CHARACTERISTICS OF MID-DEPTH WATER IN SUMMER OFF QUEEN MAUD-ENDERBY LANDS, ANTARCTICA

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Abstract: Summer oceanographic conditions off Queen Maud-Enderby Lands are examined using temperature, salinity and dissolved-oxygen data from 177 hydrographic stations. The most characteristic feature of the area covered is the presence of a mid-depth water. It is composed of three distinct water masses: less saline, oxygen-rich water at a nearly freezing temperature; warm, saline, oxygen-poor water; and a third water which has properties between the above two. Finally, the regional distribution of the characteristic water masses and their sources are discussed.

1. Introduction

The ocean surrounding Antarctica plays an important role as a connector between abyssal waters of the world ocean.

The general oceanography of the Southern Ocean is known fairly well from the early studies of WÜST (1933), MOSBY (1934) and DEACON (1937). Our knowledge of the structure and circulation of Antarctic water masses has been greatly expanded by GORDON (1966, 1967, 1971a, b, c), REID and LYNN (1971), CALLAHAN (1972), CARMACK (1974, 1977) and JACOBS and GEORGI (1977). However, most of their remarks about the problem are still speculative, particularly the sources of characteristic water masses in the Antarctic Ocean proposed by them. Since information on hand is too short as yet for us to solve the problem quantitatively, we are called on to accumulate data based on hydrographic observations closer in space and time throughout the ocean surrounding Antarctica.

Japanese Antarctic Research Expeditions (JARE) have carried out, aboard the icebreaker FUJI, hydrographic observations off Queen Maud-Enderby Lands in austral summers since 1965. Although the spatial density of hydrographic stations in a single field season is extremely small, accumulated data cover the region between 5°W and 60°E, and north to 55°S (Fig. 1). This region is important because North Atlantic Deep Water and Antarctic Bottom Water, both of which are sources of abyssal water in the world ocean, are believed to pass through this area and circulate toward the Indian and Pacific Oceans. In addition, CALLAHAN (1972) infers the possibility of advection of the eastern South Pacific Deep Water, which has the smallest oxygen content in the world ocean, into this area.

The purpose of this study is to clarify the characteristics of water masses persistently existing in this area.

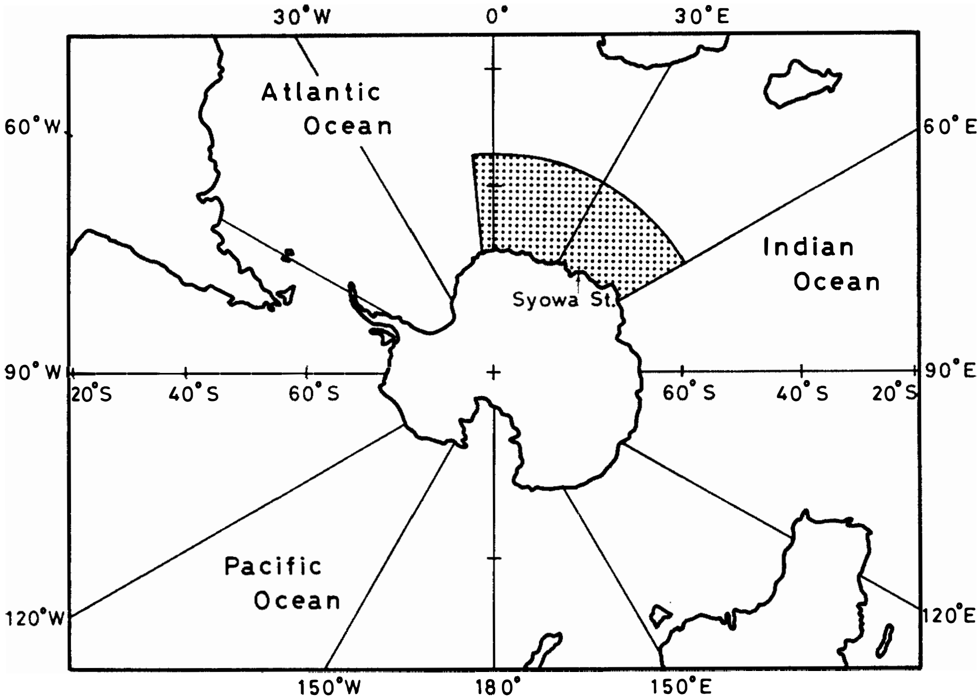


Fig. 1. Geographical location of study area.

