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

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ABSTRACT

Oceanographic observation data obtained by JARPA and JARPA II were analyzed to clarify physical oceanographic conditions in the JARPA area as a basis for understanding of habitat environment of whales. About 2500 profiles were obtained by XBT, XCTD and CTD observations from 1990/1991 to 2008/2009. Obtained profile data were converted to the same format and utilized to describe the oceanographic feature of JARPA area. The data set enabled to describe the averaged feature of the oceanographic structure in JARPA area for two decades. The Southern Boundary (SB) of the Antarctic Circumpolar Current (ACC), which detected by a 0ºC temperature contour line on the 27.6σ_{0} isopycnal surface, characterize the JARPA area. It is evident that the position of the SB is controlled by major features of bottom topography such as the Kerguelen Plateau and the Pacific-Antarctic Ridge. In the area east of the Kerguelen Plateau, the position of the SB changes on decadal timescale. The southward shift of SB in the region is observed in the early 2000s, and northward shift is observed in the later 2000s. Although the global warming is important forcing for the Southern Ocean, the JARPA and JARPA II temperature data shows no statistically significant warming in the JARPA area for the two decade unlike the Antarctic Peninsula region.

KEYWORDS: ANTARCTIC, SURVEY VESSEL, OCEANOGRAPHY, CLIMATE CHANGE, HABITAT, HUMPBACK WHALE,

INTRODUCTION

Oceanographic observation has been included in JARPA and JARPA II and a lot of subsurface temperature and salinity profile data were collected from JARPA area (Pacific and Indian sector of the Southern Ocean, poleward of 60ºS) for 22 years period from 1987/1988 to 2008/2009. The purpose of the oceanographic observations is to obtain fundamental information of the ecosystem in the JARPA area and to contribute to clarify the relationship between the oceanographic conditions and whales.

The repeat oceanographic observations of coastal region conducted in the JARPA is also important for oceanography as the Southern Ocean plays key roles in the global thermohaline circulation through water mass formation in the area. The North Atlantic Deep Water (NADW) is formed in the northern North Atlantic flows into the Southern Ocean and is 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). Although oceanographic observation by autonomous profiling floats (ARGO) is expanded in deeper area of the Southern Ocean in recent years, sustained observations in the coastal regions where the ARGO floats are difficult to get in are still important oceanographical issue (Rintoul *et al*. 2012). The oceanographic observation in JARPA oceanographic data contribute to the monitoring of the coastal ocean of the Southern Ocean.

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 reaching to the deeper layer (Orsi *et al*. 1995). The oceanographic conditions of the JARPA area are also under the strong influence of the southern part of ACC. The Southern Boundary (SB) of the ACC, which is southern limit of 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 (Figure 1). Nicol *et al*. (2000) indicated the results of the BROKE (baseline research on oceanography, krill and the environment) in the area from 80ºE-150ºE 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. In this study, by using the expanded JARPA oceanographic data set by JARPA II, we advance the analysis of the oceanographic structure and year-to-year variation of JARPA region.

DATA

Vertical oceanographic structures were observed by using XBT (eXpendable Bathy Thermograph), CTD (Conductivity-Temperature-Depth profiler) and XCTD (eXpendable CTD). Total number of available profiles is 2557 from 1990/1991 to 2008/2009. XBT was mainly used in the first stage of JARPA (1987/1988-1996/1997). XCTD (1997/1998-present) and CTD (SBE19 SEACAT profiler, 1998/1999-present) were introduced to get temperature and salinity profiles that were important for dynamics of ocean currents and water mass analysis. These data were stored in same format to be treated by the Ocean data View (Schlitzer, R., Ocean Data View, http://odv.awi.de, 2011). Figure 2 shows oceanographic observation stations of JAPRA. In our analysis, we used the data obtained after 97/98 JARPA when salinity data available for water mass analysis. 1178 XCTD stations and 675 CTD stations were occupied during 12 JARPA cruises from 1997/1998 to 2008/2009. 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. The 10m interval smoothed profile data set was created from original 1-m interval data and used for analysis. The accuracy of temperature and salinity data was also checked by comparing with existing data downloaded from the database operated by JODC (Japan Ocean Data Center). The data at the depth range from 410 to 500m in the northern part of area IV (70ºE-130ºE, 60ºS-65ºS) were used for the comparison. The results of the comparison of the appearance probability for temperature value and salinity value are shown in Figure 3. The figure shows that the JARPA data set has same statistical characteristics with existing data set. The peaks of appearance probability for salinity of the two data sets coincide with the difference of less than 1/100 psu. These results show the JARPA data have enough accuracy for understanding the Southern Ocean.

