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PRELIMINARY RESULTS OF HYDROGRAPHY UNDER FAST ICE IN LÜTZOW-HOLM BAY, ANTARCTICA IN 1990

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Abstract: Seasonal variations in water structure under fast ice in Lützow-Holm Bay, Antarctica, were observed from April to December, 1990. Two warm and oxygen-poor waters were observed. One is warmer water with temperatures higher than 0°C, salinities of more than 34.6 and oxygen less than 6 m*l*/*l*, and is found in the bottom layer deeper than 700 m in the Shirase Submarine Valley. The other is found in the upper layer with temperatures of −1.4∼−1.5°C, salinities of around 34.2 and oxygen of 6.3–6.9 m*l*/*l*. The origin of both waters is a blob of the Circumpolar Deep Water (CDW) drawn from offshore, and they are admixtures of CDW with overlying Winter Water in various proportions. Due to high density, the former is confined to the bottom layers of deep troughs; on the contrary, the latter with low density can migrate in the upper layer with the water circulation in the bay. In spring a cold and oxygen-rich water ($T<-1.6$°C, $O_2>7.2$ m*l*/*l*) was observed at the intermediate depth of about 250 m–350 m near the top of the downslope of the submarine valley. It is probable that this water was formed by sea ice processes during winter.

1. Introduction

As a part of the Antarctic Climate Research Project, an air-sea ice-sea interaction study was conducted off Queen Maud–Enderby Lands, Antarctica, in 1990 and 1991 by the Japanese Antarctic Research Expedition (JARE). One of the major subjects of this study was to clarify the role of the Circumpolar Deep Water (CDW) in sea ice processes and modification of water masses. The CDW is by far the most voluminous water in the Southern Ocean and is found in mid- and deep-depths. It is characterized by a temperature maximum and oxygen minimum at intermediate depth, and a somewhat deeper salinity maximum. Typical properties of CDW in the open ocean are 1–2°C in temperature, slightly above 34.7 in salinity, and less than 5 m*l*/*l* in dissolved oxygen content.

The CDW is the warmest water around Antarctica, except for summer surface water. Hence the advection of CDW from open ocean to ice-covered sea would involve a simultaneous transport of heat. When CDW mixes with cold

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surface water, it discharges a significant amount of heat to the upper layer, which results in increase of heat flux from the sea to the air through the ice.

The presence of CDW off Lützow-Holm Bay has been demonstrated by WAKATSUCHI *et al.* (1984) and NAGANOBU (1991). Using characteristic diagrams of the water properties in the bay, OHSHIMA *et al.* (1991) showed that a mixture of CDW and Winter Water (WW) appears at mid-depth in Ongul Strait in Lützow-Holm Bay. Further, they suggested that CDW enters the bay along a glacial trough. There are several oceanographic observations in Ongul Strait (WAKATSUCHI, 1982; FUKUCHI *et al.*, 1985; SATOH *et al.*, 1986; MATSUDA *et al.*, 1987). Besides Ongul Strait, WAKATSUCHI (1982) took observations in the Hovdebukta (Hovde Bay) and a coastal area off Langhovde to Skarvsnes. In the central part of Lützow-Holm Bay, a small number of hydrographic casts in summer was made on board. Thus we have had no knowledge of the seasonal or year-to-year variations of oceanographic conditions under fast ice in Lützow-Holm Bay. In particular, no concept of a mechanism of inflow of CDW and subsequent migration has been proposed. Therefore, in order to evaluate the air-sea interaction and sea ice processes in Lützow-Holm Bay, we carried out a two-year oceanographic observation program in the eastern half of Lützow-Holm Bay in 1990 and 1991.

In this paper, on the basis of the oceanographic data obtained by JARE-31 in 1990, we describe the results of a preliminary analysis of hydrography in Lützow-Holm Bay.

2. Observations and Methods

Oceanographic stations were chosen in three areas: Ongul Strait, the eastern half of Lützow-Holm Bay and the Hovdebukta. Ongul Strait is located between East Ongul Island and the Antarctic Continent. Its width is about 4 km and the maximum depth is about 700 m. At the four stations across the Strait, monthly observations were made from April to December 1990 (Fig. 1a). The stations in Lützow-Holm Bay were occupied three times: in fall, late winter and spring (Fig. 1b). The observations at Stns. OW-4, 5 and L-5, however, were not made in fall. The Hovdebukta is a drowned glacial trough off the Langhovde Glacier; its depth is more than 600 m (Fig. 1a). WAKATSUCHI (1982) maintained that glacial melt water flowed into the intermediate layer of the Hovdebukta beginning in spring time. To confirm his finding and to examine the influence of fresh water input on the water structure were the main reasons in selecting the Hovdebukta. The locations and ice/snow conditions of oceanographic stations are listed in Table 1. The submarine topography of Lützow-Holm Bay is demonstrated in Fig. 2.

The temperature and salinity data were obtained with a conductivity-temperature-depth unit (Seabird SBE-19). Water samples were collected with Nansen bottles from 3–10 layers according to the water depth of the station. Dissolved oxygen was determined by the Winkler method.

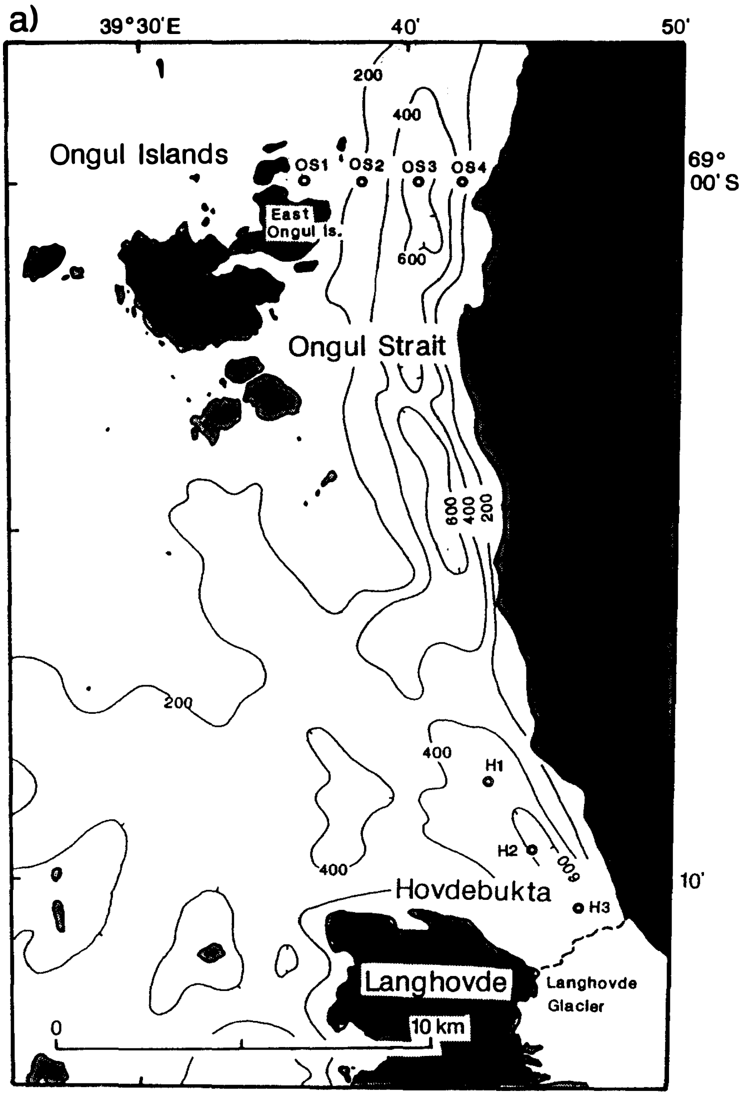


Fig. 1. Locations of oceanographic stations. (a) Ongul Strait and the Hovdebukta (Hovde Bay), (b) Lützow-Holm Bay. The depth contour interval is 200 m.

Lützow-Holm Bay was covered with fast ice throughout the year 1990. A number of puddles were formed along the northeast coast of the bay in summer. Particularly, a small ice-free area developed in late summer near Langhovde, but it did not extend to Ongul Strait. Figure 3 shows the ice thickness and snow depth distributions in the eastern part of Lützow-Holm Bay. Since the measurements were done just before the melting season, their values seem to indicate maxima for 1990. The ice near the coastline from the Ongul Islands to Skarvsnes was second-year ice, and the rest which covered the greater part of the bay was third-year ice formed in the winter of 1988.

