Distribution patterns and biomasses of Antarctic krill (*Euphausia superba*) and ice krill (*E. crystallorophias*) with referece to Antarctic minke whales in the Ross Sea in 2005 using *Kaiyo Maru*-JARPA joint survey data

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ABSTRACT
Distribution patterns and biomasses of Antarctic and ice krill in the Ross Sea in austral summer in 2005 were studied using a multi-disciplinary survey data set combining cetacean, krill and oceanography data. Two research vessels, KM and KS2, conducted the echo sounder survey independently in same area. Distribution patterns and length frequency information for two species were collected from RMT and stomach contents of Antarctic minke whale. Ice krill distributed on the continental shelf region (shallower than 1000m water depth). In contrast, Antarctic krill distributed mainly in the oceanic waters where water depth is deeper than 1000m though it distributed on the continental shelf where the integrated mean water temperatures between 0-200m was higher than -1°C. Distribution pattern of Antarctic minke whales was related to the distribution patterns of Antarctic krill. School sizes of Antarctic minke whales were large where the densities of Antarctic krill were high. Distribution pattern of Antarctic minke whales in the Ross Sea could be regulated by distribution patterns of Antarctic krill. The Ross Sea was stratified into two strata based on the distribution patterns of two krill species to estimate their biomasses. Biomass densities of Antarctic krill using KM and KS2 data were estimated as 5.36±7.45 and 2.64±2.35 g/m^2, respectively. Biomass densities of ice krill using KM and KS2 data were estimated as 3.44±1.96 and 1.56±0.89 g/m^2, respectively. Because there was no significant difference between the biomass density estimates from both vessels, two data sets were combined to estimate the biomass. The biomasses of Antarctic and ice krill in this study were estimated as 1.46 (CV=0.32) and 0.82 (CV=0.18) million t, respectively. Though KS2 had conducted echo sounder survey without net sampling since 1998, the results of inter-ship comparison of biomass estimates in this study suggested estimates by KS2 in the past were robust in terms of acoustical units. The study suggested that Antarctic minke whales could be considered as a biological sampler to monitor krill which plays key role in the Antarctic ecosystem

INTRODUCTION

It has long been known that two euphausiid species, Antarctic krill (*Euphausia superba*) and ice krill (*E. crystallorophias*) distribute in the Ross Sea and its adjacent area (Marr, 1962). More resent studies suggested that those species showed clear habitat segregation with respect to the bottom topography (Sala et al, 2002; Azzali et al., 2006). Antarctic and ice krill played important role in the Ross Sea ecosystem as preys. It was reported that many notothenioid fishes relied on two euphausiid species as food in the Ross Sea shelf waters (Mesa, 2004). No baleen whales except blue *(Balaenoptera musculus*) and Antarctic minke (*B. bonaerensis*) whales distributed in the Ross Sea (Matsuoka et al., 2005). Encounter rates of Antarctic minke whale in the Ross Sea was high in comparison with other Antarctic waters (Kasamatsu et al, 1998). Though blue whale distributed in the area, the population level is still low (Matsuoka et al., 2005). Antarctic minke whales mainly fed on ice krill in the continental shelf of the Ross Sea while they fed on Antarctic krill in the waters north of the continental shelf (Ichii et al., 1998). It was hypothesized that the presence of Antarctic minke whale near the colonies of Adélie penguin (*Pygoscelis adeliae*) could be the driving force of the prey switching from ice krill to Antarctic silverfish (*Pleuragramma antarcticum*) of Adélie penguin because feeding of Antarctic minke whales could cause local depletion of ice krill (Ainley at al., 2006). Given direct evidence of competition for food between krill predators, concurrent studies of krill and the predators is necessary to understand their relationship in the Ross Sea marine ecosystem. To study the magnitude of interactions among krill predators, biomass estimates of Antarctic and ice krill are critically important. Ichii et al. (1998) pointed out that paradox of high density of Antarctic minke whales in low supply in the Ross Sea and they termed it as "Paradox in the Ross Sea" but the reason is still to be tested. To solve those ecologically important questions, multi-disciplinary study combining surveys on cetacean, krill and oceanography should be conducted.

The Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) has been conducted during the austral summer every year since the 1987/1988 season. One of the primary objectives of the JARPA is "Elucidation of the role of whales in the Antarctic marine ecosystem through the study of whale feeding ecology". The JARPA interim review meeting took place in May, 1997. In the meeting, it was pointed out that concurrent studies on the distribution and abundance of prey species was required to achieve the objective. In addition, it was also pointed out that process oriented studies would be useful which integrated information from physical and biological oceanography with zooplankton and predator studies at meso-scale. In response to those suggestions, a multi-disciplinary study combining surveys on cetacean, krill and oceanography was conducted in the Ross Sea in 2005 involving six research vessels. In this study, two vessels conducted acoustic surveys to estimate the biomasses of Antarctic and ice krill in the Ross Sea. Samples of krill were collected both from net and stomach contents of Antarctic minke whales. This paper presents the results of krill biomass estimation in the Ross Sea in 2005. In this paper, following points were examined: 1) comparability of krill biomass estimates using echo sounders from two independent vessels, 2) utility of krill samples from stomach contents of Antarctic minke whales in the study of krill ecology and 3) paradox in the Ross Sea

MATERIAL AND METHODS

Survey area, period and vessels

The research area of the *Kaiyo Maru*-JARPA joint survey was in the Ross Sea region of the Antarctic. The Ross Sea in this survey was defined as the water south of 69°S and, approximately between 165°E and 155°W. The joint survey was conducted from 14 January to 15 February 2005. Two vessels, *Kyoshin Maru No. 2* (KS2: 368GT) and *Kaiyo Maru* (KM: 2630 GT), conducted acoustic survey to estimate krill biomass. Tracklines of KM was set on four longitudinal lines: 175°E, 180°, 175°W, 170°W and 165°25'W. Zigzag trcaklines was set for KS2 in the survey area. KS2 and KM conducted oceanographic observations. KS2 also conducted cetacean sighting survey while it steams on the tracklines. KM conducted zooplankton sampling using a Rectangular Midwater Trawl with 8m^2 and 1m^2 mouth opening (RMT8+1). Three vessels, *Yushin Maru* (YS1: 720GT), *Yushin Maru No.2* (YS2: 747GT) and *Kyo Maru* No. 1 (K01: 812GT), were engaged in the whale survey consisting of sighting and sampling of whales. Those three vessels were terms as sighting and sampling vessels (SSVs). Stomach contents of sampled Antarctic minke whales were examined on the research base ship, *Nisshin Maru* (NM: 7,659GT).

Oceanographic observations

Oceanographic observations were conducted by KM and KS2 to calculate Integrated TEMperature Mean water depth from surface to 200m (ITEM-200). Initial idea of ITEM-200 was derived from Naganobu and Hirano (1982, 1986). They suggested that an integrated water temperature from 0 to 200m ($\overline{Q}_{200}$ in their term) could be used as an index of distribution patterns of Antarctic krill. The index expresses not only absolute value but also gradient of temperature pattern reflecting seasonal change in surface layer. Recently, ITEM-200 was used as an indicator of macorzooplankton community in the Antarctic (Hosie et al., 2000). ITEM-200 was extrapolated horizontally using kriging methods. KM and KS2 recorded water temperature profiles using Conductivity-Temperature-Depth profiler (CTD, SBE-9-Plus (KM) and SBE-19 (KS2), Seabird, USA) and expendable CTD (XCTD, Tsurumi Seiki Co., Japan). KM conducted oceanographic observations south of 60°S so that overall oceanographic conditions surrounding the Ross Sea could be observed. To see the conditions of sea ice at the time of survey, satellite derived sea ice concentration data, DMSP SSM/I daily polar gridded sea ice concentrations, were used (Comiso, 1990).

Sampling and analysis methods of krill

To acquire distribution patterns and length frequency data of krill, samples from the stomach contents of Antarctic minke whales and the RMT8+1 were used. Depth, temperature and salinity sensors as well as flow meter were equipped with RMT8+1. RMT8+1 was obliquely towed by KM at the routine sampling stations. Sampling depth was from surface to 1000m water depth. Nominal towing speed was 2.0konts. If the bottom depth was shallower than 1000m, sampling depth was from surface to 50m above the bottom. Species identification and weight and length measurement were conducted on KM. Minimum of 100 individuals were examined. If the sampled individuals were less than 100, all individuals were examined. Individual density of Antarctic was caluculated at each sampling station.

Antarctic minke whales were sampled randomly by SSVs and their stomach contents were sampled and preserved in a 10% buffered formalin solution for laboratory analysis on NM. Baleen whales have a four-chambered stomach system but because the forestomach contents only gives information about the last feeding event (e.g. Lindstrøm et al. 1997), contents from only the forestomach were used in this study to avoid including prey species of whales which might have been consumed outside the survey area. Furthermore, only undigested krill in the stomachs was used in this analysis. Species identification and length measurement were conducted at the laboratory. As in KM, minimum of 100 individuals were examined. If the sampled individuals were less than 100, all individuals were examined.

