Antarctic Polar Frontal Zone from Australia to the Drake Passage

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ABSTRACT

North-south temperature sections drawn from historical XBT observations averaged over various longitude bands are compared with sections drawn from existing hydrographic data. Corresponding features in both types of sections are related to changes in upper-layer water masses by the use of temperature-salinity relationships. A series of six of these sections covering the area from south of Australia east to the Drake Passage are employed to define the positions of two discontinuities or fronts. These fronts are the northern and southern boundaries of a complex transition region, called the Antarctic Polar Frontal Zone, between the Antarctic and Subantarctic Surface Waters. This transition region varies in width both zonally and seasonally, and is the site of eddies and meanders of the boundaries.

1. Introduction

The thermal structure in the upper layers of the Antarctic circumpolar region has been previously examined mainly on a regional basis from individual north–south sections. These studies, such as that by Gordon (1972), have given rise to the identification of many different fronts to describe the changes in water masses across the Antarctic Circumpolar Current (ACC). The complexity of the thermal structure in these north-south sections prompted Gordon (1967, 1971) to suggest that one of these fronts, the Polar Front, separates into primary and secondary fronts in the area southeast of Australia.

Adding to the difficulty in identifying these many fronts are the different definitions applied to them. As an example, an early study of sea surface temperature by Mackintosh (1946) defined the position of the "Antarctic Convergence" as the maximum surface temperature gradient. He considered this convergence to be the northern limit of Antarctic Surface Water (ASW). Later investigators (Ostapoff, 1962; Gordon, 1967, 1971) proposed the name Polar Front for this boundary between ASW and Subantarctic Surface Water (SSW) since neither convergence nor divergence could be confirmed at the front. Ostapoff suggested that since salinity is more conservative than temperature the salinity at 200 m would be a more reliable indicator of the northern limit of ASW and hence of the Polar Front. Gordon (1971) also proposed a subsurface definition suggesting that the place where the subsurface temperature minimum rapidly increases in depth should be marked as the Polar Front. He adds that this descent of the temperature minimum is usually associated with the secondary polar front which lies to the south of the primary front when observed.

Recently efforts have been made to classify the various frontal features of the ACC into zones. In the Australasian sector Gordon *et al.* (1974) identify four such zones starting with a shelf zone near the Antarctic continent. The three oceanic zones, from south to north, are: the Antarctic zone, the Complex zone and the Subantarctic zone. The Polar Front was contained within the Complex zone which was dominated by the interleaving of different water masses.

A similar zone of interleaving was found in the Drake Passage by Nowlin *et al.* (1977) using recent hydrographic data. This region, identified by discontinuities in the temperature-salinity (T-S) relationships across the Drake Passage, was considered to be a transition zone between ASW and SSW. As such it was referred to as the Polar Frontal Zone. Using similar terminology Gordon *et al.* (1977) also identify the Polar Front Zone to be a transition zone between ASW and SSW in the western Scotia Sea. In this recent study both Subantarctic and Antarctic limits of the Polar Front Zone are discussed with the Antarctic boundary to the south resembling the Polar Front as defined earlier by Gordon (1971).

The present study began as a review of existing XBT data to establish a background for new XBT sections being taken from Antarctic supply vessels. Historical hydrographic as well as XBT data were used together to describe the large-scale seasonal distribution of the Antarctic and Subantarctic boundaries of the Antarctic Polar Frontal Zone (APFZ). The boundaries of this transition zone between ASW and SSW are identified by features of the temperature

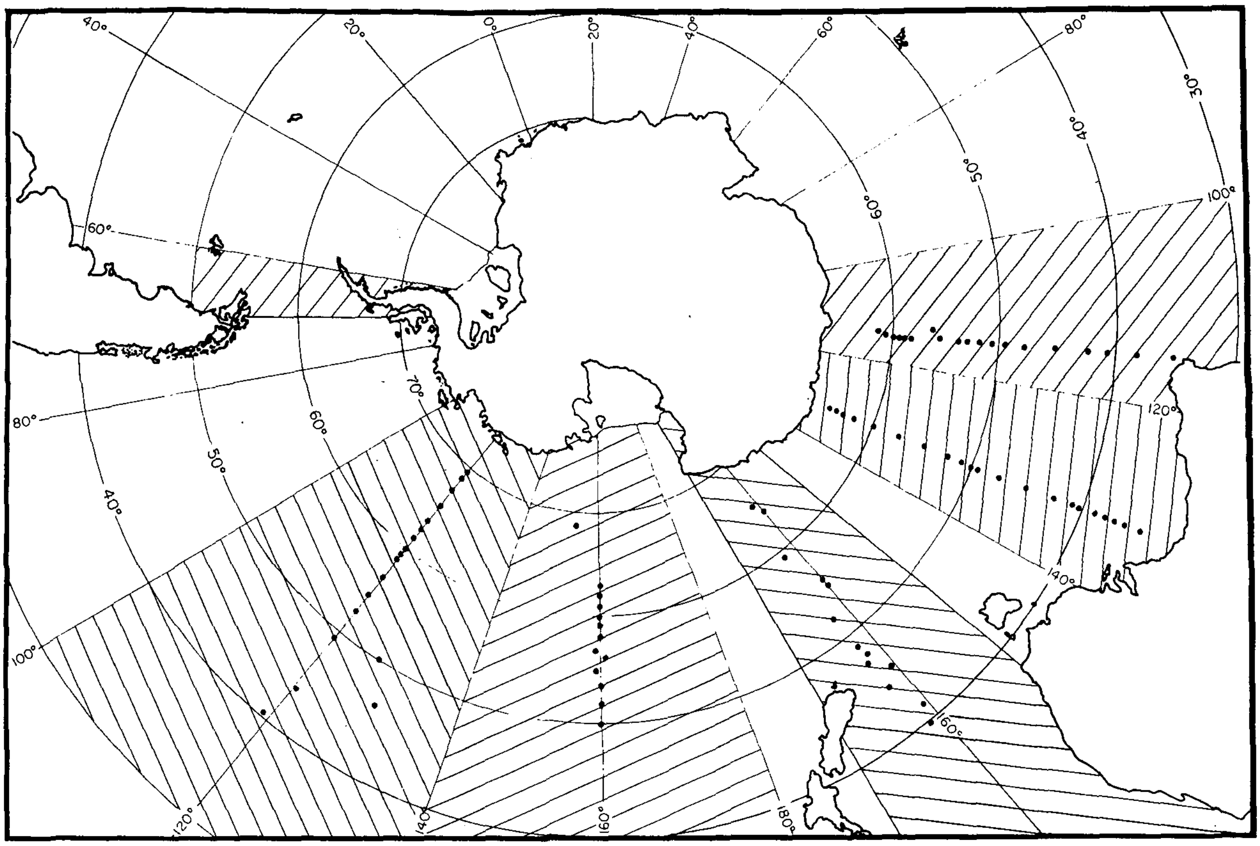

FIG. 1. Locations of hydrographic stations (dots) and XBT data used in this study; cross-hatching indicates longitudes over which XBT data were averaged.

structure and by changes in the *T-S* relationships. Longitudinal and seasonal changes in this zone and its boundaries are discussed on the basis of six north-south sections between Australia and the Drake Passage.