2. Data

Most data used in the present study was obtained in austral summers, mainly during February, aboard the Fuji which occupied 94 hydrographic stations from 1965 to 1979. Where the spatial density of stations was relatively small, data from three other ships were added; 34 stations by the Japanese Umitaka Maru (January to March 1957, December 1961 to January 1962) (Ishino *et al.*, 1958, 1963); 15 stations

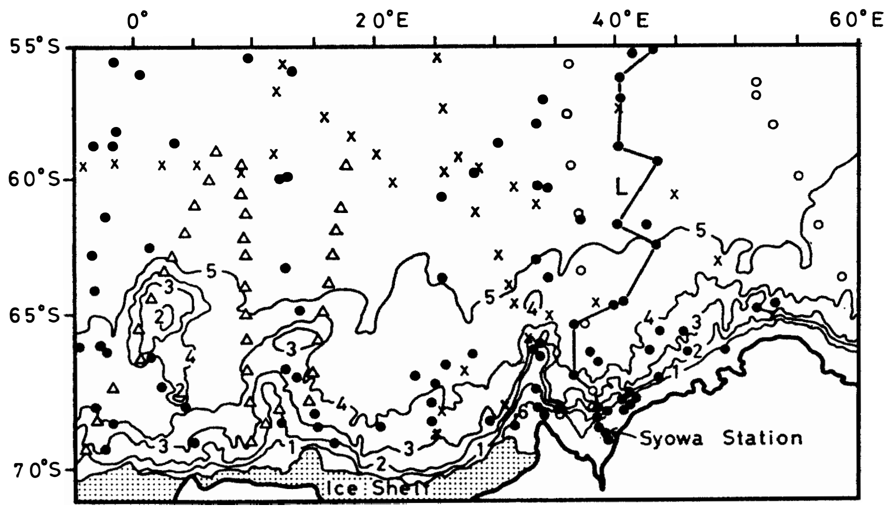


Fig. 2. Bathymetry of study area and locations of hydrographic stations occupied by four ships, Fuji (●), Umitaka Maru (×), U. S. S. Conrad (○) and A. R. A. Islas Orcadas (△). Depth in km.

by the U.S.S. CONRAD (January to March 1974) (JACOBS *et al.*, 1980); 34 stations by the A.R.A. ISLAS ORCADAS (January to February 1977) (HUBER *et al.*, 1981). Station locations and bathymetry are shown in Fig. 2. A relatively narrow continental shelf exists along the Antarctic continent. The summer pack-ice edge near Syowa Station runs approximately parallel to the edge of the continental shelf (KUSUNOKI and ONO, 1964). A broad basin deeper than 5 km, which is part of the Atlantic-Antarctic Basin, spreads north of 65°S. The other bathymetric features in this area are the presence of two ridges extending northward along the meridians of 13°E and 35°E, and of the Maud Rise (65°S, 3°E).

3. Hydrographic Section and Classification of Water Masses

A hydrographic section along a meridian of about 40°E was selected to investigate the general features and water masses in the ocean area covered (see Fig. 2). Sections of temperature (T), salinity (S) and dissolved-oxygen content (O_2) are shown in Fig. 3.

