Interactions between oceanography, krill and baleen whales in the Ross Sea and Adjacent Waters: An overview of *Kaiyo Maru*-JARPA joint survey in 2004/05

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Abstract

A joint survey of the R/V *Kaiyo Maru* and the Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) was carried out to study an interaction between oceanography as environmental condition, distribution of krill as prey and baleen whales as predators in the Ross Sea and its adjacent waters, Antarctica, in austral summer of 2004/05. Results indicated close interactions between the oceanography, krill and baleen whales. The oceanography of the surface layer was summarized as an oceanographic environmental index that integrated temperature mean from 0 to 200 m in depth (ITEM-200). Distribution of ITEM-200 was used as background information for comparing with distribution patterns of each species. Antarctic krill mainly distributed in the Antarctic Surface Water (ASW) area (ITEM-200 = 0 to -1^{o}C) and extended in the Shelf Water (SW) area (less than -1^{o}C). Ice krill clearly distributed in SW but not ASW. Humpback whales mainly distributed in the Antarctic Circumpolar Current (ACC) waters with high density around 0^{o}C near the Southern Boundary of ACC and slightly extended in ASW. Antarctic minke whales mainly distributed in ASW and SW with high density around -1 ^{o}C in a continental shelf slope frontal zone. The interaction between distributions of krill and baleen whales with ITEM-200 could give the quantitative information to identify the boundary of distribution of Antarctic krill and ice krill for biomass estimation using acoustic data in the surveys. We finally summarized a conceptual model of interaction between oceanography relating water mass and circulation pattern of the oceanic surface layer with ITEM-200, the distribution and abundance of krill and baleen whales.

1. Introduction

The study here is of interactions between oceanography, krill and baleen whales in the Ross Sea and its adjacent waters with a joint survey the R/V *Kaiyo Maru* and the Japanese Whale Research Program under Special Permit in the Antarctic (JARPA).in the 2004/05 austral summer season.

As the background of the present study, there was a cooperated survey between the *Kaiyo Maru* and JARPA. JARPA was conducted every year from 1987/88 to 2004/05 in the Area III-IV-V-VI in the waters off east Antarctica and the Ross Sea collecting data of sighting and biological sampling for whales with basic oceanographic and acoustic measurement (Hatanaka *et al*., 2006; Nishiwaki *et al*., 2006). On the other hand, the *Kaiyo Maru* has many experiences on a krill-centric ecosystem survey with physical, chemical, biological and acoustic measurement in the Antarctic Ocean. JARPA has advantage of collecting whale data. In the same manner, the *Kaiyo Maru* has advantage of collecting oceanographical and krill biological/acoustic data. It is very valuable to study interaction of oceanography as environment structure, krill as prey species and baleen whales as predators through both field surveys. Hence, the joint survey with mutual strengthening was simultaneously occurred in the same area (the Area V-VI) of the Ross Sea and adjacent waters during the same period in 2004/05 (Naganobu *et al*., 2005; Nishiwaki *et al*., 2005; Anymous, 2006).

As survey instrument and methodology have remarkably developed in recent years, we can obtain various quantity data individually for targeting subjects such as satellite, oceanography, krill biological sampling, acoustic measurement and whales in our survey compared with the past around two decades. Antarctic krill is a key species of Antarctic marine ecosystem. Comprehensive study of krill has been developing remarkably in recent year due to the advanced survey methodology (e.g., Nicol *ed*., 2000; Watkins *et al*. eds. 2004). Analysis on interaction of oceanography and krill became minutely and clearly more and more. Especially, importance of the Southern Boundary of Antarctic Circumpolar Current (SBACC)(Orsi *et al*., 1995) was indicated for the interaction of oceanography and Antarctic krill (Nicol *et al.*, 2000; Brandon *et al*., 2004; Hewitt *et al.*, 2004) in the recent years.

SBACC, however, is a front line. Although it is very useful to know variability of krill distribution influenced by oceanographic dynamics, it is hard to analyze additional species of ice krill and whales in regional and/or meso-scale like our study using the concept of SBACC only. Then, we introduced an Integrated TEMperature mean from 0 to 200 m (ITME-200) as an oceanographic environmental index. ITEM-200 could conveniently represent the stratified water mass of the surface layer with high primary production and living krill in the Antarctic Ocean. Water temperature also is basically regarded as one of the most basic environmental indicators for oceanographic structure and also marine living organisms.

Naganobu and Hirano (1982, 1986) had already provided a basic concept of an integrated temperature mean from 0 to 200 m as an environmental index (namely $\overline{Q}_{200}$) in conjunction with distribution of Antarctic krill. Although data obtained from past discontinuous vertical observations were hard to calculate detailed structures in the narrow range of temperature such as the cold Antarctic Ocean, modern continuous CTD and XCTD could provide close temperature data. Recently, Hosie *et al.* (2000) used integrated temperature mean (0-200 m) as the background oceanographic condition to compare macro-zooplankton community structure Antarctica (80-150^{o}E). Naganobu *et al.* (1995) and Thiele *et al.* (2000) also used the integrated temperature mean with distribution of whales. Here, we employed ITEM-200 (changed a term from $\overline{Q}_{200}$) as an oceanographic environmental index to analysis interaction between oceanography, krill and baleen whales.

As a result, oceanographic conditions generally indicated three water types; the Antarctic Circumpolar Current (ACC) waters over ITEM-200 = 0 ^{o}C, the Antarctic Surface Water (ASW) between 0 and -1 ^{o}C and the Self Water (SW) below -1 ^{o}C. ITEM-200 indicated the effective environmental index summarized background information of oceanographic conditions. Antarctic krill mainly distributed in ASW and extended in SW. Ice krill clearly distributed in SW but not ASW. Humpback whales mainly distributed ACC with high density around 0 ^{o}C and slightly extended in ASW. Antarctic minke whales mainly distributed in ASW and SW with high density around -1 ^{o}C. Other baleen whales (fin and blue) also were individually arranged with ITEM-200. From our results, we showed a conceptual model of interaction between oceanography relating water mass and circulation pattern of the oceanic surface layer with ITEM-200, the distribution and abundance of krill (Antarctic krill and ice krill) and baleen whales (Antarctic minke whale and humpback whale).

2. Methods

2.1 *Kaiyo Maru* survey

The survey area was bounded on the west and east by 160^{o}E and 160^{o}W and the north of 60^{o}S and south of around 78^{o}S where the ship entered waters in front of the Ross Ice Shelf (Figure 1). Bottom topography in the waters off the Ross Sea was deeper than 1000 m and until around 4000m. Bottom topography of the Ross Sea indicated shallower than 1000 and until around 400 m as a typical continental shelf (Figure 2).

The R/V *Kaiyo Maru* (2,630GT, Fisheries Agency of Japan) is a 93 m long flush-decked stern trawler, which has capability of many kinds of oceanographic, biological, acoustic survey and others. As she is not an icebreaker, her navigation was directly limited in the waters of sea ice. The ship entered into the Antarctic Circle (55^{o}S) on 24 December 2004 and went out on 26 February 2005. Then she carried over the survey south of 60^{o}S during 26 December 2004 and 24 February 2005 inquiring into the sate of sea ice. The main survey areas were the Ross Sea and its adjacent waters between 165^{o}E and 165^{o}W straddling the longitude 180^{o} south of 60^{o}S, Antarctica (Figures 2 and 3). Transect lines along 165^{o}E, 175^{o}E, 180^{o}, 175^{o}W, 170^{o}W and 165^{o}W were investigated to cover hot spots where suggest high concentrated krill and whales such as the Scott Seamounts Island, the Balleny Islands, the shelf off the Victoria Land and the almost whole of the Ross Sea. The 175^{o}E and 170^{o}W lines, especially, were surveyed in detail from the surface to near the sea bottom from 60^{o}S to the edge of the Ross Ice Shelf on physical, chemical and biological parameters.

As we predicted that there would be a heavy distribution of sea ice in the Ross Sea at the planning stage, we limited to three transect lines such as 165^{o}E, 175^{o}E and 180^{o}. The sea ice, however, melted in the almost whole of the Ross Sea during the survey period. Accordingly, the survey area was extended to the whole of the Ross Sea with additional transect lines such as 175^{o}W, 170^{o}W and 165^{o}W with decision of the scene in consideration of the sea ice condition (Figures 3 and 4).

The survey items were as the following.

(a) Oceanographic Observation

CTD, XCTD, XBT and ADCP were used to investigate the structure of water mass characteristics and circulation features. Stratified samples of water were made to investigate the spatial distribution of nutrient, chlorophyll *a*, phytoplankton and micro-zooplankton.

(b) Biological Sampling

Zooplankton, krill, micro-nekton and fishes, which are important preys for whales, were collected using the multiple rectangular mid-water trawl (RMT(1+8)M) and other nets to investigate their horizontal/vertical distribution and abundance.

(c) Acoustic Survey

The multiple-frequency echo-sounder (Simrad EK-500) were used to investigate the distribution and abundance of krill and other prey species. The acoustic survey was carried out not along only the main transect lines but also the local grid transactions of the hot spots which high concentrated krill were expected.

(d) Sighting Survey

The sighting surveys were conducted to investigate the distribution, abundance and ice-habitat use of predators such as penguins, flying birds.

2.2 JARPA survey

The area for JARPA survey in 2004/05 was composed of the western part of IWC Area VI (Area VIW, 170°W-145°W) and the entire Area V (130°E-170°W) in the area between south of 60°S and the ice edge line from 7 December 2004 to 8 March 2005. One sighting vessel (SV), three sighting/sampling vessels (SSVs) and one research base ship were engaged in the research. *Kyoshin Maru* No.2 (SV, 372GT) was dedicated to sighting survey and most of all experiments were conducted by this ship. Three sighting/sampling vessels (SSVs), *Yushin Maru* (720GT), *Yushin Maru* No.2 (747GT) and *Kyo Maru* No.1 (812.08GT) were engaged in sighting and sampling surveys. *Nisshin Maru* (8,030GT) served as a research base on which all biological examinations of collected samples were conducted.

Total searching distance of one SV and three SSVs was 18,712.0 n.miles. Out of 1,049 schools (3,045 individuals) in the primary sightings of Antarctic minke whales by SSVs, 487 schools (1,167 individuals) were targeted for sampling. A total of 440 individuals were sampled. The survey included (a) experiments for whales (sighting distance and angle experiment, photo-identification experiment and biopsy sampling), (b) oceanographic and acoustic survey (EPCS, XCTD, CTD and a scientific echo sounder EK-500) and (c) biological research. The analysis of this paper used the data on density index of baleen whales by the sightings and sex and reproductive status of sampled Antarctic minke whales in order to combine with the *Kaiyo Maru*'s data.

2.3 Satellite information

In order to take a synoptic view of the Ross Sea waters during the survey period, satellite information was summarized on the following items;

(a) the distribution of sea ice edges between 31 January 2004, 24 and 31 January 2005 (arranged by Weather and Marine Consultant Inc.),
(b) a satellite sea image on 30 January 2005 from www.polar.org/sat_image/,
(c) sea surface temperature by a satellite image on 20 February 2005 (AMSR-E, http://www.remss.com).
(d) sea surface height by a satellite image from OPEX/POSEIDON(T/P), Geosat Follow-On(GFO) and ERS-2 altimeter data on 20 February 2005, and
(e) monthly mean of oceanic chlorophyll concentration (mg / m^3) during February 2005 by SeaWiFS data from Ocean Color Website, http://oceancolor.gsfc.nasa.gov/.

2.4 Introducing of an integrated temperature index and GIS

The purpose of the present study was to find an oceanographic condition, distribution of krill as prey, and baleen whales as predators, and to examine interactions between those. We introduced Integrated TEMperature mean from 0 to 200 m in depth Z (ITME-200) as an oceanographic environmental index,

$$\text{ITEM-200} = 1/200 \int_0^{200} (temperature)dz \,.$$

The reasons why ITEM-200 was introduced were as follow. Water temperature is basically regarded as one of the most basic environmental indicators for oceanographic structure and also marine living organisms. ITEM-200 could conveniently represent the stratified water mass of the surface layer constituting of the Antarctic Surface Water, the Warm Deep Water and the Shelf Water in the survey waters during austral summer season for discussing with biological distribution.

Naganobu and Hirano (1982, 1986) had already instituted the basic concept of integrated temperature mean from 0 to 200 m as an environmental index (namely $\overline{Q}_{200}$) in conjunction with distribution of Antarctic krill. Although their papers were described shortly, those comprised key results in the regional and whole scale of the Antarctic Ocean. They expressed that the use of the index should be understood not only absolute value but also gradient of its distribution pattern, noticing seasonal change of the surface layer in the Antarctic Ocean (Rintoul *et al.* 1997; Sokolov and Rintoul, 2003). Data obtained from discontinuous vertical observations in the past years were hard to calculate detailed structures in the narrow range of temperature in the cold Antarctic Ocean. However, the present survey obtained oceanographic detailed data by modern methodology can provide closer analyses on relationships between ITEM-200 and Antarctic minke whales compared with Naganobu *et al.* (1995) examined in the past.

Accordingly, we introduced ITEM-200 as the oceanographic environmental index to investigate interaction between krill and baleen whales with oceanographic structure integrating detailed various data by our survey in this time. In the recent years, Hosie *et al*. (2000) applied an integrated temperature mean from 0 to 200 m as background of oceanographic structure in conjunction with distribution of Antarctic krill and other zooplanktons and Thiele *et al.* (2000) also used the integrated index for cetacean distribution off east Antarctica (80-150^{o}E).

In addition, we mainly used a computer software of Geographical Information System, "Marine Explore, Version 4.3", produced by Environmental Simulation Laboratory Inc. for unified mapping and overlaying analyses of the present study.

3. Results

3.1 Oceanographic environment

3.1.1 Satellite information

Satellite information is helpful to know the background of oceanographic environment such as sea ice, sea surface temperature, current and phytoplankton in the field survey area. The satellite information in the Antarctic Ocean is very effective because the existing of sea ice and icebergs interrupts survey activities by a ship. In particularly, sea ice in the Ross Sea varies not only seasonal but also yearly condition. We actually changed the survey plan from an original narrow area along 175^{o}E to a whole area in the Ross Sea because of the large melting of sea ice.

