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The importance of the Scotia Sea on the outflow of Weddell Sea Deep Water

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ABSTRACT

Weddell Sea Deep Water influences the thermohaline circulation of the world ocean directly as a component of the deep western boundary current in the South Atlantic Ocean and indirectly by cooling and freshening Circumpolar Deep Water. Because it is filled with recently ventilated Weddell Sea Deep Water, the Scotia Sea is important to both influences. The main component of the abyssal waters renewing most of the world oceans via deep boundary currents is the Circumpolar Deep Water of the Antarctic Circumpolar Current. Weddell Sea Deep Water is recognized as the main source of cold, fresh waters to Circumpolar Deep Water, and we show that Weddell Sea Deep Water is incorporated into the Antarctic Circumpolar Current within the Scotia Sea. As a result of this ventilation, the Scotia Sea provides an effective link between the deep waters of the Weddell Sea and the rest of the world abyssal ocean.

Some of the Weddell Sea Deep Water filling the Scotia Sea leaves as a westward flow via the southern Drake Passage. Weddell Sea Deep Water also enters the Georgia Basin directly from the Scotia Sea and flows beneath the Antarctic Circumpolar Current to contribute to the deep western boundary current of the Argentine Basin. In most previous studies, a deep spreading route from the Weddell Sea over the South Sandwich Trench east of the Scotia Sea had been considered the only source of Weddell Sea Deep Water for this deep western boundary current.

1. Introduction

The Southern Ocean is the vast oceanic region surrounding Antarctica and extending northward from its coast and ice shelves to the Subtropical Front. Due to the prevailing climatic conditions, an intense transfer of heat from the sea to the atmosphere takes place in the high latitudes of the Southern Ocean (Gordon and Taylor, 1975). This heat loss from the ocean must be balanced by poleward ocean heat fluxes into the Southern Ocean. As one mechanism, abyssal boundary currents transport cold waters formed in the Southern Ocean equatorward, resulting in poleward heat flux.

Stommel and Arons (1960a,b) showed that a system of polar sources and generalized upwelling in meridionally bounded ocean basins on a rotating sphere will drive a system of narrow abyssal boundary currents, principally against the western side of

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the basins. Warren (1981) presented a review of works describing the spreading of bottom waters from their source regions to the rest of the world ocean basins.

Bottom waters have been reported to form in several different places around Antarctica (Warren, 1981), and the Weddell and Ross Seas are considered the major sources. In their description of the abyssal waters of the world ocean, Mantyla and Reid (1983) showed that the Weddell Sea bottom waters are the coldest (densest) of all Southern Ocean abyssal waters. This pool of dense water represents one of the abyssal sources in the idealized ocean thermohaline circulation schema of Stommel and Arons (1960a). However, its outflow is severely restricted by bathymetry and the eastward-flowing Antarctic Circumpolar Current (Mantyla and Reid, 1983).

A distinction is made between two types of bottom waters formed in the Weddell Sea: Weddell Sea Bottom Water (WSBW) with potential temperatures lower than −0.7°C (Carmack and Foster, 1975), and warmer and less dense Weddell Sea Deep Water (WSDW). The upper boundary of the WSDW (about 0.1°C or 0.2°C) usually is defined to exclude the densest and coldest waters within the Antarctic Circumpolar Current at the Drake Passage (e.g. Reid *et al.,* 1977; Reid, 1989). In this work, water with potential temperatures between −0.7°C and 0.2°C is referred to as WSDW.

Figure 2 shows the bottom potential temperature in the southwestern Atlantic Ocean and corresponding sector of the Southern Ocean (Fig. 1). Similar maps that include this region have been presented previously, e.g. the global scale map of Mantyla and Reid (1983), but our distribution incorporates recent data and shows more detail in the study area. The base of historical hydrographic information in the Southern Ocean Atlas (Gordon and Molinelli, 1982) is used in this study. Hydrographic data obtained on more recent cruises (RV *Conrad* 16-9 and ARA *Islas Orcadas* 7-75 (Georgi *et al.,* 1979); Ajax (Scripps Institution of Oceanography/Texas A&M University, 1985); ABCS1 (Worley and Orsi, 1986); ABCS2 (Whitworth *et al.,* 1988); FS *Meteor* 11/5 (Roether, *et al.,* 1990)) were added to obtain an updated hydrographic set of the southwestern Atlantic and the corresponding sector of the Southern Ocean. The chlorofluorocarbon measurements used in this study were obtained during the Ajax expedition (Weiss *et al.,* 1990) and are reported on the SIO 1986 calibration scale.

Figure 2 shows that WSBW (with potential temperatures less than −0.7°C) is constrained to circulate within the Weddell Gyre (Orsi *et al.,* 1993), even though it extends north into the southern Georgia Basin over the South Sandwich Trench. Slow upwelling due to surface divergence and the formation of new bottom water will move it up in the water column where continuous density surfaces connect the deep waters of the Weddell Sea with adjacent basins. In contrast to WSBW, WSDW flows equatorward out of the Southern Ocean. In this paper, we will discuss two ways that WSDW influences the world ocean: directly, via the deep western boundary current in the South Atlantic, and indirectly, through the ventilation of the Circumpolar

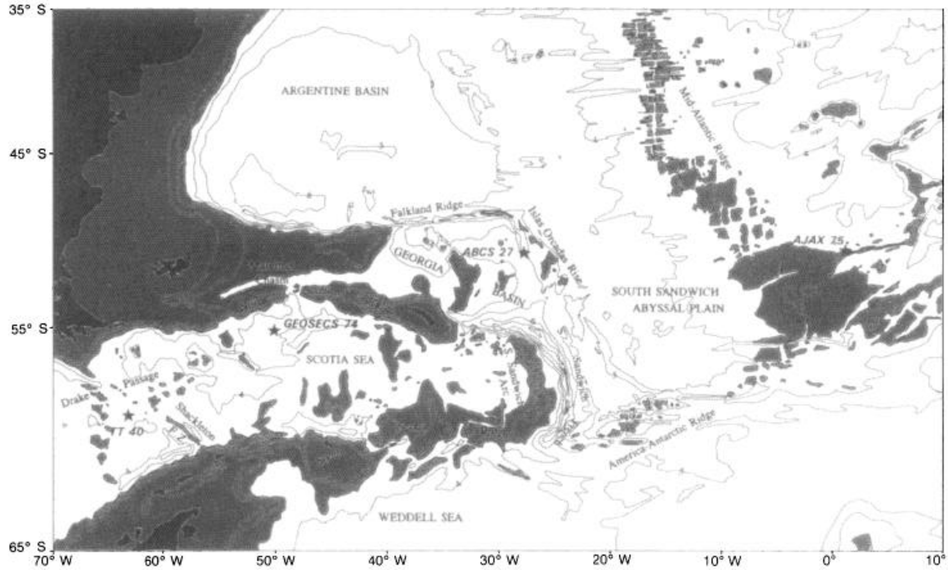

Figure 1. Bathymetric chart of the southwestern Atlantic Ocean. Depth contours are in kilometers and depths less than 3 km are shaded. Stars identify four stations selected to illustrate the ventilation of the Circumpolar Deep Water at the Polar Front.