The surface water above a depth of about 50 m is obviously produced through surface process in summer, hence its properties depend upon summer atmospheric conditions. Meanwhile, nearly homogeneous water, which is characteristic of the Southern Ocean, lies below the permanent halocline. The depth and strength of the halocline depend upon various physical processes above and below it. As shown in Fig. 3b, halocline characteristics change along the meridian; a relatively strong, shallow halocline exists around 65°S whereas weaker and deeper haloclines lie north and south of there, respectively. The classification of water masses along the meridian is done in an intermediate layer between 50 and 400 m including the halocline. Three different water types, A, B and C, are present in the above three areas with different halocline properties, and their characteristic features are given, by using vertical profiles of T, S and O_2 at representative stations in these areas (Fig. 4), as follows:

(1) Type A: This is in the southern region. Characterized in general by cold, less saline and oxygen-rich water. The layer between 50 and 250 m is nearly homogeneous in temperature (freezing point), salinity (about 34.3‰) and oxygen content (about 7.3 m*l*/*l*). The temperature maximum (T_{max}), salinity maximum (S_{max}) and oxygen minimum ($O_{2\,min}$) all occur at about 400 m, which is the deepest among the three types. These profiles seem to be a remnant of the surface process in the preceding winter, namely, convective mixing induced by brine exclusion during the sea ice formation. Near the bottom of the convection layer, upward transfers of heat and salt take place through the vertical diffusion process. Since convection and diffusion advance simultaneously, the latter apparently erodes the convection layer, limiting its depth. Therefore, although the present thickness of the homogeneous layer is about 250 m, the actual depth of convection may be 250 to 400 m. According to WAKATSUCHI (1982), the maximum thickness of the convection layer over the continental shelf near Syowa Station is about 400 m, which was obtained from oceanographic observations under growing sea ice throughout a winter.

(2) Type B: This exists around 65°S. Opposite to Type A, this type is characterized by a warm, saline and oxygen-poor water. This type has the shallowest depth

