On the fate of the Antarctic Slope Front and the origin of the Weddell Front

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[1] Data from the Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) and Antarctic Large-Scale Box Analysis and the Role of the Scotia Sea (ALBATROSS) projects are combined in the region of the Antarctic Peninsula and the South Scotia Ridge to determine the paths and transports associated with the Antarctic Coastal Current, the Antarctic Slope Front, and the Weddell Front. The Antarctic Coastal Current flows over the Antarctic continental shelf and is not tied to a particular isobath. It transports ~1 Sv westward to the Bransfield Strait. Its subsequent course is uncertain, but we speculate that it may continue southwest along the western side of the Antarctic Peninsula, close to the coast. The Antarctic Slope Front, present almost all the way around Antarctica tied to the continental slope, has not previously been mapped after it reaches the tip of the Antarctic Peninsula. We show that the frontal jet splits into two branches in the northwest Powell Basin where the isobaths diverge. The shoreward portion of the water associated with the front (lying above isobaths shallower than 1500 m) is able to cross the South Scotia Ridge and head northwestward and retains many of the properties of the Antarctic Slope Front. It is associated with a transport of ~7 Sv. The portion of the front constrained to lie above isobaths deeper than 1500 m becomes the Weddell Front. This takes a path around the northern Powell Basin and south of the South Orkney Islands. Of the ~13 Sv that circulates around the southern flank of the South Orkney Plateau, ~8 Sv of Weddell Sea Deep Water and Warm Deep Water leaves the front to continue west. The remaining shallow and intermediate water retroflects and returns south associated with the Weddell Front through the Orkney Passage. Approximately 5–7 Sv is transported eastward associated with the Weddell Front, tied closely to the southern flanks of the Bruce and Discovery Banks above the 2000–2500 m isobaths, and forming the southern boundary of the Weddell Scotia Confluence. *INDEX TERMS:* 4528 Oceanography: Physical: Fronts and jets; 4532 Oceanography: Physical: General circulation; 4536 Oceanography: Physical: Hydrography; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4223 Oceanography: General: Descriptive and regional oceanography; *KEYWORDS:* topographic interaction, Weddell Scotia Confluence, water masses

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1. Introduction

[2] Much of the margin of Antarctica hosts two features identifiable in hydrographic and/or velocity observations: the Antarctic Slope Front and the Antarctic Coastal Current. The Antarctic Slope Front defines the boundary between cold, relatively fresh waters filling the Antarctic continental shelf and the warmer, more saline waters farther offshore, at least below the near-surface layer [*Jacobs*, 1986, 1991]. It is associated with a westward transport around Antarctica. In the southeastern Weddell Sea the flow associated with the Antarctic Slope Front accounts for ~50% of the (total baroclinic and barotropic) transport of the Weddell Gyre [*Heywood et al.*, 1998]. *Deacon* [1937] and *Sverdrup* [1953] considered this flow to be a consequence of the prevailing westward winds near the Antarctic continent, inducing an Ekman transport of cold, relatively fresh surface water toward the continent and thus setting up a geostrophic westward flow around Antarctica. Observations

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during Ice Station Weddell [*Muench and Gordon*, 1995] indicate a fast frontal jet strongly constrained to the continental slope depths of 500–1000 m on the eastern side of the Antarctic Peninsula.

[3] The Antarctic Coastal Current is a fast, shallow flow over the continental shelf and is often associated with the front of the ice shelf [*Jacobs*, 1991]. In some locations (e.g., southeast Weddell Sea) the locations of the Antarctic Coastal Current and Antarctic Slope Front are difficult to distinguish from each other because the continental shelf is very narrow [*Heywood et al.*, 1998]. Where the continental shelf is broad, the Antarctic Coastal Current separates from the Antarctic Slope Front and travels over the shelf. For example, in the southwest Weddell Sea the Antarctic Coastal Current flows across the shelf toward the Filchner-Ronne Ice Shelf [*Carmack and Foster*, 1975] and may flow beneath it. The transport of the Antarctic Coastal Current, and that associated with the Antarctic Slope Front, is important for the advection of nutrients and krill, for preconditioning the shelf waters for the formation of Antarctic Bottom Water through their associated heat and freshwater fluxes, and for supplying waters beneath ice shelves, thus melting the underside of the ice shelf. Coupled ice-ocean model results have recently suggested the possibility of a westward propagating wavelike anomaly pattern that may be associated with the Antarctic Slope Front or Antarctic Coastal Current [*Beckmann and Timmermann*, 2001].

[4] The Antarctic Slope Front has been identified with the most shoreward penetration of the 0°C isotherm at depths below the Winter Water [*Ainley and Jacobs*, 1981]. *Whitworth et al.* [1998] show this definition to be applicable almost all the way around Antarctica, certainly from the southern Weddell Sea eastward to the Amundsen Sea. However, they note two peculiarities in the region of the Antarctic Peninsula. First, on the western side of the peninsula the Circumpolar Deep Water from the Antarctic Circumpolar Current extends onto the slope, and there is no Antarctic Slope Front. Second, to the east of the tip of the peninsula, although the 0°C contour exists, Whitworth et al. are "not confident that the gradient still represents the Antarctic Slope Front in this region." In this paper we address these two issues: What happens to the Antarctic Slope Front when it reaches the end of the Antarctic Peninsula, and what is the feature represented by the 0°C contour on the southern and eastern flank of the South Orkneys? We shall show that the Antarctic Slope Front splits into two features, with the shoreward portion (tied to shallower isobaths) able to cross the South Scotia Ridge to the northwest, and the portion tied to deeper isobaths becoming what is known as the Weddell Front. The fate of and volume transport associated with each are discussed.

[5] The Weddell Front marks the northern limit of waters characteristic of the Weddell Sea interior and the southern limit of the Weddell Scotia Confluence. The associated current contributes some of the cyclonic transport of the Weddell Gyre. It was first named by *Gordon et al.* [1977], who identified it as the boundary between the weakly stratified Weddell Scotia Confluence water and the more stratified Weddell Sea water. The term "confluence" is misleading. While the overall region is one of convergence between northward and eastward flowing Weddell Sea waters and eastward flowing Drake Passage waters, the confluence itself appears to be formed through injection of Antarctic continental shelf waters along the northern limb of the Weddell Gyre [*Whitworth et al.*, 1994]. This injection is followed by isopycnal mixing of waters from the Weddell Sea, from the Antarctic continental shelf, and from the Antarctic Circumpolar Current [*Whitworth et al.*, 1994; *Naveira Garabato et al.*, 2003]. In this paper we trace the path of the Weddell Front in the northwest Weddell Sea using closely spaced hydrographic surveys and show that its contorted path is tightly constrained by bathymetry. The Scotia Front (the northern boundary of the Weddell Scotia Confluence, now more commonly titled the southern boundary of the Antarctic Circumpolar Current) was mapped by *Orsi et al.* [1995], so we do not discuss it further.

2. Data

[6] We use the data from four hydrographic surveys in the region of the Antarctic Peninsula and South Scotia Ridge (Figure 1). The first is World Ocean Circulation Experiment (WOCE) section A23 on RRS *James Clark Ross* during April 1995 that crossed the region meridionally at 31°W, forming the eastern boundary of the region considered [*Heywood and King*, 2002]. The second is one of the Deep Ocean Ventilation Through Antarctic Intermediate Layers (DOVETAIL) surveys on R/V *Nathaniel B. Palmer* in August 1997 that undertook a number of zonal and meridional sections across the South Scotia Ridge [*Gordon et al.*, 2000, 2001]. The third is a Spanish survey also contributing to DOVETAIL, which we shall refer to as E-DOVETAIL. The cruise took place on BIO *Hesperides* in January–February 1998 [*García*, 1998]. The final data set is a hydrographic section undertaken in April 1999 on RRS *James Clark Ross* along the crest of the South Scotia Ridge forming part of the Antarctic Large-Scale Box Analysis and the Role of the Scotia Sea (ALBATROSS) project [*Naveira Garabato et al.*, 2002a, 2002b]. ALBATROSS and DOVETAIL provided conductivity-temperature-depth (CTD) data and lowered acoustic Doppler current profiler (LADCP) data. A23 and E-DOVETAIL provided CTD data. Transports associated with the fronts have been calculated primarily from ALBATROSS using LADCP data to provide a known reference level. The LADCP velocities were first de-tided using version 3.1 of the Oregon State University global tide model [*Egbert et al.*, 1994]. Geostrophic shears were referenced as described by *Naveira Garabato et al.* [2002b]. A section of the LADCP velocities and a comparison of the volume transports across the section calculated using the LADCP data alone and CTD geostrophic shear referenced to the LADCP data are shown by *Naveira Garabato et al.* [2002b, Figure 4].

