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Hydrography and circulation off the Antarctica in the Indian Ocean region

G S SHARMA AND BASIL MATHEW*

School of Marine Sciences, University of Cochin, Cochin 682 016, India

*Present address: Naval Physical and Oceanographic Laboratory, Cochin 682 004, India

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Abstract. The hydrography and circulation pattern off Antarctica in the Indian Ocean region are studied using vertical sections of temperature, salinity and oxyty approximately along 20°E, 77°E and 90°E, and the dynamic topography of the sea surface with reference to 1000 db. Based on the oceanographic characteristics, the whole region under study can be divided into three zones, the extreme ends being characterised by the frontal structure. The dicothermal layer is conspicuous during summer south of 50°S. The surface flow around Antarctica is mainly zonal. The East Wind Drift, found as a narrow westward flow near Antarctica, is observed at a lower latitude in the eastern Indian Ocean where the land extends northword. Contrary to expectation there is evidence of a westward flowing surface current at about 35°S between 45°E and 65°E.

Keywords. Hydrography; circulation pattern; Antarctica; Indian Ocean; meridional section.

1. Introduction

The poles and the neighbouring oceanic regions act as the sinks of the heat budget of the oceans and atmosphere. The oceanic and atmospheric circulations, to a large extent, depend on the conditions in these regions. Hence, it is imperative to know the conditions of the polar regions to understand the oceanic and atmospheric circulations.

Of the two poles, the south pole plays a major role as it is connected with the three major oceans of the world while the north pole has no connection with the Indian Ocean. Due to this land-locked nature on its northern boundary, the oceanic circulation in the North Indian Ocean and the atmospheric circulation over the intertropical Indian Ocean deviate very much from those of the other two major oceans. Further, 45% of the coastline of Antarctica is bounded by floating glacial ice sheets known as ice shelves. Thus, an understanding of their effect on the surrounding ocean seems to be necessary for establishing mass and heat balances for the waters around Antarctica.

In view of the significance of the Antarctic region in controlling the oceanic and atmospheric circulation, concentrated efforts have been made to study this region during the last decade. Most of these efforts are concerned with the oceanography off Antarctica in the regions of the Pacific and Atlantic.

Our basic understanding about the physical oceanography of the southern oceans came mainly from the German south polar expedition 1901–1902 (Meinardus 1923), R.R.S. Discovery II Cruise (Deacon 1933, 1937; Mackintosh 1946), Norwegian Antarctica Expedition 1927–1928 (Mosby 1934) and B.A.N.Z. Antarctica Research Expedition 1921–1931 (Sverdrup 1940). Further knowledge was gained through subsequent studies (Gordon 1967, 1971a, b, 1972, 1975, 1978, 1981; Gordon and Tchernia 1972; Gordon *et al* 1977a, b, 1978; Houtman 1964; Heath *et al* 1978; Georgi 1978, 1979, 1981; Emery 1977; Ivanov 1961; Jacobs and Georgi 1977; Joyce *et al* 1978, 1981; McGinnes 1974; Molinelli 1981; Nowlin *et al* 1977; Sciremammano 1979; Sievers and Emery 1978; Whitworth 1980). All these investigations, with the exception of a few, were confined to the regions in the Atlantic and Pacific, and very little is known about the hydrography off Antarctica in the Indian Ocean region. An attempt was therefore made to study the hydrography of the region and the circulation pattern using the oceanographic data already available.

2. Materials and methods

The oceanographic data for the present study came from 283 stations covered by various vessels. The details are given in table 1 and the station positions are shown in figure 1. Stations encircled are used for vertical sections.

The *in situ* temperature at times instead of decreasing increases with depth, particularly in the deeper layers displaying an apparent instability due to pressure effect. To avoid ambiguity the potential temperature is computed using the nomogram prepared by Montgomery and Pollak from Helland-Hansen's formula (Helland-Hansen 1930).

Three meridional sections of potential temperature, salinity and oxyty are presented in figures 2a, b, c to 4a, b, c approximately along 20°E, 77°E and 90° respectively, to study the hydrography off Antarctica in Indian Ocean. The vertical gradients of the hydrographic properties in the upper layers are very strong while they are weak in the deeper layers. Therefore the depth scale is exaggerated in the upper 400 m compared to that below.

Table 1. List of stations used for the present study (figure 1)

Name of the Vessel	Symbol used	No. of stations	Period
OB	⊙	20	4 March 1956 to 28 May 1956
OB	⊙	105	14 Jan. 1957 to 19 April 1957
Umitaka Maru	+	16	12 Dec. 1956 to 6 March 1957
Africana	□	19	3 July 1961 to 15 July 1961
Africana	□	13	2 June 1962 to 11 July 1962
Africana	□	7	7 April 1963 to 13 April 1963
Argo	×	5	2 Nov. 1962 to 16 Dec. 1962
Fuji	●	8	19 Dec. 1965 to 21 Feb. 1966
Fuji	●	10	25 Dec. 1973 to 24 Feb. 1974
Fuji	●	3	24 Dec. 1974 to 25 Feb. 1975
Akademic Shirshov	▽	24	21 Nov. 1970 to 6 Dec. 1970
Akademic Shirshov	▽	9	3 July 1970 to 9 July 1970
Fusakaze	▲	8	24 Dec. 1971 to 6 April 1972
Eltanin	◬	7	28 Feb. 1971 to 15 March 1971
Eltanin	◬	6	24 July 1971 to 3 Aug. 1971
Eltanin	◬	13	18 Sept. 1971 to 7 Oct. 1971
Eltanin	◬	10	27 June 1972 to 6 July 1971