2. Data

The historical XBT data were taken from the XBT data file of the National Oceanographic Data Center (NODC). These XBT data were used to form north-south temperature sections by averaging over various bands of longitude. The bands were chosen on the basis of available data and also to account for changes in bottom topography. For example, the large number of XBT observations south of Australia allowed a division into two sections while the sparse coverage in the southeastern Pacific prompted the use of a wider band in this sector. A total of six bands were selected (Fig. 1) and within these bands XBT observations were averaged over intervals of 1° of latitude for each of the four seasons. Due to the generally low data coverage in the Southern Ocean many of these sections were either blank or broken by large gaps. Other sections, however, were sufficiently well-covered to be contoured and it was possible to get at least a partial picture for summer and winter from each of the six sections.

To complement the XBT temperature sections hydrographic data from various *Eltanin* cruises were used to form temperature sections and *T-S* curves. The stations were chosen so as to constitute sections within the XBT bands (Fig. 1). All sections and *T-S* curves were restricted to the upper 500 m in order to be consistent with the mean XBT sections. In the discussion that follows both the XBT and hydrographic data will be identified by the longitude of the hydrographic section.

3. Temperature sections

a. 115°E

Temperatures from an October hydrographic section in this sector (Fig. 2) display a strong horizontal temperature gradient between 47° and 49°S. This temperature gradient, which is located at the same latitude in the average XBT section (Fig. 3), is typical of the Australasian Subantarctic Front discussed by Burling (1961), Gordon (1972) and others. This front is the southern limit of the particularly warm and saline Subantarctic water found in this sector of

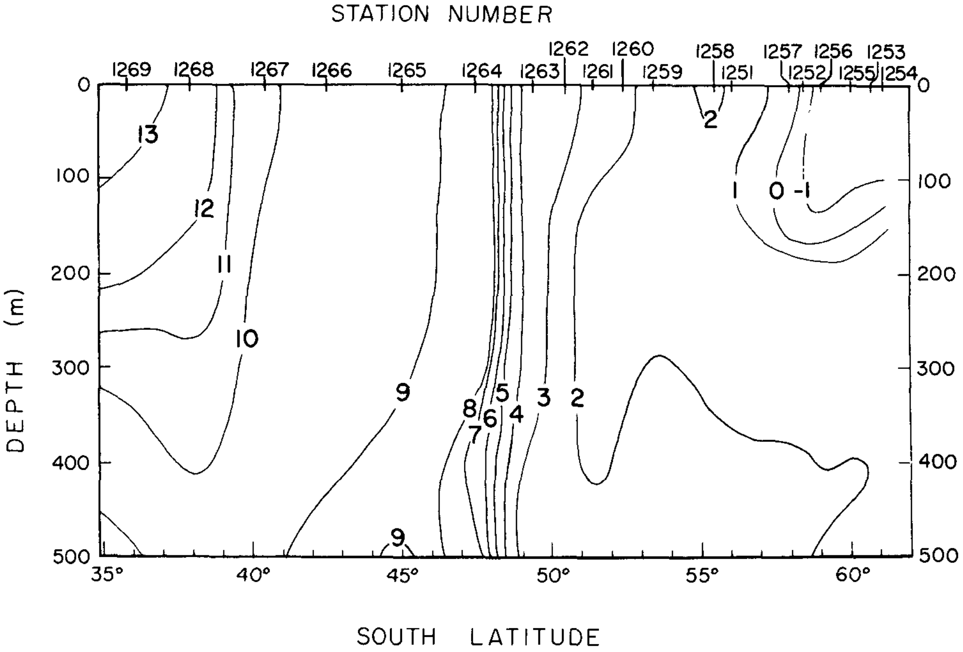

FIG. 2. Temperature section from hydrographic data along 115°E. All stations taken in October 1970.

the ACC. Farther south in both temperature sections the limit of the cold Antarctic Surface Water is marked by the 2°C isotherm which turns southward at depth. As will be shown later, typical summer temperature sections show the limit of the ASW as a temperature minimum cut off from the surface by heating.

The proximity of the limits of ASW and Australasian Subantarctic Water in both temperature sections suggests that the transition zone between these water masses in this sector is very narrow. In contrast to the spring picture of Figs. 2 and 3, the winter XBT section (Fig. 4) shows the limit of ASW shifted to the south and separated from the subantarctic boundary. This suggests that in this sector the APFZ is very narrow in the spring and widens in the winter. The narrowness of the APFZ in spring is also expressed by the *T-S* curves (Fig. 5) from the stations in Fig. 2. Here a single abrupt change between stations 1263 and 1264 indicates the strong discontinuity associated with the temperature gradient between these stations. Inflections of the *T-S* curves from stations 1262–1264, indicative of interleaving, suggest that the transition zone includes these stations.

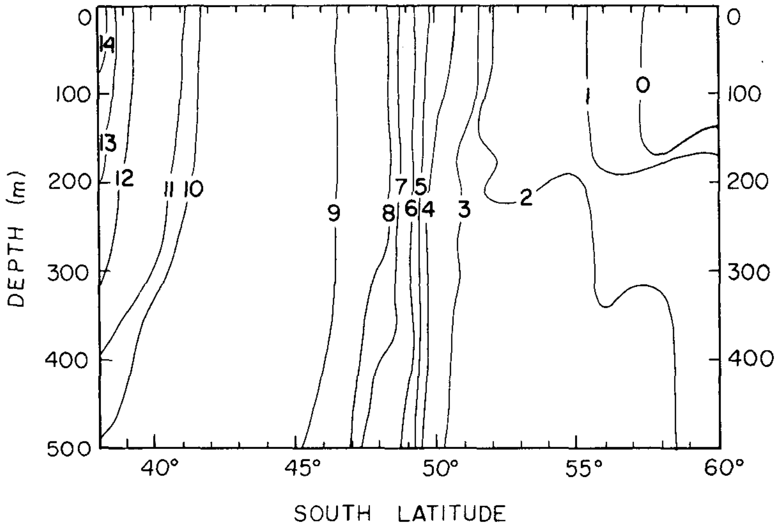

FIG. 3. Average XBT section about 115°E for September–November.

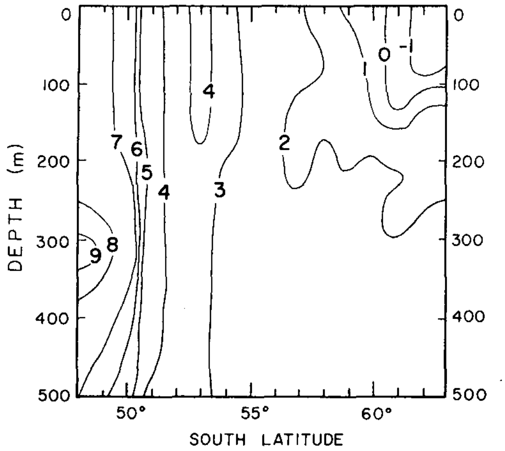

FIG. 4. Average XTB section about 115°E for June–August.