Total length from the tip of the rostrum to tip of the uropod (Standard 1 as described in Mauchiline, 1980) was measured. Length frequency analysis of Antarctic and ice krill was conducted according to Macdonald and Picher (1979) using a package of R Software (R Development Core Team, 2006), mixdist, (available from http://www.math.mcmaster.ca/peter/mix/mix.html). istribution maps were drawn using a GIS, Marine Explorer version 4 (Enviromental Simulation Laboratory Co. Ltd, Japan).

Estimation of krill biomass

EK500 scientific echo sounders (Simrad, Norway) with operation frequencies of 38 and 120 kHz were used by KM and KS2 to collect acoustic data. Data were recorded and stored using either BI500 (KS2: Simrad, Norway) or Echoview (KM: SonarData, Australia). Both ships steamed on tracklines at the nominal speed of 10 knots. Each ship carried out calibration at least once in the survey area. All data were analyzed using Echoview version 3.00. Echo from euphausiid was discriminated from other backscattering by taking the difference between the mean volume backscattering strength (ΔMVBS) of 120 and 38 kHz. ΔMVBS falling between 2 and 16 dB was classified as euphausiid (Hewitt et al., 2004). Because acoustical discrimination between Antarctic and ice krill was difficult, species allocation to acoustic data was based on the samples from RMT8+1 and stomach contents. Mean backscattering area per square nautical mile of sea surface (S_A) by species for every 1 n.mile of survey transect over defined depth interval is calculated by following formula;

$$S_A = 4\pi r_0^2 1852^2 \int_{r_1}^{r_2} s_V dr \left(\frac{m^2}{n.mi^2}\right)$$

where r is depth from the sea surface, r0 = 1m representing the reference range for backscattering strength. Depth interval was set 10 to 250m for KS2. Though the depth interval of KM was set from 15 to 500m, effective S_A values attributed to euphausiid came from upper 250m depth. Krill backscattering cross section area (σ) was calculated with the following formula based on Antarctic krill target strength (TS) described by Greene et al. (1991):

$$\sigma = 4\pi r_o^2 10^{-12.745} l^{3.485}$$

where, *l* was standard length of Antarctic krill. Because no backscattering cross section area was available for ice krill, same formula as Antarctic krill was used. Average area biomass density ($\bar{\rho}$) for each species is calculated as follows;

$$\bar{\rho} = \Sigma \frac{S_A}{\sigma} f_i W_i$$

where f_i is frequency distribution of *i*th length class. Krill wet weight (*w*)-length(*l*) relationship of krill was calculated based on RMT samples. Following procedures were adopted from Jolly and Hampton (1990). Weighted mean of S_A of each block was;

$$\overline{S_{Ak}} = \frac{\sum_{i=1}^{N_k} \overline{S_{Aki}}(n_{ki})}{\sum_{i=1}^{N_k} n_{ki}}$$

where, $\overline{s_{Ak}}$ = mean S_A in *k*th block, N_k = number of transects in *k*th block, $\overline{s_{Aki}}$ = mean S_A on the *i*th transect in *k*th block and n_{k_i} = number of 1 n. mile averaging intervals on the *i*th transect in *k*th block. In this formula, each transect was regarded as a single biomass density sample. Then variance of $\overline{s_{Ak}}$ was calculated with the formula (Jolly and Hampton, 1990);

$$Var(\overline{S_{Ak}}) = \frac{N_k}{N_k - 1} \frac{\sum_{i=1}^{N_k} (\overline{S_{Ak\,i}} - \overline{S_{Ak}})^2 n_{k_i}^{\ 2}}{\left(\sum_{i=1}^{N_k} n_{k_i}\right)^2}$$

$\overline{s_A}$ was converted to $\bar{\rho}$ using above motioned formula. Biomass was estimated as;

$$B_k = A_k \rho_k$$

where, B_k is density biomass in *k* block and A_k is area of *k* block. Variance of B_k was calculated with following formula;

$$\mathrm{var}(B_k) = A_k^{\ 2}\, \mathrm{var}(\overline{\rho_k}) .$$

Coefficient of variation of B_k was calculated as;

$$CV(B_k) = \frac{\sqrt{\mathrm{var}(B_k)}}{B_k} .$$

Overall mean density of euphausiid (Antarctic and ice krill) in the survey area was calculated as;

$$\bar{\rho} = \frac{\sum_{k=1}^{N} A_k \bar{\rho}_k}{\sum_{k=1}^{N} A_k} .$$

Variance of $\bar{\rho}$ was calculated as;

$$Var(\overline{\rho}) = \frac{\sum_{k=1}^{N} A_k^2 Var(\overline{\rho}_k)}{\left(\sum_{k=1}^{N} A_k\right)^2} .$$

