Deep Ocean Ventilation Through Antarctic Intermediate Layers

Deep Ocean Ventilation Through Antarctic Intermediate Layers: The DOVETAIL program

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A major portion of the Southern Hemisphere water conditioning that leads to formation of bottom water in the world ocean occurs in the Weddell Sea. The goal of the international program for study of Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) is to understand physical processes in the Weddell–Scotia Confluence (WSC) region sufficiently to quantify the ventilation of the world ocean achieved by Weddell Sea water masses. The WSC is a site of energetic interactions among water masses flowing from the Weddell Sea, the Pacific Ocean and Bellingshausen Sea, the Bransfield Strait, and shelf-conditioned waters from the regions surrounding the Antarctic Peninsula. It overlies a region of steep, complex bathymetry dominated by the South Scotia Ridge, which limits north-south exchange to a few deep, narrow channels, and is thought to represent a gateway for the most direct and largest of these flows of antarctic water (figure 1). It is imperative that we understand the associated physical processes so we can assess their sensitivity to changes in regional forcing, hence, the impact of such changes on world ocean ventilation.

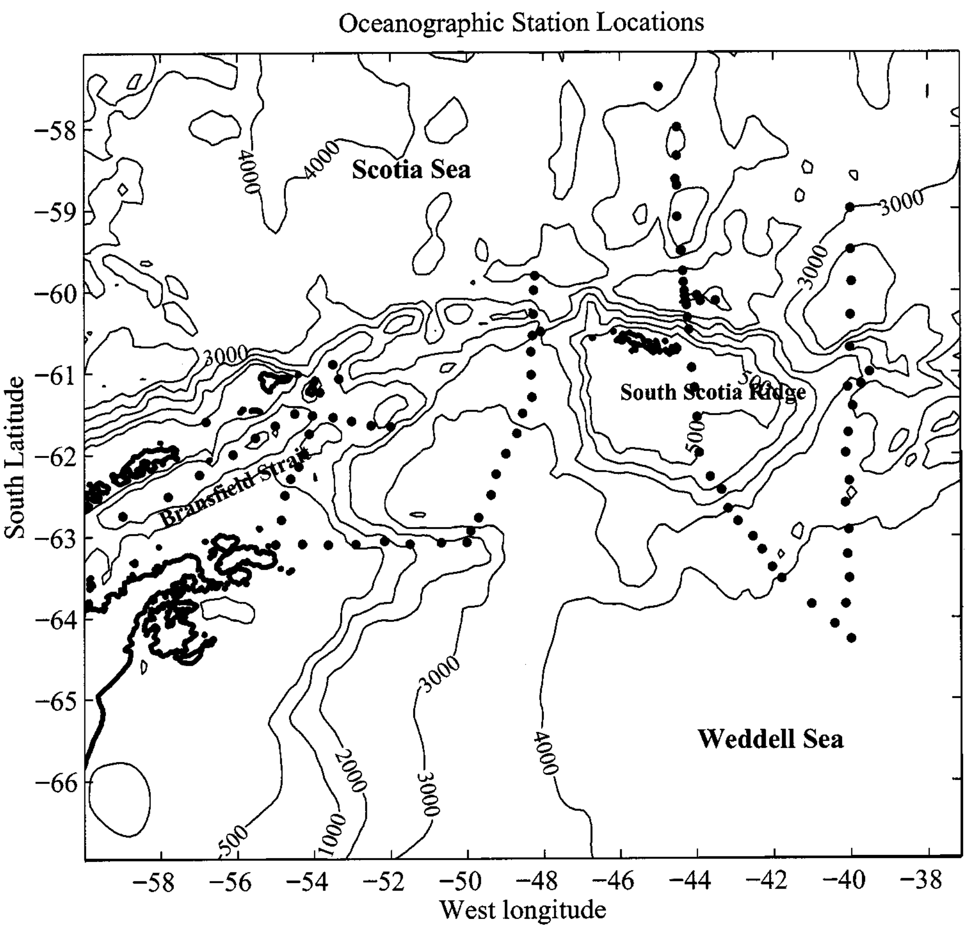

Figure 1. Location of the DOVETAIL study region. Isobaths are labeled in meters. Circles show locations of oceanographic stations occupied by the *Palmer* in August 1997. The transects are located in such a way as to sample the primary boundary currents, which tend to parallel steep bottom slopes in the WSC region.

Four objectives contribute to the overarching DOVETAIL goal. The first is to assess the quantity as well as the physical and chemical characteristics of Weddell Sea source waters for the WSC region. This assessment will tell us the maximum volume of Weddell Sea water that is available for deep-ocean ventilation as Antarctic Bottom Water. Additionally, it will provide initial values for chemical parameters and tracers that can then be compared with downstream conditions in the WSC region and used to estimate ages and sources of waters and to determine mixing relationships during passage through the WSC region. Information about the mechanisms of source-water formation is particularly important to understanding the possible influences of climate change on bottom-water production.

The second objective is to describe the dominant physical processes associated with spreading and sinking of dense antarctic waters within the WSC region. Available information based on both field and modeling efforts suggests that these waters exit the Weddell Sea either as boundary currents in deep channels or as flow along isopycnal surfaces (surfaces of equal water density). Water as shallow as about 400 meters in the Weddell Sea, following isopycnal surfaces northward, attains depths exceeding 3,000 meters during its northward passage through the WSC. The latter mechanism likely includes water-mass modification by turbulent mixing and transport by mesoscale processes such as eddies.

The third objective is to estimate the role of the Weddell Sea in ventilation of the world ocean. The northward volume transport of water, along with its physical and chemical properties, will help to quantify the mixing history of water available for deep-ocean ventilation north of the WSC.

The final objective is to estimate seasonal fluctuations in regional ocean transport and hydrographic structure and to assess the likely influence of interannual variability on rates of ventilation by Weddell Sea waters. Past field and modeling results indicate significant seasonal and interannual variability in both the Weddell Gyre and in the Antarctic Circumpolar Current (ACC). The WSC forms part of the northwestern limb of the Weddell Gyre and is bounded on the north by the ACC, and hence, must be influenced by variability in both regimes. New field measurements coupled with modeling efforts and synthesis with older results will help us to understand the physical interactions that link the seasonal and interannual changes and that might link climate change with ventilation rates.

