The kinematic and thermohaline zonation of the Antarctic Circumpolar Current at Drake Passage

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ABSTRACT

The waters of the Antarctic Circumpolar Current at Drake Passage show mesoscale horizontal zonation into four water mass regimes horizontally separated by three fronts. Vertical profiles of T, S and O_2 on opposite sides of each front are described and compared. Although the surface waters are significantly different across fronts, the vertical profiles from the same side of a specific front are remarkably uniform from year to year and from cruise to cruise. Comparing property values at specific depths across the fronts shows an offset of 500 to 1000 m in the depth at which a particular value is found. To a first approximation, the fronts may be considered to be current cores with large vertical shears of horizontal velocity associated with horizontal gradients in the depth of density surfaces.

The widths, vertical shear of through-passage speeds and relative geostrophic transports associated with the fronts are investigated based on hydrographic station data and XBT temperature data, collected principally in the summer season. The average observed widths as measured across Drake Passage are 51, 61 and 39 km for the Subantarctic Front, Polar Front and Continental Water Boundary; the respective minimum observed widths are 37, 30 and 20 km. This southward decrease in the minimum observed width seems associated with the coincident decrease in vertical stability; the minimum core widths are slightly greater than twice the local Rossby radius of deformation for the first baroclinic mode.

Vertical shears of geostrophic through-passage speed are presented for the three fronts. Comparing speeds relative to 2500 m at specific depths shows the smallest values at the Continental Water Boundary. Below 200 m the speed decreases monotonically with increasing depth at each front. The main pycnocline is found higher in the water column as one proceeds to the south; consequently, the decrease in speed with depth is more pronounced at shallower depths for the fronts located farther south.

The geostrophic mass transport of the Subantarctic Front is greater than for the Polar Front, which is greater than for the Continental Water Boundary. The transports associated with the three fronts account for approximately 75% of the total baroclinic transport relative to 2500 m while the fronts occupy only 19% of the width of Drake Passage.

Meridional zonation seems to exist throughout the Antarctic Circumpolar Current. Fronts analogous to those in Drake Passage are found south of Africa and south of Australia.

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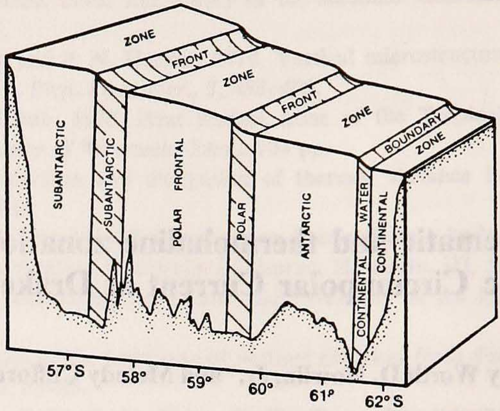


Figure 1. Schematic representation of the four water mass zones and three fronts across Drake Passage from Cape Horn to Livingston Island.

1. Introduction

Background. Transects of Drake Passage made during early 1975 as part of the International Southern Ocean Studies (ISOS) showed the Antarctic Circumpolar Current (ACC) to consist, at least at that location, of several uniform (surface) water masses separated by fronts in which horizontal gradients of property values are relatively large. These fronts have large geostrophic speed shears when compared with the vertical shear of speed in the water mass zones that they separate. Consequently, these fronts may also be referred to as current cores. Although the 1975 data were adequate to establish the presence of distinct frontal structures (Nowlin *et al.*, 1977), they were not sufficient to document particulars of the fronts.

During early 1976, ISOS work in Drake Passage continued aboard R/V *Thompson.* Station spacing of approximately 45 km was sufficiently close to show there are three fronts of large horizontal density gradients separating four surface water mass zones in the passage. Many transects in subsequent years have confirmed this to be the normal situation. For the surface water mass zones and fronts separating them in Drake Passage we use the following names (following Whitworth, 1980) arranged from north to south: Subantarctic Zone, Subantarctic Front, Polar Frontal Zone, Polar Front, Antarctic Zone, Continental Water Boundary and Continental Zone. Figure 1 is a schematic representation of the water mass zones and fronts across the Drake Passage.

The average summer and winter positions of the three fronts in Drake Passage were determined by Whitworth (1980) using all historical station data plus XBT observations. For both summer and winter seasons, he estimated the baroclinic, geostrophic transport across each front for each 500-db interval in the upper water column relative to 2500-db.

Although the circumpolar extent of the Polar Front was recognized early (Deacon, 1937), only recently have other similarities in the Antarctic Circumpolar Current structure been identified in regional descriptions. Heath (1981) has described the thermohaline structure of the Subantarctic and Polar Fronts south of New Zealand. Emery (1977) has shown that these two fronts, bounding the Polar Frontal Zone, extend across the Pacific from south of Australia to east of Drake Passage.

Many studies have focused primarily on the Polar Frontal Zone and the Polar Front. Gordon *et al.* (1977) mapped the Polar Frontal Zone in the western Scotia Sea and noted its highly meandered nature and the occurrence of isolated eddies. Mesoscale rings and meanders have also been reported by Legeckis (1977), Joyce and Patterson (1977), Sievers and Emery (1978), Patterson (1978), Sciremammano (1979) and Joyce *et al.* (1981); and studies of fine structure have been reported by Georgi (1978) and Joyce *et al.* (1978).

Studies of ISOS measurements of current and temperature have shown that the current core, at least at the Polar Front between the Polar Frontal Zone and the Antarctic Zone, is highly coherent in the vertical down to nearly 3000 m (Pillsbury *et al.*, 1979). From calculations of velocity cross correlations as functions of horizontal instrument separation, Sciremammano *et al.* (1980) estimated the velocity coherence scale near the current core associated with the Polar Front to be of the order of 30 to 40 km in the direction normal to the average current direction and 55 to 80 km in the average current direction. The zero crossings of the associated cross correlations of temperature were estimated to be at approximately 80 km.

Objectives. The first objective of this study was to examine the three fronts in Drake Passage using XBT and oceanographic station data collected from 1975 through 1980 and to describe the cross-frontal differences in property distributions. The cross-passage transects of observations (stations or XBT) were considered as if they were individual, synoptic representations of thermohaline fields.

The second study objective was to characterize major features of the fronts. Representative frontal widths and vertical profiles of relative geostrophic speed (normal to station transects) were determined for each front, and these empirical measures were related to the vertical stratification. The geostrophic mass transport relative to 2500 db was computed from pairs of stations spanning each front, and the values related to the total synoptic transport for the particular cross-passage section.

The third objective was to extend these results to frontal areas in other parts of the Antarctic Circumpolar Current system.

2. Observations and methods

Observations. Beginning with the austral summer of 1974-1975, in each year one

Table 1. XBT or oceanographic station data from the Drake Passage which were used in this study.

Vessel	Year	Months	Data
R/V *Melville*	1975	Jan-March	Serial cast, STD, XBT
AGS *Yelcho*	1976	Feb-April	Surface measurements, XBT
R/V *Thompson*	1976	Feb-March	Serial cast, STD, XBT
AGS *Yelcho*	1976	Nov (Section 1)	XBT
R/V *Hero*	1976	Nov (Section 1)	XBT
AGS *Yelcho*	1976	Dec (Section 2)	XBT
R/V *Hero*	1976	Dec (Section 2)	XBT
AGS *Yelcho*	1976	Dec (Section 3)	XBT
AGS *Yelcho*	1976	Dec (Section 4)	XBT
AGS *Yelcho*	1977	Jan (Section 5)	XBT
R/V *Melville*	1977	Jan-Feb	Serial cast, STD, XBT
AGS *Yelcho*	1977	Jan (Section 6)	XBT
AGS *Yelcho*	1977	Dec	XBT
R/V *Melville*	1979	Jan-Feb	Serial cast, XBT
AGS *Yelcho*	1979	April-May	Serial cast, XBT
R/V *Atlantis II*	1980	Jan-Feb	Serial cast, XBT
AGS *Yelcho*	1980	Jan-Feb	XBT

or more oceanographic expeditions to Drake Passage have been arranged by the ISOS program. On most of these cruises, hydrographic or STD stations were made across the passage. Most were made during the summer season.

Table 1 shows the vessels and the times of collection and types of data from Drake Passage used in this study. Data sets will be referred to by abbreviated ship name and year, e.g., "MEL 77."

Analysis methods. In order to identify the fronts in Drake Passage and to describe the associated transitions of properties and geostrophic currents, we studied vertical sections of properties from station data and temperature from XBT's. Vertical sections of properties were constructed from a total of 30 complete or partial crossings of the passage. Many of the sections proved unsuitable for our work because station spacing was too coarse or because the station lines were not long enough to adequately describe the transition of variables across the fronts. For the 14 sections judged to be useful, we considered distributions of temperature, salinity, dissolved oxygen, nutrients, stability, potential density anomaly (sigma) and through-passage geostrophic speed relative to 2500 db.