Deep Water (CDW) that comprises the deep western boundary currents in the Indian and Pacific Oceans. The Scotia Sea, the body of water bounded by the Scotia Ridge and the extension of the Shackleton Fracture Zone to the southern tip of South America (Fig. 1), plays an important role in both processes.

The coldest *bottom* waters north of the Weddell Sea occur in and just north of the South Sandwich Trench (Fig. 2); in most previous studies, this bottom distribution has been considered evidence for a deep spreading route of the WSDW that supplies the deep western boundary current in the Argentine Basin (e.g. Wüst, 1933; Georgi, 1981). Figure 2 also shows that most of the deep Scotia Sea contains WSDW, a fact that has been known for some time (Gordon, 1966), but the importance of which has been overlooked in the past.

The Scotia Sea is somewhat shallower than the adjacent basins, and with the exception of its western end, it is ringed by a formidable ridge system (Fig. 1). For these reasons it has never assumed a prominent role, even in regional circulation schemes. But at high latitudes, the great relief of isopycnal surfaces can overshadow the apparent bathymetric constraints on flow patterns. Orsi *et al.* (1993) point out that in this region, the Weddell Gyre transcends basin boundaries and that its northern limb is found well north of the South Scotia Ridge in the Scotia Sea. Weiss and Bullister (1984) conclude that the high chlorofluorocarbon concentrations in the Scotia Sea show that flow over the South Scotia Ridge is a major outflow of newly-ventilated deep water from the Weddell Sea.

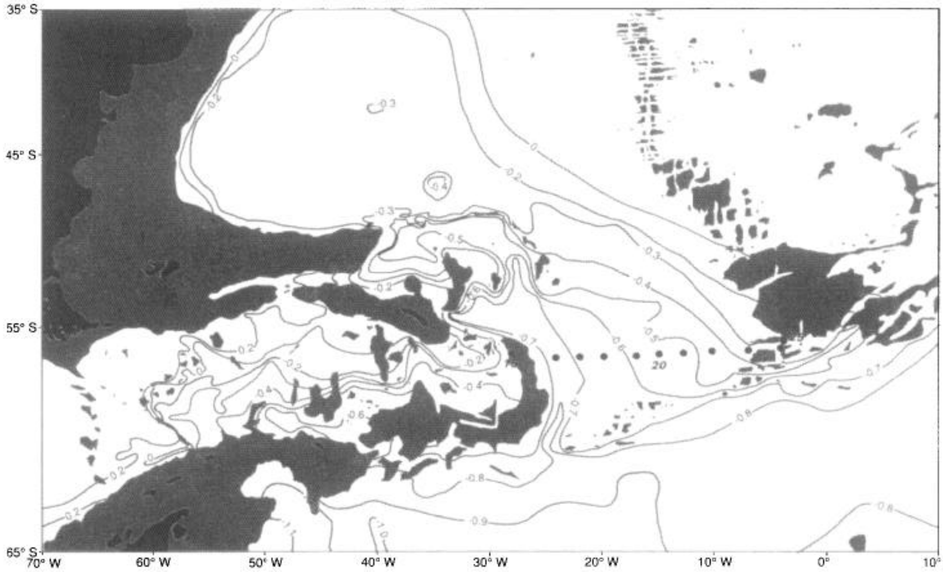

Figure 2. Bottom potential temperature (in degrees celsius) in the southwestern Atlantic Ocean showing the spread of cold waters from the Weddell Sea. ARA *Islas Orcadas* cruise 11 stations (dots) span the equatorward flow of abyssal waters colder than −0.3°C and their poleward return flow. Depths less than 3 km are shaded.

2. Equatorward outflow of Weddell Sea Bottom Water and Weddell Sea Deep Water

a. The South Sandwich Trench Route. Figure 3 shows the potential temperature in a composite vertical section extending from the northwestern corner of the Weddell Sea to the Argentine Basin. The stations included were chosen after comparing their potential temperature-salinity (θ-S) characteristics with the historical hydrographic data to insure that they represent the long-term mean potential temperature field. The path of the section (shown in Fig. 4) follows what historically has been considered the main outflow route for WSDW from the Weddell Sea to the Argentine Basin, based on property distributions at the bottom. At 25W, a gap in the mid-ocean ridge links the Weddell Abyssal Plain with the South Sandwich Trench. This gap has a sill depth greater than 4600 m and is about 70 km wide at 4500 m (LaBrecque, 1986). Waters from the Weddell Sea pass through this gap and flow northward as a deep boundary current against the eastern slope of the South Sandwich Arc (Wüst, 1933).

Although there are no bathymetric barriers along the South Sandwich Trench route that would prevent its northward flow, WSBW reaches barely north of the trench. ABCS station 28 at 51° 15.7′S in the eastern Georgia Basin marks the maximum northward extent of bottom waters colder than −0.7°C (see also Fig. 2). The geostrophic regime of the Antarctic Circumpolar Current (ACC) produces a notable equatorward descent of the isopycnals and restricts the northward extension