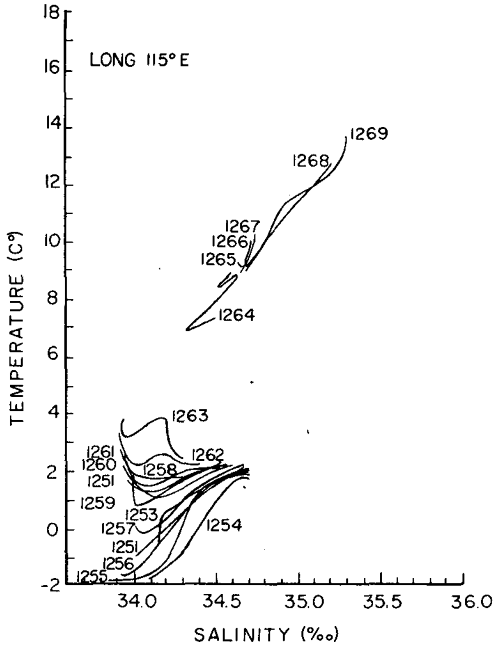

FIG. 5. Temperature-salinity curves for stations along 115°E. Only data between 0 and 500 m are used.

b. 132°E

The temperature section (Fig. 6) taken along 132°E by the *Eltanin* in the austral summer (December–January) of 1970 also indicates a strong subsurface temperature gradient between 47° and 49°S. Unlike spring section at 115°E the northern extent of ASW, marked by the subsurface temperature minimum, is well separated from the temperature gradient of the Subantarctic boundary. This separation is also suggested by the summer XBT section (Fig. 7) which unfortunately only extends north to 50°S. A spring XBT section (not shown) has the Subantarctic boundary at 49°S similar to Fig. 6. In both Figs. 6 and 7 the Antarctic boundary of the APFZ is at 55°S.

The *T-S* curves (Fig. 8) corresponding to the stations of Fig. 6 also indicate a fairly wide transition zone. A first break in the *T-S* curves between stations 12 and 13 represents the Antarctic boundary of the APFZ, while a second shift between 15 and 16 coincides with the Subantarctic boundary, which in this sector is the Australian Subantarctic Front. Between these breaks the *T-S* curves show interleaving and a transition from the colder, less-saline ASW to the warmer, saltier SSW of the Australasian sector. Burling (1961) and Houtman (1967) refer to

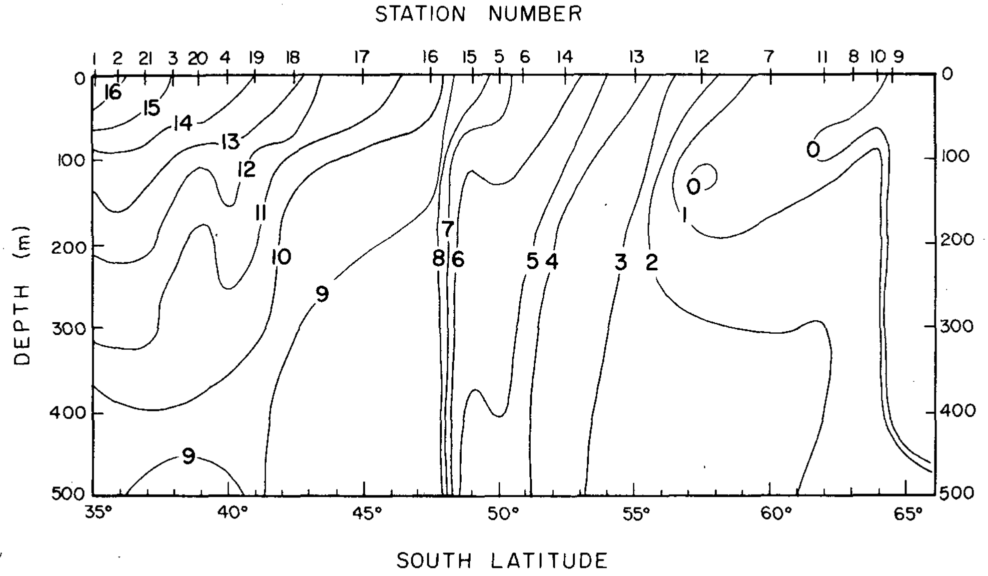

FIG. 6. Temperature section from hydrographic data along 132°E. Stations are from *Eltanin* cruise 41 taken during December and January of 1969–70.

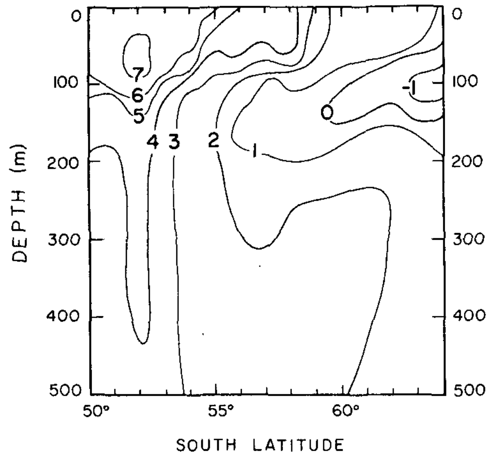

Fig. 7. Average XBT section about 132°E for December–February.

the water in this zone as Circumpolar Subantarctic Water.

An analysis of this same section by Callahan (1971) indicated two cores or jets of eastward velocity. The center of the southernmost core was located between stations 12 and 13, while the northern core was between stations 15 and 16. These cores coincide with the boundaries of the APFZ. A similar coincidence was found by Nowlin *et al.* (1977) in the Drake Passage. The Antarctic and Subantarctic boundaries of the APFZ, identified by changes in the *T-S* curves, were located at cores of relative zonal velocity. Most sections showed three such cores, two associated with the boundaries of the APFZ and the third corresponding to the boundary of shelf water as discussed by Gordon *et al.* (1977). One section, however, contained four velocity cores which might be explained by the crossing of a meander of one of the boundaries of the APFZ. From surface dynamic topography relative

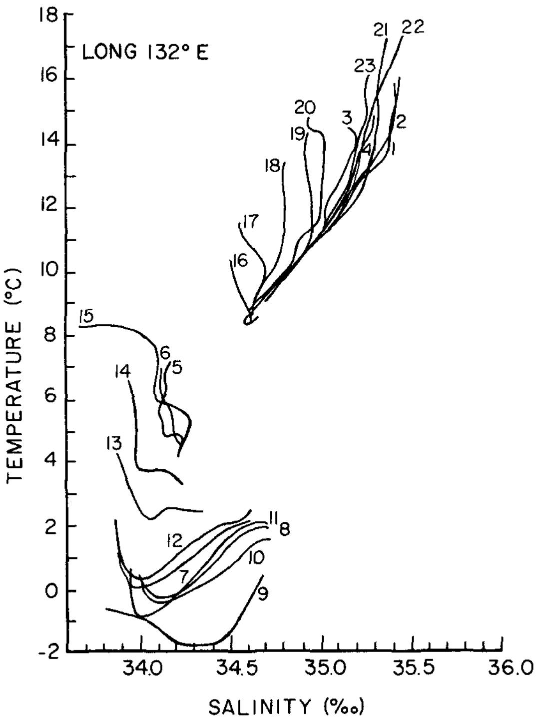

Fig. 8. As in Fig. 5 except for stations along 132°E.

to 1000 db Gordon *et al.* (1977) also suggest that the axes of flow of the ACC track along the boundaries of the APFZ.