Figure 3a shows the comparison of the distribution of sea ice edges in the Ross Sea area between 31 January 2004, 24 and 31 January 2005. The figure indicated that the sea ice during the survey in 2005 melted larger than the last year on the same day, 31 January. Although there was a small open sea along 175^{o}E south of 72-25^{o}S in 2004, the open sea extended over the whole Ross Sea. On the other hand, the sea ice edge on 31 January has changed regionally compared with 24 one week ago. Figure 3b shows a satellite image on the Ross Sea on 30 January 2005. The sea ice almost melted in the whole Ross Sea north of the Ross Ice Shelf but huge icebergs remained in the southwest area. The sea ice remarkably varied during the short period in such way and directly affected our non-icebreaker ship's activities.

Figure 3c shows sea surface temperature by a satellite image on the Ross Sea on 20 February 2005. The sea ice almost melted in the whole Ross Sea north of the Ross Ice Shelf. There was thermal zonation from the northern warmer north water to the southern cold water. High gradient of thermal zonation distributed during 60^{o}S and 65^{o}S around the frontal zone of the Southern boundary of the Antarctic Circumpolar Current. In the Ross Sea, the western waters were warmer than the eastern waters on the whole except the costal waters along the eastern continent.

Figure 3d shows sea surface height by a satellite image from OPEX/POSEIDON(T/P) on 20 February 2005. Flow indicated large pattern the areas between 150^{o}E-160^{o}E, 165^{o}E-175^{o}E and 175^{o}W-140^{o}W in the coastal and shelf slope waters rather than the offshore. The shelf slope waters during 175^{o}W-165^{o}W indicated a clockwise strong eddy which suggested upwelling. The anticlockwise eddies which suggested down-welling were distributed south of the clockwise eddy. These turbulent flow waters might contribute primary production.

Figure 3e shows monthly mean of oceanic chlorophyll concentration (mg / m^3) during February 2005 by SeaWiFS data. The figure was integrated the fragments of data in the un-clouds during February. The high chlorophyll concentration distributed around the waters of 70°S south of 65°S where roughly coincided with the Southern Boundary of ACC and the shelf slope. The figure suggested macro distribution of phytoplankton during the survey period. °C

3.1.2 Oceanographic structure

Vertical distribution

Figure 4a shows vertical section of temperature from the surface to near bottom, the deepest 4000 m from 60°S to the Ross Ice Shelf located at around 78°S along 175°E. The upper layer between 0 and 500 m was enlarged on scale compared with the downward layer below 500 m. An upper graph of the figure 4a shows the mean of mean from 0 to 200 m (ITEM-200) as an environmental index.

Considering from existing general knowledge, main water masses appeared in the present survey were generalized as follows: (i) the Antarctic Surface Water (ASW); this water mass is classified to the Summer Water over seasonal thermocline and the Winter Water indicating under the value of 0 °C, (ii) the Warm Deep Water (WDW); this water shows high temperature and salinity maximum indicating below the above ASW, and (iii) the Shelf Water (SW); this water is especially called in the case that ASW exists from the surface to near the bottom on the Antarctic continental shelf such as the Ross Sea.

In order to examine relationships between water masses and biological distribution we used ITEM-200 as environmental index as mentioned in the methods section. ITEM-200 can simply summarize stratified water masses. The upper graph of Figure 4a shows ITEM-200 calculated adjusting the lower figure. The graph indicated a north-south gradient of the upper layer temperature.

The around 3 °C line calculated from the warmer water in the Antarctic Circumpolar Current during 60-62°S abruptly dropped down to 64°S. This dropping line coincided with the so-called Southern Boundary of the Antarctic Circumpolar Current (SBACC) identified by Orsi *et al*. (1995). The line during 64-70°S indicating the thick ASW (0-150 m) and its lower WDW (150-200 m) stayed between approximately 0 and -1 °C. The line south of 70°S dropped less than -1 °C with increasing the thick of ASW except the so-called Antarctic Divergence around 72-10°S where indicated upwelling of WDW. SW above the continent shelf South of 73°S showed approximately -1 °C and/or less than -1 °C. ITEM-200 on the continental shelf indicated relatively warmer because of thicker summer surface water above the seasonal thermocline and intrusion of WDW into the continental shelf waters.

Figure 4b and 4c shows vertical sections f salinity and density respectively from the surface to near bottom between 60°S and the Ross Ice Shelf along 175°E as well as temperature. Steep north –south gradients of salinity and density distributed during 63-65°S. Lower salinity less than 33.8psu and lower density less than 27.2 distributed during 66-70°S because of probably ice melting water. Higher salinity than 34.2psu and higher density than 27.6 indicated in the surface layer (0-100 m) at the Antarctic Divergence zone during 71-30°S and 73°S. High salinity and density suggested strong upwelling of WDW. In the Ross Sea there was also higher salinity and density suggesting upwelling to the surface layer during 75-76°S. High salinity than 34.7psu and density than 27.9 existed on the shelf bottom.

Figure 4d shows vertical section of geostrophic current from the surface to referenced level depths (1000 db and 400 db) between 60°S and the Ross Ice Shelf along 175°E. On the whole, slow eastward flow and westward flow less than 2cm/sec distributed alternated along the north-south line except strong eastward flow (a maximum core 13cm/sec) estimated during 61-65°S. The relatively strong eastward flow showed along the continental slope at the Antarctic Divergence zone during 71-30°S and 73°S.

Horizontal distribution

Figure 5 shows horizontal distribution of ITEM-200 as the environmental index in the whole survey waters. A pattern of north-south thermal zonation indicated from a warm isopleth of 8 °C along 55°S to a cold isopleth of -1.5 °C on the continental shelf with meander. The thermal zonation during 8 °C and 0 °C indicated steep a north-south gradient. The zonation south of 0 °C indicated a gentle gradient. The tongue-like water along 175°W indicated southward advection and cold water during 175°E-180° remained northward during the 0 °C and -1 °C isopleth with meander. On the Ross continental shelf, the cold core water less than -1.5 °C distributed to the east and relatively warmer to the west. This distribution figure of ITEM-200 would be used as the basic environmental index for considering various biological distributions.

The ITEM-200 integrated water temperature columns would be reflected flow patterns roughly. To add flow information makes the actual use of ITEM-200 more clear. Figure 6a shows geopotential anomaly at 10 db level relative to 1000 db with the bottom topography in the waters deeper than 1000 m. Figure 6b also shows geopotential anomaly at 10 db level relative to 400 db with the bottom topography in the shallow continental shelf waters.

A steep gradient of eastward isopleths north of 65°S in Figure 6a indicated strong current in the Antarctic Circumpolar Current (ACC). A gentle gradient of southward isopleths south of 65°S suggested sluggish movement of the thick ASW to the south. Distribution pattern of isopleths in Figure 6b suggested southward advection of the oceanic waters and clockwise circulation of water. Clockwise eddies also suggested upwelling of deeper water. These flow patterns might affect large melting of sea ice in the waters in the survey year.

3.2 Marine biological gradients

3.2.1 Primary production

Figures 7a, 7b and 7c show vertical section of total chlorophyll *a* from the surface to 200 m along 180°, 175°E and 170°W respectively. Along 180°, relative high chlorophyll *a* (1.0-2.5 μgL^{-1}) appeared shallower than 50 m south of 64°S and the maximum near the waters of sea ice edge. Along 175E, relative high chlorophyll *a* (1.0-2.0 μgL^{-1}) appeared shallower than 40 m from 63-30°S to 68°S, and around 74°S where roughly coincided with the melting waters of sea ice. Along 170°W in the Ross continental shelf, relative high chlorophyll *a* (1.0 μgL^{-1} and up) appeared as patchy distribution shallower than approximately 50 m from 63-30°S to 68°S, and around 74°S near the Ross Ice Shelf.

Figure 8 shows horizontal distribution of integrated chlorophyll *a* (mg m^{-2}) from the surface to 200 m in the whole survey area with ITEM-200. Although there was a time lag during the survey period, on the whole, relative high chlorophyll *a* appeared in the waters of ITEM-200 = 0 °C where roughly coincided with SBACC and the melting marginal waters of sea ice. In the Ross continental shelf, chlorophyll *a* along 170°W showed higher compared with 175°E. The differences between the western waters (170°W) and the eastern waters (175°E) might depend on the melting timing of sea ice and water circulation.

3.2.2 Krill abundance

There is little information of krill abundance in the Ross Sea except Azzali and Kalinowski (2000) that was limited in the regional scale. Figure 9 shows distribution density of krill (*E. superba* and *E. crystallorophias*)(g/m^2) in the whole survey waters by *Kaiyo Maru*. The samples from *Kaiyo Maru*'s RMT and stomach contents of Antarctic minke whales indicated that two euphausiid species, *E. superba* and *E. crystallorophias* showed different distribution patterns in the survey waters. *E. superba* distributed in the oceanic waters north of the -1°C isopleth of ITEM-200 where nearly coincided with the deeper depth than 1000 m of the bottom topography. *E. crystallorophias* distributed on the continental shelf region south of the -1°C isopleth of ITEM-200 where coincided with shallower depth than 1000 m. Based on their distribution patterns, the survey area was divided into two strata to estimate the biomasses of two species.

Kaiyo Maru conducted the echo sounder survey using EK500 (Simrad). In the study, the difference between the mean volume backscattering strength (ΔMVBS) of 120 and 38 kHz fell between 2 and 16 dB was classified as krill. Details of the acoustic survey were described in Murase *et al.* (2006). Figure 9 showed that high density of *E. superba* was observed in the northwestern waters in the survey area. *E. crystallorophias* tended to distribute at small clockwise eddies suggested upwelling and near the ice shelf. Biomass densities of *E. superba* and *E. crystallorophias* estimated were 5.36±7.45 g/m^2 and 3.44±1.96 g/m^2, respectively. The biomasses of *E. superba* and *E. crystallorophias* in the present study were estimated as 2.04 (CV = 0.44) and 1.26 (CV = 0.21) million ton, respectively (Murase *et al*. 2006).

3.3 Interactions between the oceanography, krill and whales

3.3.1 Oceanography - krill

Figure 10a shows distribution of Antarctic krill (*Euphausia superba*) in routine trawls (0-200 m) with ITEM-200. Although appearance frequency of *E. superba* by routine trawls was 36% in the whole survey scale, it was 100% in the waters between the 0 ^{o}C and -1 ^{o}C isopleths of ITEM-200 except one station in the waters of the -1.5 ^{o}C isopleth in the Ross continental shelf. High density of *E. superba* sampled coincided with steep north-south gradients of 0 the 0 ^{o}C and -1 ^{o}C isopleths respectively. The steep north-south gradients of the 0 ^{o}C and -1 ^{o}C isopleths might understand as the Southern Boundary of ACC and a general continental slope front respectively.

Figure 10b shows distribution of ice krill (*Euphausia crystallorophias*) in routine trawls (0-200 m) with ITEM-200. Appearances of *E. crystallorophias* sampled only limited in the waters lower than -1 ^{o}C in the Ross continental shelf. *E. crystallorophias* was distributed all around in the continental shelf waters except all 3 sampling sites during 73-75^{o}S along 170^{o}W. Maximum density appeared near the Ross Ice Shelf at 78-30^{o}S in the southeast part. On the other hand, no appearances were in the warmer waters north of the -1 ^{o}C isopleth.

Figure 10c shows appearances of Antarctic krill (*E. superba*) by trawls below 200 m with ITEM-200. As each trawling site differenced a sampling depth, it was difficult to compare with each proportion of caught density. However, appearance and/or non-appearance of caught species have meaningful knowledge. *E. superba* appeared at most sampling sites in the continental shelf waters except the site near the Ice Shelf along 170^{o}W. This result pointed up the difference from the routine trawls (0-200 m) (Figure 10a) indicated only one appearance site. Non-appearances south 74^{o}S long 175^{o}W coincided with the result of the routine trawls. This result suggested non-distribution of *E. superba* in the southwestern waters in the Ross Sea.

Figure 10d shows appearance s of ice krill (*E. crystallorophias*) by trawls below 200 m with ITEM-200. This result of appearance was common to the routine trawls (Figure 10b). Appearances of *E. crystallorophias* limited south of the -1 ^{o}C isopleth and existed in the western waters along 175E. Non-appearance was north of the -1 ^{o}C isopleth. Geographical distribution of *E. crystallorophias* spread throughout the Ross continental shelf waters.

3.3.2 Oceanography - whales

Figure 11a shows distribution density of Antarctic minke whales (*Balaenoptera bonaerensis*) (number of schools sighted per 100 n. miles) with ITEM-200. The distribution of Antarctic minke whales ranged through south of the 1 ^{o}C isopleth. Relative high density index of Antarctic minke whales concentrated at the steep gradient around the 0 ^{o}C and south of the -1 ^{o}C isopleths. In addition, the density index indicated higher in the tongue-shaped southward advection along 175^{o}W between 0 and -1 ^{o}C and the tongue-shaped northward advection along 170^{o}W. The relative high density coincided with the tongue-shaped advection with north-south meander. High density indexes especially concentrated in the waters with eddies around 75^{o}S along 170^{o}W.

Figure 11b shows distribution density of Antarctic minke whales (number of individuals sighted per 100 n. miles) with ITEM-200. Although the distribution of individual density indices basically was the same pattern as school density, individual density remarkably indicated high in the tongue-shaped northward advection. The relative high density distributed in the tongue-shaped southward advection suggested that the whale migrated to the southern colder shelf water indicated its high density.

Figure 11c: Positions of sampled Antarctic minke whales by sex and reproductive status with ITEM-200. There was difference of distribution between males and females. Mature males concentrated around and north of the -1 ^{o}C except several positions in the self waters. No immature males were sampled. Mature females distributed thorough the whole waters sampled and relatively concentrated in the shelf waters. Immature females mainly distributed in the waters around and north of the -1 ^{o}C except two positions near the continent and ice shelf. Differences of distribution between sex and reproductive status were recognized depending on the condition of waters.

Figure 11d shows distribution density of humpback whales (*Megaptera novaeangliae*) (number of schools sighted per 100 n. miles) with ITEM-200. The distribution of humpback whale clearly ranged through north of the 0.6 ^{o}C isopleth. The high density indexes concentrated at the frontal zone around the 0.5 ^{o}C isopleth. There are no appearance of humpback whales in the relative colder waters south of the 0.6 ^{o}C isopleth.