3. Results and Discussion

[7] Figures 2a–2f show potential temperature, salinity, dissolved oxygen concentration, cross-track velocity, cumulative cross-track transport, and full depth bathymetry of the quasi-zonal ALBATROSS section from the tip of the Antarctic Peninsula. We focus on the properties in the upper 1000 m. DOVETAIL sections are shown by *Gordon et al.* [2000, 2001] and by *Muench et al.* [2002] and are not repeated here. Property-property plots of stations on either

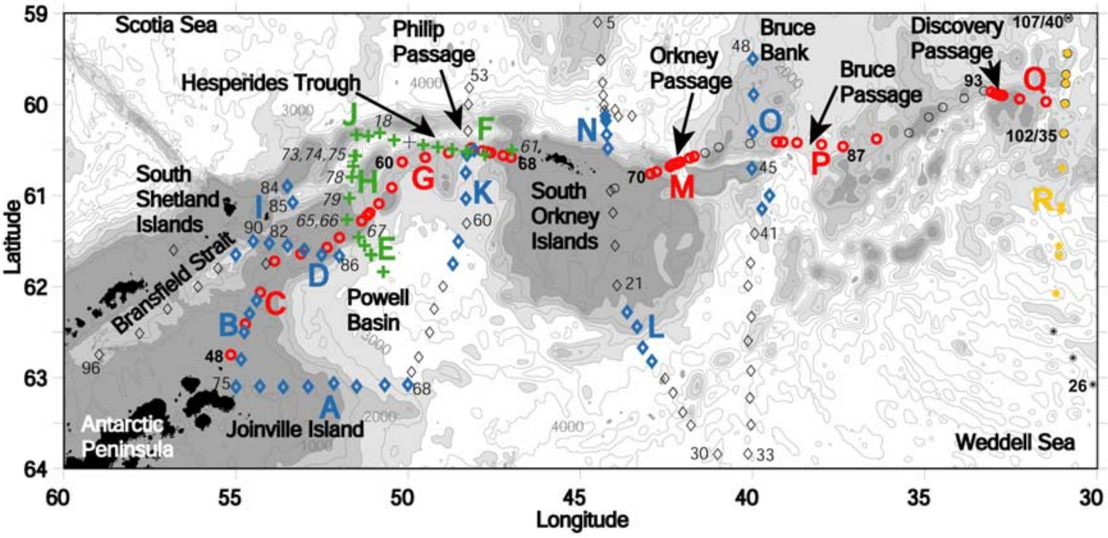

Figure 1. Bathymetry of the South Scotia Ridge region with contours every 500 m. Stations used in this study are marked: ALBATROSS stations (red circles with bold numbers), DOVETAIL stations (blue diamonds with regular numbers), E-DOVETAIL (green crosses with italic numbers), A23 stations (yellow stars with bold numbers). The same symbols in black denote stations not used for the property-property diagrams (Figures 3, 4, and 5). The color letters refer to particular subsections, detailed in Table 1.

side of the Antarctic Coastal Current, the Antarctic Slope Front, and the Weddell Front at each crossing are shown in Figures 3, 4, and 5, respectively. Subsections are given capital letters and are identified in Figure 1 and Table 1. Features will be discussed from upstream to downstream (usually west to east).

3.1. Inflow to the Region

[8] The zonal DOVETAIL section just south of 63°S (stations 68 to 75; subsection A in Table 1 and Figure 1) captures the primary Weddell inflow into the region and provides our first view of each of the features of interest since it crosses from waters representative of the central Weddell Sea to the shallow continental shelf of Antarctica (Figures 3a, 4a, 4b, and 5a). *Gordon et al.* [2000] locate the "shelf-slope transition" between stations 70–73, a view with which we concur. Stations 68–70 exhibit the distinct and uniform temperature and salinity maximum of Warm Deep Water (0.6°C, 34.69; see Figure 5a). Station 71 (on the 550 m isobath) has a significantly colder and fresher Warm Deep Water core (0.4°C, 34.66; see Figure 5a) so is clearly in a frontal zone. The greatest water mass change is between

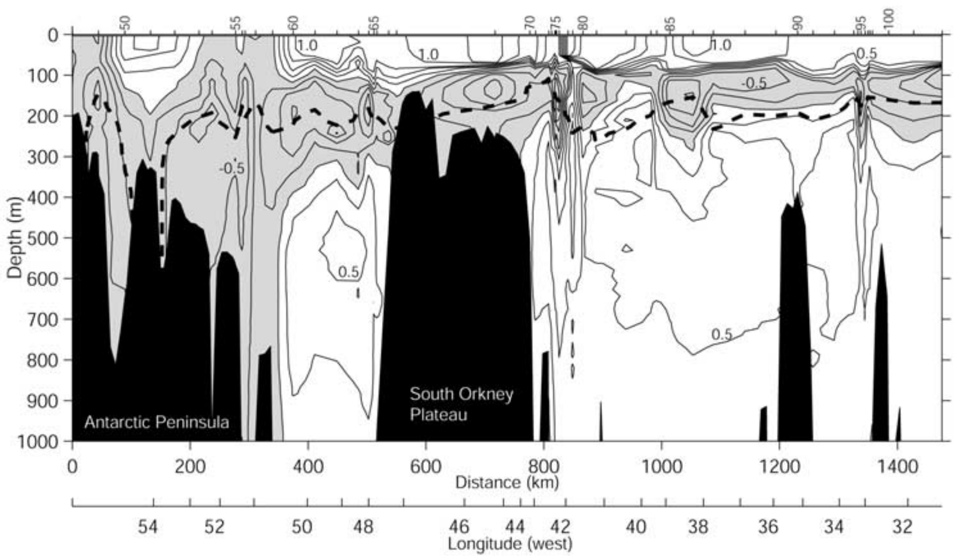

Figure 2a. Potential temperature (°C) section from the ALBATROSS survey along the South Scotia Ridge showing the top 1000 m only. Contour interval is 0.25°C, and values <0°C are shaded. The thick dashed line marks the γ^n = 28.0 neutral density surface. Selected station numbers are indicated on the upper axis.

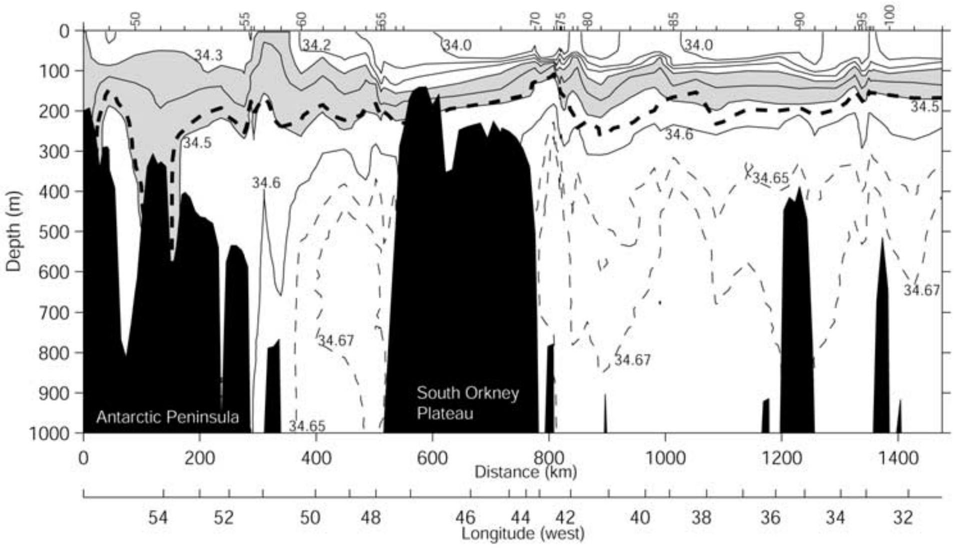

Figure 2b. As in Figure 2a but for salinity. Contour interval is 0.1, and values between 34.3 and 34.5 are shaded gray. The thin dashed contours are 34.65 and 34.67 for added detail in the Warm Deep Water.

stations 71 and 72 on the 450 m isobath (Figure 4a) where the Warm Deep Water signature reduces to −0.7°C, 34.59. This is where we place the Antarctic Slope Front. The location agrees with the established criterion of the shoreward limit of the 0°C isotherm marking the Warm Deep Water core [*Whitworth et al.*, 1998]. *Fahrbach et al.* [2001] show repeated sections east of Joinville Island, at a similar location to the DOVETAIL section. They find the location of the front between warmer Weddell deep waters and colder shelf waters to be "remarkably constant," lying above the 1000–1500 isobaths. In locations where the shelf water is dense enough to form Antarctic Bottom Water that may cascade off the shelf, the front exhibits a "v" shape in the isotherms and isohalines (for example, just upstream of our study region, off the Larsen Ice Shelf [*Muench and Gordon*, 1995]). At the locations discussed in this paper, however, where the shelf water is insufficiently dense to form Antarctic Bottom Water, the v shape is not present.