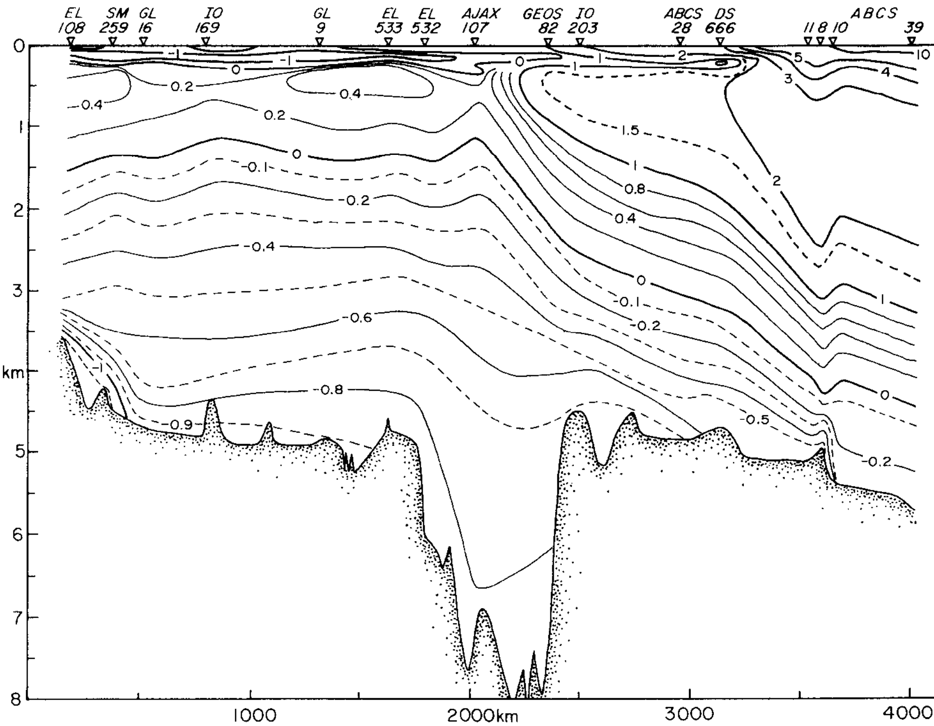

Figure 3. Potential temperature (in degrees celsius) in a composite vertical section from the Weddell Sea to the Argentine Basin along the South Sandwich Trench. The location of the section is shown in Figure 4.

of WSBW below it. North of Ajax station 107, a poleward extension of Circumpolar Deep Water (CDW) associated with the ACC can be identified in Figure 3 as a tongue of water warmer than 1.5°C.

WSDW is found above WSBW and occupies a layer 3000 m thick in the Weddell Sea (Fig. 3). The equatorward spreading of WSDW north of Ajax station 107 is also affected by the ACC but the potential temperature distributions show WSDW extending farther to the north than WSBW, filling the Georgia Basin (Figs. 2 and 3). WSDW warmer than about −0.3°C can freely enter the Argentine Basin to the north; only a few isolated patches of WSDW colder than −0.3°C are seen north of the Falkland Ridge. Recent bathymetric surveys made during the ABCS1 and ABCS2 cruises have confirmed that a gap in the Falkland Ridge at about 36W with a sill depth greater than 5000 m connects the Argentine and Georgia Basins. Despite the existence of the Falkland Ridge Gap however, potential temperature distributions show a sharp gradient where the two basins connect.

Peterson and Whitworth (1989) showed that the Subantarctic and Polar Fronts are found side-by-side flowing east just north of the Falkland Ridge. The locations of the

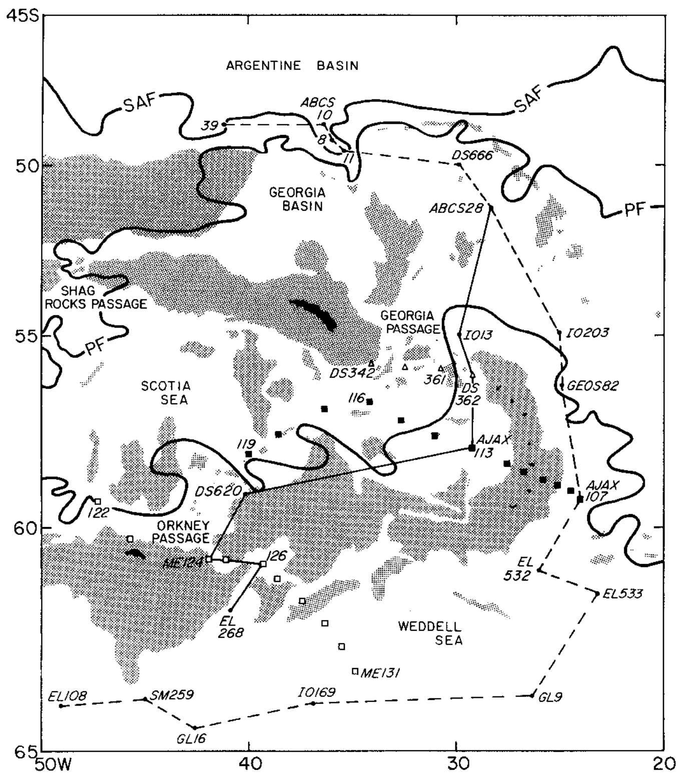

Figure 4. Locations of vertical sections used in this study. The dashed (solid) line indicates the location of the composite temperature section in Figure 3 (Fig. 7). FS *Meteor* stations (open boxes) were made in February 1990. RRS *Discovery II* stations (triangles) were made in February 1930. Solid boxes indicate the location of hydrographic stations occupied in the eastern Scotia Sea and on the South Sandwich Trench during the Ajax expedition. Also shown are the paths of the Subantarctic Front (SAF), the Polar Front (PF), and the southern boundary of the Antarctic Circumpolar Current between 50W and 20W. Depths less than 3 km are shaded.

fronts as inferred from historical data are shown in Figure 4. Also shown in Figure 4 is the approximate poleward extent of the circumpolar water of the ACC, which in the Scotia Sea follows the South Scotia Ridge and the South Sandwich Arc (Locarnini, 1991). East of Drake Passage, that portion of the ACC to the south of the Polar Front flows above the cold waters of the Weddell Gyre (Fig. 2) that fill the deeper layers of the Scotia Sea. For the purposes of the present study, the poleward extent of CDW shown in Figure 4 is considered the southern boundary of the ACC in the southwestern Atlantic Ocean. The ACC appears to restrict both the flow of the coldest WSDW from the Georgia Basin into the Argentine Basin (Whitworth *et al.*, 1991) and the equatorward flow of WSBW over the South Sandwich Trench.