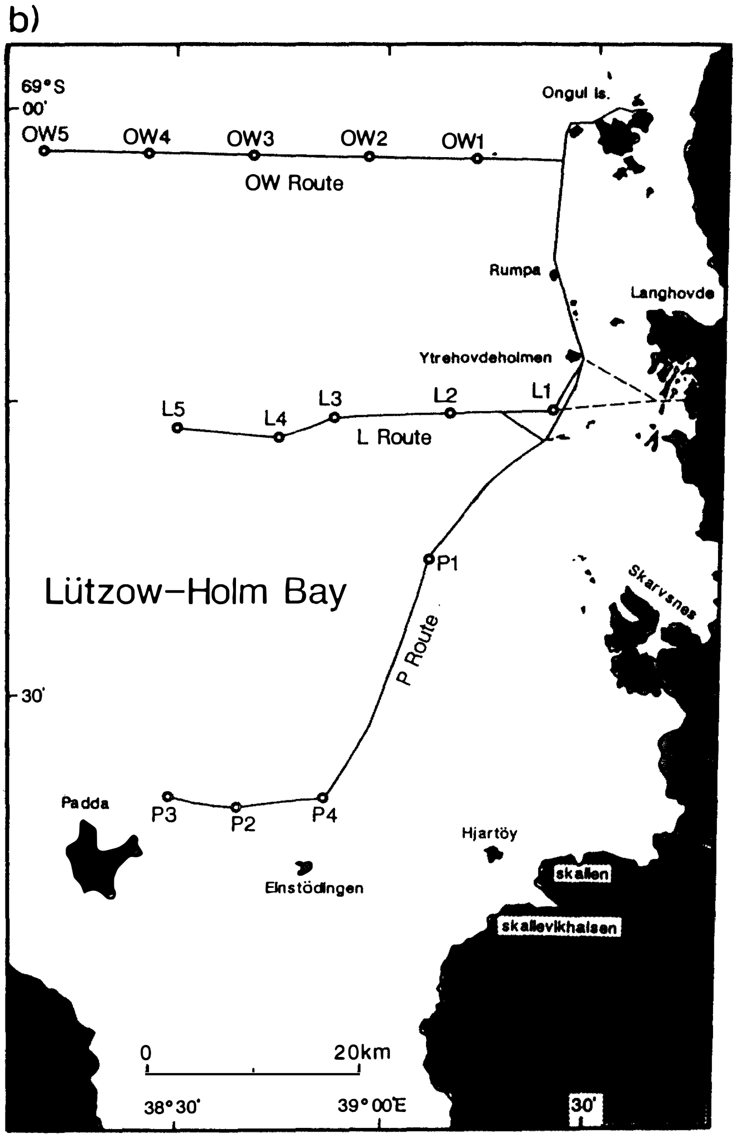


Fig. 1 (Continued).

3. Water Mass Characterization

3.1. Ongul Strait

Figure 4 shows cross sections of temperature, salinity, and dissolved oxygen content in fall, late winter and spring. The seasonal variations in oceanographic conditions at Stn. OS-3 are illustrated in Fig. 5. Relatively warm, saline, and oxygen-poor water ($T>-1.4$°C, S>34.3, $O_2<6.8$ m*l*/*l*) was seen in a deep layer in fall. From May to June, this water was gradually reduced in volume and eventually disappeared in July. The stratified structure became weak in winter and a thick homogenized water formed in mid- and deep-depth layers. It is noticeable that warm and oxygen-poor water abruptly appeared in November at the depth of about 100 m to 200 m.

Table 1. Locations of oceanographic stations and ice conditions. h_i: ice thickness (cm), h_s: snow depth (cm).

a) Ongul Strait					
Station	OS-1	OS-2	OS-3	OS-4	
Latitude (S)	69°00′	69°00′	69°00′	69°00′	
Longitude (E)	39°36.1′	39°38.3′	39°40.4′	39°42.0′	
Depth (m)	36	178	667	300	
Date		h_i/h_s			
2–5 Apr.	144/12	135/13	80/17	65/10	
15–17 May	135/11	127/22	101/0.5	90/0.5	
11–13 June	156/13	128/54	112/20	98/10	
20–22 July	151/50	130/65	108/20	115/25	
13–15 Sep.	174/39	143/75	152/10	146/14	
13–15 Nov.	173/40	163/92	169/7	158/9	
17–19 Dec.	219/40	189/71	164/0	154/0	
b) Hovdebukta					
Station	H-1	H-2	H-3		
Latitude (S)	69°08.6′	69°09.6′	69°10.4′		
Longitude (E)	39°42.9′	39°44.8′	39°46.4′		
Depth (m)	425	460	639		
Date		h_i/h_s			
17–19 Sep.	176/0	180/0	179/0		
22–23 Nov.	198/0	196/0	180/0		
c) Lützow-Holm Bay					
Station	OW-1	OW-2	OW-3	OW-4	OW-5
Latitude (S)	69°02.8′	69°02.7′	69°02.7′	69°02.7′	69°02.2′
Longitude (E)	39°12.4′	38°56.4′	38°40.0′	38°25.0′	38°11.1′
Depth (m)	158	183	430	735	758
Date		h_i/h_s			
9–11 May	– /33	190/47	128/46	–	–
29 Aug.–3 Sep.	200/53	211/98	170/72	231/130	302/113
28 Oct.–1 Nov.	201/55	219/117	226/102	285/121	277/164
Station	L-1	L-2	L-3	L-4	L-5
Latitude (S)	69°15.5′	69°15.6′	69°16.4′	69°17.3′	69°16.8′
Longitude (E)	39°24.2′	39°09.4′	38°53.2′	38°46.0′	38°30.4′
Depth (m)	320	225	510	965	645
Date		h_i/h_s			
3–8 May	144/11	220/39	210/63	220/72	–
23–27 Aug.	170/15	250/70	213/97	213/120	213/140
22–26 Oct.	196/29	222/105	224/139	232/159	212/165
Station	P-1	P-2	P-3	P-4	
Latitude (S)	69°23.0′	69°35.9′	69°35.3′	69°35.4′	
Longitude (E)	39°06.0′	38°39.0′	38°29.0′	38°51.7′	
Depth (m)	483	1110	600	465	
Date		h_i/h_s			
27 Apr.–1 May	189/27	235/65	205/60	208/56	
18–22 Aug.	208/72	225/135	210/135	208/104	
16–21 Oct.	190/86	240/152	215/145	210/125	

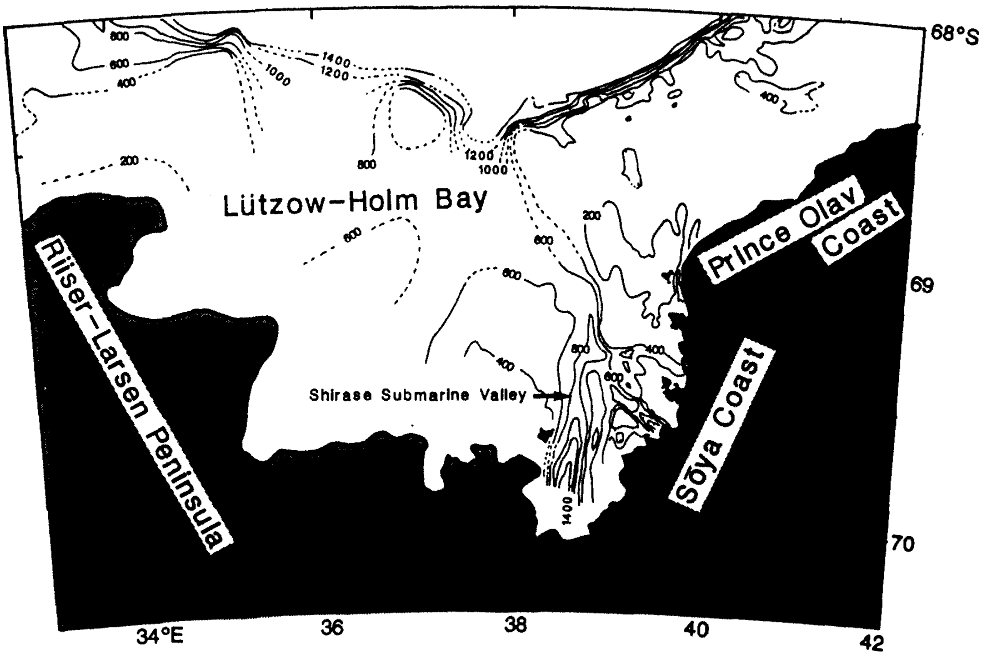


Fig. 2. Bathymetric chart of Lützow-Holm Bay. The depth contour interval is 200 m (after MORIWAKI *and* YOSHIDA, *1983).*

3.2. *Lützow-Holm Bay*

The east-west sections off Langhovde (L route in Fig. 1b) are shown in Figs. 6–8 to represent the seasonal changes of water structure in the central part of the bay. A warm, saline and oxygen-poor water (T>0.2°C, S>34.6, O_2<6.0 ml/l) was found in May near the bottom of the Shirase Submarine Valley which extends in the north-south direction (see Fig. 2). As will be described later, this water is an intrusion of CDW. The temperature and salinity gradually decreased with the progress of the seasons; conversely, the oxygen content increased. In October, cold and oxygen-rich water appeared near the top of the downslope of the valley.