The traces and vertical sections of temperature from XBT's were studied for 49 complete or partial crossings of Drake Passage. Many of the crossings were not used because the traces did not clearly define the fronts. Thirty-six of the sections proved useful in locating fronts.

Based on the property distributions in each section, two types of station pairs were selected to represent each front. Station pair type I was defined as the pair which best represents the maximum shear seen in the current core. Both stations of this pair had to be within, or themselves define the limits of the shear as determined from examination of the property distributions. Type I station pairs were used to describe the vertical shear of geostrophic speed in the through-passage direction. All sections were oriented almost across-passage. Though these stations give the best available data to characterize the maximum vertical shears at each front, it is clear that the maximum relative speeds may be underestimated for a variety of reasons, such as orientation of the front relative to the stations, nonsynopticity of stations, frontal movements or station spacing.

In Figure 2 are shown typical vertical sections of T, S, sigma and through-passage geostrophic speed relative to 2500 db. Station pairs 29-30, 38-40 and 47-48 were selected as type I pairs to represent the Subantarctic Front, Polar Front and Continental Water Boundary, respectively, from this section.

Since the type I stations frequently were located within the fronts (i.e., within regions of large horizontal gradients of property values), these stations may underestimate the widths of the current cores. Likewise, they alone could not be used to characterize the water mass regimes separated by the fronts.

The second type of station pair, called type II, was defined as the pair which spans the water mass transition. The stations had to be located in the water mass zones representative of the opposite sides of the front. Stations which appeared, on examination of property distributions in vertical section, to be in the region of large geostrophic shear were not selected as type II. Type II stations were used to describe property distributions in the water mass zones and in calculating the relative geostrophic mass transport of the core.

Station pairs 29-32, 38-40 and 47-48 were selected as type II representative of the Subantarctic Front, Polar Front and Continental Water Boundary in the THO 76 section (Fig. 2). In many cases the station pair spanning the transition zone (type II) was the most closely-spaced pair available to represent the current shear, so type I and II station pairs were identical.

In addition to selecting type I and II station pairs for each front crossed by a hydrographic section, estimates were made of apparent core widths, in the direction of the transects. This determination was subjectively based on a combination of distributions of properties and relative geostrophic speed; vertical profiles of T, S and O_2; and T-S relations. Table 2 gives the station pairs and core widths chosen from the hydrographic data. For some sections, the station pairs associated with the fronts could not be categorized; e.g., on some sections no station pair was located close enough to a specific front to be useful in defining the vertical current shear, so no type I pair was reported.

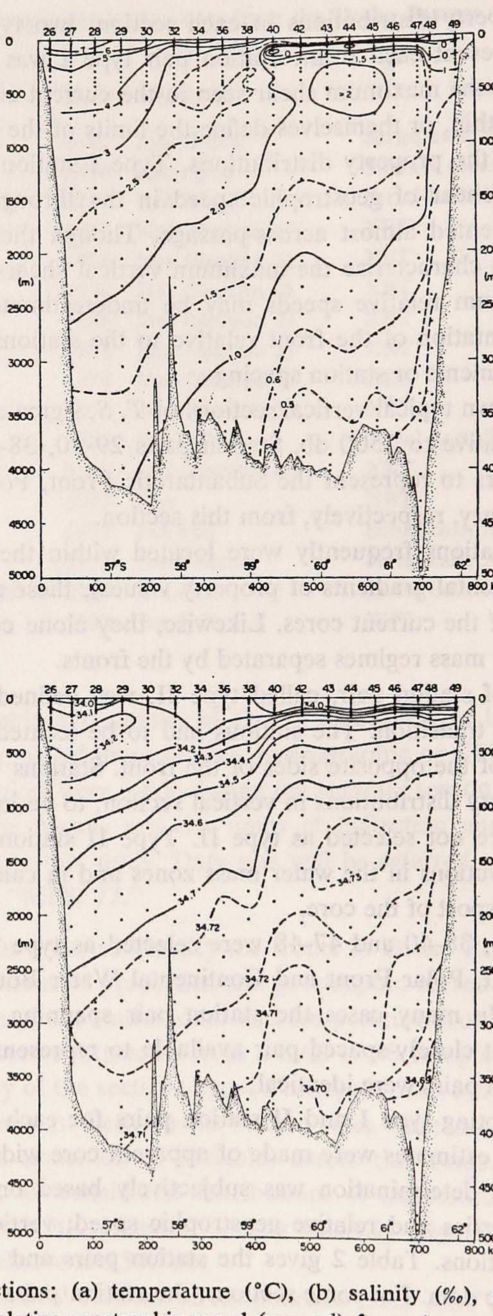
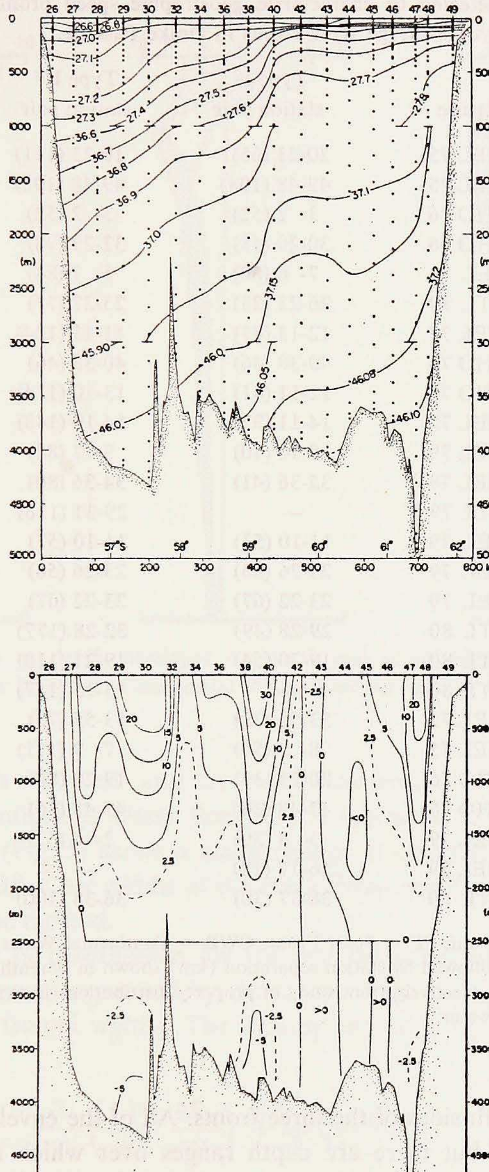


Figure 2. Vertical sections: (a) temperature (°C), (b) salinity (‰), (c) density parameter σ (Kg m⁻³) and (d) relative geostrophic speed (cm s⁻¹) from data collected during February-March 1976 aboard R/V *Thompson*. Section extends across Drake Passage from Cape Horn to Livingston Island. Dots indicate depths of bottle data.



The fronts in the XBT sections were identified mainly on the basis of the composite *T vs. Z* profiles from type II hydrographic stations from the north and south sides of each front. Envelopes were constructed for the composite profiles and scaled to the XBT temperature-depth scale. Figure 3 shows the *T vs. Z* envelopes

Table 2. Station pairs selected to characterize geostrophic speed profiles (type I) and mass transport property transitions (type II) at fronts in Drake Passage.

Front[α]	Cruise	Type I[β] station pair	Type II[β] station pair	Core width[γ] (km)
SAF	MEL 75	20-23 (65)	18-23 (111)	65
SAF	MEL 75	49-48 (108)	49-48 (108)	83
SAF	THO 76	3- 2 (52)	3- 2 (52)	50+
SAF	THO 76	30-29 (48)	32-29 (98)	80
SAF	YEL 79	7- 6 (60)	5- 7 (84)	70[Δ]
SAF	ATL 80	26-25 (23)	25-27 (77)	40-45
PF	MEL 75	12-13 (47)	11-13 (124)	—
PF	THO 76	40-38 (46)	40-38 (46)	30
PF	THO 76	12-11 (41)	13-10 (124)	80
PF	MEL 77	14-11 (92)	14-10 (148)	110
PF	MEL 79	9-10 (40)	9-17 (84)	80
PF	MEL 79	35-36 (41)	34-36 (80)	65
PF	MEL 79	—	29-31 (118)	—
PF	YEL 79	11-10 (57)	11-10 (57)	40-45
PF	YEL 79	25-26 (56)	25-26 (56)	—
PF	YEL 79	23-22 (67)	23-22 (67)	40
PF	ATL 80	29-28 (49)	32-28 (177)	—[ε]
PF	ATL 80	19-20 (54)	19-21 (110)	—
PF	ATL 80	—	13-15 (117)	—
CWB	MEL 75	53-55 (78)	53-55 (78)	70
CWB	MEL 75	8- 9 (54)	7- 9 (111)	70
CWB	THO 76	20-21 (39)	19-20 (88)	—
CWB	THO 76	47-48 (26)	47-48 (26)	20
CWB	MEL 79	3- 4 (30)	2- 4 (52)	40
CWB	MEL 79	16-17 (18)	—	20
CWB	ATL 80	38-37 (30)	36-38 (100)	55

[α] SAF = Subantarctic Front; PF = Polar Front; CWB = Continental Water Boundary.
[β] Station pair numbers followed by station separation (km) shown in parenthesis.
[γ] Core width estimated subjectively from study of property distributions in vertical section.
[Δ] Remnant of Antarctic water.
[ε] Anomalous case.

for the north and south sides of the three fronts. All of the envelopes overlap within some depth interval, but there are depth ranges over which the envelopes from opposite sides of the fronts are distinct. Each XBT trace was subjectively compared to the *T vs. Z* envelopes in order to identify the XBT's located closest to each front but clearly within one of the adjacent water mass zones.

