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Results of oceanographic analyses conducted under JARPA and possible evidence of environmental changes.

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ABSTRACT

Oceanographic observation data obtained by JARPA were analyzed to clarify physical oceanographic conditions in the JARPA area as a basis for understanding of habitat environment of whales. Accumulated XBT, XCTD and CTD data were stored in the HydroBase format and utilized to describe the oceanographic feature of JARPA area. The Southern Boundary (SB) of the Antarctic Circumpolar Current was clearly observed as a 0ºC temperature contour line on the 27.6σ_{θ} isopycnal surface. It is evident that the position of SB is controlled by major features of bottom topography such as the Kerguelen Plateau the Pacific-Antarctic ridge. The analyses presented several evidences for year-to-year variations in oceanographic conditions, including large year-to-year meridional shift of the SB found east of the Kerguelen plateau. Although the global warming is important forcing for the Southern Ocean, the influence is not clear in the JARPA region unlike the Antarctic Peninsula region. Comparison between the JARPA data and satellite-derived Chlorophyll distribution indicates that the intensity of the wintertime cooling determines the primary productivity south of SB in the following seasons. JARPA data also provided a new evidence of Antarctic Bottom Water formation in the Prydz Bay region.

INTRODUCTION

Oceanographic observation has been included in JARPA and many data were corrected from JARPA area (Pacific and Indian sector of the Southern Ocean, poleward of 60S) for 18 years period 87/88-04/05. The purpose of the oceanographic observations is to obtain fundamental information of the ecosystem in the JARPA area and to investigate the relationship between the oceanographic conditions and whales.

The repeat observation conducted in the JARPA is also important from the oceanographical view point as the southern ocean plays key roles in the global thermohaline circulation. The North Atlantic Deep Water (NADW) formed in the northern North Atlantic flows into the Southern Ocean and lifted up to subsurface depth. The Antarctic Bottom Water (AABW) which occupies the bottom layer of the world ocean is formed in the coastal area of the Antarctic continent by mixing cold and dense shelf water with the NADW (Schmitz, 1996).

The Antarctic Circumpolar Currents (ACC) is major feature of the Southern Ocean and the spatial water mass distribution of the area is characterized by the zonal structure reach to the deeper layer. The oceanographic conditions of the JARPA area are also under the strong influence of the ACC. The Southern Boundary (SB) of the ACC is thought to be most important oceanographic component of the JARPA area. The upwelling of the NADW around the SB is enriching the nutrient in the upper layer and is sustaining the rich ecosystem in the Southern Ocean.

Matsuoka et. al. (2003) investigated the relationship between oceanographic fronts and distribution of the large whale species. They showed that the humpback whale gathered in the sea area around SB east of the Keruguelen Plateau in Area IV. Nicol et al. (2000) indicated the results of the BROKE (baseline research on oceanography, krill and the environment) in the area from 80E-150E conducted in 1996. They showed that the ecosystem in the region south of the SB of the ACC is rich and the SB determines the spatial structure.

As a first step of the oceanographic analysis of JARPA data from the view point of ecosystem, we made climatological pictures of the various physical parameters by using the JARPA data to investigate the large scale feature of the oceanographic structure. The information about the year-to-year variability is also provided by using the satellite observed data.

DATA

Vertical oceanographic structures were observed by using XBT (eXpendable Bathy Thermograph), CTD (Conductivity-Temperature-Depth profiler) and XCTD (eXpendable CTD). XBT was mainly used in the first stage of JARPA (87/88-96/97). XCTD is a newly developed oceanographic instrument in the late 1990’s. We can get temperature and salinity profile for the depth range from 0m to 1000m by XCTD. In the Southern Ocean, salinity is important factor for the dynamics of ocean currents. So XCTD was promptly introduced instead of XBT in the second stage of JARPA (97/98- presents). CTD(SBE19 SEACAT profiler) was also introduced after 98/99 JARPA. These data were combined and stored in the HydroBase format (Macdonald *et al*., 2001). Figure 1 shows oceanographic observation stations of JAPRA. In our analysis, we mainly used the data obtained after 97/98 JARPA when salinity data available and the water mass analysis are possible. 915 XCTD stations and 499 CTD stations were occupied during 8 JARPA cruises. CTD sensors were calibrated every year and no significant error was reported. XCTD data was checked by using climatology of the World Ocean Atlas (WOA 2001) and the systematic positive bias found in salinity data in JARPA 97/98 was corrected. XCTD data was also checked statistically to exclude suspicious data from analysis.

RESULTS

Large scale oceanographic conditions of JARPA area

By using all the temperature profile data, the temperature section along the Date Line is constructed. The mean temperature section and standard deviation section are shown in Figures 2. The dichothermal structure (temperature minimum) is observed in the upper layer of poleward region of 64S. This structure is remainder of the mixing of upper water in former winter. The SB of the ACC coincides with the northern limit of 0ºC water. In the subsurface layer, relatively warm deep water exists under the dichothermal layer indicating the upwelling of the upper Circumpolar Deep Water (UCDW). Large standard deviation found in the surface layer around 63S reflects the year-to-year variation of the SB.

