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Preliminary Observation along a Hydrographic Section in the Weddell Sea during the 1996 Field Season

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ABSTRACT. From temperature and salinity fields observed during the 1996 field season, several water masses are identified. Those are Antarctic Surface Water, Winter Water, Lower Circumpolar Deep Water, and Antarctic Slope Front Water with low salinity. Also identified is the presence of V-shaped double front, i.e., Antarctic Slope Front. The front is located north of the shelf break. As revealed by the flow field observed by an ADCP, strongly nonlinear processes dominate the observed currents.

Key Words: Antarctic Slope Front, Antarctic Slope Front Water, nonlinear processes, Weddell Sea

Introduction

Antarctic Bottom Water (AABW) has been known to play an essential role in the abyssal circulation of the world ocean. The AABW is formed in the region near the edge of continental shelf break around Antarctica by mixing of near-surface water with Circumpolar Deep Water. The mixing and other related processes are revealed as strong subsurface gradients of water properties. The subsurface gradients are called as Antarctic Slope Front (ASF) (Jacobs 1986, 1989, 1991). Jacobs (1991) reviewed its hydrography, currents, processes, and biological productivity. The shape of the front is affected by shelf width. For narrow or relatively shallow shelves, this topographic front becomes shallow and flattens towards the north, merging with the pycnocline beneath the thick and deep temperature minimum. However, for wide shelves, V-shaped double front appears with the minimum salinity in its middle part. The slope front is weaker where shelf water and adjacent deep-water salinities are roughly equal. If nearly undiluted tongues of Circumpolar Deep Water floods the continental shelf, the front is less pronounced, as observed in the Bellingshausen Sea (Potter and Paren 1985). Temporal changes of the slope front would be mainly also subject to that of shelf water. Other studies for Antarctic coastal circulation and the slope front include Gill (1973), Carmack (1974), Foster & Carmack (1976), Carmack & Foster (1977), Foldvik *et al.* (1985a, b), Fahrbach *et al.* (1992), Ohshima *et al.* (1996), Kim (1995), and Hofmann & Klinck (1997).

This article is to document results obtained from the hydrographic survey carried out during the 10-th Korean Antarctic Research Program, 25-28 December 1996 (Fig. 1). Fields of water temperature, salinity, and velocity were observed along a hydrographic section using Sea-Bird's 911 Plus CTD system and RDI's direct reading Acoustic Doppler Current Profiler (ADCP). The section was mainly along the 55° W meridian north and south of Elephant Island. Its southern stations located over continental shelf were slightly shifted to the east. The edge of sea ice was close to the southernmost station. Because this survey was mainly for surface biological research, CTD casts were performed up to

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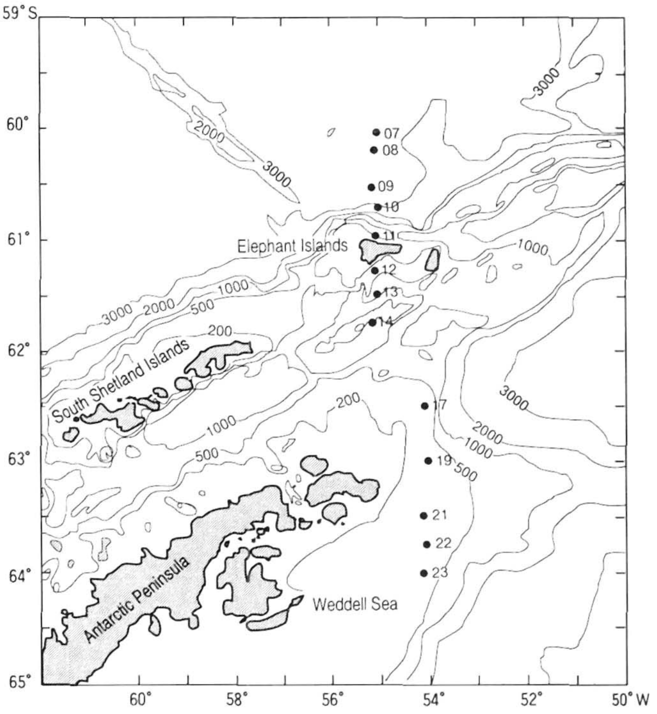

Fig. 1. Bathymetry and station location for the 10th Korea Antarctic Research Program, 1996.

the water depth of 200 m, except Stations 10, 11, 13, and 14. Locations of stations and other information are listed in Table 1.