Figure 11e shows distribution density of fin whale (*Balaenoptera physalus*) (number of schools sighted per 100 n. miles) with ITEM-200. The distribution of fin whales ranged north of the around 0 ^{o}C isopleth and especially indicated higher at around 61^{o}S and 170^{o}E. Although one exemption appeared at around 70^{o}S and 175^{o}E, this suggested that fin whales migrated in the tongue-shaped southward advection along 175^{o}E. Although the distribution of fin whales was very similar to humpback whales in latitudinal zone, both distributions slightly differed from each other in longitudinal direction.

Figure 11f shows distribution density of blue whale (*Balaenoptera musculus*) (number of schools sighted per 100 n. miles) with ITEM-200. Although only 3 appearance sites of bulue whales were observed, the appearance stopped at the -1 ^{o}C isopleth. Both of one appearance site at the 0 ^{o}C and 2 sites at the -1 ^{o}C were distributed in the waters of tongue-shaped southward advection. This suggested that blue whales migrated in the tongue-shaped southward advection along 175^{o}W.

4. Discussion

The purpose of the work was to find an oceanographic condition, distribution of krill as prey, and baleen whales as predators, and to examine interactions between those. The results indicated close interactions between the oceanographic condition, krill and whales. The oceanographic condition of the surface layer was summarized as ITEM-200. Distribution of ITEM-200D was used as background information for comparing with distribution patterns of each species.

Figure 12 shows conceptual model relating water mass and circulation pattern of the oceanic surface layer with ITEM-200, the distribution and abundance of krill (Antarctic krill and ice krill) and baleen whales. (Antarctic minke whale and humpback whale). Abbreviations indicate as the follows. ACC; the Antarctic circumpolar current, ASW; the Antarctic surface water, SW; the shelf water, SBACC; the southern boundary of ACC, ANK; Antarctic krill, ICK; ice krill, MIW; Antarctic minke whale , and HUW; humpback whale. Each line in the map indicates the Southern boundary of Antarctic Circumpolar Current (SBACC) (from Orsi *et al*. 1995) and ITEM-200 = 0 and -1 ^{o}C. A 1000 m shows the bottom line. Arrows show flow patterns.

Figure 12 summarized the result of interactions between oceanographic conditions, krill and baleen whales through the present survey. The oceanographic conditions generally indicated three water types; ACC waters over ITEM-200 = 0 ^{o}C, ASW between 0 and -1 ^{o}C and SW below -1 ^{o}C. An Eastward Arrow indicated strong eastward flow in ACC. Southward arrows suggested southward flows in ACC and ASW. Clockwise and anticlockwise arrow suggested eddies with upwelling and down-welling in SW. ITEM-200 isopleths indicated north-south meandering shape.

We also refer to recent oceanography results (e.g., Picco *et al*., 2000; Russo, 2000). We discuss the results of the interaction between oceanographic conditions, krill and baleen whales from the following viewpoints.

Firstly, ITEM-200 was considered as the effective environmental index that was summarized background information of oceanographic conditions. Antarctic krill mainly distributed in ASW and extended in SW. Ice krill clearly distributed in SW but not ASW. Overlap between Antarctic krill and ice krill was shown in the shifting waters from ASW to SW around -1 ^{o}C. Humpback whales mainly distributed ACC with high density around 0 ^{o}C and slightly extended in ASW. Antarctic minke whales mainly distributed in ASW and SW with high density around -1 ^{o}C. Overlap between humpback whales and Antarctic minke whales was in the shifting waters from ACC to ASW around 0 ^{o}C.

Secondly, ITEM-200 would be used as a quantitative environmental index for the past relative analyses. Murase *et al.* (2002) showed the relationships between distributions of krill and baleen whales in the Indian sector of the Antarctic Ocean. Matsuoka *et al*. (2003, 2006) indicated the segregation of humpback whales around the waters of SBACC and Antarctic minke whales around the waters of ice-edge and over the continental shelf slope. The relationships between distribution of krill, whales and ITEM-200 could give the quantitative information adding to their result. Murase *et al*. (2006) used ITEM-200 to identify the boundary of distribution of Antarctic krill and ice krill for biomass estimation using acoustic data in our surveys. A stomach content study of baleen whales is a key approach for understanding the interaction of krill as prey and Antarctic minke whales as predators (Ichii, 1990; Ichii *et al*., 1998). Tamura *et al*. (2006) effectively used ITEM-200 as environmental index to compare stomach content of sampled Antarctic minke whales and net sampling in the local waters in our surveys. On the other hand, Reilly *et al.* (2004) studied baleen whales on biomass and energy transfer through a biological oceanography survey in the South Atlantic sector of the Antarctic Ocean. It is interested in applying our approach to the other waters.

Thirdly, the essential interaction between ITEM-200 as environmental index, krill as preys and baleen whales as predators would apply to other Antarctic waters. Hosie *et al.* (2000) and Thiele *et al*. (2000) used integrated temperature mean (0-200 m) as the background oceanographic condition to compare macro-zooplankton community structure and whales off east Antarctica (80-150^{o}E) respectively. Although their result basically coincided with the Ross Sea survey's one, .there was a difference of regional feature. The space (ASW) during 0 and -1 ^{o}C off the Ross Sea was four times as wide as east Antarctica. This oceanographic condition reflected biological distribution of krill and whales.

On the other hand, Nicol *et al*. (2000) and Chiba *et al*. (2000) emphasized the importance of SBACC and the Antarctic Divergence respectively in structuring Antarctic marine ecosystems off east Antarctica (Wakatsuchi *et al.* 1994),. Murase *et al*. (2006) examined influential environmental factors of distribution patterns of Antarctic minke whales and suggested response to krill. These approaches suggest interesting discussion connected with ITEM-200, krill and baleen whales.

Fourthly, using the data of the joint surveys of *Kaiyo Maru* and JARPA, we overviewed various aspects and indicated the geo-ecological interaction between oceanography through ITEM-200, krill and baleen whales in the survey area. Doses the results apply to other Antarctic waters? Although there would be a regional feature in the waters, the ecological interaction would be common in the whole Antarctic Ocean. Naganobu and Hirano (1982, 1986) had already tried geographical overlay between ITEM-200 and Antarctic krill in the regional and whole Antarctic Ocean and indicated the similar structure as this time result, although un-sufficient data compared with recent survey data. Nicol (2000) edited a multidisciplinary survey of the waters off east Antarctica. Watkins *et al*. (2004) also edited a multinational, multi-ship biological oceanography survey of the Atlantic sector or the Southern Ocean. These two multidisciplinary results suggested the common interaction between the results in the present study and the circumpolar scale. In addition, continuing JARPA surveys (Nishiwaki *et al*. (2006)) would contribute to submit sufficient whale data. In the future, detailed analysis in regional and whole scale is required for comprehensive understanding of the interaction between oceanography, krill and whales.

Finally, relationships between oceanography and krill distribution is a recurrent problem. Marr (1956, 1962) and Mackintosh (1972, 1973) were certainly classical and original papers indicating the relationships between krill distribution and water mass and current in the regional and whole Antarctic Ocean scale using Discovery Committee's large data since the 1930s. Deacon and Baker (1980) indicated importance of stratified Antarctic Surface Water and Warm Deep Water for krill distribution as an idea. Continuously, Naganobu and Hirano (1982, 1986) introduced the concept of integrated temperature mean as oceanographic environmental index. Amos (1984) and Miller and Hampton (1989) contributed to advance the relationships in large scale of the Southern Ocean. Recently, Nicol *et al*. (2000) dynamically indicated well the relationships using the concept of SBACC. In these accumulated knowledge, ITEM-200 in the present study may contribute as a synthesized index of oceanographic structure with biological and ecological gradients like a concept of bioregionalsation. Further study is required in conjunction with environmental, biological and ecological distribution/gradients for understanding of the Ross Sea Ecology (Faranda *et al*., 2000; Pinkerton *et al*., 2006).

On the other hand, it is important to analyze not only interaction but also variability of oceanography, krill and whales in the recent years. There are many oceanographic papers on variability in the JARPA survey waters (Yabuki 2006, Watanabe *et al.* 2006) and variability of the Antarctic/Southern Ocean scale (e.g., White *et al*. 1996; Gille, 2002; Aoki *et al*., 2005). Especially, freshening of the Antarctic Bottom Water in the Ross Sea (Jacobs *et al*. 2002) and warming in the Antarctic Peninsula waters (Marshall *et al.* 2006) should be noted. On the other hand, there are biological papers on change of Antarctic krill (Siegel and Loeb 1995; Loeb *et al*. 1997; Naganobu *et al*. 1999 and Atkinson *et al*. 2004) including predators such as birds (Croxall *et al*. 2002) and whales (Fujise *et al*., 2006). To study correlation with these variability papers in the future, we concentrated synoptic interaction between oceanography, krill and whales in this paper. It is needed to find the interaction as basic structure for understanding of ecological variability.

5. Conclusions

A joint survey of the R/V *Kaiyo Maru* and the Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) was carried out to study the interaction between an oceanographic condition, distribution of krill as prey, and baleen whales as predators in the Ross Sea and its adjacent waters, Antarctica in austral summer of 2004/05.

The results indicated close interactions between the oceanographic condition, krill and whales. The oceanographic condition of the surface layer was summarized as the oceanographic environmental index ITEM-200. Distribution of ITEM-200 was used as background information for comparing with distribution patterns of each species. Antarctic krill distributed mainly in the Antarctic Surface Water (ASW) area (ITEM-200 = 0 to -1 ^{o}C) and extended in the Shelf Water (SW) area (less than -1 ^{o}C) Ice krill clearly distributed in SW but not ASW. Overlap between Antarctic krill and ice krill was shown in the shifting waters from ASW to SW around -1 ^{o}C. Humpback whales mainly distributed in the Antarctic Circumpolar Current (ACC) waters with high density around 0 ^{o}C near Southern Boundary of ACC and slightly extended in ASW. Antarctic minke whales mainly distributed in ASW and SW with high density around -1 ^{o}C in a continental shelf slope frontal zone. Overlap between humpback whales and Antarctic minke whales were in the shifting waters from ACC to ASW around 0 ^{o}C. The interaction between distribution of krill, whales and ITEM-200 could give the quantitative information to identify the boundary of distribution of Antarctic krill and ice krill for biomass estimation using acoustic data in the surveys. We finally summarized a conceptual model of interaction between oceanography relating water mass and circulation pattern of the oceanic surface layer with ITEM-200, the distribution and abundance of krill and baleen whales.

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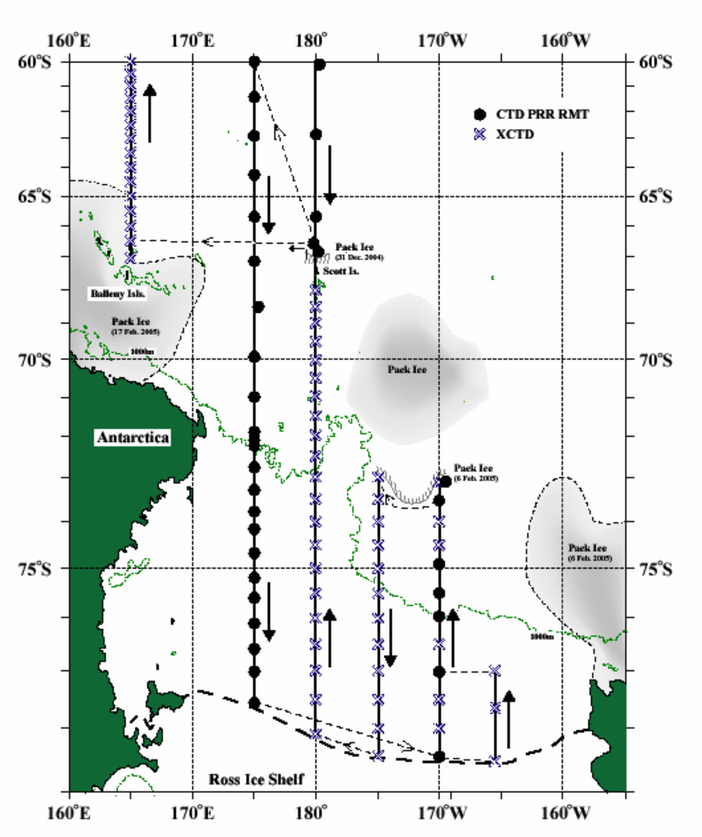

Figure 1: Transect lines and stations by research items of the *R/V Kaiyo Maru* during 26 December 2004 and 24 February 2005.

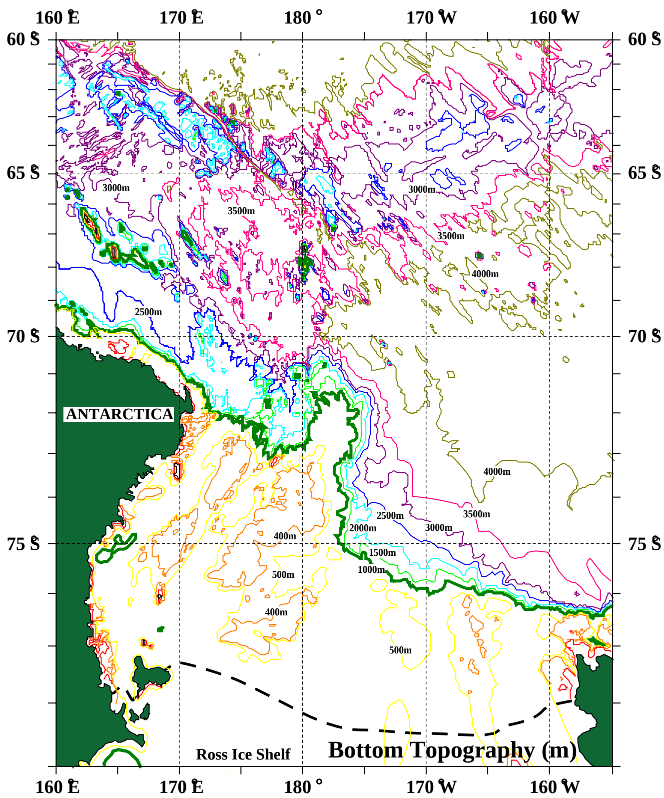

Figure 2: Bottom topography off and of the Ross Sea.

