JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. C5, PAGES 9005–9017, MAY 15, 2001

Export of Weddell Sea Deep and Bottom Water

Arnold L. Gordon, Martin Visbeck, and Bruce Huber
Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York

Abstract. An extensive set of conductivity-temperature-depth (CTD)/lowered acoustic Doppler current profiler (LADCP) data obtained within the northwestern Weddell Sea in August 1997 characterizes the dense water outflow from the Weddell Sea and overflow into the Scotia Sea. Along the outer rim of the Weddell Gyre, there is a stream of relatively low salinity, high oxygen Weddell Sea Deep Water (defined as water between 0° and −0.7°C), constituting a more ventilated form of this water mass than that found farther within the gyre. Its enhanced ventilation is due to injection of relatively low salinity shelf water found near the northern extreme of Antarctic Peninsula's Weddell Sea shelf, shelf water too buoyant to descend to the deep-sea floor. The more ventilated form of Weddell Sea Deep Water flows northward along the eastern side of the South Orkney Plateau, passing into the Scotia Sea rather than continuing along an eastward path in the northern Weddell Sea. Weddell Sea Bottom Water also exhibits two forms: a low-salinity, better oxygenated component confined to the outer rim of the Weddell Gyre, and a more saline, less oxygenated component observed farther into the gyre. The more saline Weddell Sea Bottom Water is derived from the southwestern Weddell Sea, where high-salinity shelf water is abundant. The less saline Weddell Sea Bottom Water, like the more ventilated Weddell Sea Deep Water, is derived from lower-salinity shelf water at a point farther north along the Antarctic Peninsula. Transports of Weddell Sea Deep and Bottom Water masses crossing 44°W estimated from one LADCP survey are 25×10^6 and 5×10^6 m^3 s^{-1}, respectively. The low-salinity, better ventilated forms of Weddell Sea Deep and Bottom Water flowing along the outer rim of the Weddell Gyre have the position and depth range that would lead to overflow of the topographic confines of the Weddell Basin, whereas the more saline forms may be forced to recirculate within the Weddell Gyre.

1. Introduction

Along the continental margins of the Weddell Sea, Antarctica, from the Filchner Depression to the tip of Antarctic Peninsula (Figure 1), dense water of varied characteristics descends into the deep ocean [*Gordon et al.*, 1993; *Fahrbach et al.*, 1994, 1995; *Weppernig et al.*, 1996; *Mensch et al.*, 1996, 1998; *Gordon*, 1998]. Streams of newly formed Weddell Sea Deep Water (WSDW, defined as deep water with potential temperatures between 0° and −0.7°C [*Fahrbach et al.*, 1995]) and Weddell Sea Bottom Water (WSBW, defined as water colder than −0.7°C [*Carmack and Foster*, 1975]) are carried by the western boundary current of the Weddell Sea into the northwest corner of the Weddell Gyre [*Deacon*, 1979; *Orsi et al.*, 1993]. From there these water masses flow eastward, either within the northern limb of the Weddell Gyre or reaching northward into the Scotia Sea [*Gordon*, 1966; *Locarnini et al.*, 1993], eventually cooling the lower 2 km of the world ocean as Antarctic Bottom Water. The objective of this study is to describe the characteristics of Weddell Sea Deep Water (WSDW) and Weddell Sea Bottom Water (WSBW) within the northwest Weddell Sea and their overflow into the southern Scotia Sea.

2. DOVETAIL Data

The data set used in this study was collected during cruise 97-5 of the polar research vessel *Nathaniel B. Palmer* from July 31 to September 8, 1997, in the southern Scotia Sea, northern Weddell Sea, and Bransfield Strait (Figure 2), as part of the international Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) program [*Muench*, 1997]. Profiles of the water column from surface to near bottom were obtained at 97 sites using a SeaBird Electronics SBE9plus conductivity-temperature-depth (CTD) recorder with an oxygen sensor and water samplers for calibration purposes and for tracer chemistry. A lowered acoustic Doppler current profiler (LADCP) was attached to the CTD. The Scotia Sea and Weddell Sea stations characterize the thermohaline and oxygen concentration fields of the dense water outflow from the Weddell Sea and its overflow into the Scotia Sea. The LADCP data provide a snapshot of the velocity field at the time of the CTD stations. The Bransfield Strait data set is dealt with in a separate paper [*Gordon et al.*, 2000].

Paper number 2000JC000281.
0148-0227/01/2000JC000281$09.00

2.1. 44°W Section

The approximately meridional section composed of stations 1–32 along 44°W (Figures 2 and 3) crosses the South Orkney Plateau separating the Scotia Sea to the north from the Weddell Sea to the south. The South Orkney Trough is immediately north of the South Orkney Plateau. Circumpolar Deep Water (CDW), marked by a potential temperature maximum θ_{max} of >1.6°C, is introduced to the Scotia Sea by the Antarctic Circumpolar Current (ACC) from the Pacific Ocean. Accompanying the CDW θ_{max}, at a slightly deeper level, are salinity maximum and oxygen minimum core layers. A stream of CDW enters the Weddell Gyre at the eastern margin of the gyre near 30°E [*Deacon*, 1979; *Orsi et al.*, 1993]. The θ_{max} to the south of

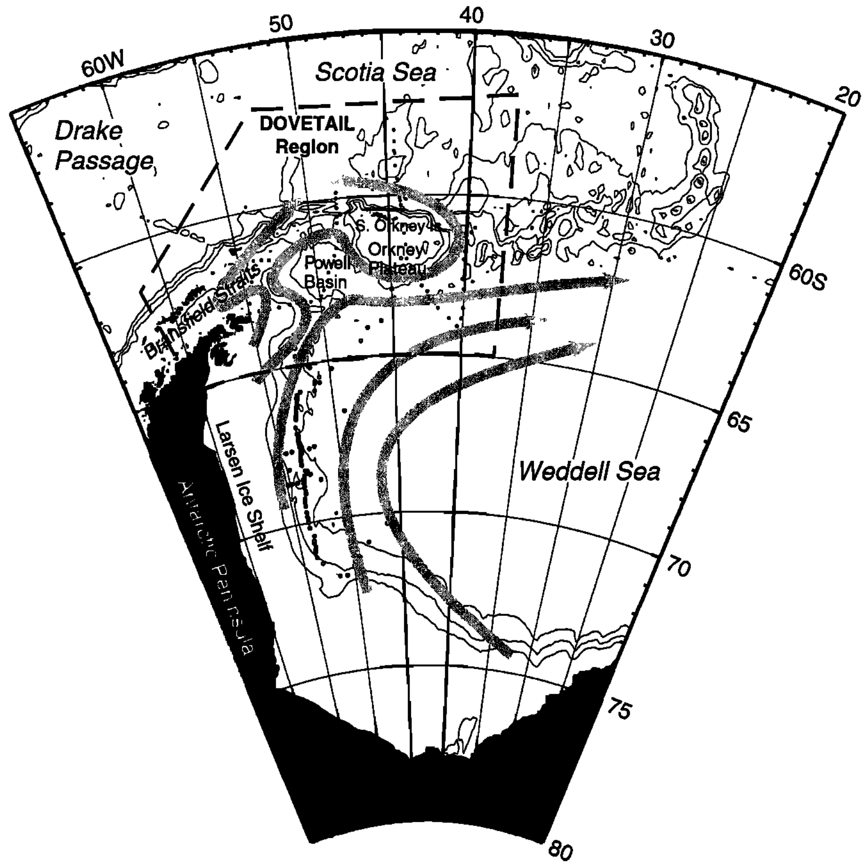


Figure 1. Distribution of Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) program [*Muench*, 1997] stations obtained from the polar research vessel *Nathaniel B. Palmer* cruise 97-5 from July 31 to September 8, 1997, shown as dots. The DOVETAIL study region is delineated by the dashed line. Stations obtained as part of the 1992 Ice Station Weddell program [*Gordon*, 1998], many of which are used in this study, are shown as open circles. The bathymetry is a smoothed composite of the *Smith and Sandwell* [1997] bathymetry and ETOPO5, joined at 72°S. The 1, 2, and 3 km isobaths are shown. Arrows denote deep and bottom flow pattern.

the South Orkney Plateau defines the Weddell Deep Water (WDW), which is a modified remnant of CDW. WDW advected along the outer rim of the Weddell Gyre is generally cooler than 0.6°C in the northwestern Weddell Sea. Within the WDW the salinity maximum and oxygen minimum core layers nearly coincide with the WDW θ_{max}.

The CDW and WDW cores are weakened as the South Orkney Plateau is approached from both the Scotia and Weddell Seas. The θ_{max} of ~0°C over the plateau marks the Weddell-Scotia Confluence [*Gordon*, 1967; *Patterson and Sievers*, 1980; *Whitworth et al.*, 1994]. The confluence zone, emanating from the northern tip of Antarctic Peninsula, is sandwiched between the eastward flowing ACC to the north and the eastward flowing limb of the Weddell Gyre. The Weddell-Scotia Confluence may be considered as a seaward advected stream of continental margin waters of the Weddell Gyre, though some deep-reaching convection has been suggested [*Deacon and Foster*, 1977].

