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SEASONAL VARIATIONS IN OCEAN STRUCTURE AND CURRENT IN ONGUL STRAIT, ANTARCTICA, IN 1991

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Abstract: Ocean structure and current were observed below fast ice in Ongul Strait, Antarctica, over a nearly full annual cycle in 1991. In the austral fall, fresh, cold and oxygen-rich water accumulates in the upper layer. This water is diffused or mixed with the lower-layer water gradually in winter. From spring to summer, warm, saline and oxygen-poor water appeared in the mid-depth and deep layers. These features seem to be common in every year. Horizontal oceanic advection is dominant in the heat and salt budget. In spite of no direct wind forcing and negligible thermohaline forcing, the current in Ongul Strait is found to be strong, with a typical velocity being 0.3 m/s. The strong current is confined only to the upper 100–300 m from the surface. The direction of the mean current changes drastically from southward to northward in May.

1. Introduction

In the sea-ice-covered region near Antarctica, there have been few oceanographic observations covering a full year so far. In the Antarctic coastal region, ALLISON *et al.*(1985) observed water temperature and salinity profiles below fast ice near Mawson Station over a full annual cycle. They examined the annual heat and salt budget and showed that oceanic advection plays an important role in both the heat and salt balance.

Syowa Station is located near Ongul Strait in Lützow-Holm Bay, a fast-ice-covered region in Antarctica. WAKATSUCHI (1982) first observed the oceanographic conditions in Ongul Strait over a nearly full annual cycle in 1976 during the 17th Japanese Antarctic Research Expedition (JARE-17). In 1982–1985 (JARE-23, -24 and -25), under the Japanese BIOMASS project, more intensive oceanographic observations were carried out in Ongul Strait (FUKUCHI *et al.*, 1985a; SATOH *et al.*, 1986; MATSUDA *et al.*, 1987). OHSHIMA *et al.* (1991) showed, using these data, that water influenced by Circumpolar Deep Water (CDW) is advected from open ocean to Ongul Strait and that the advected water becomes more like CDW from winter to summer.

In 1990–1992, under the Japanese Antarctic Climate Research (ACR) project, extensive observations of ocean, sea ice and atmosphere have been carried out in and off Lützow-Holm Bay by JARE-31 and -32 for better understanding of interaction among air, sea and sea ice in sea-ice-covered regions. Special emphasis is paid to the seasonal variations in ocean structure, which are not yet well understood. Preliminary results in 1990 by JARE-31 were reported by TAKIZAWA *et al.* (1992).

During JARE-31 and -32, most intensive observations have been made in Ongul Strait. Ongul Strait is a good site for examining interannual variabilities, since most of the observations in the past were made in Ongul Strait. In JARE-31, CTD and water sampling observations were made from April to December almost monthly in Ongul Strait. As suggested by OHSHIMA *et al.* (1991) and TAKIZAWA *et al.* (1992), oceanic advection plays an important role in the variations in ocean structure. Thus, in JARE-32, in addition to the observations of ocean structure, current measurements were also made. This paper is a preliminary report on the seasonal variations in ocean structure and current in Ongul Strait in 1991.

2. Observational Sites and Methods

Ongul Strait is located between East Ongul Island and the antarctic continent in the eastern part of Lützow-Holm Bay (Fig. 1). Its width is about 4 km and the maximum depth is about 700 m. The observational sites are almost the same positions as those of JARE-31. CTD, water and ice-core samples were taken monthly and moored current measurements were made at St.OS3 (68° 59.9′S, 39°40.3′E; the water depth is 649 m). Only the final CTD observation on January 4th, 1992 was made near OS2, since a number of puddles were formed around OS3. Ongul Strait was covered with fast ice throughout 1991. At OS3, the sea ice thickness increased from 92 cm in March to 161 cm in December. The sea ice conditions in Ongul Strait are described in KAWAMURA *et al.* (1993).