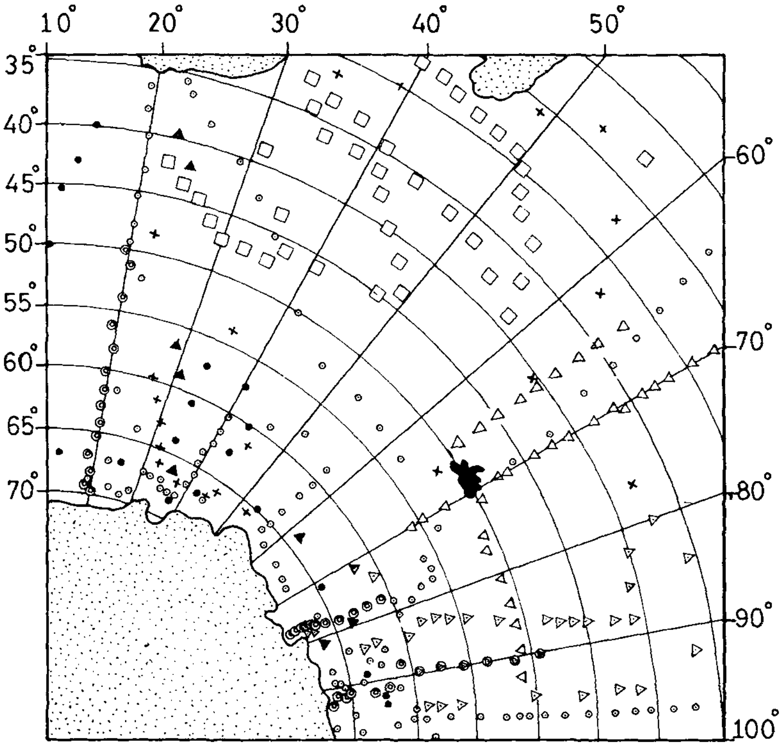

Figure 1. Station positions as in table 1.

To study the circulation at the surface and subsurface at the depths of 100 and 200 m, dynamic topographic charts with reference to 1000 db surface have been worked out. On examination, the circulation pattern at all these levels is similar except that the horizontal gradients of dynamic height are weak at subsurface depths. Therefore, only the surface circulation through dynamic height is presented in figure 5.

Deacon (1982) critically discussed the nomenclature used for different zones in the southern oceans and it is obvious that there is diversity in the nomenclature. The intention of this paper is not to go into those details but to adopt our own nomenclature.

3. Distribution of hydrographic properties

3.1 *Meridional section along* 20°E

The distribution of temperature is conspicuously divided into three zones in this section. The southernmost and northernmost regions are marked by meridional temperature gradients. The central zone is conspicuous in its vertical temperature gradients in the upper 200 m. The southernmost region, south of 68°S is termed the Polar Front Zone while the region north of 54° is the Sub-Antarctic Convergence Zone

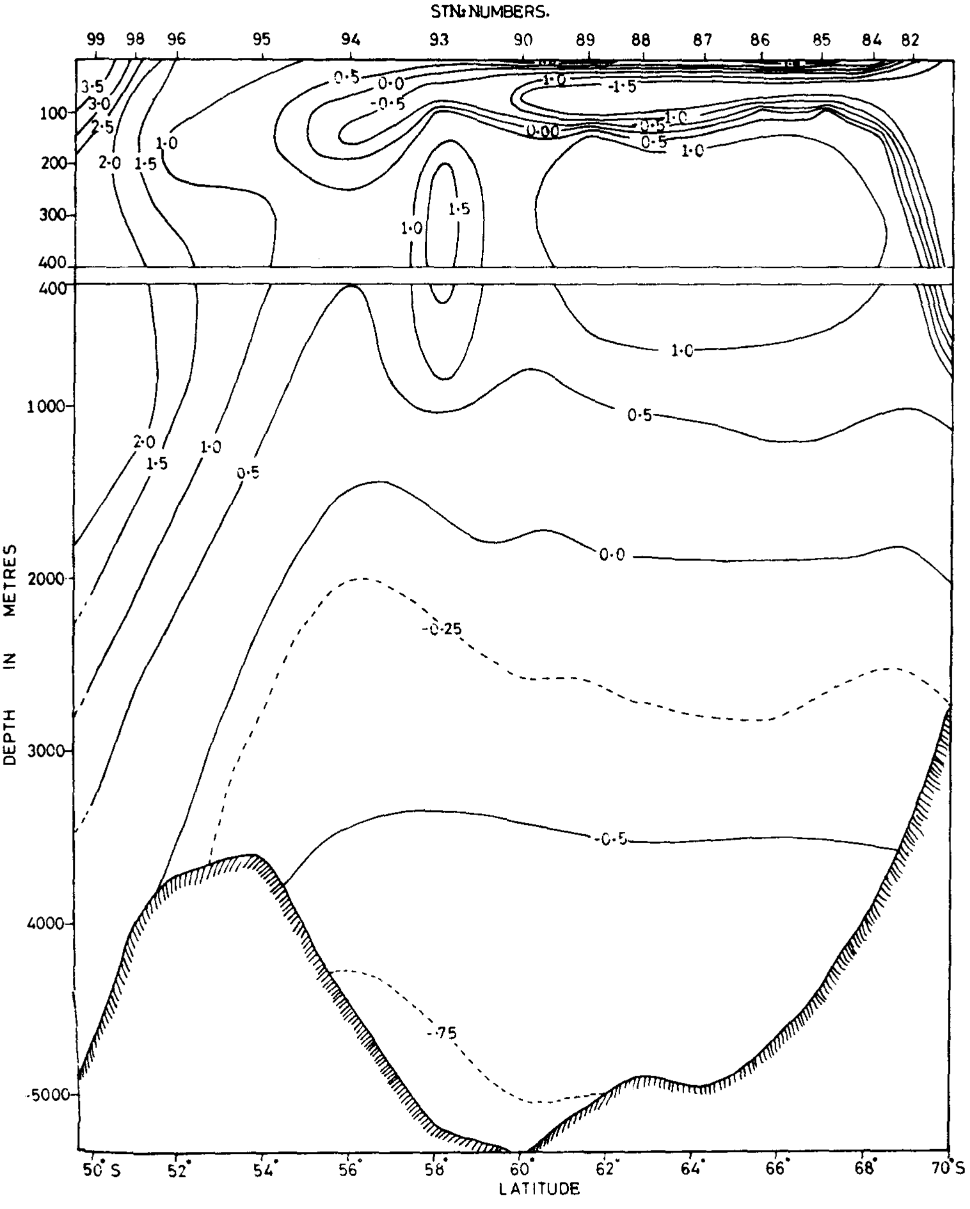

Figure 2(a). Vertical section of potential temperature (°C) approximately along 20°E.

