Comparison between the CCAMLR 2000 and KY 1988 Surveys on environmental variability of krill in the Scotia Sea, Antarctica

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Abstract.

We assessed the environmental variability of Antarctic krill (*Euphausia superba*) distribution with comparison between the CCAMLR 2000 Survey and similar scale datasets partially by the Japanese R/V *Kaiyo Maru* Survey in the 1987/88 austral summer season in the Scotia Sea. There were distinct differences between the 2000 and 1987/88 Surveys with regard to sea ice extent, oceanographic structure and krill distribution. The sea ice cover in 1987/88 extended northward widely during the last winter season such that sea ice remained around the South Orkney Islands until December 1987. In contrast, the sea ice cover in 1999/2000 reduced southward such that no sea ice remained around the South Orkney Islands in December 1999. The Antarctic Surface Water mass, consisting of Winter Water and Summer Surface Water, in 1987/88 extended northward and covered a large area in the Scotia Sea. In contrast, the Antarctic Surface Water in 2000 reduced southward. Geographical distribution of krill, which approximates the area of the Antarctic Surface Water, in 1987/88 extended northward with high density. In contrast, the distribution of krill in 2000 reduced southward with low density. To generally understand the above relationships between oceanographic structure and krill distribution, we introduced integrated water temperature from the

surface to 200m ($\overline{Q}_{200} = 1/200\int_0^{200}(Temperature)dz$) as an environmental index indicating the structure of the upper ocean, that is referred to as the Environmental Index (EI $\overline{Q}_{200}$). The isoline of EI $\overline{Q}_{200}$=0.0°C was located near 60S northward off the South Shetland Islands in 1987/88. In contrast, the isoline of 0.0°C in 2000 was located in the Bransfield Strait and Weddell Sea southward off the South Shetland Islands. The Antarctic Surface Water in 1987/88 clearly developed northward compared with 2000 reduced southward. The geographical distribution of krill ranged over the area under the isolines of EI $\overline{Q}_{200}$=1.0°C in the western waters and 2.0°C in the eastern waters of the Scotia Sea. Krill density became higher with the colder isolines of EI $\overline{Q}_{200}$=0.0 °C, especially south of its steep gradient, namely, the Southern Boundary of the Antarctic Circumpolar Current. It suggested that the geographical distribution of three krill size clusters in the 2000 Survey (Siegel et al., 2002) corresponded with the distribution pattern of EI $\overline{Q}_{200}$ on the whole.

Key Words: Antarctic krill, Scotia Sea, oceanographic structure, environmental variability

1. Introduction

Long-term analyses of Antarctic krill (*Euphausia superba*) recruitment and density in the Antarctic Peninsula area indicated significant inter-annual variability (Siegel and Loeb, 1995; Loeb et al., 1997; Siegel et al., 1998, Siegel, 2000). The biological variability of krill is generally affected by physical environmental processes. Siegel and Loeb (1995) qualitatively presumed that annual variability of the recruitment and density of krill was related to the sea ice condition, that is, years with extensive ice coverage and a long duration of the ice cover produced high recruitment of krill and vice versa. Hewitt (1997) devised an index of sea ice cover in the Antarctic Peninsula area and estimated the inter-annual variability index of the sea ice cover.

Naganobu et al. (1999) indicated a strong positive correlation between the index of krill recruitment (Siegel and Loeb, 1995) and the index of sea ice cover (Hewitt, 1997) based on the hypothesis of the atmospheric-sea ice process, that is, the inter-annual variability of the prevailing westerlies in this area. Moreover, Naganobu et al. hypothesized that the extent of the sea ice affected the distribution pattern of the Antarctic Surface Water, which is characterized by cold temperature less than 0℃.and the dynamics of the Antarctic Surface Water strongly influenced the biological variability of krill.

However, the key question is whether both oceanographic and krill data in comparable different years exist synoptically. The CCAMLR 2000 Synoptic Survey contains the categories of both oceanographic and krill data in the Scotia Sea (Figure 1). In addition, we have similar scale data of another synoptic survey of both oceanographic and krill data conducted by the Japanese R/V *Kaiyo Maru* during the austral summer of 1987/88 (the KM 1988 Survey:) although the survey area is smaller than that of the CCAMLR 2000 Survey (Figure 2).

We studied the environmental variability of krill by the comparative method for the CCAMLR 2000 and KY 1988 Surveys using data of sea ice and sea surface temperature by satellite, oceanographic structure by CTD and XBT, and krill distribution and density by net samplings. As a result of the comparative analysis, there were strong contrasts between the CCAMLR 2000 and KY 1988 Surveys.

In the CCAMLR 2000 Survey, the extent of sea ice was narrow and the edge of the sea ice was located southward. The sea surface temperature was generally warm. The water mass of the Antarctic Surface Water was narrow and retreated southward. According to the weak extent of the Antarctic Surface Water, the distribution of krill also retreated southward and the density of krill was low. In contrast, in the KY 1988 Survey, the extent of sea ice was wider and the edge of sea ice was located northward. The sea surface temperature was generally colder. The water mass of the Antarctic Surface Water was larger and extended northward. According to the strong extent of the Antarctic Surface Water, the distribution of krill also extended northward and the density of krill was higher. The comparison of both surveys in different years at the same area showed that the dynamic of Antarctic Surface Water indicating the characteristic of the upper ocean structure strongly affected the distribution and density of krill.

2. Materials and Methods

2.1 Field surveys

The present study area was the Scotia Sea including the regions of the South Shetland Islands, South Orkney Islands, South Georgia Island and South Sandwich Islands, which were investigated by the CCAMLR 2000 Survey between approximately 20 and 70W (Figure 1). Since the area investigated by the KY 1988 Survey was smaller than the CCAMLR 2000, comparison of the data of both surveys restricted the area extending from approximately 56 to 62-30S and 44 to 61W including the regions of the South Shetland Islands and South Orkney Islands (Figure 2).

The CCAMLR 2000 Survey was conducted in January and February 2000 by four vessels from CCAMLR member nations; RV *Kaiyo Maru* (Japan), MV *Atlantida* (Russia), RRS *James Clark Ross* (UK) and MV *Yuzhmorgeologiya* (USA). Each vessel carried out standardized acoustic measurements, net sampling and CTD observations. The KY 1988 Survey took place in December 1987 and January 1988 by the *Kaiyo Maru,* which carried out acoustic measurements, net sampling, and oceanographic observations (XBT etc.). The parameters of both surveys analyzed in this study were the temperature of the CTD and XBT and krill distribution and density (Table 1).

2.2 Satellite: sea ice and sea surface temperature

Satellite images of sea ice concentrations in the Antarctic Ocean were provided electronically by the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder. Images were derived from daily averaged temperature brightness data. Images were compiled in polar stereographic format. The pixel size was a 25x25 km grid. The Antarctic Peninsula area was cut out from the sea ice images of the entire Antarctic Ocean. We averaged the monthly mean of sea ice concentrations from July 1999 to June 2000 for the CCAMLR 2000 Survey (Figure 3) and from July 1987 to June 1988 for the KY 1988 Survey (Figure 4). We compared the sea ice concentrations in 1999/2000 with 1987/88 in the same area around the Antarctic Peninsula.

Satellite data of the sea surface temperature were provided electronically by NASA. NASA distributes weekly mean global gridded MCSST (the multichannel sea surface temperature) images derived from the NOAA AVHRR(Advanced very High Resolution Radiometer). We picked up the

MCSST images in the Scotia Sea at the early, middle and end of January 2000 and 1988 for the CCAMLR 2000 Survey and for the KY 1988 Survey, respectively (Figure 5 and 6). We compared the sea surface temperature in January 2000 with 1988 in the same area of the Scotia Sea.

2.3 Oceanographic structure of water temperature

Four vessels of the CCAMLR 2000 Survey carried out the CTD (Sea-Bird 911 plus) sampling to 1000 m and the near-bottom, that is, within 10 m of the sea bed at any station where the water depth was less than 1000 m. The all CTD casts are shown in Figure 1. On the other hand, the *Kaiyo Maru* of the KY 1988 Survey carried out XBT sampling in minute scale as shown in Figure 2. We focused an analysis on comparable water temperature from both surveys to identify environmental characteristics of the survey area, in particular, the water masses that influence krill distribution and density and the approximate geographic location of significant fronts.

Firstly, the horizontal distributions of temperature at 10 m, 100 m and 400 m in the CCAMLR 2000 and KY 1988 Survey were prepared to understand the temperature structure of each layer as shown in Figure 7 and 8, respectively. Second, the integrated temperature from 0 to 200 m in depth z ($\overline{Q}_{200}$) was introduced as an environmental index of the upper ocean where:

$$\overline{Q}_{200} = 1/200\int_0^{200}(Temperature)dz$$

This index is hereinafter referred as the Environmental Index $\overline{Q}_{200}$ (EI $\overline{Q}_{200}$). Third, the vertical distribution of temperature along approximately 45W across the South Orkney Islands in the CCAMLR 2000 and KY 1988 Surveys were prepared to understand the vertical temperature structure as shown in Figure 9 and 10, respectively. Fourth, the north-south lines of EI $\overline{Q}_{200}$ along 45W Islands in the CCAMLR 2000 and KY 1988 Surveys were prepared to understand the north-south gradient of environmental structure as shown in Figure 11 and 12.