RESULTS

Large scale oceanographic conditions of JARPA area

In order to classify the oceanographic structure of the JARPA area, a claster analysis was performed for the JARPA and JARPA II temperature profile data by using K-means method. The profiles were classified to five clusters, as shown in Figure 4. The geographical distribution of each cluster is mapped in Figure 5. The Cluster-1 is the typical temperature profile observed in the coastal area and in the Ross Sea, the Prydz Bay region.

Cluster-3,-4,-5 are profiles observed in the offshore region. These profiles have dichothermal structure (temperature minimum) in the upper layer from 50 to 100m depth and temperature maximum layer below 300m depth. The cluster-4 is dominant in the offshore region of the JARPA area IV and the cluster-3 is remarkable in the southern part of the area V. Cluster-2 has the intermediate character between the coastal water (Cluster-1) and the offshore water (Cluster-3, -4, -5). The distribution of the profile types shows the layer structure in the meridional direction corresponding to the current system in the Southern Ocean.

By using all the profile data, horizontal temperature structures at the dichothermal layer which is remainder of the mixing of upper water in former winter and temperature maximum layer indicating the upwelling of the upper Circumpolar Deep Water (UCDW) are shown in Figure 6a and 6b respectively. The 80m temperature was used as the temperature at dichothermal layer and the 350m temperature was used as the temperature at temperature maximum layer. Figure 6c is the horizontal temperature distribution on the 27.6σ_0 isopycnal surface. Frontal structure observed along the 0ºC contour coincides with the southern limit of UCDW and indicates the Southern Boundary (SB) of the Antarctic Circumpolar Current (ACC) (Orsi *et al*., 1995). Horizontal distributions of 80m temperature, 350m temperature and temperature on the 27.6σ_0 isopycnal surface reveal almost same pattern each other. As pointed out by Watanabe *et al*. (2006), the SB indicated by the 0ºC contour on 27.6σ_0 is affected by the bottom topography of the Kerguelen Plateau and the Pacific-Antarctic Ridge. In Figure 6a-6c, the temperature contours on each level show the same characteristics around the Kerguelen Plateau and the Pacific-Antarctic Ridge.

Year-to-Year variation of the temperature field and SB

In order to investigate the year-to-year variation of the JARPA area from the 1990s to the 2000s, two typical oceanographic structures, dichothermal layer and temperature maximum layer, and SB of ACC were analyzed. For the Area IV, the temperature profile data in the region between 100º E and 130º E and south of 60ºS were used to construct the time-latitude diagram of 80m and 350m temperature (Figures 7a and 7b). Year-to-year variation of temperature on 27.6σ_0 isopycanal surface is also shown in Figure 7c. For the Area V, data in the region between 170º E and 170ºW and south of 60ºS were used. Time-latitude diagram of 80m, 350m temperature and temperature on 27.6σ_0 isopycnal surface are shown in Figures 8a – 8c. Temperature distribution on the 27.6σ_0 isopycnal surface was calculated for the period after 1997/1998 season when the XCTD observation started.

The position of SB in the area IV is around 62ºS to 63ºS and shows the decadal change. The position shifted southward from late 1990s to early 2000s and shifted northward after mid-2000s (Figure 7c). The SB in the area V is located around 63ºS to 64ºS and the similar changes with area IV are observed (Figure 8c). The southward shift of SB was reported for the region east of the Kerguelen Plateau from the analysis of the JARPA data for 1997/1998, 1999/2000, 2001/2002, 2003/2004 by Watanabe *et al.*(2006). The present results suggest that the position of the SB has variation with decadal timescale.