(Polar Front according to Deacon 1982), characterised by frontal structure. While the surface temperature between 52°S and 68°S ranges from 0·64 to 1·49°C only, the temperature difference in both the frontal zones over a horizontal distance of about 2° latitude is more than 2°C.

The strong meridional gradient in the temperature in the Polar Front Zone appears to be the consequence of the boundary between the East and West Wind drifts. Within

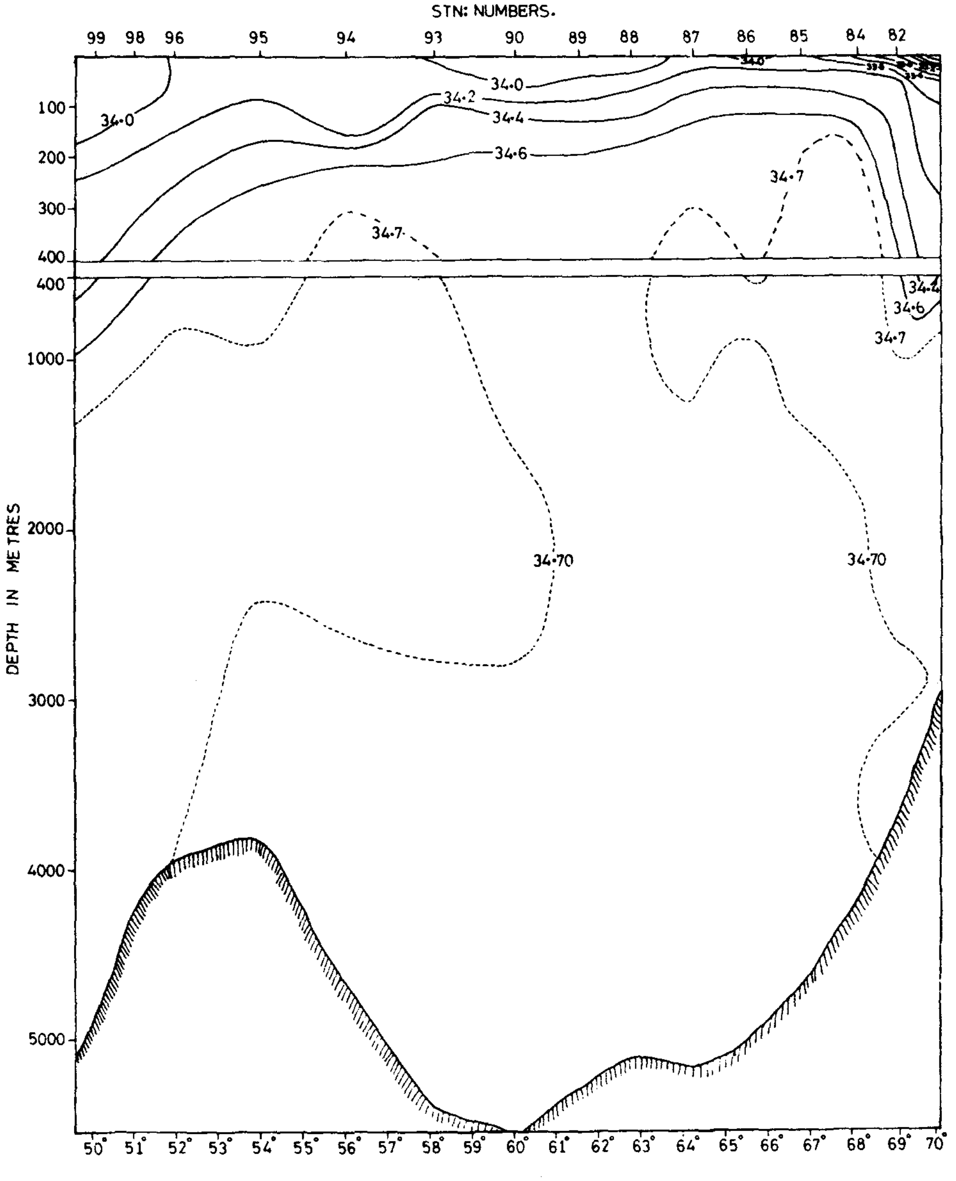

Figure 2(b). Vertical section of salinity (‰) approximately along 20°E.

the Polar Front Zone the orientation of isotherms, isohalines and isolines of oxyty is almost similar and they indicate the gliding of the subsurface water to deeper layers accompanied by the sliding of the Antarctic Water at the surface. In the central region the temperature decreases with depth attaining the lowest and then increases. From south to north within this zone, the subsurface temperature minimum deepens, decreases in magnitude and finally terminate at about 54°S.