Front systems of the ACC are important for the marine ecology of the Southern Ocean. The SB is a southernmost front of the ACC and is recognized as an important oceanographic feature for large whale in the JARPA area. To detect the SB in the JARPA area, we construct the spatial temperature and salinity map on 27.6σ_θ isopycnal surface. Frontal structure is clearly observed along the 0ºC contour on temperature map (Fig. 3). The contour line shows the southern limit of UCDW and indicates the southern boundary of ACC (Orsi *et al*., 1995). The path of the SB closely follows the bottom topography (Fig. 4). The ACC strongly influenced by the bottom topography deep structure of the ACC.

Ice edge is another important boundary which restricts movement of whale. Relationship between the SB of the ACC and seasonal variation of ice edge position was analyzed. Figure 5 shows seasonally changing ice edge positions in the summer season with the SB position. Seasonal variation is larger in the regions west of the Kergualen Plateau and east of 160E. As to the region east of 160E, it is obvious that wide area without ice appears south of the SB in months from January to March. The figure is also suggesting that there is some delay in time when ice edge reaches the SB position in the Ross sea region compared with other region.

Detailed structure of the SB in Area IV and V

The SB of ACC for 8 JARPA cruises (Fig. 6) in the Area IV and Area V. The position of the SB is defined as the positions of 0ºC temperature contour on 27.6σ_θ isopycnal surface. Figure 7 shows the observation line and the position of the SB. In Area IV, the meandering path east of the Kergualen Plateau was observed in all four years. The year-to-year variation of the meridional position of the SB was obviously indicated. The dichothermal structure developed in the south of the SB, and its temperature and thickness change each year. In AREA V, the SB approaches the continent west of 150E and is left offshore east of 150E and it clear that the SB runs along the Pacific-Antarctic ridge in the east of 160E. These maps show the stable structure of SB in Area V.

SB detection by satellite altimeter data

The position of SB detected by oceanographic data of JARPA was compared with the dynamic topography at the sea surface relative to 2000dbar derived from satellite altimeter data and hydrographic climatology. It was shown that the contour line of 0.815m is good indicator for the SB position. By using the relationship, we made a data set of the SB position for the period from 1993 to 2005 when the satellite altimeter is available. Figure 8 shows all the data for JARPA area and the probability distribution of the SB. It is indicated that the SB position in Area V is stable as observed by analysis of the JARPA oceanographic data. On the other hand, the SB position is highly variable in the east of the Kerguelen Plateau. Standard deviation is 0.4 degree in Area V and is 0.8 degree or more between the Kerguelen Plateau and 110E. Year-to-year variability of SB in each area is shown in Figure 9. Temporal variation with 5-6 year periodicity is obvious in Area IV and V. In Area III-east and Area VI, northward shift of SB was also found after 2000.

Year-to-year variation of Chlorophyll fields in the JARPA area derived from the satellite observation

Chlorophyll distribution observed by satellite ocean color sensor SeaWiFs was compared with the oceanographic conditions in Area IV. The chlorophyll-a concentration was low in January 1998 (Fig. 10-1-A). The hydrographic section shows dichothernal water was weak during JARPA 97/98, indicating weak wintertime cooling in the previous winter (Fig.10-1-B). On the other hand, the chlorophyll-a concentration was high in January 2000 (Fig. 10-2-A). The dichothermal water was intense during JARPA 99/00, indicating intense wintertime cooling in the previous winter (Fig. 10-2-B). These observations suggest that the wintertime cooling affects the primary productivity in the following seasons. The chlorophyll-a concentration in January 2002 was high (Fig.10-3-A), which is consistent with the intense dichothermal water (Fig.10-3-B). The high concentration area was confined near the coast, which is possibly related to the SB approaching the coast during JARPA 01/02 (Fig. 7).

Year-to-year variation of SST in the JARPA area

Time series of Sea surface Temperature (SST) along the circle of latitude at 62S were analyzed. Year-to-year variations of March SST in Area IV are characterized by warming after 2001 and extraordinary high SST in 1988 and low in 2000 (Fig. 11). In Area V, year-to-year variation of March SST is larger than Area IV (Fig. 12). Warm SST in the eastern part of Area V is related to El Nino 1982/83, 1986/87, 1991-93 and 1997/98 (Kwok and Comiso, 2002). In both areas, no significant long-term trend is observed for the period 1982-2004. On the other hand, the SST time series around the Antarctic Peninsula include warming trend of about 0.02 degree C/year for 23 years period from 1982 to 2004 (not shown). This trend is related to remarkable warming observed in the Antarctic Peninsula where the influence of global warming has appeared notably.