Stations 21–23 over the South Orkney Plateau (depths of 500 to 1500 m) reveal a cold benthic layer (−0.4°C) with low salinity (slightly <34.66) and high oxygen (5.4 mL/L), relative to waters of similar depth or density σ_0 within the Scotia and Weddell Seas. The benthic layer water mass properties indicate that it may be considered to be a better ventilated component of WSDW (see section 3).

The waters below the CDW and WDW progressively cool, decrease in salinity, and increase in oxygen as the seafloor is approached. Gradients are much enhanced within the lower 500 dbar in the Weddell Sea, a trait which increases in intensity in the western Weddell Sea [*Gordon*, 1998]. In the deep ocean south of the South Orkney Plateau, bottom temperatures are as cold as −1.01°C, with salinity of 34.633 and oxygen of >6.36 mL/L, 79% of full saturation (station 30). The very cold benthic layer is composed of WSBW formed along the Weddell margins to the west and south. North of the plateau lies the South Orkney Trough, with warmer, more saline and less oxygenated bottom water relative to that of the Weddell Sea. This water can be traced to Weddell flow over a 3200 m sill in the South Scotia Ridge near 38°W [*Gordon*, 1966; *Locarnini et al.*, 1993].

2.2. Potential Temperature Versus Salinity and Oxygen

Potential Temperature versus salinity (θ/S, Figure 4a) and oxygen (θ/O_2; Figure 4b) plots display the varied water masses of the northwest Weddell Sea and southern Scotia Sea. A near-freezing point (within 0.1°C) surface mixed layer with a wide range of salinity caps the water column, with coldest (at the freezing point, −1.91°C), most saline (34.60) water at the seafloor adjacent to Joinville Island. The oxygen of the winter surface layer varies from 6.9 to 8.2 mL/L, 85 to 100% of

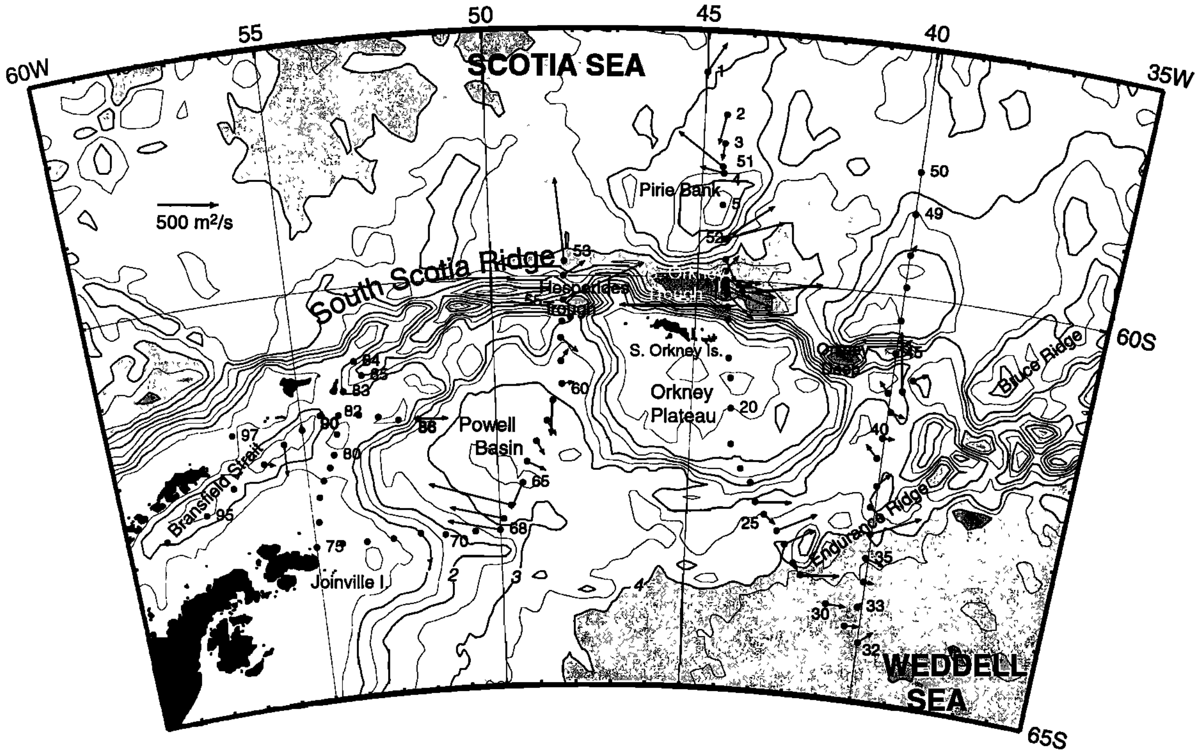


Figure 2. Distribution of Palmer 97-5 DOVETAIL (CTD)/lowered acoustic Doppler current profiler (LADCP) stations. Integrated velocities derived from LADCP for stations deeper than 2000 m are shown as vectors. Bathymetry is from *Smith and Sandwell* [1997].

saturation, respectively. Lower oxygen levels occur within the Weddell Sea, where snow-covered sea ice blocks oxygen exchange with the atmosphere which would otherwise mitigate the effect of incorporation of oxygen poor WDW into the surface layer [*Gordon and Huber*, 1990]. The highest surface oxygen is found in the Scotia Sea, where the sea ice cover is of shorter duration and generally <100% coverage.

The oxygen concentration within the surface and shelf water adjacent to Joinville Island is 7.56–7.73 mL/L (92% saturation), ~0.5 mL/L higher than the surface layer to the east. Elevated oxygen levels suggest better exposure to the atmosphere, most likely through coastal polynyas, with limited access to the offshore WDW. Joinville Island shelf water is less saline than 34.61 and so is considered as low-salinity shelf water, in comparison to the more saline shelf waters farther to the south [*Whitworth et al.*, 1998, Figure 11; *Gordon*, 1998, Figure 14]. Presumably, this is a reflection of greater winter sea ice formation in the southwestern Weddell Sea and/or injection of more freshwater water from the Antarctic Peninsula along the western Weddell Sea.

The pycnocline within the Scotia Sea is significantly warmer and less saline than the Weddell Sea pycnocline. The Weddell Sea pycnocline is of much lower stability than the Scotia Sea pycnocline, as the Weddell winter surface water attains relatively high density, forcing the underlying pycnocline toward reduced stability.

At depths greater than the WDW θ_{max}, mixtures of WDW with waters from the continental margins result in a decrease in temperature and salinity with increasing depth, accompanied by an increase in oxygen concentrations. While the θ/S slope of the water column below the WDW is approximately linear, there are noticeable departures from linearity, indicative of a more complex "recipe" than a simple two-end-member mixing process. In both WSDW and WSBW strata, there are two groupings: a higher-salinity branch and a lower-salinity branch. These subsets of WSDW and WSBW are discussed below.

2.3. Bottom Water Distribution

Bottom water properties for the northwest Weddell Sea and southern Scotia Sea provide a view of bottom water flow patterns at the time of the 1997 DOVETAIL cruise. The 1992 Ice Station Weddell data [*Gordon*, 1998] are added to provide information on the upstream bottom water properties. *Locarnini et al.* [1993] shows bottom θ for the DOVETAIL region and farther north, to 35°S; *Gordon* [1998] shows θ and salinity for the Weddell Sea west of 20°W. The bottom θ distribution (Figure 5) reveals a mass of water with $\theta < -1.0$°C drawn from the continental margins of the western Weddell Sea. Within the northwest Weddell Sea the cold bottom water stream shifts from a generally northward orientation into an eastward orientation, reflecting the sense of the Weddell Gyre. Bottom water colder than -0.7°C is traditionally called WSBW, as at that isotherm the θ/S curve makes an abrupt change in slope [see *Carmack and Foster*, 1975] (Figure 4a). The coldest bottom water along the northern Weddell Sea occurs along the 4000 m isobath, with cold water filling the depressions both west and east of the Orkney Plateau, including the Powell Basin and the passage leading the primary overflow into the Scotia Sea.