2.4 Krill distribution and density

Four vessels of the CCAMLR 2000 Survey carried out standardized hydro-acoustic measurements along parallel transects between 20 and 70W and two net sampling stations using the RMT1+8 (Rectangular Midwater Trawl) by each vessel every day (Siegel et al., this volume). The dimensions of the RMT1 are 1 m^2 mouth area and 0.315 mm mesh size. Dimensions of the RMT8 are 8 m^2 mouth area and 4.5 mm mesh size. Station net tows were carried out around local midnight. A quantitative standard oblique tow was conducted from the surface down to 200 m or to within 10 m of the sea bed at any station where the water depth was less than 200 m at each station. A constant ship speed of 2.5 knots was suggested during the hauls. A total of 135 net sampling stations was carried out during the survey.

On the other hand, the *Kaiyo Maru* of the KY 1988 Survey carried out net sampling stations using the KYMT (*Kaiyo Maru* typed Midwater Trawl) along four transects between 40 and 60W. Dimensions of the KYMT are 9 m^2 mouth area and 3.4 mm mesh size. A quantitative standard oblique tow was conducted from the surface down to 100 m as a general rule. A constant ship speed of 2.5 knots was maintained during the hauls. A total of 87 net sampling stations was carried out during the survey.

Krill catches by the RMT and KYMT net samplings were standardized to density data (gram per 1000 m^3). To understand the spatial distributions of krill density, the distribution maps of krill density in the CCAMLR 2000 and KY 1987 Surveys were prepared (Figure 13 and 14). Next, we assessed the relations between sea ice (paragraph 2.2), oceanographic structure (paragraph 2.2 and 2.3) and spatial distribution of krill density of both of the surveys. We also added to assess the relation between oceanographic structure and spatial distribution of krill density in the entire area of the CCAMLR 2000 Survey.

3 Results

3.1 Sea ice

Time series of the monthly mean from July to June of sea ice concentrations in 1999/2000 and 1987/88 are shown in Figure 3 and 4, respectively. The series in 1999/2000 and 1987/88 have the period of the CCAMLR 2000 Survey and the KY 1988 Survey, respectively. Comparing two series of sea ice in 1999/2000 and 1987/88 clarified the difference of sea ice condition in both surveys.

The extent of sea ice in July 1999 (Figure 3) was narrower than in July 1987 (Figure 4). The 1999 sea ice did not cover the South Shetland and South Orkney Islands. Sea ice did not cover the South Shetland Island in August and following months, either, except the South Orkney Islands. In contrast, the extent of sea ice from July to September 1987 was very wide northward and entirely covered the South Shetland and South Orkney Islands. The 1987 sea ice covered the South Orkney Islands until December, although there was entirely open sea around the South Orkney Islands in the same December. There were areas of low sea ice density around each island and the north tip of the Antarctic Peninsula. A large polynya developed between the South Shetland and South Orkney Islands in September.

During January to March in both surveys, there were open seas around the South Shetland and South Orkney Islands. However, the extent of sea ice in 2000 was narrower than 1988 around at the tip of the Antarctic Peninsula. Although the edge of the sea ice in 2000 retreated southward in the Weddell Sea, the edge in 1988 extended wider northward. From April the extent of sea ice developed northward again. The edge of the sea ice in May 1988 had already reached the South Orkney Islands while there was still open sea in May 2000. In June 1988 the sea ice had already covered the South Shetland and South Orkney Islands while there was no sea ice in June 2000. The development of sea ice in 1999/2000 including the period of the CCAMLR 2000 Survey, was obviously weaker than the 1987/88 including the year of the KY 1988 Survey.

3.2 Sea surface temperature

Time series of the weekly mean of sea surface temperatures by satellite in January 2000 and 1988 are shown in Figure 5 and 6, respectively. The series in 2000 and 1988 coincide with the period of the CCAMLR 2000 Survey and the KY 1988 Survey, respectively. comparing two series of sea surface temperatures in 2000 and 1988 clarified the difference of sea surface temperature condition in both surveys.

The sea surface temperature in January 2000 (Figure 5) showed two characteristic areas with a boundary of approximately 45W between east and west. Although little water less than the 0℃ isopleth of sea surface temperature was distributed in the western area around the Antarctic

Peninsula, its waters extended greatly northward in the eastern area around South Georgia at the first and middle of January. At the end of January, the 0℃ isopleth shifted southward and became warmer overall. The northern edge of the –1.0℃ isopleth shifted from 60S in the eastern area in the first ten days to 70S in the western area in the last ten days.

In contrast, water less than the 0℃ isopleth of sea surface temperature in 1988 distributed more widely than in 2000 in the western area around the Antarctic Peninsula (Figure 6). The north and south gradient of the isopleths were sharp in the Drake Passage and continued to South Georgia on the first of January, although gently in 2000. Cold waters less than the 0℃ isopleth covered the South Shetland Islands. Although the cold waters became gradually warmer from the first to end of January, they still covered the South Shetland Islands compared with 2000. Waters less than the 0℃ isopleth, however, were not distributed in the eastern area in the middle and last ten days contrasting with 2000.

Summarizing sea surface temperature in the western area around the Antarctic Peninsula, cold waters were distributed more widely in 1988 than in 2000. In contrast, in the eastern area around South Georgia, warm waters were distributed more widely in 1988 than in 2000.

3.3 Oceanographic structure

Horizontal distributions of temperature at 10, 100 and 400 m in the area surrounded by 56S to 62-30S and 44W to 61W in the CCAMLR 2000 Survey are shown in Figure 7 (a), (b) and (c), respectively. Similarly, horizontal distributions of temperature at 10, 100 and 400 m in the area surrounded by 56S to 62-30S and 44W to 61W in the KY 1988 Survey are shown in Figure 8 (a), (b) and (c), respectively. To basically compare the oceanographic structure of both surveys, we chose the above distribution maps of the same factors in the same area.

The distribution of temperature at 10 m in the CCAMLR 2000 Survey indicated the north and south gradient from the 3.0 to 0.0℃ isopleth (Figure 7(a)). Although the 1.0℃ isopleth was located north of the South Orkney Islands along approximately 45W in the eastern area, south the South Shetland Islands westward approximately 54W in the western area. In contrast, the distribution of temperature at 10 m in the KY 1988 Survey indicated that the 1.0℃ isopleth was located north of the South Orkney and South Shetland Islands more widely than in 2000 (Figure 8(a)). The isopleths in 1988 also indicated that the north and south gradient from 5.0 to 0.0℃ were steeper than in 2000 (Figure 8(a)).

The distribution of temperature at 100 m in both surveys differed widely from one another (Figure 7(b) and 8(b)). The distribution of temperature in 2000 were colder overall than in 1988. The isopleths in 2000 were a minimum of –1.2℃ below 1.0℃ overall except for a small warm core of 1.4℃ at 58S, 47W. In contrast, the isopleths in 1988 were distributed over a wide range between a minimum of –1.6℃ and a maximum of 2.8 ℃ with sharp north and south gradients. Cold waters less than -1.0℃ in 2000 showed only a small range south the South Orkney Islands. In contrast, cold waters in 1988 occupied a wide range around the South Shetland and South Orkney Islands.

The distribution of temperatures at 400 m in both surveys also differed widely from one another (Figure 7(c) and 8(c)). The distribution of temperature in 2000 indicated warmer temperatures overall compared to 100 m. The cold core less than 0.0℃ was only small in the southern area between the South Orkney and South Shetland Islands. Warm waters with a maximum 2.2℃ isopleth extended southward. In contrast, the 0.0℃ isopleth was wider northward in 1988 than in 2000. Cold waters below 1.0℃ in 1988 covered the South Orkney and the South Shetland Islands more northerly than in 2000.

Next, the vertical distribution of temperatures along 45W in the CCAMLR 2000 and the KY 1988 Surveys are shown in Figure 9 and 10, respectively. The difference between the surveys was indicated in the distribution pattern of the Antarctic Surface Water and the Warm Deep Water. The Antarctic Surface Water is composed of Summer Surface Water, distributed shallower than the seasonal thermocline at approximately 50 m, and Winter Water, indicated less than 0.0℃ with the minimum temperature layer at approximately 150 m. Warm Deep Water indicates the warm waters more than 0.0℃ distributed under the Winter Water.

The vertical distribution of temperatures along 45W in 2000 (Figure 9) were generally warmer than in 1988 (Figure 10). The extent of Winter Water in 2000 was smaller than 1988. Cold waters less than 0.0℃ south of 60S in 2000 were smaller in range than in 1988. Cold waters less than 0.0

°C north of 60S in 2000 was also distributed less widely than in 1988. In addition, warm waters more than 0.0°C under the Winter Water in 2000 with a maximum isopleth of 2.0°C were warmer than in 1988 with a maximum isopleth of 1.40°C. These distribution patterns of temperature implied that the extent of the Antarctic Surface Water in 2000 was weaker than in 1988. Conversely, the extent of the Warm Deep Water in 2000 was stronger than in 1988.

In addition, we expressed the horizontal distribution of the environmental index of the integrated temperature from the surface to 200 m (EI $\overline{Q}_{200}$) to understand simply the oceanographic structure of the upper ocean for the CCAMLR 2000 and the KY 1988 Surveys, respectively (Figure 11 and 12). There was a distinct difference in the upper ocean between the two surveys. The distribution of EI $\overline{Q}_{200}$ below 0.0°C in 2000 was smaller than in 1988. Although the 0.0°C isopleth in 2000 was distributed narrowly north of the South Orkney Islands, the isopleth was located south the South Shetland Islands. In contrast, the 0.0°C isopleth in 1988 was distributed north not only in the South Orkney Islands but also in the South Shetland Islands. The cold area below 0.0°C in 2000 was 98.8x10^3km^2, which occupied 14.2 % of the total. On the other hand, the same cold area below 0.0°C in 1988 was 232.6x10^3km^2, which occupied 33.4 % of the total. The area below 0.0°C in 2000 was 2.4 times as large as in 2000. Over the entire survey area, the differences between maximum and minimum of EI $\overline{Q}_{200}$ were wider and indicated higher gradient in 1988 than in 2000.