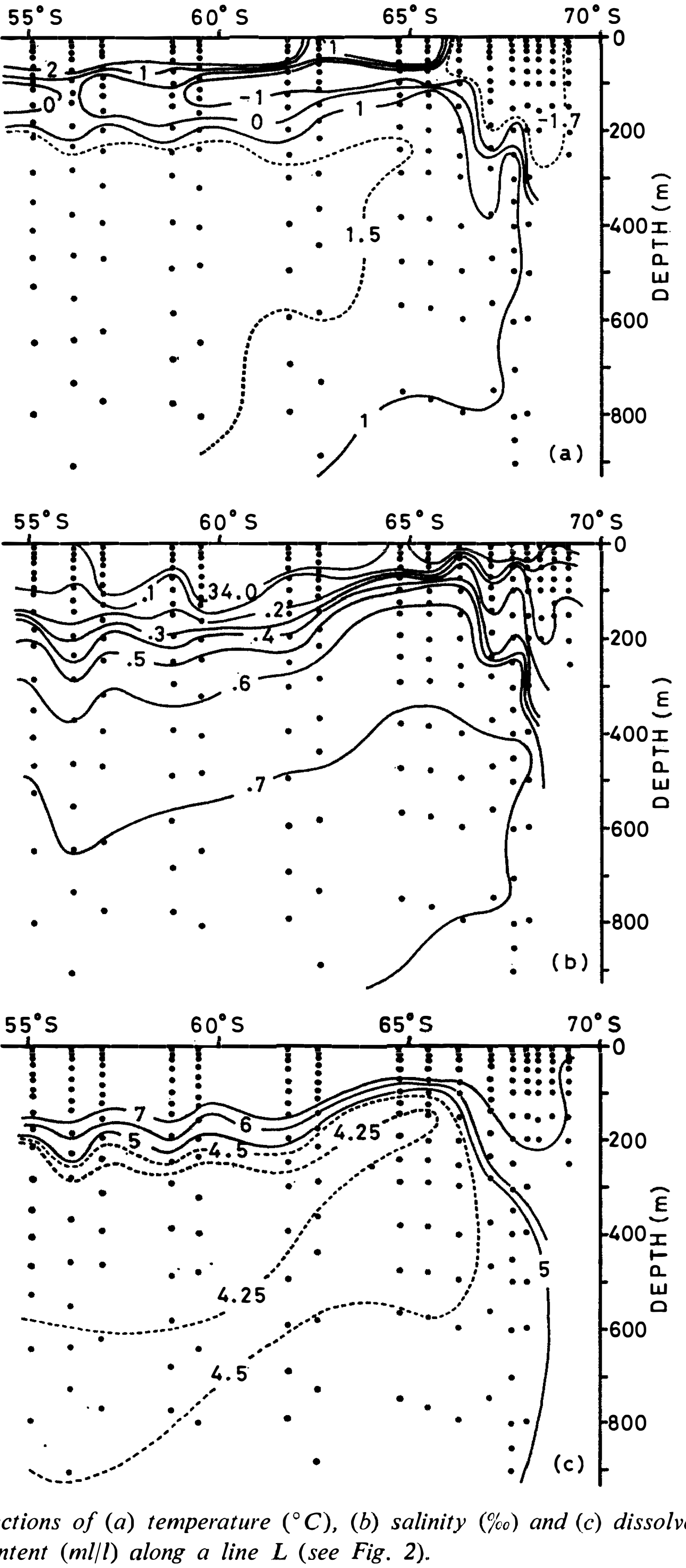


Fig. 3. Sections of (a) temperature (°C), (b) salinity (‰) and (c) dissolved-oxygen content (ml/l) along a line L (see Fig. 2).