In the following section, properties of water masses are summarized, which are identifiable in the study area. In section 3 observed fields of temperature and salinity are described at sampled stations and along the section. In section 4 geostrophic currents are compared with ADCP velocity fields measured. Summary and discussion are in the final section.

Water-Masses over the Antarctic Continental Shelf and Slope

Summarized below and in Table 2 are properties of water masses found over the Antarctic continental shelf and slope (Carmack 1986; Kim 1995).

Antarctic Surface Water (AASW) and Winter Water (WW)

AASW is found from the surface to approximately 300 m depth in the oceanic regime. Though its salin-

Table 1. Information on CTD observations

Station	Observation time / (Local time)	Cast used	Casted depth (m)	Latitude & Longitude
7	Dec. 26 1996 / (18:25)	up	200	60° 04.26' S, 54° 58.19' W
8	Dec. 26 1996 / (22:15)	up	200	60° 12.98' S, 55° 01.85' W
9	Dec. 27 1996 / (05:25)	up	200	60° 31.98' S, 55° 02.40' W
10	Dec. 27 1996 / (13:10)	up	728	60° 46.37' S, 55° 03.38' W
11	Dec. 27 1996 / (15:15)	up	307	60° 58.95' S, 54° 56.71' W
12	Dec. 27 1996 / (21:10)	up	199	61° 17.31' S, 55° 01.25' W
13	Dec. 28 1996 / (00:06)	up	748	61° 29.11' S, 54° 55.86' W
14	Dec. 28 1996 / (06:30)	down	748	61° 44.72' S, 55° 04.45' W
17	Dec. 26 1996 / (00:55)	up	200	62° 30.17' S, 54° 04.11' W
19	Dec. 25 1996 / (20:20)	up	202	62° 59.97' S, 53° 57.40' W
21	Dec. 25 1996 / (14:05)	up	203	63° 29.77' S, 54° 05.14' W
22	Dec. 25 1996 / (11:30)	up	205	63° 44.49' S, 54° 01.12' W
23	Dec. 25 1996 / (07:30)	up	202	64° 00.00' S, 54° 03.00' W

Table 2. Generalized characteristics of water mass in the subpolar region. S at θ_{min} is for the salinity at the base of the potential temperature minimum layer of Antarctic Surface Water in the oceanic regime. *s* and *w* with AASW are for summer and winter seasons, respectively. *l* and *h* with SW and ASFW are to indicate low- and high-salinity, respectively. From Kim (1995)

Water mass	Potential temperature(°C)	Salinity (psu)	Oxygen (*ml/l*)	Potential density
AASW(*s*)	$\theta>-1.7$	$S<34.35$	$O_2>7.5$	$\sigma_0<27.65$
AASW(*w*)	$-1.9<\theta<-1.7$	$34.35<S<$ S at θ_{min}	$7.0<O_2<7.5$	$27.65<\sigma_0<27.70$
LCDW	$\theta>0$	$S>34.66$	$4.0<O_2<5.5$	$27.77<\sigma_0<27.87$
SW(*l*)	$\theta<-1.7$	S at $\theta_{min}<S<34.60$	$O_2<7.0$	$27.70<\sigma_0<27.87$
SW(*h*)	$\theta<-1.7$	$S>34.60$	$O_2<7.0$	$\sigma_0>27.87$
ASFW(*l*)	$-1.7<\theta<0$	S at $\theta_{min}<S<34.60$	$5.5<O_2<7.0$	$27.70<\sigma_0<27.87$
ASFW(*h*)	$-1.7<\theta<0$	$S>34.60$	$5.5<O_2<7.0$	$\sigma_0>27.87$