3.4 Krill distribution and environmental structure

To compare krill with the upper structure of the ocean, overlaid distributions of krill and EI $\overline{Q}_{200}$ in the area surrounded with 56S to 62-30S and 44W to 61W in the CCAMLR 2000 and KY 1988 Surveys are shown in Figure 13 and 14, respectively.

As mentioned above, the distribution of EI $\overline{Q}_{200}$ in the CCAMLR 2000 Survey was generally warmer than the KY 1988 Survey. Although the isopleth of 0.0°C in the KY 1988 Survey was located at approximately 60S, the isopleth in the CCAMLR 2000 Survey shifted southward between 60 and 62S. Similarly, although the isopleth of 1.0°C in the KY 1988 Survey was located between approximately 57 and 59S, the isopleth in the CCAMLR 2000 Survey shifted southward between 58 and 62S.

The krill density generally corresponded with the pattern of EI $\overline{Q}_{200}$ distribution. The entire krill distribution was located south of 1.0°C and the high density of krill distributed south of 0.0°C. Since the range south of 0.0 and 1.0°C in the KY 1988 Survey was wider than in the CCAMLR 2000 Survey, the krill distribution and density in the KY 1988 Survey was wider and higher than 2000.

For example, the krill distribution in the KY 1988 Survey along 45W showed a level of 100 g/10^3m^3 to 56S and further 2 g/10^3m^3 at 52S. However, the krill distribution in the CCAMLR 2000 Survey along 45W showed only 1 g/10^3m^3 near 59S and no appearance north of 59S. The highest krill density (755.3 g/10^3m^3) along 45W in the KY 1988 Survey was situated at 60-19S south of EI $\overline{Q}_{200}$=0.0°C near the South Orkney Islands. Similarly, the highest krill density (1425.1 g/10^3m^3) along 45W in the CCAMLR 2000 Survey was situated at 60-29S south of EI $\overline{Q}_{200}$=0.0°C near the South Orkney Islands. The krill density dropped greatly to less than the level of 10 g/10^3m^3 in both surveys around 61S south of the South Orkney Islands in the Weddell Sea.

In addition, overlaid distributions of krill density and EI $\overline{Q}_{200}$ in the entire scale of the CCAMLR 2000 Survey are shown in Figure 15. Krill was distributed mostly in waters less than 2.0 °C. High densities of krill distributed especially between 1.0 and –1.0°C. In the zonal range between 2.0 and 1.0°C, there was a high north-south gradient of EI $\overline{Q}_{200}$ west of approximately 48W, where krill were distributed less, but there was a low north-south gradient of EI $\overline{Q}_{200}$ east of 48W, where krill were distributed greater. In the zonal range between 1.0 and 0.0°C, krill were also distributed greater in the low north-south gradient of EI $\overline{Q}_{200}$ such as west of 55W. In the zonal range between 0.0 and –1.0°C, krill were distributed throughout and there were higher densities of krill in waters extending to the north in the South Sandwich Islands area between 25 and 30W.

4 Discussion

There were distinct differences in parameters; sea ice, sea surface temperature, temperature structure of the upper ocean (EI $\overline{Q}_{200}$) and distribution of krill between the CCAMLR 2000 and the KY 1988 Survey (Table 2). There was a striking contrast between the two surveys. The extent of sea ice in 1999/2000 of the CCAMLR 2000 Surveys was narrower than in 1987/88 of the KY 1988 Survey. The temperature of sea surface in the CCAMLR 2000 Survey was generally warmer than in the KY 1988 Survey, especially around the Antarctic Peninsula region. The temperature structure of the upper ocean in the CCAMLR 2000 Survey was warmer overall than in the KY 1988 Survey. The distribution pattern of krill in the CCAMLR 2000 Survey was a narrower range and lower density compared with the KY 1988 Survey.

There were relationships between the above parameters. The essential point was the difference in the development of Winter Water between the two surveys. Winter Water in the CCAMLR 2000 Survey had not developed more than in the KY 1988 Survey. When the extent of sea ice developed wider, sea surface temperatures became colder. Simultaneously, the temperature structure of the upper ocean, which indicated the development of Winter Water, became colder and wider northward such as in the KY 1988 Survey. The above are physical parameter. Physical parameters also affect biological parameters. Since the distribution of krill corresponded to the range of Winter Water, the krill density distributed wider northward and higher in the KY 1988 Survey than in the CCAMLR 2000 Survey.

The differences of physical parameters in both surveys depend on environmental variability in the Antarctic Peninsula area (Naganobu et al. 1999; Amos 2001; Cunningham et al. 2002). Naganobu et al. (1999) stated that the Drake Passage Oscillation Index (DPOI), represented by long time series on sea level pressure differences across the Drake Passage, affected sea ice and the Antarctic Surface Water. Amos (2001) studied oceanographic variability in small-scale surrounding Elephant Island for 10 recent years. Cunningham et al. (2002) indicated variability in the Polar Front position and the Antarctic Bottom Water temperatures on the continental shelf of Antarctica. Physical variability was considered to produce the differences in the two surveys. Antarctic Surface

Water developed larger and the Polar Front position was located more northwardly in the 1987/88 season of the KY 1988 Survey than in the 1999/2000 season of the CCAMLR 2000 Survey.

Many papers have suggested that oceanic variability relates strongly to the distribution pattern of krill density (e.g., Amos 1984; Brinton 1985; Priddle et al. 1988; Hoffmann et al. 1998; Brierley et al. 1999; Naganobu et al. 1999; Sushin and Shulgovsky, 1999; Nicol et al. 2000; Hewitt et al. 2002). However, there were no common environmental indices for the relationships between oceanic structure and krill distribution. Accordingly, we used EI$\overline{Q}_{200}$ as the environmental index to understand simply the relationships between the temperature structure of the upper ocean and krill distribution. The integrated temperature from 0 to 200 m has already been used as the environmental index for krill distribution (e.g., Naganobu and Hirano 1982, Hosie et al. 2000).

EI$\overline{Q}_{200}$ has the following merits as an environmental index of the upper ocean:

(a) it can simply express the temperature and oceanographic structure of the upper Antarctic Ocean, which consists of the Antarctic Surface Water and Warm Deep Water;

(b) it is relatively easy to grasp environmental variability because it is a quantitative index based on ordinary temperature; and

(c) it can be corresponded to the vertical distribution of krill and/or other organisms because of the integrated environmental structure of the upper ocean.

We show the horizontal distribution of EI$\overline{Q}_{200}$ in the entire scale of the CCAMLR 2000 Survey and its extended flow images in Figure 16. As we indicated in the third section, there were good correlations between distributions of EI$\overline{Q}_{200}$ and krill density. On the other hand, Siegel et al. (2002) indicated that krill distribution showed three distinct geographical clusters of size frequency distributions. Small juvenile and immature krill (cluster 1) occurred east of the South Orkney Islands. Adult krill smaller than 50 mm mean length (cluster 2) dominated in the shelf areas of the Antarctic Peninsula and to the north of juvenile stock across the Scotia Sea. Adult krill larger than 50 mm mean size (cluster 3) were restricted to the area west of the South Orkney Islands.

These cluster distributions of krill size frequency approximately corresponded to the geographical distribution of EI $\overline{Q}_{200}$. The area of cluster 1 corresponded to the waters in which the cold water of EI $\overline{Q}_{200}$ strongly extended northward in the east of the South Georgia from the Weddell Sea. The area of cluster 2 corresponded to the waters in which the cold water of EI $\overline{Q}_{200}$ extended eastward from the Antarctic Peninsula and northward to the west of the South Georgia. The area of cluster 3 corresponded to the waters in which the warm waters of EI $\overline{Q}_{200}$ meandered eastward in the north area of the Antarctic Peninsula.

When analyzing the relationships between krill and oceanic structure, most papers discuss this using concepts of oceanographic boundaries such as the Polar Front, the Southern Antarctic Circumpolar Current Front and the Weddell Front and oceanographic water masses such as Summer Surface Water, Winter Water and Warm Deep Water. Although these concepts provide a general perspective and are inseparably related to EI $\overline{Q}_{200}$, they are too conceptual for the minute distribution of krill to clarify the relationship between krill and oceanic structure. Naganobu and Hirano (1982) calculated $\overline{Q}_{200}$ of the Southern Ocean and found that it corresponded to the krill distribution generally although their paper was the substance of analyses.

It is considered that EI $\overline{Q}_{200}$ provides related background information as the standard environmental index with a combination of .oceanographic boundaries of the Antarctic Circumpolar Current (Belkin and Gordon 1995; Oris et al. 1995) and environmental variability in the entire Southern Ocean scale (White and Peterson 1996; Comiso 2000). The environmental index of EI $\overline{Q}_{200}$ can be applied not only to regional scales but also the entire scale of the Antarctic Ocean. It is also important to grasp the variability of EI $\overline{Q}_{200}$ over long times and broad spaces, since EI $\overline{Q}_{200}$ is regarded to be a environmental index of the upper Antarctic Ocean presuming the impact of global warming.