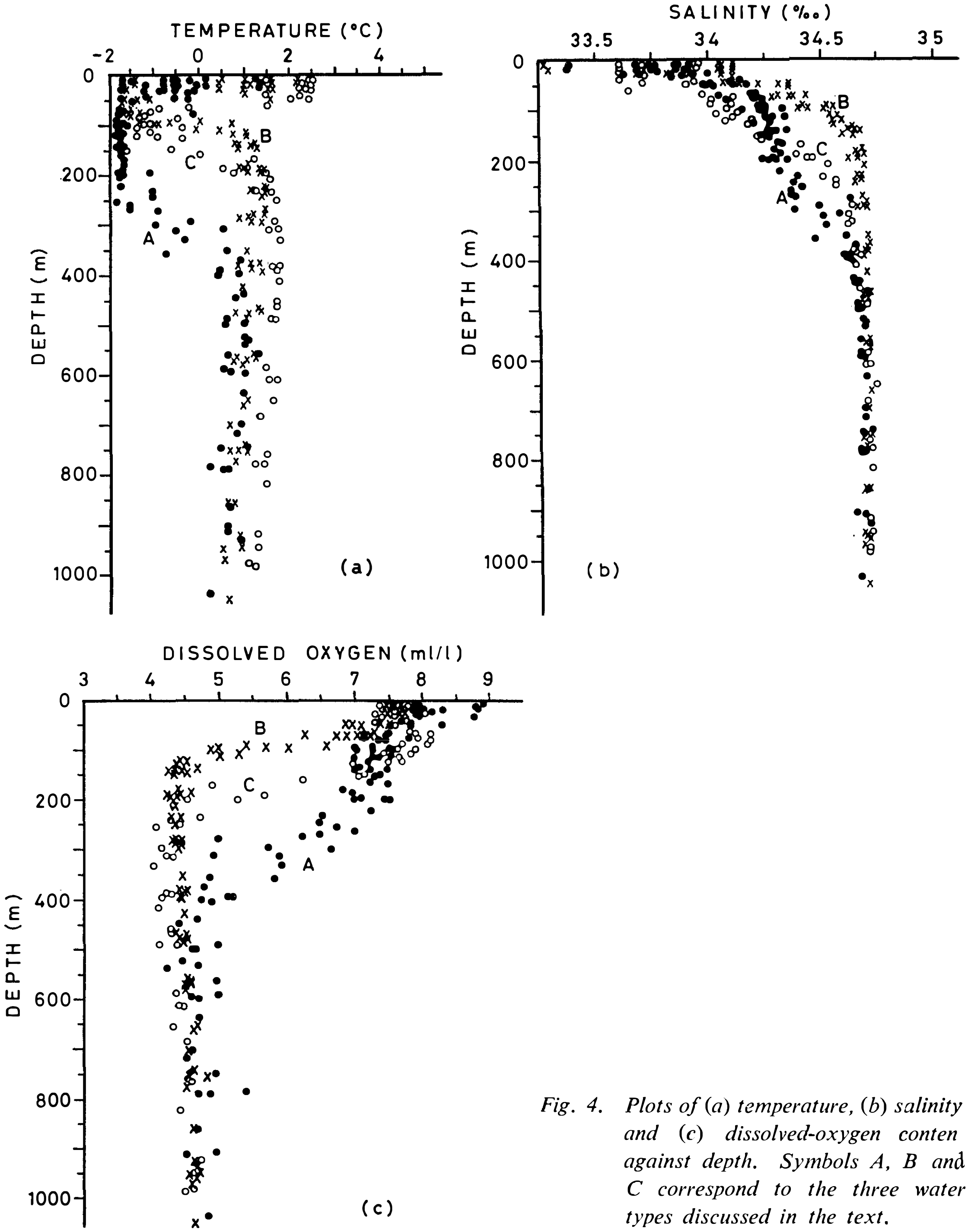


Fig. 4. *Plots of* (*a*) *temperature,* (*b*) *salinity and* (*c*) *dissolved-oxygen conten against depth. Symbols A, B and C correspond to the three water types discussed in the text.*

for T_{max}, S_{max} and O_{2min}, and hence the most abrupt thermocline, halocline and oxycline among the three types.

(3) Type C: This spreads north of Type B water. In general, this type has characteristics intermediate between Types A and B. As shown in Figs. 4b and 4c, however, the upper water above a depth of 150 m has the lowest salinity and the