Oceanographic structure of the Prydz Bay region

While the major formation sites of AABW are located in the Weddell Sea and the Ross Sea, recent studies suggested a few other sites including the Prydz Bay region (Orsi et al. 1999). The hydrographic data in the Prydz Bay region during the JARPA 99/00 and 01/02 were analyzed to seek an evidence for the AABW formation (Fig. 13). One of the essential elements for the AABW formation is high salinity shelf water (HSSW), which is cold and saline (S>34.6) shelf water. HSSW was observed near the shelf break in the Bay at the station JARPA99/00-113 (Fig. 14), which is a clear additional evidence for the AABW formation in the Prydz Bay region

SUMMARY AND REMARKS

Basic oceanographic structure of JARPA area was realized by the JARPA oceanographic data. The position of the SB of ACC is mainly determined by bottom topography such as the Kerguelen Plateau the Pacific-Antarctic ridge. The JARPA area is also characterized as upwelling area of Circumpolar Deep Water, which provides nutrients to support high primary productivity. Large interannual variations in the meridional position of SB of ACC in the east of the Kerguelen plateau are revealed. By using the chlorophyll data, we made several map and compare the chlorophyll distribution with the oceanographic structure in area IV. In the area south of the SB, low chlorophyll concentration in 97/98 season was related to weak dichothermal structure and relatively high chlorophyll concentration in 99/00 and 01/02 season were related to colder and thick dichothermal structure. The relationship suggested that wintertime mixing of surface layer affect the production in the summer season. Influence of El Nino on SST in area V –VI is also suggested. Although the global warming is also important forcing for the Southern Ocean, it is not clear that the JARPA region is affected like the Antarctic Peninsula region does. By water mass analysis of JARPA oceanographic data, it is suggested that the Prydz Bay region can be one of the formation area of the AABW.

The most important aspect of JARPA is that observation is repeated in the same area in the same season. Useful marine environment information is beginning to be extracted from JARPA data. We regard JARPA as one of the important monitoring platform of the marine environment in the Southern Ocean. Sufficient consideration based on the experience of JARPA 1987/88-2004/05 is needed to get an efficient future observation plan for the JARPA area. It is also important to make JARPA oceanographic observation link with the monitoring by other in-situ observation projects (Argo, IPY, etc.) and satellite observations. The fundamental information about physical oceanographic environment in the JAPPA area has been accumulated for 18 years, which will be fully utilized to investigate the relation among physical environment, biochemical environment and habitat environment of the whale in the future stage of JARPA.

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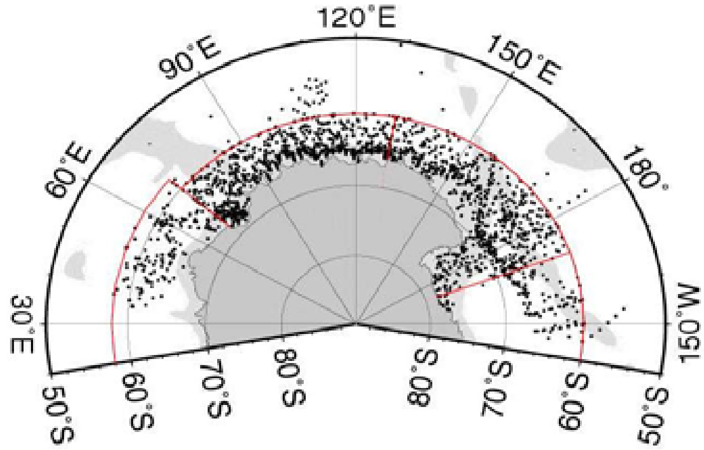

Fig.1. Oceanographic observation in the JARPA.

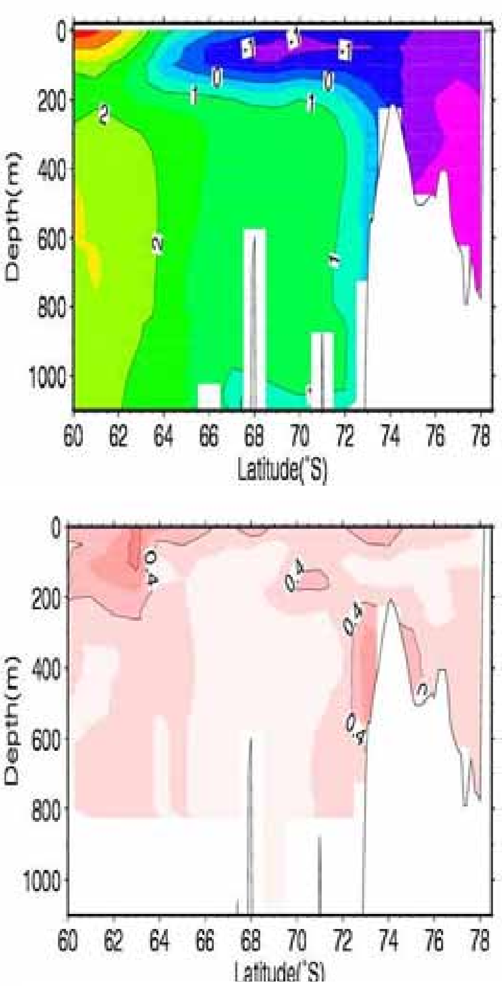

Fig. 2. Long-term mean meridional temperature section (left) and standard deviation (right) along the date line.

