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Article

Distribution and Vertical Structures of Water Masses around the Antarctic Continental Margin

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Abstract : Spatial distribution and vertical structures of water masses around the Antarctic continental margin are described using synthesized hydrographic data. Antarctic Surface Water (AASW) over the shelf regime is distinguished from underlying other water masses by the cut-off salinity, varying from approximately 34.35 to 34.45 around Antarctica. Shelf Water, characterized by salinity greater than the cut-off salinity and potential temperature less than −1.7°C, is observed on the Ross Sea, off George V Land, off Wilkes Land, the Amery Basin, and the Weddell Sea, but in some shelves AASW occupies the entire shelf. Lower Circumpolar Deep Water is present everywhere around the Antarctic oceanic regime and in some places it mixes with Shelf Water, producing Antarctic Slope Front Water (ASFW). ASFW, characterized by potential temperature less than about 0°C and greater than −1.7°C, and salinity greater than the cut-off salinity, is found everywhere around Antarctica except in the Bellingshausen-Amundsen sector. The presence of different water masses over the Antarctic shelves and shelf edges produces mainly three types of water mass stratifications: no significant meridional property gradient in the Bellingshausen and Amundsen Seas, single property gradient where ASFW presents, and a V-shaped front where Shelf Water exists.

Key words : water stratification, Antarctic Slope Front, Antarctic Surface Water, Lower Circumpolar Deep Water, Antarctic Slope Front Water, Shelf Water

1. Introduction

The Southern Ocean is important in oceanography and climate studies due to its immense volume (about one fifth of the total world ocean) and free communication with other oceans. In particular, the Antarctic continental margin is regarded as a key area for the ventilation of deep water and for the production of bottom water. The bottom water produced along the Antarctic continental margin is known to influence the climate of the global ocean, and thus, the importance of this water has drawn interest in analyzing the characteristic mixing of water masses that contribute to the formation of bottom water.

The gigantic wind-driven Antarctic Circumpolar Current (ACC) flows eastward (Deacon 1937), exchanging waters between the Southern Ocean basins (Callahan 1972). Since Deacon's (1933, 1937) recognition of the Polar Front (Antarctic Convergence in his report), the ACC has been shown to consist of two additional strong zonal jets and four water mass zones (Orsi 1993). Beneath the surface layer, the Southern Ocean is filled with Circumpolar Deep Water, which extends to the bottom at the northern limit of the Southern Ocean and rises to shallow depths along the Antarctic continental margin. From water mass observations, Orsi (1993) postulated that the southern limit of the upper part of Circumpolar Deep Water (UCDW) is a reasonable definition for the southern boundary of the ACC (Fig. 1).

Deacon (1933, 1937) suggested that the prevailing easterly wind close to Antarctica drives a westward current. At approximately 65°S the wind regime changes to westerly. In the Weddell Sea and the Ross Sea, there is enough area between the southern limit of the ACC and Antarctica for these opposing wind regimes to produce

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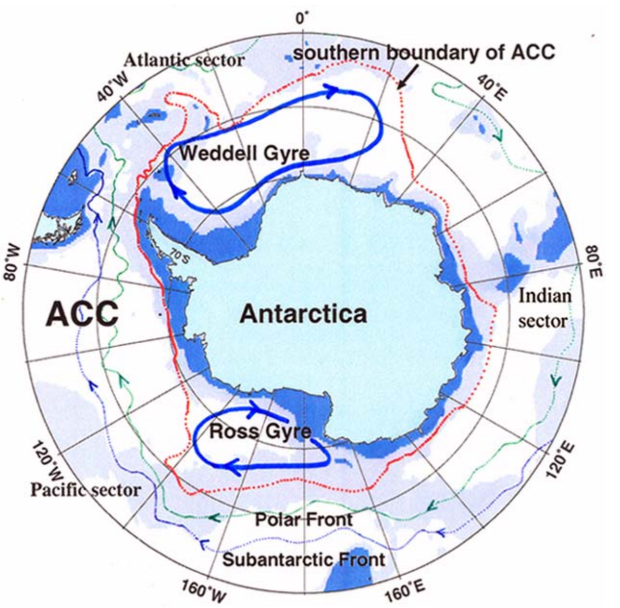

Fig. 1. Basemap of the Southern Ocean where depths less than 2000 m are represented by dark blue and depths less than 4000 m by light blue. The red lines represent the southern boundary of the Antarctic Circumpolar Current according to Orsi (1993). Solid lines show the schematic representation of the Weddell and Ross gyres.

large cyclonic subpolar gyres (Fig. 1). Besides the well-known Weddell and Ross gyres, small-scale cyclonic circulations may exist elsewhere in the subpolar regime (Middleton and Humphries 1989).

In the oceanic regime around Antarctica, lower part of Circumpolar Deep Water (LCDW) occurs as the most voluminous water mass with relatively high temperatures, salinities, and low nutrients. Wüst (1933) showed that the high salinity of LCDW reflects the influence of North Atlantic Deep Water (NADW). Below LCDW, Antarctic Bottom Water (AABW) is observed with characteristics of temperature less than 0°C (Gordon 1971), while above it Antarctic Surface Water (AASW) is present. In winter AASW occupies a narrow potential density range from about σ_0 = 27.65 to 27.70 kg m^{-3} with potential temperature less than −1.7°C and salinity between 34.35 and 34.45, whereas in summer precipitation, surface heating, and consequent ice melting make the upper layer of AASW warmer and fresher, resulting in a temperature minimum layer in the lower part. This summer remnant of winter AASW is called "winter water" (Mosby 1934).

The layer of AASW tends to thicken towards Antarctica and sometimes reaches the bottom on some Antarctic shelves. On other shelves (e.g., the Weddell Sea, the Ross Sea, Prydz Bay, and off George V Land, etc.), more saline water is found (Gill 1973; Foster and Carmack 1976; Jacobs *et al*. 1970, 1985; Middleton and Humphries 1989; Gordon and Tchernia 1972; Rintoul 1998, etc.). The water on the shelf has been classified into low and high salinity varieties by salinity values (e.g., 34.62 by Mosby 1934; 34.51 by Fofonoff 1956; 34.6 by Carmack 1977; 34.5 by Smith *et al*. 1984) and the high salinity variety may participate in the formation of AABW. Carmack (1977) showed that the highest salinity water (up to 35) is observed in the Ross Sea and the second most saline water (up to 34.8) is found in the Weddell Sea. Gordon and Tchernia (1972) reported that the salinity of water on the shelf is slightly greater than 34.70 at the Adélie Coast, suggesting the possibility of bottom water formation in that region as shown by Rintoul (1998).