[9] An even clearer water mass distinction across the Antarctic Slope Front (Figure 4b) is shown in the dissolved oxygen variations with neutral density γ^n [*Jackett and McDougall*, 1997]. The Warm Deep Water on the offshore side of the front exhibits a pronounced oxygen minimum at densities lighter than 28.2 (the units of density, kg m^{-3}, will be omitted throughout the paper). The shelf side of the front exhibits much greater dissolved oxygen, indicating more recent or intense ventilation, and the oxygen minimum is reached at densities close to, or denser than, 28.2. This distinction is, we suggest, a clearer criterion than temperature or salinity properties. Note that during DOVETAIL (winter), there is no definitive signature of the Antarctic Slope Front in either sea surface temperature or sea surface

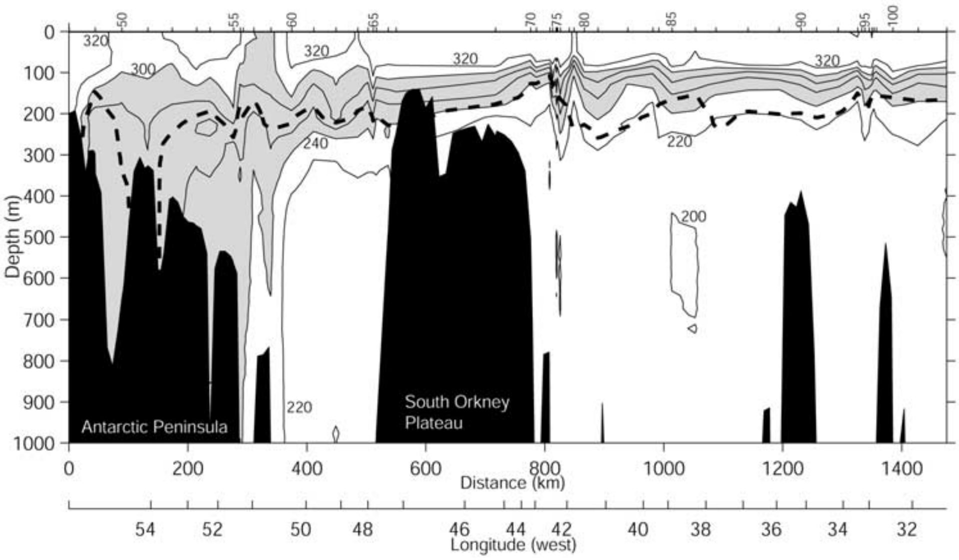

Figure 2c. As in Figure 2a but for dissolved oxygen (μmol kg^{-1}). Contour interval is 20 μmol kg^{-1}, and values between 240 and 300 μmol kg^{-1} are shaded gray.

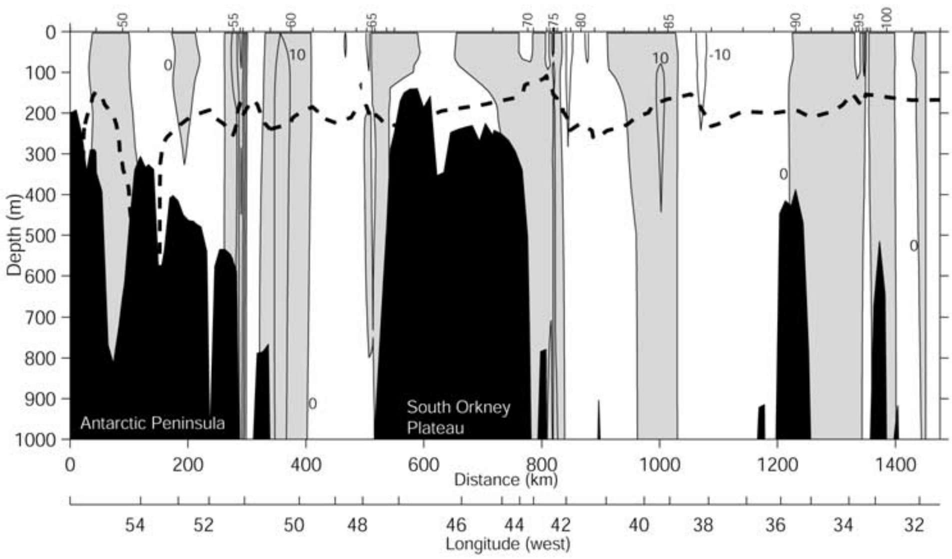

Figure 2d. As in Figure 2a but for geostrophic velocity (cm s^{-1}) referenced to the lowered acoustic Doppler current profiler profiles. Contour interval is 10 cm s^{-1}, and northward (positive) values are shaded gray.

salinity. Surface salinity increases toward the shelf; station 72 is 0.01 more saline than station 71. Surface temperature decreases, but there is no sharp boundary.

[10] Farther inshore, another current flows northward on the continental shelf. It is associated with a front between stations 73 (on the 350 m isobath) and 74 (400 m isobath). This is the Antarctic Coastal Current [*Jacobs*, 1991] and has a transport of 1 Sv between those stations. The water mass characteristics inshore of the current are well mixed in temperature and are stratified only in salinity, lacking the subsurface temperature maximum which penetrates past the Antarctic Slope Front onto the shelf up to this point (Figure 3a) (also shown in the sections published by *Gordon et al.* [2000, Figure 3]). It would be possible to locate this current using sea surface salinity, which increases by ~0.02 between stations 73 and 74.

3.2. Fate of the Antarctic Coastal Current

[11] We now trace the path of this Antarctic Coastal Current in DOVETAIL and ALBATROSS data past Joinville

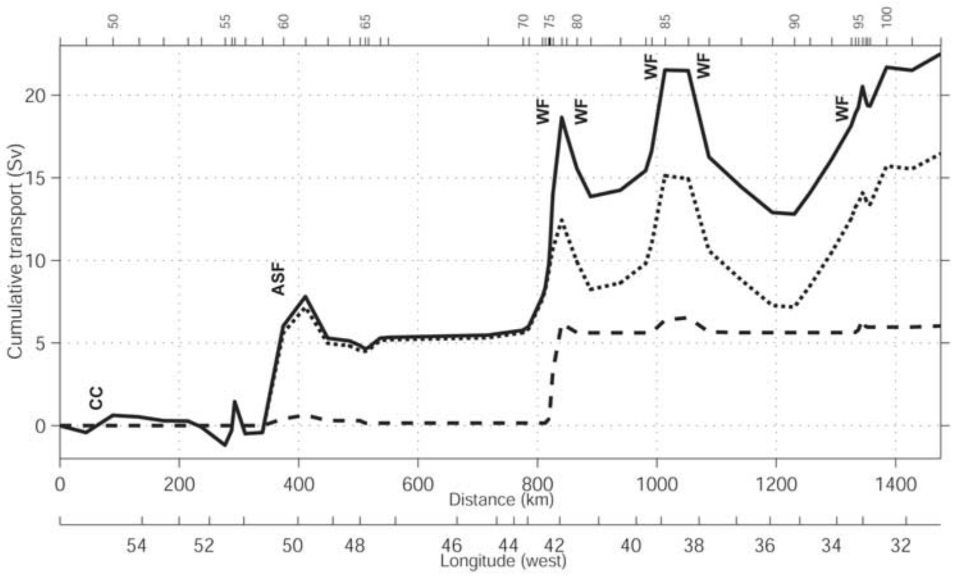

Figure 2e. Volume transports (Sv) from the ALBATROSS survey along the South Scotia Ridge, presented as cumulative transport from the tip of the Antarctic Peninsula. Geostrophic shear has been referenced to LADCP profiles as described by *Naveira Garabato et al.* [2002b]. All water masses (full depth water column) are depicted by the solid line; surface and intermediate water masses are depicted by the dotted line, and Weddell Sea Deep Water is depicted by the dashed line. The Antarctic Coastal Current (CC), Antarctic Slope Front (ASF), and Weddell Front (WF) crossings are marked.