Inversion below the temperature minimum layer indicates an apparent instability

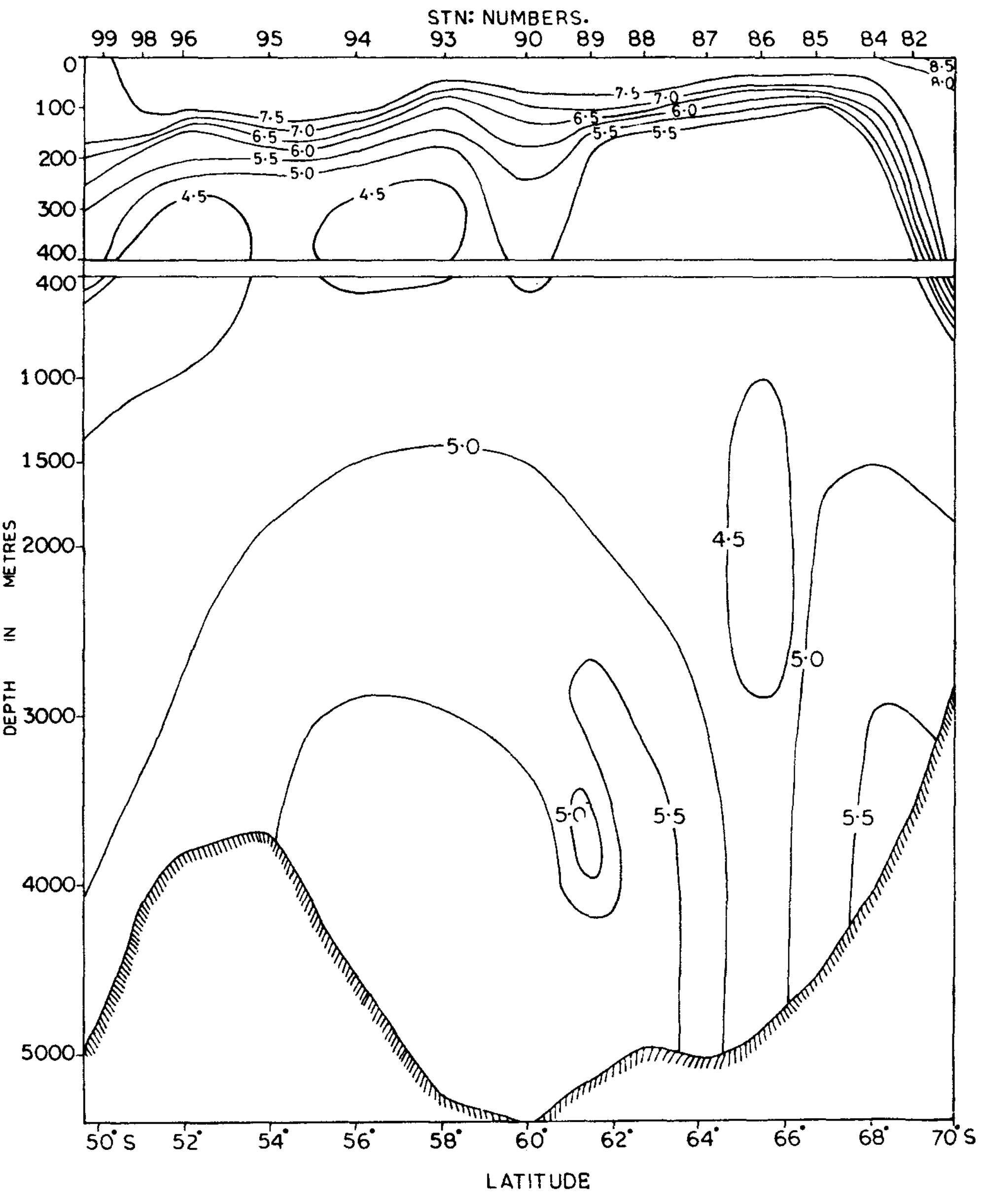

Figure 2(c). Vertical section of oxyty (ml/l) approximately along 20°E.

but the effect of the temperature is overcompensated by the increase in salinity to maintain the stability. The waters between 150 and 700 m record the highest temperature and it is associated with higher salinity and lower oxyty.

In the Antarctic Convergence Zone the meridional gradients extend almost to the bottom. The orientation of the isolines of the properties reveals the sinking of relatively cold surface waters from the south.

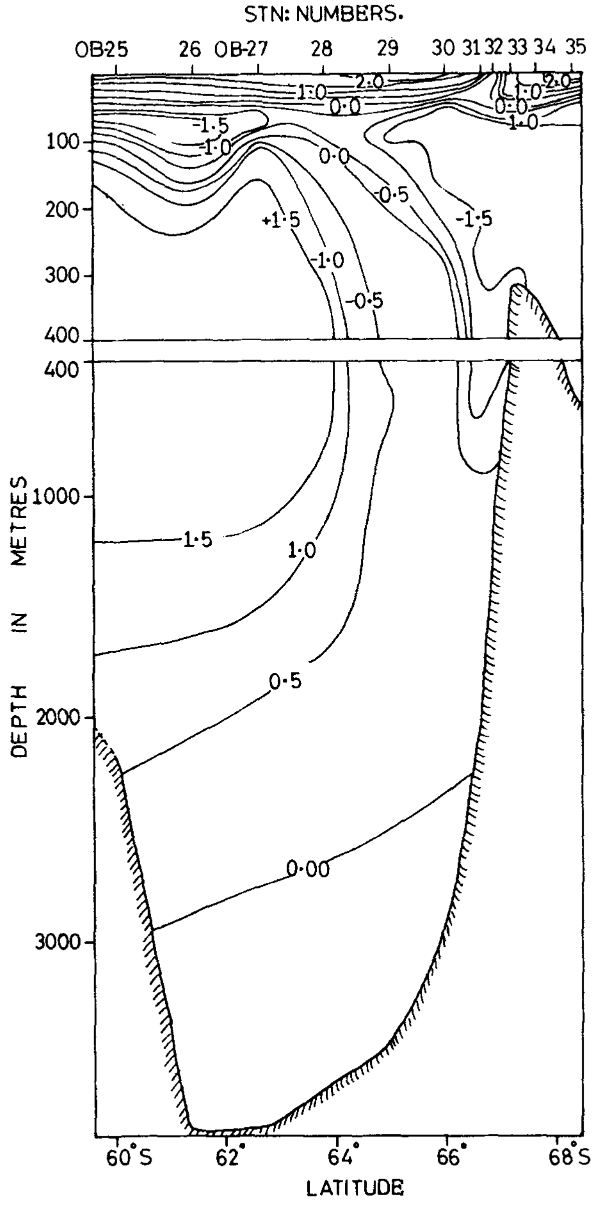

Figure 3(a). Vertical section of potential temperature (°C) approximately along 77°E.