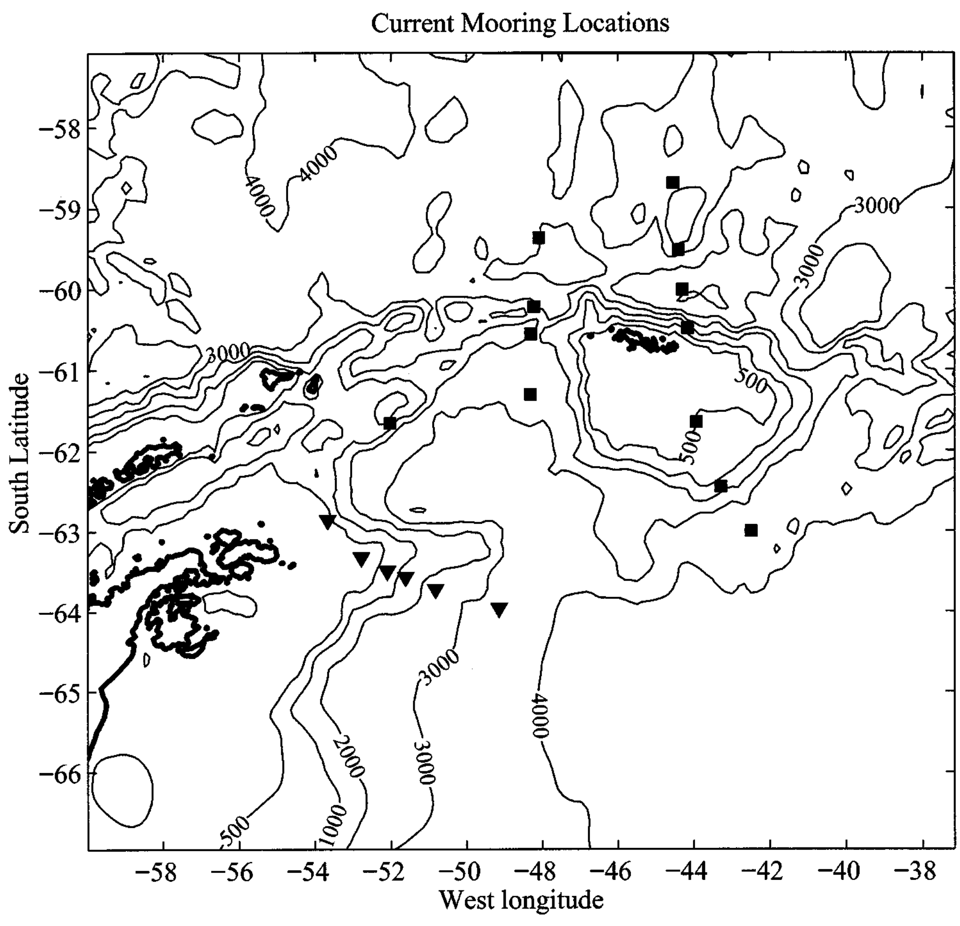

Figure 2. Locations of the DOVETAIL current moorings. Isobaths are labeled in meters. Triangles show locations of the German/Spanish current moorings deployed by *Polarstern* during March 1996 and scheduled to be recovered in late autumn 1998. Squares show locations of the current moorings deployed during August 1997 by the *Palmer.* Current meters deployed by the *Palmer* are designed to self-release and return data via the Service Argos satellite link, so will not need to be recovered.

DOVETAIL pursues its goal and objectives using a closely integrated field and modeling program. The field component measures critical hydrographic, tracer, and chemical parameters and currents in the northwestern Weddell Sea, a source region for the WSC, through the WSC itself, and in the southern Scotia Sea, which is the sink for water that has passed through the WSC. The hydrographic, tracer, and chemical observations take place during cruises in the austral summer, autumn, and winter seasons. Currents are being measured in the same region using moored current meters deployed as long as 26 months. These observations will be used to describe the mean hydrographic and current fields, to estimate seasonal differences, and to assess the roles of mesoscale processes. Numerical models will use these field data, in conjunction with historical data, to specify boundary conditions, for parameterizations, and for verification. The models will serve to interpolate and extrapolate the data and will aid in identification and quantification of regional processes.

Two major field programs have been carried out, to date, under the DOVETAIL umbrella. The first of these took place during March 1996 when the German icebreaking research vessel *Polarstern* carried out a sampling program for water column physical, chemical, and tracer parameters and deployed six long-term current-meter moorings as part of a joint German/Spanish study (figure 2). The moorings are planned to be recovered by *Polarstern* in late autumn 1998. The second took place during August 1997 when the U.S. icebreaking research vessel *Nathaniel B. Palmer* occupied a series of transects in the WSC along which physical, chemical, and tracer parameters were measured (figure 1). On this latter cruise, 11 long-term current moorings were deployed and will commence returning data as early as April 1998 (figure 2).

The DOVETAIL program is the third in a sequence of integrated field and modeling programs that were initiated in 1992 and carried out in the Weddell Sea. All three programs have been coordinated by the international Antarctic Zone (iAnZone) group, now a Commission of the Scientific Council on Ocean Research (SCOR). The first two programs have focused on processes associated with ocean ventilation in the polar waters. DOVETAIL proposes to build upon the results from these two preceding programs by focusing on the escape of recently ventilated deep water from the Weddell Sea into the world ocean. In this way, it hopes to better define and understand the role of antarctic waters and processes in the ocean and climate systems.

DOVETAIL priorities parallel, and the results will contribute to, ongoing global change research. The processes responsible for vertical and horizontal fluxes within the ocean and associated interaction with the sea ice and atmosphere in polar regions must be properly represented. The DOVETAIL study region, off the tip of the Antarctic Peninsula, serves as the primary gateway between the southern polar waters and the world ocean. Results from the DOVETAIL experiment will aid in establishing a basis for long-range monitoring of this critical region, inasmuch as both the Global Ocean Observing System (GOOS) and the ocean component of the Global Climate Observation System (GCOS) have been established by a number of international bodies to provide such monitoring data.

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Surface ice-drifters in the Weddell–Scotia Confluence for the DOVETAIL program

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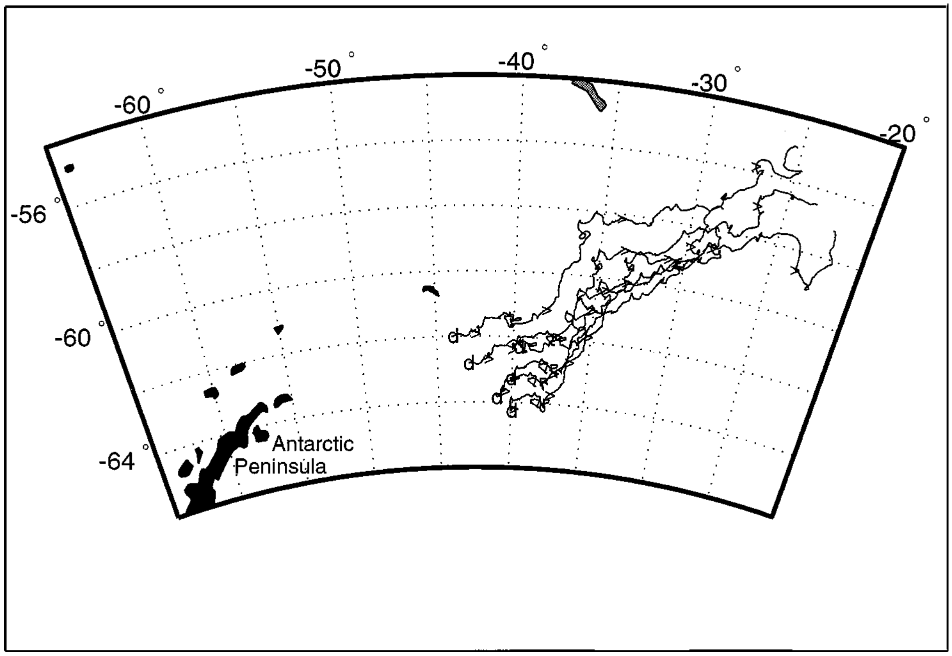
This module of the Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) experiment (see overview by Muench, *Antarctic Journal,* in this issue) is designed to contribute a field component and modeling study. Initial results from our modeling activities are reported in a companion article (Holland and Martinson, *Antarctic Journal*, in this issue). This article addresses the field component. In particular, we have deployed six surface ice-drifters in an effort to monitor ice motion, air temperature, and pressure, providing surface forcing, or ground truthing of model-based forcing fields, for the ocean modeling component and DOVETAIL program in general.