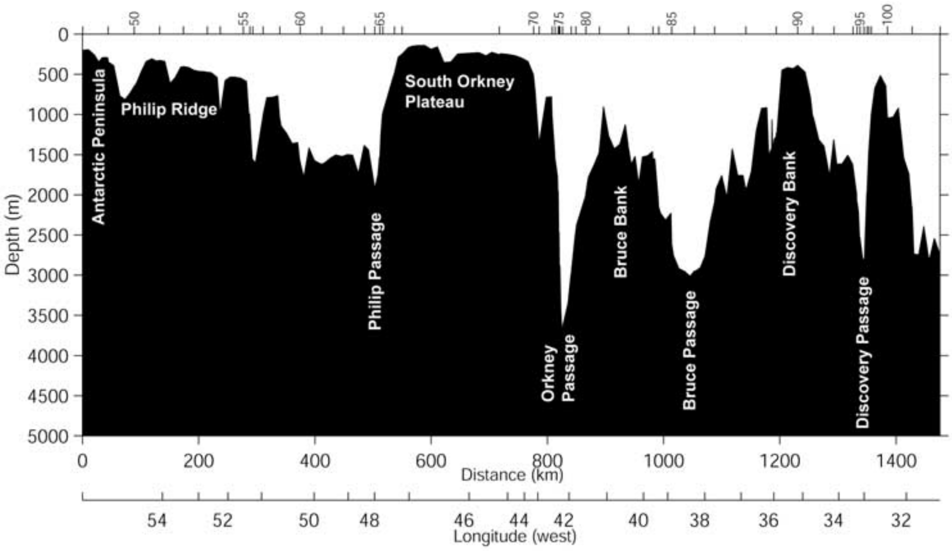

Figure 2f. Full depth bathymetry from the ALBATROSS survey along the South Scotia Ridge.

Island (subsections B and C, respectively, in Table 1 and Figure 1). The ALBATROSS temperature section (Figure 2a) shows a sharp thermal gradient between stations 49 (depth 290 m) and 50 (depth 640 m). Inshore, the waters are cold (<0.5°C, Figure 3b) and well oxygenated (>330 μmol kg^{-1}, Figure 2c). *Gordon et al.* [2000] indicate the flow of Weddell Sea shelf waters into the Bransfield Strait using DOVETAIL data. Their Figure 5 suggests two primary flow paths (note, however, that their paths are intended to signify schematic pathways rather than fronts). The first is just inshore of the westernmost ALBATROSS station (48). We do not see westward transport in the ALBATROSS LADCP data at this station, although of course this does not preclude it since the flow may be farther inshore or the LADCP data may be dominated by a remaining tidal signal. However, the current located between ALBATROSS stations 49 and 50 is the same westward flow seen by *Gordon et al.* [2000] near DOVETAIL station 79. In Figure 3a we locate the associated boundary in properties between DOVETAIL stations 77 (depth 280 m) and 78 (560 m). It is noteworthy that we observe the same westward current at this location on the two cruises in different seasons and years. Gordon et al. suggest that this water passes into the central and eastern basins of the Bransfield Strait and then eastward through the Northeast Channel. *Smith et al.* [1999] argue that there is insignificant escape westward for waters from the Bransfield Strait onto the shelf of the west Antarctic Peninsula. Tracer particles deployed into a numerical model [*Schodlock et al.*, 2002] show flow on the continental shelf to the west around the tip of the Antarctic Peninsula (their Figure 10). A similar release of particles into the model of *Matano et al.* [2002] indicated flow to the west, but all of it retroflected in the Bransfield Strait and none continued to the southwest along the western side of the Antarctic Peninsula, in contrast to the results of *Schodlock et al.* [2002]. Further observations would be required to determine whether this surface intensified current does indeed circulate around Bransfield Strait, returning eastward to mix into the Weddell Scotia Confluence, or whether it can possibly escape westward close to the coast through the Gerlache Strait. After flowing west across the ALBATROSS and DOVETAIL sections northeast of the tip of the Antarctic Peninsula, the Antarctic Coastal Current is not observed again in the data sets considered here.

[12] *von Gyldenfeldt et al.* [2002] use moored current profile data located on the continental shelf just north of Joinville Island to estimate that 2.4 (±1.0) Sv flows northward between the tip of the peninsula and the shelf edge (just north of DOVETAIL station 73). Approximately 1 Sv is transported around the tip of the peninsula in the Antarctic Coastal Current, as measured on both ALBATROSS and DOVETAIL using geostrophy referenced to LADCP measurements.

3.3. Fate of the Antarctic Slope Front

[13] Figure 4 shows the water mass contrasts across the Antarctic Slope Front. Downstream of Joinville Island (subsection A, Figures 4a and 4b), the Antarctic Slope

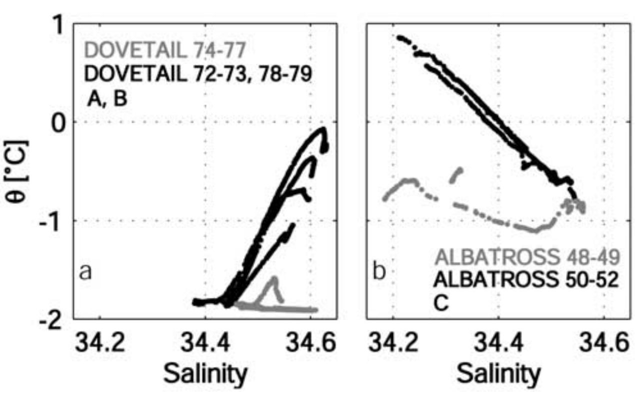

Figure 3. Potential temperature–salinity diagrams across the Antarctic Coastal Current (a) east and northeast of the Antarctic Peninsula and (b) northeast of the Antarctic Peninsula. Conductivity-temperature-depth (CTD) stations west/east of the front are marked by gray/black dots. For locations of subsections, indicated by capital letters, see Figure 1 and Table 1.