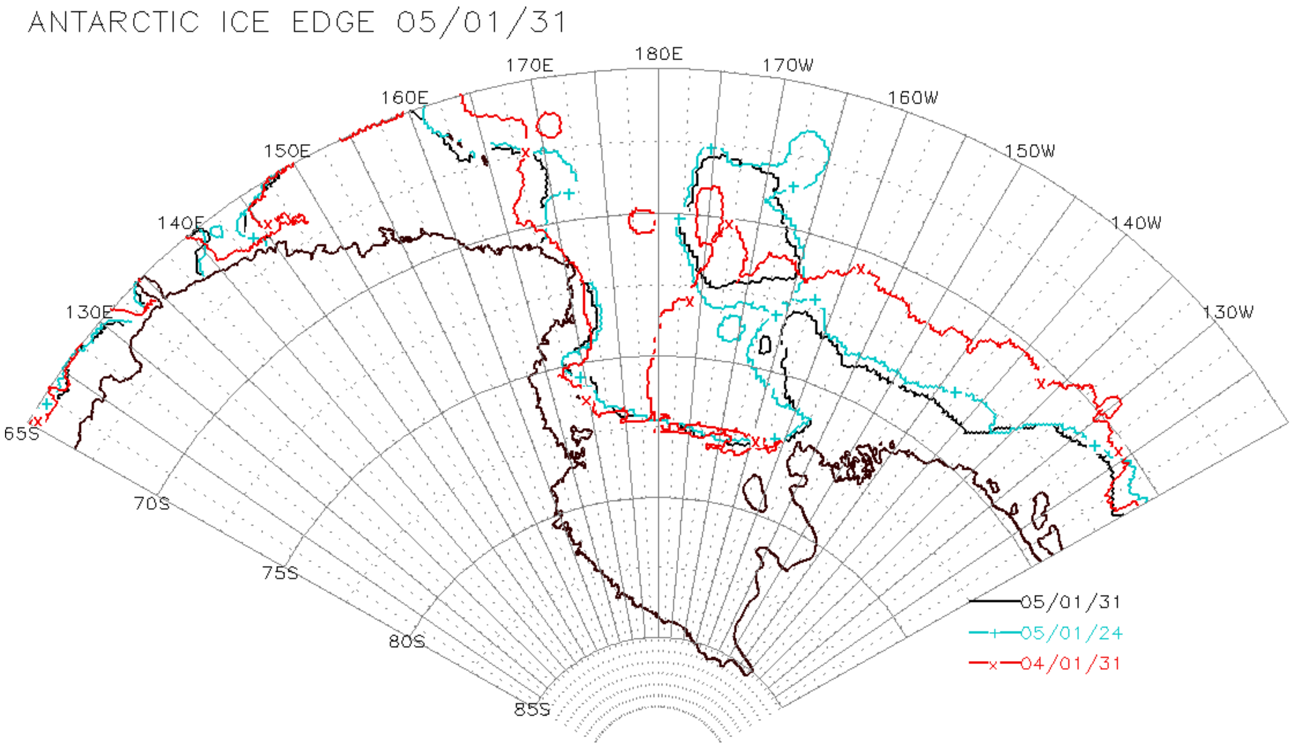

Figure 3a: Comparison of the distribution of sea ice edges in the Ross Sea area between 31 January 2004 (red line), 24 (blue line) and 31 (black line) January 2005. The sea ice during the survey in 2005 melted larger than the last year on the same day. The sea ice edge on 31 January has changed regionally compared with 24 one week ago.

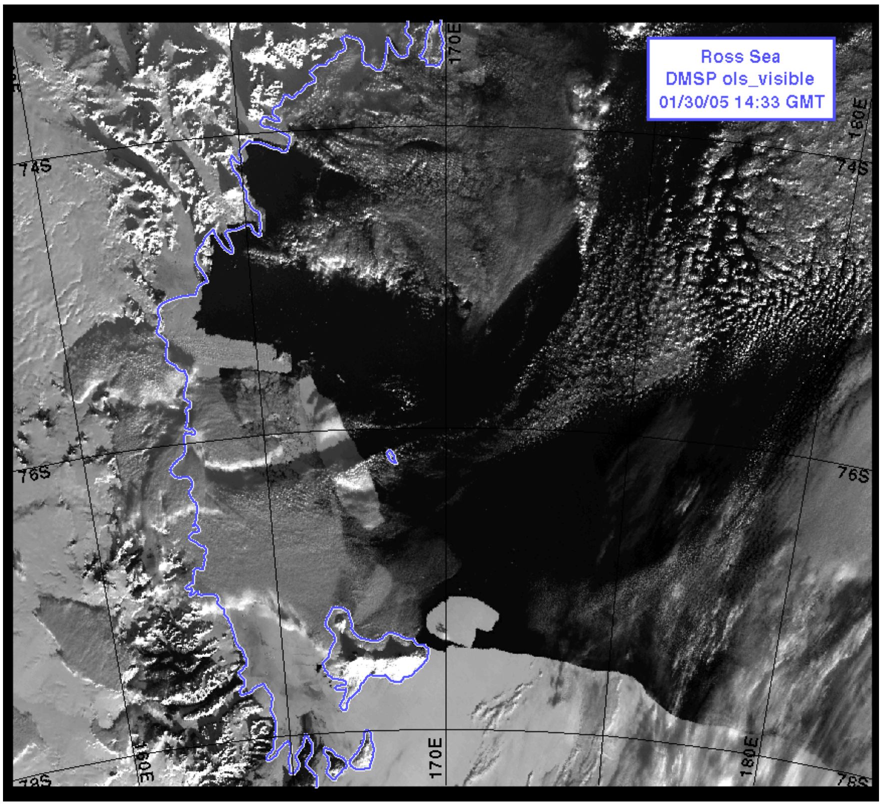

Figure 3b: A satellite image on the Ross Sea on 30 January 2005. The sea ice almost melted in the whole Ross Sea north of the Ross Ice Shelf. from www.polar.org/sat_image/.

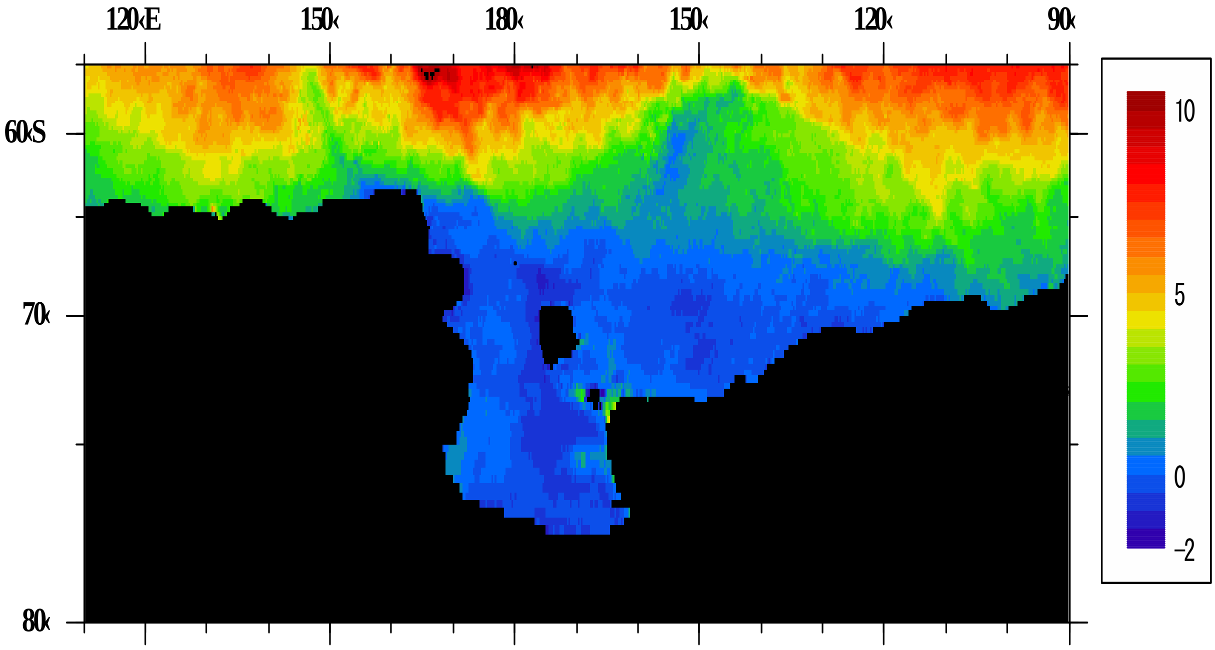

Figure 3c: Sea surface temperature by a satellite image on the Ross Sea on 20 February 2005. The sea ice almost melted in the whole Ross Sea north of the Ross Ice Shelf.

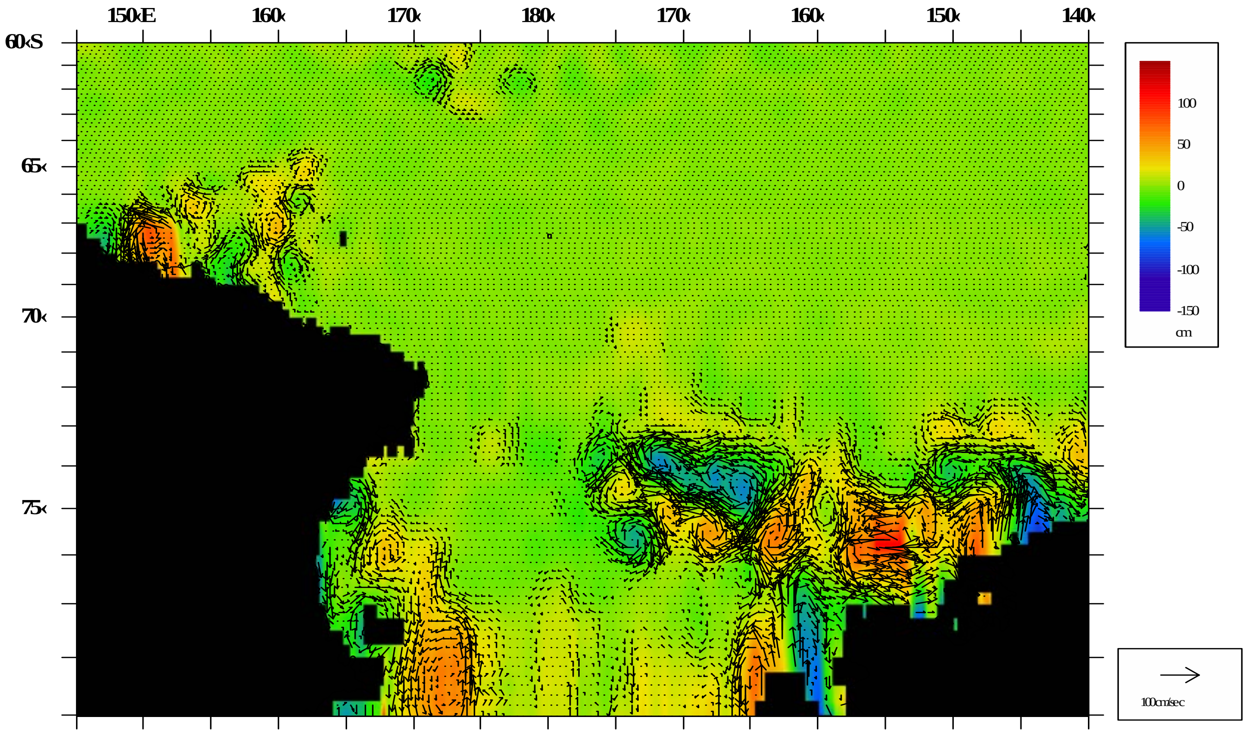

Figure 3d: Sea surface height by a satellite image from OPEX/POSEIDON(T/P), Geosat Follow-On(GFO) and ERS-2 altimeter data on 20 February 2005.

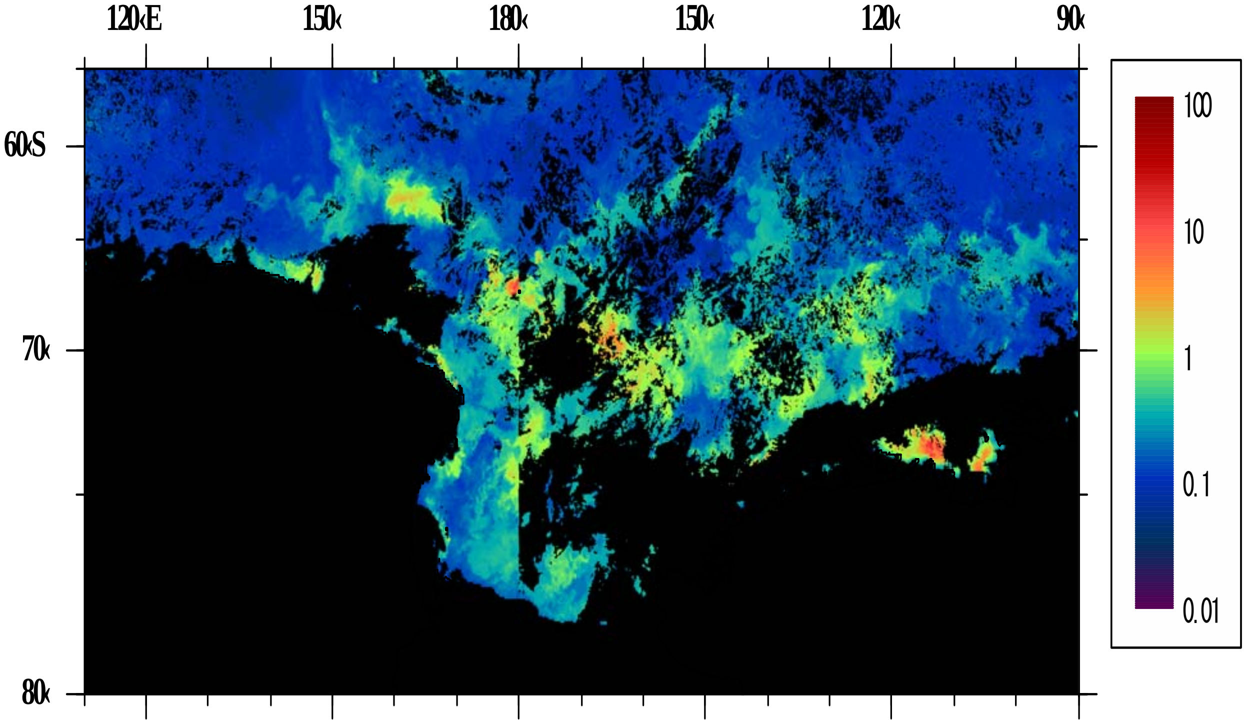

Figure 3e: Monthly mean of oceanic chlorophyll concentration (mg / m^3) during February 2005 by SeaWiFS data from Ocean Color Website, http://oceancolor.gsfc.nasa.gov/.