ity varies with space and time, salinity range is from approximately 34.35 to 34.45 psu. In winter its density is in approximate range of σ_0 from 27.65 to 27.70. In summer, due to precipitation, surface heating, and ice melting, the upper layer of AASW becomes warmer and fresher than the lower layer, resulting to Winter Water (WW). The WW is thought to be a remnant of wintertime convection, which is represented by temperature minimum layer. Near the continental margin and in the central Weddell and Ross gyres, the WW shows temperature near the freezing point and salinity approaching the critical value for the onset of the cabelling instability (Fofonoff 1956). Toole (1981) has discussed the seasonal maintenance of the temperature minimum layer.

Shelf Water (SW)

It is defined as water over the Antarctic shelf regime with salinity greater than the cut-off salinity and potential temperature less than -1.7°C. The cut-off salinity is defined as the salinity at the base of the potential temperature minimum layer of the AASW in the oceanic regime, whose value is approximately from 34.35 to 34.45 psu (Kim 1995). Low-salinity Shelf Water is distinguished from high-salinity Shelf Water by the maximum potential density of Lower Circumpolar Deep Water ($\sigma_0 = 27.87$).

Lower Circumpolar Deep Water (LCDW)

LCDW shows potential temperature greater than 0°C and salinity greater than 34.66 psu. It is observed everywhere around Antarctica with almost no change in characteristics.

Antarctic Slope Front Water (ASFW)

According to Kim (1995), the ASFW is characterized by potential temperature between -1.7°C and about 0.2°C, and salinity greater than the cut-off salinity. The ASFW is observed everywhere around Antarctica along the Antarctic continental slope except in the Bellingshausen-Amundsen sector between 63° and 155° W. Low-salinity ASFW is produced by isopycnal mixing of LCDW with low-salinity Shelf Water. High-salinity ASFW is produced by diapycnal mixing of low-salinity ASFW with high-salinity Shelf Water, which has densities greater than the maximum density of LCDW.

Temperature and Salinity Fields Observed

In this section observed properties of temperature and salinity are described, while referring to the properties of water masses summarized. Vertical profiles of temperature, salinity, and density are shown at stations north and south of Elephant Island, and the northernmost station over the continental shelf (Fig. 2). Spatial distributions of the three variables are also shown along the hydrographic section in Fig. 3. Hereafter temperature is used in place of the potential temperature used in the previous section.

As shown in Fig. 2, temperature minimum is located within the WW at each station north of Elephant Island. At Station 7, the northernmost station, the temperature minimum of -0.15°C is located at the depth of 80 m. Temperature minimum of -0.5°C appears at the depth of 100 m at Station 10. The temperature minima located at the core depth of WW are deeper at Stations 10 and 11 than those at other stations further north (Fig. 3a). The line connecting the temperature minima curves out toward the free surface about the depth of 100 m in the north of Elephant Island. However, the presence of WW is not observed at Stations 13 and 17 (Fig. 2), actually all stations south of Elephant Island (Fig. 3a).

At Stations 7 and 10 depths of mixed layer are slightly shallower than those of the temperature minimum (Fig. 2). At Station 13 temperature decreases with depth, while being interrupted by signals of interleaving waters centered at depths of 150 m and 240 m, for example. There is no well-defined mixed-layer at this station. At Station 17, the northernmost station over the Antarctic continental shelf, the upper layer of approximately 50 m thick almost coincides with the mixed layer. It is also observed that the temperature below the mixed layer decreases and then increases with depth, while salinity and density increase monotonically with