South of the ACC boundary, LCDW moves upward toward the Antarctic continental margin and meets colder and denser water at the edge of the continental shelf, producing a third water mass and resulting in strong gradients of temperature, salinity, and density. Gill (1973) described the front between the shelf regime and the oceanic regime for the Weddell Sea continental margin and in the Ross Sea Ainley and Jacobs (1981) described a zone of horizontal gradients in water properties below the subsurface and referred it as the Antarctic Slope Front. Gill (1973) and Jacobs (1986) pointed out that there is a V-shaped double front at the edge of the western Weddell Sea and the Ross Sea continental shelf.

The objective of this research is to investigate the distribution and vertical structures of water masses around the Antarctic continental margin using synthesized hydrographic data. This requires clear descriptions of the water masses. There have been many regional studies on the characteristics and distribution of water masses around Antarctica, for example, in the Weddell Sea by Gill (1973), Foster and Carmack (1976), Foldvik *et al*. (1985, 2004), Gordon *et al*. (1984), Fahrbach *et al*. (1992, 2001, 2004), Heywood *et al*. (1998), Meredith *et al*. (2000); in the Ross Sea by Jacobs *et al*. (1970, 1985), Locarnini (1994), Jacobs and Giulivi (1998); in the Amery Basin by Smith *et al*. (1984), Middleton and Humphries (1989), Wong *et al*. (1998); off George V Land by Gordon and Tchernia (1972), Rintoul (1998); off Wilkes Land by Carmack and Killworth (1978); in the west of the Antarctic Peninsula by Capella *et al*. (1992), Hofmann *et al*. (1996), Hofmann and Klinck (1998); in larger extent by Gordon (1971), Carmack (1977), and Whitworth *et al*. (1998), etc. This study synthesizes the information of water mass characteristics, refine some of water mass definitions, and generalize them to apply everywhere around the Antarctic continental margin.

2. Data and methods

The study region is the entire continental margin of Antarctica south of 60°S. Historical station data were obtained from the National Oceanographic Data Center. The positions of stations used in this study are shown in Fig. 2. It is important to note that the remoteness and harsh conditions make it difficult to sample in winter. The hydrographic data used in this study are limited to austral summer except for a few winter stations in the oceanic regime. The most closely-spaced hydrographic stations are in the Ross Sea because it is almost completely ice-free during the austral summer. Almost permanent ice cover in the western Weddell Sea and the Bellingshausen and Amundsen Seas limits the sampling and data are almost completely absent in those regions (Fig. 2) and the water mass analysis in these regions are not included in this study.

Water masses are readily identified on property-property diagrams by characteristic relationships between their physical-chemical properties. In particular, the potential temperature (θ) versus salinity (S) diagram has been used to identify and classify water masses since its introduction

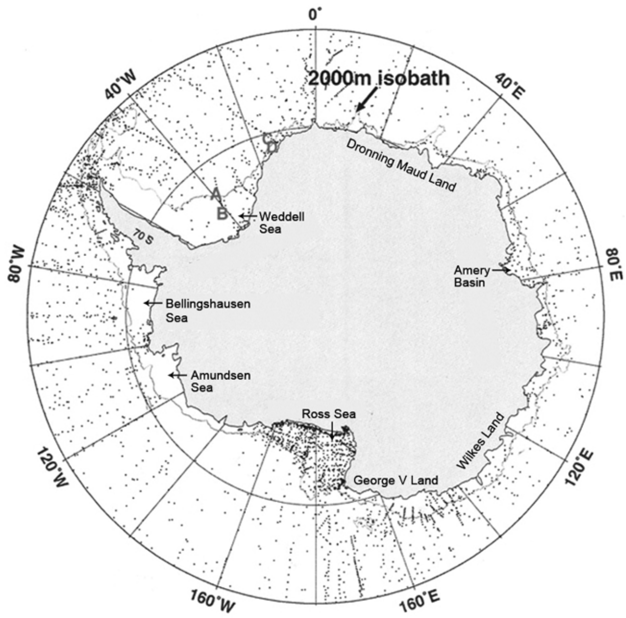

Fig. 2. Positions of hydrographic stations available for use in this study. Dotted lines indicate the 2000 m isobath.

by Helland-Hansen (1916). In this study, property diagrams, particularly of θ-S, are used to describe the water masses. As nomenclature, definitions of a water type as a point and a water mass as a curve in θ-S space by Sverdrup *et al.* (1942) is adopted. The properties of water mass are determined by the local climatic environment at the sea surface when it is formed. When water moves along isentropic surfaces, it retains its properties, particularly temperature and salinity, without great modification. In θ-S space, therefore, the thermal and haline properties describe a water mass regardless of its depth.

3. Results

Water masses around the Antarctic Continental Margin

In this section, the water masses found around the Antarctic continental margin is described in detail. In particular, the definition of Shelf Water is refined by distinguishing it from other water masses with a salinity criterion. The general θ and S characteristics and formation mechanisms of ASFW is introduced. Those generalized characteristics of water masses around the Antarctic continental margin including oxygen concentrations are summarized in Table 1.

LCDW and AABW

In the Antarctic continental margin, LCDW is characterized by maxima in potential temperature (θ) and salinity (S) at intermediate depths (Fig. 3). In θ-S space, LCDW is found at temperatures greater than 0°C and salinities greater than 34.66, in the potential density range between $\sigma_0 = 27.77$ and 27.87 kg m^{-3}. It has the lowest oxygen ($4.0 < O_2 < 5.5$ m*l* *l*$^{-1}$) among the water masses in the Antarctic subpolar regime. Even though there are slight variation in θ-S properties among different sectors of the Southern Ocean, LCDW appears to be the least spatially variable and the most voluminous water mass in the Antarctic subpolar regime.