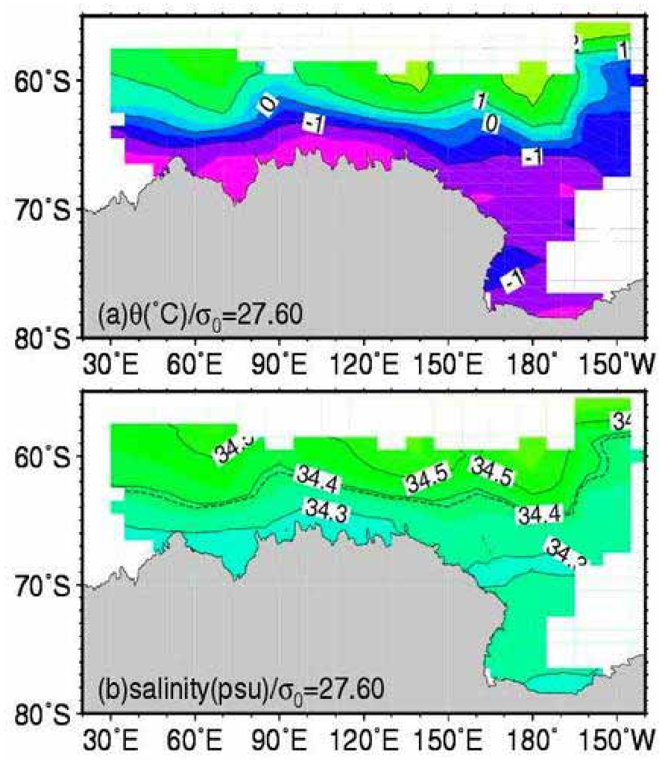

Fig. 3. Temperature (top panel) and salinity (bottom panel) distribution on 27.6σ_θ isopycnal surface.

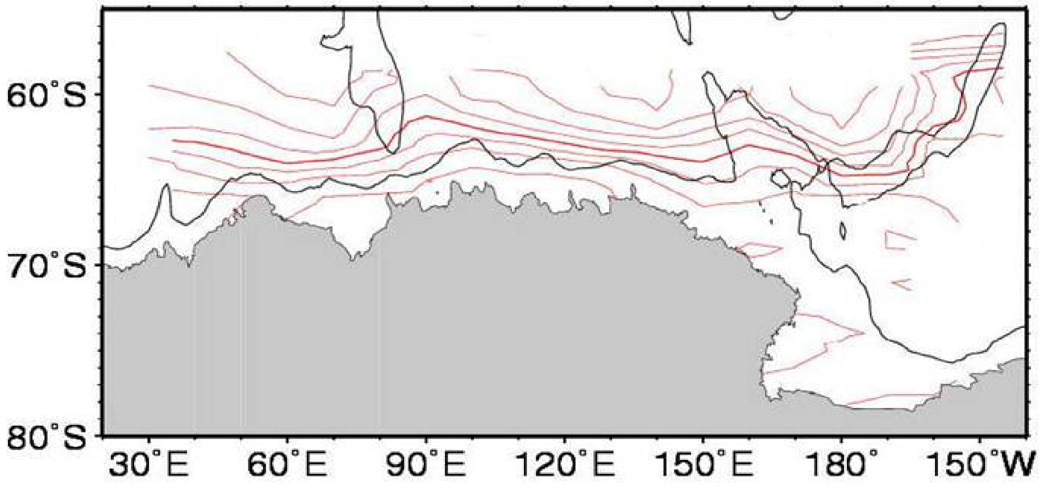

Fig. 4. Relationship between SB of ACC and bottom topography. Red curves indicate temperature contours on 27.6σ_θ isopycnal surface. Thick line is 0ºC contour. Black curves are 3000m depth contour.