3.2 *Meridional section along 77°E*

This section runs across 60°S to 68°19′S. The surface water between 60° and 65°S is almost isothermal south of which the temperature decreases meridionally upto 67°S and then increases. The highest temperature of 2·68°C recorded at the surface at the southernmost point may perhaps be due to continuous summer heating. The

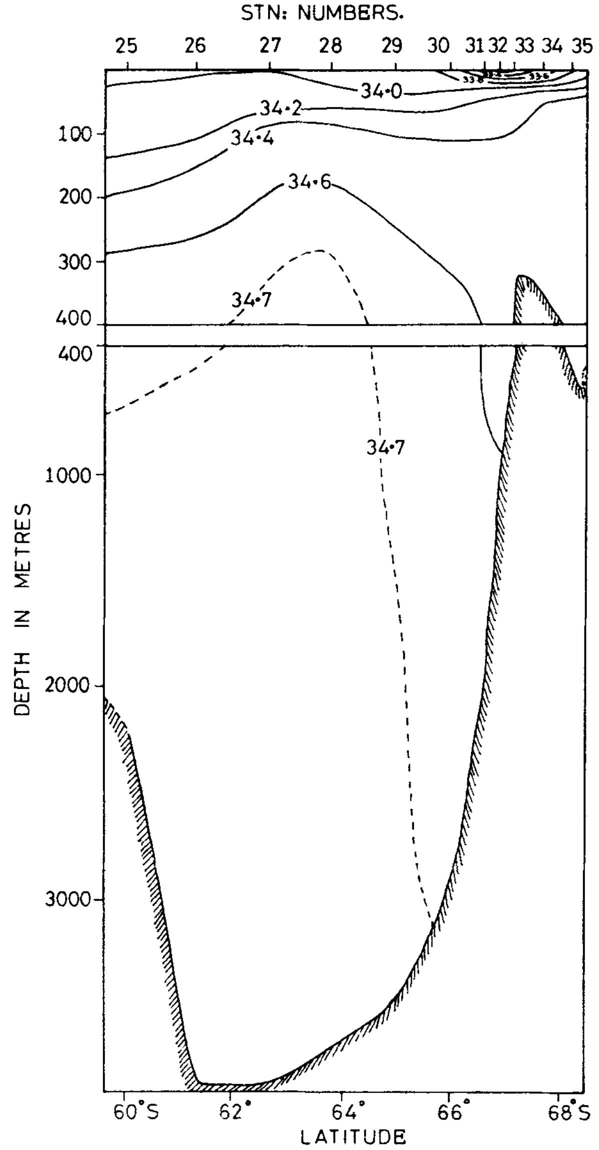

Figure 3(b). Vertical section of salinity ($^0/_{00}$) approximately along 77°E.

temperature minimum layer in the southern region of the section extends from about 50 m to more than 300 m. The lowest temperature recorded is in a basin in the slope of Antarctica. The coldest water is associated with relatively higher salinity and higher oxyty. This water seems to have been trapped in the basin during the previous winter. It is interesting to note that the orientation of the isolines of temperature and oxyty is almost symmetrical. The thickness of the colder water in the subsurface depths in the northern region is very small unlike in the south. The salinity distribution shows a continuous increase with depth upto the bottom whereas warm and low oxygen water is

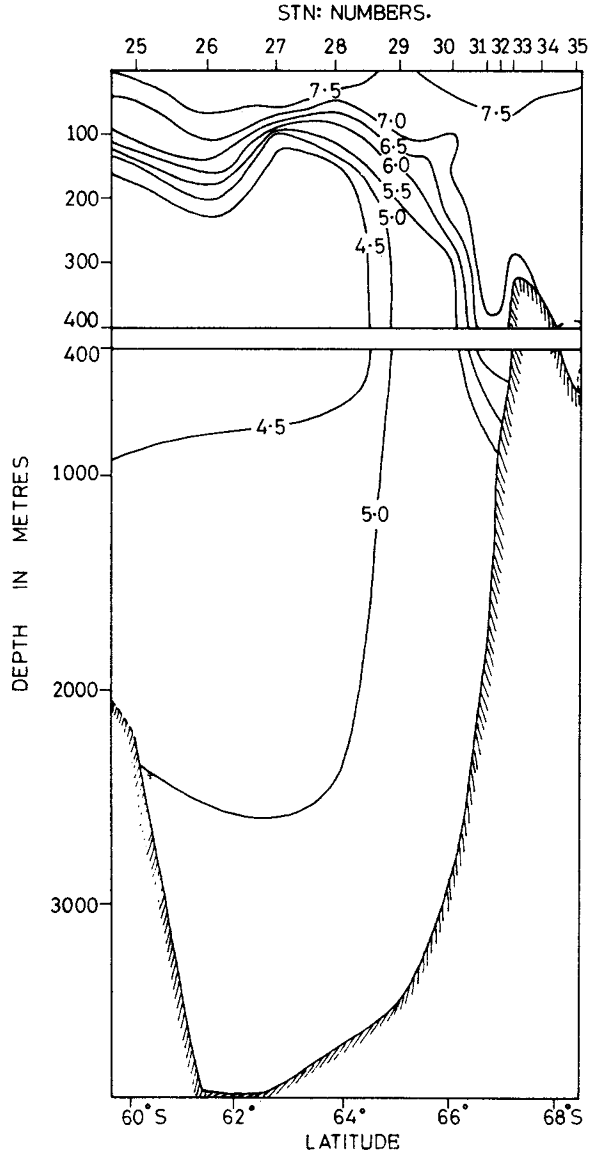

Figure 3(c). Vertical section of oxyty (ml/l) approximately along 77°E.

trapped approximately within the depth range of 200 to 1000 m. The deep waters are almost homogenous in character.