The -0.7°C isotherm intersects the seafloor near the 3200 m isobath of the South Scotia Ridge's Weddell flank (Figure 3a). Over the interior of the Weddell Sea the -0.7°C isotherm lies between 4000 and 4200 dbar [*Fahrbach et al.*, 1994]. Thus the

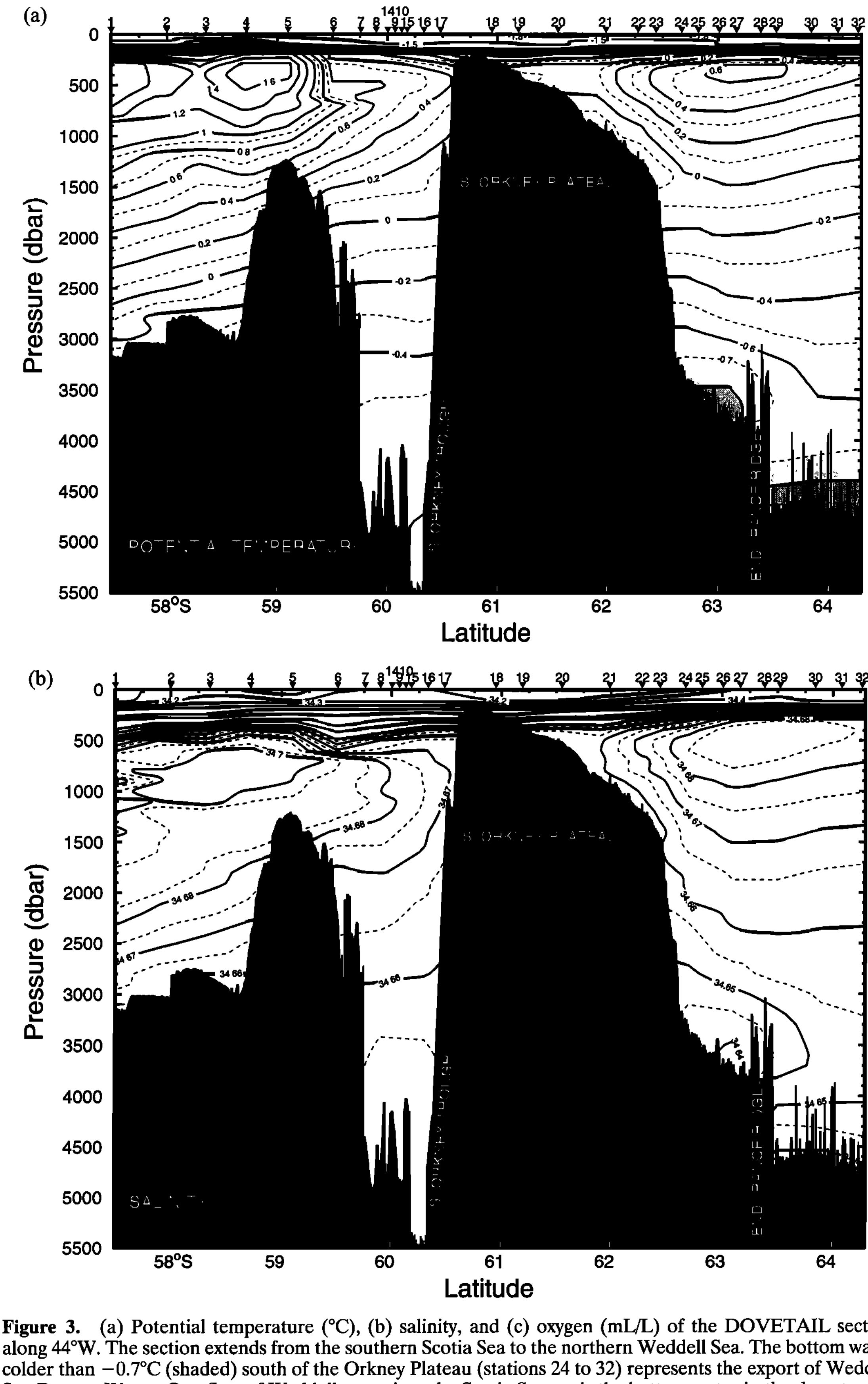


Figure 3. (a) Potential temperature (°C), (b) salinity, and (c) oxygen (mL/L) of the DOVETAIL section along 44°W. The section extends from the southern Scotia Sea to the northern Weddell Sea. The bottom water colder than −0.7°C (shaded) south of the Orkney Plateau (stations 24 to 32) represents the export 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 <0°C, colder than water derived from the Drake Passage. The <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 m 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. Bathymetry is derived from underway echo soundings obtained during the cruise.

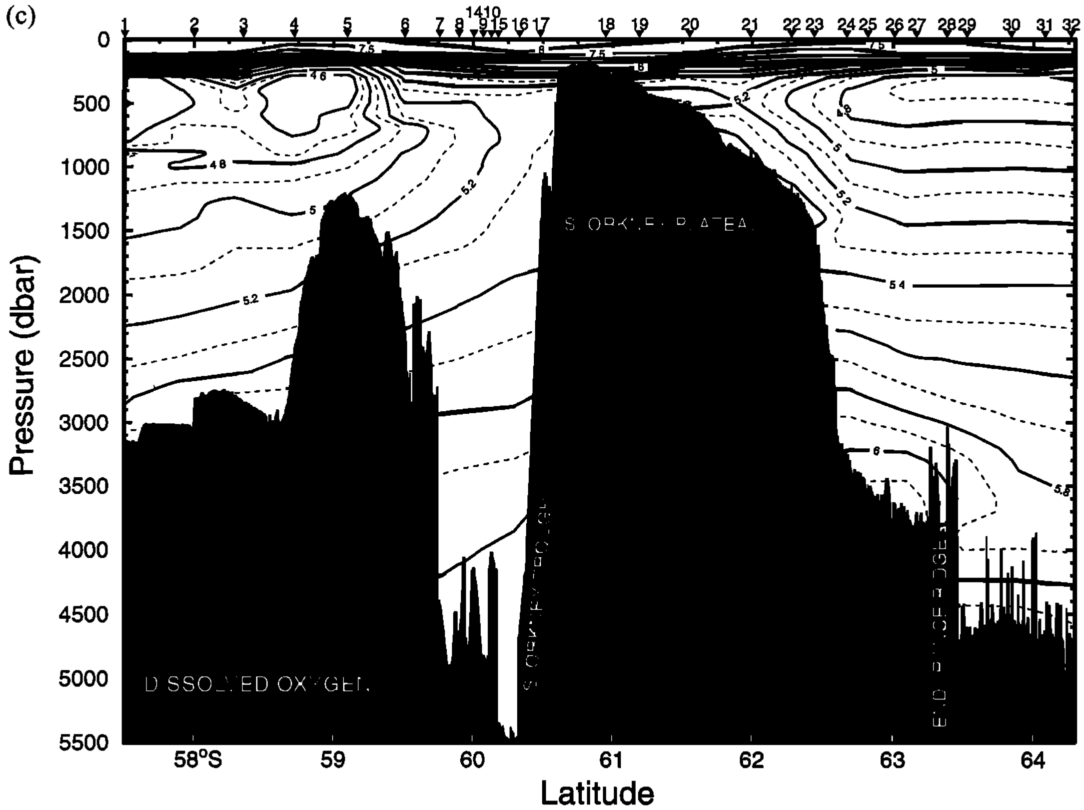


Figure 3. (continued)

WSBW shallows over South Orkney Ridge. Overflow of Weddell Sea water into the Scotia Sea occurs at a 3200 m sill [*Gordon*, 1966], the Orkney Passage, just east of South Orkney Plateau. Overflow of −0.6°C renews the bottom water of the South Orkney Trough of the Scotia Sea (Figures 3a and 5). As the overflow water is slightly warmer than −0.7°C, it is designated as WSDW, but in view of the proximity to the sill depth and the expected mixing at the sill, components of WSBW probably contribute to the overflow. The Weddell overflow into the Scotia Sea flows westward into the southern Drake Passage [*Gordon*, 1966; *Nowlin and Zenk*, 1988], then curls back to the northeast, passing through the deep passages east of South Georgia Island into the western South Atlantic [*Locarnini et al.*, 1993].