In this sector (132°E) a winter XBT section (Fig. 9) demonstrates the dramatic seasonal changes in the Southern Ocean. In winter there is no subsurface temperature minimum and ASW has its northern limit at the surface. North of this limit the subsurface temperature maximum stops and the isotherms appear vertical from 0 to 500 m. In summer (Fig. 7) heating

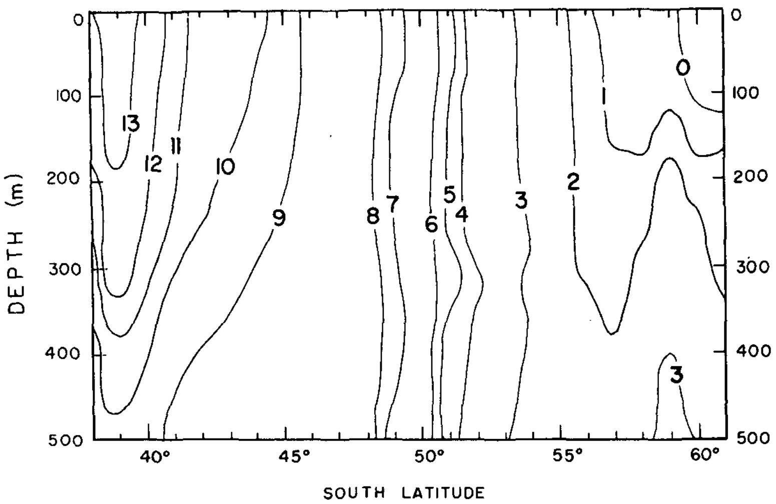

Fig. 9. Averaged XBT section about 132°E for June–August.

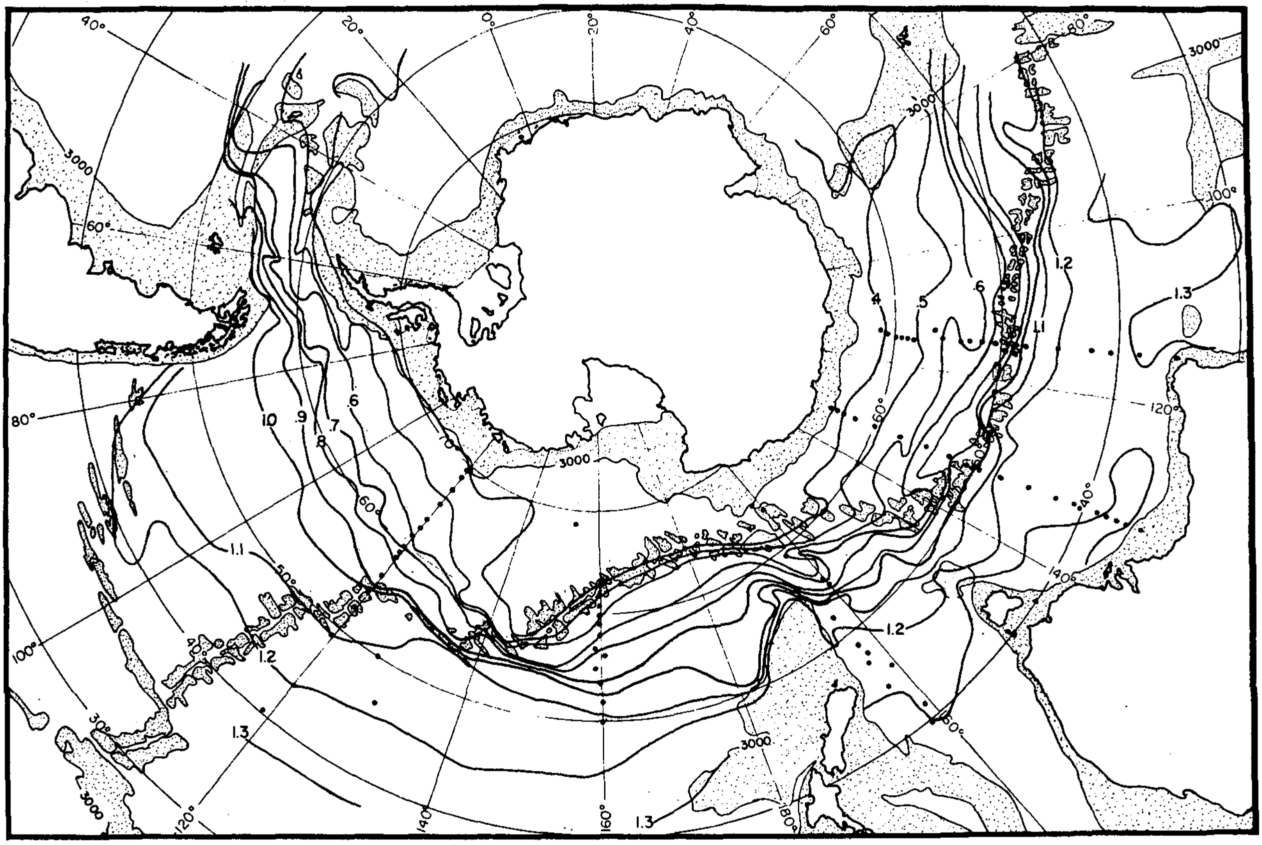

FIG. 10. Dynamic topography 0/1000 db (dyn m), and the 3000 m bottom contour (from Gordon and Molinelli, 1975).

cuts off the cold Antarctic Water from the surface creating the subsurface temperature minimum. This temperature minimum layer is often referred to as "winter water" (Mosby, 1966). It is interesting to note that in both summer and winter the northern extent of ASW is at the same latitude. Thus the southern or Antarctic boundary of the APFZ does not position seasonally as it did in the previous sector.

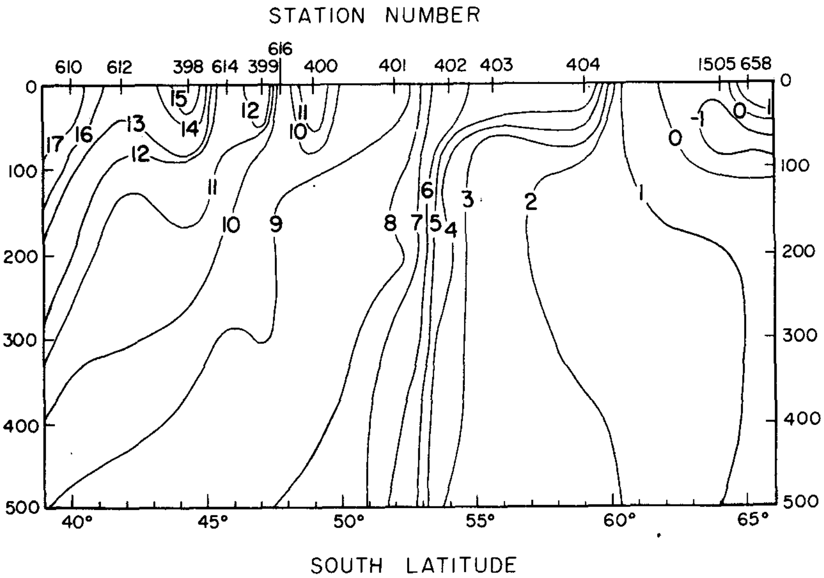

FIG. 11. Temperature section from hydrographic data along 160°E. Stations from December–February of different years.