The surface forcing will help differentiate between changes in the mixed layer due to surface fluxes and those induced by lateral displacements. These data provide the only time series of the surface forcing that drives local temporal modification of the thermohaline fields in this program.

Specifically, the ice-drifters provide hourly samples of air-temperature and pressure and an Argos transmitter to relay position, and the other data, via satellite. These measurements provide information about surface stress, geostrophic winds, and thermodynamic forcing and give estimates of surface winds and freshwater input.

The surface stress is quadratically proportional to the ice velocity; the latter extracted from ice position. The geostrophic winds will be determined from the pressure data, supplemented by the larger pressure field data available from the numerous weather stations situated throughout the Antarctic Peninsula region. The thermodynamic forcing is provided by the air-temperature observations in conjunction with standard bulk aerodynamic formulae. The near-surface air temperature will also be used to estimate the longwave back-radiation, because it is fairly well established that the ice-surface temperature is in equilibrium with average surface-air temperature (Guest personal communication). Incoming radiant heat fluxes will be computed using standard radiative transfer schemes (cloud cover will be obtained from AVHRR images when possible).

Surface winds will be estimated using the relationship of Martinson and Wamser (1990), which shows a strong correlation between ice speed and 3-day average wind speed. The relationship between wind direction and ice direction is typically 20°±20°. These surface-wind estimates will be compared to those estimated by extrapolating from the geostrophic winds to the surface (e.g., Hoeber and Gube-Lehnhardt 1987) assuming a typical stability profile from the region (e.g., Wamser and Martinson 1993; Andreas and Claffey 1995). They will also be compared to the ECMWF and NCAR gridded field values, which will be used to force the longer term model simulations, to provide some consistency checks. The winds are required for the turbulent heat-flux bulk formulae, and the derived values should be of sufficient accuracy to constrain the forcing within statistically reasonable limits (which will be tested through sensitivity studies).



Buoy tracks for the six ice-drifters deployed in August during the DOVETAIL cruise. "d" denotes the deployment locations and ">" marks every 30 days.

The freshwater (ice melt) input is proportional to the thermal anomaly across the ice-water interface and quadratically related to the relative ice-water speed (McPhee 1994). The water temperature and surface-water velocity will be predicted by the model and diagnosed by comparison to the near-surface current meters and hydrographic survey data.

The drifters, which are low-cost, off-the-shelf devices that have 6-month battery life, are provided by Metocean Data Systems. They were deployed in August 1997 during the DOVETAIL cruise. The buoys do float but were deployed atop ice floes since they are not designed for open-ocean measurements because they are inherently unstable in a wave field. Thus, once the ice platforms drift north into warm waters and melt, the drifters will likely fail, or return only sporadic data. The ice-drifters were placed on typical ice floes at the southeastern edge of the study region (figure) after which they drifted northeasterly as seen in the figure. Originally, the drifters were to be deployed in triads (providing ice divergence); one triad deployed during each DOVETAIL cruise to provide the most continuous coverage of the study region over the longest period. Unfortunately, because of the loss of one of the cruises due to ship problems, all six drifters were deployed during the solo cruise. They were deployed in two triads. Though we lose our ability to provide long-term monitoring of the surface conditions, we gain a more robust image of the conditions during the central winter months allowing a more thorough assessment of the period monitored and its spatial variations. At the present time, the drifters are still functioning.

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Modeling deep ocean ventilation in the Weddell–Scotia Confluence

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The relatively large heat capacity of the global ocean makes it likely to be an important player in determining both the general nature and variability of our climate system. In this regard, an important aspect of the ocean that requires better understanding is the rate at which it forms and ventilates its deep waters. In this study, we focus on the contribution of antarctic waters, and in particular those waters forming in the Weddell Sea, to the ventilation of the global ocean. At present, a large international program is underway to study this process under the name of the Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) experiment (see overview by Muench, *Antarctic Journal*, in this issue). The geographical setting for the study, shown in figure 1, is the vicinity of the Weddell–Scotia Confluence (WSC), which is a key region for the exchange of water masses between the Weddell Sea and global oceans.

The specific objectives of the DOVETAIL study are fourfold:

- to determine the quantity of Weddell Sea and Scotia Sea waters that are likely to be exchanged in the WSC;
- to identify the key physical processes that control the exchange;
- to quantify the relative contribution and importance of the WSC region to the overall ventilation of the world ocean; and
- to look at seasonal and interannual variability of the ventilation process to help in understanding its possible importance to variability of global deep-water mass properties.