3. Discussion

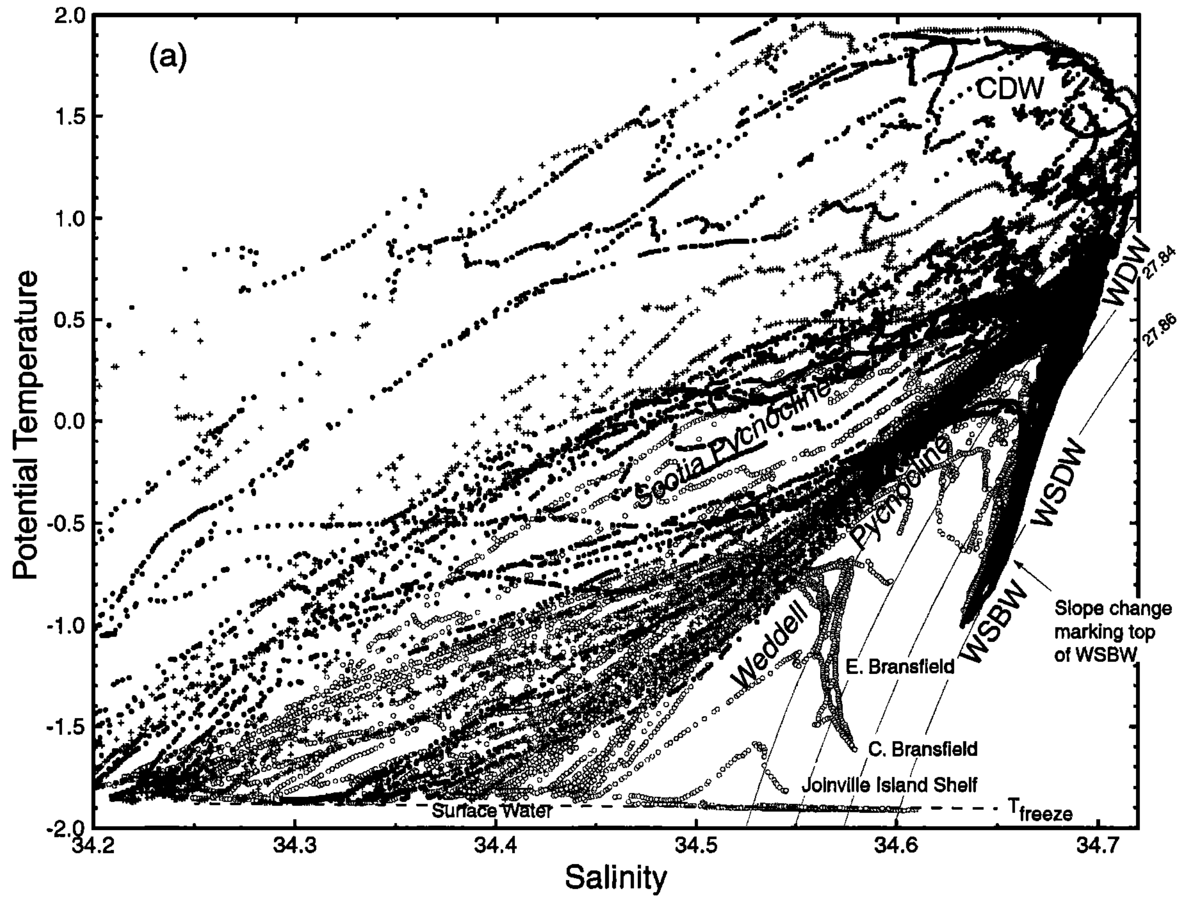
3.1. Weddell Sea Deep Water

The WSDW is defined as the deep water between 0.0°C and −0.7°C [*Fahrbach et al.*, 1994; *Carmack and Foster*, 1975]. Within this temperature range many DOVETAIL stations reveal a relatively low salinity, high oxygen form of WSDW (Figure 6). We refer to this water mass as a better ventilated form of WSDW, which we designate as VWSDW, meaning it is WSDW that has been subjected to greater influx of high oxygen surface water. It is most distinct from the more widespread WSDW between the −0.3°C and −0.4°C isotherms. *Meredith et al.* [2000] describe a CFC-11 maximum found within the WSDW stratum near −0.45°C in the southeastern Weddell Sea, which they attribute to a WSDW source outside the Weddell Gyre to the east. However, the θ/S characteristics of that feature do not display the freshening observed in the VWSDW described here.

The VWSDW is most pronounced at DOVETAIL stations in the Weddell Sea with bottom depths between 1500 and 2000 m: stations 69 and 70 over the Joinville Ridge, 86 at the western boundary of Powell Basin, 56 at the northern boundary of the Powell Basin, and 20–22 over the South Orkney Plateau. The VWSDW overrides what may be considered somewhat less well ventilated WSDW (more saline, less oxygenated) near the −0.4°C isotherm, between 2000 and 2500 dbar at stations 23–25 over the southern flank of the South Orkney Plateau and at stations 57–62 along 48°W. It is not found at the 40°W section, indicating that VWSDW exits the Weddell Sea to enter the Scotia Sea before reaching 40°W. Over the Joinville Ridge at stations 70 and 71 and along the western boundary of Powell Basin, station 86, an extreme form of VWSDW (much lower in salinity and elevated in oxygen) is observed (Figure 6). Presumably, an admixture of this deep water with WSDW forms the VWSDW observed downstream.

At station 55, VWSDW characteristics extend to the seafloor at 5300 m. It is proposed that station 55 falls within an isolated deep basin within the eastern end of the Hesperides Trough. The θ/S relationship and potential temperature–salinity profiles indicate the source of the Hesperides Trough bottom water is VWSDW, with a controlling sill at ~1800 m.

Stations 17 and 54, both within the Scotia Sea along the southern wall of the South Orkney Trough, reveal traces of VWSDW. Station 51 (northern side of Pirie Bank) shows a slightly lower salinity in the temperature range of the VWSDW. It is suggested that VWSDW (see inset on Figure 6), guided by isobaths, enters the Scotia Sea following a counter-



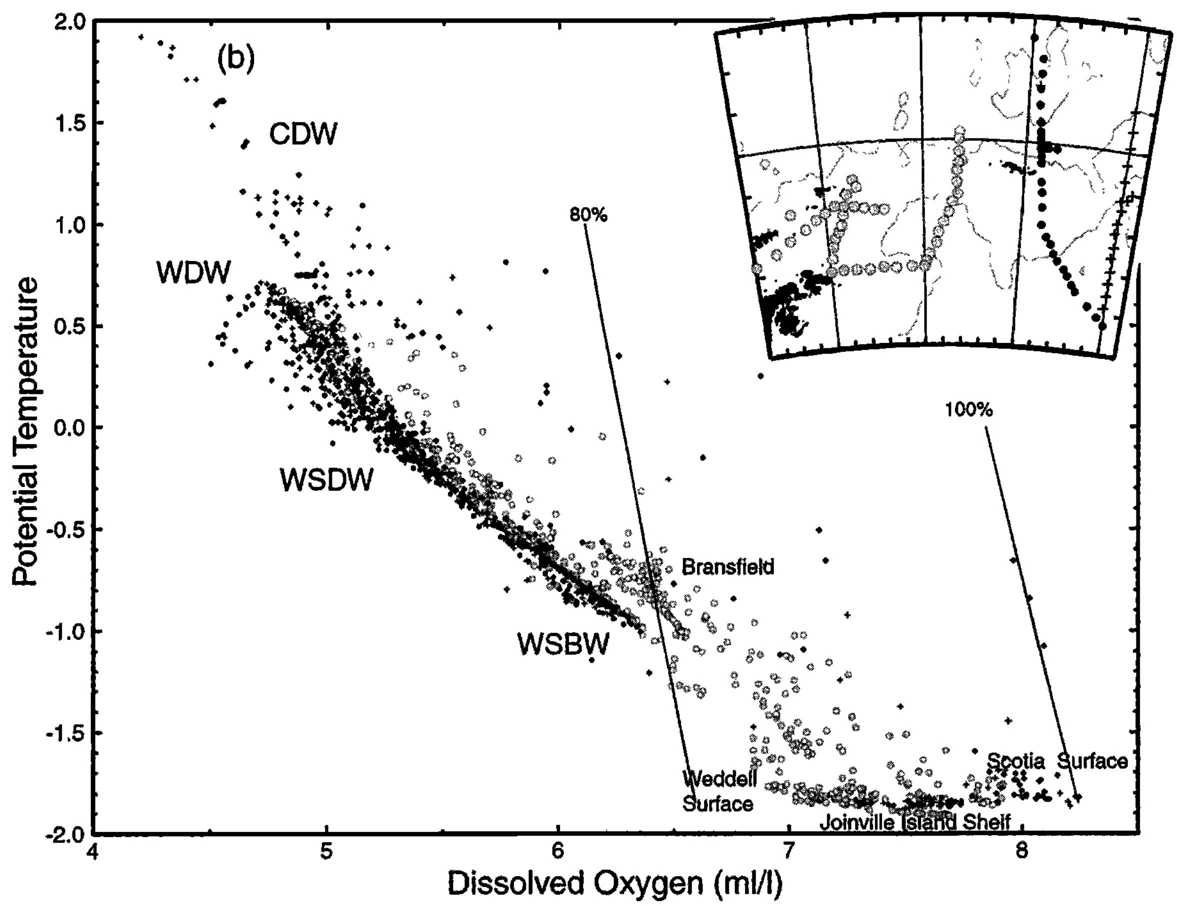


Figure 4. Potential temperature (°C) versus (a) salinity (CTD data) and (b) oxygen (mL/L) (oxygen bottle data) for all *Nathaniel B. Palmer* cruise 97-5 CTD/rosette stations (shaded circles). Data from the 44°W section are highlighted as solid symbols.