LCDW core layers shoal towards the Antarctic continental margin and the core of maximum potential temperature is found at depths from 150 to 900 m (about 500 m average) and its salinity maximum core is observed between 300 and 1200 m (about 700 m average) in the Antarctic subpolar regime. The potential densities at the potential temperature and salinity maximum cores of LCDW are $\sigma_0 = 27.80$ kg m^{-3} and $\sigma_0 = 27.82$ kg m^{-3}, respectively. The potential density at the salinity maximum core is almost coincident with the isopycnal values found in the Drake Passage by Sievers and Nowlin (1984) and in the Weddell

Table 1. Generalized characteristics of water masses observed in the Antarctic subpolar regime. Summer surface water (AASW(s)), winter water (AASW(w)), Lower Circumpolar Deep Water (LCDW), low- salinity Shelf Water (SW(l)), high-salinity Shelf Water (SW(h)), low-salinity Antarctic Slope Front Water (ASFW(l)), high-salinity Antarctic Slope Front Water (ASFW(h)), and Antarctic Bottom Water (AABW). The cut-off salinity varies from 34.35 to 34.45.

Water mass	Potential temp. (EC)	Salinity	Oxygen ($ml\,l^{-1}$)	Potential density ($kg\,m^{-3}$)
AASW(s)	$\theta > -1.7$	S < 34.35	$O_2 > 7.5$	$\sigma_0 < 27.65$
AASW(w)	$-1.9 < \theta < -1.7$	34.35 < S < cut-off S	$7.0 < O_2 < 7.5$	$27.65 < \sigma_0 < 27.7$
LCDW	$\theta > 0$	S > 34.66	$4.0 < O_2 < 5.5$	$27.77 < \sigma_0 < 27.87$
SW(l)	$\theta < -1.7$	cut-off S < S < 34.6	$O_2 < 7.0$	$27.7 < \sigma_0 < 27.87$
SW(h)	$\theta < -1.7$	S > 34.6	$O_2 < 7.0$	$\sigma_0 > 27.87$
ASFW(l)	$-1.7 < \theta < 0$	cut-off S < S < 34.6	$5.5 < O_2 < 7.0$	$27.7 < \sigma_0 < 27.87$
ASFW(h)	$-1.7 < \theta < 0$	S > 34.6	$5.5 < O_2 < 7.0$	$\sigma_0 > 27.87$
AABW	$\theta < 0$	S > 34.65	$5.0 < O_2 < 6.0$	$\sigma_0 > 27.87$

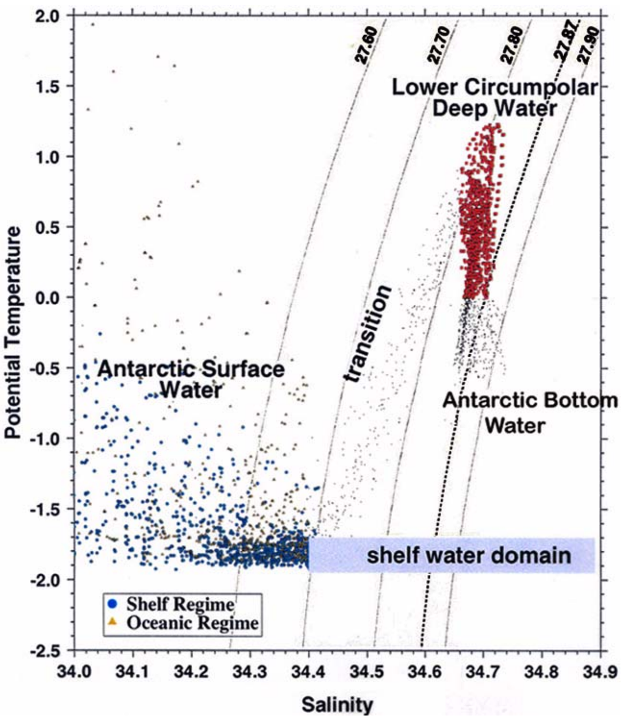

Fig. 3. Potential temperature versus salinity diagram showing Antarctic Surface Water, Lower Circumpolar Deep Water, and Antarctic Bottom Water. In Antarctic Surface Water, blue dots and yellow triangles indicate data from the oceanic regime and the shelf regime, respectively.

Sea by Orsi *et al*. (1993). The least dense potential temperature maximum is found on the western Ross Sea (σ_0 = 27.78 kg m^{-3}).

In the oceanic regime, LCDW is bounded by surface water above and bottom water below. The water mass below LCDW is AABW, having potential temperature less than 0°C and salinity greater than 34.65 (Fig. 3).

AASW and Shelf Water

AASW in the oceanic regime is clearly distinguished in θ-S space from underlying warm and saline LCDW as illustrated in the sample oceanic station A in Fig. 4. This is due to the temperature minimum layer corresponding to the summer remnant of winter AASW. In the shelf regime, on the other hand, Antarctic Surface Water is not clearly distinguished from the underlying water masses as shown on B in Fig. 4 because there is usually no distinct temperature minimum layer as in the oceanic regime. For this reason, the summer remnant of winter AASW in the shelf regime has sometimes been identified as separate water mass, e.g. Low Salinity Shelf Water. However, there is no reason to give a single water mass two different names depending on its location because a water mass is defined by its T-S characteristics, not by geographic location. In defining AASW commonly applicable for both regimes, Whitworth *et al*. (1998) proposed to use the salinity at the base of winter temperature minimum layer in the neighboring oceanic regime. This salinity is referred to as the “cut-off salinity” in this study. The cut-off salinity is the salinity at the temperature minimum layer. In this particular region, thus, the water on the shelf having salinity less than the cut-off salinity (34.4) is classified as Antarctic Surface Water.