Overall biomass was calculated as;

$$B = \sum_{k=1}^{N} A_k \overline{\rho}_k$$

Variance of *B* was;

$$Var(\overline{\rho}) = \sum_{k=1}^{N} A_k^2 Var(\overline{\rho}_k) .$$

CV of *B* was;

$$CV_{B.} = \frac{\sqrt{Var(B)}}{B} .$$

Sighting survey of cetaceans

KS2 was engaged in the sighting of the minke whales as well as other large baleen whales over the entire area. Principally the KS2 conducted the survey 8 hours per day by passing mode and 4 hours per day by limited closing mode. The sighting survey was conduced during diurnal hours.

RESULTS

Oceanographic observations

CTD casts were conducted at 15 and 34 stations (total=49 stations) by KS2 and KM, respectively. XCTD casts were conducted at 21 and 71 stations (total=92 stations) by KS2 and KM, respectively. A map of ITEM-200 was shown in Fig. 1. Sharp north-south gradient of ITEM-200 was observed. In the Ross Sea, ITEM-200 was lower in eastern part than it in western part.

Distribution patterns and length frequencies of Antarctic and ice krill

RMT sampling was conducted at 14 stations. Krill samples in stomach contents of Antarctic minke whales were collected at 27 locations. Sampling of stomach contents had wider geographical coverage than RMT. The samples from RMT8+1 and stomach contents of Antarctic minke whales indicated that Antarctic and ice krill showed different distribution patterns in the Ross Sea (waters south of 69°S) with respect to the bottom topography (Fig. 2 and 3). Ice krill distributed on the continental shelf region (shallower than 1000m water depth). In contrast, Antarctic krill distributed in the oceanic waters where water depth is deeper than 1000m though it distributed on the continental shelf where ITEM-200 was higher than -1°C. Based on their distribution patterns, the survey area was divided into two strata for the acoustical biomass estimation for two species.

Because length frequency pattern at each RMT and stomach content sampling point was highly heterogeneous, all sampled krill individuals were pooled to construct representative length frequency for each euphausiid species in the survey area. Age group compositions of Antarctic and ice krill were summarized in Table 1. Length frequency histograms of Antarctic and ice krill were shown in Fig. 3 and 4, respectively. Antarctic krill consisted of 2 age groups in both RMT and stomach content samples although proportion of older animals (4+) was high in stomach content. Ice krill consisted of 3 age groups though proportion of older animals (3+) was high in the stomach content samples. Length(l)-weight(w) relationships of Antarctic and ice krill were estimated as w=0.0153l+0.0261 and w=0.0018l+0.0448, respectively. Mean length of Antarctic and ice krill using stomach content samples were 45.0±3.8(SD) (N=1526 individuals from 17 stomachs) and 22.7±6.0(SD) mm (N=1100 individuals from 11 stomachs), respectively. Corresponding wet weights of Antarctic and ice krill were estimated as 0.175 and 0.086 g, respectively.

Estimated biomass of Antarctic and ice krill

Distribution patterns of Antarctic and ice krill using acoustic data collected by KM and KS2 were shown in Fig. 6. Distribution patterns were similar for both vessels. High density of Antarctic krill was observed in the northwestern part of the survey area. Ice krill tended to distribute near the ice shelf. Mean TS of Antarctic and ice krill were -69.7 dB and -79.0 dB, respectively. Biomasses were estimated using those TS values. Results of biomass estimation were summarized in Table 2. Biomass densities of Antarctic krill with 95% CI using KM and KS2 data were 5.36±7.45 and 2.64±2.35 g/m^2, respectively. Biomass densities of ice krill with 95% CI using KM and KS2 data were 3.44±1.96 and 1.56±0.89 g/m^2, respectively. Because there was no significant difference between the biomass density estimates from both vessels, two data sets were combined to estimate the biomass. The biomasses of Antarctic and ice krill in this study were estimated as 1.46 (CV=0.32) and 0.82 (CV=0.18) million t, respectively. Total biomass of euphausiid in the survey area was estimated as 2.28 million t (CV=0.22).