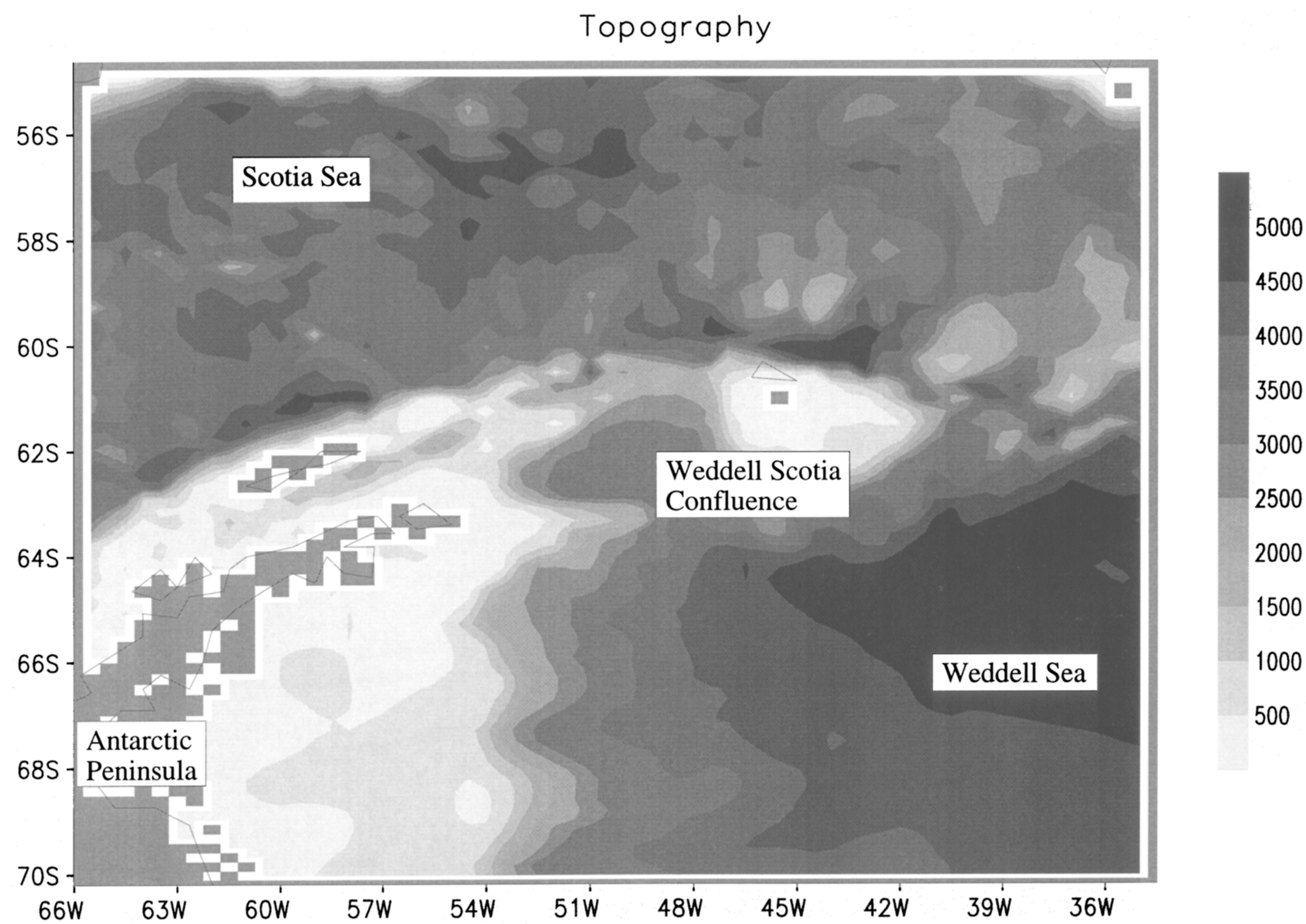

Figure 1. Model domain and bathymetry (in meters). The main morphological features of the study area are the Antarctic Peninsula, the Weddell Sea, the Scotia Sea, and the Weddell–Scotia Confluence.

These objectives are to be met by carrying out an integrated field and modeling program. This article is a preliminary report on one of the DOVETAIL modeling activities.

The WSC is a region of extreme characteristics, dominated by strong currents, intense storms, and complex bottom topography. Therefore, our modeling activity focuses on assessing statistically robust features of the ventilation and flow and general sensitivities of the rate, paths, and variability of the flow to the forcing and lateral boundary conditions. Specifically, we are addressing these statistical aspects by experimenting with two different models and performing a series of experiments under a variety of statistically reasonable forcings and boundary conditions.

Our initial modeling activity has involved the configuration of the Miami Isopycnal Coordinate Ocean Model (MICOM); a layered model that uses density as its vertical coordinate (Bleck et al. 1992). This model discretizes the ocean into a series of horizontally stacked isopycnal layers with the exception of the mixed layer, which is nonisopycnal because it is driven by surface buoyancy fluxes. For each layer, we solve for temperature, salinity, thickness, and velocity using the appropriate shallow-water equations. Our motivation for choosing an isopycnal coordinate model is that we believe that the subsurface waters in the real ocean flow and mix primarily along isopycnal surfaces. The present modeling framework allows us to mimic that behavior. An additional benefit is that the only vertical mixing processes that occur between layers are the diapycnal fluxes that we explicitly choose to include in our model—there is no hidden or otherwise implicit numerical vertical diffusive contribution. We have also coupled a

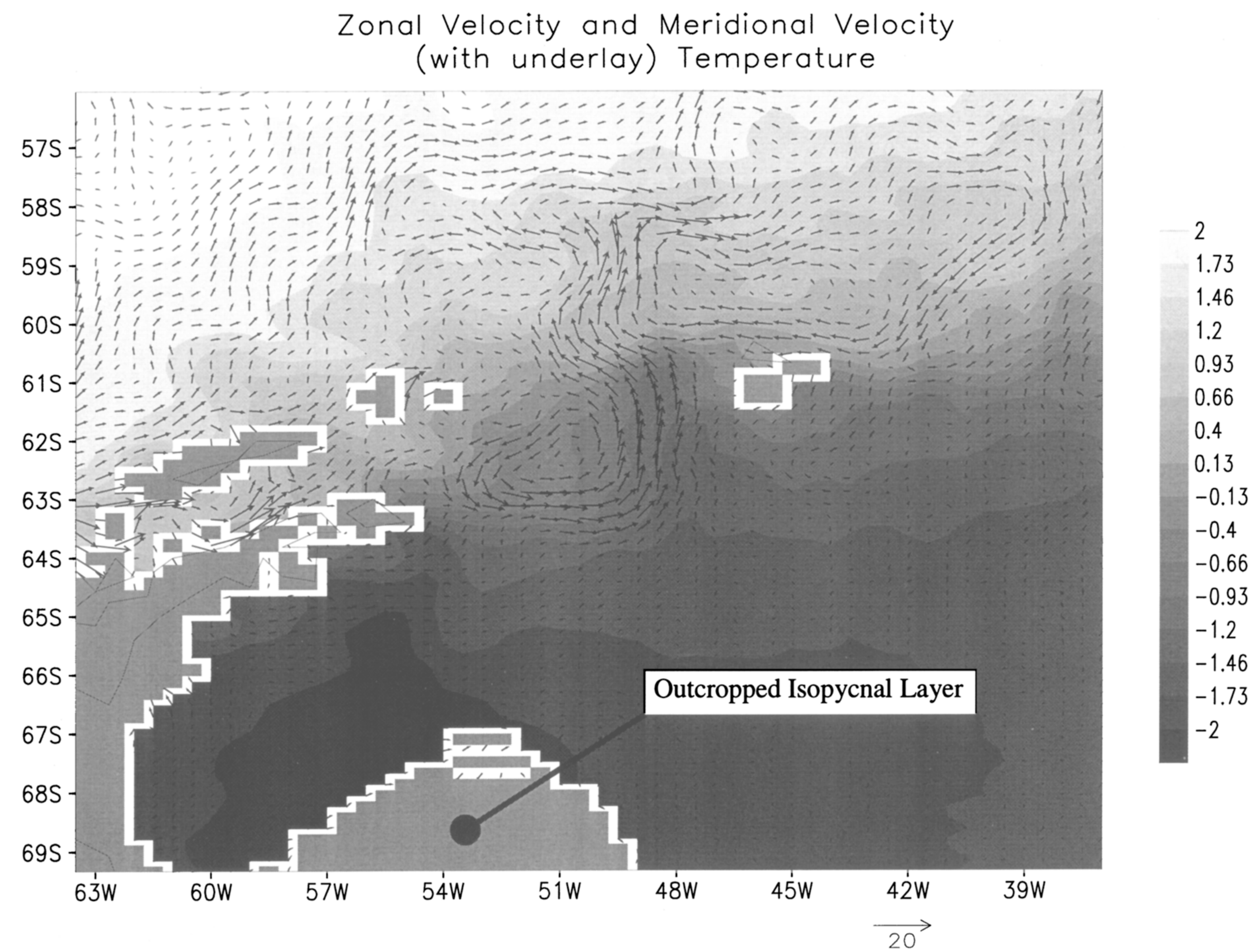

Figure 2. Modeled flow vectors (in centimeters per second) on the 1,027.7-kilogram-per-cubic-meter isopycnal surface. The scale length for velocity shows 20 centimeters per second. The shaded underlay indicates the potential temperature (°C) on the isopycnal surface. The nature of isopycnal surfaces in this region is such that they shoal as one traverses the domain from the Scotia Sea southward into the Weddell Sea. Additionally, the cyclonic circulation of the Weddell Gyre causes the isopycnal surface to dome and hence outcrop in the center of the gyre.

dynamic-thermodynamic sea-ice model to our ocean model for the purpose of more accurately estimating the exchange fluxes of heat, mass, and momentum at the ocean surface in the WSC region. The coupled ice-ocean model is driven by standard atmospheric forcing products available from the National Center for Atmospheric Research and the European Center for Medium Range Weather Forecasting archives.