5 Conclusions

We found distinct differences in sea ice, sea surface temperature, environmental index of integrated temperature from 0 to 200 m (EI $\overline{Q}_{200}$) in depth and krill distribution between the 1999/2000 and 1987/88 season in the Scotia Sea using the data of satellite images and the CCAMLR 2000 and the KY 1988 Surveys. The 2000 season formed a striking contrast to the 1988. The extent of sea ice in 2000 was narrower than in 1988. The temperature of the sea surface in 2000 was generally warmer than in 1988, especially around the Antarctic Peninsula region. EI $\overline{Q}_{200}$ in 2000 was warmer overall than in 1988. The distribution of krill in 2000 indicated a narrower range and lower density compared with 1988 in the western area of the Scotia Sea. The krill density corresponded entirely to the geographical distribution of EI $\overline{Q}_{200}$; the entire krill distribution was located south of approximately 1.0℃ and high densities were distributed in cold waters less than 0.0℃. It is presumed that EI $\overline{Q}_{200}$ is an environmental index of the upper Antarctic Ocean for th distribution of krill and other organisms.

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Figure captions

Figure 1. Map of the Scotia Sea and adjoining waters, with the filled circles showing the location of the CTD stations in the CCAMLR 2000 Survey during January and February in the 2000 austral summer.

Figure 2. Map of the western waters of the Scotia Sea, with the filled circles showing the location of the XBT stations in the KY 1988 Survey during December and January in the 1987/88 austral summer.

Figure 3. Sea ice extent from July 1999 to June 2000. Each figure indicates the monthly mean of sea ice concentration.

Figure 4. Sea ice extent from July 1987 to June 1988. Each frame figure indicates the monthly mean of sea ice concentration.

Figure 5. Sea surface temperature (℃) at (top) the first, (middle) middle and (bottom) end of January 2000.

Figure 6. Sea surface temperature (℃) at (top) the first, (middle) middle and (bottom) end of January 1988.

Figure 7a. Distribution of temperature (℃) at 10 m in the CCAMLR 2000 Survey.

Figure 7b. Distribution of temperature (℃) at 100 m in the CCAMLR 2000 Survey.

Figure 7c. Distribution of temperature (℃) at 400 m in the CCAMLR 2000 Survey.

Figure 8a. Distribution of temperature (℃) at 10 m in the KY 1988 Survey.

Figure 8b. Distribution of temperature (℃) at 100 m in the KY 1988 Survey.

Figure 8c. Distribution of temperature (℃) at 400 m in the KY 1988 Survey.

Figure 9. Vertical section of temperature (℃) along 45W in the CCAMLR 2000 Survey.

Figure 10. Vertical section of temperature (℃) along 45W in the KY 1988 Survey.

Figure 11. Distribution of the integrated temperature (℃) from 0 to 200 m (EI$\overline{Q}_{200}$) in the CCAMLR 2000 Survey.

Figure 12. . Distribution of the integrated temperature (℃) from 0 to 200 m (EI$\overline{Q}_{200}$) in the KY 1988 Survey.

Figure 13. Distribution of krill (*Euphausia superba*) overlaying the integrated temperature (℃) from 0 to 200 m (EI $\overline{Q}_{200}$) in the CCAMLR 2000 Survey. Abundance circles are logarithms to krill density (g/10^3m^3). x: sampling sites where no krill was caught.

Figure 14. Distribution of krill (*Euphausia superba*) overlaying the integrated temperature (℃) from 0 to 200 m (EI $\overline{Q}_{200}$) in the KY 1988 Survey. Abundance circles are logarithms to krill density (g/10^3m^3). x: sampling sites where no krill was caught.

Figure 15. Distribution of krill (*Euphausia superba*) overlaying the integrated temperature (℃) from 0 to 200 m (EI $\overline{Q}_{200}$) in the whole scale of the CCAMLR 2000 Survey in the Scotia Sea. Abundance circles are logarithms to krill density (g/10^3m^3). x: sampling sites where no krill was caught.

Figure 16. Distribution of the integrated temperature (℃) from 0 to 200 m ($\overline{Q}_{200}$) and the schematic flow pattern in the whole scale of the CCAMLR 2000 Survey.

Table captions

Table 1. Summary of data categories and sources analyzed for comparison between the CCAMLR 2000 Survey and the KY 1988 Survey.

Table 2. Summary of results by comparison between the CCAMLR 2000 Survey and the KY 1988 Survey.

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Table

Table 1. Summary of data categories and sources analyzed for comparison between the CCAMLR 2000 Survey and the KY 1988 Survey.

Category	CCAMLR 2000	KY 1988
Sea ice cover	Satellite (NSIDC)	Satellite (NSIDC)
Sea surface temperature	Satellite (NASA)	Satellite (NASA)
Oceanographic structure	CTD	XBT
Krill distribution/density	RMT net	KYMT net

Abbreviations are defined as follows: CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources; CTD, Conductivity-Temperature-Depth profiler; KY, RV *Kaiyo Maru*; KYMT, Kaiyo Maru typed Midwater Trawl; NASA, National Aeronautics and Space Administration; NSIDC, National Snow and Ice Data Center; RMT, Rectangular Midwater Trawl; XBT, eXpendable BathyThermograph.

Table 2. Summary of results by comparison between the CCAMLR 2000 Survey and the KY 1988 Survey.

Survey	Year	Sea ice extent	Sea surface temperatur e	Antarctic Surface. Water extent & temperature	Krill distribution & density
CCAML R 2000	1999/2000	South Reduction & Smaller	Warmer	South reduction & warmer	North expansion & higher
KY 1988	1987/88	North Expansio n & Larger	Colder	North expansion & colder	South reduction & lower
ootnote	Comparabl e suitable data	Variabilit y of sea-ice Extent	Variability of sea surface temperatur e	Environmental index:integrate d temperature from 0 to 200 m	Northern limit of appearance and density; periodicity or regime Shift?

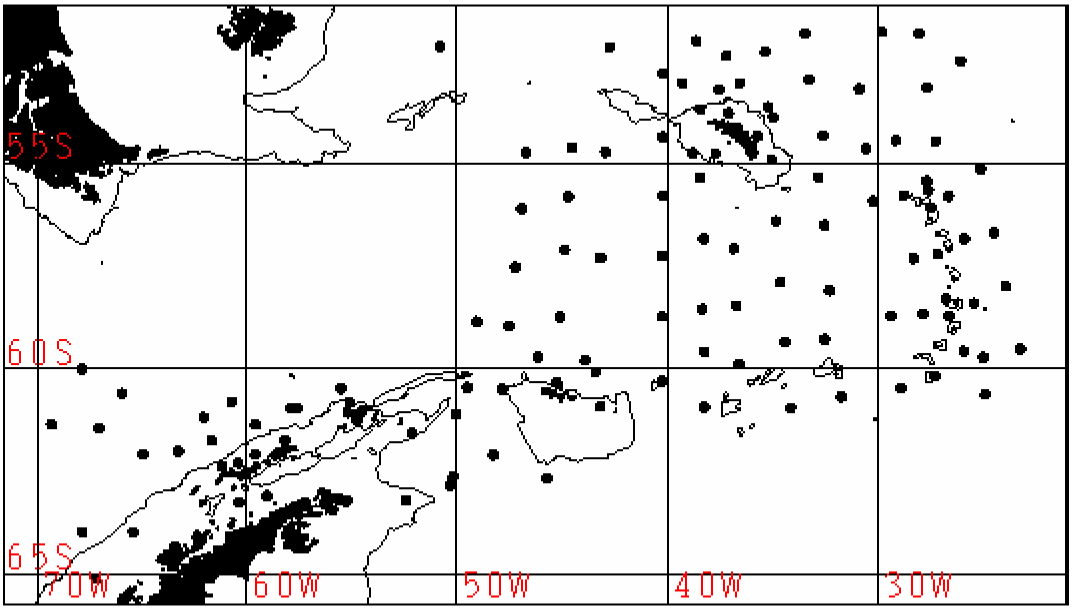
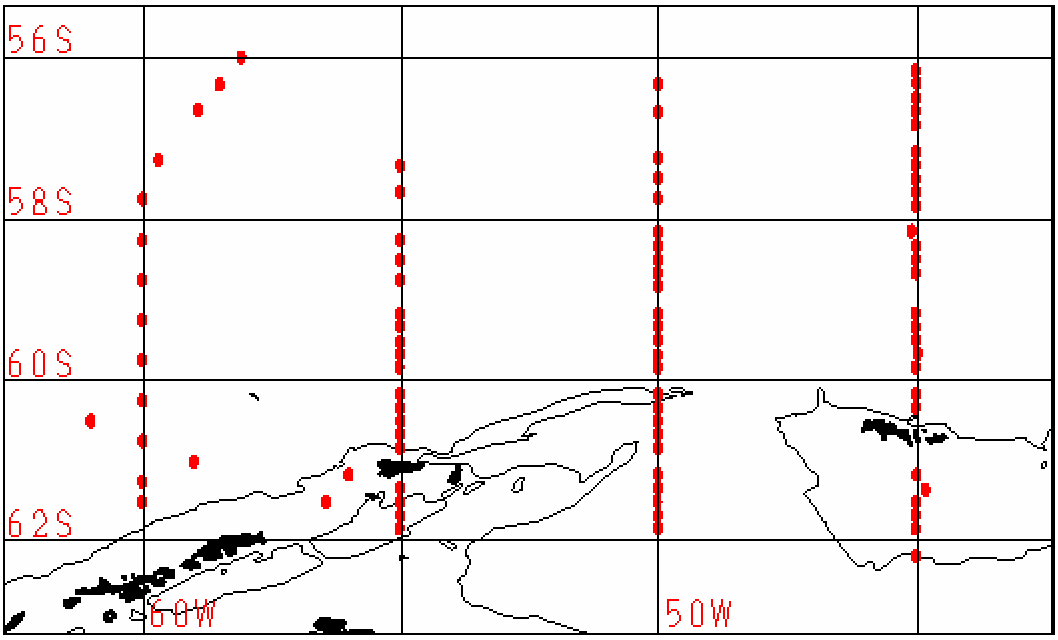