The XBT vertical temperature sections were used to check the trace selections and to narrow down the core widths if possible. Figure 4 shows a sequence of XBT traces near the Continental Water Boundary with the north and south CWB envelopes overlaid. Looking at XBT 35 through 39, one can identify the north side of

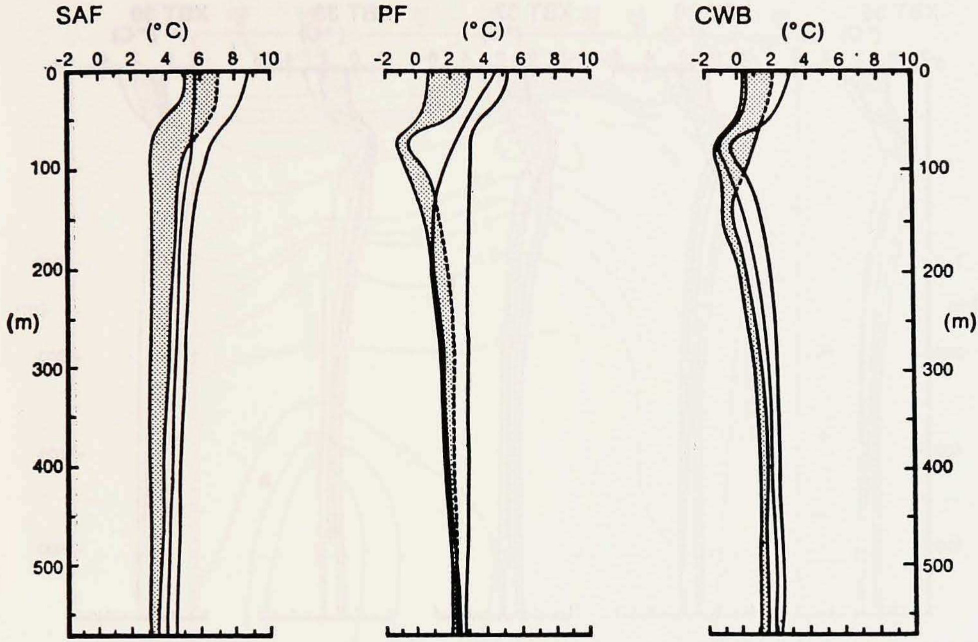


Figure 3. Temperature *vs.* depth envelopes for north and south (shaded) sides of the Subantarctic Front, Polar Front and Continental Water Boundary in Drake Passage.

the front with XBTs 36 or 37 and the south side with XBT 38. In this section, the width of the Continental Water Boundary is estimated as 42 km. The vertical temperature section (Fig. 5) shows a major change in isotherm depths to occur between XBT 36 and 38. Core widths of the Polar Front and Subantarctic Front were estimated by the same method.

The Rossby radii of deformation for the first baroclinic mode were calculated for the water mass zones separated by the fronts. These radii were related to the minimum observed frontal widths. The Rossby radius is based on the following equation:

$$\frac{\partial}{\partial Z}\left(\frac{1}{N^2}\,\frac{\partial F_n}{\partial Z}\right) + \lambda_n F_n = 0\,,$$

subject to the boundary conditions

$$\frac{\partial F}{\partial Z} = 0 \text{ for } Z = 0, -H\,,$$

where $N^2 = -\dfrac{g}{\rho}\dfrac{\partial \rho}{\partial Z}$, λ_n's are a discrete countable set of eigenvalues, F_n's are the associated eigenfunctions and H is the water column depth. The counter n is 1 for

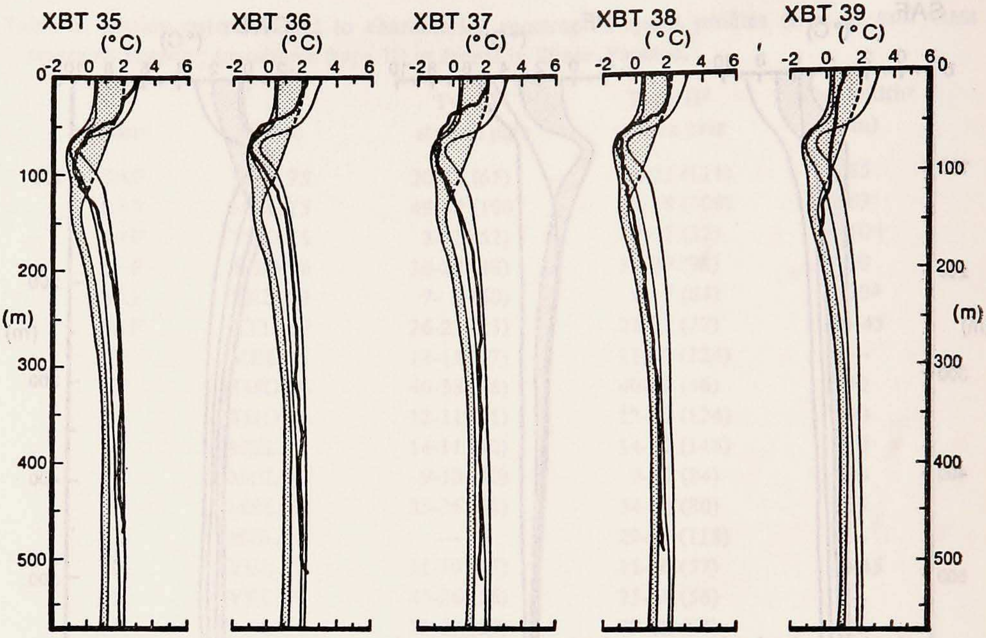


Figure 4. Typical XBT traces for Continental Water Boundary with the north and south (shaded) CWB envelopes overlaid. XBT trace identified by darker line. Data collected during January-February 1979 aboard R/V *Melville*.

the first baroclinic mode. The above equation is solved numerically for the λ_n's and associated F_n's, and the Rossby radius for the first baroclinic mode is given by $\lambda_1^{-1/2}/f$, where f is the Coriolis parameter.

3. Property variations and scales

Variations of T, S and O_2 across fronts. Type II stations, selected to represent the water mass regimes separated by the fronts, show remarkable year-to-year uniformity in the vertical distributions of properties across the three fronts in Drake Passage. It should be noted that with the exception of XBT and station data taken aboard the AGS *Yelcho* during April and May 1979, the data used in this study were taken during the austral summer season and thus may not reflect the details of conditions in other seasons. The vertical profiles of T and S, as well as the T-S relations from the six pairs of type II stations (Table 2) spanning the Subantarctic Front are shown in Figure 6.