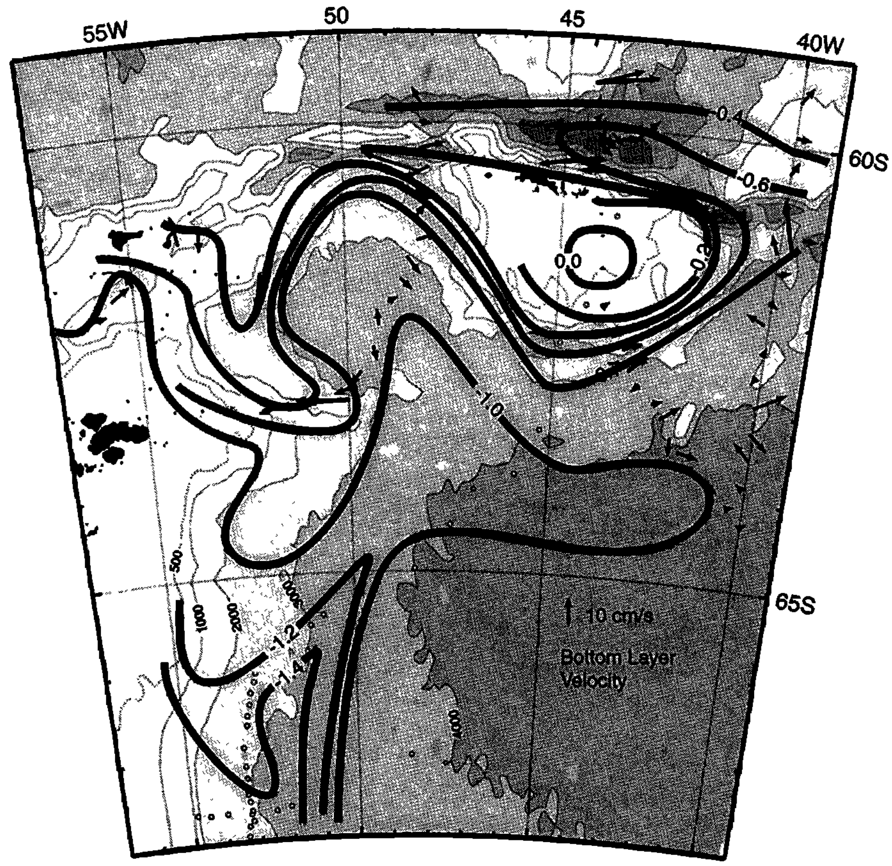


Figure 5. Bottom Water potential temperature of the lower 10 dbar of the CTD cast, if within 30 dbar of the seafloor (a station where the last scan is 30 dbar from the bottom would have a value that is the average of data 40–30 m from the bottom). Average velocity within the lower 120 dbar derived from (bottom referenced) LADCP data is shown as vectors. The majority of DOVETAIL stations approached within 10 m of the bottom. Temperature data from the 1992 Ice Station Weddell data set are included [*Gordon*, 1998] as shown by the open circles with no velocity vectors.

clockwise path around South Orkney Plateau, then clockwise around the South Orkney Trough, to enter into the interior of the Scotia Sea. Exit from the Scotia Sea into the South Atlantic is expected [*Locarnini et al.*, 1993].

The most probable source of the surface water component of VWSDW is freezing point shelf water. Near-freezing point surface and shelf water over Joinville Island Ridge exhibits a wide range of salinity (though <34.61, which would be dense enough to directly reach the deep-sea floor) and oxygen (Figure 4, stations 72–75). It may be thought of as low-salinity shelf water, as it is not dense enough to descend to the deep-sea floor [*Gordon*, 1998]. It is proposed that VWSDW is formed from low-salinity shelf water from Antarctic Peninsula which descends to the 1500–2000 dbar level somewhere south of 63°S, where it mixes with the resident WSDW of the Weddell Gyre.

3.2. Weddell Sea Bottom Water

Below 2000 dbar significant spatial variability is exhibited by potential temperature, salinity, and oxygen profiles (Figures 6–8). Over shallower waters (bottom depth <3800 m, stations 24–28 and 38–41), there is a relatively low salinity, high oxygen grouping for water colder than −0.4°C. We refer to this water, that component colder than −0.7°C, as a more ventilated form of WSBW, which we designate as VWSBW. The water between −0.4 and −0.7°C may be considered VWSDW, but in view of the separation in θ/S space from the main mass of VWSDW discussed above, it is more likely produced at a more remote site to the south, with a stronger component of WSDW.

The stations over the seafloor deeper than 3800 m (30–33) fall within a more saline, lower-oxygen WSBW. Stations 29 and 34–36, along the southern slope of the Endurance Ridge, fall within the deeper water group and may represent more of a transition between branches. On proceeding from −0.55° to −0.82°C, they display an increasing component of VWSBW with increasing depth; below −0.82°C they fall within the VWSBW θ/S space. *Nathaniel B. Palmer* cruise 92-2 (the Ice Station Weddell recovery cruise in June 1992 [*Gordon*, 1998]) shows an abrupt separation between the two branches between stations 9 (bottom depth 4000 m) and 10 (3000 m), near 63.5°S and 46°W, west of 97-5 station 29.

Powell Basin bottom water is similar in characteristics to the low-salinity, high-oxygen VWSBW group at 44°W, though lower in salinity and higher in oxygen. This suggests a similar upstream source from Antarctic Peninsula.

It is proposed that the more saline, lower-oxygen WSBW is derived from shelf water descending into the deep ocean in the southwest Weddell Sea. The higher salinity of this WSBW is due to injection of high-salinity shelf water characteristic of

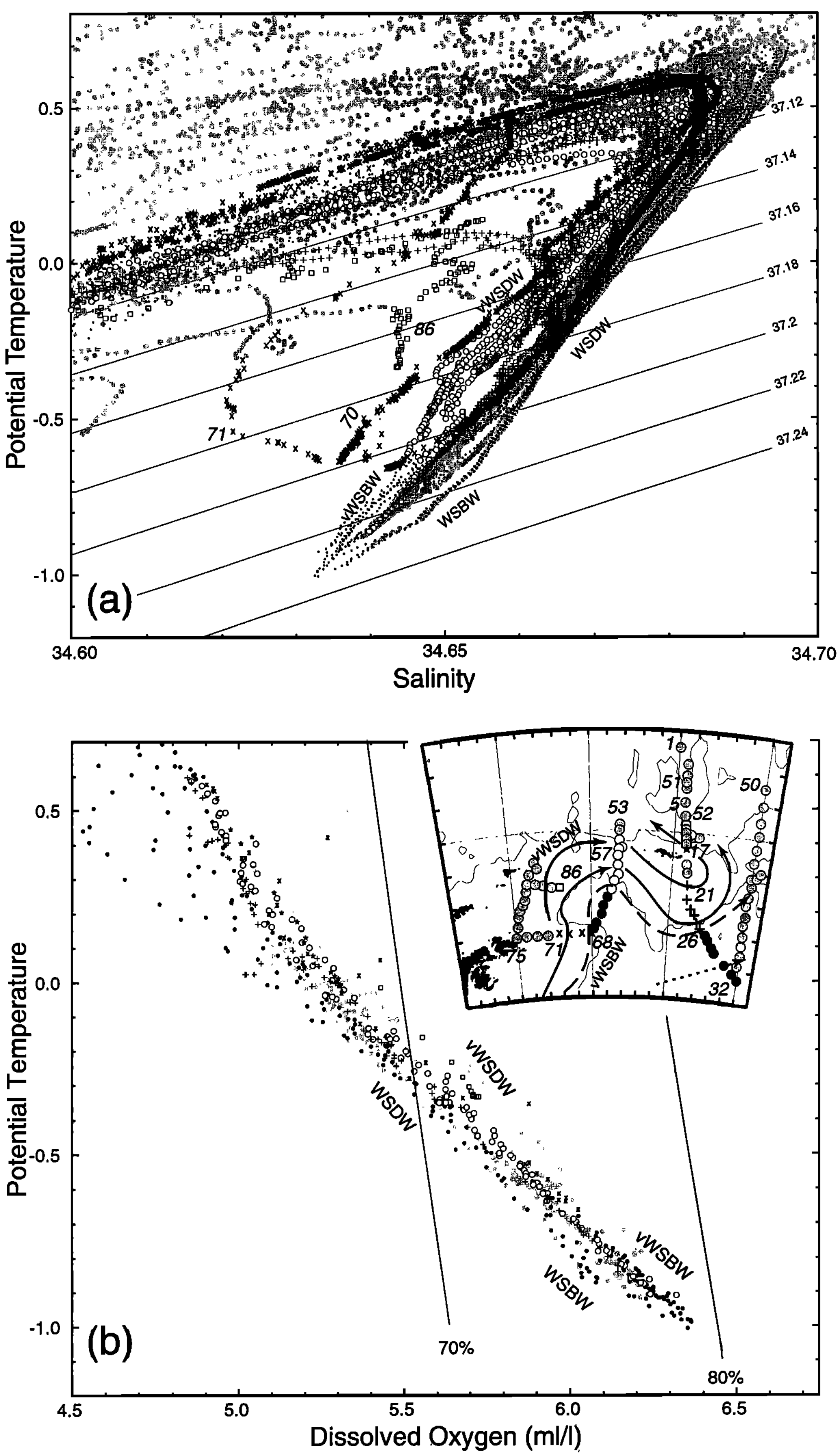


Figure 6. Potential temperature (°C) versus (a) salinity (CTD data) and (b) oxygen (mL/L) (oxygen bottle data below the θ_{max}) for select stations exhibiting ventilated WSDW. The insert station map displays the varied symbols used to denote regions. The arrows on the map insert show the advective pattern for the more ventilated forms of Weddell Sea Deep Water (VWSDW) and Weddell Sea Bottom Water (VWSBW).