Figure 1



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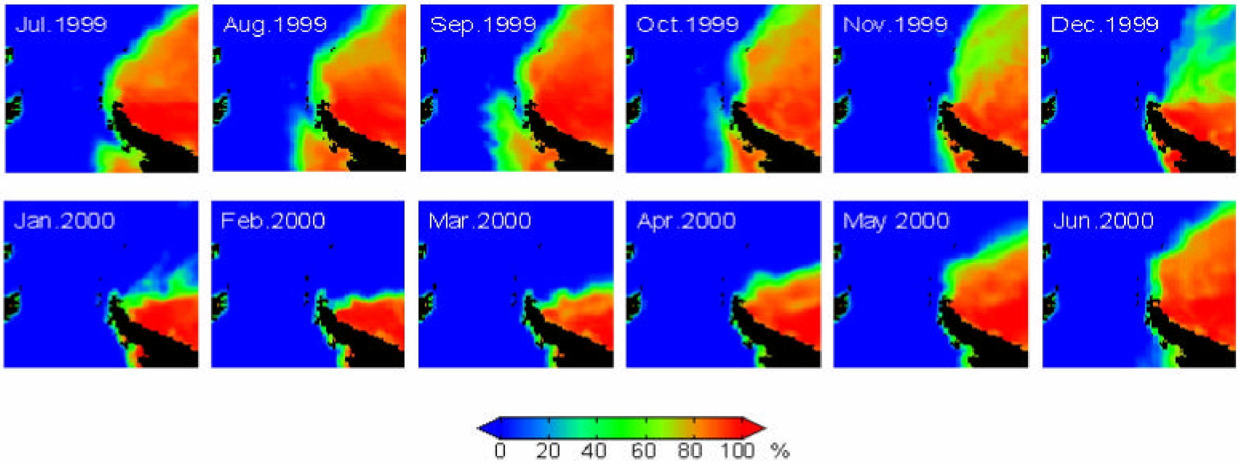

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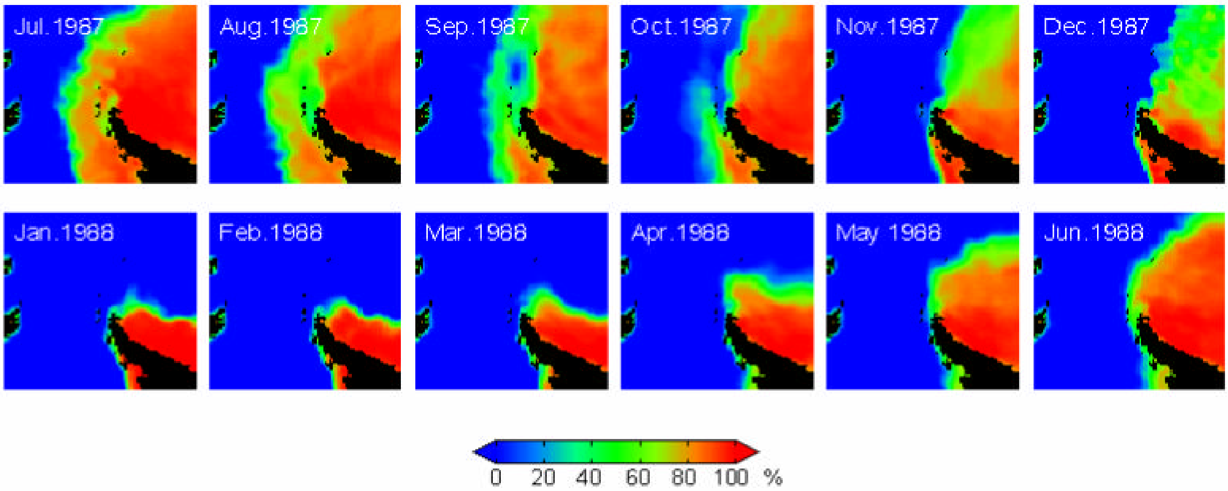

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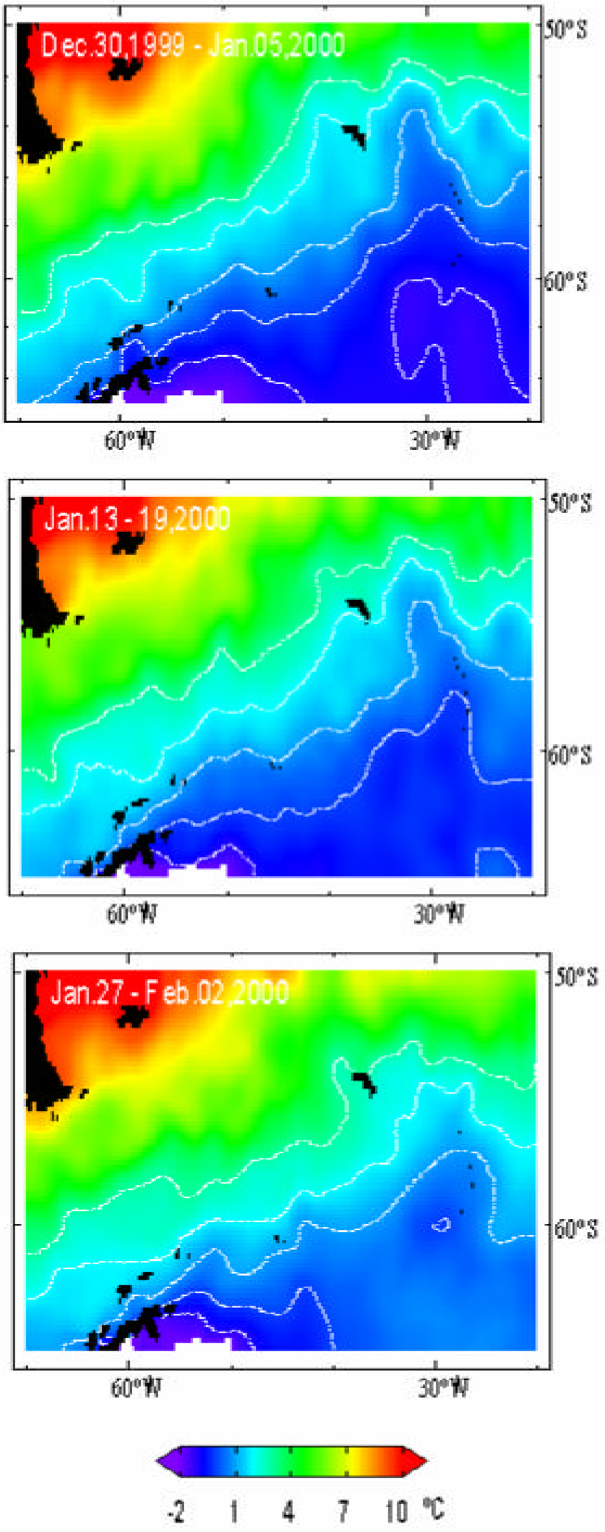
Dec.30,1999 - Jan.05,2000
Jan.13 - 19,2000
Jan.27 - Feb.02,2000
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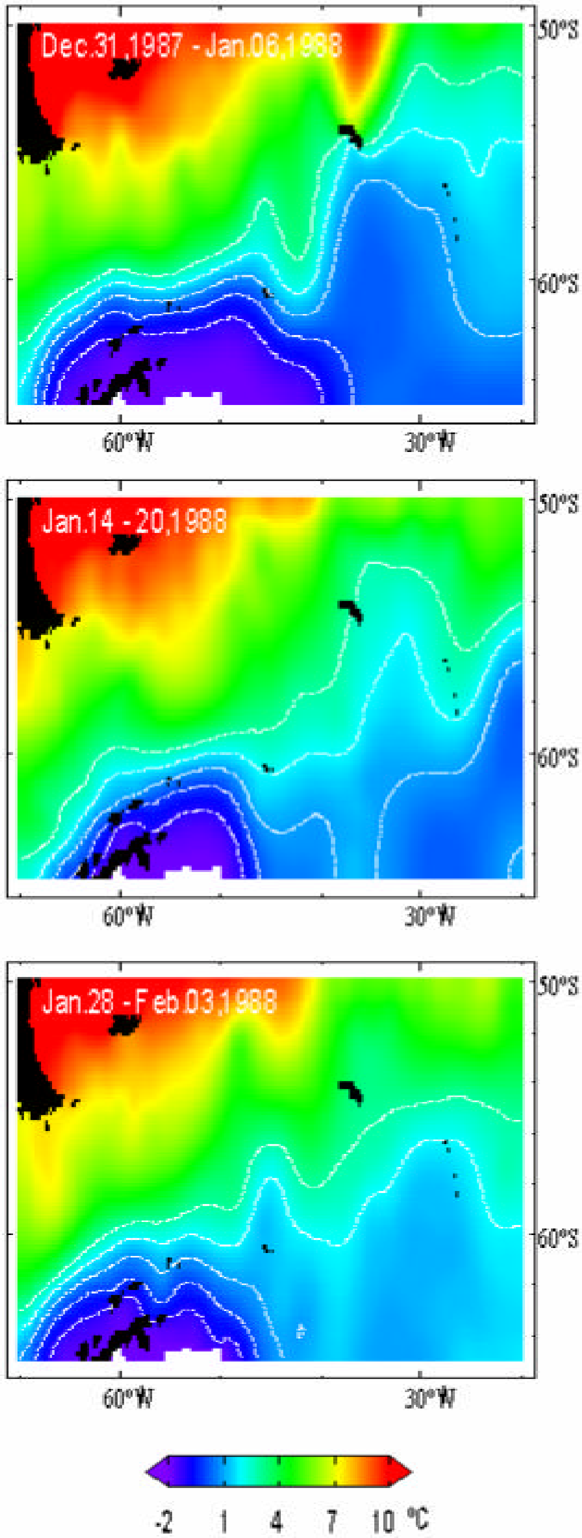
60°S
60°W
30°W
-2
1
4
7
10
°C