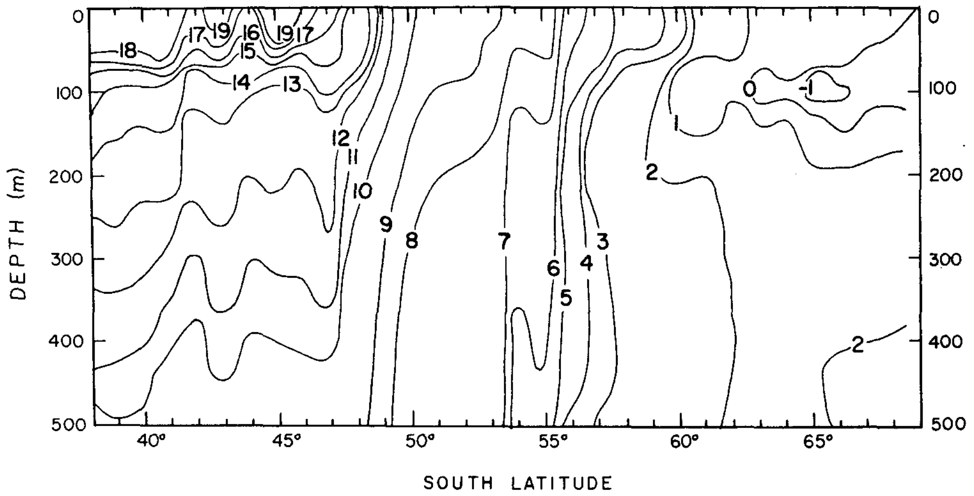

Fig. 12. Average XBT section about 160°E for December–February.

c. 160°E

In this sector, west of the Macquarie Ridge, the ACC and the related APFZ turn south due to topographic restrictions (Fig. 10). An XBT section averaged over this region of strong north-south change will not represent well a temperature section at any one longitude. This may explain the differences between the hydrographic temperature section (Fig. 11) and the corresponding average XBT section (Fig. 12). Both show a subsurface temperature gradient at the Subantarctic boundary of the APFZ separated from the Antarctic boundary at the temperature minimum. In the XBT section, however, these features are shifted to the south relative to their positions in the hydrographic section. It is interesting that both sections show a shift toward the south of the temperature gradient at 100 m.

Unfortunately, the wide station spacing in Fig. 11 makes it difficult to separate the southern water masses. Inflections in the *T-S* curves (Fig. 13) as far north as station 400 suggest the continued presence of the transition zone at this latitude. Such inflections do not appear in the *T-S* curves of stations 403 and 404 but these curves are substantially different than those farther south.

d. 160°W

The hydrographic temperature section (Fig. 14) in

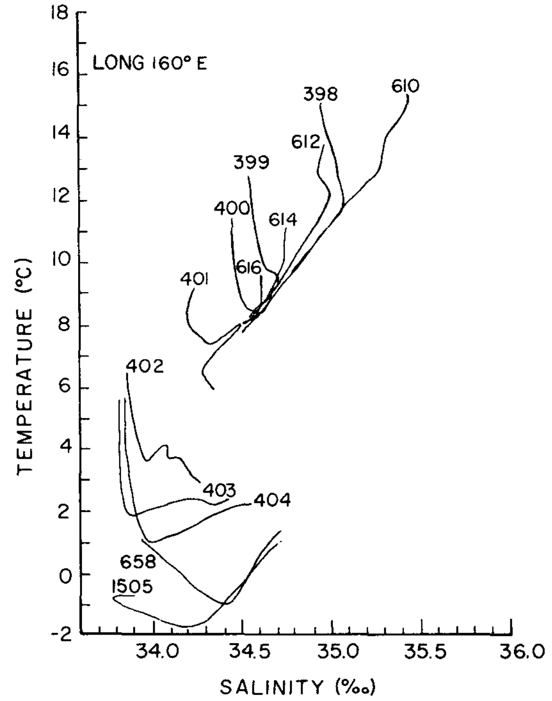

Fig. 13. As in Fig. 5 except for stations along 160°E.

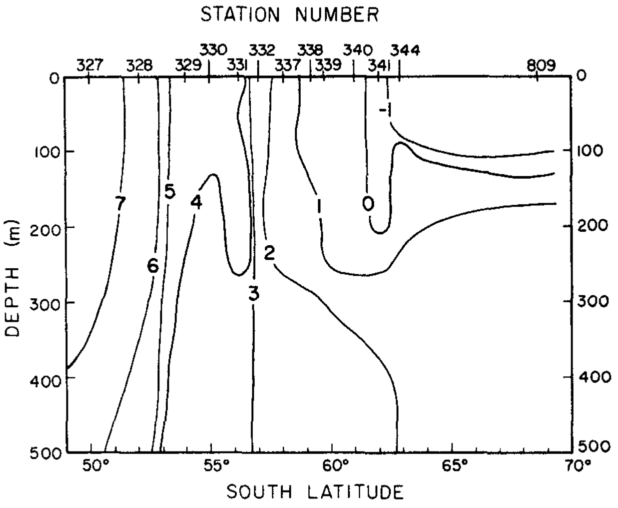

Fig. 14. Temperature section from hydrographic data along 160°W. Stations taken during August 1964.

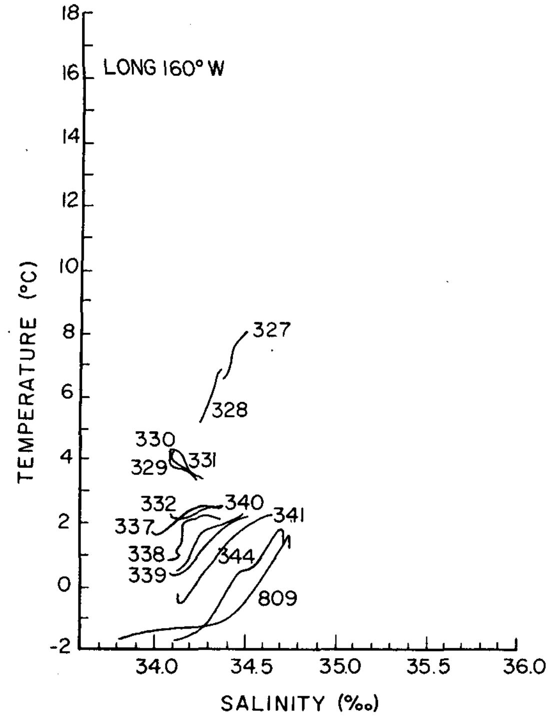

FIG. 15. As in Fig. 5 except for stations along 160°W.