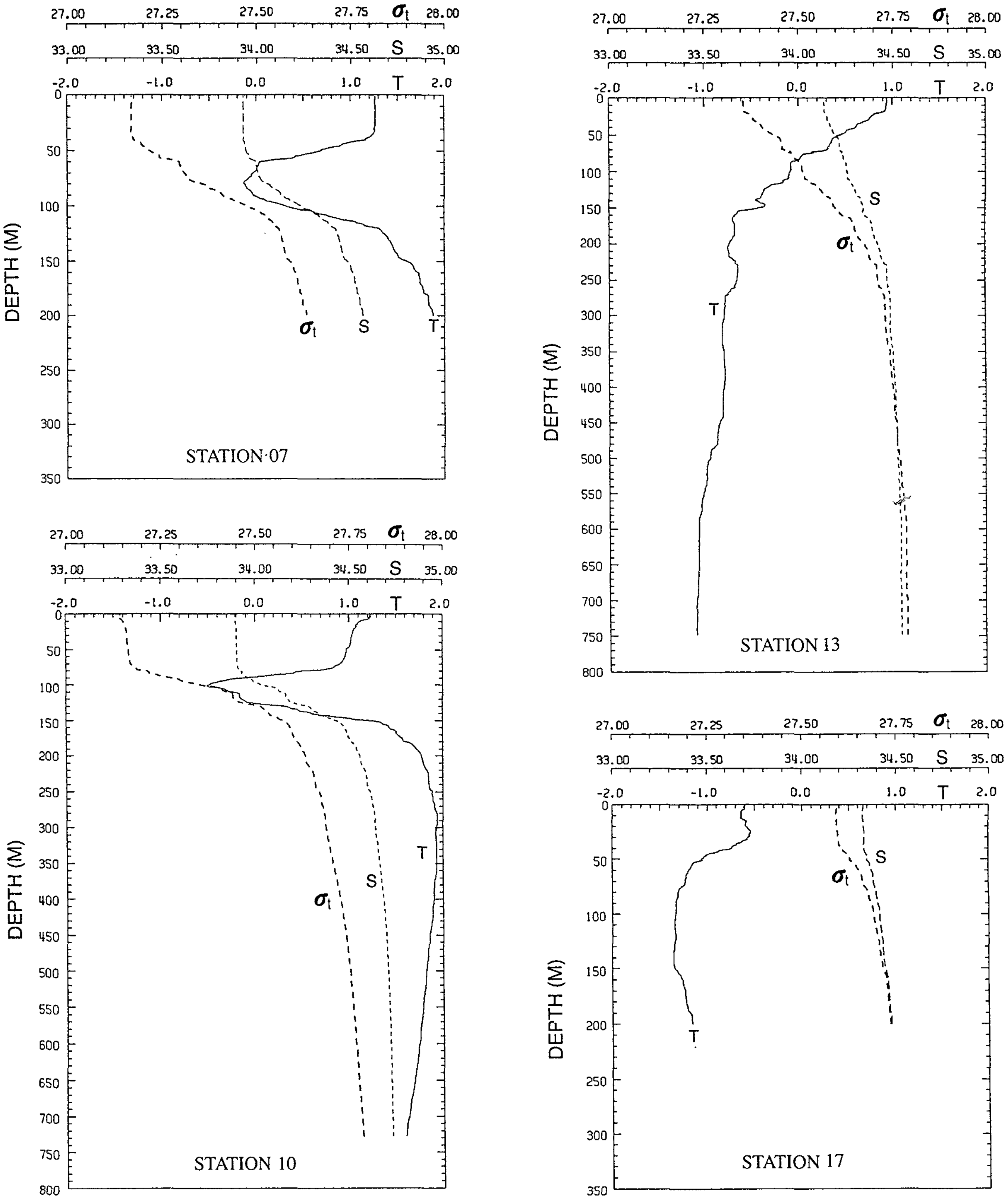

Fig. 2. Temperature, salinity, and density profiles at sample stations.

depth. Temperature profile is also interrupted by signals of interleaving water.