To test the suitability of the MICOM model to our study region, we set up the model with a vertical resolution of 10 isopycnal layers ranging from a surface density of 1,027.4 kilograms per cubic meter (kg/m^3) to a bottom density of 1,028.2 kg/m^3. The horizontal resolution is approximately 20 kilometers. The model domain spans from 65 west to 35 west and from 70 south to 55 south. We initialize the model temperature and salinity fields using the Levitus (1982) climatology. Along the open boundaries of our domain, we restore the model hydrography in a relatively narrow band to that of the Levitus climatology throughout the model run. We are presently analyzing the model output from our first completed runs to determine how the model simulates water mass exchange and transformation between the Weddell Sea and Scotia Sea via the channels and passageways of the WSC.

As an example of the simulated exchange, we show the modeled temperature and flow field (figure 2) as well as salinity and flow field (figure 3) for the intermediate 1,027.7 potential density surface. This surface occurs at an intermediate depth in the confluence region and is thus representative of how water masses flow and mix there. We clearly see the southward flowing warm and salty water from the Scotia Sea as it travels through the confluence; likewise, the northward flowing cold and fresh Weddell waters are also evident. Even at this modest horizontal resolution, the strong impact of topographic steering is quite evident by comparing the correlation between topographic features in figure 1 and the flow fields in figures 2 and 3.

Our next modeling activities are to increase both the horizontal and vertical resolutions to increase, we hope, the accuracy of the simulation. The increased horizontal resolution to approximately 3-kilometer size will mean that we can begin to resolve mesoscale eddies. The output from such higher resolu-

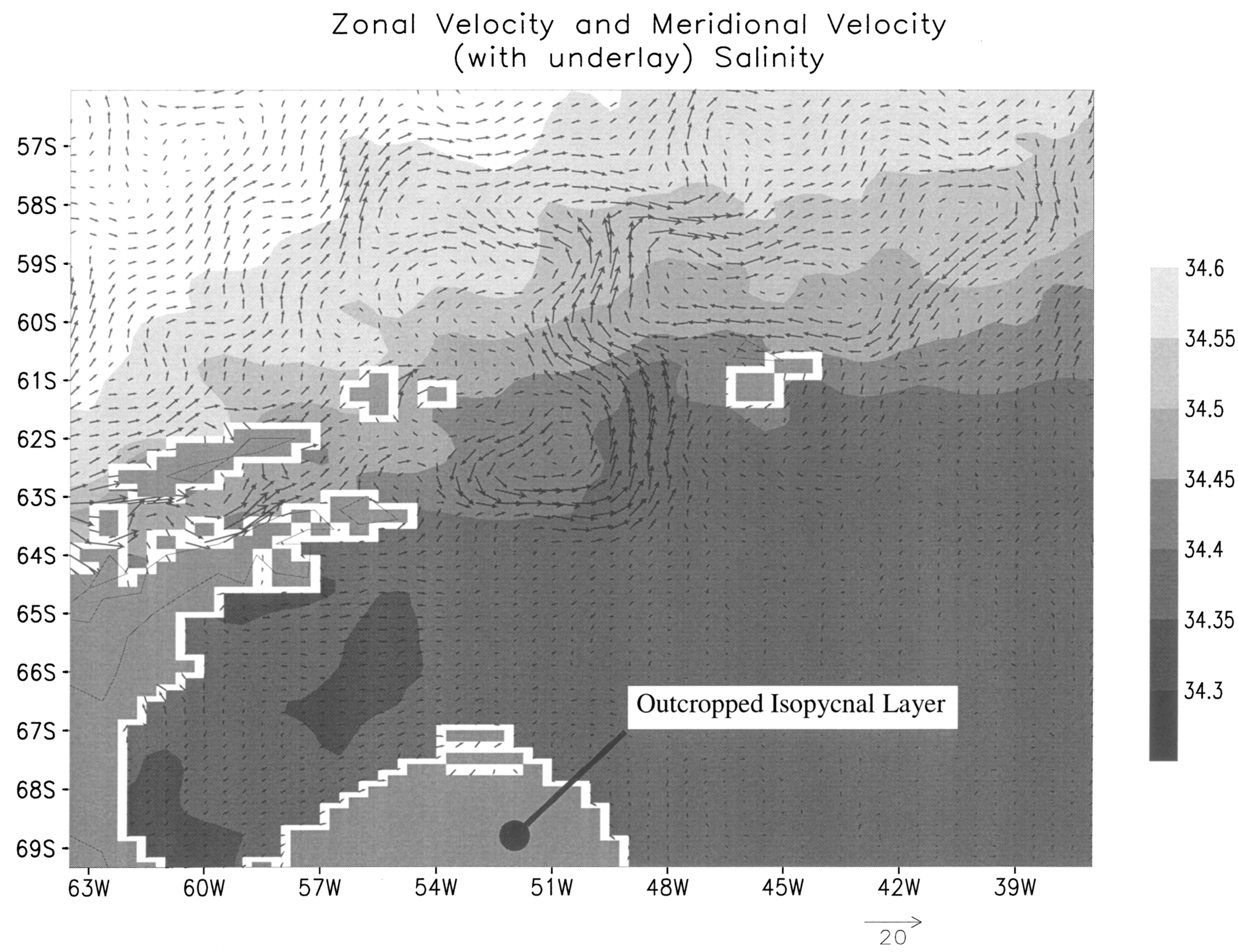

Figure 3. Same as for figure 2 except with salinity (in practical salinity units) projected onto the isopycnal surface instead of temperature.

tion model runs will be used in diagnostic studies to quantify the amount of Weddell Sea deep water that is flowing through the confluence zone and thereby contributing to the deep waters of the world ocean. In that context, we will be comparing the amount of heat and freshwater that is transported laterally by the ensemble mean circulation, the stationary eddies, and the transient eddies in an effort to determine the dominant mechanism for lateral transport and ventilation. These runs and their robust aspects will ultimately be compared to the observational data once those become available (the moorings have been deployed for a year, although the conductivity-temperature-depth data acquired during the deployments will provide some initial constraints and diagnostics).