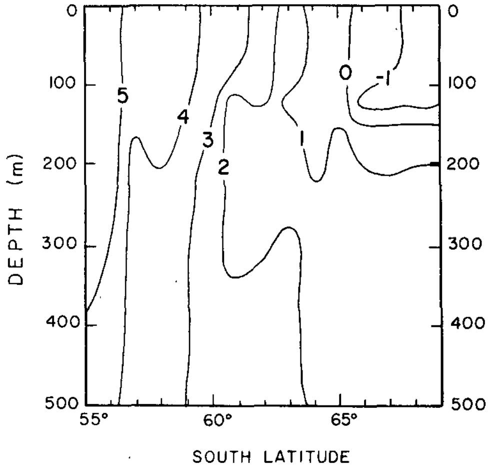

FIG. 16. Average XBT section about 160°W for March–May.

this sector is unusual in that the data were collected during the austral winter (August 1964). As in all winter sections the limit of ASW is at the surface underlain by a temperature maximum. The limit of SSW is marked to the north by a somewhat weaker subsurface temperature gradient between 4 and 6°C. The role of this gradient as a water mass boundary is clearly indicated by the *T-S* curves (Fig. 15) which change abruptly between stations 329 and 328. The northern stations (328, 327) indicate a Subantarctic water which is cooler and less saline than that found to the west in the Australasian sector. Topographic restrictions of New Zealand and the Macquarie Ridge limit the eastward extent of Australasian Subantarctic Water.

The tight group of *T-S* curves from stations 329–331 is part of the APFZ. Stations 332 and 337 may also be included in the transition zone. The lack of definition at the Antarctic boundary may be due to the unique character of this boundary in this sector where it has a strong surface temperature gradient just north of the ASW. The 4°C isotherm contributes to

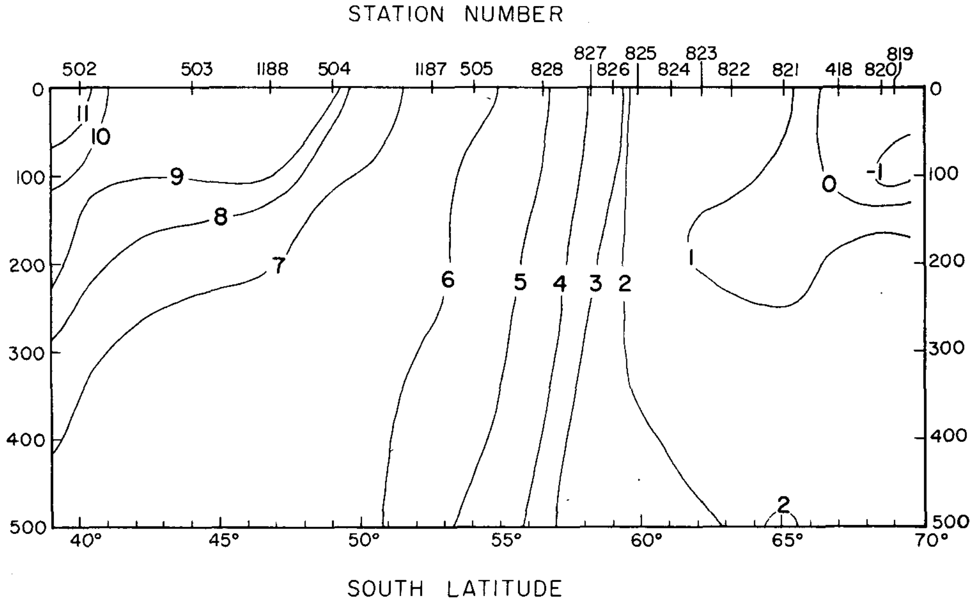

FIG. 17. Temperature section from hydrographic data along 120°W. Stations taken from November to April of various years.

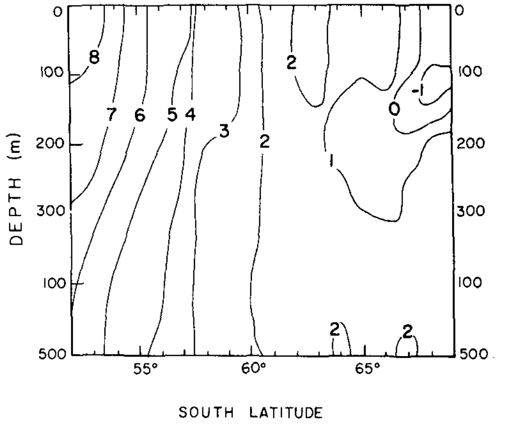

Fig. 18. Average XBT section about 120°W for March–May.

this gradient and then shifts north to the Subantarctic boundary at 200 m (Fig. 14). Such a shift of the 4°C isotherm is also a feature of the average XBT section (Fig. 16). As in the previous sector the isotherms of the XBT section are shifted to the south relative to the hydrographic section. This may again be due to zonal averaging over a region of strong north-south changes or to the non-winter conditions of the fall XBT section (Fig. 16).

e. 120°W

Hydrographic observations from December to May were combined to make up the temperature section in Fig. 17. Despite the inclusion of summer data Antarctic Surface Water has its northern limit at the surface. A subsurface temperature minimum is evidenced farther south by the 1°C isotherm. These same features can also be found in the fall XBT section (Fig. 18) for this sector. In both of these sections the temperature gradient of the Subantarctic boundary is very weak. In fact without the analogy of the previous sectors a northern or Subantarctic boundary could not be identified. The diffuse character of this boundary is also indicated by the *T-S* curves (Fig. 19) from the hydrographic stations in Fig. 17. The curves do not show a distinct break but transition smoothly to the warm Subantarctic water in this sector. The presence of the APFZ is revealed by the interleaving

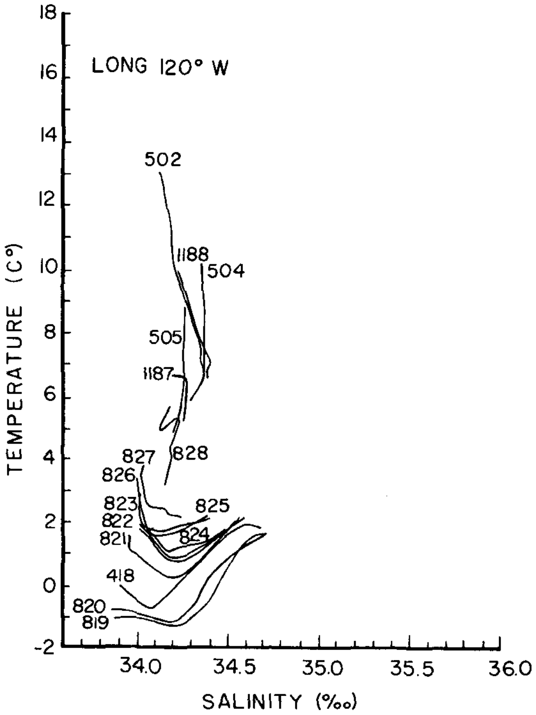

Fig. 19. As in Fig. 5 except for stations along 120°W.

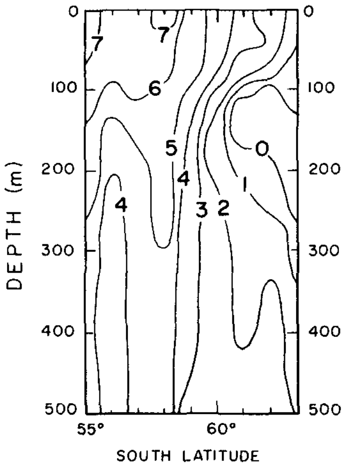

Fig. 20. Average XBT section in the Drake Passage for December–February.