To investigate the year-to-year variation of the temperature in the dichothermal layer and temperature maximum layer, vertically averaged temperature data sets for 50-100m depth range and 300-500m depth range were constructed for the three regions. In the Area IV, offshore region from 60ºS to 63ºS and the coastal region from 64ºS to 67ºS were selected. In the Area V, middle region from 65ºS to 70ºS, where the temperature profiles classified into cluster-3 were dominant, was selected. Time series of temperature for the three areas are shown with error bar of standard deviation in Figures 9a–9c. Large Standard deviations of dichothermal layer temperature in the north region and of temperature maximum layer temperature in the south region of the Area IV for show the large spatial variability in each depth layer. On the other hand, temperature variability at the dichothermal layer in the south and temperature variability at temperature maximum layer in the north are smaller and show the some warming trend. But the statistical examination shows that these trends are not significant. In the middle region of the Area V, subsurface temperature shows smaller variation (Figure 9c).

DISCUSSION

In this study, climatological oceanographic structure of the JARPA area was identified by the JARPA and JARPA II oceanographic data for about 20 year period. The JARPA area was characterized by the meridional zonation of the water mass distribution, the distribution is consistent to the typical structure of fronts and water mass summarized by Talley *et al*. (2011). The SB was recognized as the major front in JARPA area and which was also indicated by a boundary of clusters of temperature profiles by the cluster analysis. The temperature profiles in the coastal area were clearly classified into one cluster and the large differences from other clusters were revealed. The northern limit of the distribution of cluster of coastal water is the Antarctic Shelf Front (ASF), and the front has important meanings for oceanography and for marine biology of the Southern Ocean. These oceanographic front systems were clearly identified for the JARPA and JARPA II periods.

The reanalysis of the meridional shift of the SB in the Area IV, which was pointed out by Watanabe *et al.* (2006), suggested that the shift was a part of the fluctuation with longer timescale. Giarolla and Matano (2013) analyzed the sea surface height data and identified the eastward propagating wavelike pattern on decadal time scale in the Southern Ocean. Though the coastal region is the edge of their analysis area because of insufficient data affected by sea ice, the long-term variation of the SB depicted in this study might to be related to the large scale fluctuation observed in the offshore sea surface height field.

Massom *et al*. (2013) analyzed the satellite observed sea ice and sea surface temperature data in east Antarctic sea. Their results about long-term variation showed the showed the shortening of the ice season duration in the northern part of the JARPA area IV and the lengthening in the southern part. They also showed the long-term trends in the sea surface temperature for each calendar month for the period from 1982 to 2010. Their results show that significant warming occurred in the region north of JARPA area IV. On the other hand, the complicated situations observed in the JARPA area IV where cooling in the sea ice edge region and warming in the offshore region were detected. These results seems consistent to our findings about the year-to-year variation obtained by analyzing in-situ oceanographic observation data.

Several analyses of the satellite observed sea surface height field in the Southern Ocean indicate the trend of sea level rise is dominant component of variation for 1990s and 2000s. The trend is found in almost whole area the Southern Ocean and is thought to be a part of global sea level rise related to the global warming issue (Giarolla and Matano, 2013). The trends in the sea ice and the sea surface temperature reported by Massom *et al*. (2013) are thought to have some relation with the sea surface height. Thus, satellite observed data is effective indicator of the marine environment of the Southern Ocean. However, these satellite observations are less available in the coastal area of the Southern Ocean. For this reason, in order to understand the structure and change of the marine ecosystem of the JARPA area, monitoring of the marine environment by in-situ observation and matching of in-situ data and satellite observed data are necessary.

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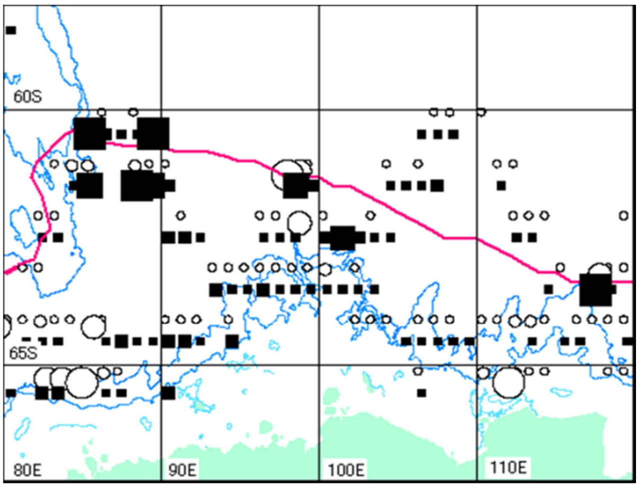

Figure 1. Relationship between distribution of Hampback whale (square) and the Southern Boundary (red curve) cited from Matsuoka *et al*. (2003).