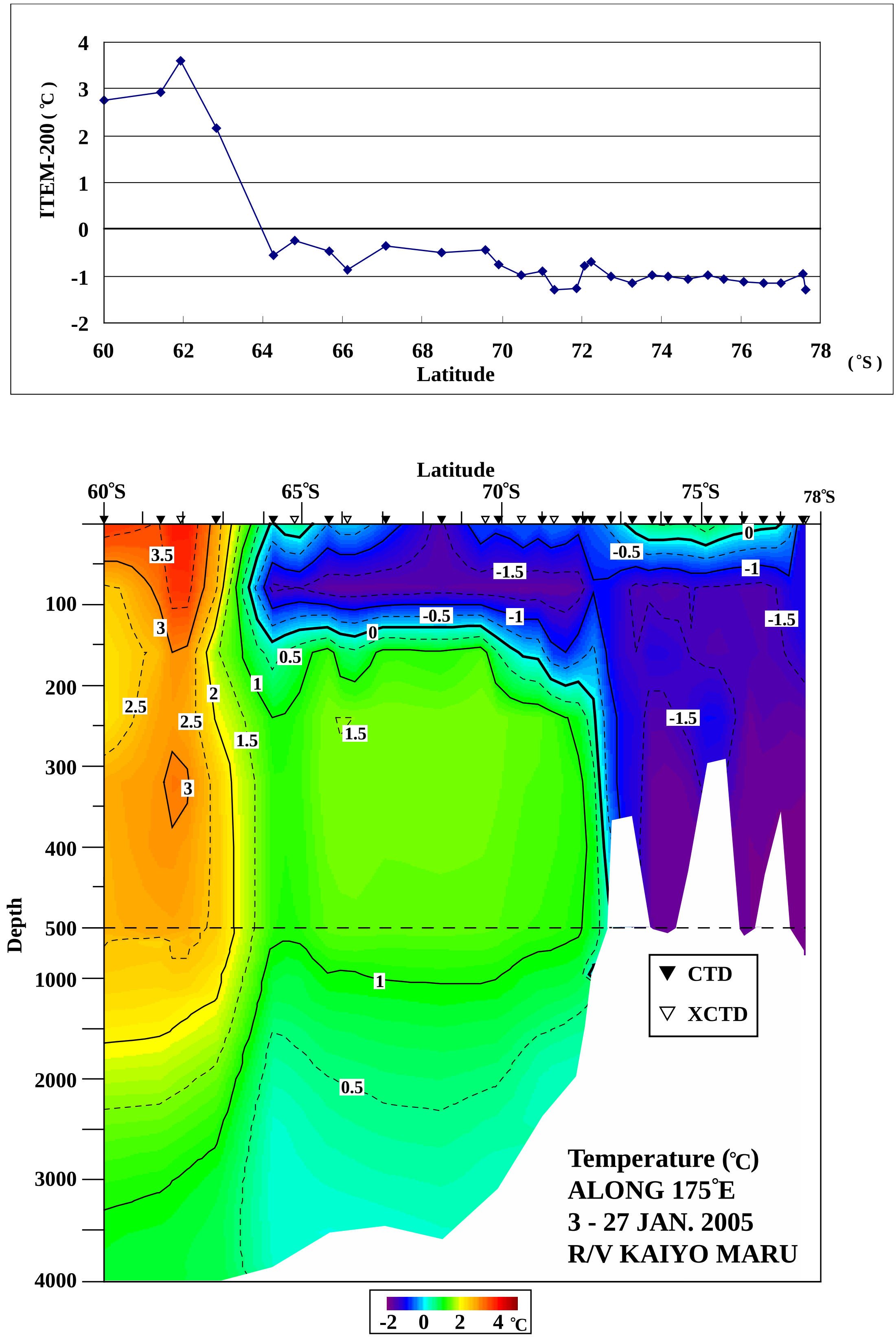

Figure 4a: Vertical section of temperature from the surface to near bottom between and the Ross Ice Shelf along 175E. An upper graph shows the mean of integrated temperature between the surface (0) and 200 m as an environmental index (ITEM-200) introduced by Naganobu and Hirano (1982). SBACC: the Southern Boundary of the Antarctic Circumpolar Current.

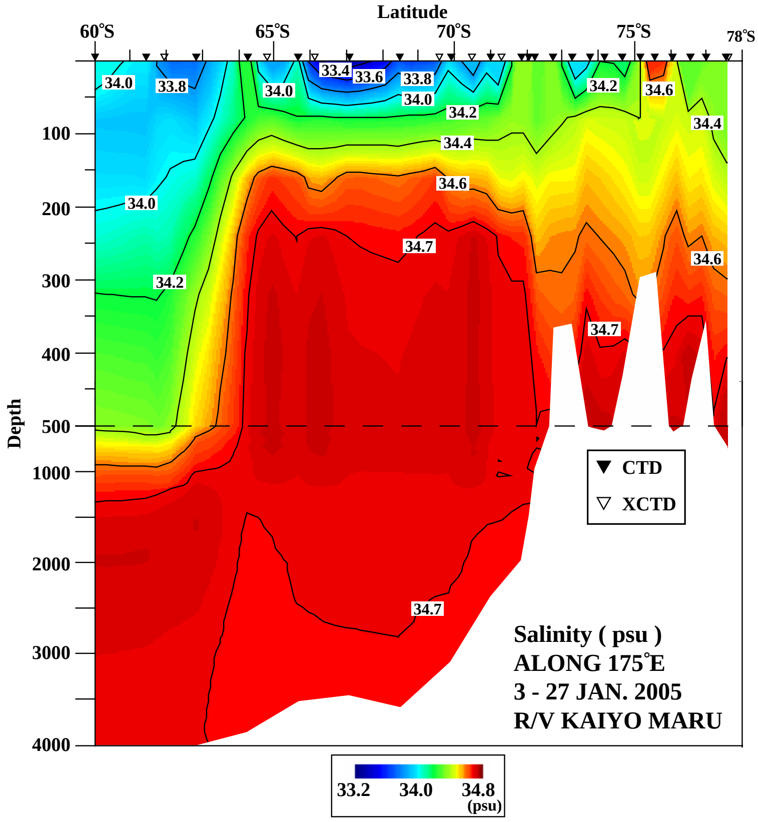

Figure 4b: Vertical section of salinity from the surface to near bottom between 60°S and the Ross Ice Shelf along 175°E.

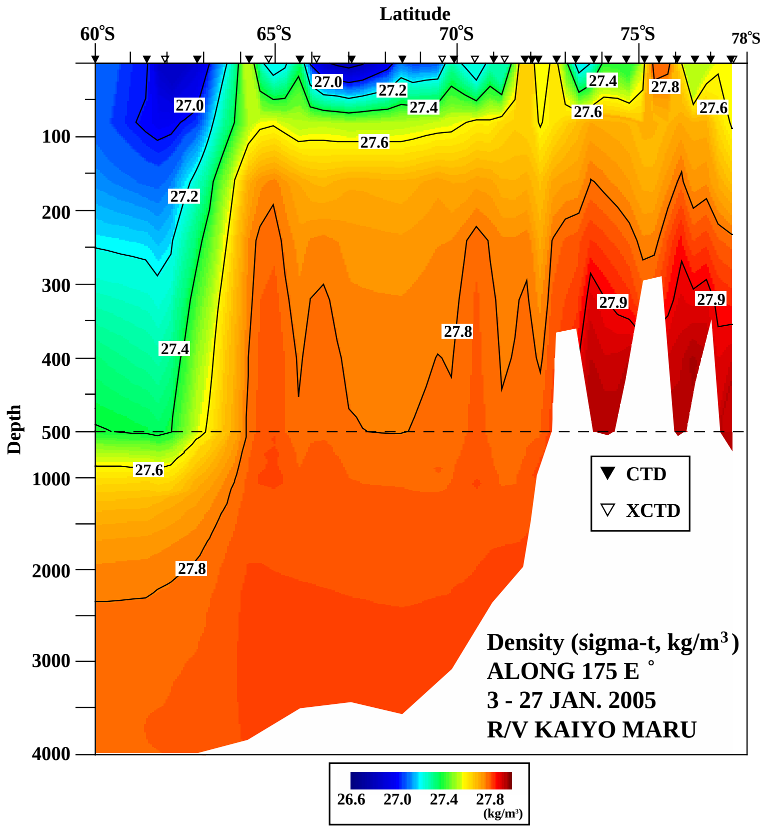

Figure 4c: Vertical section of density from the surface to near bottom between 60°S and the Ross Ice Shelf along 175°E.

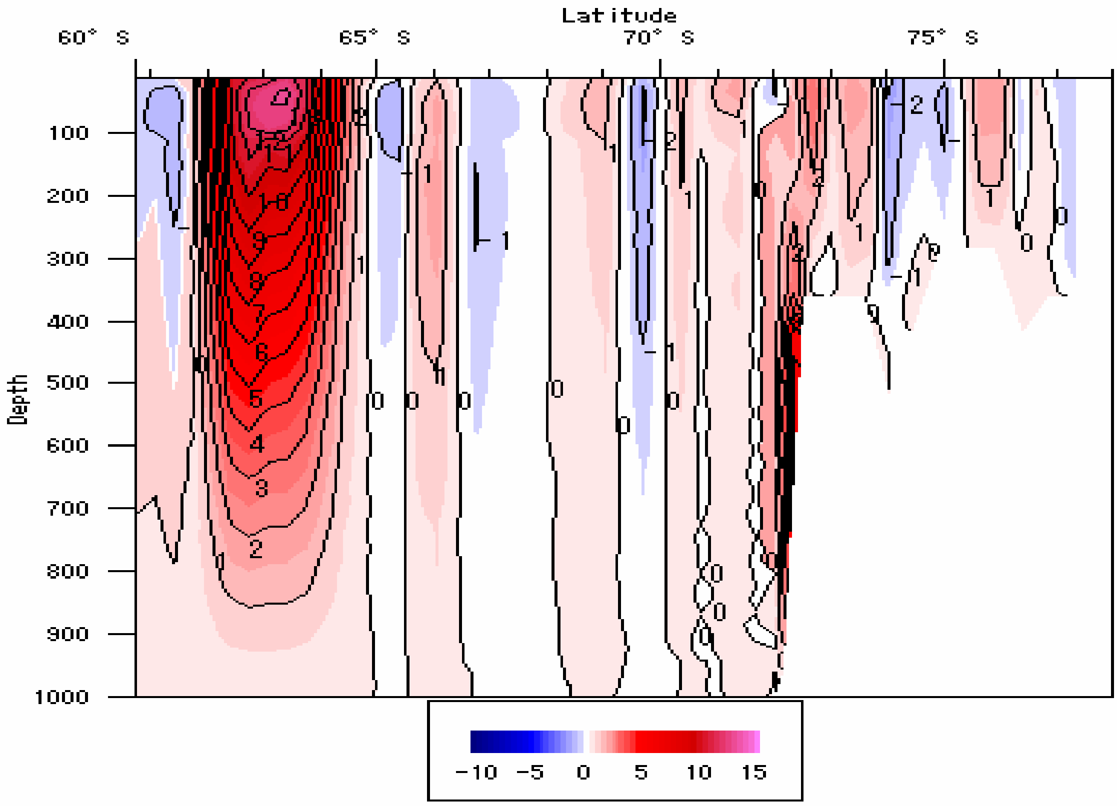

Figure 4d: Vertical section of geostrophic current from the surface to referenced level depths (1000 db and 400 db) between 60°S and the Ross Ice Shelf along 175°E. Positive values indicate the eastward velocity and negative westward.

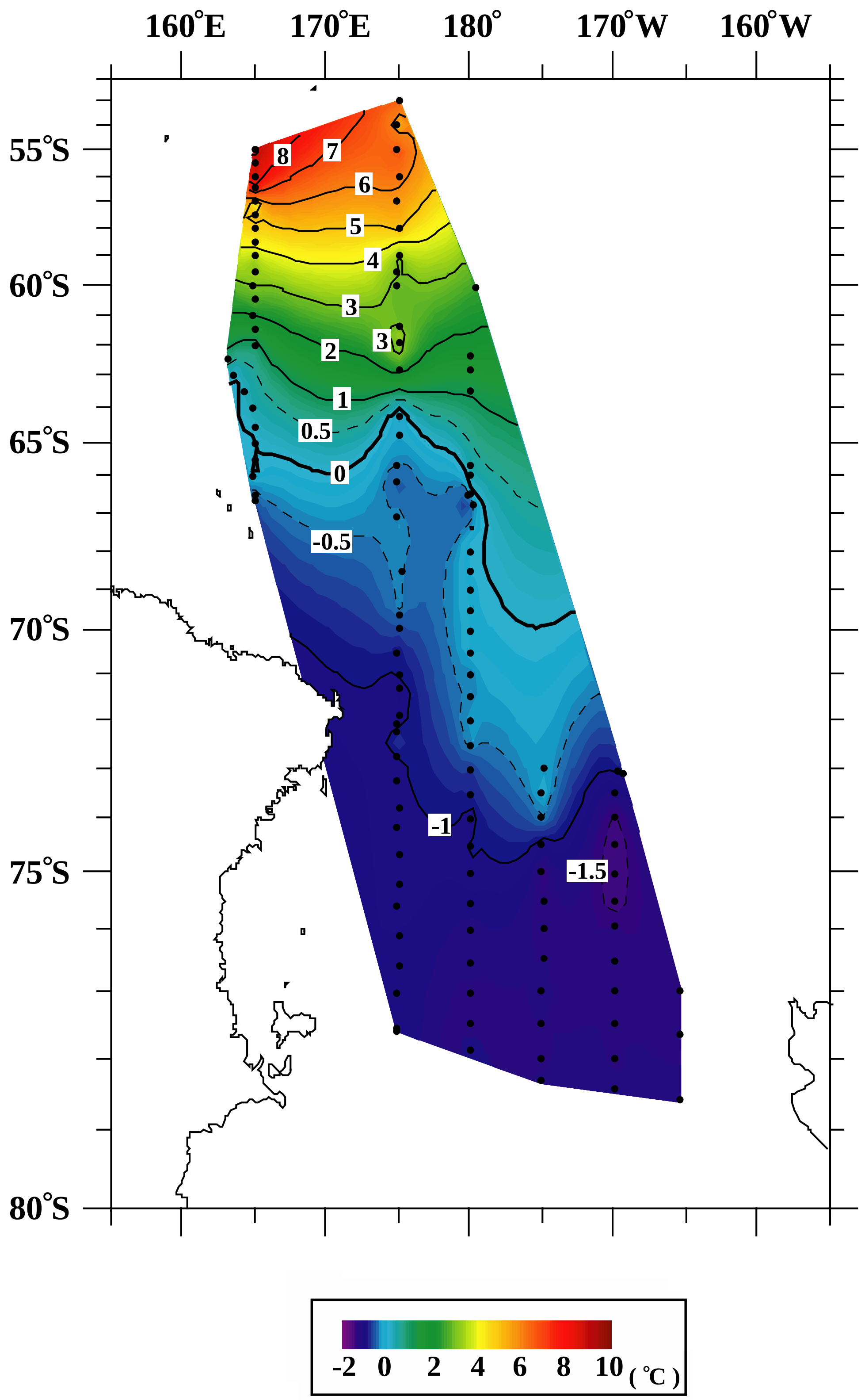

Figure 5: Horizontal distribution of integrated temperature (0-200 m) (ITEM-200). Bullets (•) indicate the observed sites.