In the Subantarctic Zone north of the SAF, the T-S relations and the vertical profiles of T, S and O_2 (not shown in Fig. 6) show little scatter. The vertical profiles and T-S curves south of the SAF are somewhat less uniform, but even so there is a

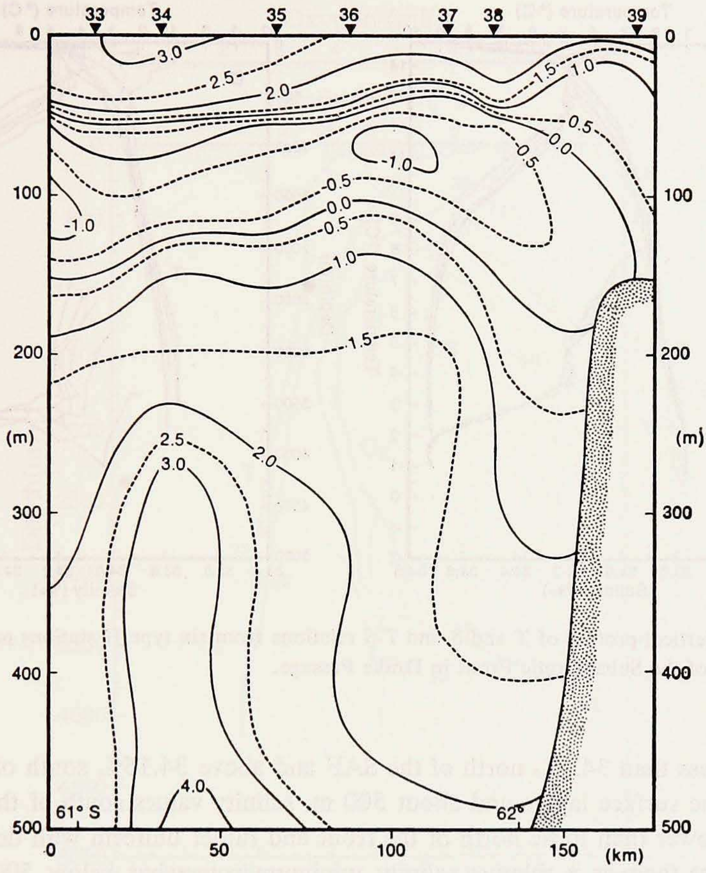


Figure 5. Vertical section of XBT temperature data of R/V *Melville* 1979 for region around the Continental Water Boundary off Livingston Island.

relatively tight pattern to these relations in the northern part of the Polar Frontal Zone. The notable exception to the pattern is YEL 79 station 7, which was located at the center of what appeared to be the remnant of a ring of Antarctic Water in the Polar Frontal Zone. This remnant was observed principally as a relatively cold lense of water between 100 and 500 m, although the salinities down to 2000 m were somewhat greater than at other neighboring PFZ stations.

THO 76 stations 29 and 32 are typical of the type II stations across the SAF and may be compared (Fig. 7) in order to contrast the property distributions. Temperatures in the Subantarctic Zone north of the SAF are considerably greater throughout the water column, but especially between the surface layers and 1000 m due to the presence of a rather monotonic thermocline throughout this zone in contrast to the relative temperature minimum of the Polar Frontal Zone. Surface salinity is

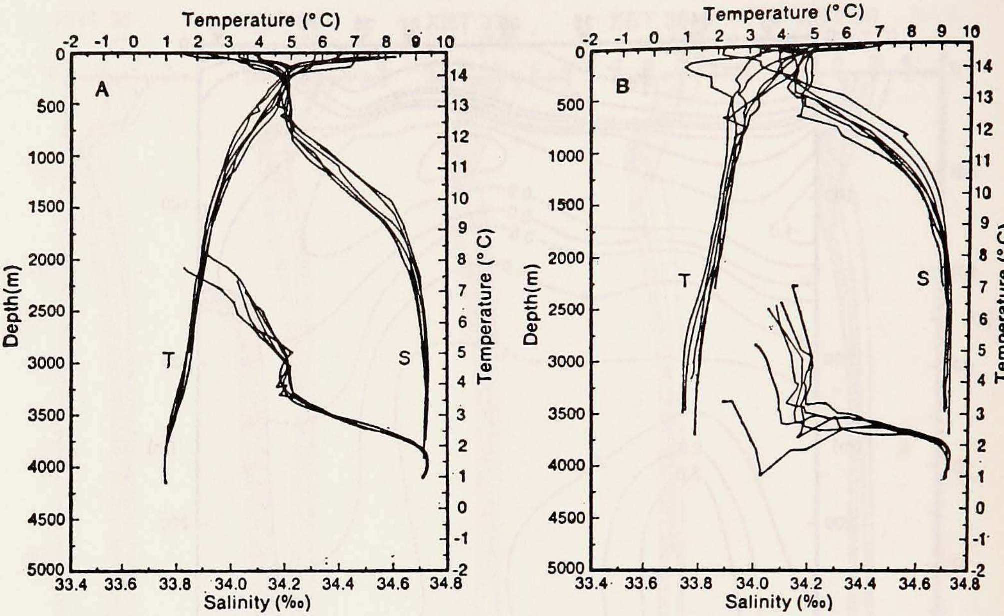


Figure 6. Vertical profiles of *T* and *S* and *T-S* relations from six type II stations north (A) and south (B) of the Subantarctic Front in Drake Passage.

generally less than 34.1‰ north of the SAF and above 34.15‰ south of the front. Between the surface layers and about 500 m, salinity values south of the SAF are generally lower than those north of the front and rather uniform with depth. North of the front there is a relative salinity minimum somewhat below 500 m which marks the Antarctic Intermediate Water. Between that minimum and the surface layer, Subantarctic salinities are generally greater than PFZ salinities; salinities below that minimum are lower in the Subantarctic Zone. North of the SAF the dissolved oxygen concentration has a broad relative minimum extending from 1300-1700 m depth.

There are also marked differences in distributions of *T*, *S* and O_2 across the Polar Front. Figure 8 contrasts THO 76 stations 38 and 40 which typify conditions in the PFZ north of the front and in the Antarctic Zone to its south. The temperature profiles change most prominently across the PF. First there is a pronounced temperature minimum south of the front; but also the temperature at greater depths is colder south of the PF, by 0.3 to 0.5°C. Together with systematic salinity differences above the Circumpolar Deep Water, these temperature differences yield significantly different *T-S* relations across the Polar Front. Near-surface salinities are greater in the Polar Frontal Zone, but below the *T*-minimum core and above the Circumpolar Deep Water (from about 175 m to 1850 m) the salinities south

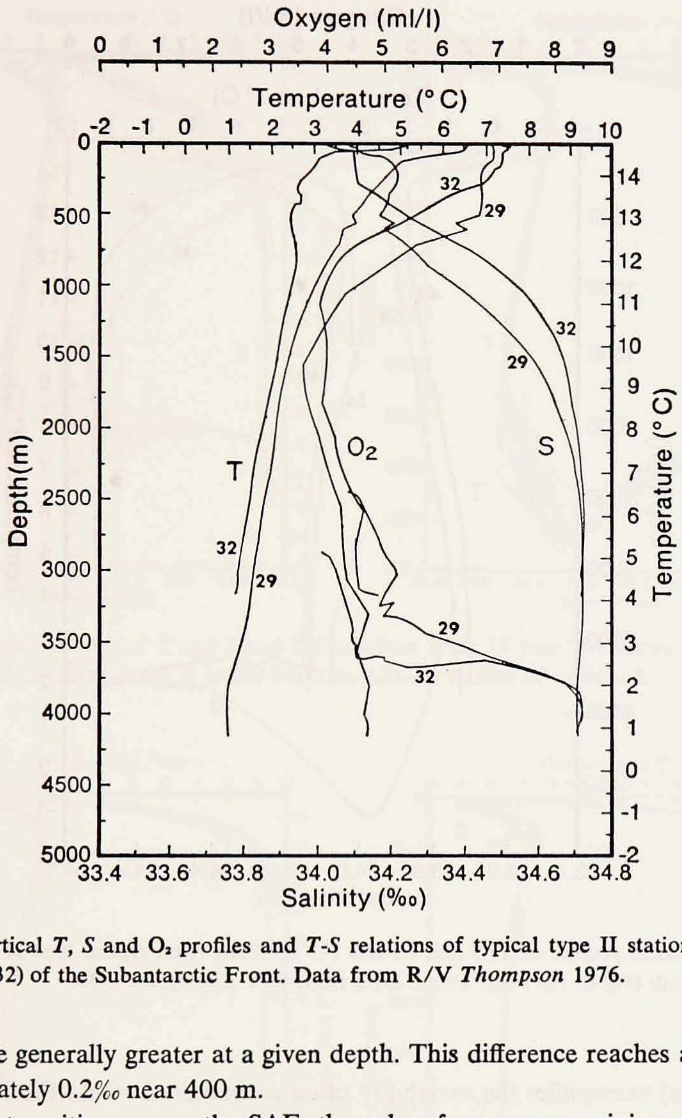


Figure 7. Vertical *T*, *S* and O_2 profiles and *T-S* relations of typical type II stations north (29) and south (32) of the Subantarctic Front. Data from R/V *Thompson* 1976.

of the PF are generally greater at a given depth. This difference reaches a maximum of approximately 0.2‰ near 400 m.

As in the transition across the SAF, the subsurface oxygen minimum is slightly more pronounced and occurs deeper north of than south of the Polar Front. This is due to the general southward rising of isopycnal surfaces across the Antarctic Circumpolar Current and to the fact that the sources of the low oxygen waters lie north of the Southern Ocean.