Distribution patterns of Antarctic mink whales

Total cetacean searching effort of KS2 was 1995 n.miles. Numbers of sightings of Antarctic minke whales were 601 individuals in 300 schools. Other baleen whales, Blue and humpback (*Megaptera novaeangliae*) were sighted in the survey area but numbers were small (2 individuals in 1 school for each species). Distribution pattern of Antarctic minke whales was shown in Fig. 7. Distribution pattern of Antarctic krill and Antarctic minke whales were overlapped. School sizes of Antarctic minke whales were large where the densities of Antarctic krill were high.

DISCUSSION

As previous surveys (e.g. Azzali et al., 2006) suggested, the samples from RMT and stomach contents of Antarctic minke whales indicated that two euphausiid species, Antarctic and ice krill showed different distribution patterns in the Ross Sea (waters south of 69°S) with respect to the bottom topography. In this study, distribution area of Antarctic and ice krill was separated by the combination line of 1000 m bottom depth counter and -1°C isotherm line of ITEM-200 though some overlap was found around the line. Haul catches of Antarctic krill was almost coincident with the intrusion of surface waters coming from the open ocean onto the self area in the west of 175°W until 73-74°S (Sala et al., 2002). Their observation was confirmed in our study but our results showed that oceanographic condition could not be a controlling factor of distribution of Antarctic krill. Stomach contents of Antarctic minke whales in the east of 175°W suggested that Antarctic krill distributed in low ITEM-200 where the bottom depth was deeper than 1000m. Ichii et al. (1998) also found that Antarctic krill distributed near the continental slope in the east of 175°W. Those findings suggested that distribution patterns of Antarctic krill could be regulated by the combination of oceanographic conditions and bottom topography.

Azzali et al. (2006) postulated that the distribution pattern of Antarctic and ice krill shifted to north as the ice edge moved to northward in austral summer but the magnitude of movement was more significant for Antarctic krill. As the results, density of Antarctic krill in January 2000 was low by comparison with November in 1994 and December in 1994 and 1997 though one need caution of the interpretation because of methodological differences among those surveys (Azzali et al., 2006). Our survey in the Ross Sea were mainly conducted in January. It seemed that there was general agreement between our results and the hypothesis proposed by Azzali *et al.* (2006). Densities of Antarctic and ice krill were similar to the value in January in Azzali *et al.* (2006) while biomass estimates were in the comparative range regardless of month (Table 3). Even if densities were low in January, surveyed area in January was generally large as the result of sea ice retreat. Dispersal response of euphausiid distribution to seasonal sea ice retreat in the Ross Sea should be studied further in the future cruises.

There is no reported values of TS for ice krill at the presentation of this paper. Because TS of Antarctic krill was applied to ice krill in this analysis, interpretation of biomass estimate of ice krill need caution. Measurement of TS of ice krill should be conducted in the near future. It should be noted that Demer and Conti (2005) proposed the new TS for Antarctic krill using Stochastic Distorted-Wave Born-Approximation (SDWBA) model. If the new TS applied to our results, krill biomass would be 2.5 times higher than the current estimates.

The results of comparison of biomass between KM and KS2 suggested that data from two vessels were comparable. KS2 had conducted echo sounder survey as a part of JARPA without net sampling since 1998. The results of inter-ship comparison of biomass estimates in this study suggested estimates by KS2 in the past were robust in terms of acoustical units.

Differences of proportions of age groups of Antarctic and ice krill were observed between samples from RMT and stomach contents of Antarctic minke whales though estimated mean length of each age group was almost same. The proportions of age groups of RMT8+1 samples were similar to the reported values of Antarctic and ice krill in the Ross Sea (Table 1, Sala et al., 2002). Antarctic minke whales fed on larger krill than those in the net hauls. Antarctic minke whales are agile engulfing feeder. Though there was no measurement for Antarctic minke whales, it was reported that the average of foraging lunge speed of blue whales was 2.4m/s (≈4.7konts) (Croll et al, 2001). The speed of foraging lunge of Antarctic minke whales would exceed the speed of towing speed of RMT8+1 (2knots). While the course of the vessel could not change during towing of RMT8+1, Antarctic minke whales could change their swimming direction in response to the behavior of krill. It was known that direct sampling of euphausiid using net has problems such as net avoidance to construct length frequency data (Watkins, 2000 for review). Considering those points, length frequency of krill using the stomach contents Antarctic minke whales could be more reliable than using the RMT8+1 samples. However, it was reported that smaller size classes were represented in the diet of fur seals because of either active or passive (lack of availability) prey selection (Murphy and Reid, 2001). Our results might indicate that Antarctic minke whales show prey selectivity toward large size euphausiid. Because this was the firsrt attempt to compare the length frequency of euphausiid between samples from RMT8+1 and stomach contents of Antarctic minke whales, further concurrent study of baleen whales and euphausiid should be conducted to conclude whether Antarctic minke whales have prey selectivity or not. Because JARPA has long term stomach contents data series, euphausiid population dynamics could be construct if the appropriate selectivity is estimated (Reid et al., 2004). This study suggested that Antarctic minke whales could be used as biosampler to study the Antarctic marine ecosystem.