3.3. *Hovdebukta*

Two hydrographic sections were occupied in September and November, corresponding to the pre-melting season and melting season respectively (Figs. 9 and 10). WAKATSUCHI (1982) described the appearance of less saline glacial melt water at the depth of 200–400 m at the end of October 1976. The section in November (Fig. 10), however, does not indicate any evidence of melt water. The main feature of the section is warm and oxygen-poor water from about 100 m to 250 m in depth. This water has the same properties as the water appearing at the depth of 100–200 m in Ongul Strait in November (Fig. 5).

4. Discussion

Water mass characteristics off and in Lützow-Holm Bay are shown in Fig. 11. Hydrographic station 31001 (66°34′S, 39°00′E) was located in the open ocean

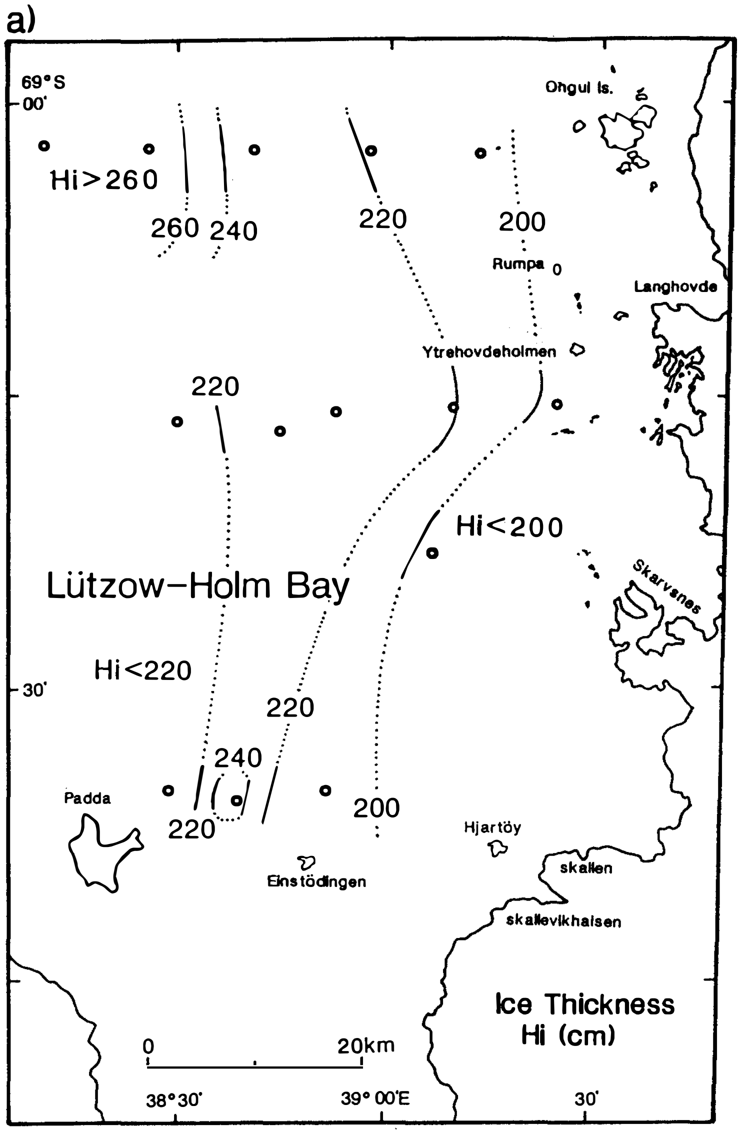


Fig. 3. Sea ice thickness (a) and snow depth (b) distributions in Lützow-Holm Bay, based on measurements between October 16 and November 1, 1990.

off the bay, and occupied in February 1990, by the summer party of JARE-31 (IKEDA and KOJIMA, 1992). The Circumpolar Deep Water (CDW) is found between about 300 m and 1500 m in depth at Stn. 31001 with temperatures 0.5–1.4°C, salinities 34.60–34.72 and oxygen 4.5–5 m*l*/*l*. As is generally known in the Southern Ocean, the Antarctic Bottom Water (AABW) underlies CDW (FOSTER and CARMACK, 1976a, b). The temperatures and salinities of AABW are roughly $-1\sim+0.5$°C and 34.6–34.7, respectively. The AABW off Lützow-Holm Bay is found below 1500 m in depth with temperatures 0.1–0.4°C and salinities 34.67–34.68.

The T-S and O_2-S characteristics show that warm and oxygen-poor water at the depth of more than 700 m of Stn. L-4 in May was an intrusion of offshore

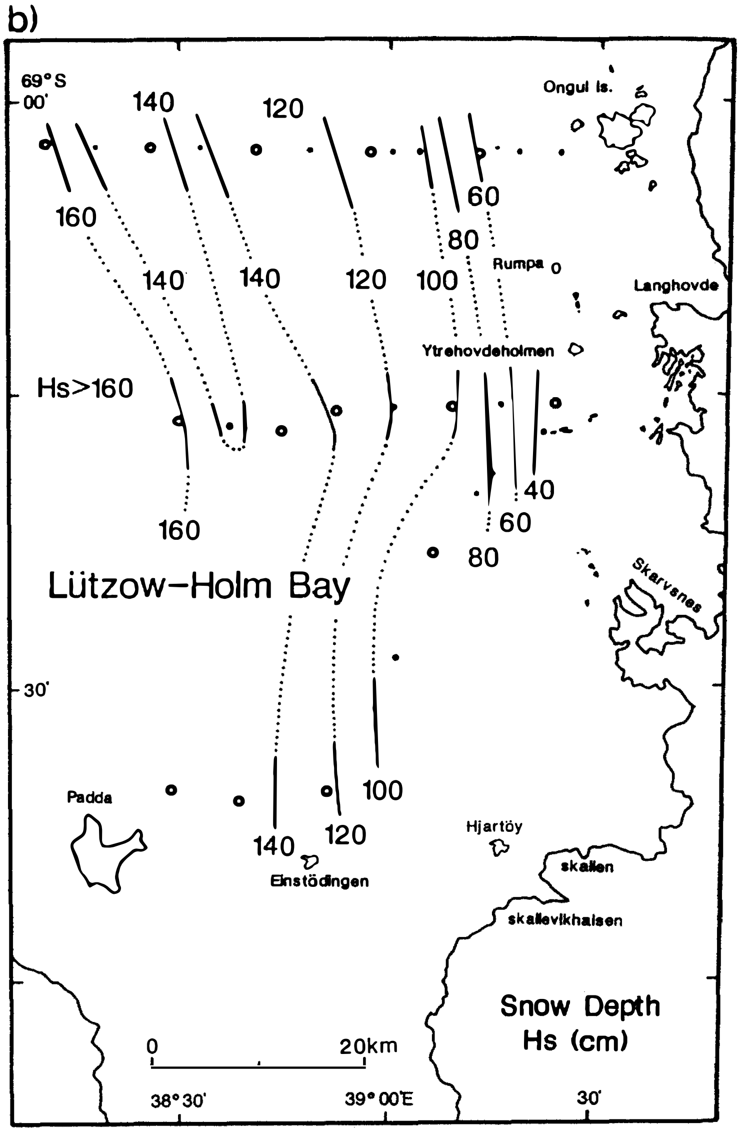


Fig. 3 (Continued).

deep water. Tentatively, we name this bottom water at Stn. L-4 "Lützow-Holm Bottom Water" (LHBW). Then how was LHBW formed? The properties of LHBW (T=0–0.2°C, S=34.58–34.63) are quite similar to those of AABW. An intrusion of AABW into Lützow-Holm Bay, however, is unlikely to occur. The submarine topography of the northeastern part of the bay has not been well surveyed (Fig. 2). The Shirase Submarine Valley is about 700 m deep, west of the Ongul Islands. Figure 2 would suggest that the valley runs at 600–700 m in depth to the shelf break. Meanwhile AABW is located in the bottom layer deeper than 1500 m. Hence the intrusion of AABW is hardly admissible. The alternative explanation is an intrusion of CDW. Thus the following scenario would be acceptable. The CDW, at depths of about 400 m to 700 m, intrudes isentropically along the submarine vally. The intruded CDW is the densest in the bay, so that it flows down to the depression over 700 m. Simultaneously it is modified by mixing with overlying Winter Water (WW) and becomes LHBW.