In the Antarctic Zone south of the Polar Front, vertical property distributions and *T-S* relations change little from year to year (Fig. 9). North of the PF the scatter is larger, which is expected due to the nature of the PFZ as a transition zone with enhanced mixing activity. ATL 80 station 28 (identified by high temperature and

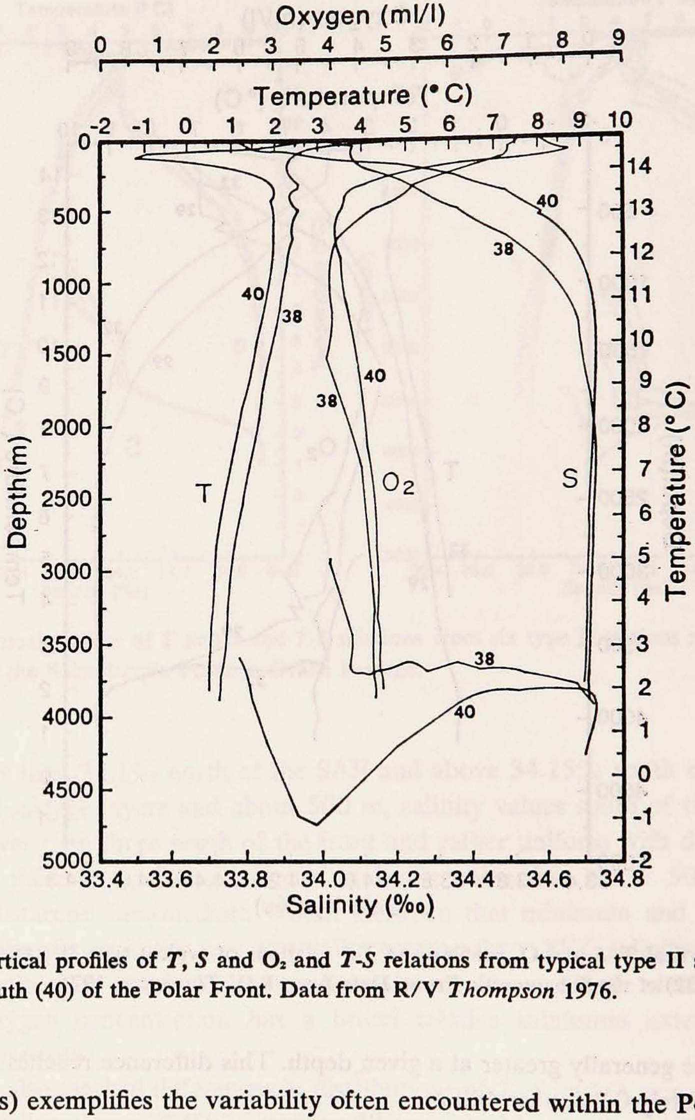


Figure 8. Vertical profiles of *T*, *S* and O_2 and *T-S* relations from typical type II stations north (38) and south (40) of the Polar Front. Data from R/V *Thompson* 1976.

low salinities) exemplifies the variability often encountered within the Polar Frontal Zone.

As with the Antarctic Zone south of the PF, the deep profiles of *T* and *S* for type II stations north of the CWB (Fig. 10) are quite uniform, except in the very surface layer and for variations of *S* above the salinity maximum of the Circumpolar Deep Water. The station-to-station differences above 1500 m are greater south of the CWB than north of it, resulting in somewhat more scatter for *T-S* curves shown from the Continental Zone than those shown from the Antarctic Zone. The contrast between properties on either side of the CWB are illustrated by MEL 75 station 53 and 55 (Fig. 11).

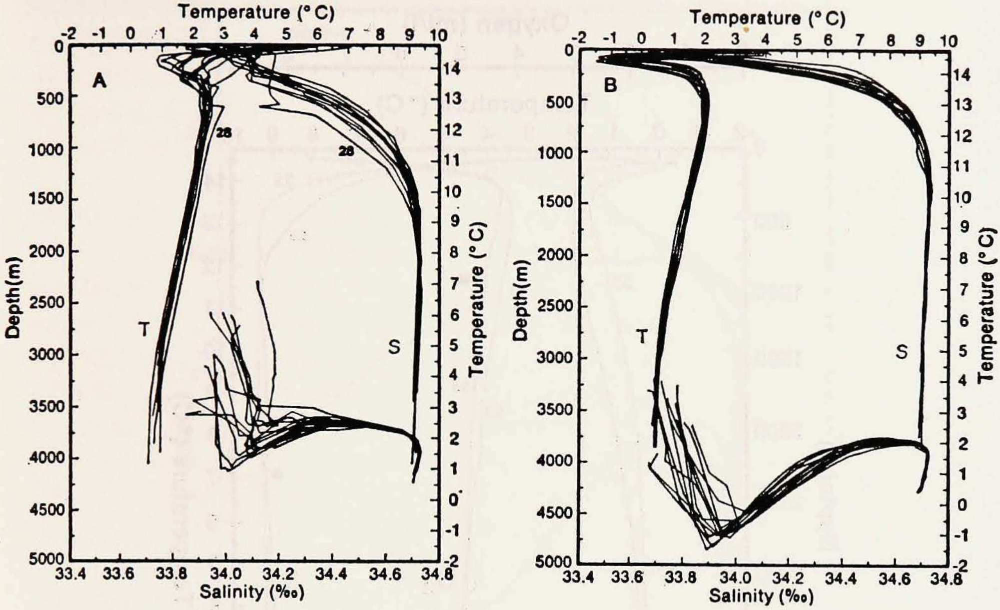


Figure 9. Depth profiles of *T* and *S* and *T-S* relations from 13 type II stations north (A) and south (B) of the Polar Front in Drake Passage. ATL 80 station 28 indicated.

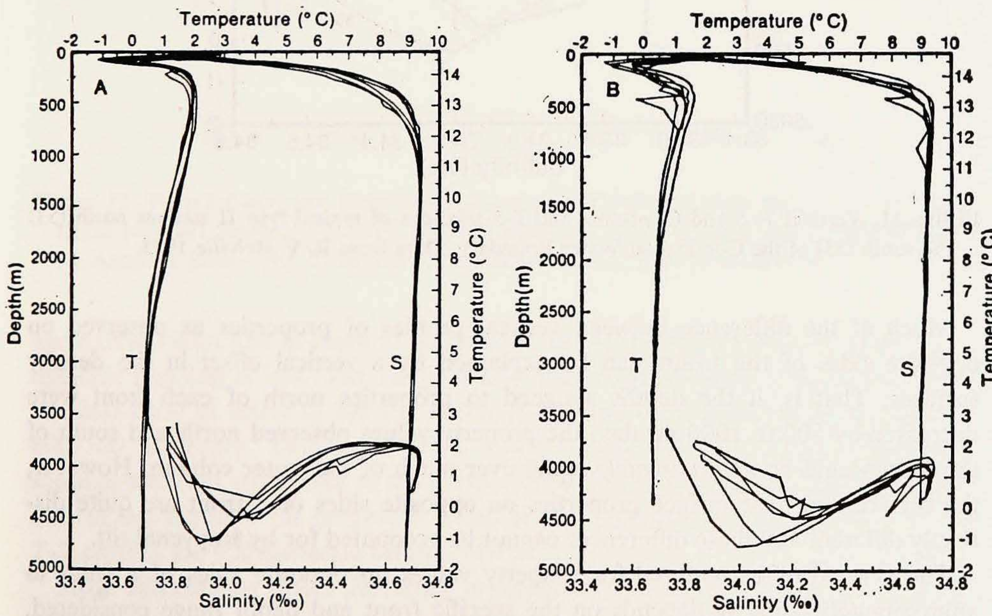


Figure 10. Vertical profiles of *T* and *S* and *T-S* relations from six type II stations north (A) and south (B) of the Continental Water Boundary in Drake Passage.