Vertical isotherms over the northern flank of the island bend to the north direction and follow the curve of temperature minima above (Fig. 3a). The bent isotherms appear to enclose warmer and more

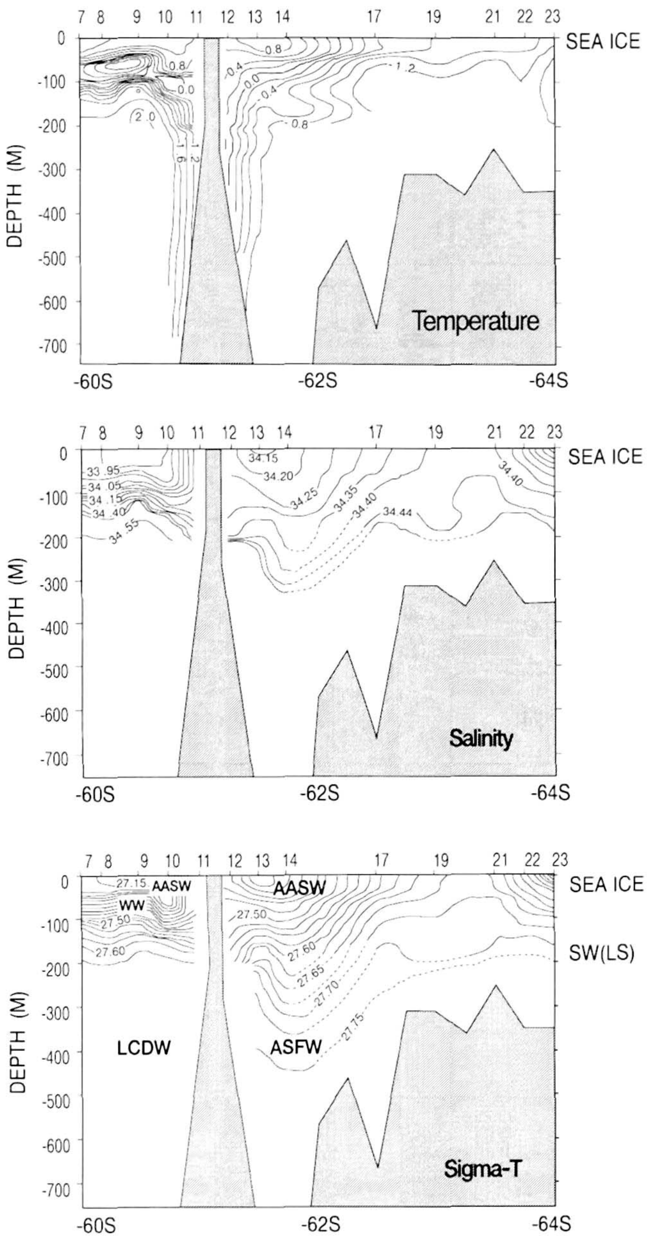

Fig. 3. Hydrographic section taken during the tenth KARP: (a) temperature, (b) salinity, and (c) density.

saline water mass than any other water-masses observed (Figs 3a and 3b). At the depth of 290 m at Station 10, the temperature maximum of 1.935°C is appeared (Fig. 2). Its salinity value is very close to the minimum value of salinity characterizing the LCDW. Though the CTD cast is up to the depth of 200 m at Station 7, values of temperature and salinity are higher than those observed at Station 10. Thus the LCDW is located below the bent isotherms.

Vertical isotherms over the southern flank curve to the south and reach the free surface (Fig. 3a). These isotherms look like a barrier to the body of water whose temperature is colder than 0°C and which occupies over the Antarctic continental shelf with the ice edge close to the southern end of the hydrographic section.

In contrast to the vertical isotherms reaching the free surface, isohalines below 200 m depth, south of the island, can be connected to those over the shelf and show V-shape between Stations 12 and 17 (Fig. 3b). The pattern of σ_t distribution is very similar to that of salinity due to the fact that, in polar regions, salinity controls seawater density more strongly than temperature does (Fig. 3c). The feature can be described as the V-shaped front (Gill 1973; Jacob 1986, 1989, 1991). Water mass of the V-shaped front is identified as the ASFW (Kim 1995) by ranges of temperature and salinity. The observed ASFW turns out to be the low-salinity ASFW which would be produced by the isopycnal mixing of LCDW with low-salinity SW. The low-salinity SW is definitely located further south.