3.3 *Meridional section along* 90°*E*

This section runs from 48 °S to 66 °S. It is covered in two seasons. The stations north of 59 °S were occupied during winter while the southern stations were occupied in

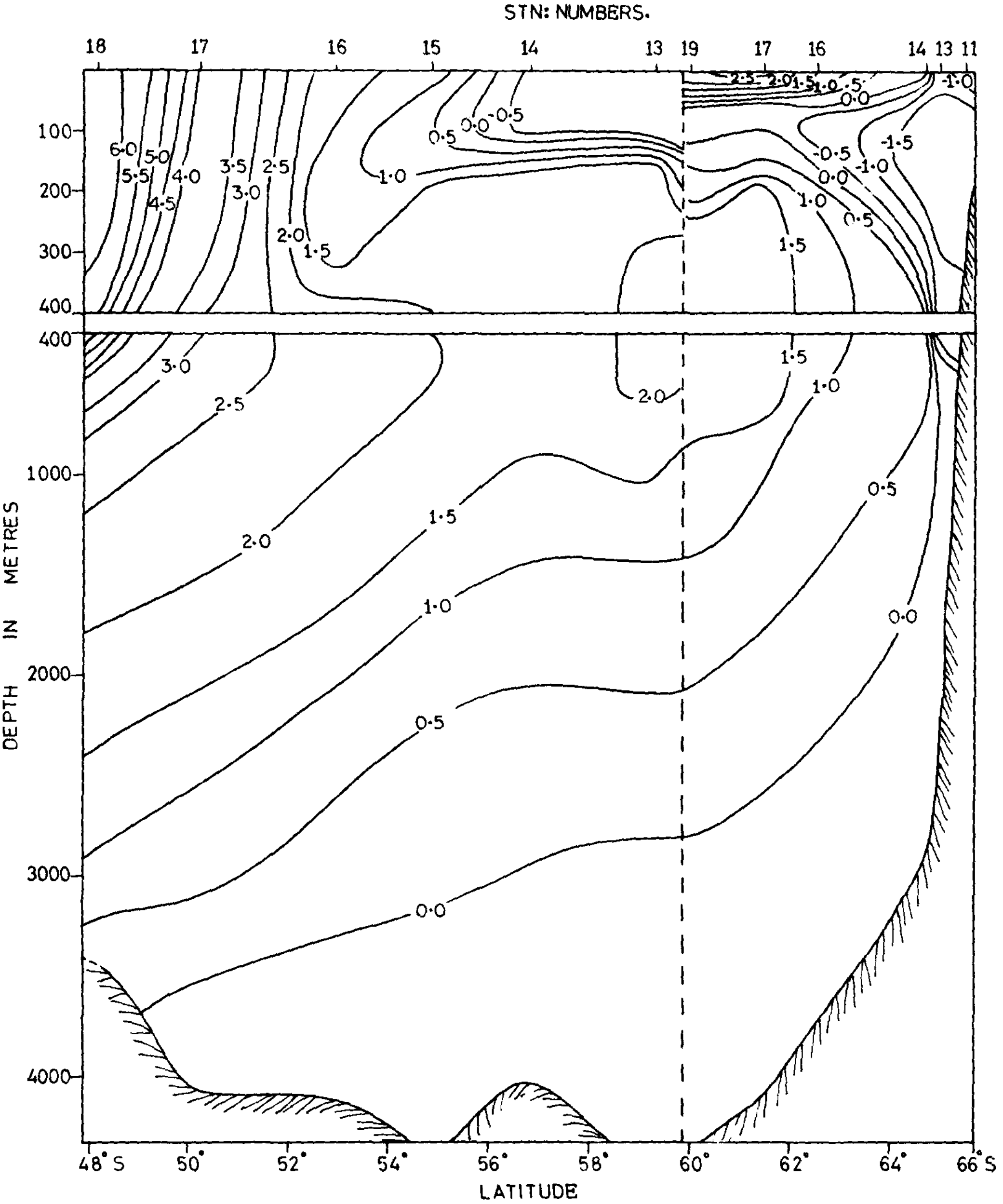

Figure 4(a). Vertical section of potential temperature (°C) approximately along 90°E.

summer. From this section it is evident that the temperature minimum in subsurface depths does not occur in winter but it is a phenomenon associated only with summer. The surface temperature continuously decreases southward and the lowest temperatures might have been recorded near the continental shelf due to lack of radiation for about 6 months. It can also be inferred from this section that during winter, the