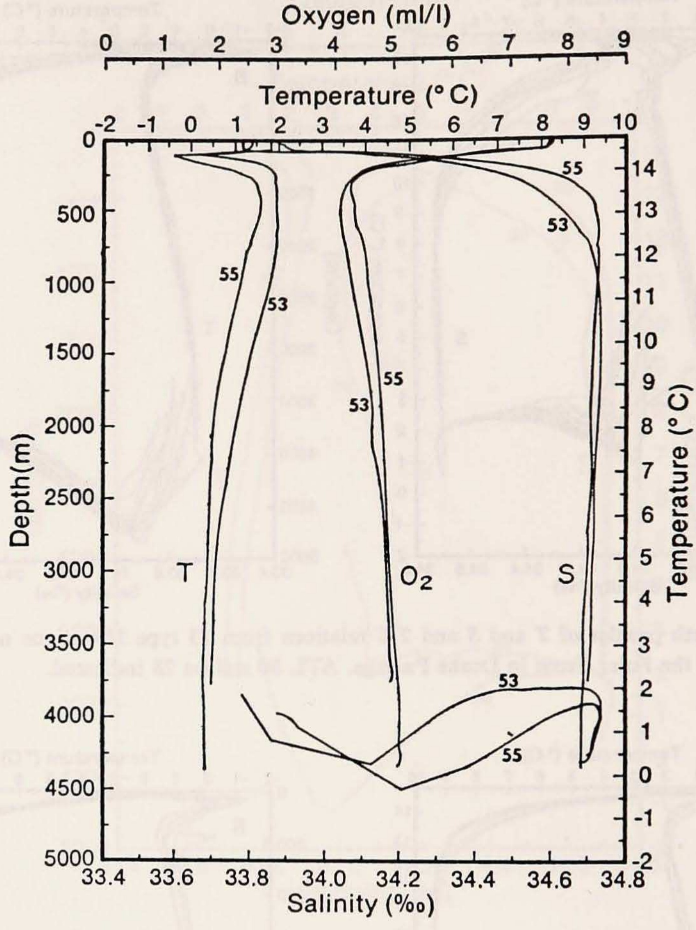


Figure 11. Vertical *T*, *S* and O_2 profiles and *T-S* relations of typical type II stations north (53) and south (55) of the Continental Water Boundary. Data from R/V *Melville* 1975.

Much of the difference between vertical profiles of properties as observed on opposite sides of the fronts can be explained by a vertical offset in the density surfaces. That is, if the depths assigned to properties north of each front were decreased by 500 to 1000 m, then the property values observed north and south of the front would be *approximately* equal over much of the water column. However, the surface and near-surface properties on opposite sides of a front are quite distinctly different and these differences cannot be accounted for by isopycnal tilt.

The vertical offset required for property values on opposite sides of a front to approximately coincide depends on the specific front and depth range considered. The *T-Z* and *S-Z* profiles for depths below 750 m south of the CWB correspond to those 1000 m deeper north of this front. With this same offset, the O_2-*Z* profiles

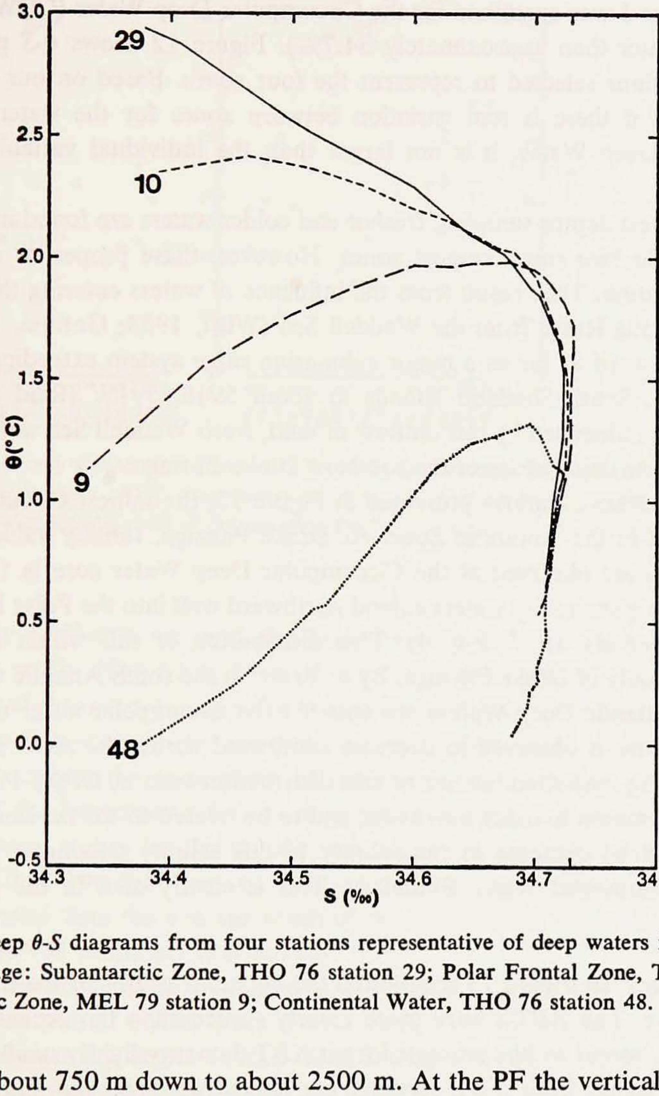


Figure 12. Deep θ-S diagrams from four stations representative of deep waters in zones across Drake Passage: Subantarctic Zone, THO 76 station 29; Polar Frontal Zone, THO 76 station 10; Antarctic Zone, MEL 79 station 9; Continental Water, THO 76 station 48.

agree from about 750 m down to about 2500 m. At the PF the vertical offset due to dynamic banding is less. The temperatures and oxygen values from about 600 m to 2000-2500 m south of the PF match fairly well those north of the front some 600-700 m deeper. That same offset would match salinities below 800-1000 m south of the front with those to the north. About 500 m offset gives fair correspondence across the SAF for properties found below 1000 m south of the front, though T-Z profiles are still disparate below 2000 m.

After allowing for depth difference in isopycnals across the fronts, we have been able to detect few systematic differences between the deep and bottom waters of the different water mass zones. For each zone the bivariate relationship of θ (potential temperature) to S was examined for the Circumpolar Deep Water (CDW) and below (salinities greater than approximately 34.7‰). Figure 12 shows θ-S plots of data from four stations selected to represent the four zones. Based on our examination of ISOS data, if there is real variation between zones for the waters below the Circumpolar Deep Water, it is not larger than the individual variability between stations.

At the greatest depths sampled, fresher and colder waters are found at the stations representing the two southernmost zones. However, these properties do not seem related to zonation. They result from the influence of waters entering the Scotia Sea over the S. Scotia Ridge from the Weddell Sea (Wüst, 1933; Gordon, 1967) which penetrate westward as far as a major submarine ridge system extending northwestward from the South Shetland Islands to about 59½S, 59½W (Reid and Nowlin, 1971). Waters influenced by this outflow of cold, fresh Weddell Sea water are found as far west as the depressions of the southern Drake Passage.

For the illustrative stations presented in Figure 12, the saltiest Circumpolar Deep water is found in the Antarctic Zone. At Drake Passage, salinity values somewhat above 34.73‰ are observed at the Circumpolar Deep Water core in the Antarctic Zone; frequently such salty waters extend northward well into the Polar Frontal Zone (e.g., Nowlin *et al.*, 1977, Fig. 4). This distribution of salt within the CDW is characteristic only of Drake Passage. By contrast, in the south Atlantic Ocean where salty North Atlantic Deep Waters are entering the circumpolar water mass, salinity at the CDW core is observed to decrease southward across the ACC system (Reid *et al.*, 1977, Fig. 6a). One feature of salt distribution seen at Drake Passage which seems to be common to other longitudes and to be related to the horizontal zonation is the pronounced decrease in the salinity of this salinity maximum to the south across the Continental Water Boundary. This is clearly seen in the θ-S relations (Fig. 12).

Widths of fronts. In Figure 13 are plotted the apparent widths of the three fronts in Drake Passage. The XBT's were more closely spaced than the oceanographic stations, and the frontal widths estimated from XBT data are slightly smaller. However, the widths selected from XBT sections are almost as large and show as great a range as do those selected from vertical section data, so we have chosen to use station and XBT data to estimate the distances in which property transitions occur across the fronts.

The widths selected will generally be larger than the actual widths since the sections are not necessarily normal to the fronts. The average observed widths and associated standard deviations using both XBT and hydrographic station data are: Subantarctic Front, 51 ± 13 km; Polar Front, 61 ± 20 km; Continental Water Boundary, 39 ± 15 km. The sum of these average frontal widths accounts for only 19% of the total width of the passage (800 km) from Cape Horn to Livingston

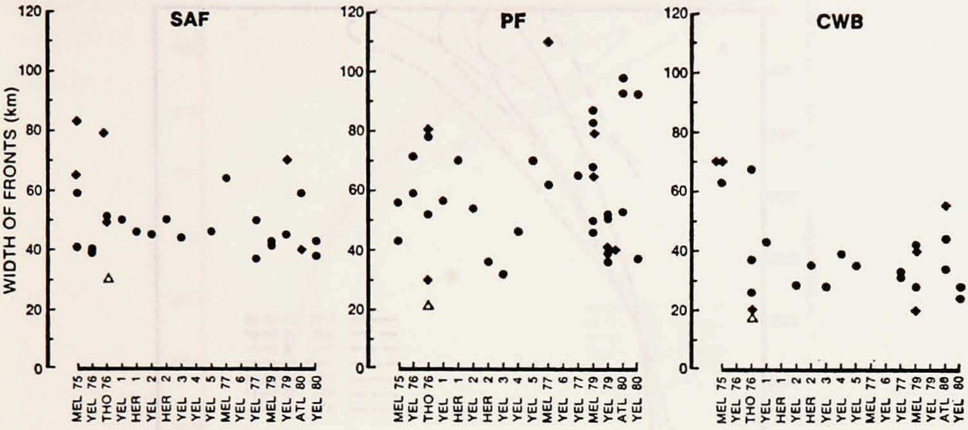


Figure 13. Apparent widths of Subantarctic Front, Polar Front and Continental Water Boundary in Drake Passage. XBT data shown as dots and hydrographic station data shown as diamonds. Twice Rossby radii of deformation for first baroclinic mode shown as triangles.