Present study suggested that distribution of Antarctic minke whales in the Ross Sea could be regulated not by ice krill but by Antarctic krill. Because “Paradox in the Ross Sea” was hypothesized thoroughly based on information from stomach contents of Antarctic minke whales (Ichii et al, 1998), this hypothesis should be reevaluated using both concurrent cetacean and eupusaiid survey data. Distributional relationship of euphausiid and Antarctic minke whales should be examined quantitatively using statistalcal model such as applied to the Western Antarctic Peninsula Region (Friendlaender et al., 2006).

Overall, a multi-disciplinary study combining surveys on cetacean, krill and oceanography gives new insight for the study of the Ross Sea ecosystem. Continuation of this kind of study is essential of management and conservation of the Antarctic marine living resources.

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REFERENCES

Ainley, D. G., Ballard, G., and Dugger, K. M., 2006. Competition among penguins and cetaceans reveals trophic cascades in the western Ross Sea, Antarctica. Ecology 87:2080-2093.

Azzali, M., Leonori, I., De Felice, A. and Russo, A. 2006. Spatial-temporal relationships between two euphausiid species in the Ross Sea. Chem. Ecol. (Suppl) 22:219-233.

Croll, D A., Acevedo-Gutiérrez, A., Tershy, B R. and Urbán-Ramirez, J. 2001. The diving behaviour of blue and fin whales:is dive duration shorter than expected based on oxygen stores? *Comp. Biochem. Physiol.* A 129:797-809.

Comiso, J. 1990, updated current year. DMSP SSM/I daily polar gridded sea ice concentrations, June to September 2001. Edited by J. Maslanik and J. Stroeve. Boulder, CO: National Snow and Ice Data Center. Digital media.

Demer, D. A. and Conti, S. G. 2005. New target-strength model indicates more krill in the Southern Ocean. ICES J. Mar. Sci. 62:25-32.

Friedlaender, A. S., Halphin, P. N., Qian, S. S., Lawson, G. L., Wiebe. P. H., Thiele, D. and Read, A. J. 2006. Whale distribution in relation to prey abundance and oceanographic processes in shelf waters of the Western Antarctic Peninsula. Mar. Ecol. Prog. Ser. 317:297-310.

Greene, C. H., Stanton, T. K., Wiebe, P. H. and McClatchie, S. 1991. Acoustic estimates of Antarctic krill. Nature 349: 110.

Ichii, T., Sinohara, N., Fujise, Y., Nishiwaki, S. and Matsuoka, K. 1998. Interannual changes in body fat condition index of minke whales in the Antarctic. Mar. Ecol. Prog. Ser. 175: 1-12.

Hewitt, R. P., Watkins, J., Naganobu, M., Sushin, V., Brierley, A. S., Demer, D., Kasatkina, S., Takao, Y., Goss, C., Malyshko, A., Brandon, M., Kawaguchi, S., Siegel, V., Trathan, P., Emery, J., Everson, I., Miller, D. 2004. Biomass of Antarctic krill in the Scotia Sea in January/February 2000 and its use in revising an estimate of precautionary yield. Deep Sea Res. II 51:1215-1236.

Hosie, G. W., Schultz, M. B. Kitchener, J. A., Cochran, T. G. and Richards. 2000. Macrozooplankton community structure off East Antarctica (80-150°E) during the Austral summer of 1995/1996. Deep Sea Res. II 47:2437-2463.

Jolly, G. M. and Hampton, I. 1990. A stratified random transect design for acoustic surveys of fish stock. Can. J. Fish. Aquat. Sci. 47: 1282-1291.

Kasamatsu, F., Ensor, P. and Joyce, G. G.. 1998. Clustering and aggregation of minke whales in the Antarctic feeding grounds. Mar. Ecol. Prog. Ser. 168:1-11.