Vertical profiles of temperature and salinity were obtained with a conductivity-temperature-depth unit (Seabird SBE-19). Water samples were collected with Nansen bottles from March to October. Dissolved oxygen concentration was determined by Winkler's method. Vertical profiles of current were measured with

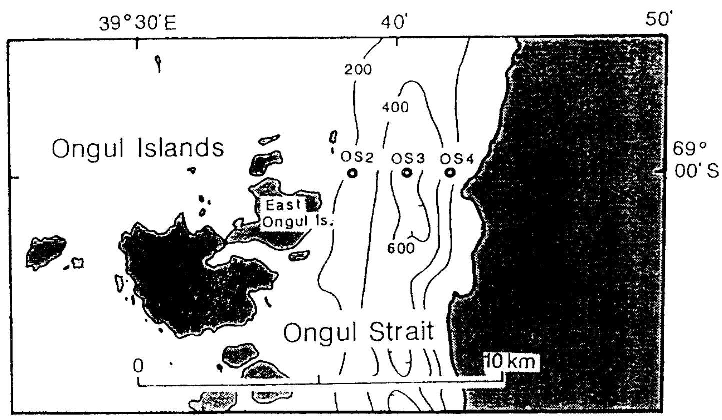

Fig. 1. Locations of oceanographic stations in Ongul Strait. The depth contour interval is 200 m.

an electromagnetic current meter (ALEC ACM8M). The currents were usually measured at every 20 m depth from the sea surface. Aanderaa current meters (RCM-7) were moored for current measurements over a long period. The current meters were suspended at the depths of 70 m and 370 m from the fast ice through a hole in the ice. Observational periods were from April 1 to July 17, from July 18 to November 7, and from November 8 to December 10. In the first two periods, only the upper layer (70 m below the fast ice) was measured at intervals of 30 min, while in the final period two layers were measured at intervals of 10 min.

3. Results

Figure 2 shows the cross sections of the vertical profiles of (a) temperature (b) salinity and (c) velocity in Ongul Strait in early April. It is found that the ocean structure and current are almost horizontally uniform in the strait. TAKIZAWA *et al.* (1992) showed that, also in other seasons, the ocean structure is almost horizontally uniform in the strait. Thus, we consider that properties at OS3 represent those in Ongul Strait.

Figure 3 shows the seasonal variations in (a) water temperature (b) salinity and (c) dissolved oxygen profiles at OS3. In the austral fall (from March to May), fresh, cold and oxygen-rich water is accumulated in the upper layer and can be distinguished from the lower-layer water, which is more saline, warmer and oxygen-poorer. In winter (from June to August), the boundary between these two waters gradually becomes unclear, which suggests that vertical diffusion or mixing between the two waters has progressed. From spring to summer, warmer, more saline and oxygen-poorer water appeared in the mid-depth and deep layers. These characteristics are almost the same as those in 1990 (TAKIZAWA *et al.*, 1992), and similar to those in 1982 and 1983 (FUKUCHI *et al.*, 1985a; SATOH *et al.*, 1986). It is inferred that the ocean structure in Ongul Strait shows similar seasonal variations every year.

ODAMAKI *et al.* (1991) and NAGATA *et al.* (1993) showed that sea level at Syowa Station has large seasonal variations, with maximum in May and minimum in January. The amplitude of the variation (the difference between the maximum and minimum values) is about 26 cm. To examine to what degree the density variation of the water column in Ongul Strait explains the variation of sea level, the geopotential anomalies are calculated at the reference level of 600 dB in Fig. 4a. Though the seasonal pattern of the geopotential anomaly is similar to that of sea level, the amplitude is only about one-fourth of it. Hence, the seasonal variations in sea level cannot be explained only by the variations in ocean structure in Ongul Strait.