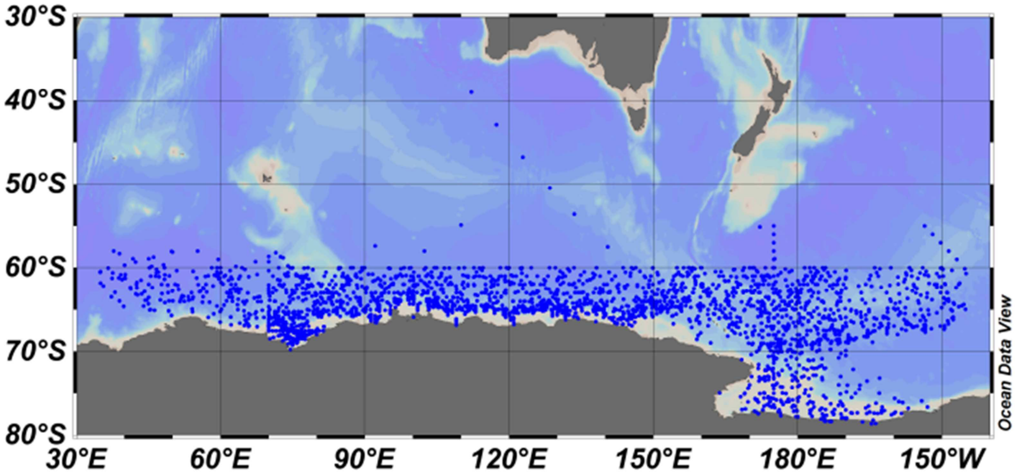

Figure 2. Oceanographic observation in the JARPA and JARPAII research area.

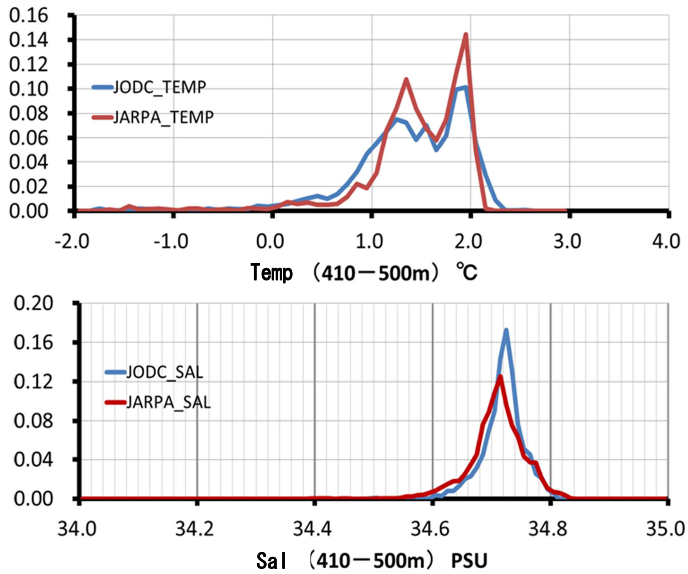

Figure 3. Appearance probability of temperature value (upper) and salinity value (lower).

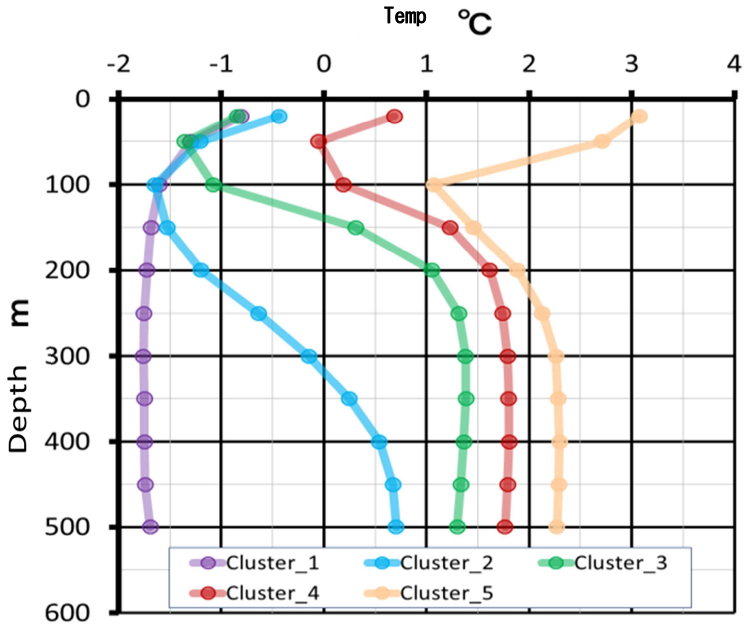

Figure 4. Five typical temperature profiles observed in the JARPA area obtained by a claster analysis using the K-means method.