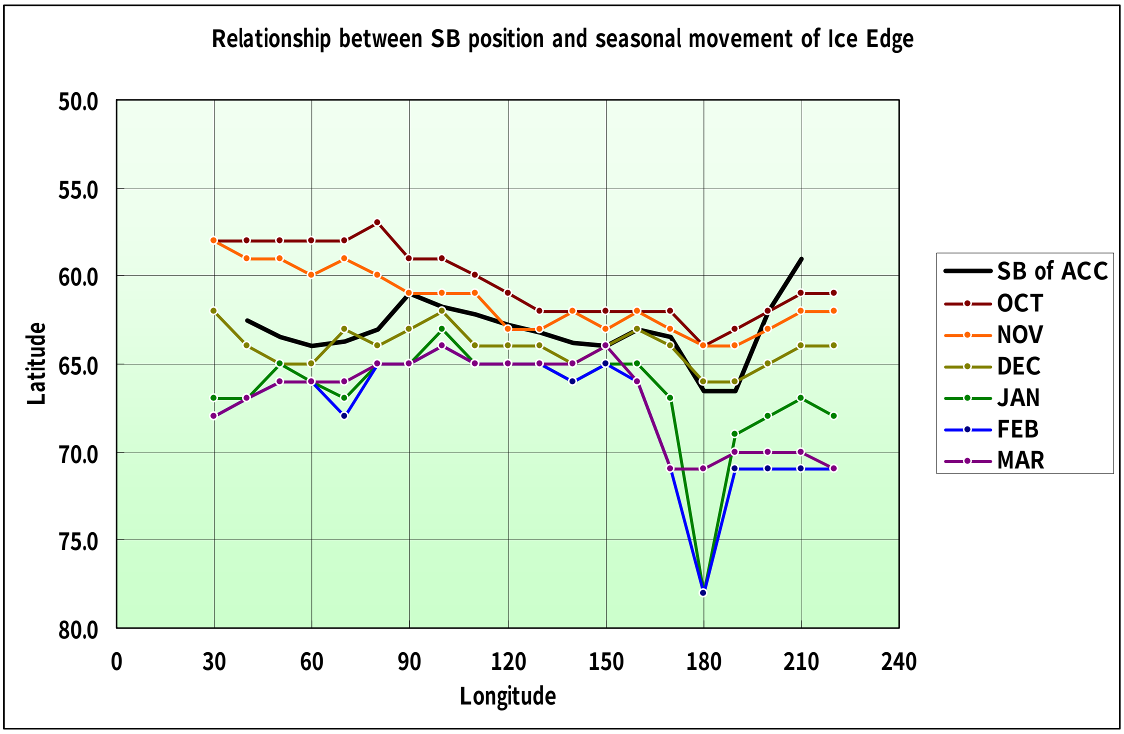

Fig. 5. Relationship between SB of ACC and ice edge for months, October – March.

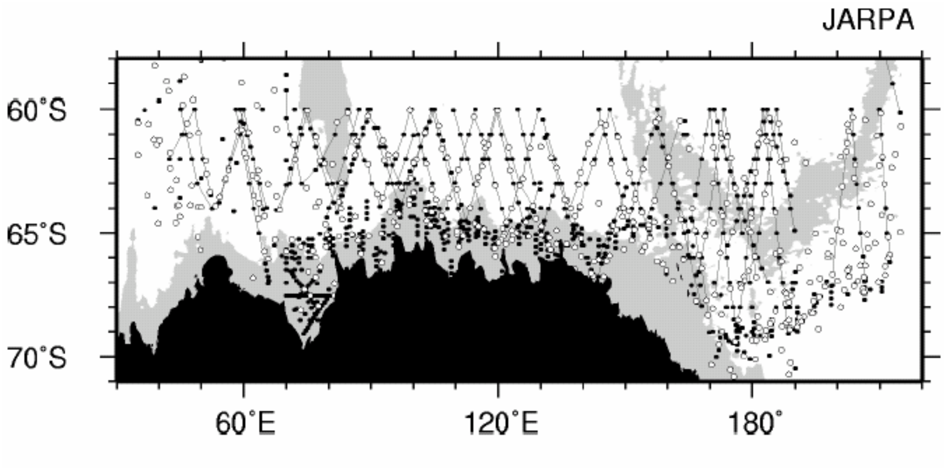

Fig. 6. Oceanographic stations of JARPA from 97/98 to 04/05. Closed circle and open circle indicate XCTD and CTD stations, respectively. The region shallower than 3000m is shaded.

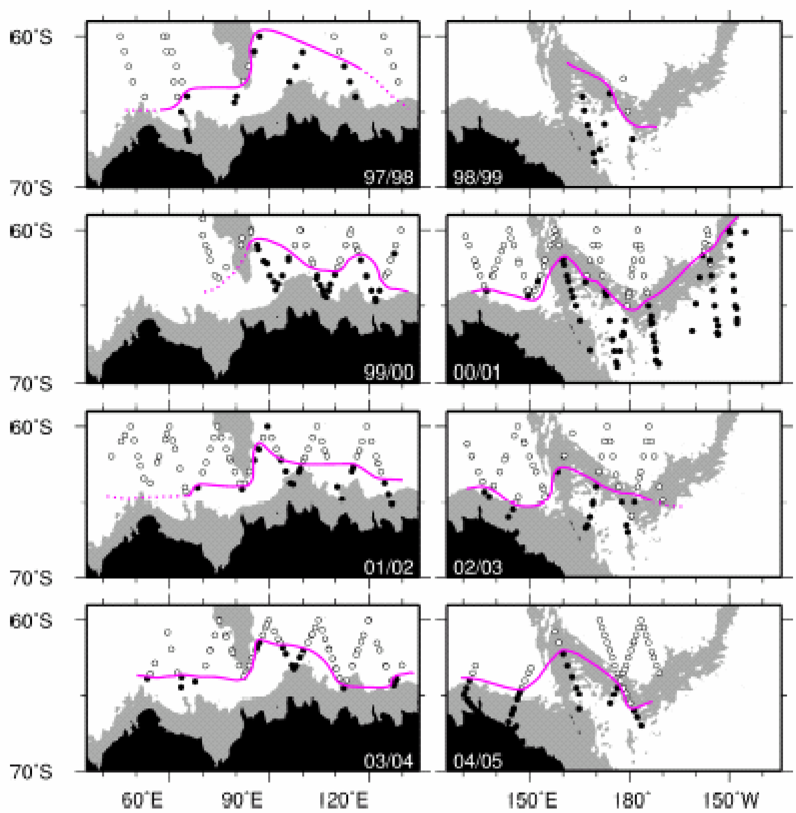

Fig. 7. SB of ACC detected by the XCTD and CTD data of JARPA-97/98 – 04/05 Cruise. Red line shows position of SB.