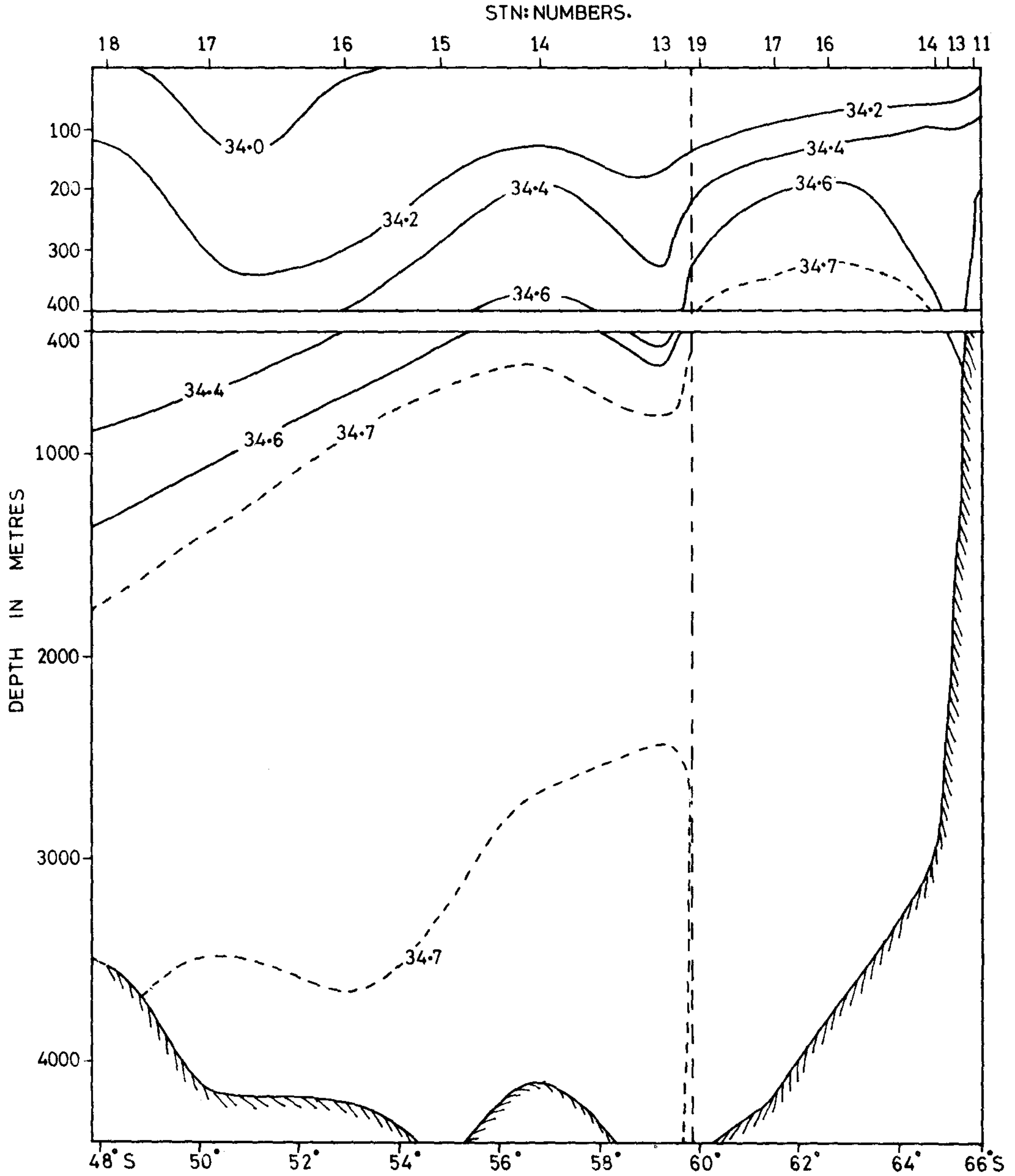

Figure 4(b). Vertical section of salinity ($^0/_{00}$) approximately along 90°E.

Subantarctic Convergence Zone shifts southward and the meridional gradients also strengthen. The thickness of the warmer water in the subsurface depths is much higher in winter compared to that in summer. Within the Polar Front Zone a subsurface maximum in oxygen and a minimum in salinity are seen to extend from the surface layer downward to the north. Surprisingly, the vertical salinity gradient is the least in this

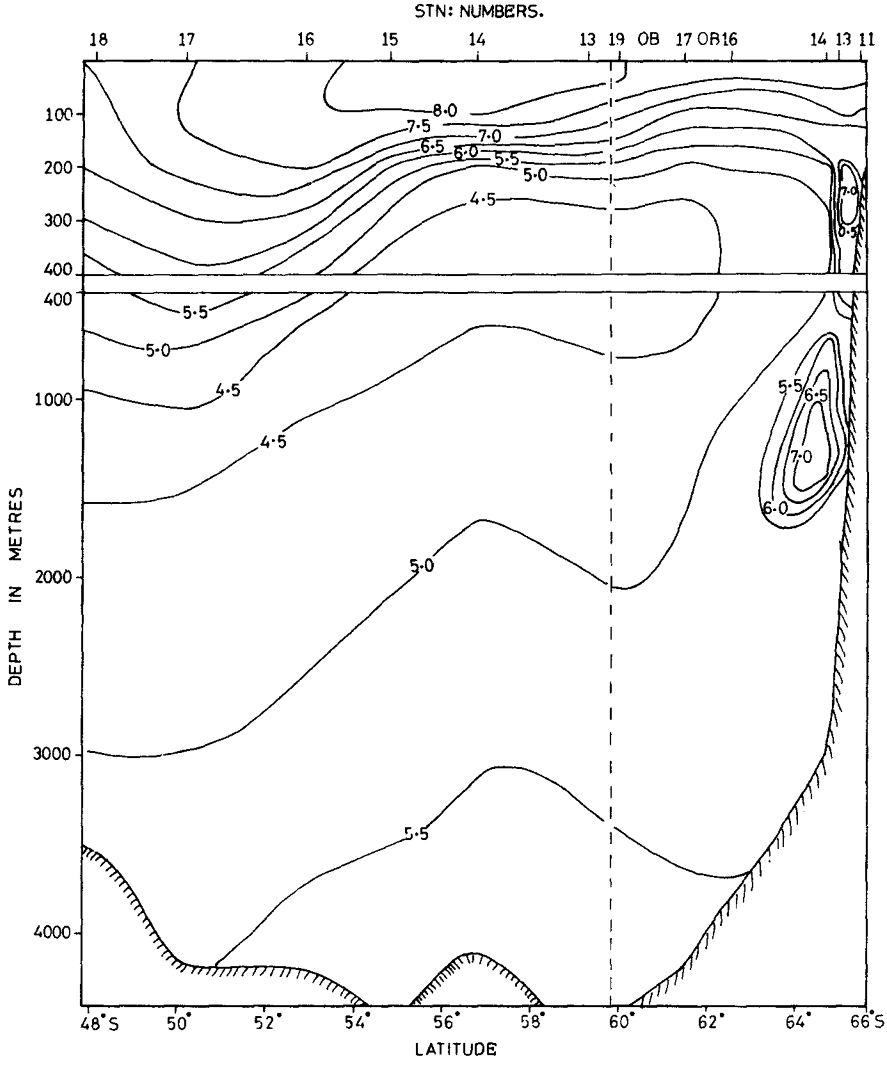

Figure 4(c). Vertical section of oxyty (ml/l) approximately along 90°E.

section, probably, because of winter convection. During winter the oxygen minimum layer becomes thinner and deeper northward.

4. Circulation

Near the Antarctic continent the East Wind Drift is present, north of which the Circumpolar Current is noticed. The Circumpolar Current has northwest to southeast orientation between 50°S at 10°E and 65°S at 70°E. The northward continuation of the Circumpolar Current in the Indian Ocean region merges with the West Wind Drift.