The changes in heat and salt contents of the water column to the depth of 600 m have been calculated from the measured temperature and salt profiles, and are shown in Figs. 4b and c, respectively. Salt flux is represented by an increase(+) or decrease(−) of sea-ice thickness corresponding to the salt change in water column between the two observations. Heat and salt budgets in the total

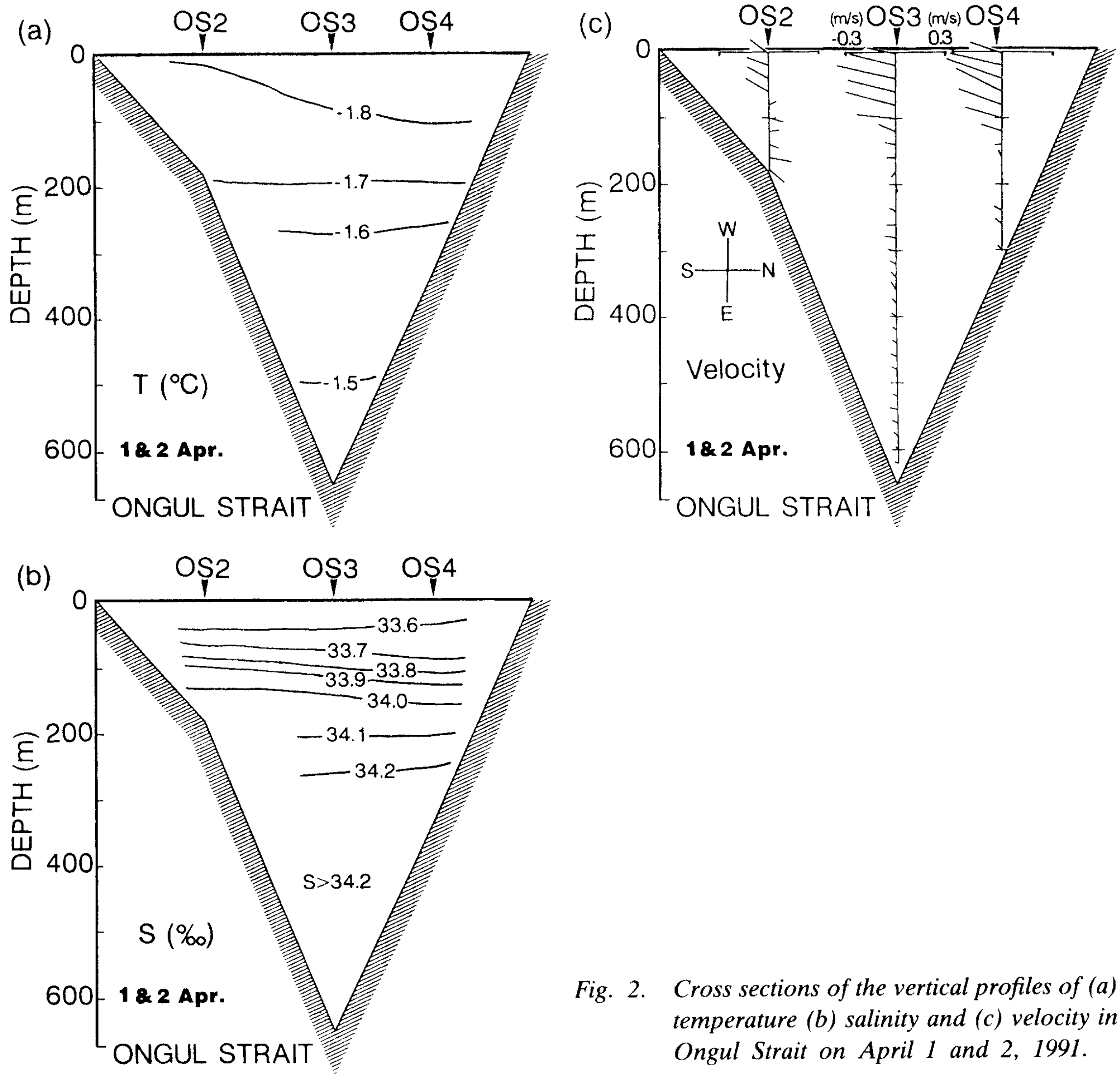

Fig. 2. Cross sections of the vertical profiles of (a) temperature (b) salinity and (c) velocity in Ongul Strait on April 1 and 2, 1991.

water column are determined by the exchange at the ice-water boundary and the horizontal oceanic advection.