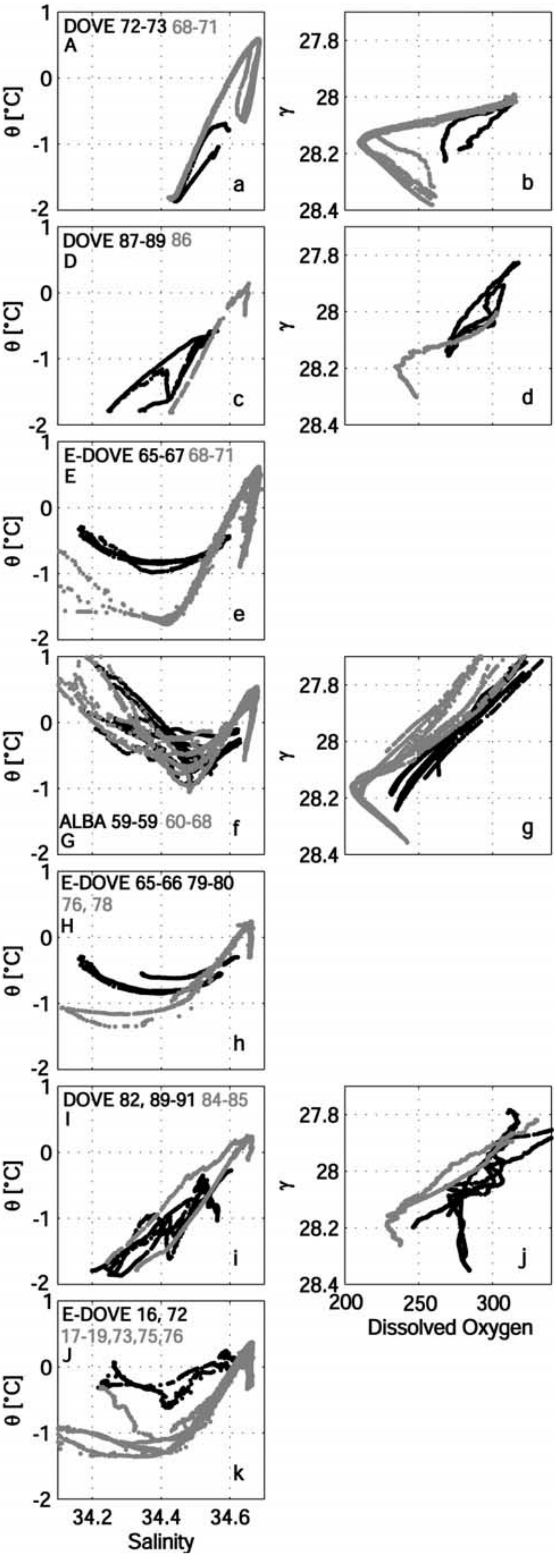

Figure 4. Diagrams of (left) potential temperature–salinity (right) and neutral density–dissolved oxygen (μmol kg^{-1}) across the Antarctic Slope Front (ASF) for (a, b) Joinville Island, east of the Antarctic Peninsula; (c–e) northwestern Powell Basin; (f–h) Philip Passage; and (i–k) Hesperides Trough. Stations in gray are to the south or east of the ASF; stations in black are to the north or west of the ASF. Dissolved oxygen data are not available for the E-DOVETAIL survey. For locations of subsections, indicated by capital letters, see Figure 1 and Table 1. DOVETAIL, E-DOVETAIL, and ALBATROSS are indicated by DOVE, E-DOVE, and ALBA, respectively.

Front is encountered on both DOVETAIL (subsection D) and E-DOVETAIL (subsection E) at ~61.5°S close to the steep topography of the Antarctic continental slope. It is crossed between DOVETAIL stations 86 and 87 (Figures 4c and 4d) and E-DOVETAIL stations 67 and 68 (Figure 4e). Although the stations are closely spaced, the slope is extremely steep here; in both cases the stations on either side are at widely differing depths (470 and 2210 m and 900 and 2870 m), so the data cannot distinguish if the front is located above a particular range of isobaths.

[14] The Antarctic Slope Front is encountered once on the ALBATROSS section (subsection G), with associated northwestward flow between stations 59 and 60 (Figure 2), above isobaths at 1000 and 1600 m, respectively. At this location we place the splitting of the Antarctic Slope Front, into a front that crosses the South Scotia Ridge, and another (the Weddell Front) which continues eastward. This splitting is most likely caused by the topography, since we observe a divergence of the isobaths at this location [*Warren*, 1969]. That portion of the water associated with the front inshore of the 1500 m isobath is able to pass over the South Scotia Ridge here; it is the first opportunity that this water has encountered to do so. That portion of the water associated with the front that is tied to a deeper isobath is unable to pass over the ridge here and continues cyclonically around the Powell Basin as the Weddell Front, described in section 3.4.

[15] The Warm Deep Water to the west of the front (black dots in Figure 4) is considerably colder and more oxygenated than that to the east (gray dots in Figure 4). The shifts in properties across the Antarctic Slope Front in the summer data from ALBATROSS (Figures 4f and 4g) are consistent with those observed in winter (Figures 4a and 4b), but obviously, the near surface waters are considerably colder, more saline, and denser in winter. During ALBATROSS the Antarctic Slope Front is marked most clearly by a local maximum in sea surface salinity (Figure 2b). This is also seen in the crossing of this front in the southeast Weddell Sea during A23 [*Heywood and King*, 2002; *Heywood et al.*, 1998]. Both A23 and ALBATROSS occurred during late austral summer when the sea ice is at its minimum extent and ice melt has freshened the surface waters. E-DOVETAIL was also a summer campaign. However, this is not the case during DOVETAIL, a winter cruise, which shows the salinity increasing monotonically toward the coast. Sea ice formation is clearly in progress on the continental shelf. The elevated sea surface salinity in the core of the Antarctic Slope Front in summer is reminiscent of the similarly

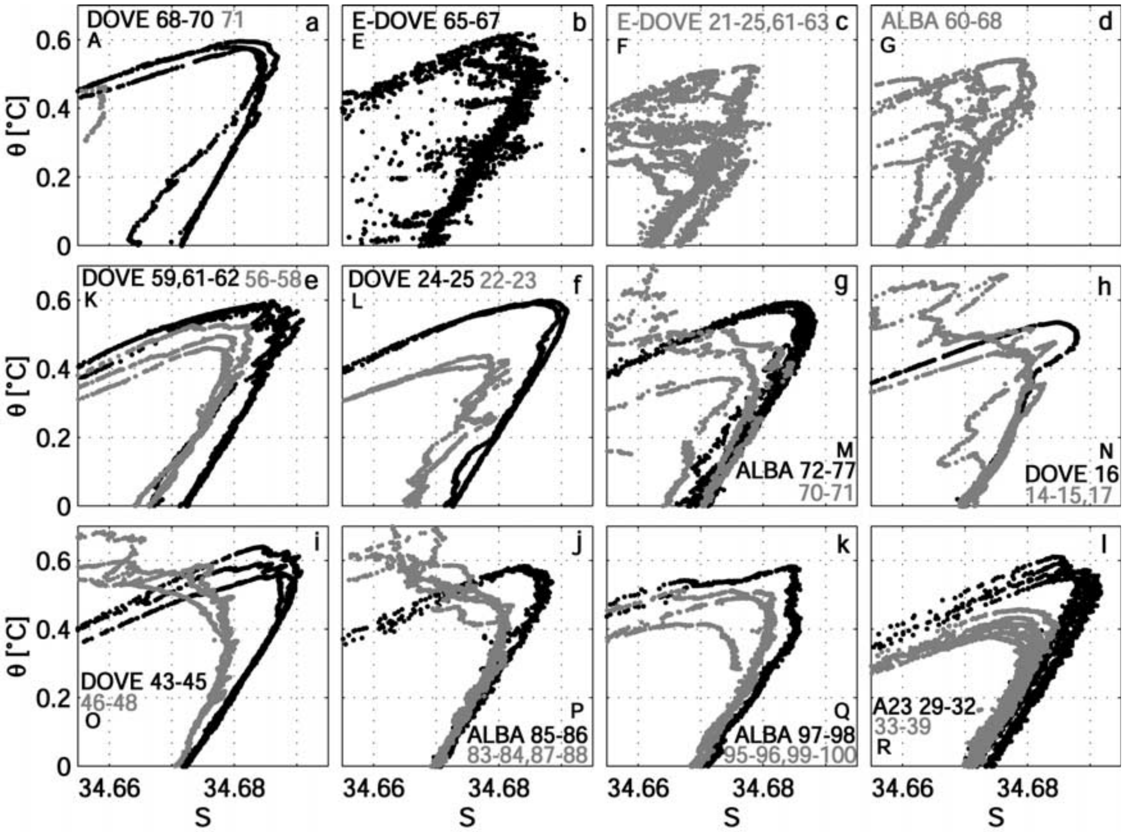

Figure 5. Potential temperature–salinity diagrams across the Weddell Front for (a) Joinville Island, east of the Antarctic peninsula; (b) Powell Basin (station 80 in gray is out of range of the plot); (c–e) Philip Passage, (f) south of the Orkney Plateau; (g) Orkney Passage; (h) north of the Orkney Plateau; (i) south of Bruce Bank; (j) Bruce Passage; (k) Discovery Passage; and (l) 31°W. CTD stations north/south of the front are marked by gray/black dots. For locations of subsections, indicated by capital letters, see Figure 1 and Table 1. DOVETAIL, E-DOVETAIL, and ALBATROSS are indicated by DOVE, E-DOVE, and ALBA, respectively.