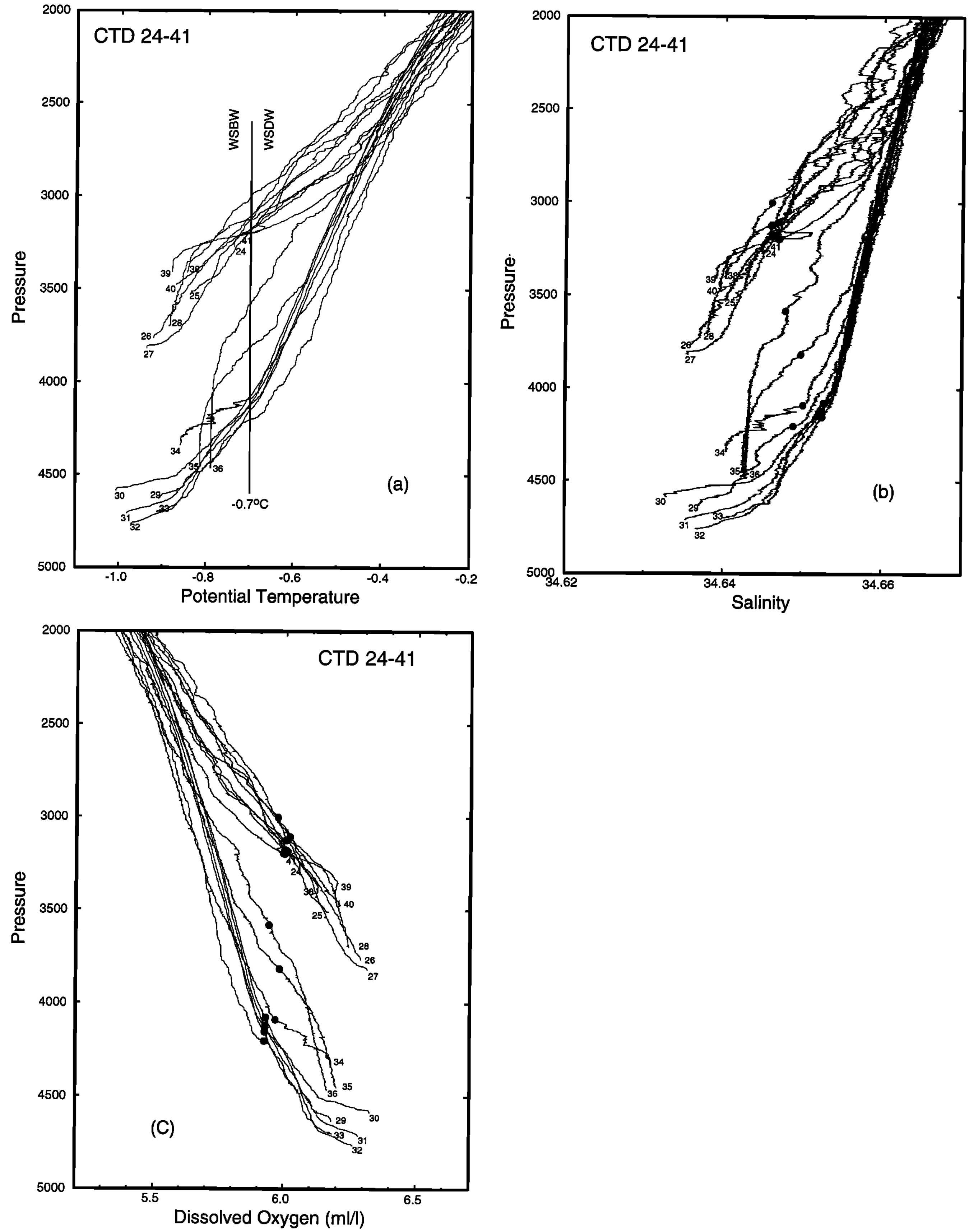


Figure 7. (a) Potential temperature, (b) salinity, and (c) oxygen versus depth (pressure, dbar) profiles below 2000 dbar for stations 24–41. Shaded dots on Figures 7b and 7c indicate salinity and oxygen at a potential temperature of −0.7°C, taken as the upper limit of WSBW.

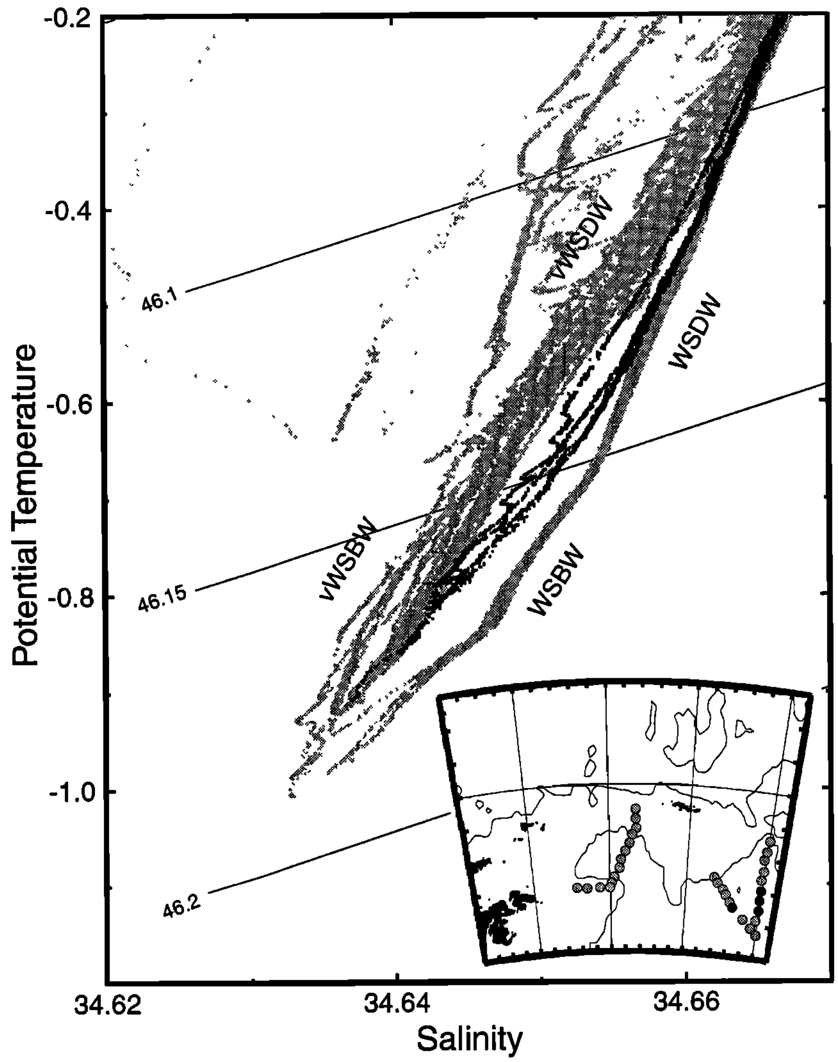


Figure 8. Potential temperature versus salinity and versus oxygen for stations 24–41 and 58–71 (Powell Basin). Transition stations 29 and 34–36 are highlighted.

this region [*Gordon*, 1998]. The VWSBW with lower salinity and enriched in oxygen is derived from the shelf water farther north along Antarctic Peninsula's Weddell Sea shelf. *Fahrbach et al.* [1995] propose that low-salinity bottom water is formed near the Larsen Ice Shelf. The transition from WSBW to VWSBW with increasing depth (stations 29 and 34–36) may be explained as follows. The VWSBW branch passing through the Powell Basin is split into two streams, one continuing eastward over the shallow plain north of the Endurance Ridge and the other descending into deeper water along the southern escarpment of the Endurance Ridge.