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Export of Weddell Sea water along and over the South Scotia Ridge

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As part of the international DOVETAIL (Deep Ocean Ventilation Through Antarctic Intermediate Layers) program, 97 conductivity-temperature-depth (CTD) with Lowered Acoustic Doppler Current Profiler (LADCP) and tracer stations were obtained from the *Nathaniel B. Palmer* (cruise 97-5) from 31 July to 8 September 1997 in the southern Scotia Sea and northern Weddell Sea. Muench (*Antarctic Journal*, in this issue) shows the station distributions; the figure shows various parameters along the 45°W section. 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 provide a snapshot of the velocity field at the time of the CTD stations.

The DOVETAIL CTD/LADCP/tracer data set is very extensive and a number of research topics pertaining to Weddell Sea forced ocean ventilation can be pursued. Preliminary findings are as follows.

Warmer Weddell Deep Water temperature maximum

The warming of Weddell Deep Water observed during the last few decades within the central Weddell Gyre extends into the northwestern Weddell Sea. Weddell Deep Water warming in that region between 1992 and 1997 amounts to nearly 0.2°C. This trend may result from decrease of deep-water heat loss to the atmosphere and cryosphere or increase of injection of warm circumpolar deep water into the Weddell Gyre.

Benthic layer

The DOVETAIL CTD/tracer data along with the 1992 Weddell Ice Station data set nicely define the stratification and spatial pattern of the Weddell Sea Bottom Water benthic layer in the western and northwestern Weddell Sea. The DOVETAIL LADCP provides a glimpse of the velocity field associated with the Weddell Sea Bottom Water. The Weddell Sea Bottom Water benthic layer takes on varied forms: a thick well-mixed layer; a thin, stratified form; and a more complex form having attributes of both types. The transition from thin to thick benthic layer may be aided by diminished importance of the thermobaric effect as mixing of the benthic layer proceeds.

Weddell–Scotia Confluence low-salinity deep water

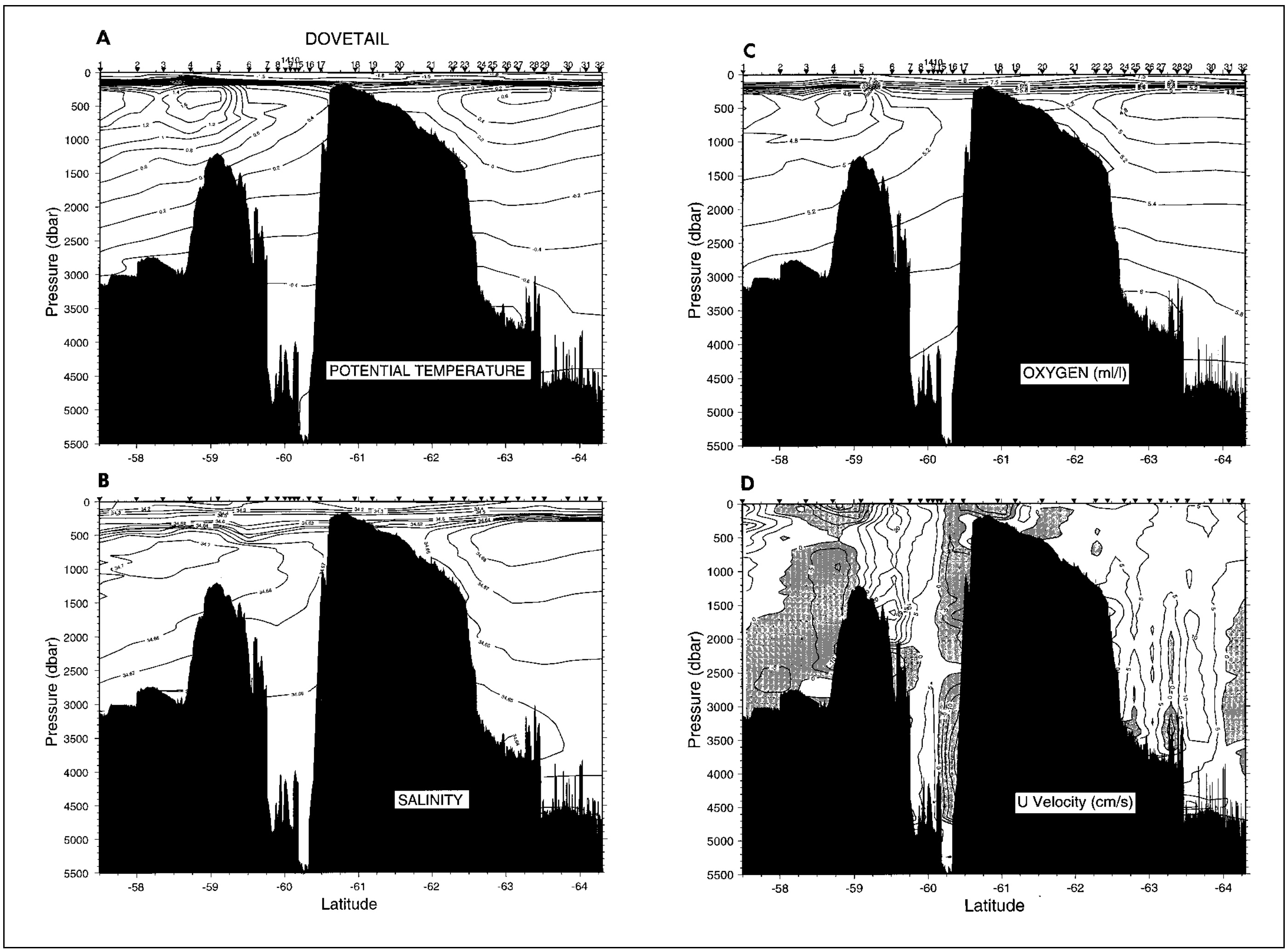
Within the Weddell–Scotia Confluence over the South Scotia Ridge west of the South Orkneys, there is a well-ventilated, low-salinity deep water, which may be referred to as Weddell–Scotia Confluence Deep Water. It advects eastward to provide the bottom water on the southern, deeper parts of the South Orkney Plateau and then passes northward into the Scotia Sea. The DOVETAIL data clearly show it is coming from the Antarctic Peninsula eastern shelf. It may be considered as a less dense form of Weddell Sea Bottom Water. It rides the "outer-rim" of the Weddell Gyre to feed into the Weddell–Scotia Confluence. The Weddell–Scotia Confluence Deep Water spreads on density surfaces into the Powell Basin and Scotia Sea, overriding the Weddell Sea Bottom Water and may influence the thickness of the benthic layer.

Bransfield Strait

The Bransfield basin waters are clearly derived from the freezing-point waters that pass from the Weddell Sea around Joinville Island. The saltiest freezing-point Joinville water contributes to the basin bottom water, whereas the less saline Joinville water contributes to the weak salinity minimum at mid-depth. The warm end member for the deep salinity minimum is derived from the pycnocline water probably coming from the Bellingshausen Sea or southern Drake Passage.