Table 1. Details of the Subsections Used in the Analysis

Subsection[a]	Cruise	Stations	Coastal Current[b]	Slope Front[b]	Weddell Front[b]
A	DOVETAIL	68–75	3a	4a, 4b	5a
B	DOVETAIL	75–79	3a		
C	ALBATROSS	48–52	3b		
D	DOVETAIL	86–89		4c, 4d	
E	E-DOVETAIL	65–71, 80		4e	5b
F	E-DOVETAIL	21–25, 61–63			5c
G	ALBATROSS	50–68		4f, 4g	5d
H	E-DOVETAIL	65, 66, 76, 78–80		4h	
I	DOVETAIL	82, 84–85, 89–91		4i, 4j	
J	E-DOVETAIL	16–19, 72–73, 75–76		4k	
K	DOVETAIL	65–69, 61–62			5e
L	DOVETAIL	22–25			5f
M	ALBATROSS	70–79			5g
N	DOVETAIL	14–17			5h
O	DOVETAIL	43–48			5i
P	ALBATROSS	83–88			5j
Q	ALBATROSS	95–100			5k
R	WOCE A23	29–39			5l

[a]Letters refer to the labels shown in Figure 1.
[b]Numbers refer to the figures showing the changes in water properties across each crossing (or not) of a particular front or current.

elevated sea surface salinity observed in the Weddell Scotia Confluence in summer [*Gordon et al.*, 1977] but not in winter [*Muench et al.*, 1990].

[16] The transport between ALBATROSS stations 59 and 60, spanning the Antarctic Slope Front, only 35 km apart, is 6.5 Sv. This is essentially barotropic transport since the shear component is negligible (some tenths of sverdrups). It consists of Warm Deep Water and surface waters, since the Weddell Sea Deep Water is too dense and deep to cross the South Scotia Ridge here [*Naveira Garabato et al.*, 2002b]. There are few published values for comparison with this. In the southern Weddell Sea, *Heywood et al.* [1998] obtained a total transport of 14 Sv, of which 10 Sv was barotropic, derived from referencing geostrophic shear relative to the deepest common level to ship-borne ADCP measurements, although the Antarctic Slope Front was converged with the Antarctic Coastal Current because the continental slope is very narrow there.

[17] After the Antarctic Slope Front is observed crossing the South Scotia Ridge, it is next encountered hugging the steep topography at the southern side of the Hesperides Trough, associated with a southwestward flow (subsection H). It is located between E-DOVETAIL stations 78 (on the 2600 m isobath) and 79 (on the 1100 m isobath) (Figure 4h). At the western end of the Hesperides Trough (subsection I), DOVETAIL stations 84 (on the 700 m isobath) and 85 (on the 1900 m isobath) lie on the ''Weddell'' side of the Antarctic Slope Front, exhibiting a relatively warm and low-oxygen Warm Deep Water core (Figures 4i and 4j). The DOVETAIL stations at the eastern end of the Bransfield Strait, on the other hand, display the properties of the Antarctic continental shelf, shown by stations 82 (above the 900 m isobath) and 90 (above the 1500 m isobath). Therefore the Antarctic Slope Front must be located along the flank of the Hesperides Trough, retroflecting to the east at its western end between the two sets of DOVETAIL stations. Station 84 is probably lying in the front.

[18] Our final crossing of the Antarctic Slope Front is at the northern limit of the E-DOVETAIL sections (subsection J). E-DOVETAIL stations 16 and 72 are colocated above the 550 m isobath, and both show properties indicating the northern (or shelf) side of the front (Figure 4k), although the signature is less clear here. Stations to both the south (stations 73, 74, and 75, above the 3100 m isobath) and the east (stations 17 and 18, above the 3300 m isobath) exhibit properties of the southern (Weddell) side of the front. Thus we believe that our last sighting of the Antarctic Slope Front is as it hugs the steep northern flank of the Hesperides Trough, associated with an eastward flow. There is no signature of the Antarctic Slope Front at DOVETAIL stations 53 to 55 north of the Philip Passage, so the front must lose its characteristics here, possibly because of turbulent mixing over rough topography [*Naveira Garabato et al.*, 2004].

[19] The 0°C contour at the depths of the Warm Deep Water temperature maximum layer has been used as an indicator of the Antarctic Slope Front [*Whitworth et al.*, 1998]. *Whitworth et al.* [1998] map the 0°C contour as continuous from the Antarctic Shelf, around the Powell Basin and passing anticyclonically around the South Orkneys. However, the ALBATROSS and DOVETAIL data show that the 0°C contour crosses the South Scotia Ridge at 50°W with the Antarctic Slope Front, between the Antarctic Peninsula and the South Orkneys. On ALBATROSS the zonal section across the South Orkney shelf shows that all stations exhibit Warm Deep Water (at ~300–600 m) with temperature maxima greater than 0°C. Similarly, the DOVETAIL quasi-meridional section (stations 10 to 25) [*Gordon et al.*, 2001, Figure 3a] shows Warm Deep Water warmer than 0°C. Therefore we can conclude that the 0°C contour at 400 m drawn by *Whitworth et al.* [1998] extending east from the Antarctic Peninsula and around the South Orkneys is not consistent with the DOVETAIL, E-DOVETAIL, and ALBATROSS data sets. These new detailed data sets were collected in winter (DOVETAIL) and summer (E-DOVETAIL and ALBATROSS), so the discrepancy between the mapped historical data and the new sections is not caused by seasonality. It is possible that the Warm Deep Water has warmed slightly over the recent decade. Indeed, *von Gyldenfeldt et al.* [2002] document a warming of ~0.4°C of the Warm Deep Water layer in the region of the Antarctic Peninsula and the South Orkneys, from the early 1980s to the late 1990s (they include the ALBATROSS, E-DOVETAIL, and DOVETAIL data discussed here and show corroborating data from 1998 and 2000). The Warm Deep Water temperature maximum observed on ALBATROSS west of the South Orkney islands is ~0.6°C (Figure 4e), so a long-term trend in temperature may partly explain the discrepancy.

3.4. Origin and Path of the Weddell Front

[20] The location of the Weddell Front is most clearly identified by a jump in the temperature and salinity properties of the Warm Deep Water. Figure 5 illustrates that shift at nine locations between the Antarctic Peninsula and 35°W and shows three instances in which the front was not crossed. The first two regime shifts (Figures 5a and 5b) illustrate the Antarctic Slope Front to the east of the Antarctic Peninsula (subsections A and E) as discussed in the previous sections, included here for completeness and comparison of the water masses graphically on the same scales. We locate the splitting of the Antarctic Slope Front, and the origin of the Weddell Front, in the northwest Powell Basin and can identify each crossing farther east in our data sets. At each crossing, the Weddell Sea water (black dots) is warmer and saltier than the water to the north (or east) of the Weddell Front (gray dots). The Weddell Sea water is unvarying in its characteristics, whereas the Weddell Scotia Confluence to the north is more variable.

[21] The Weddell Front is not seen on either the E-DOVETAIL or ALBATROSS zonal sections along the South Scotia Ridge across the Philip Passage, west of the South Orkney Plateau (Figures 5c and 5d, subsections F and G, respectively). The ALBATROSS velocity data show little meridional transport here (Figure 2e). Just west of the Orkney Plateau, the Weddell Front is crossed on the meridional DOVETAIL section (subsection K) between stations 58 (above the 2500 m isobath) and 59 (above the 2800 m isobath) (Figure 5e), associated with an eastward flow. Thus it does not pass northward from the Powell Basin into the Scotia Sea but rather follows the ~2600 m contour (and the cyclonic Weddell Gyre circulation) to the south of the plateau. Our observations thus confirm the flow south of the South Orkneys predicted by the numerical models described by *Matano et al.* [2002, Figure 6b] and *Thorpe et*

al. [2002, Figure 11]. The sill depth in the Philip Passage is only 1500–2000 m, consistent with the Weddell Front being tied to a deeper isobath. The Weddell Front is crossed a second time on the DOVETAIL cruise (Figure 5f) on the meridional section south of the Orkney Plateau (subsection L). This is one of the most distinct crossings where there is a clear jump between station 23 on the 1500 m isobath (Warm Deep Water core 0.4°C, 34.68) and station 24 on the 3200 m isobath (Warm Deep Water core 0.6°C, 34.69).