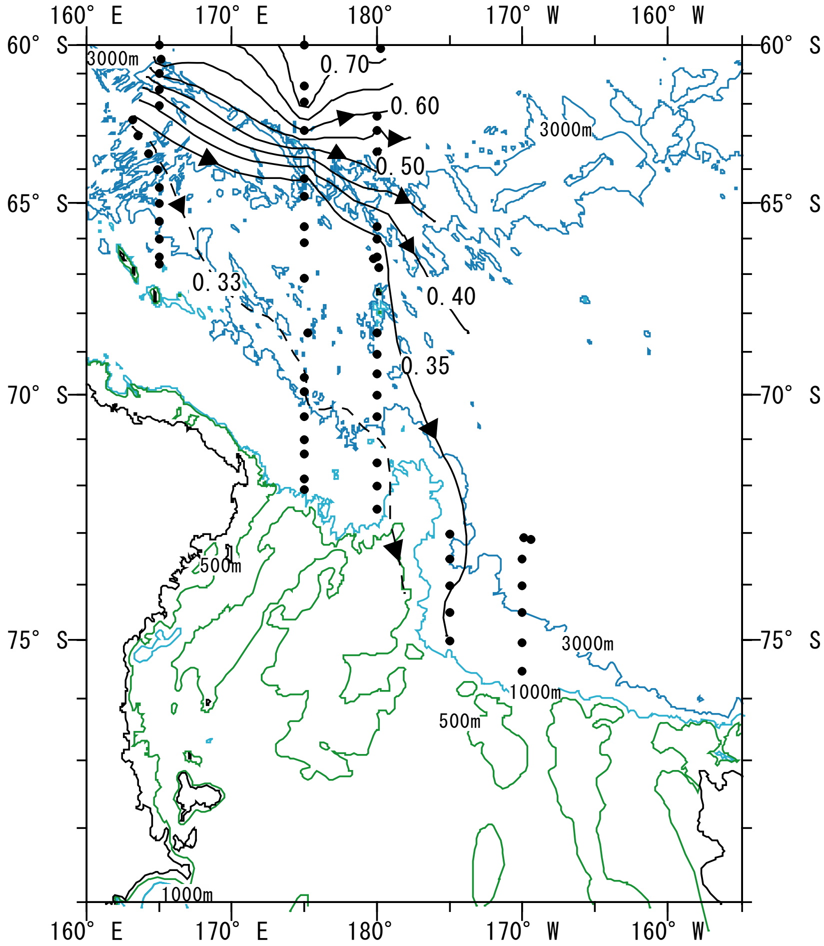

Figure 6a: Geopotential anomaly (m^2s^{-2}) at 10 db level relative to 1000 db with the bottom topography. Bullet (•) indicates the observed sites.

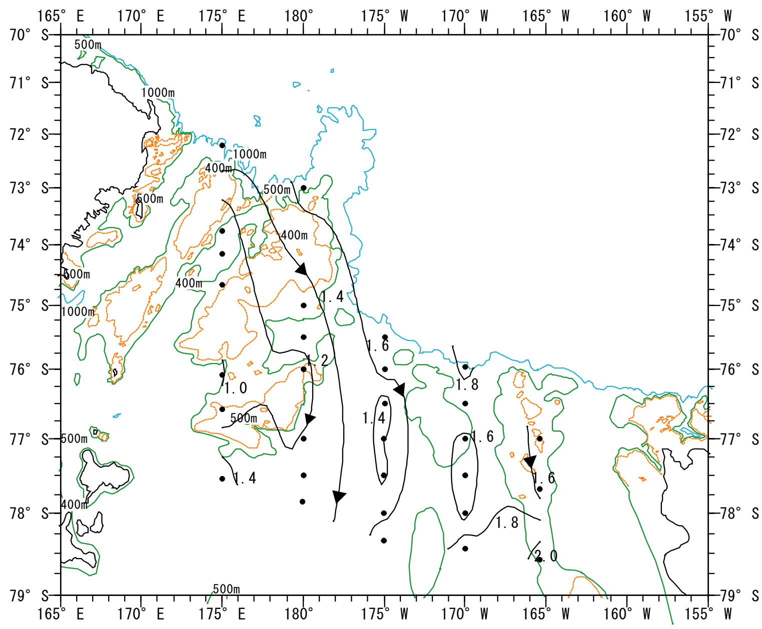

Figure 6b: Geopotential anomaly (m^2s^{-2}) at 10 db level relative to 400 db with the bottom topography. Bullet (•) indicates the observed sites.

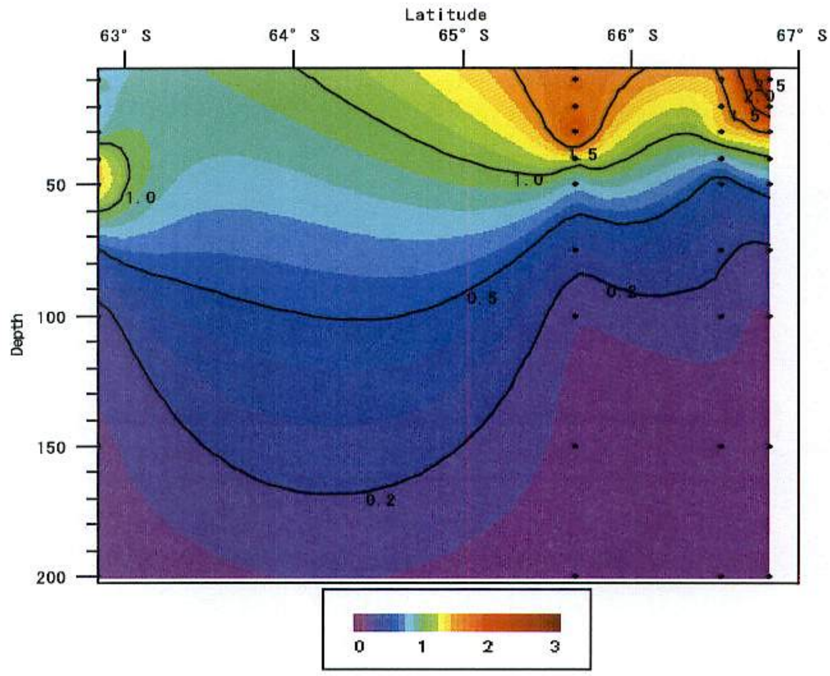

Figure 7a: Vertical section of total chlorophyll a (μg L^{-1}) from the surface to 200 m along 180°.

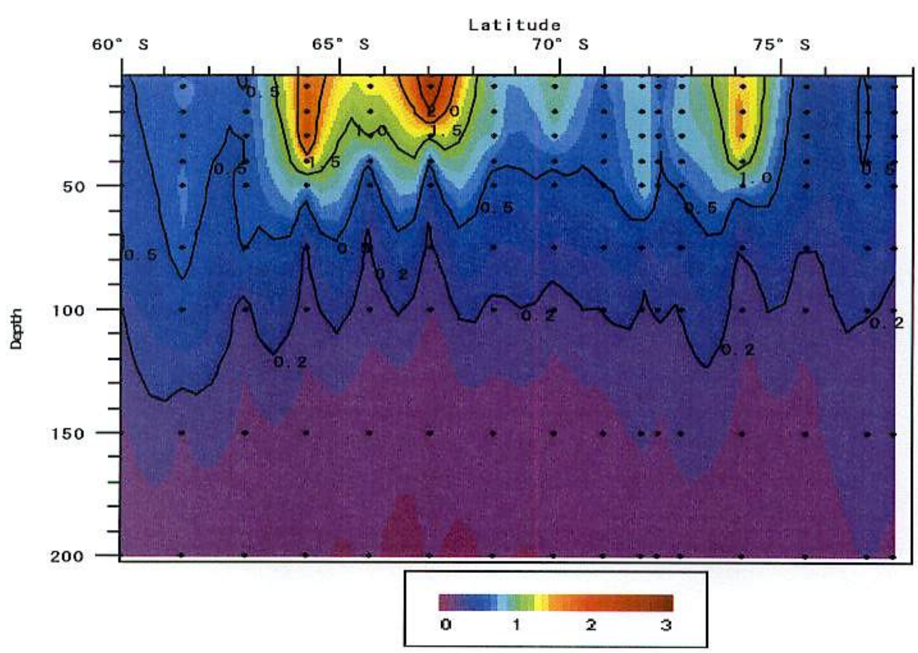

Figure 7b: Vertical section of total chlorophyll a (μg L^{-1}) from the surface to 200 m along 175°E.

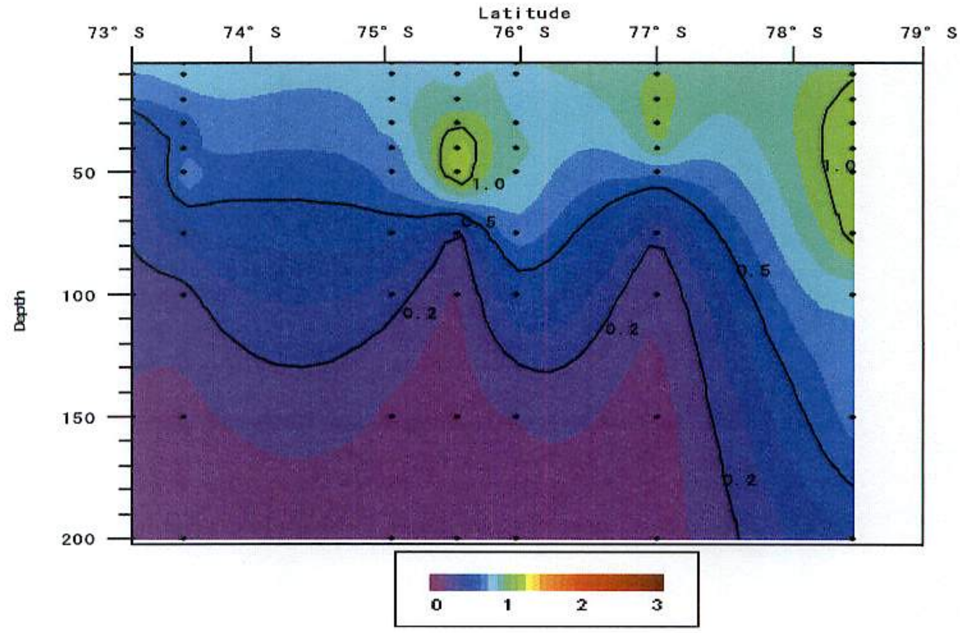

Figure 7c: Vertical section of total chlorophyll *a* (μg L^{-1}) from the surface to 200 m along 170^{o}W.

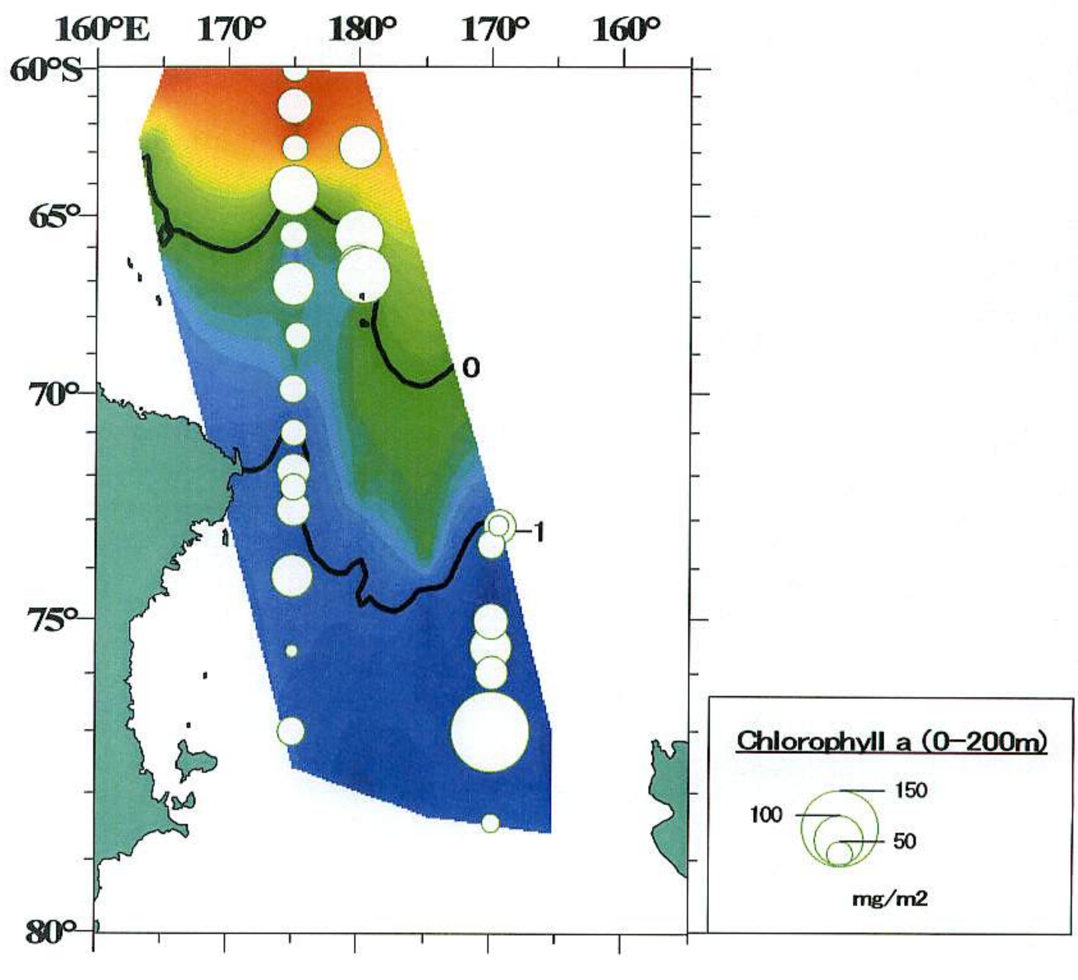

Figure 8: Horizontal distribution of integrated chlorophyll *a* (mg m^{-2} from the surface to 200m.