Using the same principle, a salinity of 34.37 is taken to define the base of the oceanic AASW for the oceanic regime station C in Fig. 4. However, shelf station D has no salinities greater than 34.37; i.e. the bottom salinity of the water on this shelf is not greater than the cut-off salinity. This is because in this case AASW occupies the

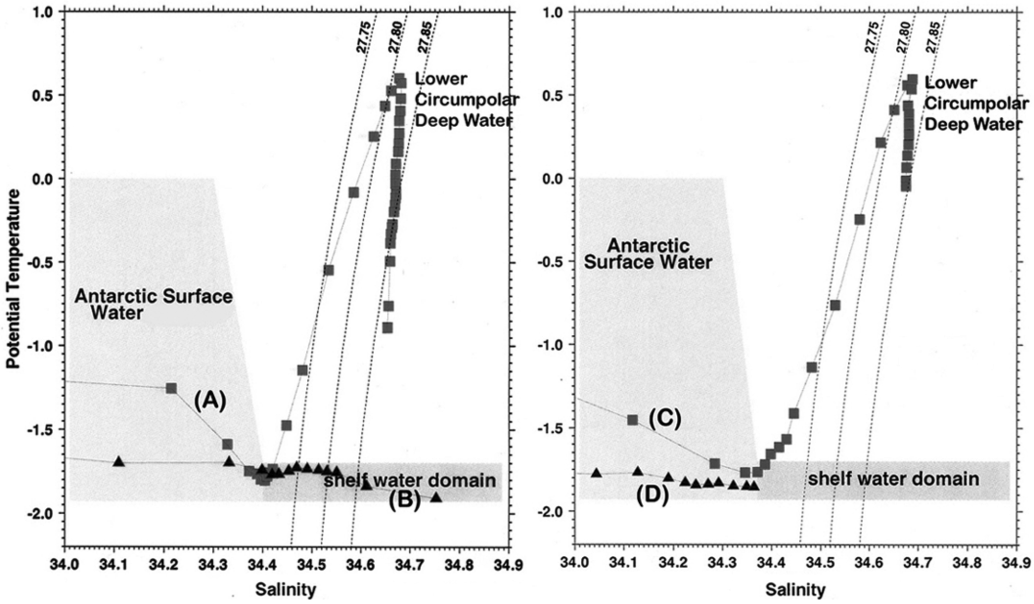

Fig. 4. Potential temperature versus salinity diagram illustrating the definition of Antarctic Surface Water in the shelf regime using the cut-off salinity taken from the station in the neighboring oceanic regime. The sample stations (A) and (B) were selected from the middle Weddell Sea and (C) and (D) in the eastern Weddell Sea (see Fig. 2).

entire water column over the shelf and is not underlain by denser water masses. Now one can define AASW in both the oceanic regime and the shelf regime as the water with salinity less than the cut-off salinity. The cut-off salinity varies in space and time from 34.35 to 34.45 around the Antarctic continental margin and 34.4 on average as illustrated in Fig. 5. Even though the cut-off salinity varies slightly in space and time, it is the best criterion to distinguish shelf AASW from underlying water masses.

Based on the concept for defining AASW, Shelf Water is defined as the water mass in the Antarctic continental shelf regime with salinity greater than the cut-off salinity and potential temperature less than an arbitrary −1.7°C (Fig. 5). The temperature criterion to bound upper temperature limit of Shelf Water is adopted from Whitworth *et al.* (1998), who chose that value because water colder than −1.7°C is seldom found away from the Antarctic continental shelf. The high-salinity variety of Shelf Water has been distinguished from the low salinity variety by the minimum salinity required for the formation of AABW as noted in section 1. In this study, high-salinity Shelf Water is distinguished from low-salinity Shelf Water by the maximum potential density of LCDW (σ_0 = 27.87 kg m^{-3}). The salinity at this density is about 34.6 at the freezing point (Fig. 5), which is close to the value chosen by Mosby (1934) and Carmack (1977).

The oxygen saturation of winter water supports the argument that AASW in the oceanic and shelf regimes are

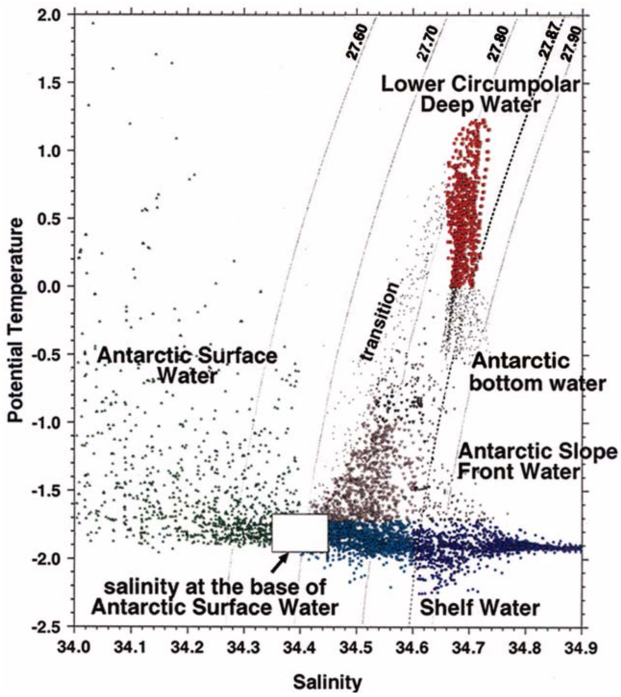

Fig. 5. The composite potential temperature versus salinity diagram showing the waters in the Antarctic continental margin. The open box shows the domain of the potential temperature minimum layer in Antarctic Surface Water around Antarctica. The separation between low-salinity Shelf Water (blue) and high-salinity Shelf Water (dark blue) is taken to be the maximum density of Lower Circumpolar Deep Water.

the same. Weiss *et al.* (1979) pointed out the oxygen under-saturation of both winter water and Shelf Water in the Weddell Sea (see also Table 1 for the mean oxygen concentration around the Antarctic continental margin) and suggested three possible reasons: sea ice cover, rapid oxidation of organic material by biological activity, or the admixture of oxygen poor Warm Deep Water (LCDW in this study). Gordon *et al.* (1984) wrote that the oxygen undersaturation (about 86%) of the winter mixed layer of the Weddell Polynya is likely due to the vertical entrainment of the underlying oxygen-poor Warm Deep Water (between about 4 and 5.5 ml l^{-1}) rather than to winter ice, snow cover, or biological consumption. In the oceanic regime, winter water has an average oxygen content of about 7.05 (±3.5) ml l^{-1}, which is about 84.5% of oxygen saturation.