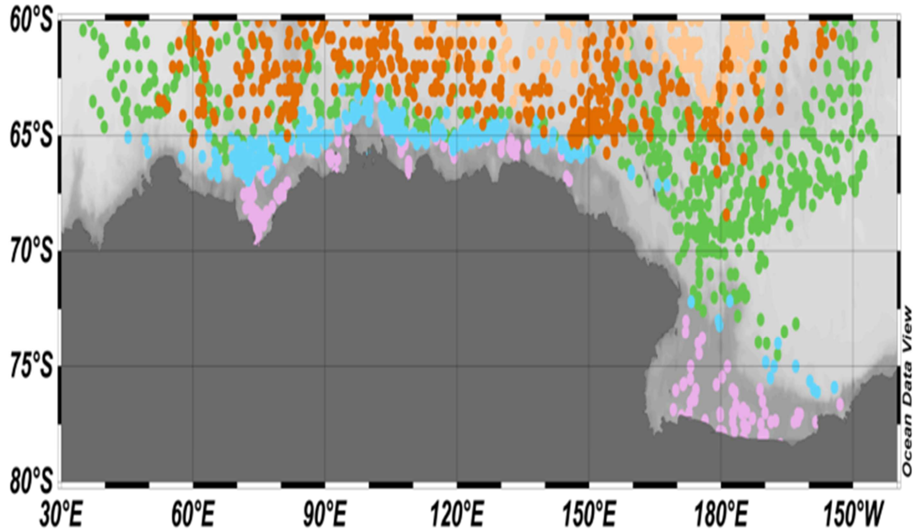

Figure 5. Horizontal distribution of five types of temperature profile in the JARPA area. Legends are as follows. ●:Temperature profiles classified in to Cluster-1, ●:Cluster-2, ●:Cluster-3, ●:Cluster-4, ●:Cluster-5.