Figure 5



Dec.31,1987 - Jan.06,1988
50°S
60°S
60°W
30°W
Jan.14 - 20,1988
50°S
60°S
60°W
30°W
Jan.28 - Feb.03,1988
50°S
60°S
60°W
30°W
-2
1
4
7
10 °C

Figure 6

a

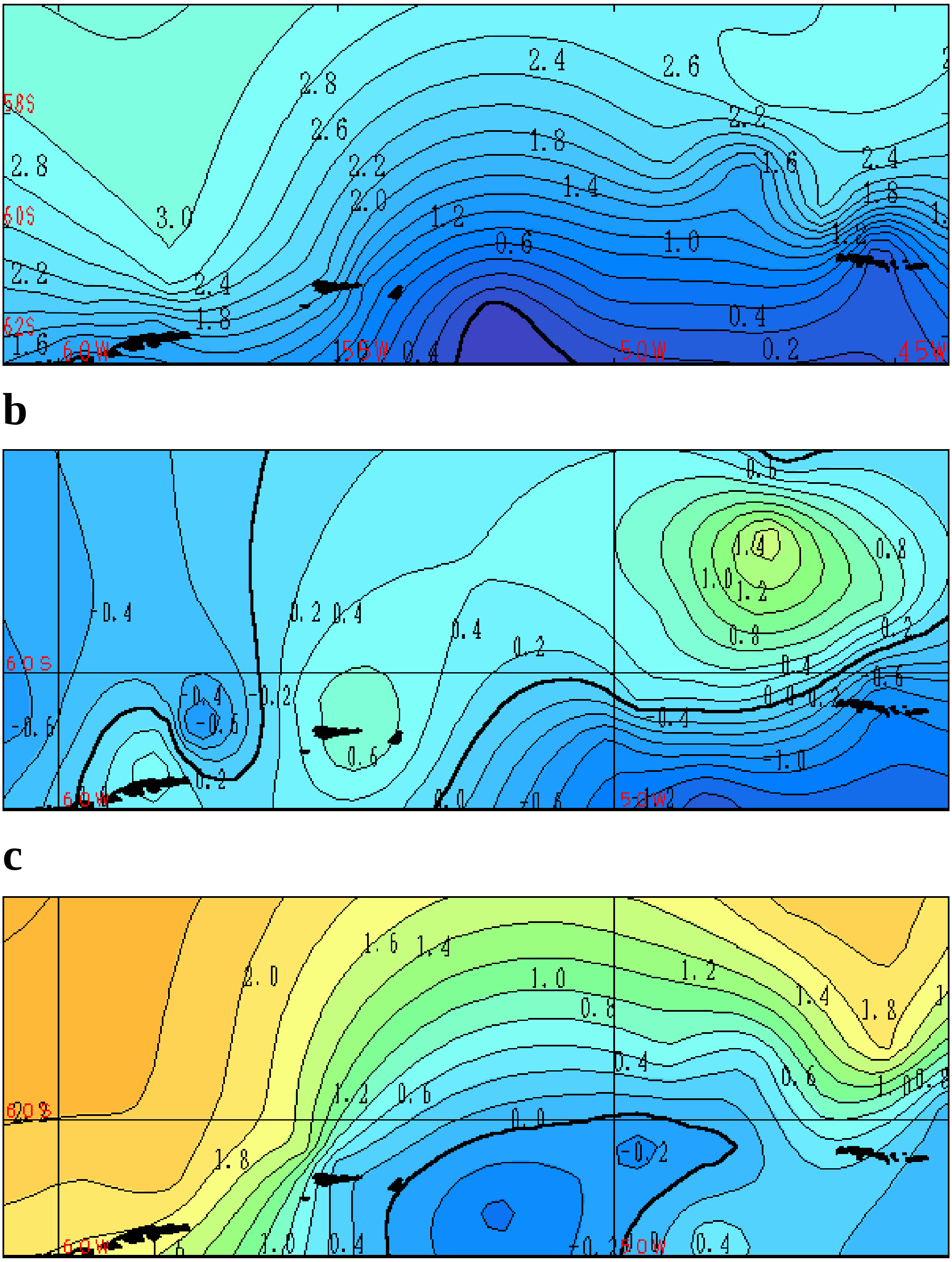
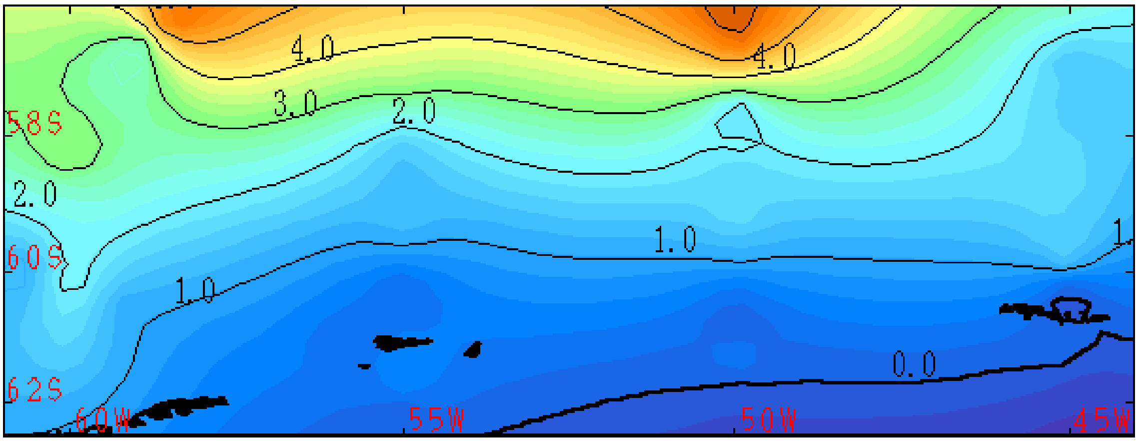
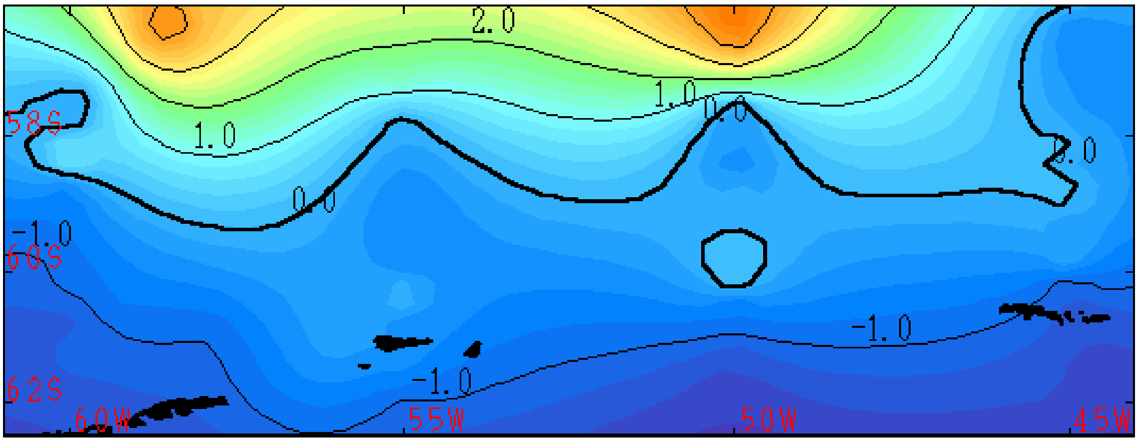