The water in the shelf regime has almost the same oxygen content about 7.2 (±3.9) ml l^{-1} and saturation (approximately 84.6%) as that in the oceanic regime, even though it is not directly influenced by LCDW. This indicates that the summer remnant of AASW in the shelf regime originates in the oceanic regime and is moved south by a shoreward Ekman transport induced by prevailing westward wind (Sverdrup 1953; Gill 1973).

Antarctic Slope Front Water

At the edge of the shelf break in many locations, warm and saline LCDW meets cold and less saline Shelf Water, producing a third water mass. The waters observed between the shelf regime and the oceanic regime have been called different names as, e.g., modified CDW by Jacobs *et al.* (1970) in the Ross Sea, slope water by Gordon and Tchernia (1972) in the Adélie Coast, Modified Warm Deep Water by Carmack (1977), Warm Core by Jacobs *et al.* (1985) in the Ross Sea, Weddell Scotia Confluence Water by Whitworth *et al.* (1994), and Modified CDW by Whitworth *et al.* (1998). In this study, the water mass listed here is called Antarctic Slope Front Water (ASFW). Found in a triangle in θ-S space, ASFW is characterized by potential temperature less than 0°C but greater than −1.7°C, and salinity greater than the cut-off salinity (Fig. 5). Most of ASFW is within the density range of LCDW and low-salinity Shelf Water (between about σ_0 = 27.70 and 27.87 kg m^{-3}), but some of it is denser than LCDW.

Fig. 6 illustrates mixing process involved in the formation of ASFW. ASFW within the density range of LCDW is presumably produced by isopycnal mixing with low-salinity Shelf Water because isopycnal mixing is much more efficient energetically. It may be also possible for

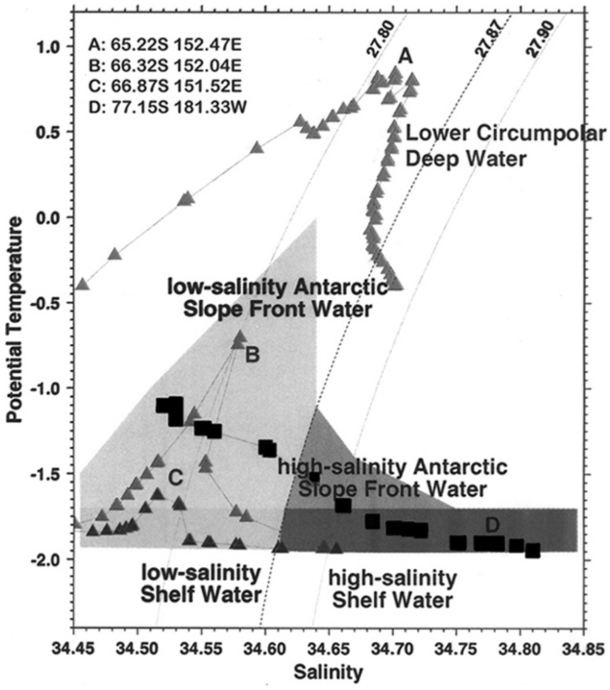

Fig. 6. Potential temperature versus salinity relation selected to illustrate the isopycnal mixing between Lower Circumpolar Deep Water and low-salinity Shelf Water that produces low-salinity Antarctic Slope Front Water and the diapycnal mixing between low-salinity Antarctic Slope Front Water and high-salinity Shelf Water that produces high-salinity Antarctic Slope Front Water.

Shelf Water to mix with overlying AASW by diapycnal mixing and produce ASFW, but this is highly unlikely to occur. ASFW produced by isopycnal mixing is referred to as low-salinity ASFW. The isopycnal mixing produces waters over the continental slope (B) that are warmer and saltier at the potential temperature maximum cores than Shelf Water (C) and colder and fresher than LCDW (A). The θ-S characteristics of ASFW are determined by the mixing ratio of the two water types. In this example, about 60 percent of Shelf Water mixed with about 40 percent of LCDW results in ASFW at the potential temperature maximum of station B.

Small portion of ASFW is denser than LCDW having σ_0 greater than 27.87 kg m^{-3} (dark shading in Fig. 6). This water, referred to as high-salinity ASFW, is presumably produced by diapycnal mixing between overlying low-salinity ASFW and underlying high-salinity Shelf Water. This mixing seems to be associated with convection in regions like coastal polynyas where sea ice freezing and brine release leads to a very active vertical mixing.

Spatial distribution of water masses adjacent to Antarctica

Based on the information of the water mass characteristics examined in the previous section, this section describes the spatial distribution of water masses around the Antarctic continental margin. AASW and LCDW are found everywhere around the Antarctic continental margin. This study primarily focuses on the distribution of ASFW and Shelf Water over the Antarctic continental shelf and slope.

To illustrate the distribution of ASFW, a map based on potential temperature (between −1.7°C and 0°C) at potential temperature maximum is prepared (Fig. 7), because ASFW is easily identified as an intermediate temperature maximum core within the potential density range σ_0 = 27.70 and 27.87 kg m^{-3} (see Fig. 5). In Fig. 7, low-salinity Shelf Water identified as blue color is the water on the shelf with potential temperature less than −1.7°C within the same density range of ASFW. Note that ASFW in Fig. 7 is the low-salinity variety.

In the Ross Sea from about 155°W, ASFW is observed everywhere except in the southwestern corner between 160°W and 170°W where low-salinity Shelf Water is found. ASFW follows the continental margin westward to George V Land where a relatively large region of low-salinity Shelf Water also occupies the southern shelf. In the Indian sector, ASFW is observed along the continental slope, while close to the continent low-salinity Shelf Water is also observed, especially off Wilkes Land (100°-140°E), around Prydz Bay (60°-80°E). In the Atlantic sector, only narrow bands of ASFW exists in the east of the Weddell Sea, but it is observed in a relatively large area west of about 20°W. ASFW extends past the tip of Antarctic Peninsula, disappearing near the western end of the South Shetland Islands (about 63°W) and in the Pacific sector it is absent all the way to the east of the Ross Sea. The absence of ASFW in these regions is associated with the absence of Shelf Water which is one parent water mass for ASFW.

The distribution of Shelf Water is shown in the map based on the bottom salinity and the potential temperature (Fig. 8). The low- and high-salinity varieties of Shelf Waters are identified by red and blue colors, respectively. The distribution of Shelf Water used here includes only waters on the shelf with potential temperature less than −1.7°C and salinity greater than the cut-off salinity (see Fig. 5).