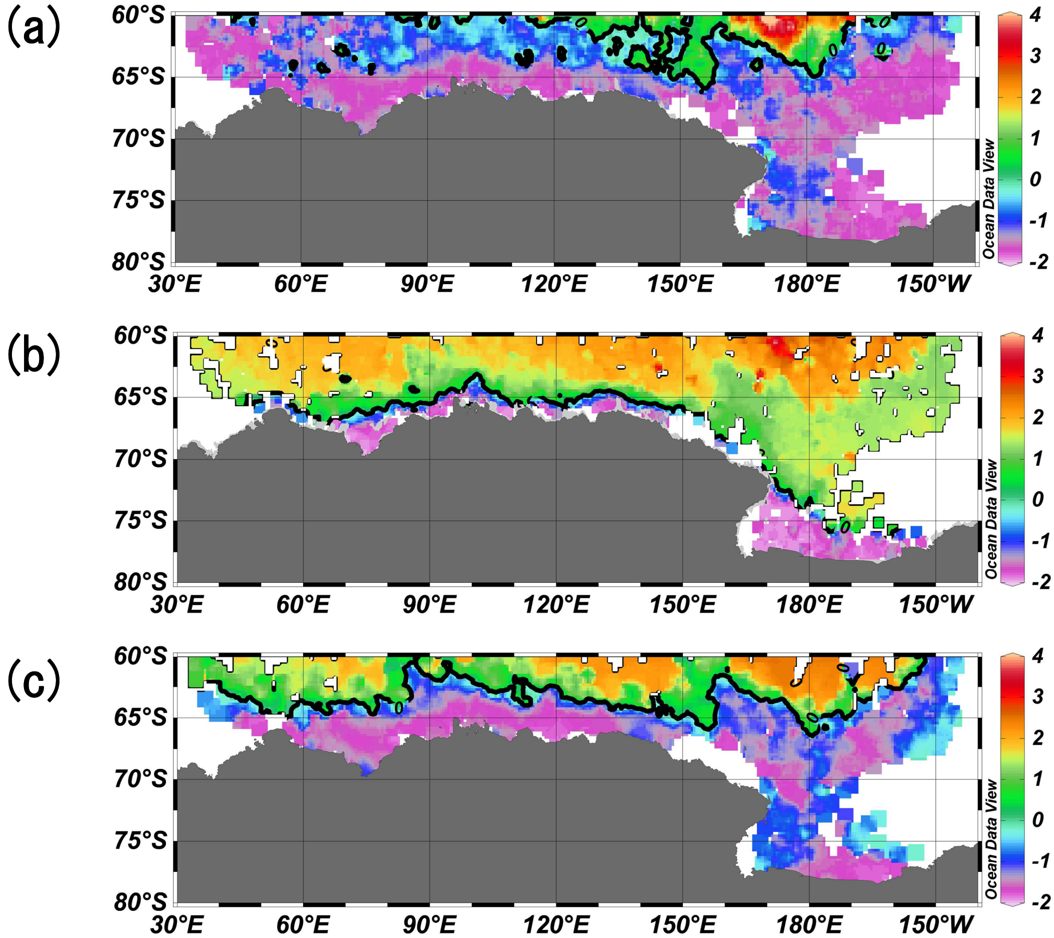

Figure 6. Climatological horizontal temperature distribution calculated by using JARPA and JARPA II data for the period from 1990/1991 - 2008/2009. (a) Temperature at 80m depth corresponding to the dichothermal layer. (b) Temperature at 350m depth corresponding to the temperature maximum layer in the offshore region. (c) Temperature at 27.6σ_0 isopycnal surface. Thick line indicates the 0℃ contour at each layer.

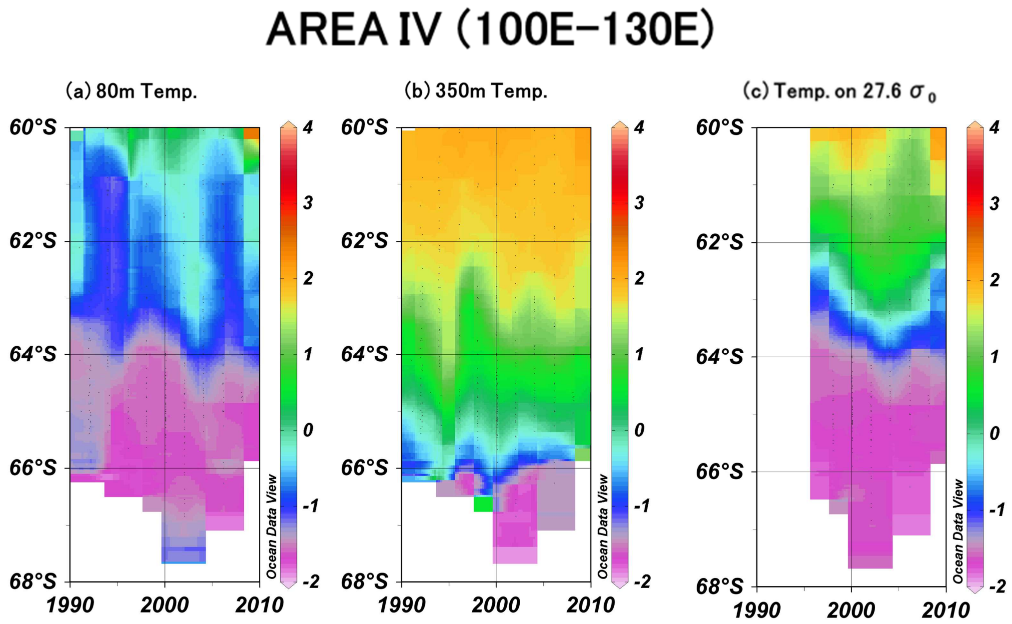

Figure 7. Time-latitude diagram of (a) 80m temperature, (b) 350m temperature, (c) temperature on the 27.6σ_0 isopycnal surface for the Area IV.