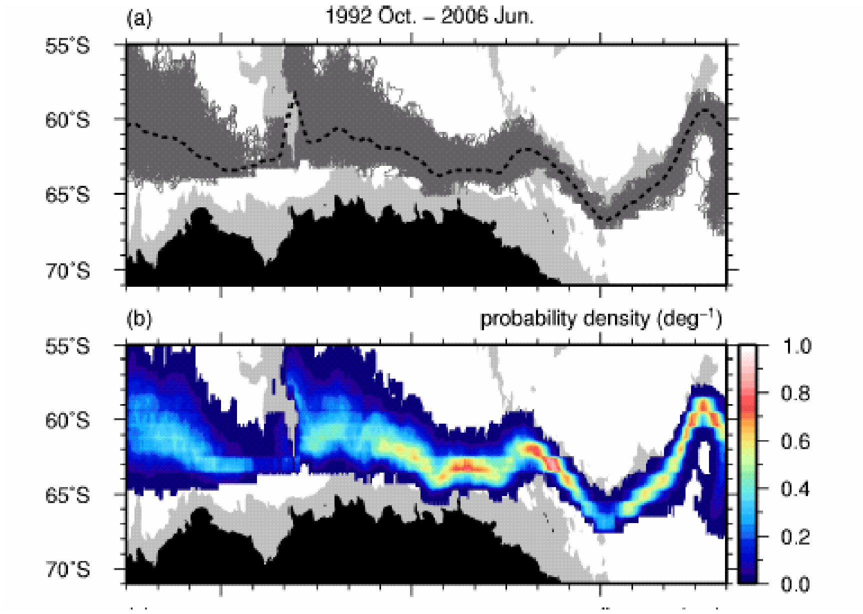

Fig. 8. (a) The map of the Southern Boundary of the Antarctic Circumpolar Current estimated from sea surface height. Average position is indicated by dashed line. (b) The map of probability density of SB.

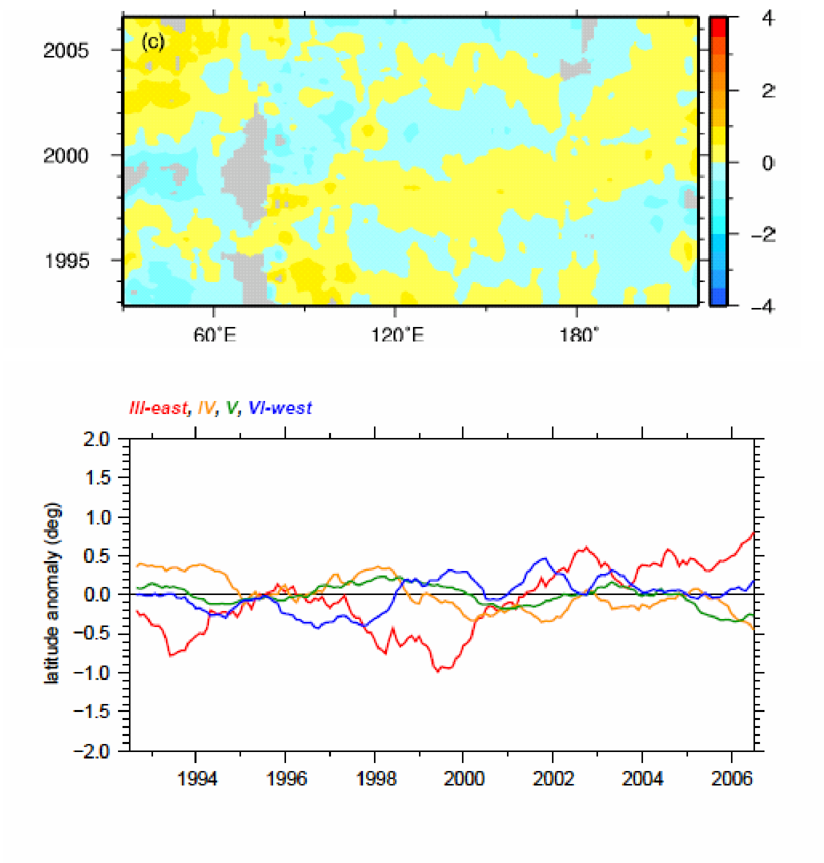

Figure 9. Upper: Time-longitude diagram of interannual variation of SB position. Positive value indicate northward shift. Lower: Interannual variation of SB position of each JARPA Area.