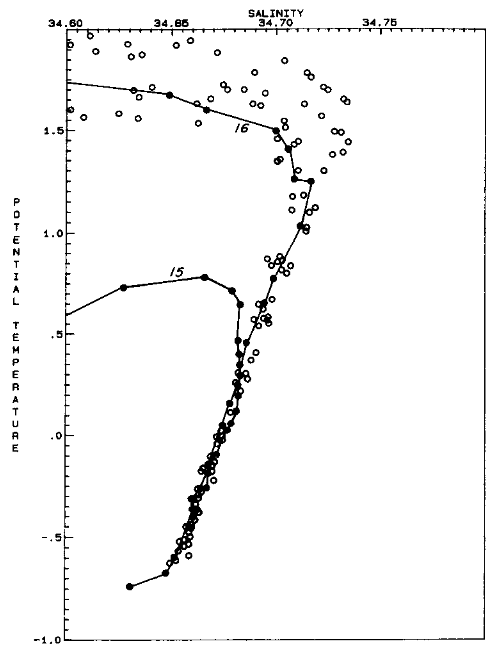

Figure 5. Potential temperature-salinity relationships for ARA *Islas Orcadas* cruise 11 stations over the South Sandwich Abyssal Plain (Station locations are shown in Fig. 2). The deep θ-*S* relationship for the stations spanning the equatorward flow of Weddell Sea Deep Water (full circles) is almost identical to that of the stations spanning its southward return flow (open circles).

Figure 2 shows that the isotherms for bottom waters colder than −0.3°C follow the bend of the South Sandwich Arc as far north as the Georgia Basin. Some of these cold waters may advect upward across isopycnals and modify the characteristics of the deep waters above them. However, we believe that most of the water colder than −0.3°C returns poleward above the South Sandwich Abyssal Plain (Fig. 1). The contours of isotherms in Figure 2 indicate that this poleward return flow occurs from the eastern edge of the South Sandwich Trench to the western flank of the Mid-Atlantic Ridge. We infer, from the uniform spacing of isotherms over a broad region, that if bottom flow is poleward it is at lower speeds than in the equatorward flowing western boundary regime. This concept agrees with the abyssal circulation patterns hypothesized by Stommel and Arons (1960a), with slow poleward return flows in the interior of the ocean basins, east of deep western boundary current regimes.

Unfortunately, we cannot determine a level of reference in an objective way to quantify the magnitude of the return flow by geostrophic calculations. But to support the contention that most of the deep and bottom waters return poleward, we present in Figure 5 the θ-*S* relationship of waters colder than 2.0°C for a zonal section over the South Sandwich Abyssal Plain occupied during cruise 11 of ARA *Islas Orcadas* (Huber *et al.*, 1981; see Fig. 2 for station locations). The stations in Figure 5 span the northward flow of WSBW and WSDW and their suggested poleward return flow. The deep θ-S relationship within the northward flow (Stations 15 and 16, full circles) is almost identical to that of the southward flow (Stations 17–25, open circles). This suggests little interaction between the deep waters of the ACC and the cold bottom waters, supporting the idea of a direct poleward return flow of WSBW and WSDW.

b. Flow of WSDW into the Scotia Sea. The deepest gap in the South Scotia Ridge is east of the South Orkney Islands, near 40W (Fig. 4), and here is referred to as the Orkney Passage. This narrow gap, with a sill depth of about 3500 m (LaBrecque *et al.*, 1981), connects the Weddell Sea with the central Scotia Basin. The bottom potential temperatures (Fig. 2) show that the coldest WSDW found in the Scotia Sea enters through the Orkney Passage as noted first by Wüst (1933). Figure 6 shows the potential temperature in a vertical section completed in February of 1990 during FS *Meteor* cruise 11/5 (Stations 122–131, see Fig. 4 for locations). This is the first synoptic section along the Orkney Passage and portrays the characteristics of the abyssal water masses flowing through it. For the sake of clarity the section is broken into three short segments.

Stations 126–131 extend from the southern entrance into Orkney Passage across a series of isolated highs into the northern Weddell Sea. WSBW ($\theta < -0.7$°C) is in evidence at stations 129–131 (Fig. 6c). Station 124 (Fig. 6b) shows the coldest waters that have entered the Scotia Sea from the Weddell Sea; the bottom potential temperature at station 124 ($\theta = -0.682$°C) is found at about 3300 m at station 129 in the Weddell Sea just south of the gap. Stations 124 and 125 are 35 km apart on opposite sides of the Orkney Passage. Figure 6b shows a change in the tilt of the isotherms between 0°C and -0.1°C, which indicates a change in the sign of the geostrophic shear at about 1500 m. The sharp upward slope of the isotherms toward station 124 below 2000 m indicates northward flow into the Scotia Sea as a narrow, bottom-intensified current on the western side of the passage, relative to an intermediate level of reference.

A considerable volume of WSDW seems to be flowing into the Scotia Sea through the narrow Orkney Passage. Between stations 124 and 125 a bottom layer about 3000 m thick exists with WSDW characteristics: potential temperature less than 0.2°C, salinity lower than 34.67, and dissolved oxygen content higher than 5.0 ml l^{-1}. Station 125 is about 1 km shallower than station 124; the extrapolation of the geostrophic shear down to the bottom of the passage gives a northward transport relative to 1500 m of about 1.5×10^6 m^3 sec^{-1} (1×10^6 m^3 sec^{-1} = 1 Sverdrup) of WSDW into the Scotia Sea.

Between stations 122 and 123 (Fig. 6a) the characteristics are consistent with upper flow to the east for this regime of transition marking the southern boundary of

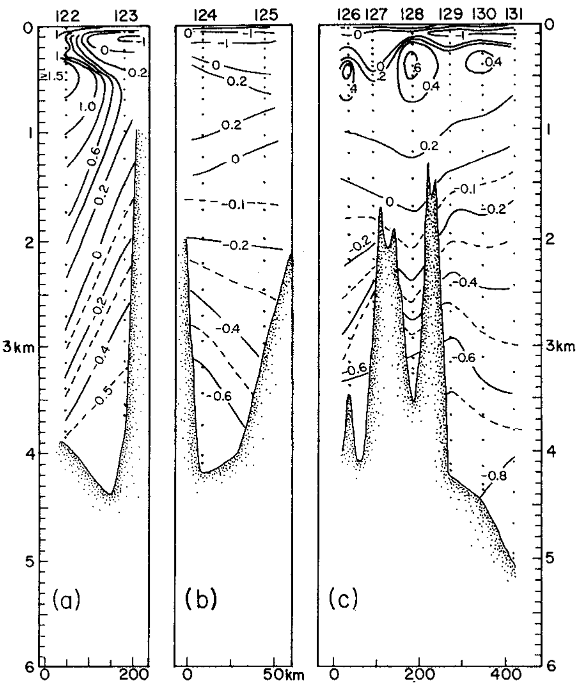

Figure 6. Vertical section of potential temperature (in degrees celsius) along the Orkney Passage from FS *Meteor* cruise 11/5 (February 1990) showing the coldest inflow of Weddell Sea Deep Water into the Scotia Sea. (a) Scotia Sea; (b) Orkney Passage; (c) Weddell Sea. Station locations are shown in Figure 4.