In accordance with the accumulation of cold and fresh water, the water column loses considerable heat and salt from March to May. The heat loss reaches about -50 W/m^2 in March and April (Fig. 4b). ONO (1983) estimated, using the data of 1976, that the heat flux from water to fast ice in this region is about 6 W/m^2. This value is likely to apply in 1991, since the sea ice conditions were almost the same as those in 1976. Thus, the large heat loss in this season can be attributed mostly to oceanic advection. The salt budget also suggests the importance of oceanic advection. From May to December, the sea ice thickness increased by 70 cm at OS3. Nevertheless, in April, the water loses large salt, corresponding to the melting of a sea-ice thickness of about 1.7 m (Fig. 4c).

Note in Fig. 4b that large heat gain occurs in November. ALLISON *et al.*, (1985) also showed that oceanic heat advection increases in November near Mawson Station on the antarctic coast. Persistent positive salt gain from May to

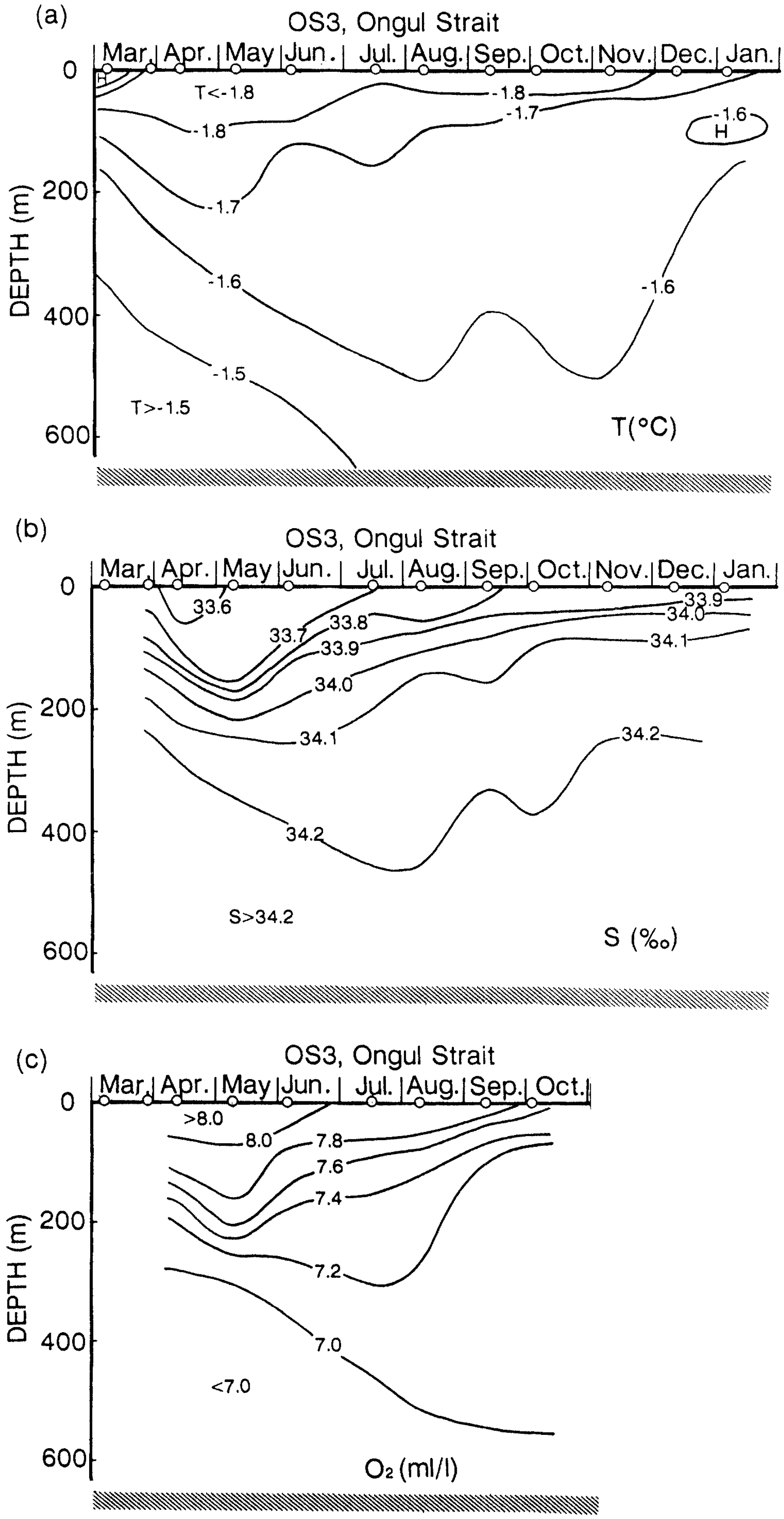

Fig. 3. Seasonal variations in (a) water temperature (b) salinity and (c) dissolved oxygen profiles at station OS3 in Ongul Strait, in 1991.

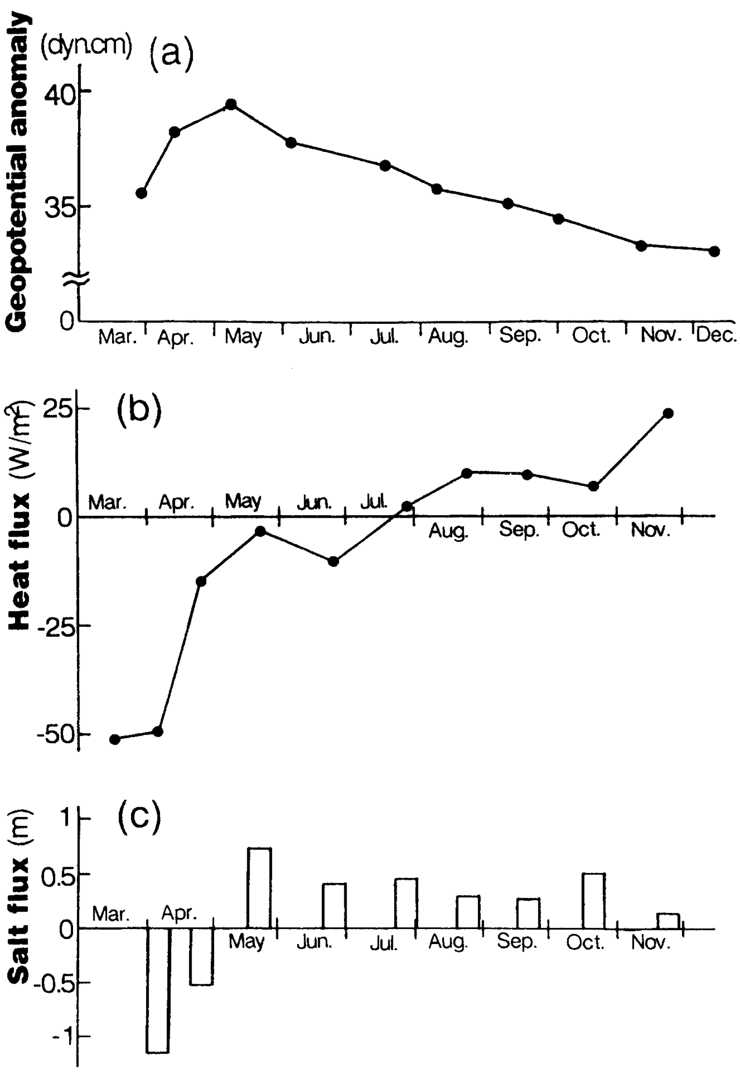

Fig. 4. Seasonal variations in (a) geopotential anomaly (b) heat flux and (c) salt flux in the water column to the depth of 600 m at OS3. Plus (minus) heat flux means heat gain (loss) in the water column. Salt flux is represented by an increase (+) or decrease(−) of sea-ice thickness corresponding to the salt change in water column between the two observations, in which salinity of sea ice is assumed to be 4 ‰.