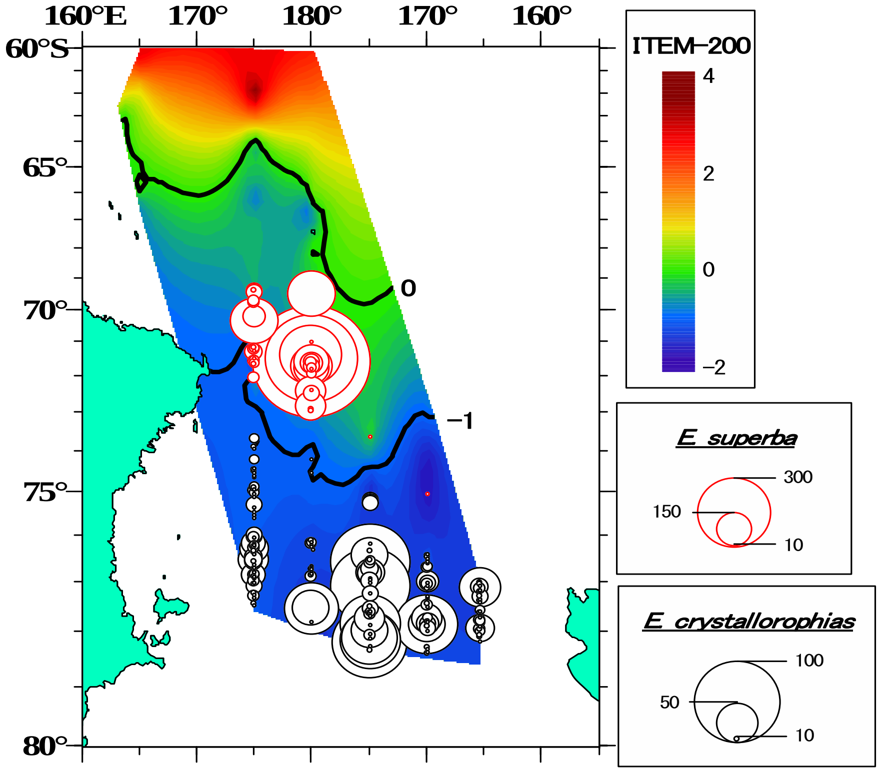

Figure 9a: Distribution and density (g/m^2) of krill; *E. superba* and *E. crystallorophias* by the acoustic survey with ITEM-200.

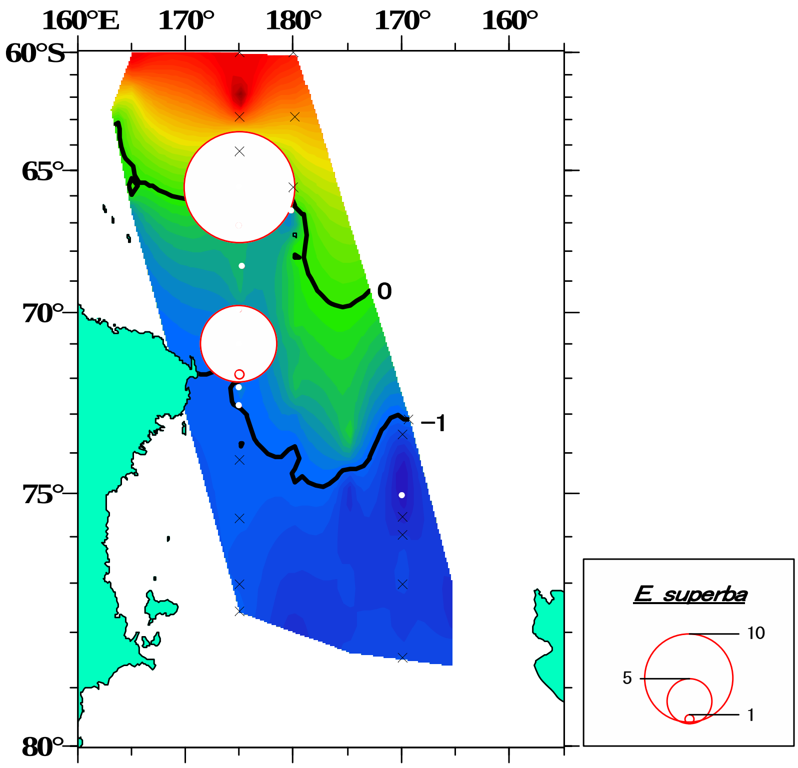

Figure 10a: Distribution of Antarctic krill (*Euphausia superba*) in routine trawls with ITEM-200. Abundance circles are proportional in area to density (individuals 1000 m^{-3}). × sampling sites where no specimens where were caught.

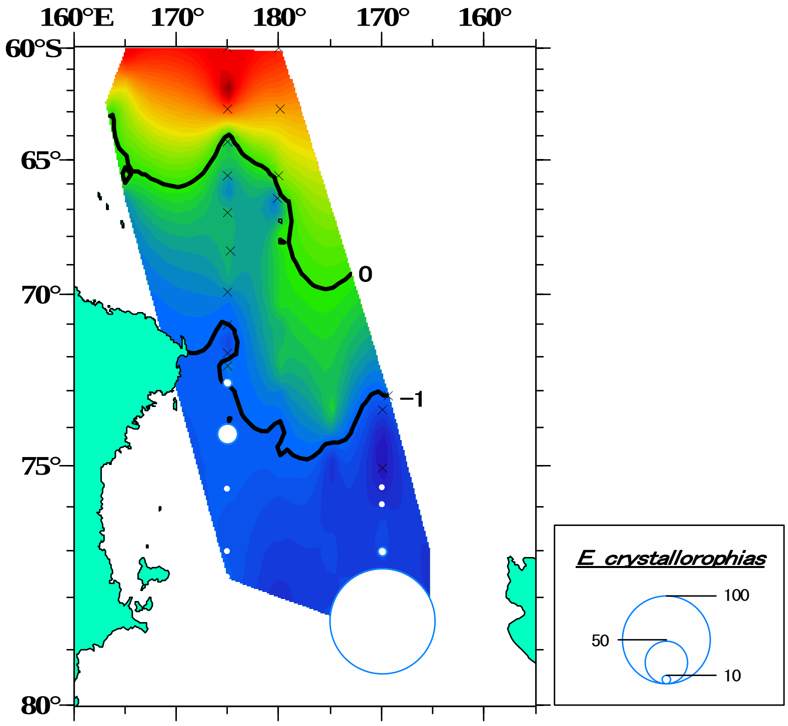

Figure 10b: Figure 12a: Distribution of ice krill (*Euphausia crystallorophias*) in routine trawls with ITEM-200. Abundance circles are proportional in area to density (individuals 1000 m^{-3}). × sampling sites where no specimens where were caught.

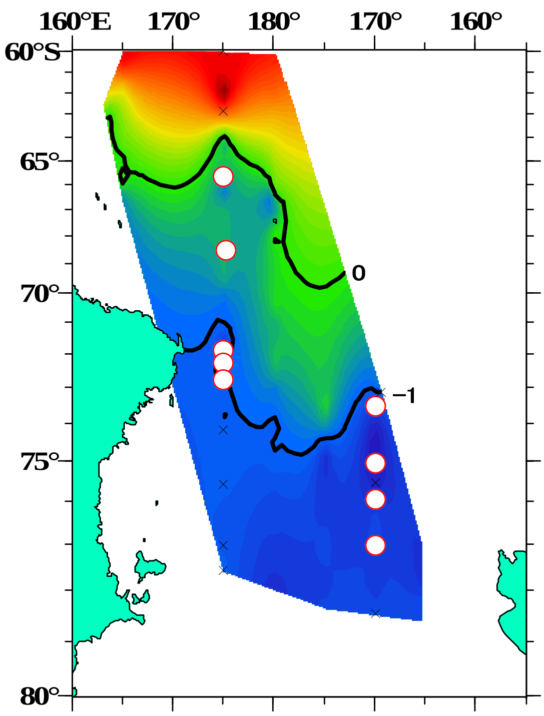

Figure 10c: Appearance s of Antarctic krill (*Euphausia superba*) below 200 m with ITEM-200. Abundance circles are proportional in area to density (individuals 1000 m^{-3}). × sampling sites where no specimens where were caught.

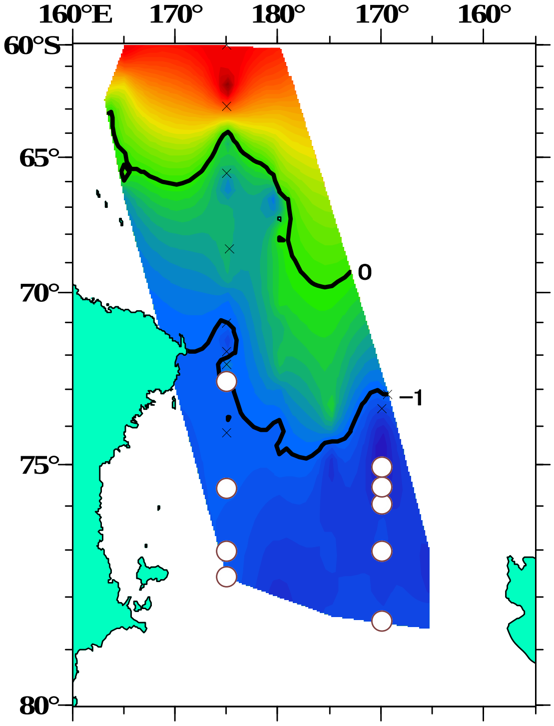

Figure 10d: Appearance s of ice krill (*Euphausia crystallorophias*) below 200 m with ITEM-200. Abundance circles are proportional in area to density (individuals 1000 m^{-3}). ×sampling sites where no specimens where were caught.

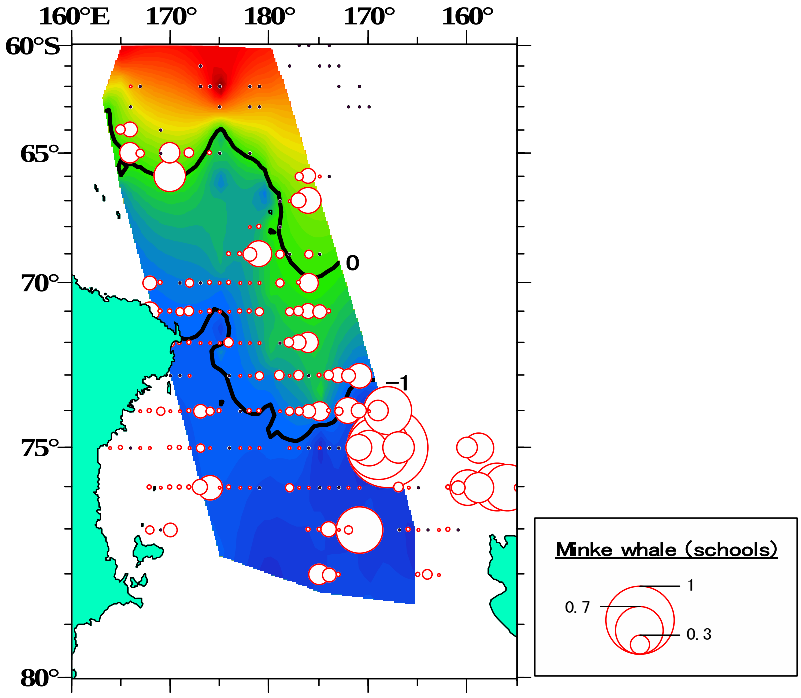

Figure 11a: Distribution of Antarctic minke whale (*Balaenoptera bonaerensis*) with ITEM-200. Abundance circles are proportional in area to density (number of schools sighted per 100 n. miles). A black mark (･) indicates naught.

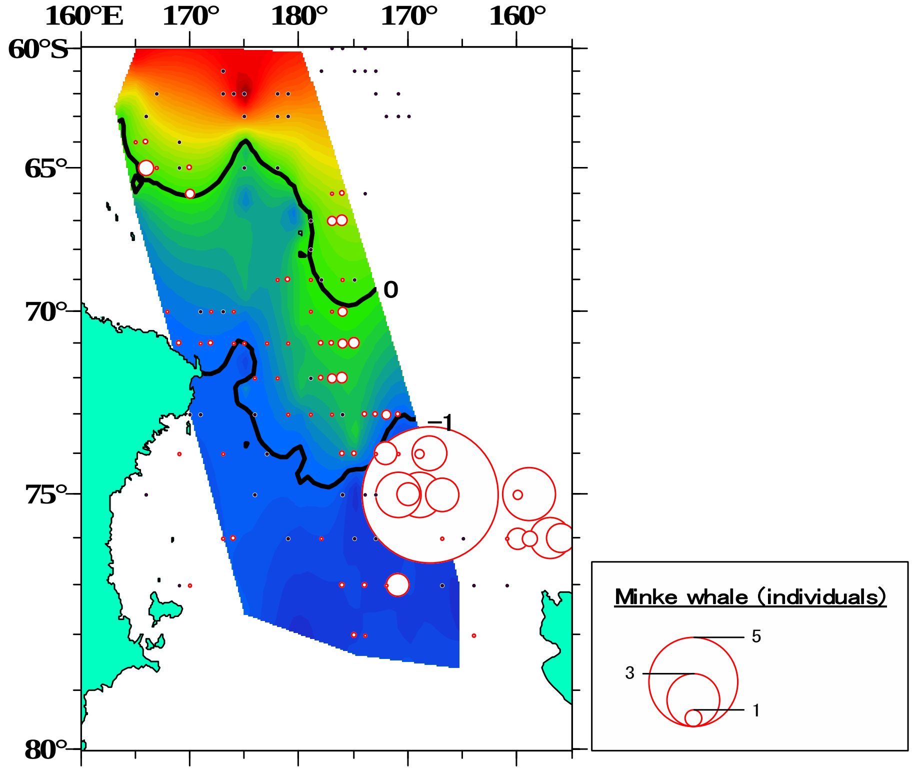

Figure 11b: Distribution of Antarctic minke whale (*Balaenoptera bonaerensis*) with ITEM-200. Abundance circles are proportional in area to density (number of individuals sighted per 100 n. miles). A black mark (･) indicates naught.