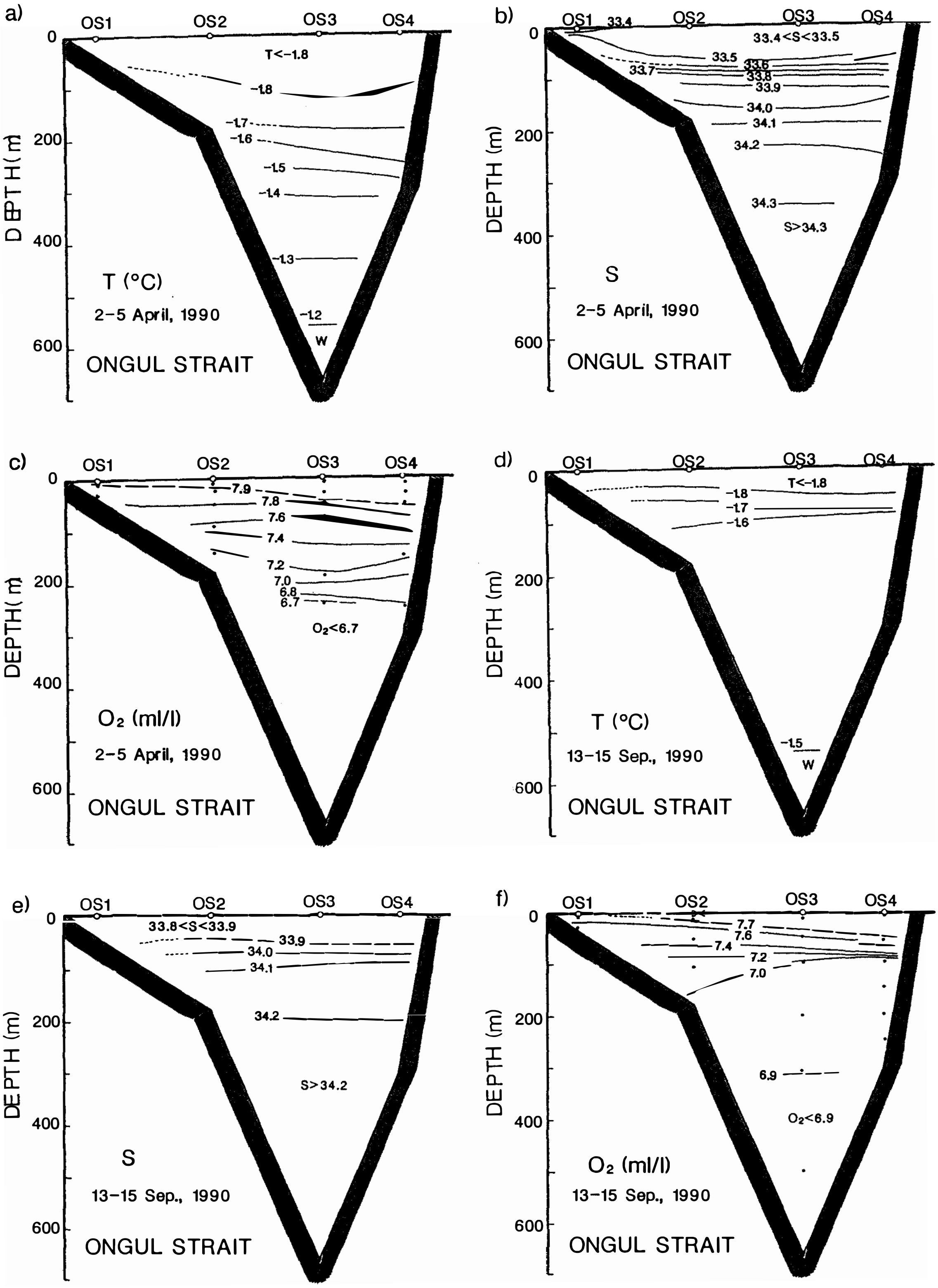


Fig. 4. Temperature, salinity, and dissolved oxygen sections in Ongul Strait in April (a)–(c), September (d)–(f) and November (g)–(i).

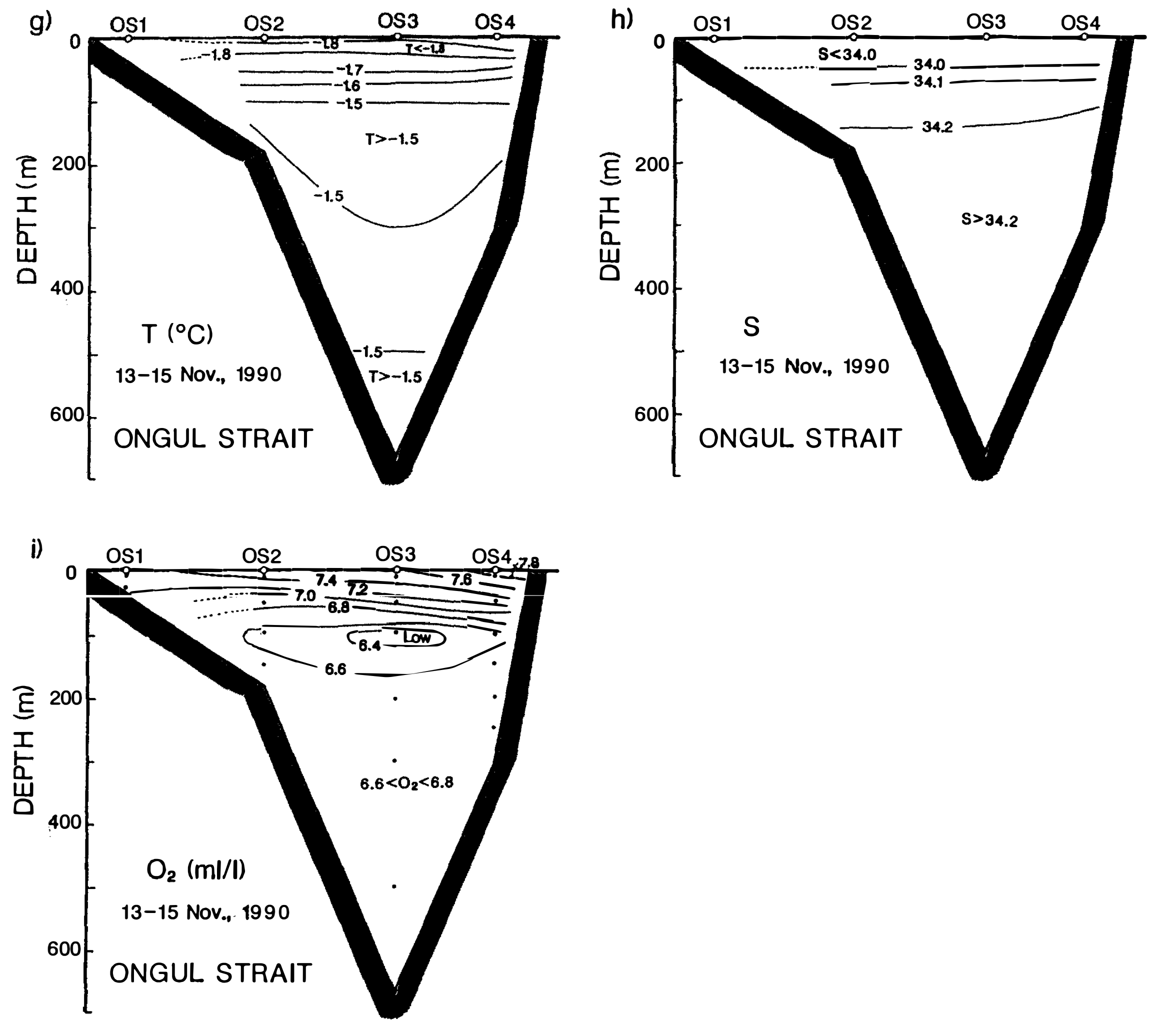


Fig. 4 (Continued).

Figure 11a suggests that the mixing ratio of CDW:WW was 4:1–2:1. The LHBW cannot come into Ongul Strait and the Hovdebukta, because the sill depths in those areas are about 300 m.