The bottom water in the western Ross Sea consists of largely high-salinity Shelf Water, whereas in the eastern

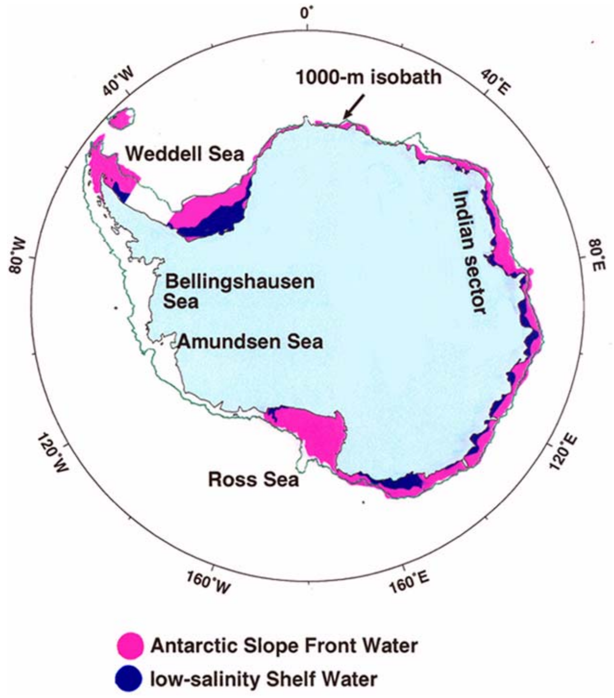

Fig. 7. Spatial distribution of Antarctic Slope Front Water and low-salinity Shelf Water around Antarctica based on potential temperature at potential temperature maximum.

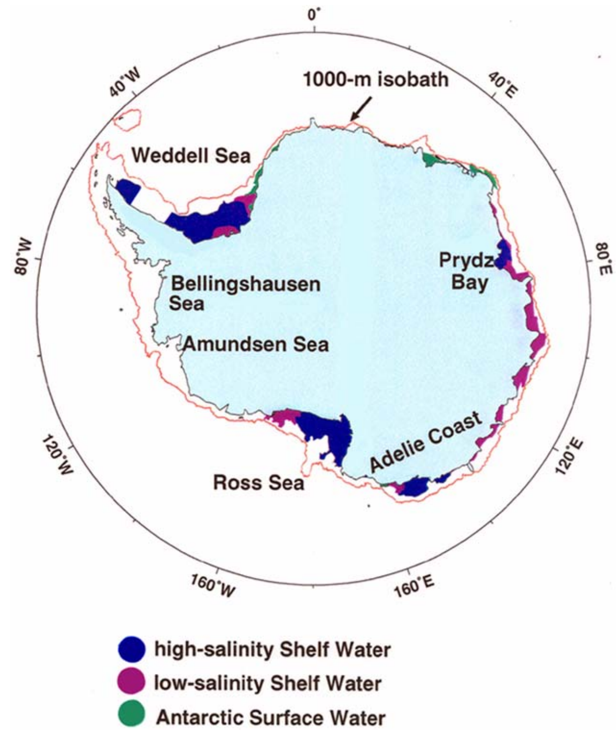

Fig. 8. Spatial distribution of the waters on the Antarctic shelf based on the bottom salinity.

Ross Sea low-salinity Shelf Water is observed. High-salinity Shelf Water is also observed off George V Land, especially in the western part between 140° and 155°E. Low-salinity Shelf Water is dominated in the Indian sector except for Prydz Bay where high-salinity Shelf Water occupies the large portion of the shelf. In the Weddell Sea, the water on the shelf having salinity greater than the cut-off salinity is found in the western part (25°-60°W).

On some Antarctic continental shelves such as the western Indian sector (30°-50°E) and the eastern Weddell Sea (20°-35°W), Shelf Water is absent and AASW fills the shelf bottom. These regions are identified by green colors in Fig. 8. The waters on those shelves are too light to mix isopycnally with LCDW (see Fig. 5 and Fig. 6), suggesting there is no local production of ASFW. However, ASFW is observed even in those regions (see Fig. 7). To sustain ASFW in those regions, the water mass is presumably advected from other source regions.

The composite map of the horizontal distribution of the vertical structures of water masses in the Antarctic continental margin is shown in Fig. 9. Six vertical water mass structures on the Antarctic slope and shelf are identified. First, over most of the Antarctic continental slope, AASW is overlying ASFW as represented by dark shading. This structure is found everywhere along the slope except in the Bellingshausen and Amundsen Seas (73°-155°W) and just east of the Weddell Sea. Note that in the Bellingshausen and Amundsen Seas hydrographic data are few and the water structures analyzed in this study should be further investigated in future studies. Second, in many parts of the continental shelves ASFW overlies Shelf Waters, lying below AASW (hatching over dark background). This is particularly prominent in the Ross Sea.

Third, Shelf Water underlies AASW in the some places close to Antarctica such as the southwestern Weddell Sea, the Indian sector, and the eastern Ross Sea (hatching over the open background). Fourth, where the Antarctic shelf is relatively narrow (e.g., the western Weddell Sea and the western Indian sector), Shelf Water is not found and AASW occupies the entire water column (orange colored regions). Fifth, in a small portion of the southwestern Ross Sea ASFW is found at the surface, overlying Shelf Water (red color). Sixth, in the Bellingdhausen and Amundsen Seas, below AASW LCDW fills the shelf bottom and this structure is identified by crosses in Fig. 9.