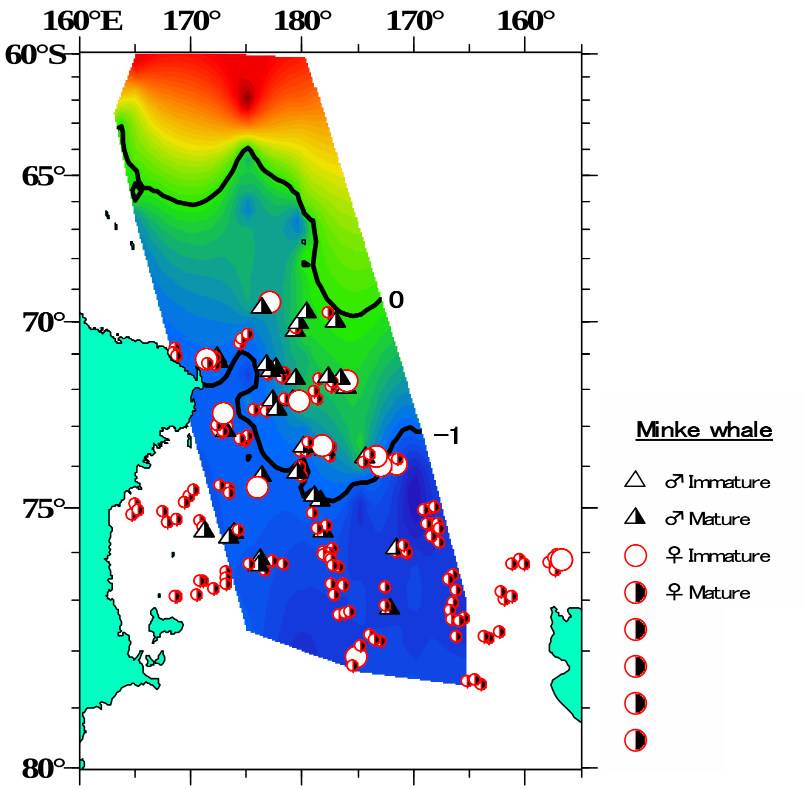

Figure 11c: Positions of sampled Antarctic minke whales by sex and reproductive status with ITEM-200.

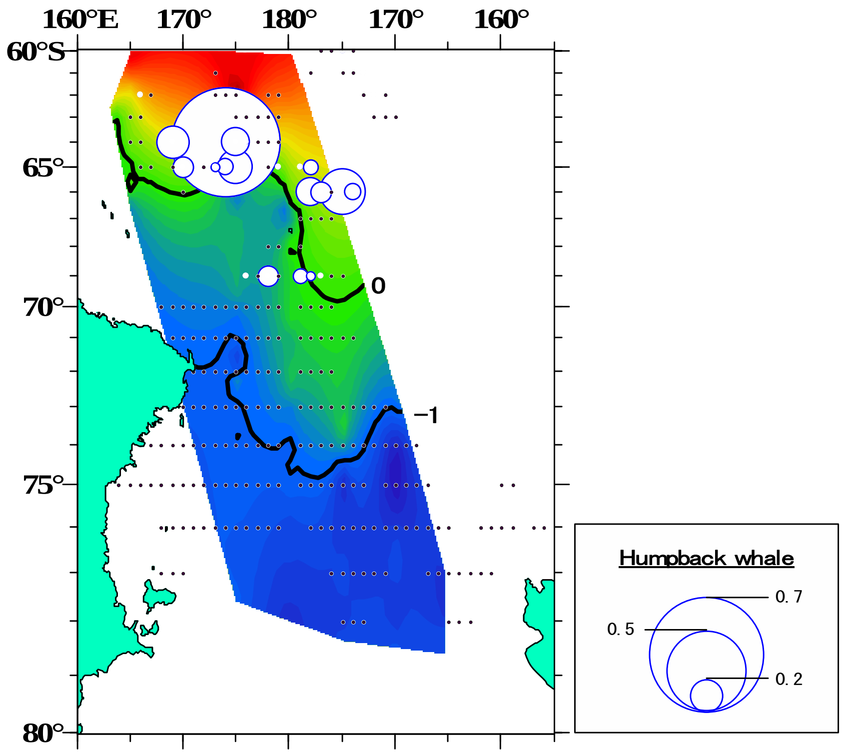

Figure 11d: Distribution of humpback whale (*Megaptera novaeangliae*) with ITEM-200. Abundance circles are proportional in area to density (number of individuals sighted per 100 n. miles). A black mark (･) indicates naught.

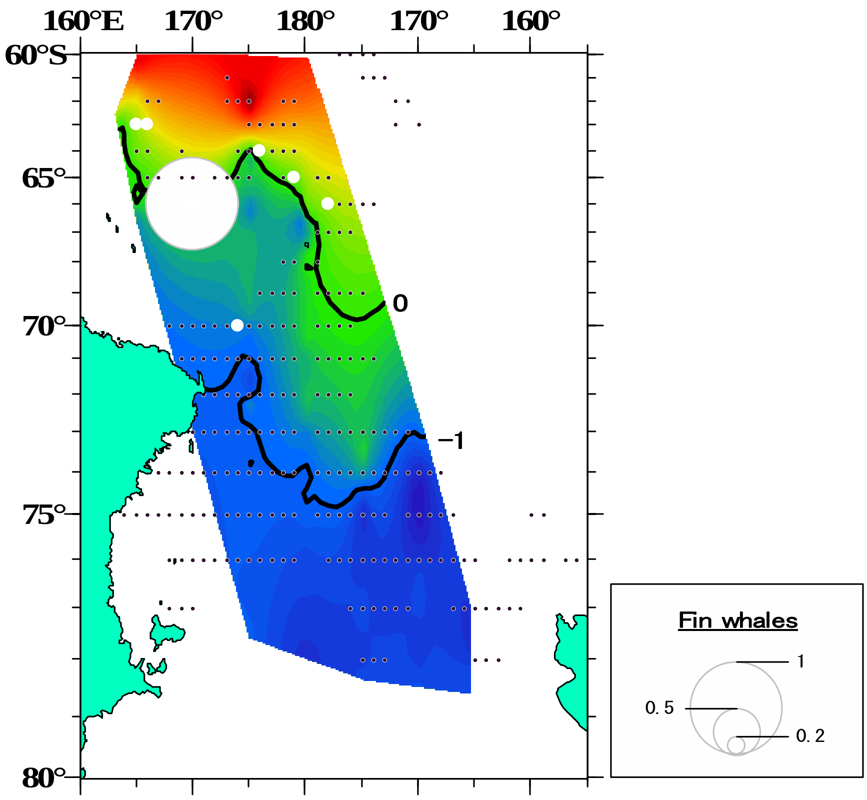

Figure 11e: Distribution of fin whale (*Balaenoptera physalus*) with ITEM-200. Abundance circles are proportional in area to density (number of individuals sighted per 100 n. miles). A black mark (･) indicates naught.

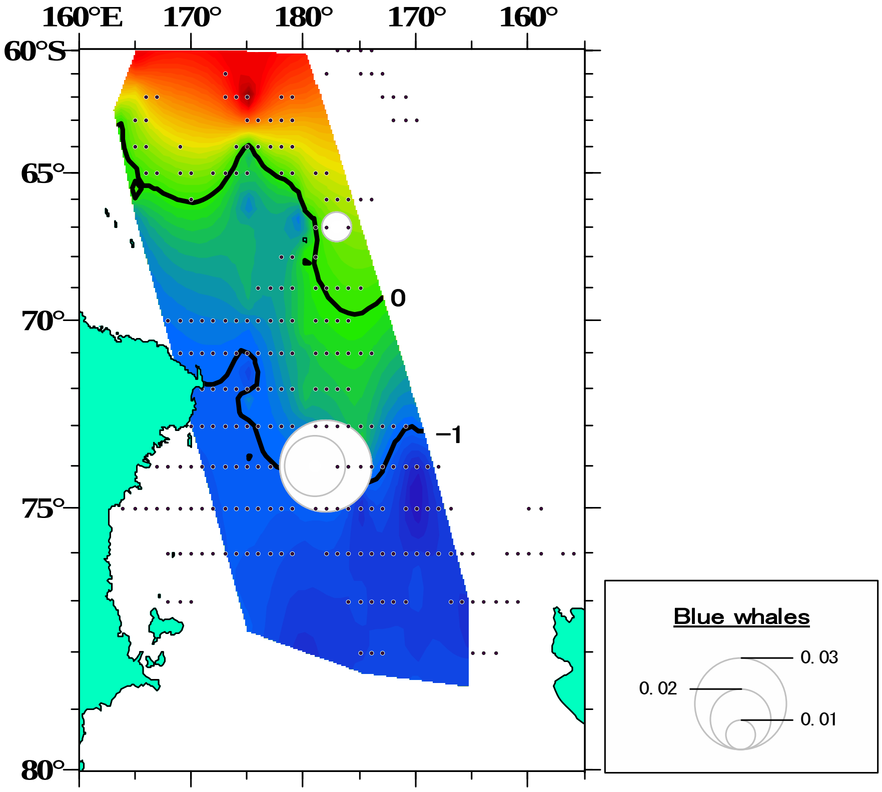

Figure 11f: Distribution of blue whale (*Balaenoptera musculus*) with ITEM-200. Abundance circles are proportional in area to density (number of individuals sighted per 100 n. m individuals iles). A black mark (･) indicates naught.

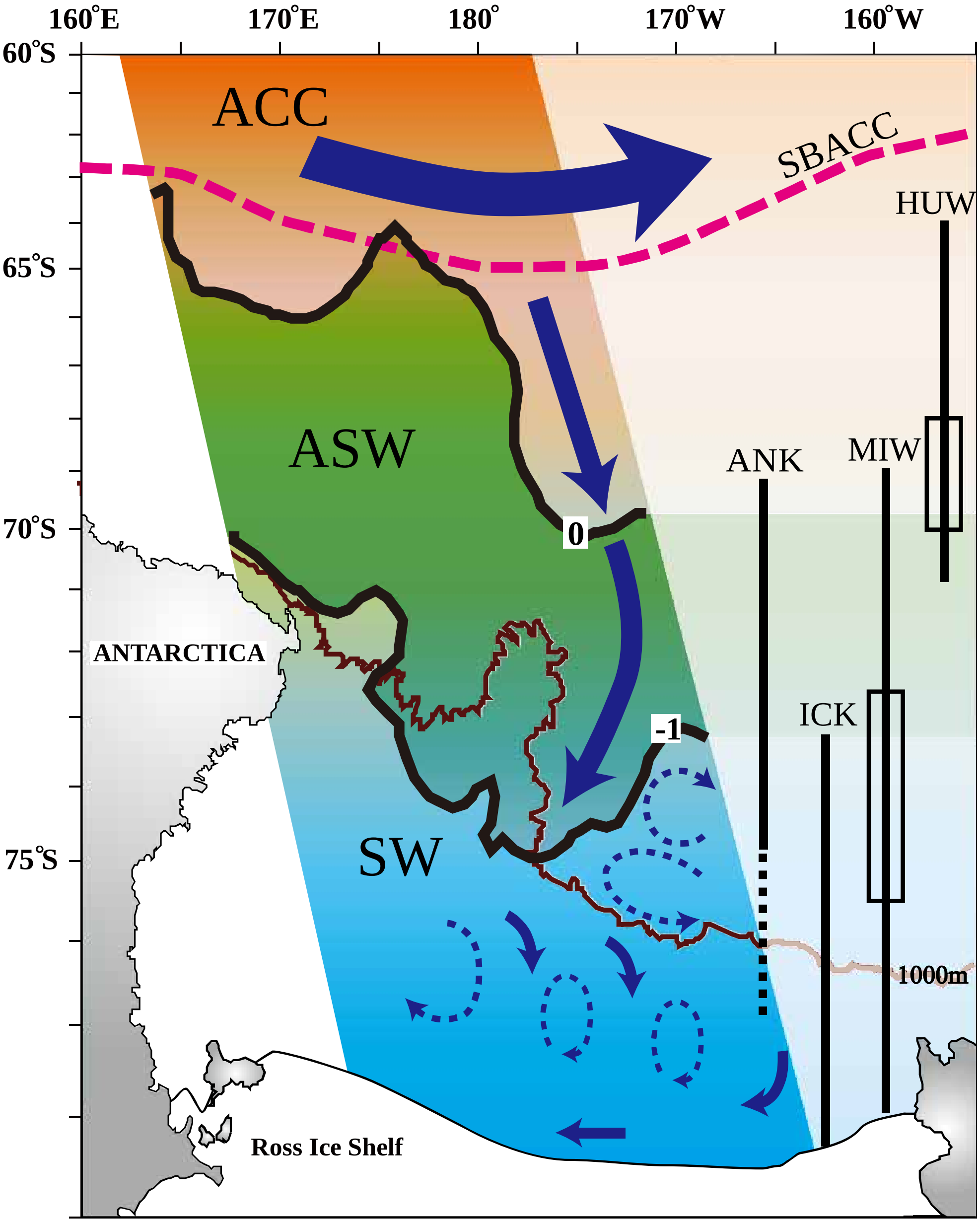

Figure 12: Conceptual model relating water mass and circulation pattern of the oceanic surface layer, the distribution and abundance of krill and baleen whales. Each line in the map indicates the Southern boundary (of Antarctic Circumpolar Current) and ITEM-200 = 0 and -1 (°C). A 1000 m bottom line is shown.

ACC: Antarctic Circumpolar Current. ASW: Antarctic Surface Water. SW: Shelf Water. SBACC: Southern Boundary of ACC (Orsi *et al*., 1995). ANK: Antarctic krill. ICK: Ice krill. MIW: Antarctic Minke Whale. HUW: Humpback Whale.