Lindstrøm, U., Haug, T. and Nilssen, K. T. (1997) Diet studies based on contents from two separate stomach compartments of Northesat Atlantic minke whales *Balaenoptera acutorostrata*. Sarsia 82: 63-68.

Macdonald, M. D. P., and Pitcher, J. T., 1979. Age-Groups from Size-Frequency Data: A Versatile and Efficient Method of Analyzing Distribution Mixtures. J. Fish.Res.Board Can 36:987-1001.

Mauchline, J. 1980. Measurement of body length of *Euphausia superba* Dana. BIOMASS Handbook No. 4. 9pp.

Mesa, M. La., Eastman, J. T. and Vacchi, M. 2004. The role of notothenoid fish in the food web of the Ross Sea shelf waters: a review. Polar Biol. 27: 321-328.

Matsuoka, K., Hakamada, T., Kiwada, H., Murase, H. and Nishiwaki, S. 2005. Abundance increases of large baleen whales in the Antarctic based on the sighting survey during Japanese whale research program (JARPA). Global Env. Res. 9:105-115.

Marr, J. W. S. 1962. The natural history and geography of the Antarctic krill (*Euphausia superba* Dana). Discovery Rep. 32:33-464.

Murphy, E. J. and Reid, K. 2001. Modeling Southern Ocean krill population dynamics: biological processes generating fluctuations in the South Georgia ecosystem. Mar. Ecol. Prog. ser. 217:175-189.

Naganobu, M., and T. Hirano. 1982. Geographical distribution of the Antarctic krill, *Euphausia superba* DANA, and its environmental structure (extended abstract). Mem. Natl. Inst. Polar Res. Spec. Issue. 1982. 23:1–4.

Naganobu, M. and Hirano, T. 1986. Environmental factors for geographical distribution of *Euphausia superba* Dana. Natl. Inst. Polar Res. Spec. Issue. 40:191-193.

R Development Core Team 2006. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Reid, K., Jessopp, M. J., Barrett, M. S., Kawaguchi, S., Siegel, V. and Goebel, M. E. 2004. Widening the net: spatio-temporal variability in the krill population structure across the Scotia Sea. Deep Sea Res. II. 51:1275-1287.

Sala, A., Azzali, M., and Russo, A.,2002. Krill of the Ross Sea: distribution, abundance and demography of *Euphausia superba* and *Euphausia crystallorophias* during the Italian Antarctic Expedition (January-February 2000). Scientia Marina 66:123-133.

Watkins, J. L. 2000. Smapling krill. In: Everson, I. (ed.), Krill, Biology, Ecology and Fisheries, Fish and Aquatic resources, Series 6. Blackwell Science, Oxford University Press, Oxford, pp.8-39.

Table 1. Mean length, standard deviation (SD) of mean length and proportions of Antarctic and ice krill in the Stomach contents of Antarctic whales and RMT samples. Results in the Ross Sea in 2000 (Sala et al., 2002) was also shown for comparison purpose.

Speciese	Age Group	Stomach Contents			RMT			Sala *et al.* (2002)		
		Length (mm)	SD	%	Length (mm)	SD	%	Length (mm)	SD	%
Antarctic krill	2+	-	-	-	-	-	-	37.4	2.5	6
	3+	40.9	2.9	34	43.2	2.6	74	42.8	2.4	52
	4+	46.4	3.2	66	47.4	1.8	26	47.2	2.6	42
Ice krill	1+	12.1	1.3	18	12.3	1.4	48	13.5	1.9	36
	2+	21.0	2.0	28	21.9	1.8	17	21.5	1.9	32
	3+	26.4	3.3	54	25.8	4.3	35	25.5	3.4	32

Table 2. Density and biomass of Antarctic and ice krill using quantitative echo sounder in the Ross Sea in 2005.

	Antarctic krill			Ice krill			
	KM	KS2	Total	KM	KS2	Total	Gross Total
Weighted mean ρ (g/m^2)	5.4	2.6	3.9	3.4	1.6	2.2	3.1
Surveyed area ($n.mile^2$)		110792			106800		217592
Biomass (million t)	2.04	1.00	1.46	1.26	0.57	0.82	2.28
CV (million t)	0.44	0.36	0.32	0.21	0.26	0.18	0.22

Table 3. Summary of biomasses of Antarctic and ice krill in the Ross Sea from 1994 to 2005.

