-12190; 4/15/94 -3/31/95, Collection of Tritium/Helium Samples from the Amundsen and Bellingshausen Seas $25,000

We collected about 300 tritium and 300 helium isotope samples on the shelves and across the continental slope of the Ross, Amundsen and Bellingshausen seas [*Jacobs et al.,* 1994]. The He isotope and neon measurements conducted in the framework of CORC (Consortium on the Ocean's Role in Climate) typically show very high concentrations of glacial meltwater related to frontal melting. The data were summarized in a manuscript that has been submitted to JGR [*Hohmann et al.,* 2001a].

OPP 93-17231 Scope B; 5/1/94 - 4/30/97, ANZFLUX (Antarctic Zone Flux Experiment) CTD/Tracer Program $262,203

We collected, measured, and interpreted about 400 helium isotope samples in the framework of ANZFLUX. The results show the expected signals, i.e., ^{3}He supersaturation in the surface waters due to entrainment of Weddell Deep Water during winter. The ^{3}He and DO data that were obtained simultaneously were converted into entrainment rates of WDW into the winter mixed layer and the related heat fluxes. The results have been submitted to JGR [*Hohmann et al.,* 2001b, revised manuscript]. They also contributed to an overview publication [*Muench et al.*, 2001a].

OPP 95-28805; 3/1/97 - 2/28/01; DOVETAIL $292,742

In the framework of the DOVETAIL experiment we collected about 600 tritium, helium isotope and δ^{18}O samples in the regions of the northwestern Weddell Sea, the Weddell-Scotia Confluence Zone and the Bransfield Strait. All samples (except some δ^{18}O samples) have been measured and the data set is presently prepared for publication. First results were presented at the DOVETAIL workshop at Barcelona (May 00).

Publications and presentations containing results from previous NSF grants :

Refereed Journals - *Hohmann, et al.* [2001a]; *Hohmann, et al.* [2001b]; *Mensch, et al.* [1996*]; Mensch, et al.* [1998]; *Muench, et al.* [2001a]; *Weppernig, et al.* [1996].

Other publications and presentations:

Huber, B.A., Schlosser, P., and Martinson, D.G., 1995. Thermohaline structure and tracer studies during ANZFLUX. Antarctic Journal of the US. 30(5), p.129-131

ISW Group, 1993. Weddell Sea Exploration from Ice Station. EOS, 74, no. 11 121, 124-126.

Jacobs, S.S.; Hellmer, H.H.; Schlosser, P.; Smethie, W.M., Jr. 1994. Oceanographic expedition to the Amundsen and Bellingshaussen Seas. Antarctic Journal of the United States; p. 109-111; 29(5).

Muench, R.D., Morison, J.H., Padman, L., Martinson, D.G., Schlosser, P., Huber, B., and Hohmann, R., 1999. Sea-air heat fluxes in the eastern Weddell Sea. EOS Transactions, American Geophysical Union, 80, p. OS188.

Schlosser, P., Weppernig, R., Bullister, J.l., Mensch, M., and Bayer, R., 1997. Results from tracer studies of the deep water formation and circulation in the Southern Ocean. IAPSO Proceedings, 19, 326.

Weppernig, R. Schlosser, P., Fairbanks, R.G., and Khatiwala, S., 1997. Deep Water formation in the Weddell Sea: implications from Ice Station Weddell tracer observations. IAPSO Proceedings, 19, 321.

Weppernig, R. and Schlosser, P., 1994. Helium isotope data from Ice Station Weddell. Antarctic Journal of the US, XXVIII, 76-77, 1994.

Weppernig, R., P. Schlosser, D. Grabitz and R. Fairbanks, 1993. Deep water formation in the Weddell Sea studied by helium and oxygen isotope data; presentation at the Nansen Symposium, Bergen, Norway.