[22] On ALBATROSS the majority of the section along the crest of the South Scotia Ridge lies to the north of the Weddell Front. However, at a number of stations east of the South Orkneys the ALBATROSS section clearly crosses into "pure" central Weddell Sea waters. These crossings occur in each of the deep passages in the South Scotia Ridge: the Orkney Passage (42°W, subsection M), the Bruce Passage (39°W, subsection P), and the Discovery Passage (33°W, subsection Q). In the Orkney Passage (Figure 5g) we see for the first time the properties of the Weddell Scotia Confluence to the north of the Weddell Front (gray dots). Unlike the properties on the South Orkney shelf and Antarctic Peninsula, which showed a clear subsurface temperature/salinity maximum, in the Weddell Scotia Confluence, there is much interleaving and often only a salinity maximum. The Weddell Front is crossed between ALBATROSS stations 71 (1400 m) and 72 (1000 m) with associated northward flow from the Weddell Sea into the Scotia Sea (subsection M). At this location, there is an important outflow of Weddell Sea Deep Water [*Naveira Garabato et al.*, 2002b] which is present beneath the Weddell Front. The Weddell Front must, however, retroflect somewhere to the northwest of the Orkney Passage. It is observed on the eastern flank of the Orkney Passage with an associated southward flow, between ALBATROSS stations 77 (3650 m) and 78 (2950 m) (Figure 5g). The front is now located on a considerably deeper isobath after its incursion into the Scotia Sea. The associated northward flow is ~13 Sv, of which 7 Sv is Weddell Sea Deep Water. The southward flow is ~5 Sv, of which only 1 Sv is Weddell Sea Deep Water (Figure 2e). Most of the Weddell Sea Deep Water has clearly left the Weddell Front and will continue westward through the Scotia Sea to penetrate Drake Passage as a westward bottom current [*Nowlin and Zenk*, 1988]. We deduce that ~8 Sv of water leaves the Weddell Front to continue west, consisting of the Weddell Sea Deep Water plus some intermediate and surface waters. This westward near-bottom flow has been observed in western Drake Passage at 65°W [*Naveira Garabato et al.*, 2003].

[23] We now discuss the question, where does the Weddell Front retroflect? There is no clear crossing in the DOVETAIL section north of South Orkney (subsection N). However, at station 16 (on the 4800 m isobath), there is an indication of water mass properties very close to those of the Weddell Sea, suggesting that the Weddell Front is probably retroflecting just east of here (Figure 5h). *Gordon et al.* [2001] also describe a retroflection in the South Orkney Trough of circulating Weddell Sea Deep Water based on the water mass characteristics in these DOVETAIL stations. They refer to the properties at station 17 (which lies on the 1400 m isobath to the north of the South Orkney Plateau) as representing a recently ventilated form of Weddell Sea Deep Water that has passed through the Orkney Passage. We argue that a similar circulation path is also taken by the intermediate and upper water masses and is associated with the Weddell Front. The numerical model of *Matano et al.* [2002] suggests a retroflection at ~44°W (their Figure 6b), but the retroflected water does not subsequently return through the Orkney Passage; rather, it sets off to the northeast toward South Georgia along a pathway more reminiscent of the Southern Antarctic Circumpolar Current Front [*Thorpe et al.*, 2002].

[24] On the southern flank of the Bruce Bank (subsection O) the Weddell Front is located between DOVETAIL stations 45 and 46 (Figure 5i). ALBATROSS station 82 lies on the same section slightly south (and downslope) of DOVETAIL station 46 and is north of the front. Thus the front lies between the 5500 m isobath (DOVETAIL station 45) and 1400 m isobath (ALBATROSS station 82). The Weddell Front is crossed again during ALBATROSS on the flanks of the Bruce Passage (subsection P, Figure 5j). It is associated with northward flow between stations 84 (above the 2050 m isobath) and 85 (above the 3560 m isobath), presumably retroflects just north of this, and returns south between stations 86 (above the 2900 m isobath) and 87 (above the 2100 m isobath). The front can therefore be located approximately at the 2500 m isobath. On both crossings, the transport associated with the front is 7–8 Sv, in agreement with the estimate of eastward transport of 6 Sv at DOVETAIL station 45.

[25] On the eastern flank of the Discovery Bank (subsection Q), there is a significant component of flow northward across the ALBATROSS section (Figure 2d). The water mass properties are intermediate between those of the Weddell Scotia Confluence and the Weddell Sea (Figure 5k), so we conclude that the flow associated with the Weddell Front and the Weddell Front itself lie nearly parallel to the section. ALBATROSS stations 97 and 98 are the only ones that have properties close to those of the Weddell Sea south of the Weddell Front (Figure 5k). The Weddell Front lies between the 1970 and 2850 m isobaths (stations 96 and 97, respectively) associated with a northward flow.

[26] On A23 at 31°W the crossing (being meridional) is much more distinct (subsection R, Figure 5l). The Weddell Front is located by a sharp change in the potential temperature and salinity of the Warm Deep Water core, from 0.55°C, 34.69 south of the front to 0.4°C, 34.68 north of the front. The front lies between the 2500 and 3500 m isobaths on the southern flank of the South Scotia Ridge. It has negligible associated baroclinic transport (<1 Sv), but lowered ADCP data are not available to provide an estimate of the (probably much larger) barotropic transport.

[27] Another indicator of each crossing of the Weddell Front on ALBATROSS is clearly seen using the neutral density surface $\gamma^n = 28.0$ (overlaid as a thick dashed line in Figures 2a–2d). To the west of the South Orkneys this density surface lies close to the temperature minimum of Winter Water. To the east of the South Orkneys, in the Weddell Scotia Confluence, this density surface lies in the stratified region some 100 m below the temperature minimum, at temperatures less than 0°C. Each time the Weddell Front is crossed, the density contour returns to the temperature minimum layer (particularly well illustrated for stations 85 and 86). We see graphically that to the east of

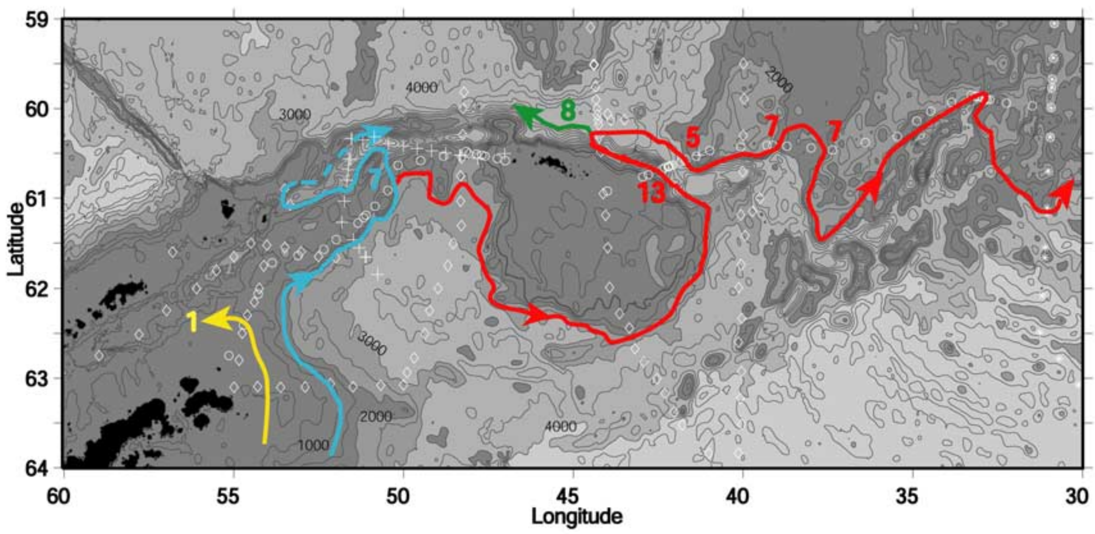

Figure 6. Schematic of the paths of fronts as deduced in this study: Antarctic Coastal Current (yellow line), Antarctic Slope Front (blue line), and Weddell Front (red line). The bathymetry and stations are shown in Figure 1. Full depth transports associated with the fronts are marked where we have measurements. The dashed blue line indicates that further observations would be needed to confirm the pathway indicated. The green line indicates the path of the Weddell Sea Deep Water that escapes westward, and the transport value given in green is for that water mass only.

station 98 the ALBATROSS section lies along, and close to, the front since the neutral density surface does not return to the temperature minimum layer. This is also seen in Figure 2e since the volume transport associated with the Weddell Front does not return south of the section.