Island. If only XBT data are used, the frontal widths with standard deviations are, from north to south: 46 ± 8 km, 60 ± 18 km and 37 ± 12 km.

The standard deviation is larger for the width of Polar Front than for the Continental Water Boundary or the Subantarctic Front. This could be because relative to the data transects the orientation of the Polar Front changes more than the orientation of the Subantarctic Front and Continental Water Boundary. The larger range of apparent widths for the Polar Front might also be due to actual variations in its widths. It is clear that average observed widths of the Subantarctic and Polar Fronts are greater than the average width of the Continental Water Boundary even taking the observed variability into account.

Under the assumptions that at least some transects were made normal to the fronts, and that frontal widths do not vary much, the minimum observed widths should approximate the actual widths. With the large numbers of crossings made, the first assumption seems justified; the second assumption may be questioned. The minimum observed frontal width decreases from Subantarctic Front (37 km) to Polar Front (30 km) to Continental Water Boundary (20 km).

The Rossby radius of deformation for the first baroclinic mode (R), indicated for each front in Figure 13, also decreases from north to south across the passage. These values of R are based on STD data collected during THO 76. Average values of R for the four water mass zones are: Subantarctic Zone, 16.7 km; Polar Frontal Zone, 13.0 km; Antarctic Zone, 9.5 km; Continental Water, 7.4 km. Here the Rossby radius appropriate to a front is taken as the average of values observed in the waters which the front separates. The minimum observed frontal widths appear

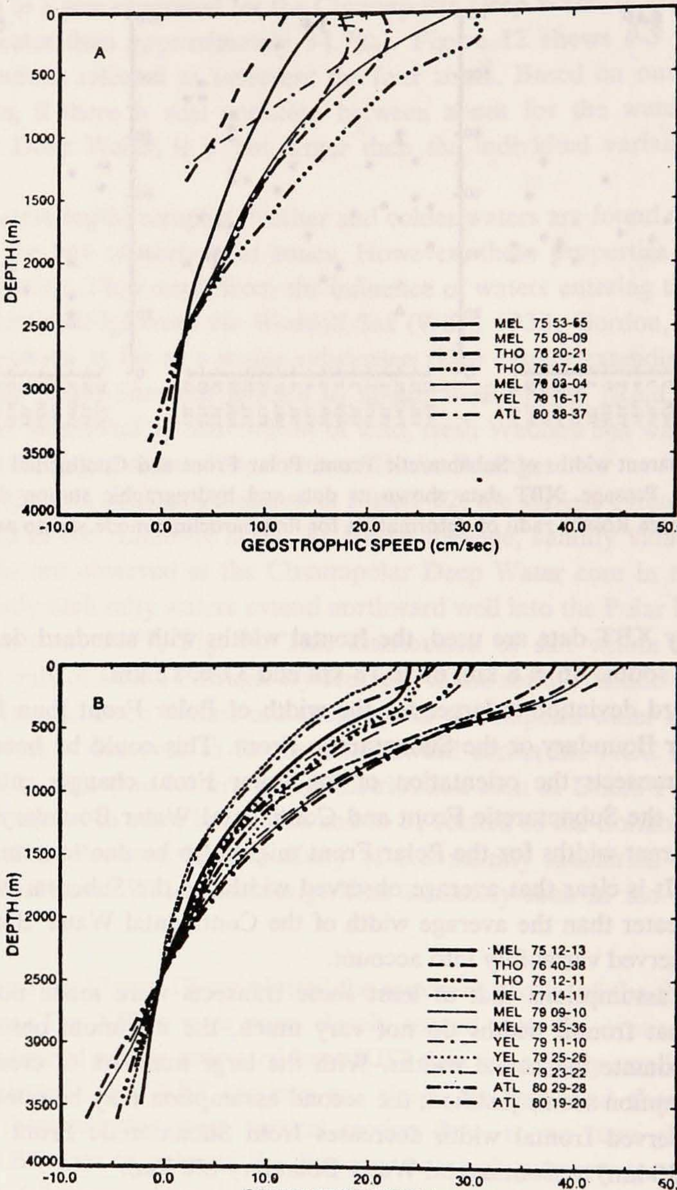
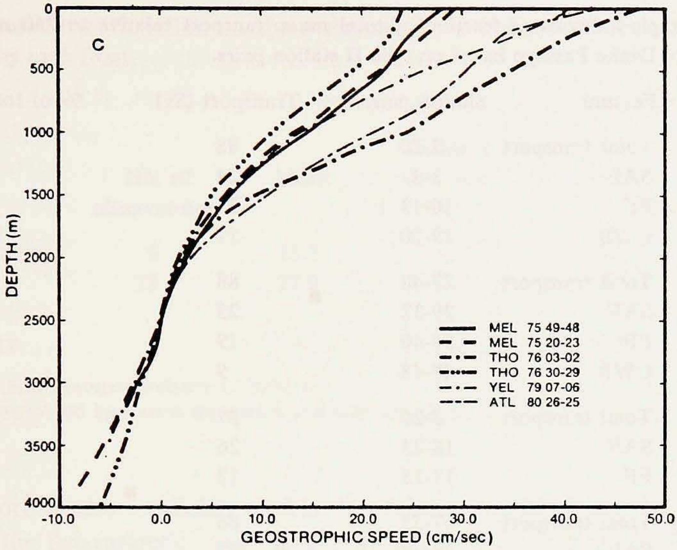


Figure 14. Vertical profiles of the component of velocity normal to type I station pairs for Continental Water Boundary (A), Polar Front (B) and Subantarctic Front (C) in Drake Passage.

to correspond closely to values between 2 R and 2.5 R as suggested by Csanady (1978) for surface to bottom fronts.



4. Profiles of geostrophic speed

Estimates of the vertical shear of horizontal speed at the three fronts in Drake Passage have been made. Assuming geostrophy, the horizontal pressure gradients between type I stations were used to calculate vertical profiles of the component of velocity normal to the station pairs (Fig. 14). All speeds were calculated relative to 2500 m except for 2 station pairs at the Continental Water Boundary for which sampling did not reach 2500 m: MEL 75 stations 8 and 9; and YEL 79 stations 16 and 17.

As expected, the geostrophic shear increases to the north with increasing vertical density stratification. The speeds in the upper 500 m are about the same in the PF and SAF, 30-45 cm s^{-1}. Speeds at these fronts are considerably greater than for the CWB in the upper 1000 m. The SAF has greater speeds deeper in the water column than has the PF, which in turn has larger speeds deeper in the water than the CWB. This might be expected from the density stratification. The fit of direct current observations in Drake Passage to dynamic normal modes calculated from stability profiles for the appropriate water mass zones (Inoue, personal communication) shows that most of the energy is accounted for by the barotropic and first baroclinic modes. The first baroclinic mode calculated from the stability profiles for the four water mass zones shows that the greatest increase in amplitude occurs higher in the water column in the north than in the south.

For the Continental Water Boundary, two of the geostrophic speed profiles (YEL 79 stations 16 and 17 and THO 76 stations 47 and 48) show small inversions in the upper 200 m. These near-surface inversions in geostrophic speed are features seen frequently in the Continental Water Boundary.

Table 3. Example analyses of fraction of total mass transport relative to 250 m contained in each front in Drake Passage based on type II station pairs.

Cruise	Feature	Station pair	Transport (Sv)	% of total transport
THO 76	Total transport	2-20	88	100
	SAF	2-3	24	27
	PF	10-13	21	24
	CWB	19-20	17	19
	Total transport	27-48	88	100
	SAF	29-32	25	28
	PF	38-40	19	22
	CWB	47-48	9	10
MEL 75	Total transport	8-26	87	100
	SAF	18-23	26	30
	PF	11-13	18	21
	Total transport	47-55	86	100
	SAF	48-49	32	37
	CWB	53-55	14	16
ATL 80	Total transport	25-38	88	100
	SAF	25-27	27	31
	PF	13-15	19	22
	PF	19-21	23	26
	PF	28-32	33	37
	CWB	36-38	18	20

5. Relative mass transport

We estimated the relative geostrophic mass transport of each front based on type II station pairs and compared this to the total relative transport obtained from stations made at the northern and southern edges of Drake Passage on the same cruise. Examples of these estimates are given in Table 3.