circumpolar ACC waters. There is a sharp downward slope to the north of the isopleths below about 500 m. An intermediate level of no motion will give a westward direction of flow for the WSDW between stations 122 and 123, which agrees with the bottom potential temperatures (Fig. 2) and previous descriptions of the abyssal westward current along the northern side of the South Scotia Ridge (e.g. Wüst, 1933; Nowlin and Zenk, 1988). The contours in Figure 2 also show that most of the WSDW flowing in this deep current is blocked by bathymetric features and turns cyclonically to follow the predominant eastward flow of the ACC. In this way, the westward current feeds eastward return flows that distribute WSDW throughout the rest of the Scotia Sea.

There is no doubt regarding the Weddell Sea as the origin of waters colder than 0.2°C in the Scotia Sea, and we have described the coldest WSDW inflow. WSDW is also able to enter the Scotia Sea over the South Scotia Ridge and through other gaps in the ridge shallower than Orkney Passage (Gordon, 1966; Nowlin and Zenk, 1988). Figure 7 shows the topography of the 0.2°C surface, which defines the shallowest layer of WSDW. Above the South Scotia Ridge, this surface lies near 1000 m deep; it is clear that WSDW spills into the Scotia Sea from the Weddell Sea along the entire

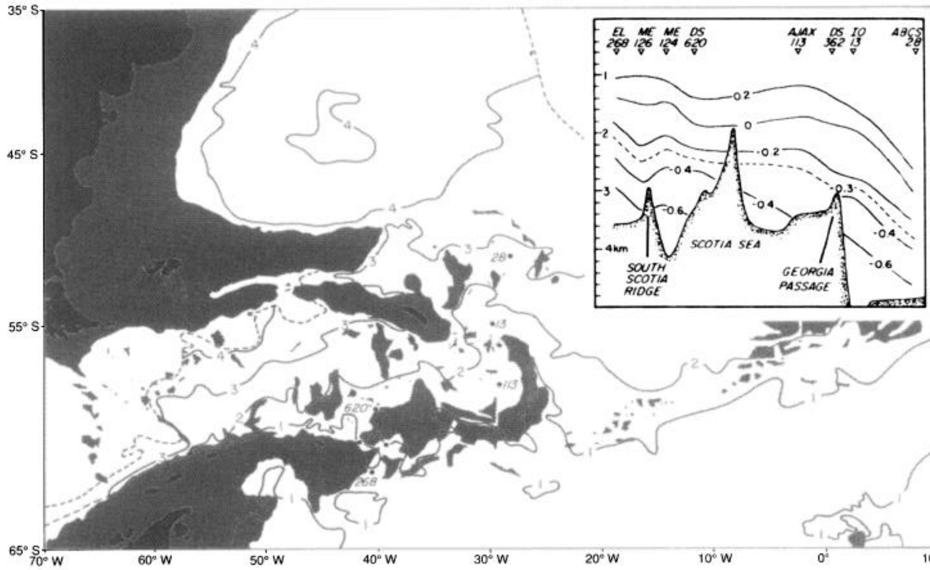

Figure 7. Depth (in kilometers) of the surface defined by 0.2°C in potential temperature in the southwestern Atlantic Ocean. The dashed line indicates the intersection of that isotherm with the ocean bottom. Bottom depths less than 3 km are shaded. The inset shows the deep isotherms in a composite section through the Scotia Sea. Station positions are shown on the map and in Figure 4.

length of the ridge and fills it with recently ventilated cold waters (Weiss and Bullister, 1984). The northern extension of the Weddell Gyre into the Scotia Sea provides the first opportunity for this WSDW to influence waters north of the subpolar gyre. We will discuss two ramifications of this influence.

3. Outflow of WSDW from the Scotia Sea

Studies have been reported of the flow of cold bottom water from the Scotia Sea at two locations: through the Shag Rocks Passage (Wittstock and Zenk, 1983), and through the Shackleton Fracture Zone into the southern Drake Passage (Nowlin and Zenk, 1988). Evidence presented in this section suggests that young WSDW as cold and dense as the deep boundary current in the Argentine Basin (Whitworth *et al.*, 1991) can reach the Georgia Basin via the Scotia Sea.

It is unlikely that WSDW can exit the South Scotia Sea to the north. Figure 7 shows that in the north Scotia Sea the 0.2°C surface lies deeper than the sill of the North Scotia Ridge, and intersects the ocean bottom south of the deep Shag Rocks Passage near 50W (Fig. 4). The WSDW found in the narrow Malvinas Chasm north of the Scotia Ridge (Fig. 2) is not supplied from the Scotia Sea through the Shag Rocks Passage (sill depth of about 3200 m), but from the east, probably as a branch of the abyssal cyclonic circulation of the Georgia Basin.

Wittstock and Zenk (1983) reported northwestward flow of cold bottom waters through the Shag Rocks Passage. Their bottom current-meter observation at Shag Rocks Passage extends over an 11-month period, and shows about a dozen cold events ($\theta < 0.2°C$) associated with northwestward flow. The temperature record is significantly correlated with the westward velocity component for a 99% confidence interval but is not correlated even for a 90% confidence interval with the northward component. It is not clear from our analysis of their current-meter data whether these cold events are due to WSDW flowing northward from the northern Scotia Sea, or westward from the Georgia Basin. We consider the outflow of WSDW from the Scotia Sea through the Shag Rocks Passage to be small, in agreement with the hydrographic data from the region, none of which show waters colder than 0.2°C continuing through the passage.

Figures 2 and 7 show that WSDW flows westward into Drake Passage through the Shackleton Fracture Zone (Fig. 1) and leaves the Scotia Sea, as described by Nowlin and Zenk (1988). They estimated that the westward current along the South Scotia Ridge transports between 1.4 and 3.2×10^6 m^3 sec^{-1}. The bottom flow of WSDW ($\theta < 0.2°C$) accounts for about 25% of that transport (0.4–0.8×10^6 m^3 sec^{-1}), with the rest consisting of CDW and Antarctic Surface Water flowing along the slope and continental shelf.