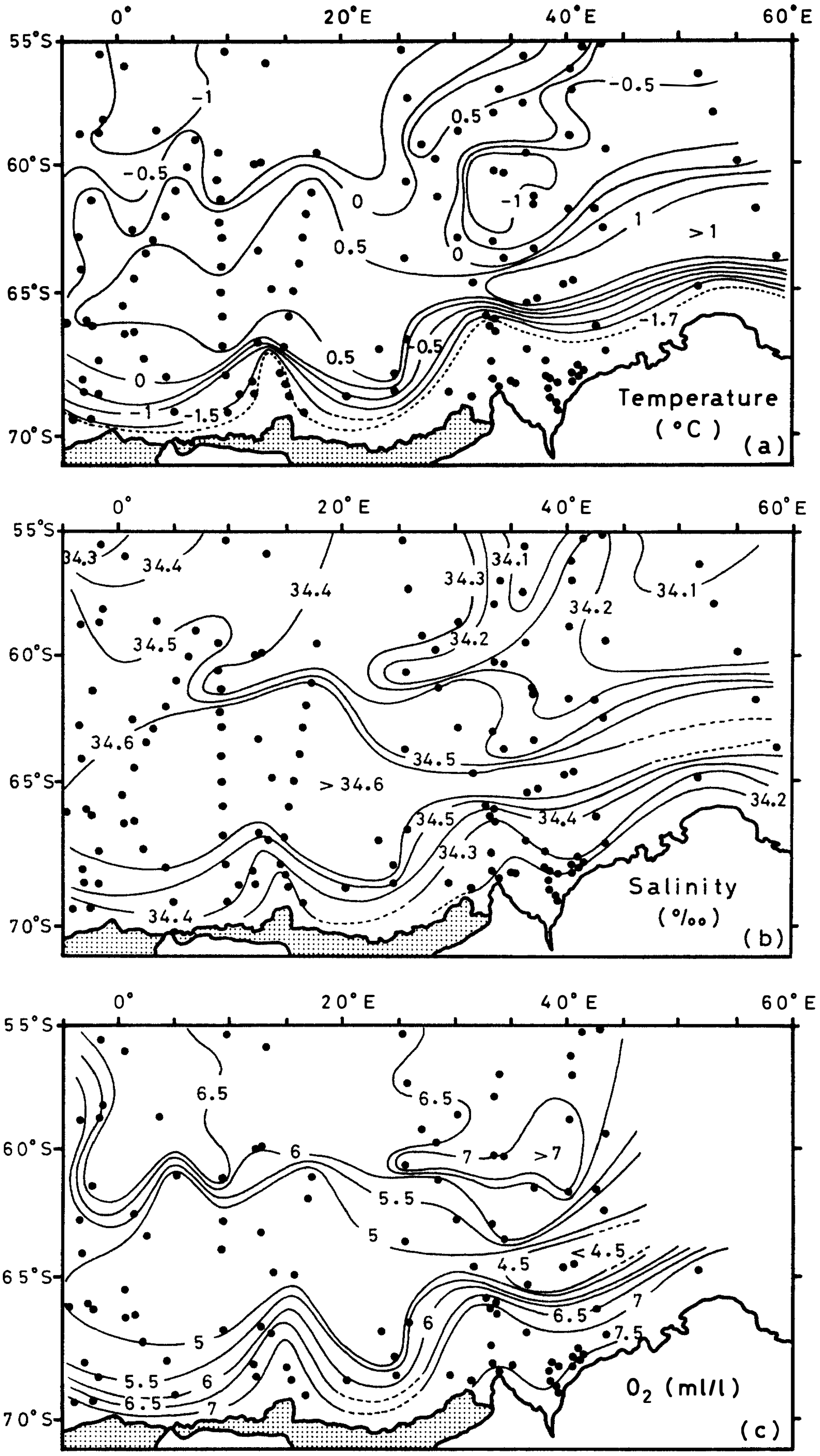


Fig. 5. *Isotherms* (*a*), *isohalines* (*b*) *and isooxygen contours* (*c*) *at a depth of 150 m. Dots denote hydrographic stations.*

highest oxygen content among the three types. This implies that the upper water of this type was primarily produced through the same surface process as that in Type A.

4. Regional Distribution of Water Masses

To examine the regional distribution of the above three water types, it is useful to construct isopleth maps for T, S and O_2. In constructing the maps, a depth of 150 m was adopted as the best level for distinguishing the water masses, as clearly shown in the vertical temperature profiles (Fig. 4a) and hydrographic sections (Fig. 3).

The isopleth maps (Figs. 5a, 5b and 5c), which were constructed using data at all of the hydrographic stations used in this study, revealed the following characteristics of water masses: the middle part of the study area is broadly occupied by water which is warmest in temperature (above 0.5°C), highest in salinity (above 34.6‰) and lowest in oxygen content (below 5 m*l*/*l*). As seen clearly in Figs. 5a, 5b and 5c, this water is horizontally homogeneous in T, S and O_2 and its area narrows east of 25°E. According to the classification of water masses mentioned in the previous section, this water corresponds to Type B.

Meanwhile, Type A water exists on the coastal side of Type B water, forming an oceanic front along the boundary between both waters. This coastal water, which is characterized by nearly freezing temperature (below −1.7°C), high oxygen content (more than 7 m*l*/*l*) and low salinity (less than 34.3‰), lies over the continental shelf shallower than about 1 km in depth.

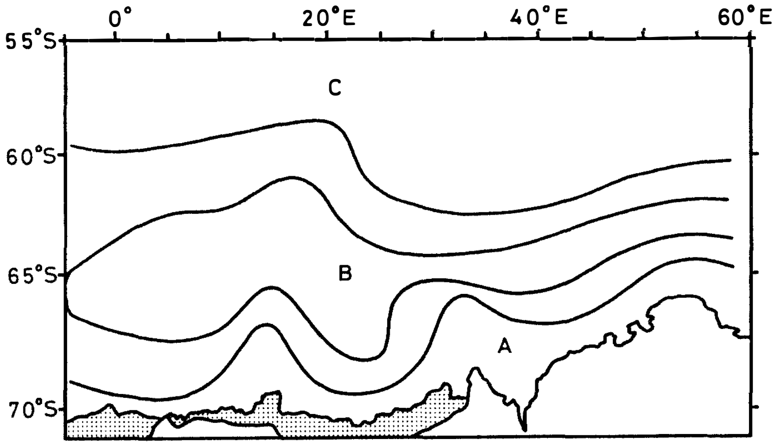
A water with properties between those of Type A and B waters spreads in the most offshore area in the study area, having relatively complicated structures in T, S and O_2. This water belongs to Type C.