November implies that the advected water becomes more like Circumpolar Deep Water from winter to summer, as suggested by OHSHIMA *et al.* (1991). In summary, the heat and salt budgets are determined mostly by oceanic advection, not by the local balance. This is consistent with the existence of strong current as will be shown next.

Stick diagrams of the current velocity at 70m depth (below fast ice) at OS3 are shown in Fig. 5. It is found that the velocity has a typical value of 0.3 m/s. The most remarkable phenomenon is that the direction of the mean current changes drastically from southward to northward in May. This phenomenon

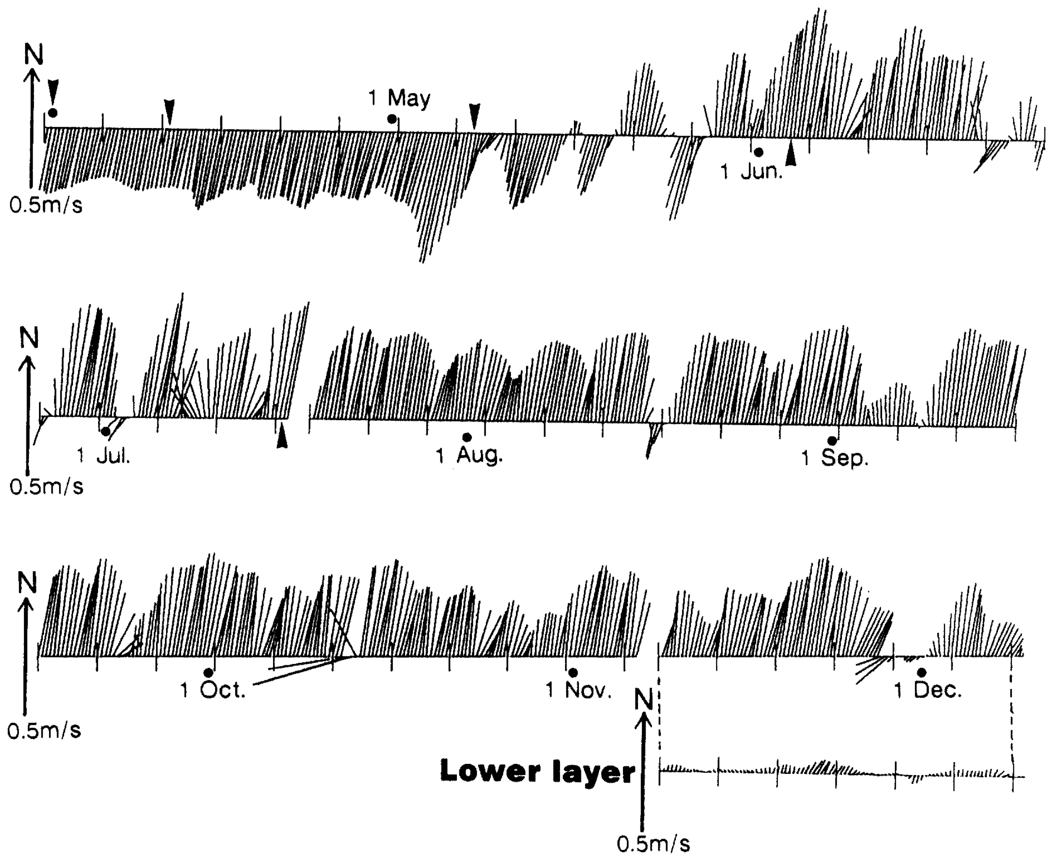

Fig. 5. Stick diagrams of the current velocity at the depth of 70 m and 370 m below fast ice at OS3. The upper layer was measured from April 1 to December 10, 1991, and the lower layer from November 8 to December 10. Running means of 25 hours have been calculated. Tick marks denote 5-day intervals.

differs from the results in 1982, in which the mean current was always northward (FUKUCHI *et al.*, 1985b). It is also noted in Fig. 5 that the current variability on a time scale of about a week is relatively strong from May to mid-July.