The WSBW is unstable in σ_0, as is characteristic of the benthic layer in the western and southwestern Weddell Sea [*Gordon*, 1998]. Thermobaric effects are needed to produce in situ stable stratification. The benthic layer mixes as it flows along the seafloor, and the resultant homogeneous layer warms as it incorporates warmer water from above. This decreases the thermobaric effect and leads to an interesting result: As the bottom homogeneous layer thickens, its susceptibility to further mixing increases, inducing a positive feedback to mixing. As an example, station 32 (a thin stratified benthic layer; bottom 4764 dbar) is inspected. Initially, the density difference in σ units between waters at the seafloor and waters above the benthic layer is 0.0128. Upon mixing the water column from the seafloor, the density difference decreases to 0.0098 for a 40 dbar mixed layer, 0.0070 for an 80 dbar mixed layer, and 0.0048 for a 160 dbar mixed layer. Further mixing beyond 240 dbar causes a slight increase in mixed layer stability. Thus, under constant forcing, one may expect the layer to increase rapidly in thickness to at least 200 dbar. Thermobaric-assisted mixing may be an important factor in upward mixing of WSBW as required for such water to escape over the confining topography of the Weddell Basin.

3.3. Transport of WSBW and WSDW

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 combined range of 300 m depth at a rate of one profile per second, making it possible to obtain bottom-referenced flow velocities within 300 m range of the bottom. The depth-averaged shear profile is vertically integrated to give a full ocean depth velocity profile

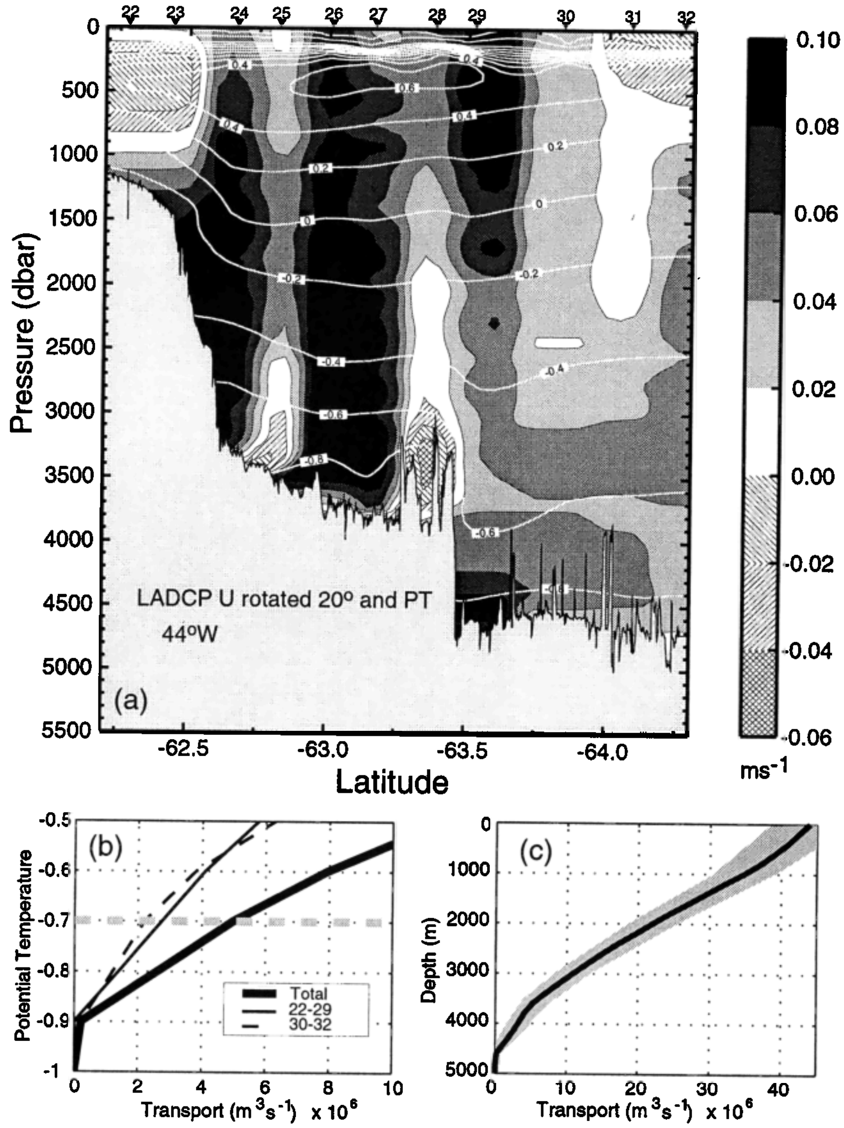


Figure 9. Currents and transports across the 44°W section (stations 22–32) estimated from the LADCP data. (a) LADCP-derived velocity computed approximately normal to the section with potential temperature isotherms superimposed. (b) Cumulative transport of ventilated (thin solid line) and unventilated (dashed line) varieties of deep and bottom water as a function of temperature. (c) Total cumulative transport as a function of depth, with error envelope estimated assuming a worst-case barotropic velocity error of 1 cm s throughout.

with an unknown barotropic mean flow [*Fischer and Visbeck*, 1993]. However, in combination with accurate ship's positioning (GPS) at the beginning and end of each cast, the unknown barotropic mean flow can be determined with an accuracy of ~1 cm s. As this error is random, the error in estimating transport across a series of stations is expected to be small. In the transports presented below, a worst-case error is given, which assumes a 1 cm s barotropic velocity error in each of the profiles used. Obviously, a single LADCP survey can only measure the synoptic velocity field, which need not to be representative of the long-term mean.

For most stations the velocity profile is strongly barotropic, with significant vertical shears only in the vicinity of the seafloor. Figure 2 depicts the depth-integrated flow at all stations deeper than 2000 m where the tidal contribution is assumed to be small. *Robertson et al.* [1998, their Figure 3] show that in deep water south and east of the Orkney Plateau, tidal currents are <3 cm s. In northern and western parts of Powell Basin the tidal currents reach 5 cm s, and over shallower topography of ridges and shelves, tidal speeds are quite large, over 10 cm s.

In the northwestern Weddell Sea we find a cyclonic flow through the Powell basin with a transport obtained from stations 57–65 of 18 ± 6 Sv (1 Sv = 10^6 m^3/s). South of the Orkney Plateau the flow is directed eastward, clearly marking the northern limb of the Weddell gyre, with a total transport of 40 ± 5 Sv across 44°W (stations 22–32, Figure 9). There the flow has two cores separated by the Endurance Ridge at 63°S. From water mass properties and the measured transports we expect that about half of that transport across 44°W is derived from the Powell Basin gyre, the rest passed eastward along a path south of the Powell Basin (Figure 1).

Farther to the north the flow around Pirie Bank (59°S) is anticylonic, as expected from vorticity dynamics. The largest flow was observed just north of the South Orkney Plateau with westward currents exceeding 25 cm s at a depth of 4000 m. This boundary current is one of the pathways by which WSDW enters into the Scotia Sea. We have estimated a westward transport of ~10 Sv north of the South Orkney Islands. The bottom-referenced velocities, averaged over the lower 120 m of the profiles, show a qualitatively similar circulation pattern (Figure 5).

The near-bottom flow seems to have two cores, one following the slope south of the South Orkney bank and the other just south of the Endurance Ridge (Figure 2). The flow vectors in the vicinity of the ridges are strongly influenced by the local topography. At station 29 our observations corroborate the 10 cm s eastward flow through a gap in the ridge as recorded earlier by a year-long current meter mooring [*Barber and Crane*, 1995].

The LADCP-derived velocities across the 44°W section (Figure 9a) allow an estimate of volume transports for WSDW and WSBW and their more ventilated components. The total eastward transport for waters colder than −0.7°C is 5 Sv (Figure 9b) with about equal contributions from the ventilated VWSBW north of 63.5°S and the saltier forms of WSBW. The transport of WSDW across 44°W is 25 Sv, which with the WSBW, yields ~30 Sv of eastward transport for water column below roughly 1500 m (Figure 9c), the approximate depth of the 0°C isotherm marking the warm upper bound of WSDW.

The LADCP presents a snapshot view of the velocity field at higher spatial resolution than offered by mooring arrays and thus better defines the horizontal and vertical scales of high-speed cores and their relationship to the bottom bathymetry. Cognizant of the lack of temporal resolution offered by the LADCP section, we compare the LADCP results with the mooring data of *Fahrbach et al.* [1994], which offer more of a climatic mean. For the period September 1989 to January 1993 their measurements off Joinville Island yield 2.6 Sv of WSBW and 1.2 Sv of WSDW. The DOVETAIL measurements along 44°W suggest either temporal variability (which no doubt exists to some extent) or, more likely, that the DOVETAIL section incorporates more of the WSDW transport within the Weddell gyre which would not be captured by observations close to Joinville Island.

4. Conclusions

Within the northwest Weddell Sea, there are two types of deep and of bottom water. There are the more saline, less oxygenated forms of Weddell Sea Deep Water (WSDW) and of Weddell Sea Bottom Water (WSBW), which are most likely derived from the southwestern Weddell Sea. A second form of these water masses, with lower salinity and higher oxygen, is observed along the outer, northwest rim of the Weddell gyre. Enhanced ventilation of these water masses, which we designate as ventilated WSBW and ventilated WSDW (VWSBW and VWSDW), relative to those forms derived from the southwest Weddell Sea is due to influx of lower-salinity shelf water descending along the continental slope from the northern end of Antarctic Peninsula.