Gordon (1966) has suggested that the abyssal water in the eastern Scotia Sea is WSDW that flows eastward from the central Scotia Sea. Near 56S, 31W, there is a gap between the North Scotia Ridge and the South Sandwich Arc connecting the eastern Scotia Sea with the Georgia Basin; it will be referred to here as the Georgia Passage (Fig. 4). The sill depth of this gap is about 3200 m (LaBrecque, 1986). The bottom potential temperatures (Fig. 2) cannot portray flow through the Georgia Passage due to the difference in the mean depth of the ocean floor on each side of the gap. However, Figure 7 shows that the 0.2°C surface is well above the sill depth in the Georgia Passage. The inset in Figure 7 shows the deep isotherms in a composite section which starts in the Weddell Sea and ends in the Georgia Basin; there it intersects the composite section along the South Sandwich Trench (see Figs. 4 and 7 for station locations). The path of this section should not be considered as the direct route of the WSDW flow between the Orkney Passage and the Georgia Passage; the details of that circulation already have been described in the previous section. The purpose here is to show the vertical thermal structure in WSDW from the Weddell Sea to the Georgia Basin, and its relationship to the main bathymetric features. It is clear that there are no bathymetric barriers that would prevent the spreading of WSDW warmer than about −0.3°C from the Weddell Sea through the Scotia Sea to the Georgia Basin. Obviously, the South Sandwich Trench route is not the only equatorward pathway available for that WSDW that flows in the deep western boundary current of the Argentine Basin.

The outflow of WSDW from the Scotia Sea into the southern Drake Passage

(Nowlin and Zenk, 1988) is easy to identify due to the sharp contrast between the characteristics of the cold and fresh WSDW and the warmer and saltier CDW that fills the rest of the Drake Passage (Sievers and Nowlin, 1984). The northeastward flow of WSDW that enters the Georgia Basin through the Georgia Passage is difficult to distinguish from WSDW flowing north over the South Sandwich Trench; they have the same source, very similar or identical characteristics, but have arrived at the same location along different routes. Previous discussions of the South Atlantic abyssal circulation focused on the waters deeper than 4000 m (e.g. Georgi, 1981), and thus did not consider the influence of the shallower Scotia Sea, which has a mean depth close to 3500 m. However, there is, in the literature, evidence of the WSDW flow through Georgia Passage. The distributions of depth, salinity, and oxygen on the isopycnal surface defined by 46.13 kg m^{-3} in σ_4 (old equation of state) of Reid *et al.* (1977), suggest a flow of WSDW from the Weddell Sea into the Georgia Basin through the Scotia Sea. Similarly, Reid (1989) showed a tongue of high oxygen on the isopycnal surface defined by $\sigma_4 = 46.04$ kg m^{-3} extending eastward along the Scotia Sea and entering the Georgia Basin through the Georgia Passage. Reid suggested that most of the waters in this tongue are from the continental shelf of the western Weddell Sea. Results from the FRAM model (Webb *et al.,* 1991) also show a bottom-reaching north and northeastward flow through Georgia Passage.

The recent introduction of chlorofluorocarbons into the ocean from the atmosphere and the increase with time in their atmospheric concentrations make them a useful tracer for deep water masses recently exposed to the atmosphere. Good quality measurements of trichlorofluoromethane (CFC-11) were obtained during the 1984 Ajax expedition (Weiss *et al.,* 1990) across the two equatorward flow routes for WSDW discussed here. Figure 8 shows the relationships between θ and CFC-11 for the deep waters colder than 0.2°C at hydrographic stations occupied in the eastern Scotia Sea and on the South Sandwich Trench (see Fig. 4 for station locations). Two distinct groups of stations clearly can be seen for waters colder than 0°: one includes stations 107 to 111, the other, stations 114 to 119. Stations 112 and 113 show characteristics intermediate between the two different groups. WSDW with the highest CFC-11 concentrations is not found in the traditional South Sandwich Trench route, stations 107 to 110, but in the northeastern Scotia Sea, stations 114 to 118, immediately southwest of Georgia Passage. Even the bottom waters at the transition stations 112 and 113 have higher CFC-11 concentrations than WSDW of similar temperatures on the South Sandwich Trench. These high CFC-11 concentrations have their source in the WSDW that flows above the South Scotia Ridge directly from the Weddell Sea (Station 119) and reaches the northeastern Scotia Sea following the circulation pattern described above. Figure 8 shows that the Scotia Sea offers an alternative and distinct route for WSDW to flow equatorward from the Weddell Sea.

The mass interchange between the Scotia Sea and the Georgia Basin can be

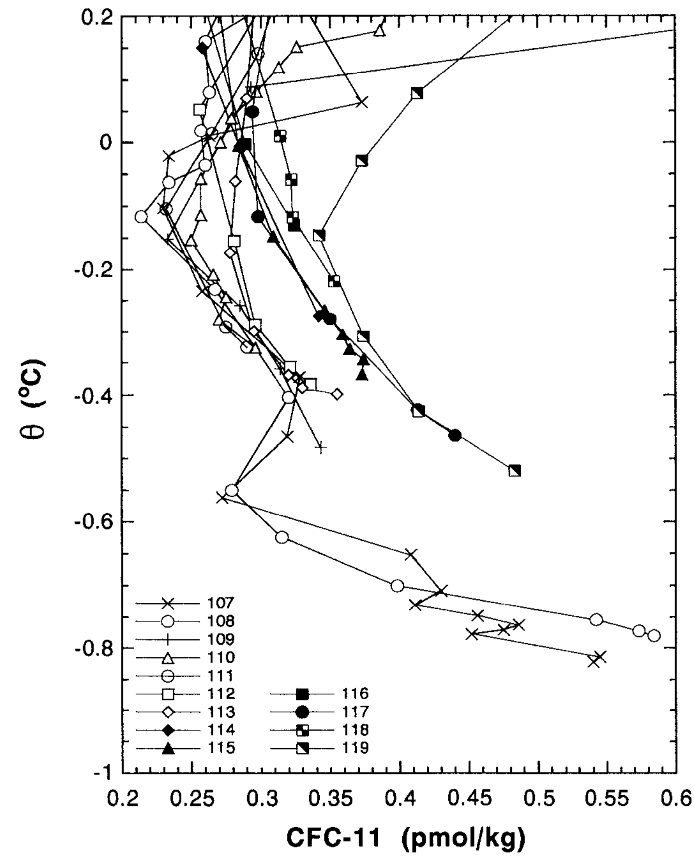

Figure 8. Potential temperature-CFC-11 relationships for stations occupied in the eastern Scotia Sea and on the South Sandwich Trench during the Ajax expedition (Station locations are shown in Figure 4). High CFC-11 concentrations in the eastern Scotia Sea (Stations 119 to 114) show that a Weddell Sea Deep Water outflow route distinct from the traditional South Sandwich Trench route (Stations 107 to 110) exists through the Scotia Sea.