South of Station 21 salinity and density contours increase radially from the top of Station 23 in the depth range of zero to 100 m (Figs 3b and 3c). The radial salinity-contour of 34.40 psu might be the boundary representing the direct effect of melting ice. Temperature shows small spatial change, but not in the radial pattern (Fig. 3a). The presence of sea ice is believed to play the role of reservoir of cold and less-saline water which provides buoyancy to the upper part of the observed water.

Between the island and north of Station 17, there appears a body of warmer and less-saline water which can be bounded by contours of 0.6°C and 34.25 psu, respectively (Figs 3a and 3b). This body of water shows similar properties to those of the AASW north of the island. Due to the buoyancy source described above, isopycnals are not horizontally extended further south, but curve to the free surface (Fig. 3c).

Comparison between Measured and Geostrophic Velocities

The ADCP was used to measure instantaneous current profiles at the CTD stations. Baroclinic part of currents are computed as follows from currents measured by the ADCP in order to compare with geostrophic currents. The measured ADCP currents at two neighboring stations are rotated into the direction of geostrophic currents at the mid-point between the two stations. The baroclinic part of currents measured by the ADCP is obtained by subtracting the rotated currents at the level of no motion from all others above. It is also presumed that tidal currents would be barotropic. Then the rotated currents are interpolated to get current velocities at the mid-point in order to obtain flows corresponding the geostrophic flows. We call it modified ADCP currents.

Flow fields in the upper 200 m are shown in Fig. 4. In the figure the top and middle frames are the geostrophic and modified ADCP currents. The bottom frame is for the difference flow field which is obtained by subtracting the modified ADCP flow from the geostrophic flow. The geostrophic currents show weaker flows than the modified ADCP currents, which has weak vertical and horizontal shears. The modified ADCP currents show stronger shears than the geostrophic currents do. Comparison of magnitudes of the two flow fields reveals the difference of an order of magnitude. The overall magnitude of the modified ADCP flow field is, roughly speaking, ten-times larger than that of the geostrophic flow field.

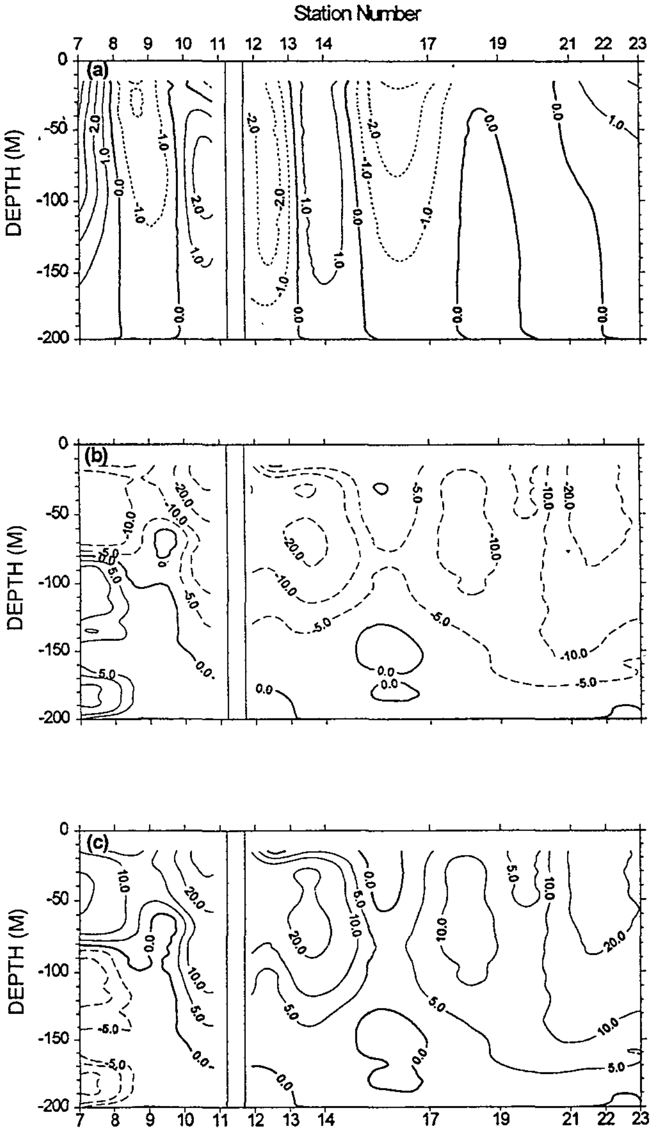

Fig. 4. (a) Geostrophic flow field computed with the level of no motion at the depth of 200 m. (b) Modified ADCP flow field (c) Flow field of the difference obtained by subtracting the modified flow field from the geostrophic flow field. Positive (negative) velocity is contoured with solid (dotted) line and flows to the east (west) approximately.