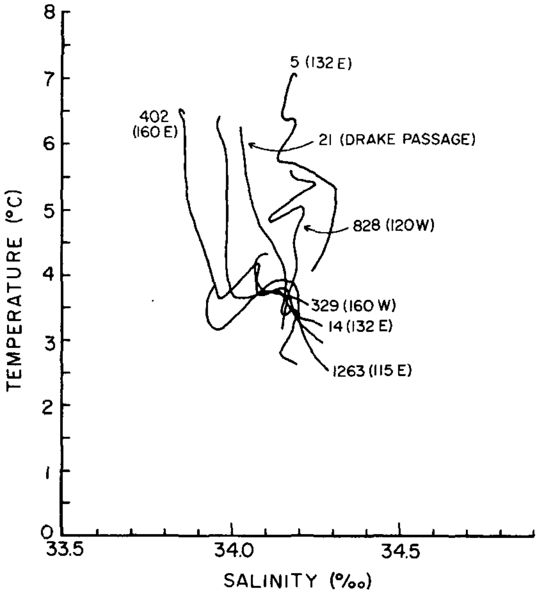

Fig. 21. Temperature-salinity curves in the Polar Frontal Zone from all sections.

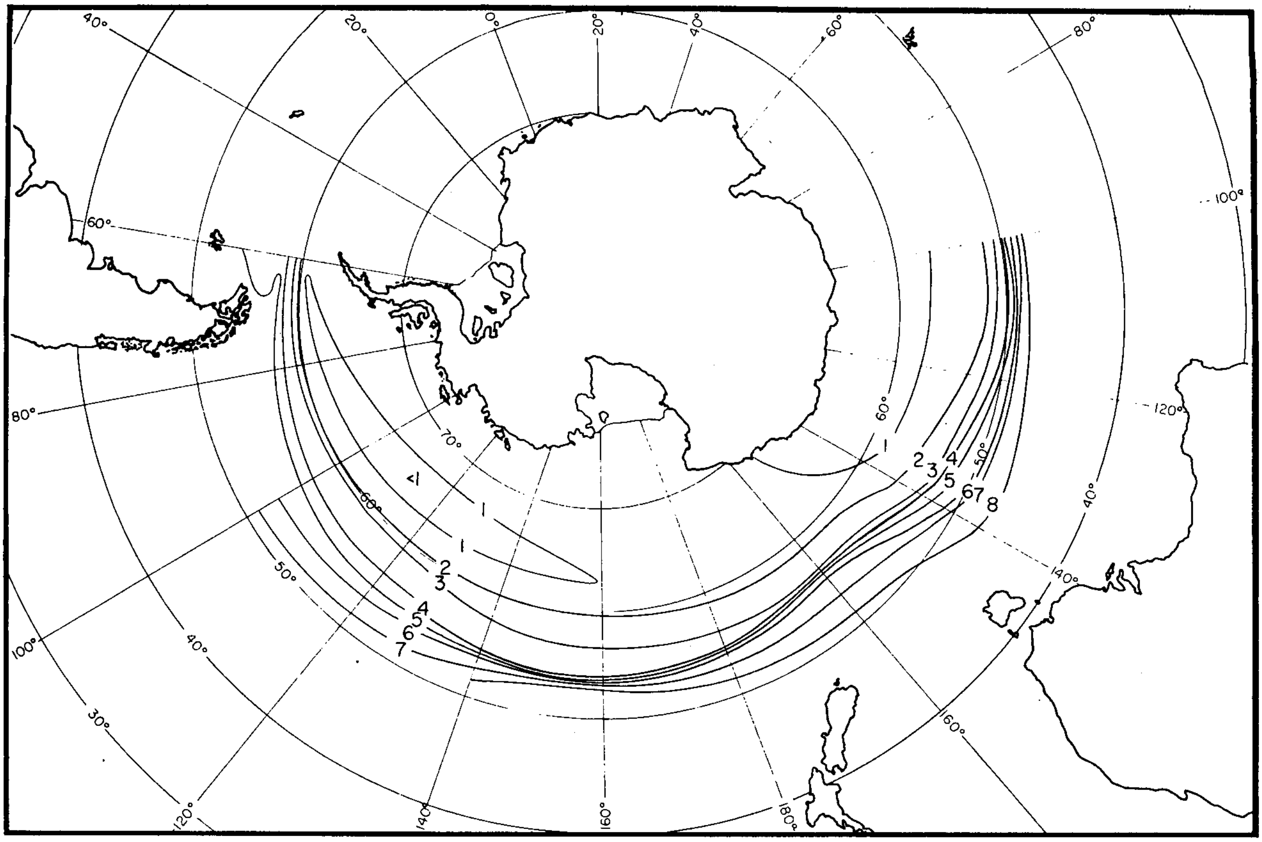

FIG. 22. Temperature at 200 m in winter from average XBT sections.

expressed in the *T-S* curves from stations 828 and 827. The lack of a distinct Subantarctic boundary of the APFZ may be explained by the absence of topographic restrictions to the north. In all the sectors considered thus far the ACC is restricted to the north by either land masses or bottom topography (Fig. 10). These restrictions cause the flow of the ACC to be concentrated in jets located at the boundaries of the APFZ. In the southeast Pacific, where no northern restriction is present, the jets spread out as does the thermal structure associated with it. Hence the transition zone (APFZ) still exists but without the clear-cut boundaries found in other sectors.

4. The Drake Passage

As has been discussed, recent hydrographic data from the Drake Passage have been used by Nowlin *et al.* (1977) to define three water mass zones across the Passage. The APFZ, identified by interleaving in the *T-S* curves, was found to be bordered to the north and south by jets of zonal current. In one section the northernmost velocity jet was located where the 3 and 4°C isotherms turn sharply downward just north of 58°S. In the average XBT section for summer (Fig. 20) this downward turn appears where the 3 and 4°C isotherms become vertical north of 59°S. A narrow APFZ is suggested by the adjacent subsurface temperature minimum indicative of ASW. The *T-S* curves of Nowlin *et al.* (1977), however, indicate that the transition waters of the APFZ extend south to the limit of the 1°C isotherm. It is important to note that the section from which the *T-S* curves were taken is unique in that it shows velocity jets both at the northernmost expression of the subsurface minimum (2°C) and also at the 1°C isotherm. Another section shows only the jet located at the northern limit of the temperature minimum. As was suggested earlier the unique case of four velocity jets might be explained by a meander of a boundary, in this case the southern or Antarctic boundary.

5. Discussion

Earlier investigators have identified the APFZ in the sectors south of Australia (Gordon *et al.*, 1974), the Drake Passage (Nowlin *et al.*, 1977) and the western Scotia Sea (Gordon *et al.*, 1977). In the present study the character of the APFZ was reviewed using individual and composite or averaged temperature sections. The good correspondence between features in the averaged XBT sections and the individual hydrographic sections indicates that these features, such as the boundaries of the APFZ, are quasi-permanent features and should be present in all temperature sections.