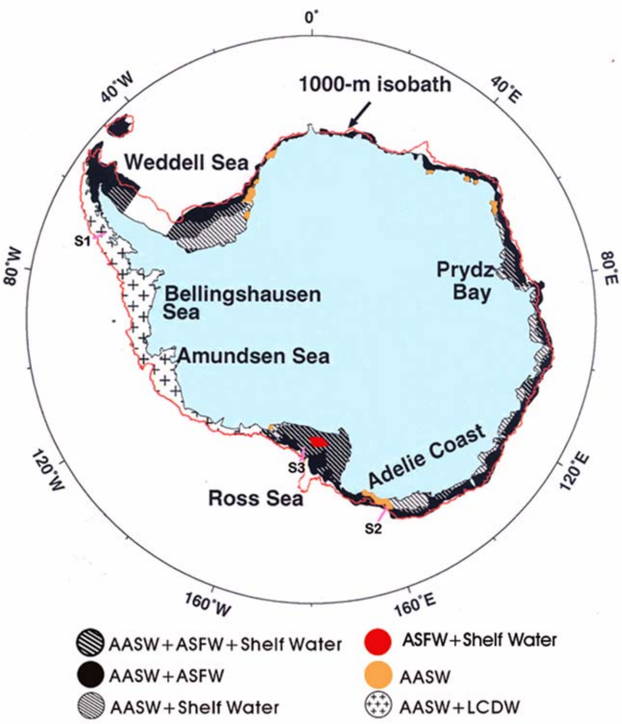

Fig. 9. Composite map of horizontal distribution of vertical water mass structures around the Antarctic continental margin.

The most conspicuous feature in the vertical water mass structure is the intrusion of ASFW onto the wide Antarctic shelves such as the Weddell Sea, the Ross Sea, and Prydz Bay. In the wide Antarctic shelves, Shelf Water, particularly the high-salinity variety, is found, whereas in the narrow shelves Shelf Water is not observed. This suggests that the shelf salinity may be associated with the intrusion of ASFW onto the Antarctic continental shelf. High-salinity shelf water is primarily produced by surface freezing and subsequent brine release. In addition to the surface freezing, Jacobs *et al.* (1985) suggested that some portion of the salinity in high-salinity Shelf Water may be originated in the intrusion of the Circumpolar Deep Water. CDW intruded on to continental shelves is subsequently modified to be ASFW by mixing with Shelf Water.

Frontal structures in the Antarctic continental margin

In this study, the water masses along the Antarctic continental margin have been examined and their definitions were generalized based on identifying characteristics and the horizontal distributions of waters on the Antarctic continental shelf and slope have been described. Here the results given in previous sections are used to describe the horizontal density structures associated with the water masses around the Antarctic continental margin.

In many parts of the Antarctic continental shelf edges, large meridional gradients of potential temperature and salinity have been observed. The meridional density gradients, implying the presence of associated zonal flow, may be in response to two factors: 1) the wind pattern over the Antarctic subpolar regime and 2) buoyancy forcing due to density difference between water masses. A predominant wind pattern in the Antarctic subpolar regime is westward, which is associated with the southern limb of the cyclonic subpolar gyres observed in the Weddell Sea (Gordon *et al.* 1980) and the Ross Sea (Reid 1986) (see Fig. 1). The westward surface flow along the Antarctic continental margin seems to be the nearly continuous connection of the southern limbs of the cyclonic gyres.

Second, over a large portion of the Antarctic continental shelf there are water masses as dense as or denser than LCDW (see Fig. 8) and can descend to an intermediate depth or the bottom. As dense water flow offshore and descends toward the level of its in situ density, it turns to the west by geostrophic adjustment. Westward subsurface flows have been observed in the Weddell Sea continental margin (Gill 1973; Foldvik and Kvinge 1974; Foldvik *et al.* 1985; Fahrbach *et al.* 1992, 2001) and in the northern margin of the South Shetland Islands (Nowlin and Zenk 1988).

There is little horizontal density structure in the surface layers, because AASW is common to both the oceanic and the shelf regimes (Fig. 3). Furthermore, below AASW in the oceanic regime LCDW has nearly uniform characteristics around Antarctica. However, the variety of water masses in the shelf regime can result in large regional differences in the stratification and consequently in the horizontal density structures between the shelf and oceanic regimes.

In the Antarctic continental margin, three types of water stratifications are observed associated with the presence of different water masses over the shelf and at the shelf edge (Fig. 10). The first type is observed in the Bellingshausen and Amundsen Seas where LCDW intrudes far onto the continental shelf and there is no significant meridional density gradient between the shelf and oceanic regimes. This situation is illustrated in vertical section 1, which is located at approximately 70°W (see Fig. 9). In this vertical section, potential temperature and salinities show no distinct meridional variations and consequently isopycnals (dashed lines) are almost flat over the continental shelf break. The meridionally flat isopycnals imply no zonal baroclinic flow. This type of vertical structure was observed