Figure 7a, 7b and 7c

a



b



c

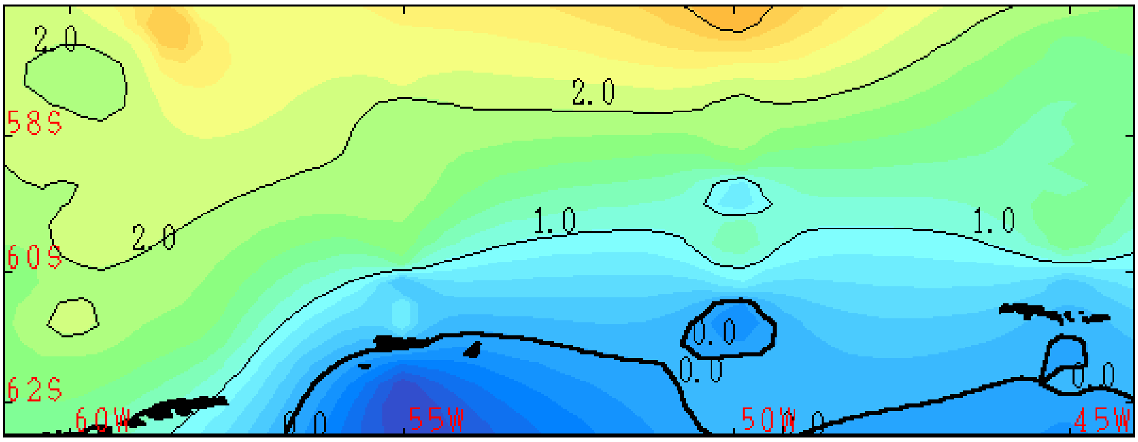


Figure 8a, 8b and 8c

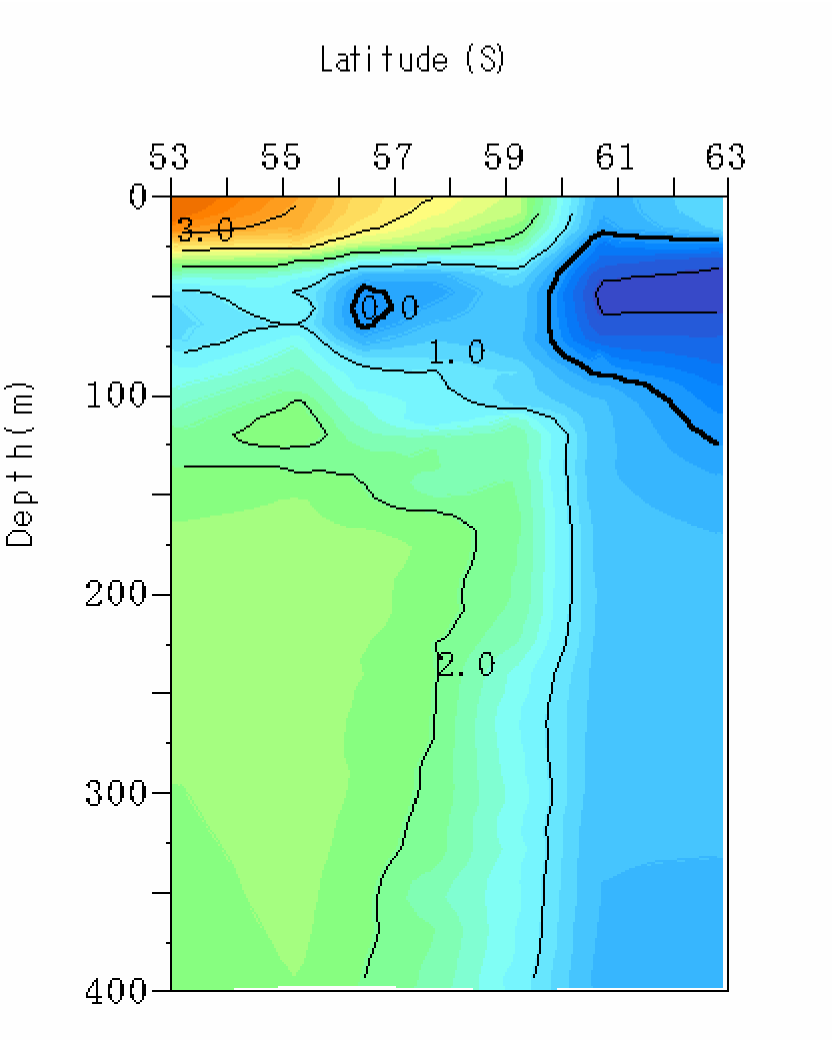
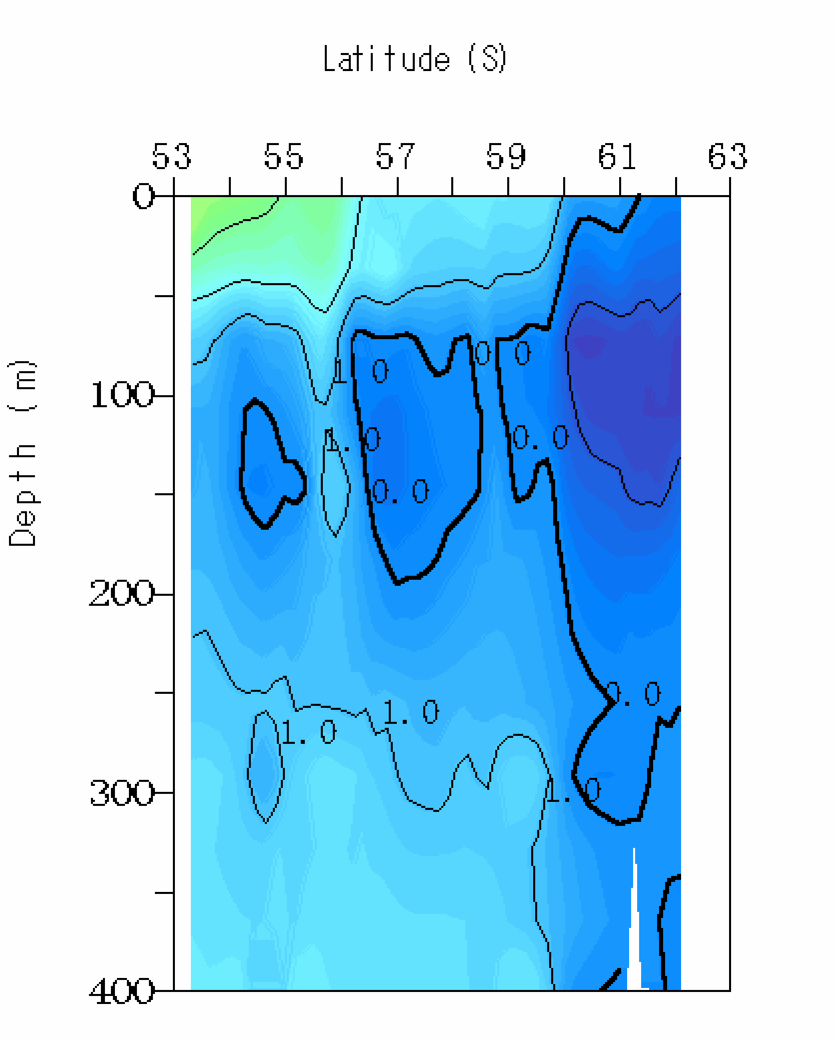


Figure 9


Latitude (S)
53
55
57
59
61
63
Depth (m)
0
100
200
300
400
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1.0
0.0
0.0
0.0
0.0
1.0
1.0
0.0
1.0