Wind stress cannot be applied directly to the water below fast ice. The thick fast ice prevents severe cooling of water from the atmosphere. Further, the growth rate of the fast ice is small in Lützow-Holm Bay, typically less than 10 cm/month. Thus, the local thermohaline forcing seems small in the fast-ice-covered region. Nevertheless, the current is appreciably strong. It is likely that the current is forced remotely rather than locally. One candidate for the driving mechanism is that the current is remotely forced by the wind in the open-water or pack-ice region off the fast ice. The margin of the fast ice region retreated until April, then advanced after June 1991. If the wind is the main driving force, the variation in the margin of the fast ice region might be closely related to the current variabilities. At present, however, we have not yet identified the driving force of the current.

In Fig. 5, results of measurements in the lower layer (370 m below fast ice) from November 8 to December 10 are also shown. The lower layer shows similar variations to the upper layer, but the magnitude of the velocity is nearly one

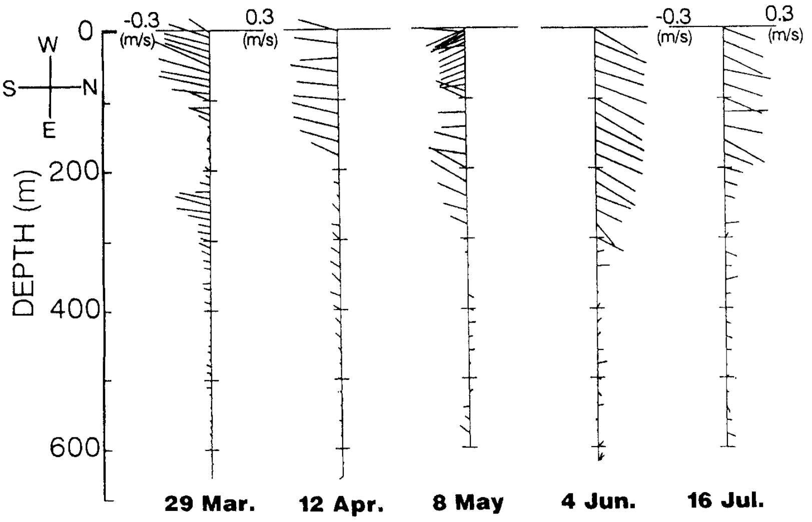

Fig. 6. Vertical profiles of the current at OS3 measured with an electromagnetic current meter. The corresponding observation times are indicated by arrow-heads in Fig. 5.

order smaller than that in the upper layer. Figure 6 shows vertical current profiles observed using an electromagnetic current meter. It is clearly shown that the strong current is confined to the upper 100–300 m layer from the surface. The current direction changes from southward to northward after the May observations. These are consistent with the results of the two-layer moored measurements.

4. Summary

Seasonal variations in ocean structure and current in Ongul Strait, Antarctica, in 1991 are summarized as follows.

In the austral fall (from March to May), cold, fresh and oxygen-rich water is accumulated in the upper layer and can be distinguished from the lower-layer water, which is more saline, warmer and oxygen-poorer. Accordingly, the heat loss reaches $-50\ W/m^2$ in March and April and the salinity drop in April corresponds to the melting of 1.7 m-thick sea ice. In winter (from June to August), the vertical diffusion or mixing between the two waters progresses gradually. From spring to summer, warmer, more saline and oxygen-poorer water appears in the mid-depth and deep layers. The heat gain is particularly noticeable in November. Horizontal oceanic advection dominates the heat and salt budgets. These features seem to be common in every year. The density variations of the water column in the strait explain only about one-fourth of the seasonal variations in sea level at Syowa Station.

In spite of no direct wind forcing and negligible thermohaline forcing, the current velocity is appreciably strong, with a typical value of 0.3 m/s, under fast ice in Ongul Strait. The strong current is confined to only the upper 100–300 m layer from the surface. The direction of the mean current changes drastically from southward to northward in May. Current variability on a typical time scale of about a week is relatively strong from May to mid-July.

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