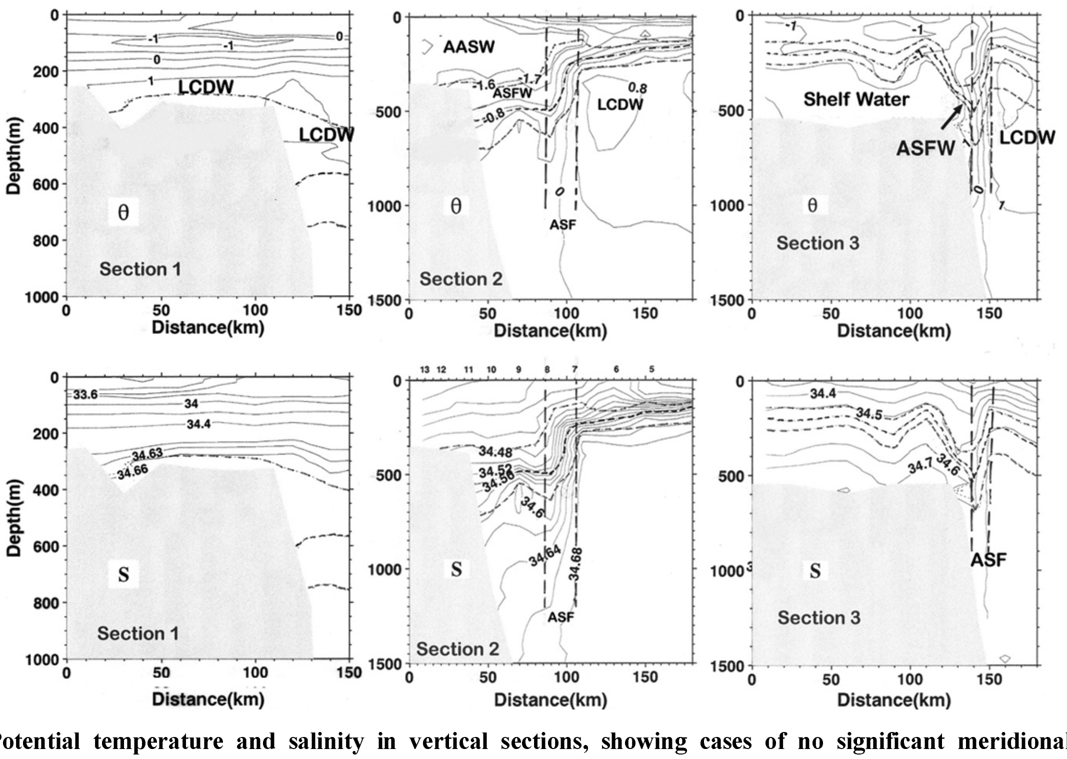

Fig. 10. Potential temperature and salinity in vertical sections, showing cases of no significant meridional property gradient (section 1), the Antarctic Slope Front (section 2), and the V-shaped double front formed by the Antarctic Slope Front and another front over the shelf break (section 3). The sections are selected in the Bellingshausen Sea, off Adélie Land, and in the Ross Sea, respectively (see Fig. 9). Dashed lines show selected potential densities σ_0 = 27.75, 27.78, and 27.80 kg m^{-3} from the upper layer.

by Capella *et al*. (1992) and Hofmann *et al.* (1993) in the Bellingshausen Sea and they speculated that the slope current observed north of the South Shetland Islands, for example, by Nowlin and Zenk (1988) may not be found west of about 63°W.

A second type of vertical stratification occurs where there is ASFW on the Antarctic shelf edge. In such regions, a strong meridional property gradient between ASFW and LCDW is formed and this meridional gradient was referred to as the Antarctic Slope Front by Ainley and Jacobs (1981), Jacobs (1986, 1991), and Whitworth *et al.* (1998). The Antarctic Slope Front is illustrated in vertical section 2 (Fig. 10), which was made off George V Land (about 160°E) where both AASW and ASFW are found. In this section, the Antarctic Slope Front is identified by the sloping sharply down toward the Antarctic continental slope. The inclination of isopycnals means that cold and fresh ASFW is less dense than warm and saline LCDW at the same isobaric level. The Antarctic Slope Front appears as a subsurface feature because the waster masses associated with it are located below the surface water. The zonal flow associated with the Antarctic Slope Front in this region was observed by Jacobs (1992). He observed the westward movement of a large iceberg driven by subsurface currents. Fig. 9 shows that zonal extent of the ASFW is associated with the presence of the Antarctic Slope Front.

The third type is found where both Shelf Water and ASFW exist in the Antarctic continental margin. In addition to the gradient (the Antarctic Slope Front) between ASFW and LCDW, a second meridional property gradient is observed over the shelf break between Shelf Water and ASFW as shown in vertical section 3 (Fig. 10). This section is located in the middle Ross Sea where both Shelf Water and ASFW exist (Fig. 9). Associated with the characteristics of Shelf Water and ASFW, the isopleths slope down toward the north and together with the Antarctic Slope Front form the V-shaped front and this type of front has been typically observed in the Weddell Sea and Ross Sea (Gill 1973; Jacobs 1986, 1991). The distribution of water masses (Fig. 9) indicates that the V-shaped double front is presumably found in many regions around Antarctica in addition to the Weddell and Ross Seas as also shown by Whitworth *et al.* (1998).

4. Summary

Using synthesized hydrographic data, the spatial distribution of water masses around the Antarctic continental margin and associated vertical stratifications are described. In the shelf regime, AASW is distinguished from underlying denser water masses by the salinity at the base of the temperature minimum layer of AASW in the neighboring oceanic regime. This salinity criterion, named the cut-off salinity, varies from 34.35 to 34.45 around Antarctica, and is 34.4 on average. In both the oceanic and shelf regimes, AASW is defined as the surface water with salinity less than the cut-off salinity.

Shelf Water is defined as the water over the continental shelf having salinity greater than the cut-off salinity and potential temperature less than an arbitrary −1.7°C. Low-salinity Shelf Water is distinguished from high-salinity Shelf Water by the maximum potential density of LCDW (σ_0 = 27.87 kg m^{-3}). This new definition of Shelf Water means that it is not found over all Antarctic shelves; in some places AASW occupies the entire shelf (e.g., in the eastern Weddell Sea and in the western Indian sector). Shelf Water, particularly the high-salinity variety, is observed on Antarctic shelves such as the Ross Sea, off George V Land, Prydz Bay, and the western Weddell Sea.

LCDW is observed everywhere around Antarctica with almost uniform characteristics. In some places it mixes with Shelf Water and produces ASFW between the shelf regime and the oceanic regime. ASFW is defined as water between the shelf regime and the oceanic regime with potential temperature less than about 0°C but greater than −1.7°C, and salinity greater than the cut-off salinity. Most ASFW is formed by near isopycnal mixing of LCDW with low-salinity Shelf Water. The resulting water mass, referred to as low-salinity ASFW, is characterized by densities less than the maximum density of LCDW (σ_0 = 27.87 kg m^{-3}). A less common (high-salinity) ASFW is found with densities greater than σ_0 = 27.87 kg m^{-3}, thus this is not a product of mixing between LCDW and high-salinity Shelf Water. This high-salinity ASFW is presumably the product of diapycnal mixing of LCDW and high-salinity Shelf Water. ASFW is found everywhere along the continental slope around Antarctica except in the Bellingshausen and Amundsen Seas.

Over the Antarctic continental margin, there are three types of frontal structures. One type, having no significant meridional property gradients at the shelf edge, is found in the Bellingshausen and Amundsen Seas where LCDW commonly exists in both the oceanic regime and the shelf regime. Second type is found where there is ASFW in the shelf edge. In this region, the large meridional gradients associated with the property differences between ASFW and LCDW is formed and this region of large meridional gradient was referred to as the Antarctic Slope Front. The front extends zonally from the eastern Ross (about 155°W), past the Indian sector, to the western end of the South Shetland Islands (about 63°W). Third type exists in places where both ASFW and Shelf Water are found. In this type of frontal structure, an additional meridional gradient is observed between ASFW and Shelf Water over the shelf break and forms the V-shaped front together with the Antarctic Slope Front.

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