LADCP velocity

Full ocean depth velocity measurements were made for the first time in the Weddell Sea Gyre and Scotia Sea. The technology used is fairly new and employs two acoustic doppler current profilers (ADCP) mounted on the CTD frame. The instruments measure the velocity shear over a range of 300 meters at a rate of one profile per second. The depth averaged shear profile is then vertically integrated to give a full ocean depth velocity profile with an unknown barotropic mean flow. In combination with accurate ship's positioning (global positioning system) at the beginning and end of each cast, however, the unknown barotropic mean flow can be determined with an accuracy of about 1 centimeter per second. It is also possible to obtain bottom-referenced flow velocities with 300-meter range of the bottom.



(*A*) Potential temperature, °C; (*B*) salinity; (*C*) oxygen, in milliliters per liter; and (*D*) cross-section velocity, in centimeters per second of the DOVETAIL August 1977 (*NBP* 97-5) section along 45°W. See Muench (*Antarctic Journal*, in this issue) for station map. The section extends from the southern Scotia Sea to the northern Weddell Sea. The –0.7°C or colder bottom water south of the Orkney Plateau (stations 24 to 32) represents the export of Weddell Sea Bottom Water. Overflow of Weddell water into the Scotia Sea cools the bottom water in the deep trough north of the Orkney Plateau (stations 7–16) to below 0°C, colder than water derived from the Drake Passage. The below 0°C bottom water over the southern slope of the Orkney Plateau (stations 21–23) represents a well-ventilated layer derived from the Weddell–Scotia Confluence. The warm deep water stratum near 500 meters is weakened over the Orkney Plateau, which also marks the influence of the Weddell–Scotia Confluence. The cold winter surface layer was covered by sea ice south of station 5.

The zonal flow along a meridional section at 45°W (figure, block *D*) is mainly equivalent barotropic with significant vertical shears only close to lateral boundaries. The flow around Pirie Bank (59°S) is anticyclonic as expected from vorticity dynamics. The largest flow was observed north of the South Orkney Plateau with westward currents exceeding 25 centimeters per second at a depth of 4,000 meters. This boundary current is one of the pathways by which modified Weddell Sea Bottom Water enters into the Scotia Sea. We have estimated a westward transport of about 10 Sverdrup (1 Sv=10^6 cubic meters per second) north of the South Orkney Islands.

Over the South Orkney Plateau, we expect a strong tidal component in the velocity signal, a component that cannot be resolved by our temporal station spacing. South of the plateau (61.5°S), we encountered the eastward-flowing wind-driven Weddell Gyre boundary current, which has typical flow speeds of 5–10 centimeters per second. The total eastward transport was about 50 Sv. A similar eastward transport was found along the 40°W section.

The circulation in the Powell Basin was cyclonic with a very confined inflow north of the Joinville Ridge. The outflow was broader, and we estimated a total recalculation transport of 18 Sv in the Powell Basin. The rough bathymetry across the gap between the Powell Basin and the Scotia Sea prohibited reliable estimates of overflow transports. Improved knowledge of the bathymetry would have helped in planning and analyzing our velocity data.

Concluding remarks

The Weddell Sea produces freezing point water covering a wide range of salinity, which on a timescale of only 1 year is advected to the South Scotia Ridge where it ventilates the antarctic circumpolar belt from the seafloor to the Antarctic Intermediate Water density horizon, eventually spreading into the deep and bottom layers of the global ocean. To detect variability of southern ocean overturning and ventilation, a Weddell outflow monitoring strategy needs to be designed and set in place. The DOVETAIL information will be invaluable in the task of establishing a cost-effective, long-term monitoring program.

Acknowledgment

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Tracer oceanography in the Weddell–Scotia Confluence during *NBP* 97-5

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As part of the U.S. contribution to the international DOVETAIL (Deep Ocean Ventilation Through Antarctic Intermediate Layers) project, water samples for the measurement of geochemical tracers were collected in the Weddell–Scotia Confluence during cruise *NBP* 97-5 of R/V *Nathaniel B. Palmer*. Muench (*Antarctic Journal*, in this issue) gives a general introduction to the overall objectives of DOVETAIL and an overview of the work carried out during *NBP* 97-5. In total, 1,837 chlorofluorocarbon (CFC) samples, 723 helium/neon samples, 840 oxygen isotope samples, and 615 tritium samples were obtained. The analyses for the CFC species CFC 11, CFC 12, and CFC 113 were performed onboard using an electron capture detector (ECD) gas chromatography (Bullister and Weiss 1988; Smethie et al. 1988). The samples for helium, neon, and oxygen isotopes and for tritium were shipped back to Lamont-Doherty Earth Observatory. Their mass-spectrometrical analyses (Bayer et al. 1989; Ludin et al. 1997) will take about 1 year, but first results should be available in mid 1998.

Tracer data increase the dimensionality of the multiparameter space that is available for water-mass analysis. For this application, stable steady-state tracers—acting essentially as dyes—are especially valuable. Transient tracers provide additional information. Because of their time-dependent delivery to the oceanic surface layer, mean residence times and circulation patterns of specific water masses, as well as the relative age structure of the deep ocean, can be obtained.

The steady-state tracer helium-3 (^{3}He) will be used to assess the contribution of deep waters that are advected from the Antarctic Circumpolar Current into the Weddell–Scotia Confluence. The characteristic high isotopic helium-3 (δ^3He) signal of these waters is caused by the release of mantle helium at the Mid Ocean Ridges, predominantly along the crest of the East Pacific Rise (Craig and Lupton 1981), into the deep waters of the Pacific, from where it penetrates into the Antarctic Circumpolar Current.

The stable isotopes helium-4 (^{4}He) and oxygen-18 (^{18}O) are powerful tools to distinguish between the various near-surface water masses contributing to Weddell Sea waters observed in the Weddell–Scotia Confluence. This potential is due to the fact that shelf waters around Antarctica frequently contain certain amounts of glacial meltwater (Carmack and Foster 1975; Weiss, Östlund, and Craig 1979; Foldvik, Gammelsrød, and Tørresen 1985a,b). Glacial ice is tagged by low δ^{18}O values [approximately –40‰ to –50‰ (Morgan 1982; Grootes and Stuiver 1983)] and high ^{4}He concentrations [about 14-fold super-saturation in pure glacial melt (Schlosser 1986)], so that very small fractions (down to 0.5‰) of glacial meltwater are detectable (Schlosser 1986; Schlosser et al. 1990). The δ^{18}O signal of the glacial ice is due to progressive depletion of water vapor in $H_2^{18}O$ with precipitation and, hence, distance from the evaporation site, i.e., the coast (Morgan 1982). As the glacial ice forms from snow through firnification, air bubbles are trapped in the ice matrix. Eventually, they constitute about 10 percent of the entire volume (Gow and Williamson 1975). Together with the low solubility of helium in water (Weiss 1971), these bubbles generate a significant ^{4}He super-saturation when the ice melts at depth. Shelf waters that acquire a glacial meltwater component and then come in contact with the atmosphere for a limited time lose their ^{4}He excess due to gas exchange but retain the δ^{18}O signal. Shelf waters that have never been in contact with glacial ice do not carry any of these signals. Their contribution can be identified through their δ^3He values close to solubility equilibrium with the atmosphere [–1.8 percent (Benson and Krause 1980)].