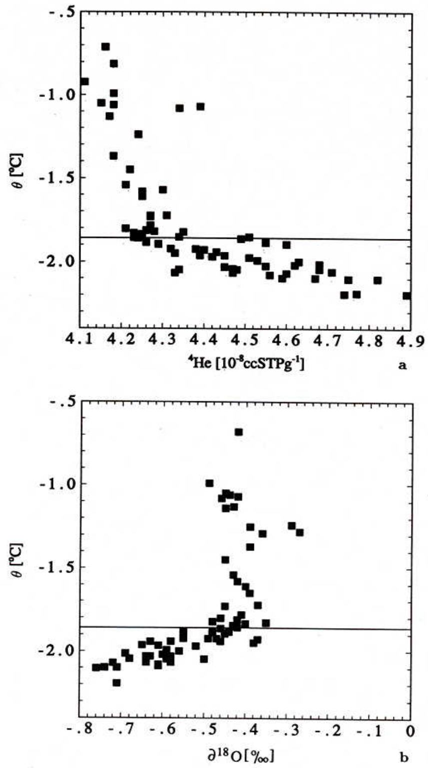

Figure 11: Plot of 4He and d18O as a function of potential temperature. There is a strong tracer signature in ISW (pot. Temp. <-1.87 C) caused by addition of glacial meltwater [data from Filcher/Ronne Trough; adapted from *Schlosser et al*., 1990].

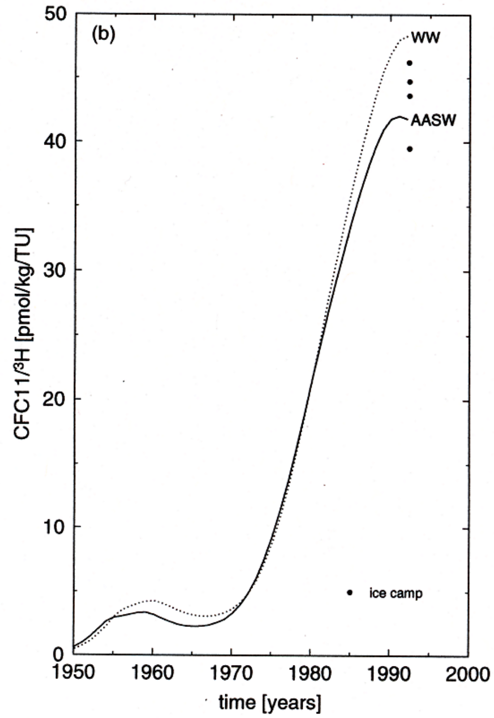

Fig. 12: Temporal evolution of the CFC11/tritium ratio in Antarctic Surface Water and In Winter Water [*Mensch et al.*, 1998].

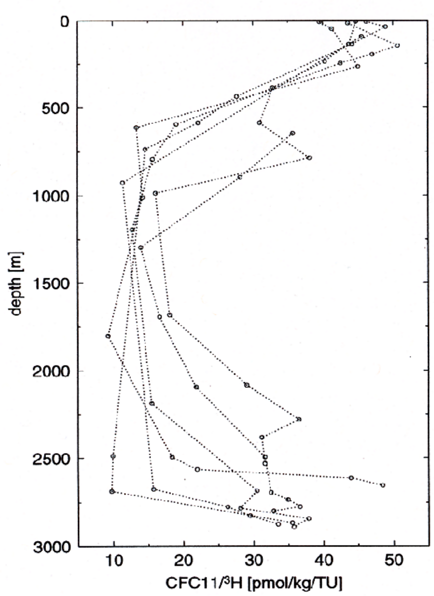

Fig. 13: CFC11/tritium ratios observed at stations in the north-western Weddell Sea. The relatively young water near the surface and close to the bottom indicated rapid renewal of these water layers [*Mensch et al.*, 1998].

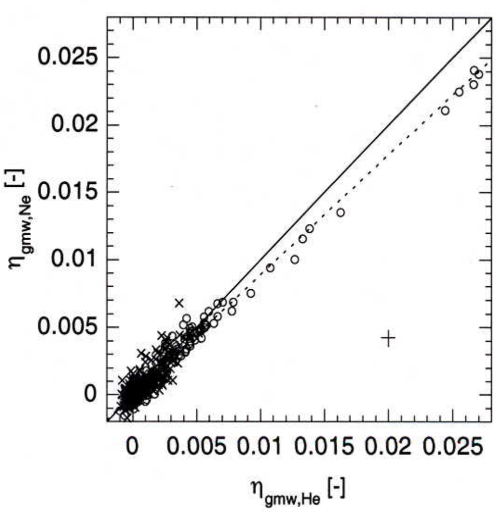

Fig. 14: Plot of the fraction of glacial meltwater derived from 4He and Ne in shelf waters from the Amundsen/Bellingshausen seas [*Hohmann et al*., 2001a]. There is a clear meltwater signal of typically a few per mil to a few percent.