inferred from analysis of the only section of deep hydrographic stations across the Georgia Passage, a section completed aboard the RRS *Discovery II* in February of 1930. The vertical distribution of potential temperature is presented in Figure 9 (see Fig. 4 for station locations). The section is not ideal: the average distance between stations is more than 100 km; station 342 was occupied two weeks earlier than the rest of the section; and the salinity data below the subsurface potential temperature maximum had to be corrected due to the scatter and anomalous values present in the original salinity observations. This was accomplished using the tight θ-S relationship observed on the Ajax expedition in the eastern Scotia Sea. At a temperature near 0.5°C, this relationship yields a salinity value with a standard deviation of ± 0.003; this error is less for colder waters.

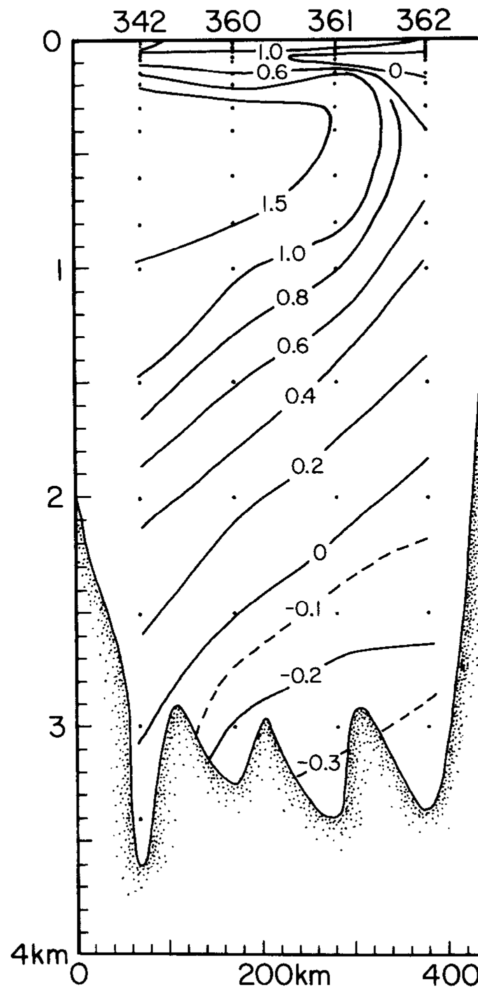

Figure 9. Potential temperature (in degrees celsius) in a vertical section across the Georgia Passage from RRS *Discovery II* (February 1930). Relative to the bottom, the slope of the isotherms suggests a flow of Weddell Sea Deep Water from the Scotia Sea into the Georgia Basin. Station locations are shown in Figure 4.

Figure 9 shows a tongue of warm water centered about 500 m identifying CDW being transported by the Antarctic Circumpolar Current (refer to Fig. 4). The tilt of the isotherms suggests a northeastward flux relative to the bottom, that is, from the Scotia Sea into the Georgia Basin (Deacon, 1937). The total geostrophic volume transport relative to the bottom is 18.5×10^6 m^3 sec^{-1}. WSDW ($\theta < 0.2$°C) extends well above the sill of the passage; the coldest waters are at the foot of the South Sandwich Arc with potential temperatures lower than -0.3°C. The geostrophic transport relative to the greatest common depth for waters colder than 0.2°C is 1.8 ×

10^6 m^3 sec^{-1}. Whitworth *et al.* (1991) have estimated that the net westward transport of WSDW into the southern Argentine Basin is 1.9×10^6 m^3 sec^{-1}. Thus, the deep flow through the Georgia Passage can supply an important portion of the coldest WSDW that leaves the Southern Ocean flowing in the deep western boundary current in the Argentine Basin.

4. ACC ventilation in the Scotia Sea

Circumpolar Deep Water, the most voluminous water mass transported by the Antarctic Circumpolar Current (ACC), is the main component of the abyssal waters that fill most of the ocean basins north of the Southern Ocean (Mantyla and Reid, 1983). Therefore, knowledge of how and where its properties are changed is of great importance. In their work on the water masses and currents of the Southern Ocean at the Greenwich Meridian, Whitworth and Nowlin (1987) discussed the modification of CDW as the ACC flows through the southwestern Atlantic Ocean. They showed that North Atlantic Deep Water (NADW) and waters from the Weddell Gyre are incorporated into the ACC between the Drake Passage and the Greenwich Meridian.

Whitworth and Nowlin (1987) noted that in the 4500 km distance traversed by the Polar Front between Drake Passage and the Greenwich Meridian, there is a significant freshening of the CDW colder than 0.8°C through mixing with waters from the Weddell Gyre. The role of the Scotia Sea in this process has not been discussed before. We show below that most of the modification of the CDW due to WSDW influence occurs within 1000 km of Drake Passage, as that portion of the ACC south of the Polar Front flows through the Scotia Sea overriding the WSDW that fills this basin (Locarnini, 1991). CDW is modified by the fresh WSDW even before it meets the salty NADW in the southern Argentine Basin.