Tritium [radioactive hydrogen, half-life 12.43 years (Unterweger et al. 1980)] was delivered to the atmosphere in a pulselike fashion as a result of the atmospheric thermonuclear weapon tests in the late 1950s and early 1960s. Its oceanic input function (surface concentration as a function of time) (Mensch, Simon, and Bayer in press) mimics the atmospheric time history. By now, tritium concentrations of oceanic surface waters have returned to the natural background level. Although this means that tritium has lost its transient properties in the near-surface layer, it will continue to be a good tracer. The observation of the further penetration of the bomb peak into the deep waters remote from their formation areas, as well as its subsequent removal from these waters, will provide valuable information on the spreading of, for example, Antarctic Bottom Water throughout the world ocean. Furthermore, tritium with its relatively short half-life will be well suited for time-series investigations of interannual variabilities.

Production and release into the atmosphere of CFC 11 and CFC 12 began in the 1930s and increased quasi-exponentially until the mid-1970s when the rise became linear. Since the early 1990s, the atmospheric CFC 11 and CFC 12 concentrations have leveled off, and CFC 11 started to decrease in 1995. The introduction of CFC 113 into the ocean-atmosphere system started only in the 1960s. Its concentration increased rapidly until the early 1990s. As for tritium, the temporal evolution of the CFC concentrations in oceanic surface waters is controlled by the atmospheric record.

Tracer ratios (CFC 11/CFC 12, CFC 113/CFC 11, CFC 11/tritium) serve as additional transient tracers with distinct input functions. They have the advantage of being less sensitive to the admixture of tracer-depleted waters and, therefore, provide better access to the age of the young component in a water-mass mixture. Although the CFC 11/CFC 12 ratio has been more or less constant since the mid-1970s and, hence, is not suited for dating water masses younger than about 20 years, the CFC 113/CFC 11 and CFC 11/tritium ratios are monotonously increasing functions of time since the early 1980s and the early 1970s, respectively. Together, the three transient tracer ratios available from the *NBP* 97-5 data set cover the time period from 1950 to present.

The figure shows the distribution of CFC 11 (preliminary shipboard data) along the *NBP* 97-1 section from the southern Scotia Sea across the South Orkney Plateau into the Jane and Weddell Basins [cf. figure 1 in Muench (*Antarctic Journal*, in this issue) for station positions]. Gordon, Visbeck, and Huber (*Antarctic Journal*, in this issue) present the hydrographic and current structure along this section. The CFC 11 concentration in the surface layer is close to the solubility equilibrium with the atmosphere (Warner and Weiss 1985) except for stations 23 to 29 in the Jane Basin. These are located in the northern limb of the Weddell Gyre and the CFC 11 undersaturation reflects the advection of waters from the ice-covered regions to the southwest.

At a depth of about 300 meters (m), the CFC 11 concentration drops to less than 1 picomole per kilogram (pmol kg^{-1}). Minimum CFC 11 concentrations approaching 0.1 pmol kg^{-1} are observed at the southeastern end of the section at about 1,000 m depth. In the Scotia Sea, minimum CFC 11 concentrations slightly above 0.2 pmol kg^{-1} seem to coincide with the lower 1°C isotherm at stations 1 to 7. In the southern part of the South Orkney Trough (stations 14 to 17), the lowest CFC 11 concentrations are about 0.45 pmol kg^{-1}.

In the Weddell Sea, CFC 11 concentrations increase rapidly as the bottom is approached. In the Jane Basin, the increase seems to start at a potential temperature of about –0.3°C, whereas in the Weddell Basin, the –0.7°C isotherm appears to mark the transition. Maximum observed values in both the Jane and the Weddell Basins are about 2.5 pmol kg^{-1}, providing evidence that a significant contribution to these water masses has been in recent contact with the atmosphere. This finding is further supported by their high oxygen content. In the Scotia Basin north of Pirie Bank (stations 2 to 4), maximum CFC 11 concentrations at the bottom are slightly below 0.8 pmol kg^{-1}. The water-mass properties observed at the bottom of station 15 in the South Orkney Trough (θ about –0.6°C, S equals approximately 34.65, O_2 equals approximately 5.94 milliliters per liter, CFC 11 equals approximately 1.32 pmol kg^{-1}) are observed about 800 m off the seafloor at stations 25 to 27 in the Jane Basin. In the Weddell Basin, no water mass having the properties of the bottom water in the South Orkney Trough was observed. This finding suggests that the bottom waters in the South Orkney Trough are replenished from the Jane Basin through the South Orkney Gap.

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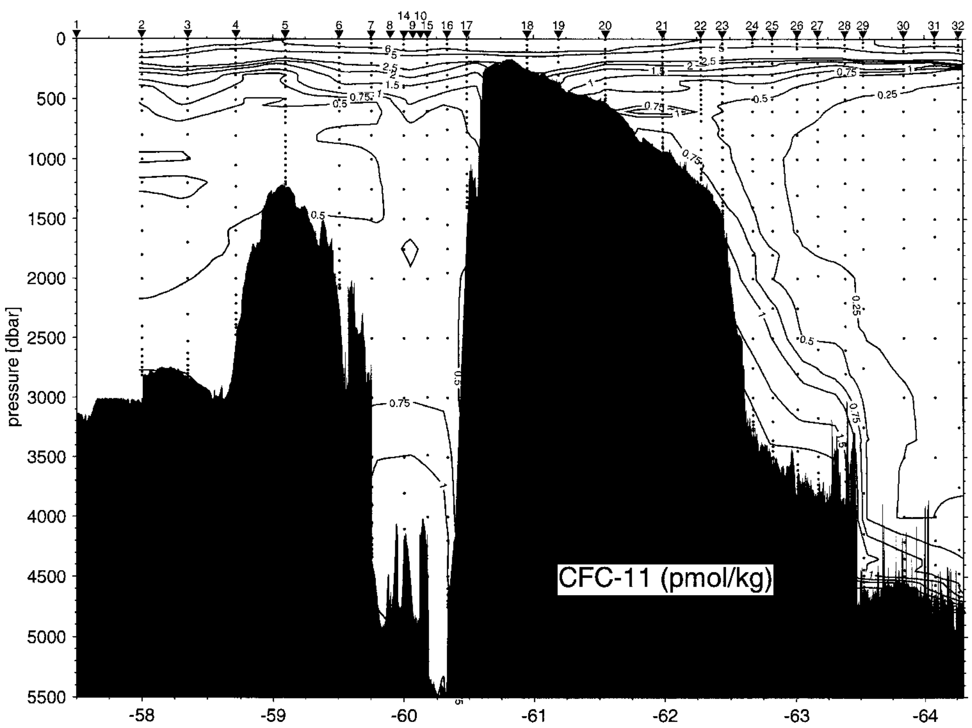

Distribution of CFC 11 (in pmol kg^{-1}, preliminary shipboard data) along a section from the southern Scotia Sea across the South Orkney Plateau into the northern Weddell Sea. (dbar denotes decibar.)

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