The total baroclinic, geostrophic transport relative to 2500 db through Drake Passage is relatively steady when compared to the total transport, as previous workers have noted. However, Whitworth (1980) has shown that the summer and winter baroclinic transports calculated from averaged data are significantly different. With the exception of data from YEL 79, the data used in this study were obtained during austral summer. Therefore, our transport estimates should be considered to represent summer conditions.

Although the fraction of the total baroclinic transport by a particular front is somewhat variable (probably due in part to the placement of station pairs selected), the fractions of total baroclinic transport carried by different fronts can be estimated by considering all the observations across the individual fronts for which total baro-

Table 4. Percent of total baroclinic transport[α] through Drake Passage and characteristic speed[β] contributed by each front.

Front	No. of observations	Transport: Mean (%)	Transport: Standard deviation (%)	Characteristic speed: Mean ($cm\ s^{-1}$)	Characteristic speed: Standard deviation ($cm\ s^{-1}$)
Subantarctic Front	6	31.5	4.4	13.1	4.0
Polar Front	13	27.0	7.2	9.5	3.7
Continental Water Boundary	4	15.1	4.3	8.6	3.5

[α] Geostrophic mass transport relative to 2500 m.
[β] Transport normalized by station separation and sampling depth (2500 m).

clinic transport is also available (Table 4). Relative to 2500 m, the geostrophic transport of the Subantarctic Front is slightly larger than that of the Polar Front. When the variability of individual estimates is taken into account however, the baroclinic transports of these two fronts are not significantly different. If the observations from YEL 79 are removed so that only austral summer observations are considered, the results are not appreciably different: based on 5 observations, the mean baroclinic transport of the Subantarctic Front is 30.5% of the total baroclinic transport with a standard deviation of 3.9%; based on 10 summer observations the corresponding mean and standard deviation for the Polar Front are 28.6% and 7.3%. As seen in Table 4, both fronts bounding the Polar Frontal Zone transport considerably more water than the Continental Water Boundary. (All observations of the CWB are from the summer.) Adding the mean values of baroclinic transport carried by the type II stations describing the three fronts, accounts for 74% of the total baroclinic transport relative to 2500 m.

These baroclinic transports relative to 2500 m agree generally with the mean summer situation described by Whitworth (1980). He found the summer baroclinic transport between the Subantarctic and Polar Frontal Zones to be about 10% greater than that between the Polar Frontal and Antarctic Zones and about 35% greater than the baroclinic transport between the Antarctic Zone and Continental Water Boundary. It should be noted that for the austral winter Whitworth found the mean baroclinic transport between the Polar Frontal Zone and Antarctic Zone to be the largest: approximately 20% larger than between the Antarctic Zone and Continental Water Boundary. Our estimates are not directly comparable with those of Whitworth in terms of transports ($m^3\ sec^{-1}$), since we have estimated the transport within fronts defined by type II stations spanning the fronts, whereas Whitworth has estimated transports between water mass zones defined by average vertical distributions of properties within the zones.

If our baroclinic transport estimates are normalized by the separation of the defining type II stations and the reference depth (2500 m), characteristic transport speeds are obtained (Table 4). For the Subantarctic Front, Polar Front and Continental Water Boundary these are 13.1, 9.5 and 8.6 cm sec^{-1}, respectively. Because of the large case-to-case variability however, these do not significantly differ from one another. (They differ from one another by only about one standard deviation.) For comparison, consider the average through-passage transport speed for the upper 2500 m through Drake Passage. Using a baroclinic transport relative to 2500 m of 88 Sv and a passage width of 700 km (at the 2500 m depth contour) yields a transport speed of 5 cm sec^{-1}.

6. Summary and discussion

The waters of the ACC at Drake Passage are differentiated horizontally into four water mass zones separated by three fronts which extend throughout the water column. We have examined this zonation based on data collected from 1975 through 1980. With the exception of data from one late fall cruise, the measurements were made in austral summer. Temperature, salinity and dissolved oxygen profiles from the same side of a specific front are remarkably uniform from year to year and from cruise to cruise.

Temperature-salinity relations are markedly different across fronts for surface and near-surface waters. Beneath the surface layers, comparing T, S and O_2 at specific depths across a front shows that there is an offset of 500 to 1000 m in the depth at which a particular property value is found. Thus to first approximation, the fronts may be considered to be current cores with large vertical shears of horizontal geostrophic velocity associated with horizontal gradients in the depths of density surfaces, and most of the ACC transport is focused at these fronts. For the Circumpolar Deep Water and below, the variation in temperature-salinity relationships between distinct water mass zones does not appear to be greater than the station-to-station variability, so that the horizontal water mass zonation in the deep waters is due to isopycnal tilting.

Based on XBT temperature data and vertical sections of properties from quasi-synoptic hydrographic stations, the average observed widths of the Subantarctic Front, Polar Front and Continental Water Boundary are 51, 61 and 39 km, respectively, although the variation in individual estimates of the SAF and PF are large enough that the average widths differ by somewhat less than one standard deviation. However, the CWB is significantly narrower than the other two fronts. The respective minimum observed widths are 37, 30 and 20 km, respectively. The southward decrease in minimum observed width may be expected because of the coincident decrease in vertical stability. These minimum core widths are slightly greater than twice the local Rossby radius of deformation for the first baroclinic mode.

The vertical profiles of geostrophic speed are different for the three cores. The surface speeds are greater for the SAF and PF than for the CWB. At each front the speed below about 300 m decreases monotonically with increasing depth. In Drake Passage the main pycnocline is found higher in the water column in the north than in the south. Consequently, the decrease in speed with depth is more pronounced at shallower depths for the fronts located farther south. The result is that larger through-passage speeds occur deeper in the water column at the SAF than at the PF than at the CWB.

The geostrophic mass transports associated with the fronts account for about 74% of the total baroclinic transport relative to 2500 m while the three fronts occupy only 19% of the width of the Drake Passage. Thus these fronts can be considered narrow zones in which transport is focused. The baroclinic transport of the SAF is slightly, though not significantly, greater than for the PF. Both have considerably greater relative transport than does the CWB.

Based on this study and previous indications that analogous frontal zones exist throughout the ACC system, core widths for other regions can be estimated from knowledge of the density structure in those areas. We have examined the zonation south of Australia based on data collected on cruise 45 of the USNS *Eltanin* in September-October 1970. We selected stations representative of water mass zones and calculated the first baroclinic Rossby radius (R) for each regime:

Station 1269	Subtropical Zone	33 km
Station 1264	Subantarctic Zone	21 km
Station 1262	Polar Frontal Zone	14 km
Station 1256	Antarctic Zone	10 km

The survey did not extend far enough south to include samples from the Continental Zone. Taking the value of R corresponding to a front to be the average of values for the water masses which it separates, estimated values of the baroclinic Rossby radius south of Australia are 27 km for the Subtropical Convergence, 17 km for the Subantarctic Front and 12 km for the Polar Front.

The *Eltanin* station spacing was not close enough for direct estimates of the frontal widths. However, during January-March 1977, R/V *Professor Zubov* made three closely-spaced XBT sections south of Australia from which the width of the Subantarctic Front can be examined. The observed widths were 59, 46 and 64 km. The minimum observed Subantarctic Frontal width is approximately 2.6 R.

The zonation south of Africa has also been examined. The data used were collected by Jacobs *et al.* (1980) on *Conrad* 17 in January-April 1974. In addition to three frontal zones corresponding to those in Drake Passage, the Subtropical convergence also passes between Africa and Antarctica. The approximate positions of the Polar Frontal Zone and Subtropical Convergence are indicated on the hydrographic cross sections in the *Conrad* 17 data report. Station spacing was not close enough to allow good direct estimation of frontal widths. We selected five *Conrad* stations representative of the water mass regimes separated by these fronts and calculated first baroclinic Rossby radii (R) for each:

Station 255	Subtropical Zone	24 km
Station 285	Subantarctic Zone	21 km
Station 224	Polar Frontal Zone	16 km
Station 275	Antarctic Zone	8 km
Station 240	Continental Zone	6 km

Again, taking the value of R appropriate to each frontal zone as the average of values in water masses which it separates, the baroclinic Rossby radius (in km) is approximately 22 for the Subtropical Convergence, 18 for the Subantarctic Front, 12 for the Polar Front and 7 for the Continental Water Boundary. These values are quite close to the corresponding values south of Australia and for Drake Passage (15 km for SAF, 11 km for PF, 8 km for CWB). Based on available data, we infer that the frontal widths are likewise similar.

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