The isopleth maps also suggest that horizontally spreading Type A and B waters at a depth of 150 m are largely affected by complex bathymetry, particularly the two northward-extending ridges (Fig. 2); the oceanic front produced along a boundary between both waters runs parallel to isobaths.

5. Discussion

By summarizing all the above analytical results, the regional distribution of the distinguished water masses in the intermediate layer in the study area is schematically illustrated in Fig. 6. This illustration was constructed on the basis of all data taken in 1965–1979. Therefore, this area is considered to have the foregoing characteristic pattern approximately every summer.

The characteristics of Type A water, having the nearly freezing temperature, lower salinity and higher oxygen content, are produced by convective mixing in the preceding winter. So it is locally-produced water. Meanwhile, the warm, saline and oxygen-poor Type B water should be advected from far away. GORDON (1967) attributed the widespread Antarctic oxygen minimum to biological depletion in low latitudes of oxygen-rich North Atlantic Deep Water. However, CALLAHAN (1972) disagrees with GORDON, showing an oxygen-content map on the 50-cl/t isanosteric surface which coincides with the vertical minimum of oxygen content over a large



	Temperature	Salinity	Dissolved Oxygen
A	Low	Low	High
B	High	High	Low
C	Middle	Middle	Middle

Fig. 6. Schematic illustration of regional distribution of three water types, A, B and C.

portion of the Antarctic Ocean. According to his map, the oxygen-poor water originating from the eastern South Pacific Ocean, which has oxygen values smaller than the poleward-flowing North Atlantic Deep Water, continues east across the South Atlantic Ocean and is no longer recognizable east of Africa.

More detailed isanosteric analyses in the study area showed that the depth of the 50-cl/t surface is shallower than 100m in the area of Type B water. The surface water above that depth is produced by the surface process during the winter as shown in Fig. 3. To derive the inflow path of oxygen-poor water into the area of

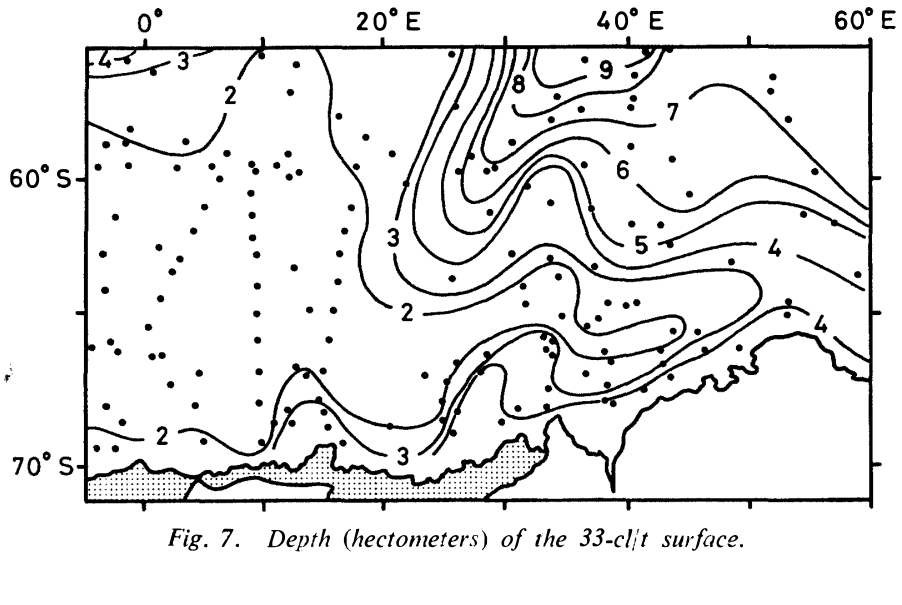


Fig. 7. Depth (hectometers) of the 33-cl/t surface.