4. Conclusions

[28] Figure 6 provides a summary schematic of the pathways identified in this study, together with the transports of the features where they cross the hydrographic sections considered. The Antarctic Coastal Current was shown to be distinct from the Antarctic Slope Front in this region. The Antarctic Coastal Current flowed on the shelf between the 400 and 500 m isobaths with a transport of <1 Sv. It rounded the tip of the peninsula and exited the region flowing west (yellow line in Figure 6); we could not trace its subsequent path farther. It was not observed at any of the DOVETAIL Bransfield Strait stations and may flow southwest on the continental shelf. Such a flow is also suggested by numerical models of the region [*Schodlock et al.*, 2002; *Matano et al.*, 2002].

[29] The Antarctic Slope Front was observed to the east of the Antarctic Peninsula above the top of the continental slope (blue line in Figure 6). It followed the bathymetric contours and crossed the South Scotia Ridge at the first available opportunity, as soon as the depth of the ridge crest was greater than 1000 m. It had an associated flow of ~7 Sv. After crossing the ridge, the flow associated with the front probably passes cyclonically around the Hesperides Trough, tightly tied to the steep flanks (dashed blue line in Figure 6). We saw no evidence that it continued west into the Bransfield Strait. Typically, the Antarctic Slope Front lies above the 1000–1500 m isobaths. Our last (and least clear) observation of this front is on the northern flank of the Hesperides Trough, associated with eastward flow. We do not know its subsequent path but suggest that it mixes with water flowing east from the Bransfield Strait south of the South Shetland Islands and thereafter becomes part of the mixture that forms the Weddell Scotia Confluence. By the time it reaches 48°W, the shift in properties across the front is no longer identifiable.

[30] *von Gyldenfeldt et al.* [2002, Figure 18] and *Gordon et al.* [2001, Figure 1] present schematics for the flow in the region of the Powell Basin and Bransfield Strait. However, they show the possible pathways of deep and bottom waters primarily, and both are more intended to show schematic pathways for water escaping from the Weddell Sea into the Scotia Sea and Bransfield Strait rather than the precise locations of bathymetrically controlled fronts. For example, their route for the deep outflow of Weddell Sea Deep Water circulates around the Powell Basin, hugs the southern flank of the South Orkney Plateau, passes through Orkney Passage, and escapes to the west. This is very similar to the Weddell Front mapped more precisely (and with more data sets available to us) in this paper, and we argue that this is no coincidence; the flow associated with the Weddell Front has a significant barotropic component and carries the Weddell Sea Deep Water along. We also describe the path of the Weddell Front to the east of the South Orkneys, not mentioned in those studies since they considered the deep water paths. They also do not show the Antarctic Slope Front crossing the ridge, for the same reason. In agreement with our Figure 6, *von Gyldenfeldt et al.* [2002] indicate a pathway for waters on the continental shelf to round the tip of the Antarctic Peninsula and to exit west. This is the flow that we identify as the Antarctic Coastal Current. Interestingly, they also suggest the existence of mixing on the Philip Ridge; it is possible that this mixing is responsible for the gradual loss of the characteristics of the water mass

change across the front that we observe to the east of Bransfield Strait.

[31] The Weddell Front became an identifiable feature distinct from the Antarctic Slope Front in the northwest Powell Basin where we locate the splitting of the Antarctic Slope Front into two branches. The Antarctic Slope Front continued associated with that portion of the flow that was shallow enough to cross the South Scotia Ridge west of the South Orkney Islands. The Weddell Front was tied to deeper isobaths (red line in Figure 6), typically 2000–2500 m. It was associated with a volume transport of ~13 Sv circulating anticyclonically around the South Orkney Plateau. North of the South Orkneys, the deepest portion of water associated with the Weddell Front, the Weddell Sea Deep Water together with some intermediate water, continued to the west (green line in Figure 6). We estimate from continuity that the volume transport of this deep core is ~8 Sv, in agreement with the measurement of ~10 Sv documented by *Gordon et al.* [2001] from the DOVETAIL data north of the South Orkneys. The shallower portion retroflected and returned to the Weddell Sea southward through the Orkney Passage. The subsequent eastward flow associated with the Weddell Front was 5–7 Sv, similar to the fraction of the shallow and intermediate flow that passed over the South Scotia Ridge in association with the Antarctic Slope Front.

[32] *Whitworth et al.* [1994] showed a schematic of the Weddell Scotia Confluence (their Figure 1) which indicates approximate locations for its northern and southern boundaries, the Scotia and Weddell Fronts, respectively. Using the high-resolution hydrographic sections reported here, we are able to define a much more precise location for the Weddell Front. This is the first time that such a detailed description of the Weddell Front has been compiled. We show significant differences from the Whitworth et al. schematic, including: (1) The Weddell Front originates from a branching of the Antarctic Slope Front; (2) it is tightly tied to the continental slope; (3) it penetrates farther northward in the Powell Basin following the bathymetry; (4) it does not cross the shelf of the South Orkney Plateau but follows the slope to the south; (5) it penetrates into the Scotia Sea through the Orkney Passage, subsequently retroflecting and returning southeast; and (6) it follows a complex path along the South Scotia Ridge, penetrating slightly northward in each of the deep passages. The connections between the Antarctic Slope Front, the Weddell Front, and the Weddell Scotia Confluence can all be traced to a divergence of the isobaths in the northern Powell Basin. It is remarkable that such a large-scale feature as the Weddell Front, identifiable as far east as 22°E [*Orsi et al.*, 1993], can be shown to originate here. The fact that the front is so closely tied to topography implies that it has associated with it a significant barotropic component of velocity. The flows at the seabed observed by the LADCP were indeed significant along the South Scotia Ridge, as large as 20–30 cm s^{-1} in the crossings of the two fronts. Some of the historical observations that suggested the Weddell Scotia Confluence to be full of eddies may in fact have been observing some of these tight retroflections and meanders of the front associated with bathymetry.

[33] Temporal variability (both secular change and natural fluctuations) in both the water mass properties and the pathways of flows is possible. *von Gyldenfeldt et al.* [2002] and *Robertson et al.* [2002] both discuss evidence of such water mass changes in this region. Nevertheless, the evidence presented here indicates a striking consistency between different cruises in different years and seasons. Currents and fronts are found in similar locations and are tied to similar isobaths, implying a surprising degree of bathymetric control.

[34] There still remain some intriguing questions that await further observations and study. The fate of the Antarctic Coastal Current west of the Antarctic Peninsula remains unclear. It is generally believed that all of the flow on the shelf of the western Antarctic Peninsula is to the northeast, whereas our westernmost observations showed the Antarctic Coastal Current departing to the southwest close inshore. Some or all of this may ultimately exit to the east from Bransfield Strait. However, initial ADCP and drifter results of the Southern Ocean Global Ecosystem Dynamics (GLOBEC) program hint at a southwestward flow close to shore on the western Antarctic Peninsula, although this flow may derive from local runoff and wind forcing along the western peninsula. We hypothesise that the Antarctic Coastal Current could indeed be circumpolar, flowing anticyclonically around Antarctica, as was originally thought, and might not be disrupted by the Antarctic Peninsula or its close proximity to the eastward flowing Antarctic Circumpolar Current on the west of the peninsula. It might flow very close to shore, under or adjacent to the ice shelves and sea ice.

[35] The Antarctic Slope Front appears to vanish into the Weddell Scotia Confluence, but the details of this process are far from understood. If, as is generally believed, the signature of the Weddell Scotia Confluence is caused by an injection of shelf and pycnocline water mixtures, how does this flow cross or interact with the Antarctic Slope Front? Our final (most tentative) identification of the front located it above the steep topography of the northern flank of the Hesperides Trough at 51°W. At this point the associated flow is northeastward. There is no indication of the Antarctic Slope Front on the meridional DOVETAIL section at 48°W. It appears that the signature of the front is mixed away in this region, possibly associated with the injection of cold shelf water that creates the signature of the confluence, possibly associated with the outflow of water from the Bransfield Strait, and possibly associated with the interaction of the flow with the rough topography.

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