Summary and Discussion

As reported in other studies, followings were identified from the CTD section mainly along the 55° W meridian north and south of Elephant Island during the 10th Korean Antarctic Research Program, 25-28 December 1996.

(1) Winter water was observed at stations north of Elephant Island. The depth of temperature minimum in the winter water is deeper than the bottom depth of mixed layer.

(2) The presence of Lower Circumpolar Deep Water was identified.

(3) Sea ice located further south provided buoyancy forcing directly to the upper layer of 100 m thick.

(4) The V-shaped double front was identified in the subsurface water north of the continental shelf break and coexisted with Antarctic Slope Front Water.

(5) The flow fields were dominated by strongly nonlinear processes.

Geostrophic currents were calculated under the assumption that the Coriolis term was in balance with the pressure-gradient term in governing equations of motion. However, the modified ADCP currents are believed to have other currents which are not in geostrophic balance, although we presumed that tidal currents were deleted. That is, nonlinear terms and the term representing local rate of change in momentum equation. There are many phenomena which are not in the geostrophic balance. Fronts, eddies, and continental shelf waves are candidates for the phenomena we can easily expect to exist in the study area. Middleton *et al.* (1987) showed strong evidence for the existence of barotropic shelf waves at diurnal frequencies in the shelf break region in the southern Weddell Sea. The barotropic shelf waves are expected to pass through the study area. It should also be pointed out that our knowledge of tides and tidal currents in the study area, actually in the whole Weddell Sea, is still poor (Lutjeharms *et al.* 1985). The features with isopycnals reaching the free surface can be explained by nonlinear phenomena. Its examples are the two features present in the south of the island which are the body of warmer and less-saline water located south of the island and the cold reservoir due to the presence of the sea-ice edge (Fig. 3c). The nonlinear processes could explains why the geostrophic and the modified flow fields are not similar to each other. In other words, the Rossby number could be estimated larger than one.

Five items listed above are just for qualitative description. There were several phenomena we could not describe further due to lack of proper data. Those are as follows.

(1) Stations 7 and 10, mixed layer depths were slightly shallower than those of temperature minimum. This could be due to, at the time of observation, wind-stirring effect was less-effective than that of net incoming radiation.

(2) Vertical isotherms north and south of Elephant Island could serve as a barrier for the possible heat flux. Or those could represent some phenomena related to the topography around the island.

(3) There are interleaving signals at Stations 13 through 17.

(4) The core of less-saline water in the upper layer south of Elephant Island could be due to the process trapped around the island. This would need three-dimensional data for process identification.

In general, we need to have oceanographic data set for the whole water column in the three-dimensional structure in order to make progress toward the full description of the phenomena mentioned above and to try dynamical interpretation further. Especially for the V-shaped double front identified, we additionally need to map the front with horizontally finer resolution than the present one at least in the cross-shelf direction. Current meter moorings are also required at several depths.

With the available data set, following can be mentioned for the V-shaped double front. Salinity distribution over the continental shelf was strongly affected by sea-ice melting. The sea-ice melting is definitely caused by the net incoming radiation and could contribute to the formation of V-shaped isohalines representing the Antarctic Slope Front. The V-shaped feature would indicate the presence of a conduit next to and along the shelf break for the fluxes of relevant tracers, as mentioned in other studies. As Jacob emphasized (1991), it is believed that the study area could be one of sites where descended water from the near-surface is on its way to the deep ocean through bottom boundary layers beneath the Antarctic Slope Front.

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