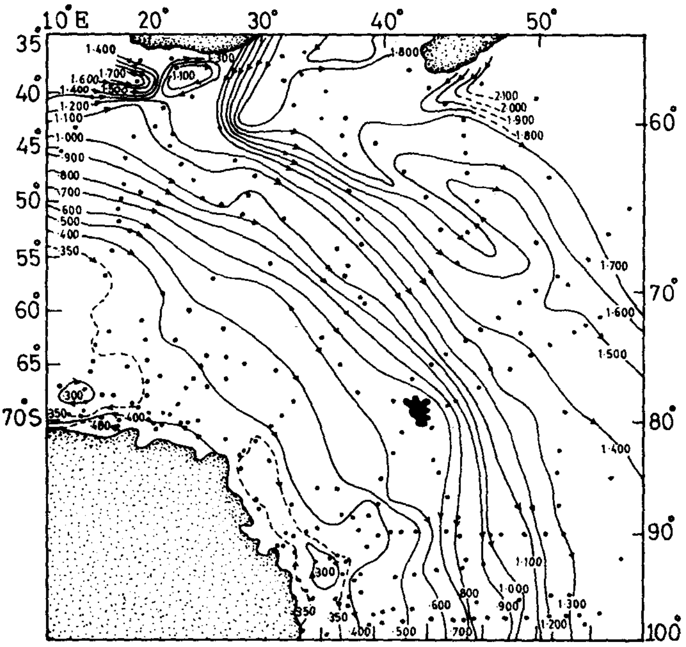

Figure 5. Dynamic topography of the sea surface with reference to 1000 db.

Within the West Wind Drift system a westerly flow between 45°E and 65°E, at about 35°S is noticed.

5. Discussion

According to the vertical sections presented, the whole region under study can be divided into three zones, the extreme ends being characterized by frontal structure. The southern one is designated as the Polar Front Zone while the northern one is termed as the Sub-Antarctic Convergence Zone.

Polar Front Zone is formed near Antarctica due to intense cooling near the continent during winter. This Front is confined only to subsurface depths. Due to freezing of surface water near the continent, the salinity increases resulting in an increase of density. The denser water near the continental shelf flows to the deepermost layers and this is the Antarctic Bottom Water characterized by lower temperature, higher salinity and higher oxyty compared to the water above, which is called the Antarctic Deep Water. The coldest water which is relatively fresh spreads in the subsurface layers towards the lower latitudes. With summer heating the surface waters are warmed and they spread upto the Sub-Antarctic Zone. Such a situation gives rise to low-saline and highly oxygenated subsurface waters with temperature having extreme values below − 1 °C and characterized by strong meridional gradients not only at the surface but extending to deeper layers. The surface water in the southern side of the convergence zone being colder, sinks to the deeper layers as a consequence of which the meridional gradients are strong. This water being fresh from the surface is characterized by lower salinity, and higher oxyty and is known as the Antarctic Intermediate Water. McCartney (1977) propsed that Antarctic Intermediate Water forms north of the Sub-Antarctic Zone primarily in the southeast Pacific Ocean where the coldest water and fresher variety of Sub-Antarctic Mode Water is transformed into Antarctic Intermediate Water. He suggested a mechanism whereby late winter heat loss to the atmosphere results in deep convection and formation of relatively homogeneous water mass, the sub-Antarctic Mode Water. Molinelli (1981) concludes that the Antarctic Intermediate Water is the composite of waters formed by late winter convection. The thermal structure in this region shows a peculiar nature of the cold water sandwiched between the warm layers above and below. This layer is called dicothermal layer (Pickard and Emery 1982) which is conspicuous only during summer (figure 4a) extending upto even 50°S in the western region due to relatively high salinity water of Antarctic origin whereas it is confined to south of 60°S in the eastern region.

The surface waters between the Polar Front Zone and the Sub-Antarctic Convergence are marked by least meridional gradients, because either surplus radiation in summer or deficit radiation in winter is used only for melting of ice or freezing of water respectively, but not to change the temperature. Nevertheless, the Sub-Antarctic Convergence Zone shifts meridionally to higher latitudes in winter and lower latitudes in summer.

The surface flow around Antarctica is mainly zonal as in the Atlantic and Pacific regions. The East Wind Drift appears as a very narrow current close to Antarctica. The boundary between the East and West Wind drifts is at a lower latitude in the eastern side of the Indian Ocean where the land extends northward compared to the western Indian Ocean. Contrary to expectations a westward flow is observed near 35°S between 45°E and 65°E. A similar flow is also noticed around the same latitude in I.I.O.E. Atlas (Wyrtki 1971). As the data in the atlas is averaged over 5-degree-latitude-longitude quadrangle, it is not certain whether this flow is a permanent feature or not and a more detailed study is required for a clear understanding of this interesting phenomenon.

6. Conclusions

In the regions of dicothermal layer the velocity of sound decreases with depth and then increases. In the regions of such sound velocity structure the sound channel extends to very long distances. Further the dicothermal layer is formed in the depth range of 50 to 100 m. The Antarctic region can be used for long distance transmission at shallow depths and this channel can even be found extended round the globe between 50°S and 60°S.

In the region between the Polar Front Zone and the Sub-Antarctic Convergence Zone the meridional variation of temperature is minimum which results in the least atmospheric pressure gradients. The winds in this region are therefore expected to be relatively very weak unlike in the two frontal zones on either side of this region where strong blizzards prevail throughout the year creating operational hazards. Hence, the region between 55°S and 60°S can be used for operations and installation of energy extraction units.

The present knowledge of the hydrography and circulation off Antarctica, particularly in the Indian Ocean region is based on the meagre oceanographic data available. For a detailed study it may be necessary to carry out oceanographic survey at closure intervals and also systematically along the longitudes and latitudes so that the zonal as well as the meridional flow pattern can be worked out with more precision, particularly in the region of Sub-Antarctic Convergence Zone.

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