Figures 6–8 indicate that the properties of LHBW were gradually changed as the season advanced; that is, temperature and salinity decreased and oxygen increased. Hence the following may be concluded: the intrusion of CDW occurred before May, probably in March or April; and no succeeding intrusion occurred; because the Shirase Submarine Valley is a dead-end valley, LHBW stagnated in the deep depression; then its properties were modified by mixing with overlying WW.

The other warm and oxygen-poor water was found in the surface layer of Ongul Strait and the Hovdebukta in November (Figs. 4g–i, 5, 10 and 11b). Figure 11a reveals that the same water was seen at a depth of about 200 m at Stn. L-3 in late October, too. As pointed out by OHSHIMA *et al.* (1991), this water should be considered as an admixture of CDW and WW.

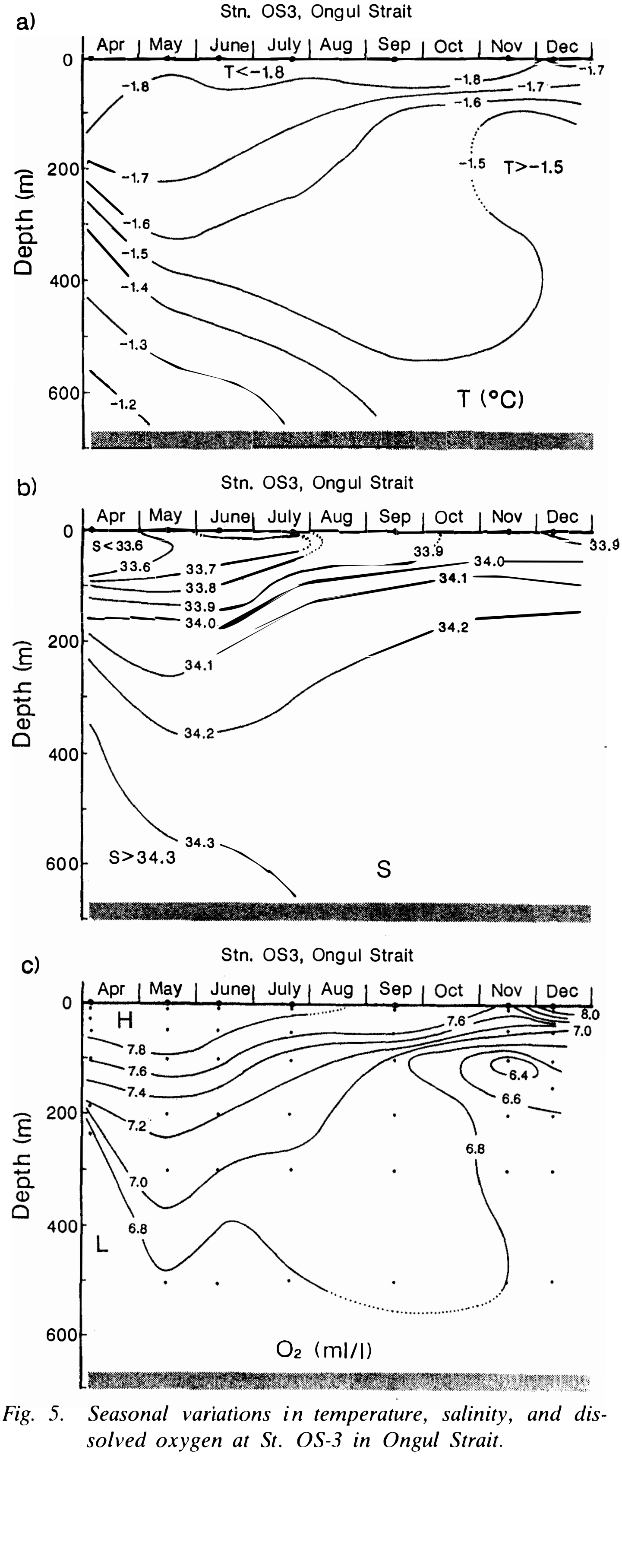
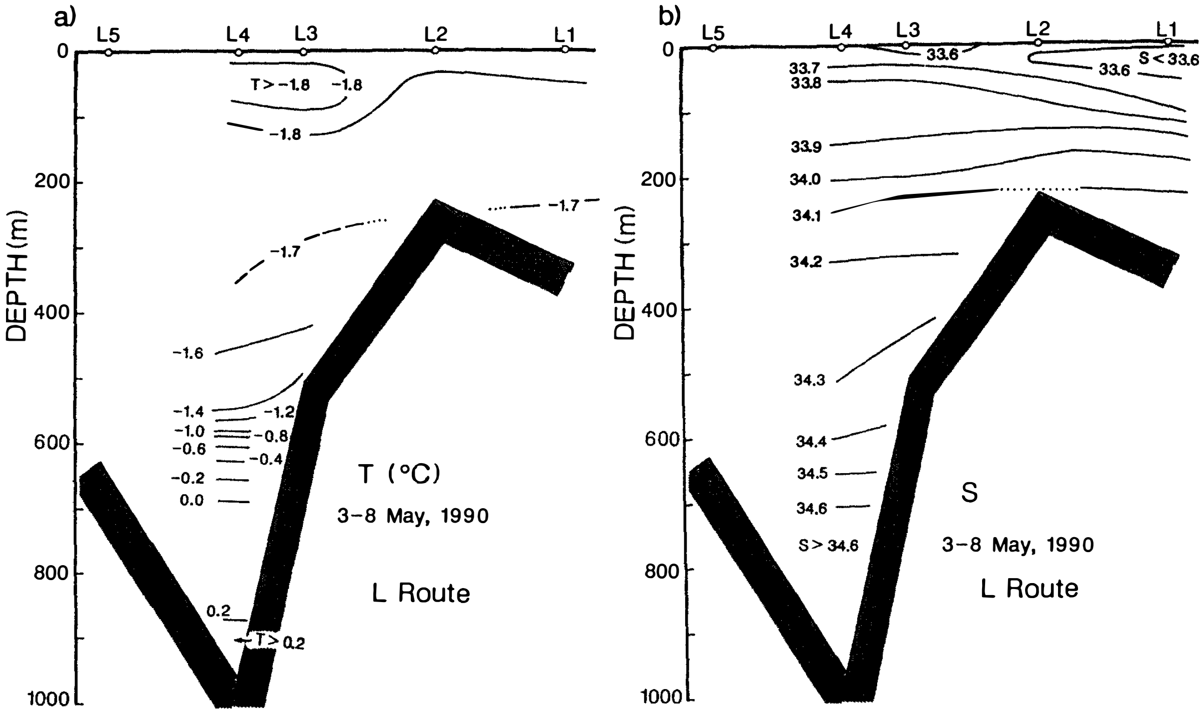


Fig. 5. Seasonal variations in temperature, salinity, and dissolved oxygen at St. OS-3 in Ongul Strait.



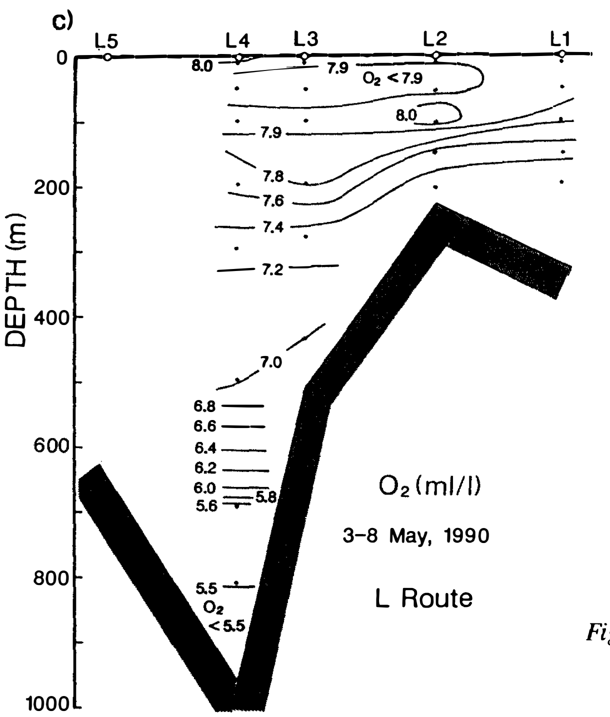


Fig. 6. Temperature, salinity, and dissolved oxygen sections in May along L route in Lützow-Holm Bay.