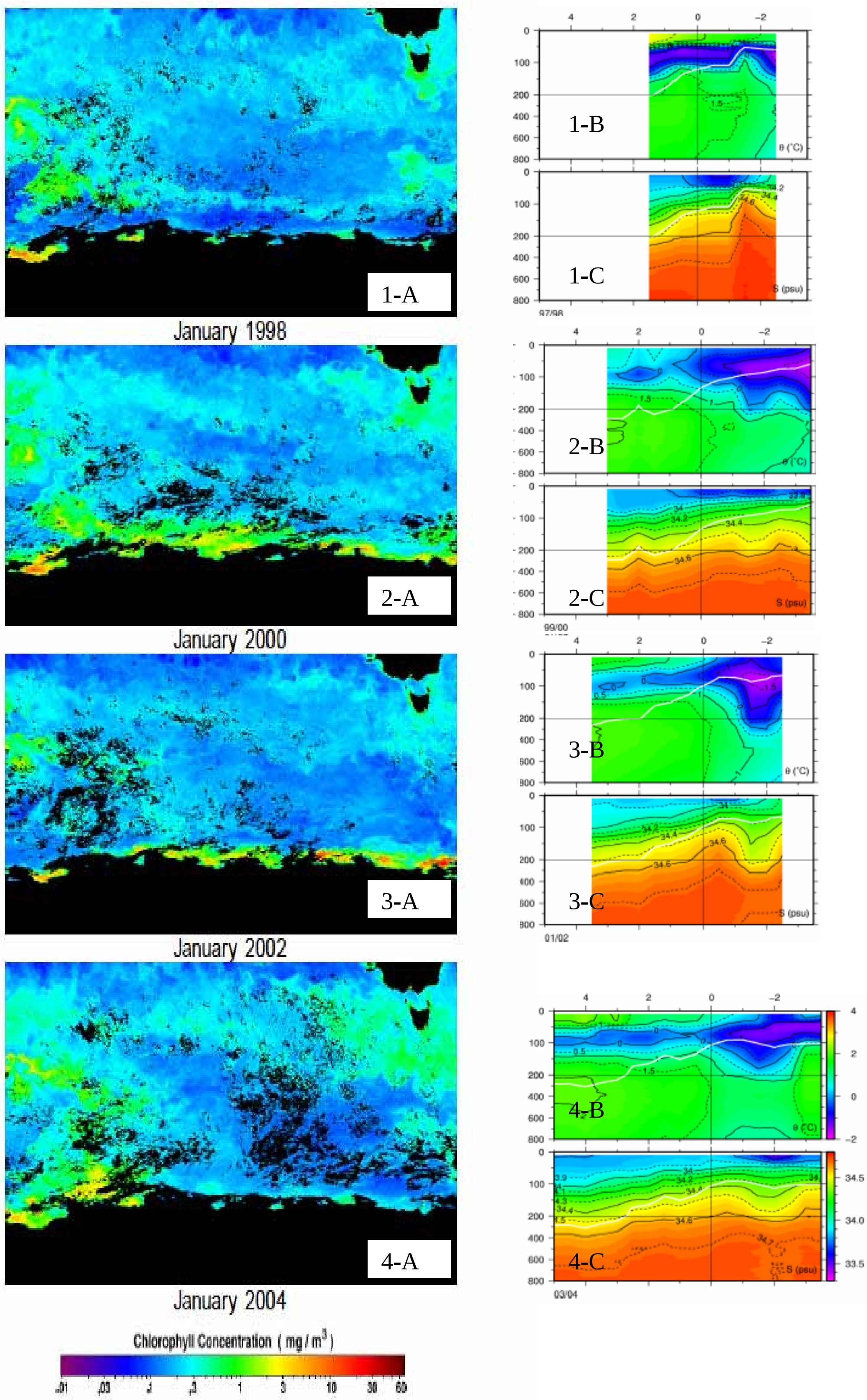

Fig.10. 1-A: Distribution of Chl-*a* in January 1998. 1-B and 1-C are temperature and salinity composited section of area IV for 1997/98 JARPA respectively. Horizontal axis of 1-B and 1-C is distance from the SB and vertical axis is depth. 2-A is for January 2000 and 2-B,C are for 1999/2000 JARPA. 3-A is for January 2002 and 3-B,C are for 2001/2002 JARPA. 4-A is for January 2004 and 4-B and C are for 2003/2004 JARPA.