This extends a pattern of bottom water flow presented by *Gordon* [1998] for the deep interior of the western Weddell Sea. He describes three plumes of newly formed bottom water. The plume most removed from the western boundary is relatively warm and salty, and it represents a mixture of Filchner Depression outflow with Weddell gyre interior bottom water. Farther west is the second plume of colder, lower-salinity bottom water derived from outflow of Ronne Ice Shelf water exiting the shelf in the region of General Belgrano Bank. The third plume is a cold, high-salinity variety of bottom water formed as high-salinity shelf water drops into the deep sea near 70°S. It is likely that some mix of the central and western plumes comprise the WSBW (stations 30–33) observed by the DOVETAIL data south of South Orkney Ridge as the saline, lower-oxygen variety of WSBW. The DOVETAIL data reveal a fourth more ventilated plume hugging the edge of the northwest Weddell Sea. This plume with lower salinity and higher oxygen characteristics is derived from the northern end of the Weddell Sea.

The water mass distribution indicates that the VWSDW is advected eastward between 1500 and 2000 dbar in contact with the seafloor; in adjacent deeper water it overrides colder layers of WSDW. The VWSDW is the source of the relatively cold bottom water over the southern South Orkney Plateau. The VWSDW passes northward into the Scotia Sea along the eastern edge of the plateau. None is observed to pass eastward of that longitude within the Weddell Sea. The VWSDW ventilates middepths of the Scotia Sea. Bottom Water in the southern Scotia Sea is derived from overflow of WSDW with warmer elements of VWSBW.

The VWSBW and VWSDW, being shallower, would have better access to escape routes into the Scotia Sea and South Atlantic, leaving the deeper, more saline versions of WSDW and WSBW to recirculate within the Weddell Gyre. Therefore the cold, lower-salinity forms of Weddell Sea waters forming near the northern end of the Weddell Sea's Antarctic Peninsula may be more active in ventilating the Atlantic Ocean than the densest components formed farther south. The more saline WSBW and WSDW may take a more indirect (diffusive) route into the Atlantic Ocean.

The VWSBW and VWSDW effectively extract freshwater from the Weddell Gyre. This may explain why the apparent cold end-member of the central Weddell Gyre is more saline than the average WSBW formed in the southwestern and western Weddell Sea [*Gordon*, 1998]. This is similar to the conclusion of *Fahrbach et al.* [1995], who say the Filchner Depression outflow dominates the central Weddell Gyre, while lower-salinity bottom water formed in the western Weddell Sea "influences the abyssal waters of the open ocean."

A simple pattern emerges (see arrows on Figure 1): Upon proceeding clockwise around the rim of the Weddell Sea from Cape Norwegia to the tip of Antarctic Peninsula, a sequence of freezing point shelf water types is encountered. This sequence is projected as a "fan" of resultant bottom water spreading across the deep western Weddell Sea. The bottom water formed at Filchner Depression enters the deeper interior of the Weddell Sea, while the lowest-salinity bottom waters arising from shelf water closer to the tip of Antarctic Peninsula track along the rim of the Weddell Sea and are the first to escape the confines of the Weddell Sea. Between these two extremes are a series of other bottom water types that may enter the central Weddell Sea or mix upward to exit the Weddell Sea.

Acknowledgments. The research is supported by National Science Foundation Grant OPP 95-28807. The LADCP Component is supported by a grant/cooperative agreement from the National Oceanic and Atmospheric Administration, grant UCSIO P.O. 10075411. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies. Lamont-Doherty contribution number 6167.

References

Barber, M., and D. Crane, Current flow in the north-west Weddell Sea, *Antarct. Sci.*, *7*, 39–50, 1995.

Carmack, E. C., and T. D. Foster, On the flow of water out of the Weddell Sea, *Deep Sea Res.*, *22*, 711–724, 1975.

Deacon, G. E. R., The Weddell gyre, *Deep Sea Res.*, *26*, 981–995, 1979.

Deacon, G. E. R., and T. D. Foster, The boundary region between the Weddell Sea and Drake Passage currents, *Deep Sea Res.*, *24*, 505–510, 1977.

Fahrbach, E., G. Rohardt, M. Schroder, and V. Strass, Transport and structure of the Weddell gyre, *Ann. Geophys.*, *12*, 840–855, 1994.

Fahrbach, E., G. Rohardt, N. Scheele, M. Schroder, V. Strass, and A. Wisotzki, Formation and discharge of deep and bottom water in the northwestern Weddell Sea, *J. Mar. Res.*, *53*(4), 515–538, 1995.

Fischer, J., and M. Visbeck, Deep velocity profiling with self-contained ADCP's, *J. Atmos. Oceanic Technol.*, *10*, 764–773, 1993.

Gordon, A. L., Potential temperature, oxygen and circulation of bottom water in the Southern Ocean, *Deep Sea Res.*, *13*, 1125–1138, 1966.

Gordon, A. L., Structure of Antarctic waters between 20°W and 170°W, *Antarct. Map Folio Ser.*, folio 6, 1967.

Gordon, A. L., Western Weddell Sea thermohaline stratification, in *Ocean, Ice, and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. Weiss, pp. 215–240, AGU, Washington, D. C., 1998.

Gordon, A. L., and B. A. Huber, Southern Ocean winter mixed layer, *J. Geophys. Res.*, *95*, 11,655–11,672, 1990.

Gordon, A., B. Huber, H. Hellmer, and A. Ffield, Deep and bottom water of the Weddell Sea's Western Rim, *Science*, *262*, 95–97, 1993.

Gordon, A., M. Mensch, Z. Dong, W. Smethie Jr., and J. de Bettencourt, Deep and bottom water of the Bransfield Strait eastern and central basins, *J. Geophys. Res.*, *105*, 11,337–11,347, 2000.

Locarnini, R. A., T. Whitworth, and W. D. Nowlin, The importance of the Scotia Sea on the outflow of Weddell Sea Deep Water, *J. Mar. Res.*, *51*, 135–153, 1993.

Mensch, M., R. Bayer, J. Bullister, P. Schlosser, and R. Weiss, The distribution of Tritium and CFCs in the Weddell Sea during the mid-1980s, *Prog. Oceanogr.*, *38*, 377–415, 1996.

Mensch, M., W. Smethie Jr., P. Schlosser, R. Weppernig, and R. Bayer, Transient tracer observations from the western Weddell Sea during the drift and recovery of ice station Weddell, in *Oceans, Ice and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. Weiss, pp. 241–256, AGU, Washington, D. C., 1998.

Meredith, M. P., R. A. Locarnini, K. A. Van Scoy, A. J. Watson, K. J. Heywood, and B. A. King, On the sources of Weddell Gyre Antarctic Bottom Water, *J. Geophys. Res.*, *105*, 1093–1104, 2000.

Muench, R. D., Deep Ocean ventilation through Antarctic intermediate layers, *Antarct. J.*, *32*, 65–67, 1997.

Nowlin, W. D., Jr., and W. Zenk, Westward bottom currents along the margin of the South Shetland Island Arc, *Deep Sea Res.*, *35*, 269–301, 1988.

Orsi, A. H., W. D. Nowlin, and T. Whitworth, On the circulation and stratification of the Weddell Gyre, *Deep Sea Res.*, *40*, 169–203, 1993.

Patterson, S. L., and H. A. Sievers, The Weddell-Scotia Confluence, *J. Phys. Oceanogr.*, *10*, 1584–1610, 1980.

Robertson, R., L. Padman, and G. Egbert, Tides in the Weddell Sea, in *Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. Weiss, pp. 341–369, AGU, Washington, D. C., 1998.

Smith, W. H. F., and D. T. Sandwell, Global sea floor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956–1962, 1997.

Weppernig, R., P. Schlosser, S. Khatiwala, and R. G. Fairbanks, Isotope data from Ice Station Weddell: Implications for deep water formation in the Weddell Sea, *J. Geophys. Res.*, *101*, 25,723–25,740, 1996.

Whitworth, T., III, W. Nowlin, A. Orsi, R. Locarnini, and S. Smith, Weddell Sea shelf water in the Bransfield Strait and the Weddell-Scotia Confluence, *Deep Sea Res.*, *41*, 629–641, 1994.

Whitworth, T., III, A. H. Orsi, S.-J. Kim, W. D. Nowlin Jr., and R. A. Locarnini, Water masses and mixing near the Antarctic Slope Front, in *Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin*, *Antarct. Res. Ser.*, vol. 75, edited by S. S. Jacobs and R. F. Weiss, pp. 1–29, AGU, Washington, D. C., 1998.

A. L. Gordon, B. Huber, and M. Visbeck, Lamont-Doherty Earth Observatory, Columbia University, Route 9W, Palisades, NY 10964. (agordon@ldeo.columbia.edu)

(Received February 28, 2000; revised January 22, 2001; accepted January 23, 2001.)