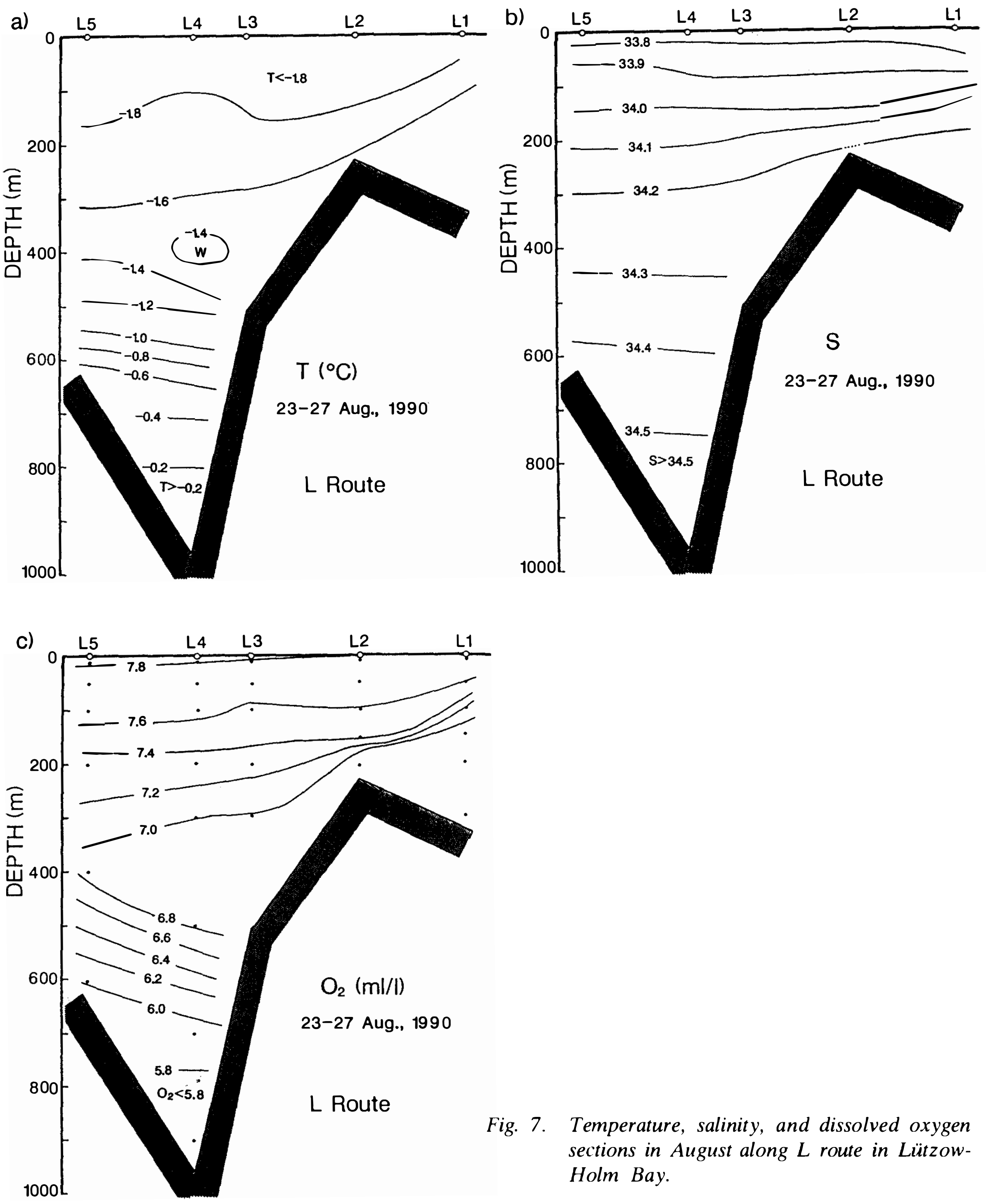


Fig. 7. Temperature, salinity, and dissolved oxygen sections in August along L route in Lützow-Holm Bay.

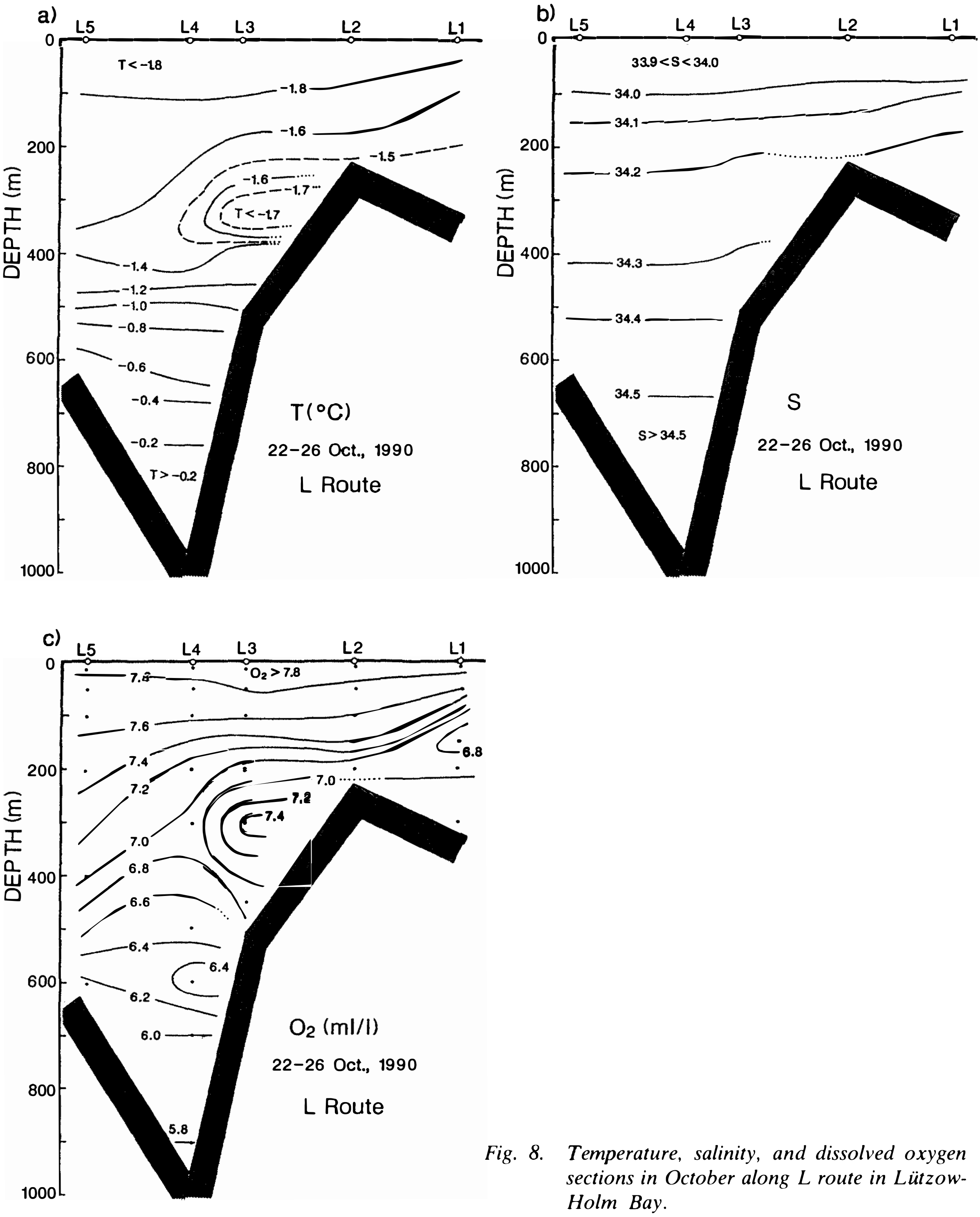


Fig. 8. Temperature, salinity, and dissolved oxygen sections in October along L route in Lützow-Holm Bay.