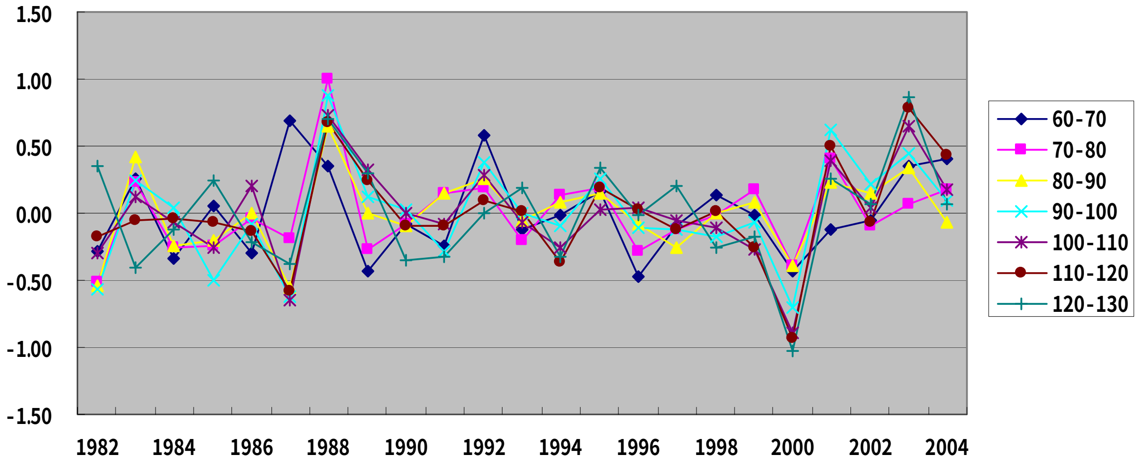

Fig. 11. Year-to-year variations of March SST for area IV

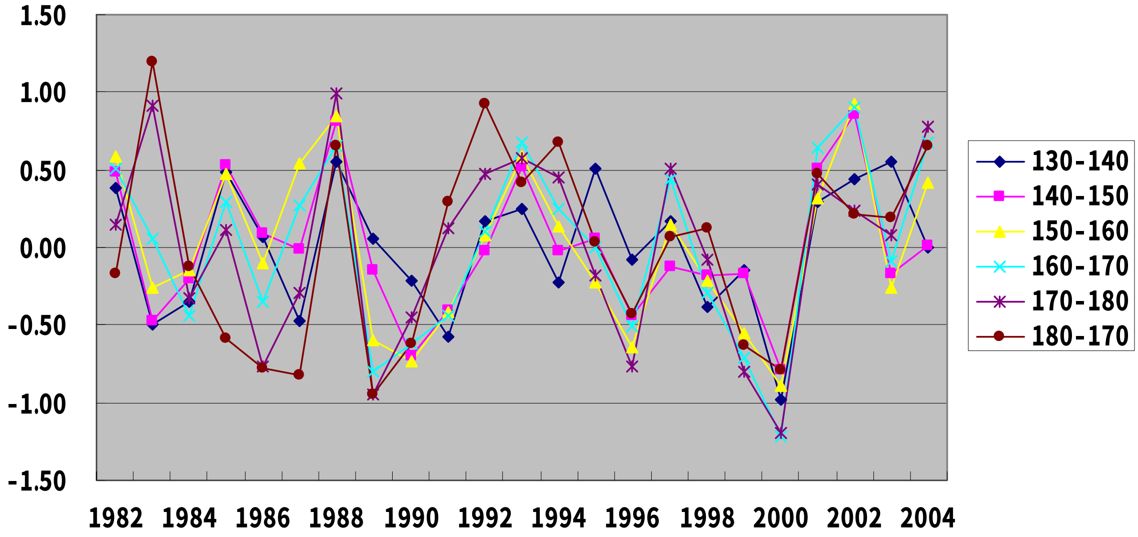

Fig. 12. Year-to-year variations of March SST for area V

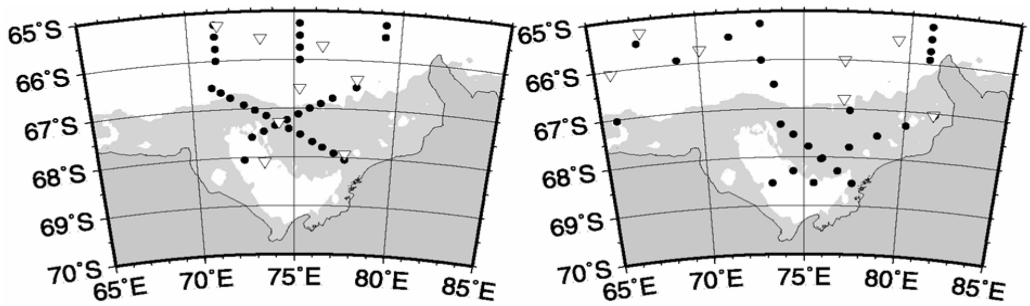

Fig. 13. Observation points in the Pridz Bay region, 1999/00 and 2001/02 JARPA Cruise.

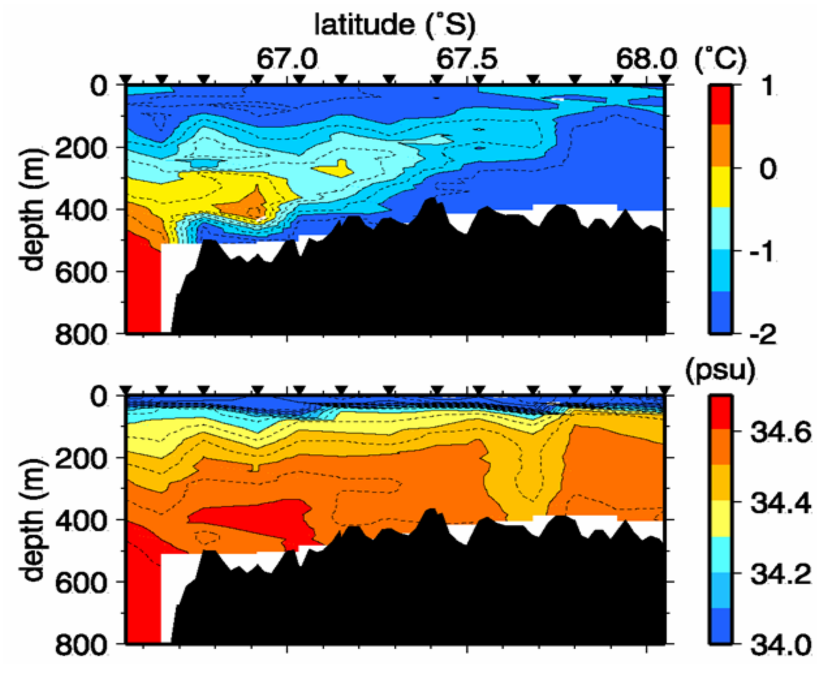

Fig. 14. XCTD sections in the Prydz Bay