The effectiveness of the ventilation of CDW by WSDW in the Scotia Sea is a consequence of circumstances that are unique in the circumpolar path of the ACC. The South American Continent forces the ACC to flow through the Drake Passage into the Scotia Sea. The Antarctic Peninsula serves as a western boundary for the Weddell Gyre, but even the relatively shallow South Scotia Ridge cannot prevent the northward penetration of the gyre into the Scotia Sea. The approximate extent of the overlap between these two current systems where the CDW of the ACC overrides the denser WSDW can be inferred from Figures 2, 4, and 7: Figure 2 shows that WSDW ($\theta < 0.2$°C) is found as far north as 55S in the Scotia Sea; Figure 4 shows the poleward extent of warm CDW is just north of the South Scotia Ridge; Figure 7 shows the topography of the boundary between these two water masses, the surface area of which encompasses almost the entire Scotia Sea. In fact, the surface area of this boundary (more than 0.5×10^6 km^2) is about five times greater than the surface area that a vertical southern boundary would represent along the circumpolar path

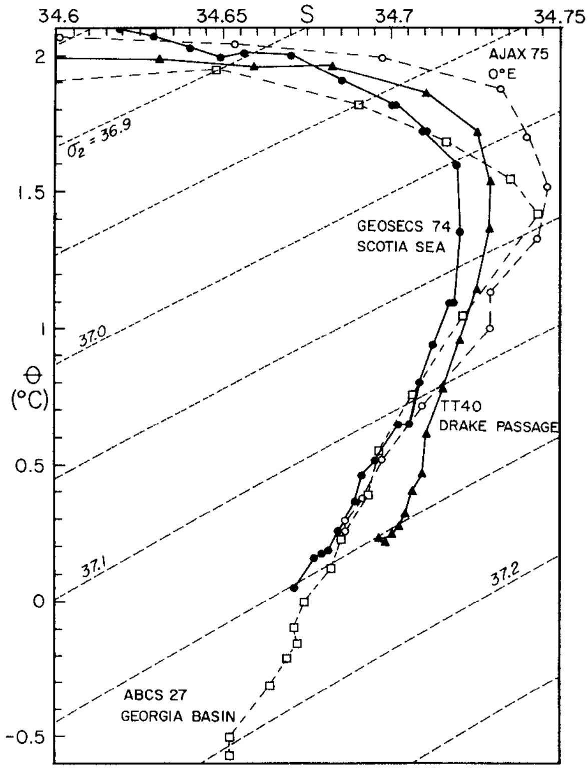

Figure 10. Potential temperature-salinity relationships for four stations just south of the Polar Front (see Fig. 1). Due to mixing with Weddell Sea Deep Water, Circumpolar Deep Water colder than 0.8°C is fresher at the Greenwich Meridian (Ajax 75) than at Drake Passage (TT40). GEOSECS 74 shows that this freshening occurs in the Scotia Sea.

of the ACC (20,000 km long by 5 km deep). Thus, the potential for mixing between CDW and WSDW in the Scotia Sea is enormous.

To illustrate the zonal modifications of the CDW as it moves from the Drake Passage to the Greenwich Meridian, we show in Figure 10 the θ-S relationship for four stations located just south of the Polar Front (see Fig. 1 for station locations). The properties of the CDW change much more dramatically across the ACC than along it, so when discussing CDW modifications, the relative position in the ACC of the hydrographic stations used is crucial. Because the Polar Front is easy to identify, and its location is usually unambiguous, the stations in Figure 10 illustrate the CDW ventilation along the ACC flow in the Atlantic sector of the Southern Ocean.

RV *Thompson* station 40 (TT40) and Ajax station 75 represent the CDW structure at Drake Passage and Greenwich Meridian, and they summarize the modification of CDW as discussed by Whitworth and Nowlin (1987): at Greenwich Meridian CDW warmer (colder) than about 0.8°C is saltier (fresher) than at Drake Passage.

However, ABCS station 27 shows that CDW colder than 1.0°C is already fresher than at the Drake Passage by the time it reaches the Georgia Basin.

GEOSECS station 74, less than 1000 km downstream of *Thompson* station 40, shows that the freshening of CDW takes place in the Scotia Sea. In fact, CDW colder than about 2.0°C is much fresher in the north Scotia Sea than in the Drake Passage (Fig. 10). The coldest CDW (θ = 0.2°C) is about 0.015 units fresher at GEOSECS station 74 than at *Thompson* station 40; warmer CDW in the Scotia Sea is about 0.01 units fresher in the Scotia Sea than at Drake Passage. In such a short distance, CDW is efficiently ventilated by WSDW filling the Scotia Sea. East of GEOSECS station 74, the salinity of the upper layers of CDW is increased by mixing with NADW, but the coldest CDW retains and carries the low-salinity signal obtained by mixing with WSDW in the Scotia Sea.

CDW is also ventilated in the Pacific sector of the Southern Ocean by the bottom waters formed in the Ross Sea. The Ross Sea influence can be inferred in the θ-S curve of RV *Thompson* station 40 (Fig. 10) by the relative high salinity of waters colder than about 0.5°C. However, the bottom waters of the Ross Sea have little global impact, since they are incorporated into the ACC downstream of the deep boundary current that transports CDW equatorward into the Pacific Ocean (Warren, 1973). The Ross Sea high-salinity signal, still present at Drake Passage, is completely eroded in the Scotia Sea by the incorporation of WSDW into the ACC.

5. Conclusions

In this study, we presented a new view on the importance that the Scotia Sea (a very small region of the world oceans) has in the global abyssal circulation. Chlorofluorocarbon measurements (Weiss and Bullister, 1984) indicate that recently ventilated Weddell Sea Deep Water (WSDW) is transported into the Scotia Sea. A portion of this WSDW is incorporated into the Antarctic Circumpolar Current (ACC) and ventilates the Circumpolar Deep Water (CDW). Because ventilated CDW is transported equatorward into the Atlantic, Indian, and Pacific Oceans, the mixing in the Scotia Sea establishes an efficient connection between changes in the WSDW production and the abyssal waters characteristics and the thermohaline circulation of most of the world ocean. Another consequence of this mixing is that the CDW is ventilated by the cold and fresh waters formed in the Weddell Sea immediately upstream of being modified by the salty North Atlantic Deep Water in the southern Argentine Basin. This stresses the importance of the southwestern Atlantic Ocean in determining the characteristics of the most voluminous water mass in the Southern Ocean.

WSDW as cold as the water in the deep western boundary current in the southern Argentine Basin can flow through the Scotia Sea. Chlorofluorocarbon measurements obtained in the eastern Scotia Sea and the South Sandwich Trench reveal that the Scotia Sea offers an alternative route for WSDW to flow equatorward from the

Weddell Sea. This WSDW flow route follows the predominant geostrophic circulation of the ACC and, entering the Georgia Basin through the Georgia Passage, provides a portion of the recently ventilated WSDW that fills this basin (Whitworth *et al.,* 1991).

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