Figure 10

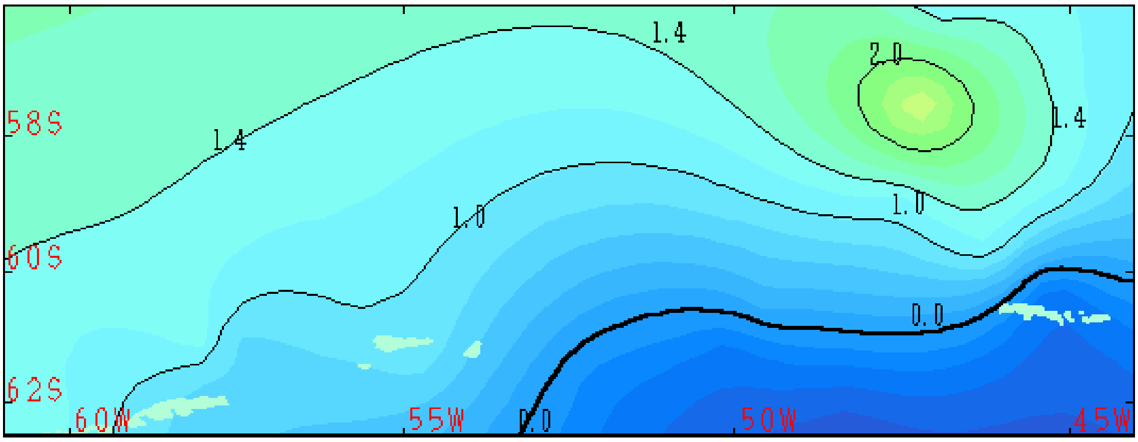

Figure 11

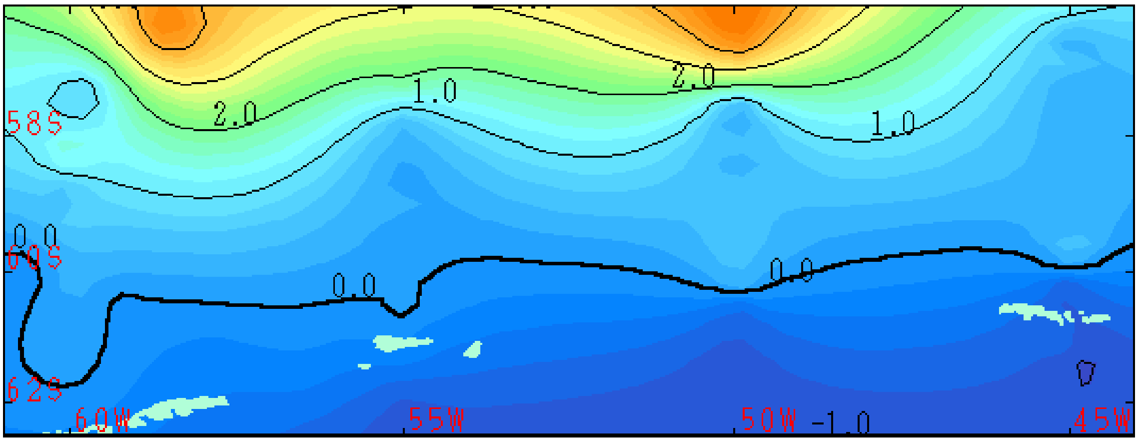

Figure 12

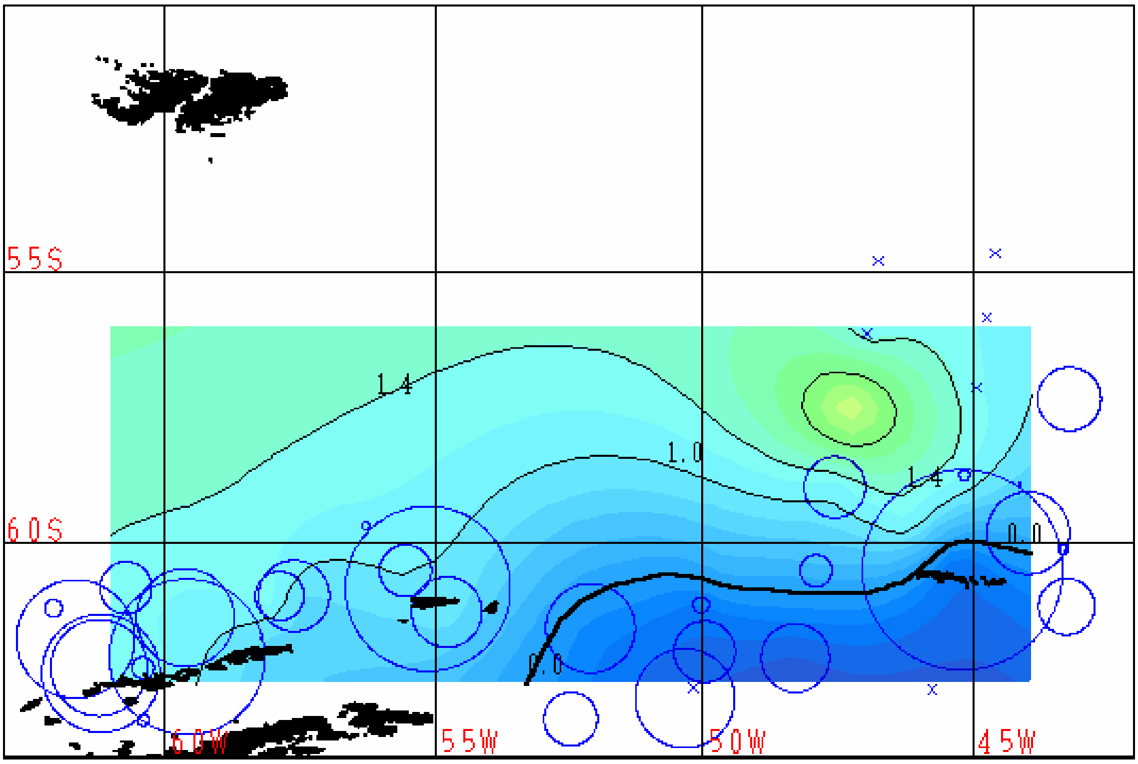

Figure 13

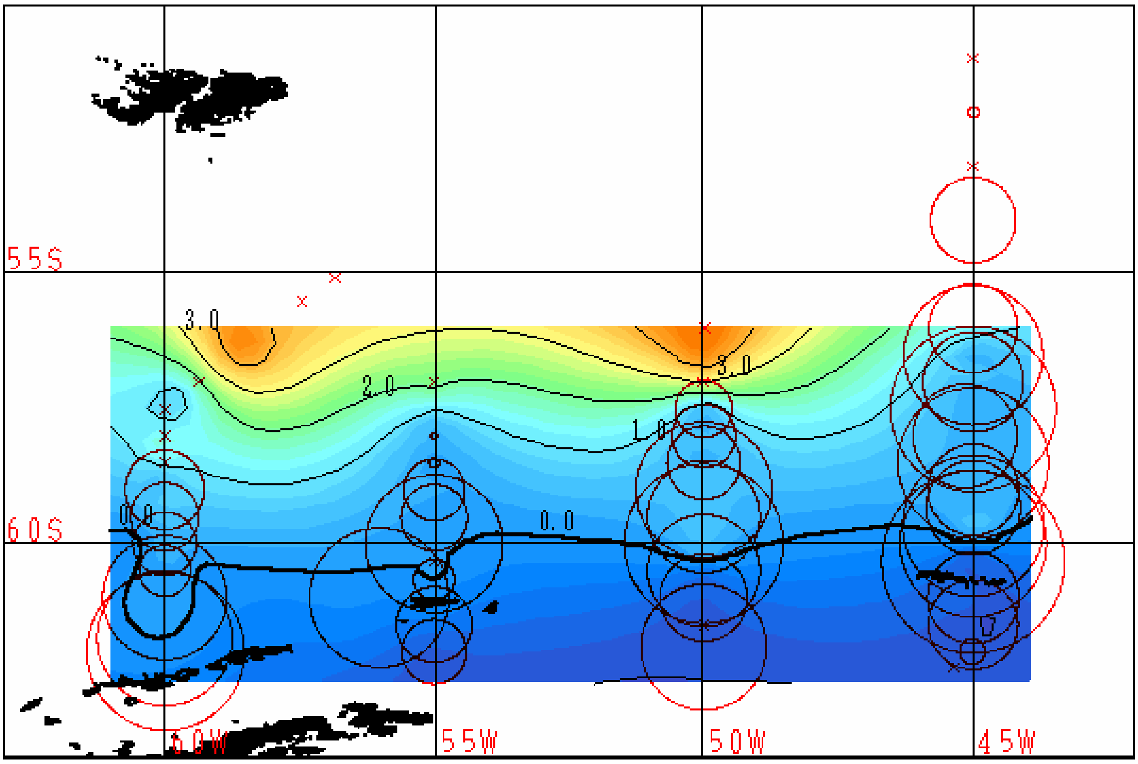

Figure 14

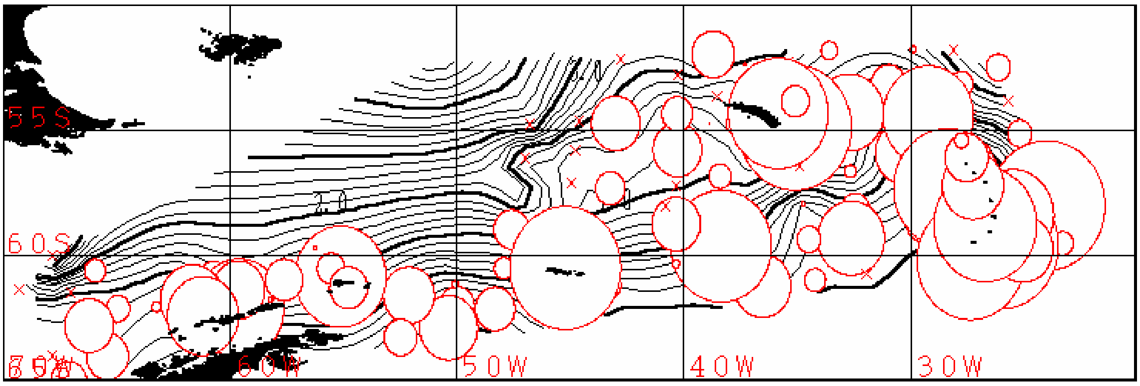

Figure 15

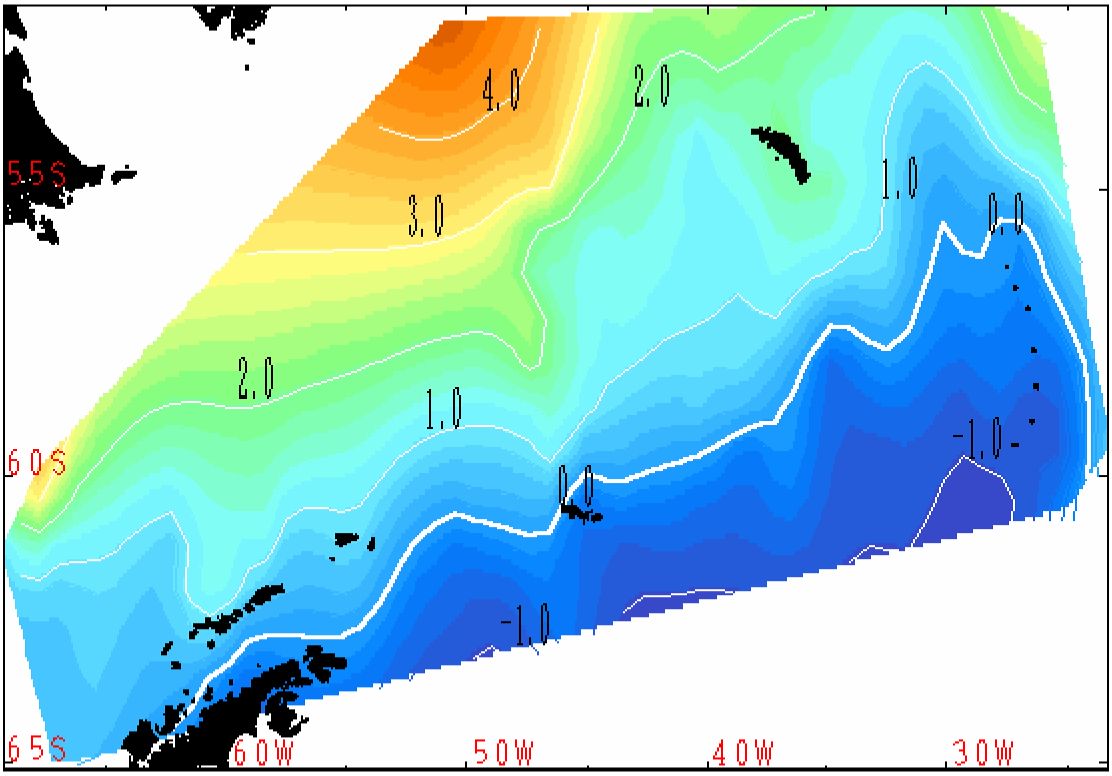

Figure 16