The identification of the APFZ in all of the sections studied suggests that the zone is continuous from Australia to the Drake Passage. A plot of *T-S* curves in the APFZ from the different sectors (Fig. 21) supports this suggestion. The tight intersection of these curves at 3.5°C and 34.2‰, compared to the spread of *T-S* curves in a north-south section, indicates the presence of the same water type in all sectors. The *T-S* curves all show the characteristic inflections of the APFZ caused by the interleaving of ASW and SSW.

Although the APFZ was found to be continuous over the region of study the boundaries of the zone were found to change both with longitude and with season. These changes can be represented by the distribution of temperature at 200 m for summer and winter drawn from the averaged XBT sections (Figs. 22, 23). At the western end of the region studied the seasonal change in the width of the APFZ is demonstrated by the southward displacement of the 2 and 3°C isotherms in winter. The 3°C isotherm exhibits a marked seasonal fluctuation at all longitudes being northernmost in the west and southernmost in the east in summer, changing to northernmost in the east and southernmost in the west in winter. A seasonal shift of the isotherms at 120°W is also observed, with the isotherms being farther north in summer.

The isotherms at 200 m also demonstrate the downstream changes in the northern or Subantarctic boundary of the APFZ. In the topographically restricted sectors from 100°E to 140°W there is always a strong temperature gradient at the northern edge of the APFZ. Farther east the isotherms spread out and the temperature gradient of the Subantarctic boundary is lost. If sufficient XBT data were available it would be interesting to see if this spreading also occurs in the open regions of the southeast Atlantic and Indian Oceans.

As was mentioned earlier the spreading of the isotherms is likely associated with the weakening of the northern velocity jet at the Subantarctic limit of the APFZ. The behavior of the southern jet cannot be easily evaluated since it is not tied to a temperature gradient. It is probable that this velocity jet also weakens in sectors not constrained to the north.

The velocity structure between these two jets, within the APFZ, is highly variable. As is suggested by Gordon *et al.* (1977) the division of the Polar Front into primary and secondary fronts (Gordon, 1967,

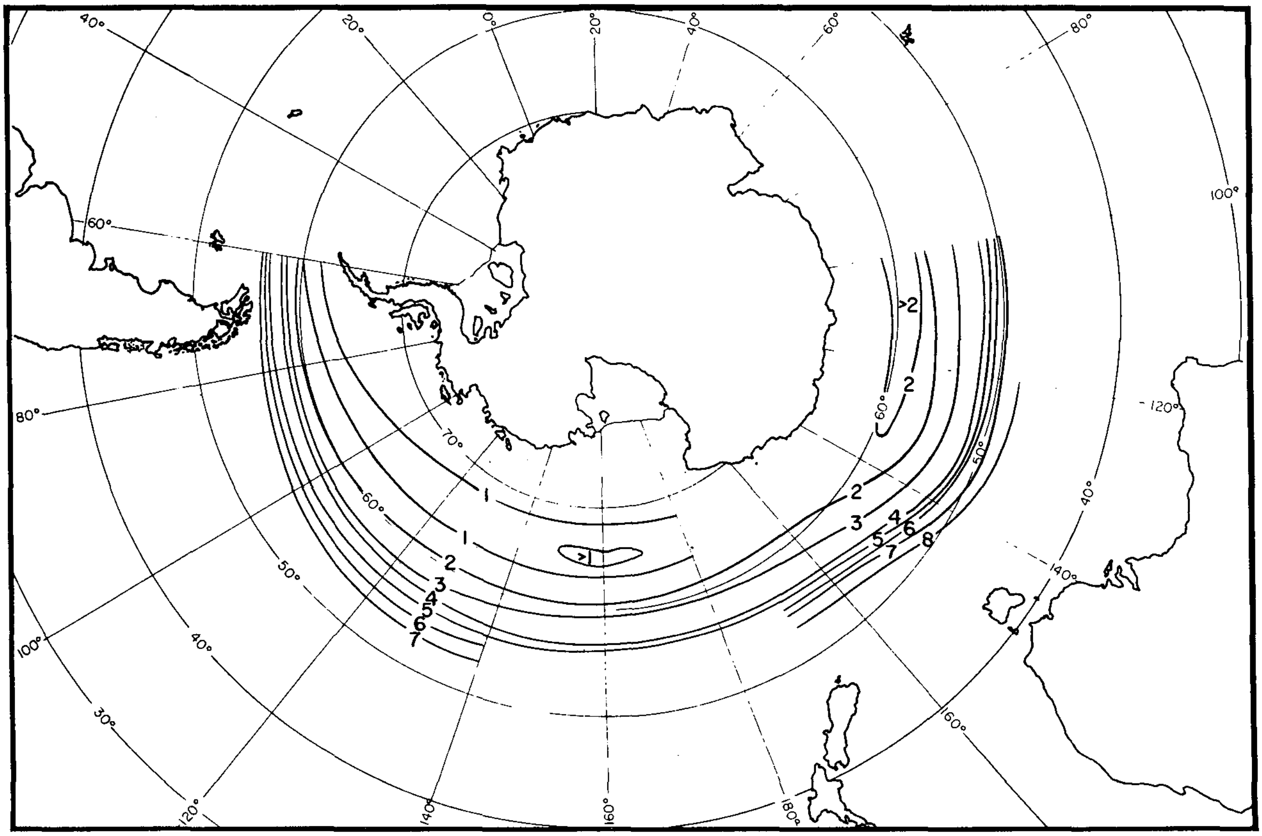

FIG. 23. As in Fig. 22 except in summer.

1971) may be explained in part by meanders of the Antarctic boundary of the APFZ forming rings as was observed by Joyce and Patterson (1977). The stretching of the primary front may be the baroclinic adjustment of features that were formed in the south and moved north. Eddies and rings have also been observed at the northern or Subantarctic boundary of the APFZ. Nowlin (personal communication) observed an eddy at the northern side of the Drake Passage. South of Australia Emery and Savchenko (1977) surveyed a ring at the southern edge of the Australasian Subantarctic Front which appeared to be part of a meander of the front. Repeated XBT sections across the APFZ along 132°E revealed a complex thermal structure of large vertical isotherm displacements. Rapid changes on time scales of a few days were observed within the APFZ while the north-south boundaries of the zone remained fixed in position.

6. Conclusions

A transition zone, called the Antarctic Polar Frontal Zone (APFZ), between Antarctic and Subantarctic Surface Waters is a feature of all six sections studied. The zone and its boundaries change from west to east between Australia and the Drake Passage. Winter-summer seasonal changes take place in both the size of this zone and the nature of its boundaries. These boundaries can be identified in averaged XBT sections as well as in temperature sections from hydrographic data, which indicates the permanence of the APFZ as a feature of the ACC. The southern boundary of this zone corresponds to the northern extent of the winter water, often expressed by a subsurface temperature minimum, and might be called the Antarctic Front. Winter and summer averaged XBT sections clearly show the formation of this winter water and its subsurface temperature minimum. The northern boundary of the APFZ usually appears as a strong temperature gradient as found at the Australasian Subantarctic Front; hence the general name Subantarctic Front is proposed. These boundaries are associated with jets of eastward flow within the Antarctic Circumpolar Current. Between these jets the Antarctic Polar Frontal Zone is likely populated with rings, meanders and other transient circulation features.

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