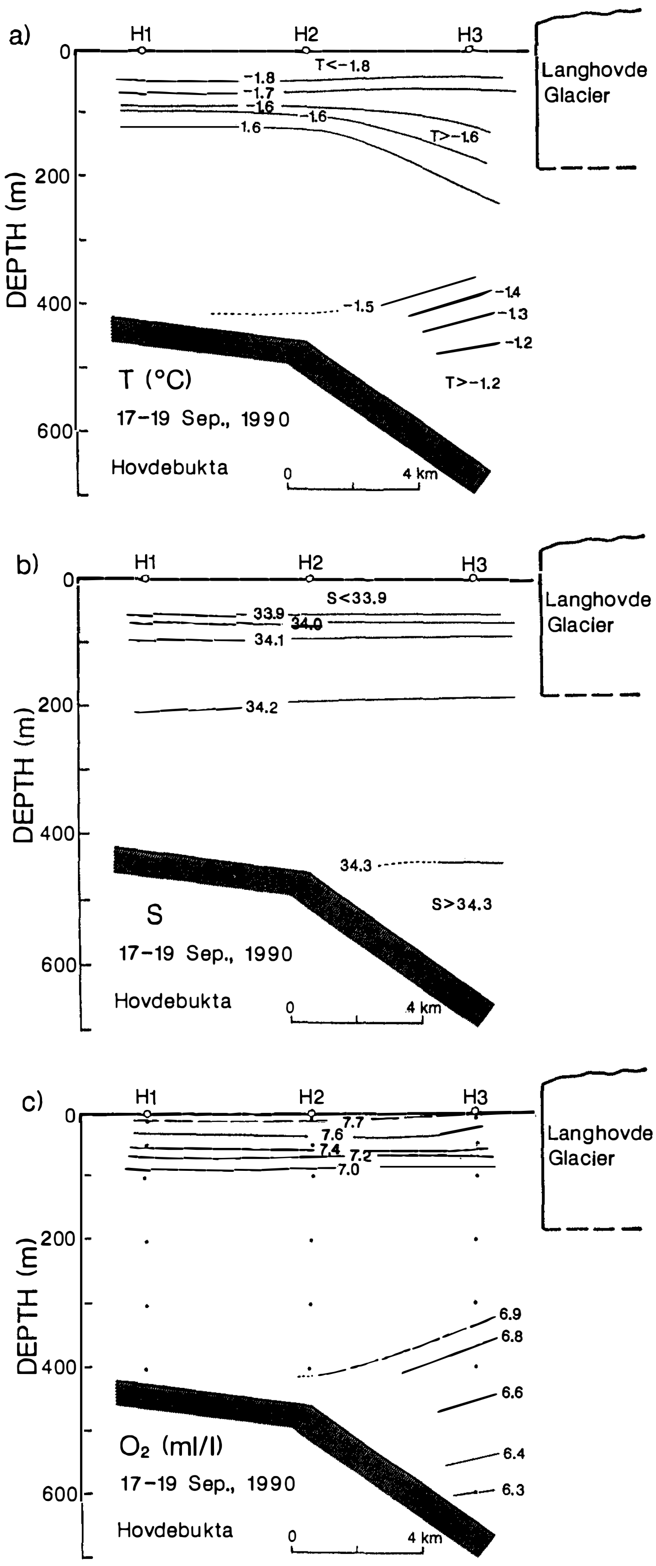


Fig. 9. Temperature, salinity, and dissolved oxygen sections in September in the Hovdebukta.

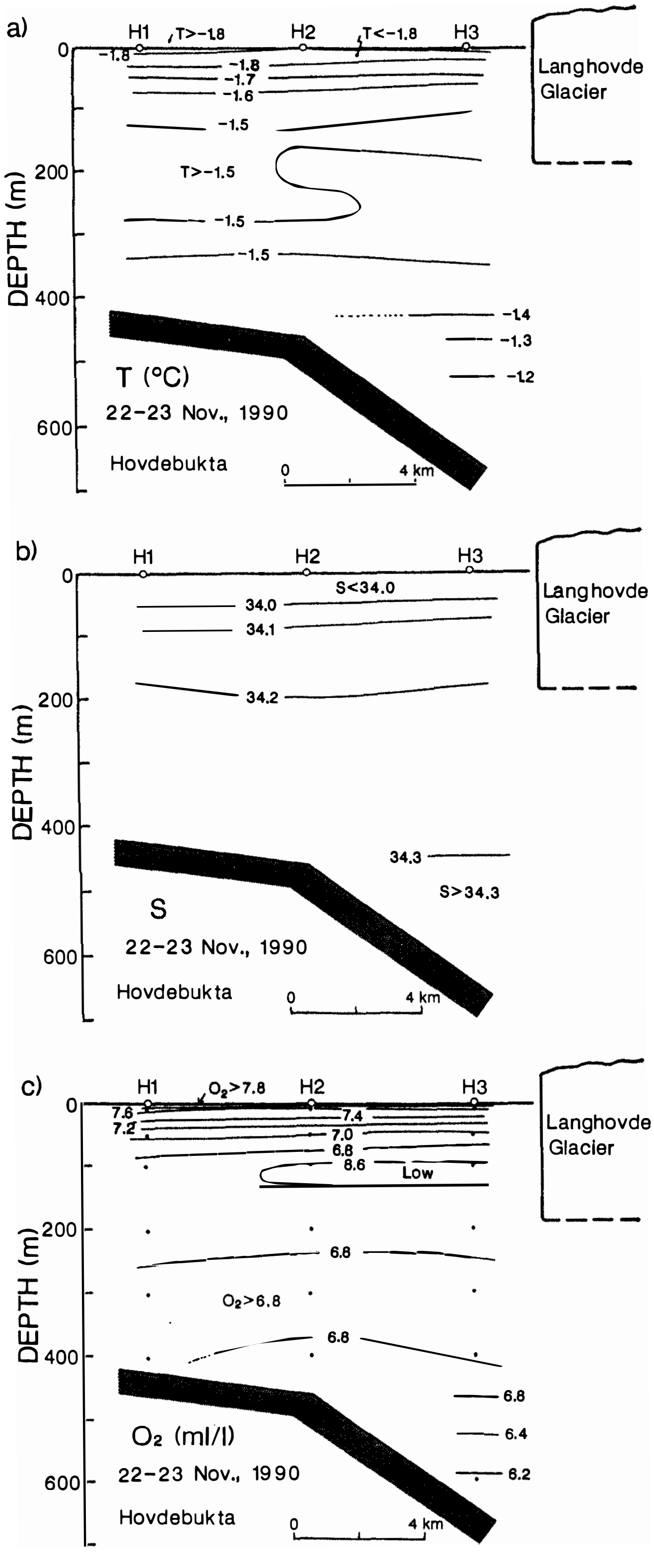


Fig. 10. Temperature, salinity, and dissolved oxygen sections in November in the Hovdebukta.