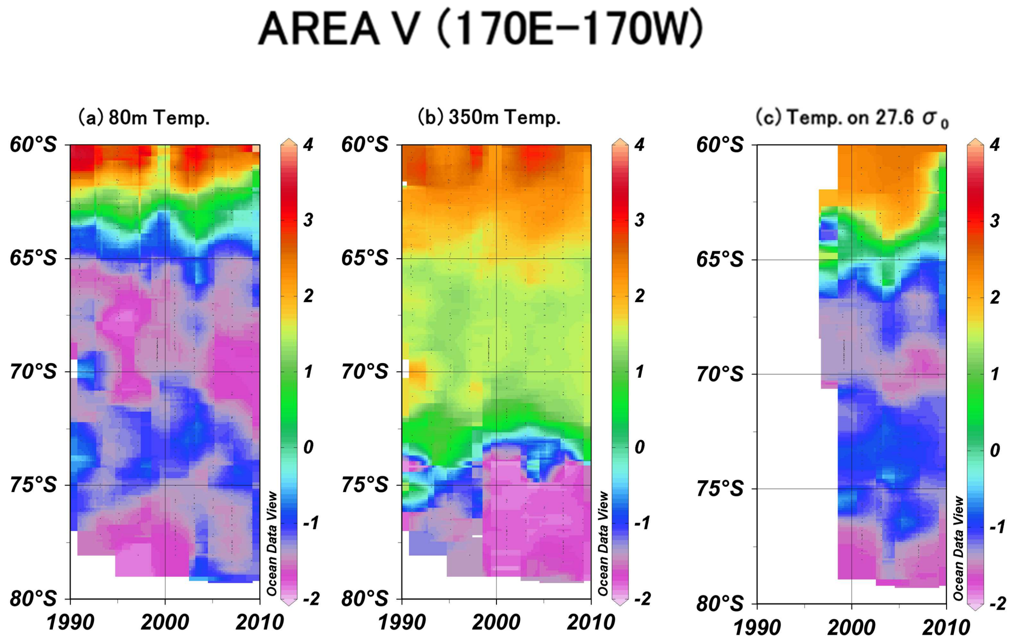

Figure 8. Time-latitude diagram of (a) 80m temperature, (b) 350m temperature, (c) temperature on the 27.6σ_0 isopycnal surface for the Area V.

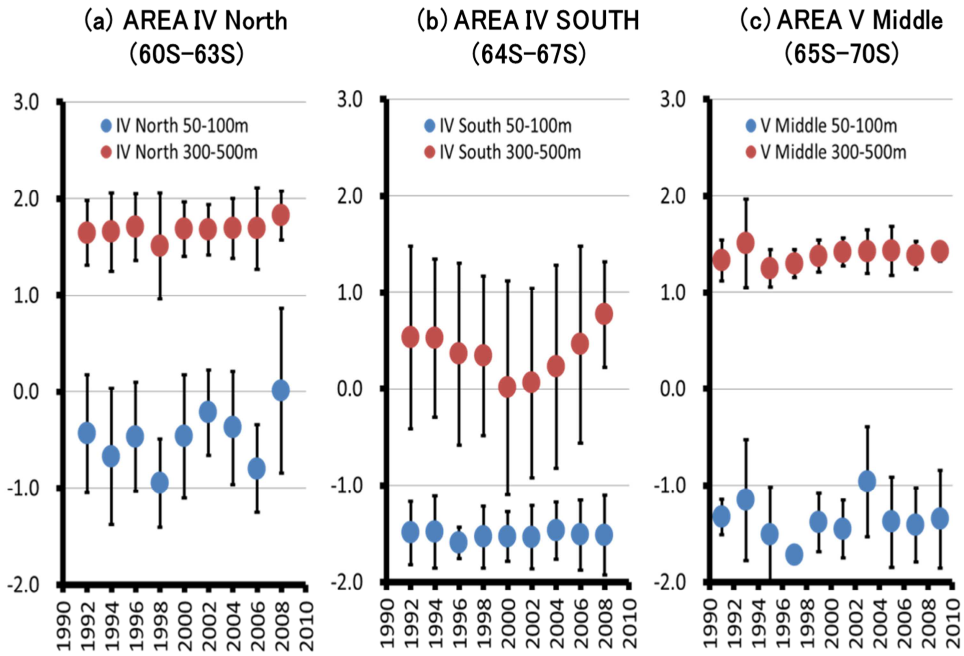

Figure 9. Year-to-year variation of temperature at the dichothermal layer and temperature maximum layer in the (a) north and (b) south regions of Area IV and (c) middle region of Area V.