Type B water, therefore, the 33-cl/t surface corresponding to the specific volume at a typical oxygen-minimum depth in the Type B water should be used. Figure 7 shows the depth of the 33-cl/t surface. The dominant flow pattern evident in the depth contours of Fig. 7 is the cyclonic Weddell Gyre. As well known, highly developed atmospheric cyclones are staying on the study area during the winter. The resulting wind-driven transport produces an upwelling zone within the center of the Weddell Gyre. Therefore, the oxygen-poor Type B water should be brought about through lateral advection along the 33-cl/t surface from low latitudes. As shown in Fig. 8, the warm, saline, oxygen-poor water on the isanosteric surface is present only in the northeastern part of the study area and also appears to flow toward the Type B water region (see Fig. 7). This is in the southwestern Indian Ocean. Meanwhile, in the western Indian Ocean, extremely oxygen-poor, saline North Indian Deep Water flows south along the east coast of Africa (CLOWES and DEACON, 1935). Therefore, the inflow of oxygen-poor, saline Type B water into the study area may originate mainly from North Indian Deep Water supplemented by oxygen-poor eastern South Pacific Deep Water, but not by North Atlantic Deep Water. The characteristic pattern of Type B water which is nearly absent from the western edge of the study area (Fig. 6) also supports the above interpretation; in addition, the low oxygen content of less than 4.5 m*l*/*l* seen in the eastern part of Type B water (Fig. 5c) is not present in the North Atlantic Deep Water.

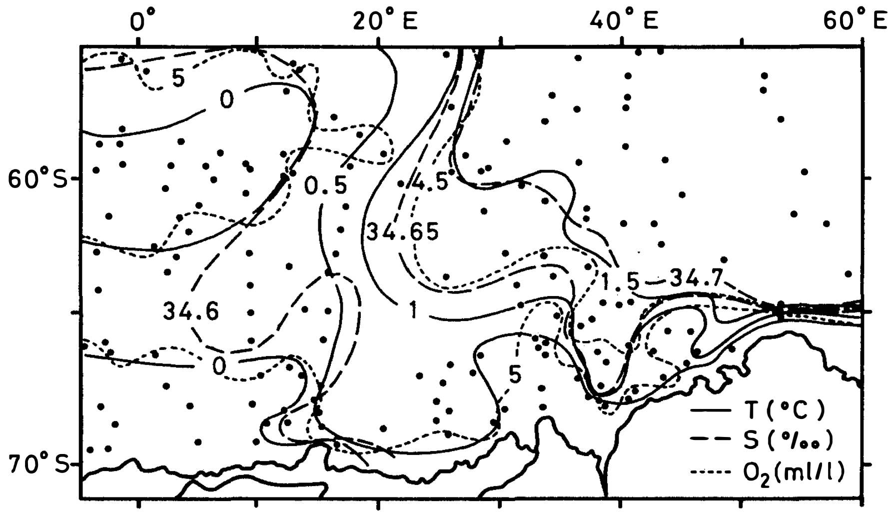


Fig. 8. Temperature, salinity and dissolved-oxygen content on the 33-cl/t surface.

As mentioned in Section 3, the upper Type C water may be produced through surface processes in winter in the coastal area. This is also clear from Fig. 8. The properties of water on the 33-cl/t surface in the western part of the Type C area are analogous to those of coastal water in the study area. The dominant component of flow in the Type C water area is eastward though it turns poleward around 35°E (Fig. 7). Therefore, at least the upper Type C water may originate from coastal water produced in the Weddell Sea. Meanwhile, the lower Type C water has a complicated structure and hence its sources are still unknown.

6. Concluding Remarks

The most characteristic oceanographic feature in summer off Queen Maud-Enderby Lands is the presence of three distinct water types at a mid-depth between 50 and 400 m. The first type, which is low salinity, oxygen-rich and at nearly freezing temperature, is present over the continental shelf and is locally produced through convection in winter.

The second type of water, which is warm, saline and oxygen-poor, is distributed broadly offshore of the first type. The major source of this water is considered to be advection of a mixture of two extremely oxygen-poor waters, namely, North Indian Deep Water and eastern South Pacific Deep Water, but not North Atlantic Deep Water. The third type of water, which has mixed properties of the above two waters, spreads in the farthest offshore part of the study area. The upper water of this type may originate mainly from coastal water produced in the Weddell Sea.

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