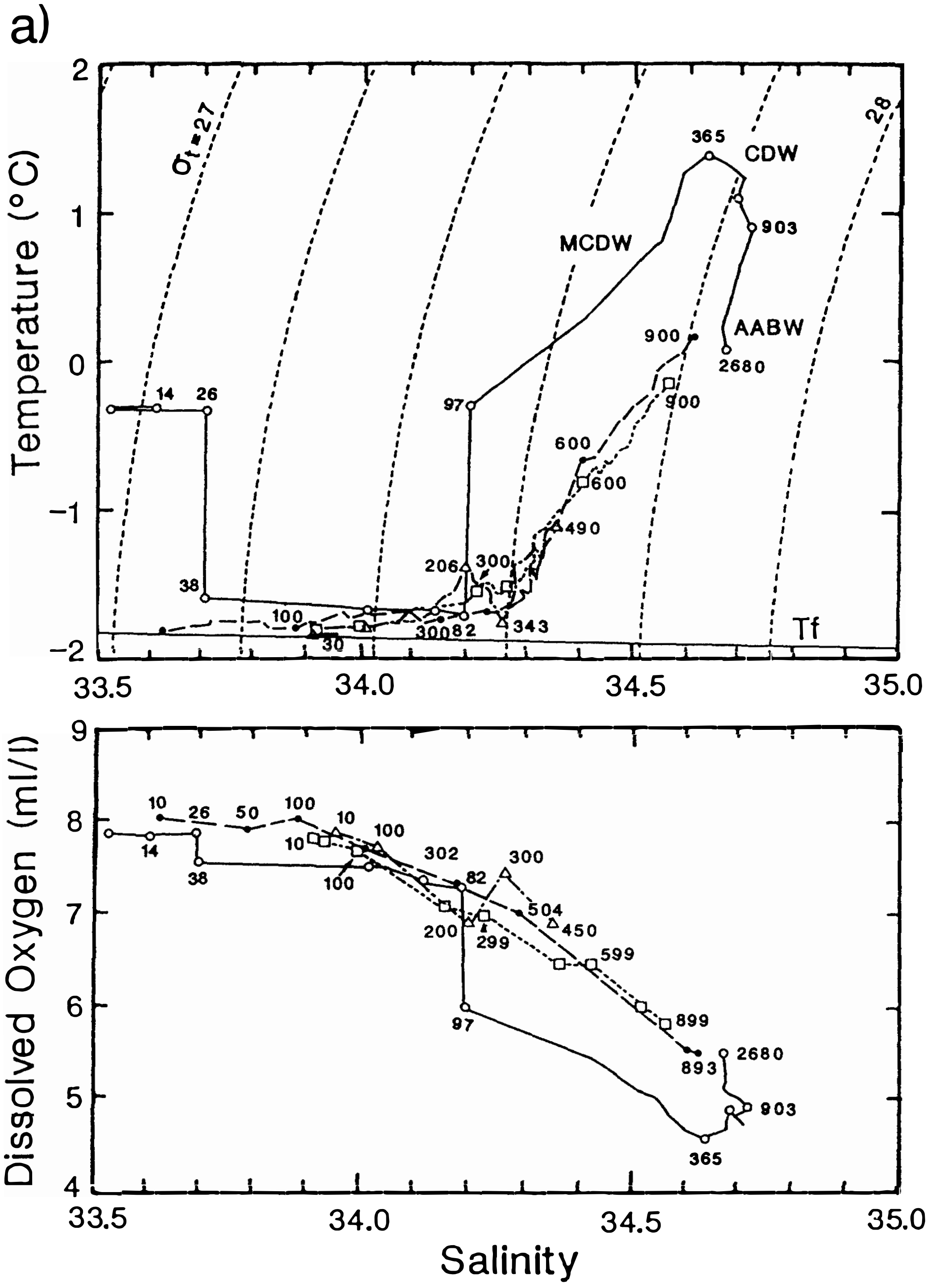


Fig. 11. Temperature-salinity and dissolved oxygen-salinity diagrams for selected stations. (a) ○ 31001 (66°34′S, 39°00′E), ● L4 in May, △ L3 in October, □ L4 in October. (b) ○ 31001, ● OS3 in April, △ OS3 in September, □ OS3 in November, ▲ H3 in November.
The numerals next to plotted points refer to depths in meters. CDW: Circumpolar Deep Water, AABW: Antarctic Bottom Water, MCDW: Modified CDW, T_f: freezing temperature.

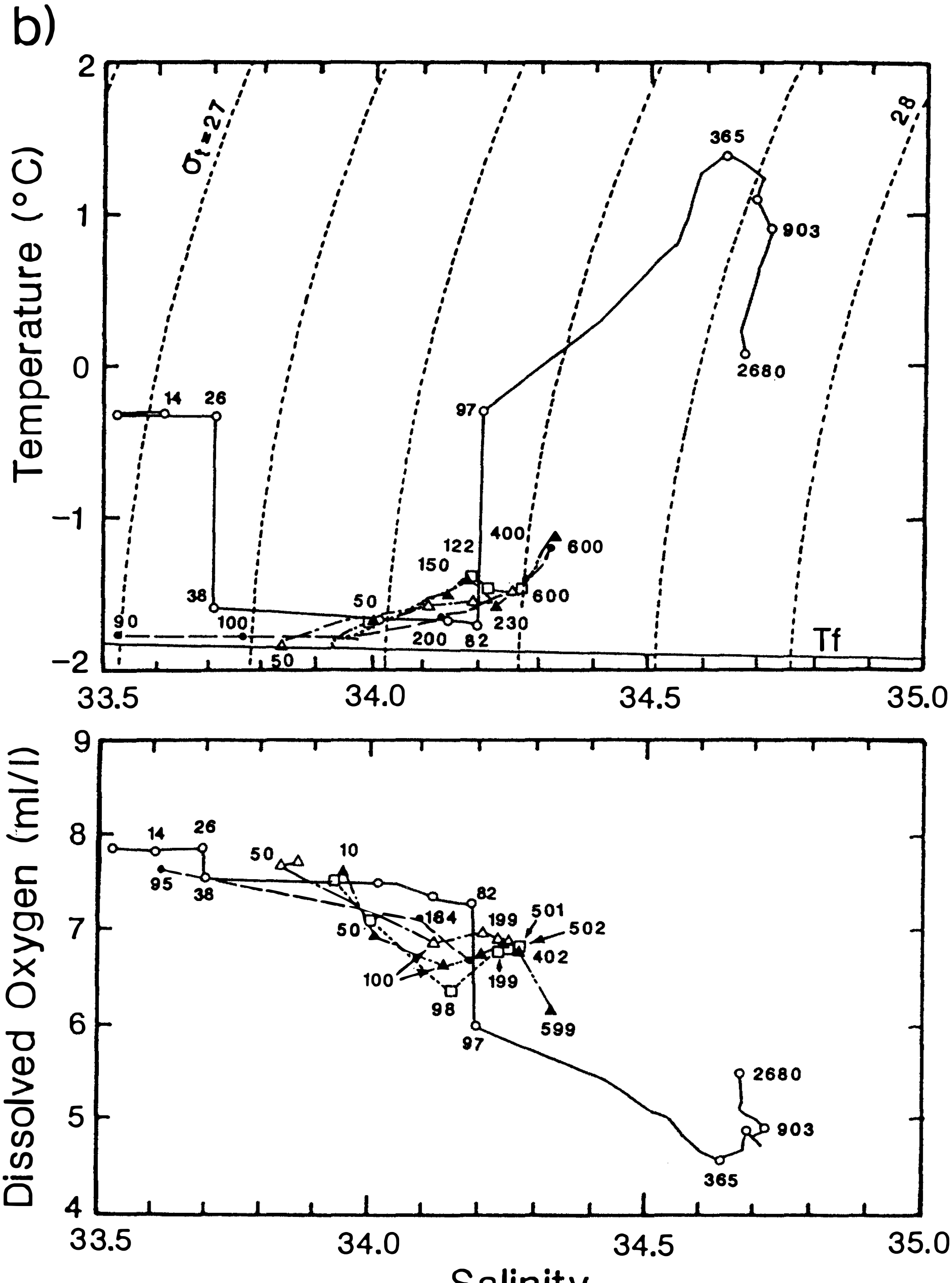


Fig. 11 (Continued).

In the Weddell Sea, Foster and Carmack (1976a) showed that the Warm Deep Water (WDW) is modified by mixing with the overlying WW in the frontal zone near the shelf break before it intrudes onto the shelf. (The CDW in the Weddell Sea is designated Warm Deep Water or Weddell Deep Water.) The same phenomenon is reported in the Ross Sea (Trumbore *et al.*, 1991). The intrusion of Modified CDW (MCDW) onto the shelf region appears to be a common occurrence in Antarctic seas. Foster *et al.* (1987) inferred that continental shelf waves are the most likely mechanism for bringing Modified WDW (MWDW) from the intermediate depths offshore onto the shelf in the Weddell Sea. Thus the same mechanism is probably responsible for the appearance of admixture of CDW and WW in the upper layer in Lützow-Holm Bay. Foster *et al.* (1987) described that blobs of MWDW are frequently brought onto the shelf through the year. On the other hand, our results suggest that the intrusion is not an usual event in Lützow-Holm Bay, and, moreover, it does not occur in winter.

Presumably it can be considered that LHBW originates by the same mechanism from CDW offshore in a deep layer. Our data indicate, however, that the intrusion in the surface layer and in the deep layer did not occur simultaneously. The observational results in 1991 by JARE-32 also showed that the intrusions occurred in the two layers and they were not synchronized (private communication).

5. Concluding Remarks

We can distinguish two warm and oxygen-poor waters by their properties with which these water masses intrude into Lützow-Holm Bay. One is warmer water with temperatures higher than 0°C; salinities of more than 34.6; and oxygen less than 6 m*l*/*l*. This water is found in the bottom layer deeper than 700 m in the Shirase Submarine Valley. The other is a relatively colder and less saline water with temperatures of $-1.4\sim-1.5$°C, salinities of around 34.2 and oxygen of 6.3–6.9 m*l*/*l*, and is found in the upper layer. The source of both waters is blobs of CDW drawn from offshore, and they are admixtures of CDW with overlying WW in various proportions. Due to its high density, the former is confined to the bottom layers of deep troughs; conversely, the latter, with low density, can migrate in the surface layer with the water circulation in the bay.

One notable feature of the section of Lützow-Holm Bay in October (Fig. 8) is the presence of a layer of $T<-1.6$°C and $O_2>7.2$ m*l*/*l* at the intermediate depth of about 250–350 m at Stn. L-3. The T-S diagram in Fig. 11a shows that its salinity is slightly higher than that of Stn. L-4 at the same depth. It is probable that this cold, oxygen-rich and somewhat more saline core (COCO) was formed by sea ice processes during winter. Haline convection due to brine exclusion during the ice freezing season produces a cold (near freezing temperature) and oxygen-rich WW, and COCO is a typical appearance of WW. We have no information as to where COCO was formed, but presumably it was on the continental shelf. Figure 8 is suggestive of a downflow COCO along the valley slope. This flow might play some role in the modification of LHBW.

Acknowledgments

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