Year	Month	Antarctic krill Density (g /m^2)	Antarctic krill Biomass (million t)	Ice krill Density (g /m^2)	Ice krill Biomass (million t)	Survey area (nm^2)	Areal coverage	Reference
1994	Nov	21.9	2.38	1.8	0.02	31800	69-30S - 78-06S 164-30E - 175-30W	Azzali et al . (2006)
1994	Dec	21.4	2.78	1.6	0.02	37800		
1997	Dec	16.3	2.21	1.4	0.02	39600		
2000	Jan	11.0	1.23	0.7	0.01	60600		
2005	Jan	3.9	1.46*	2.2	0.82**	110792* 106800**	69-00S - 78-40S 163-50E - 154-00W	This sutdy

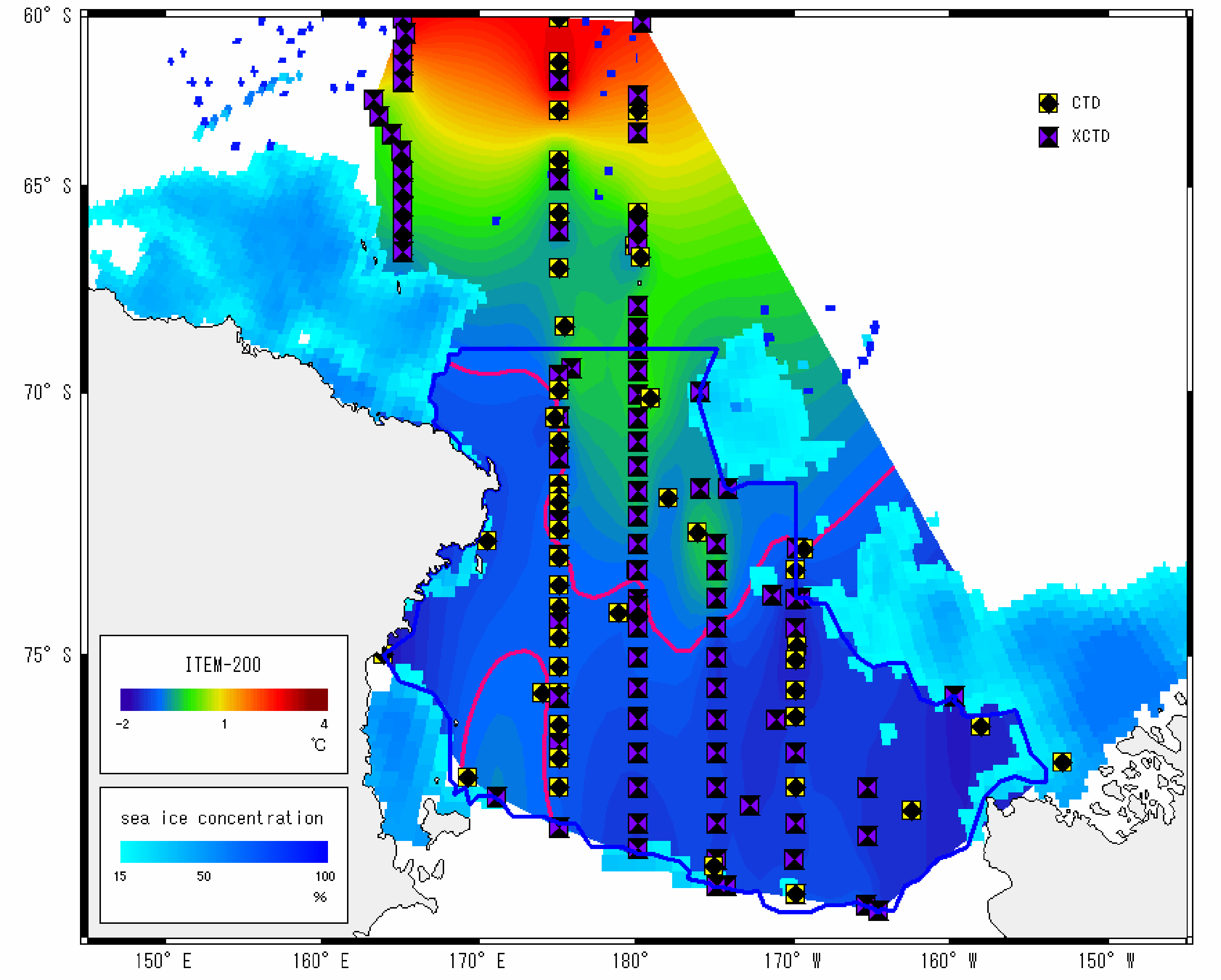
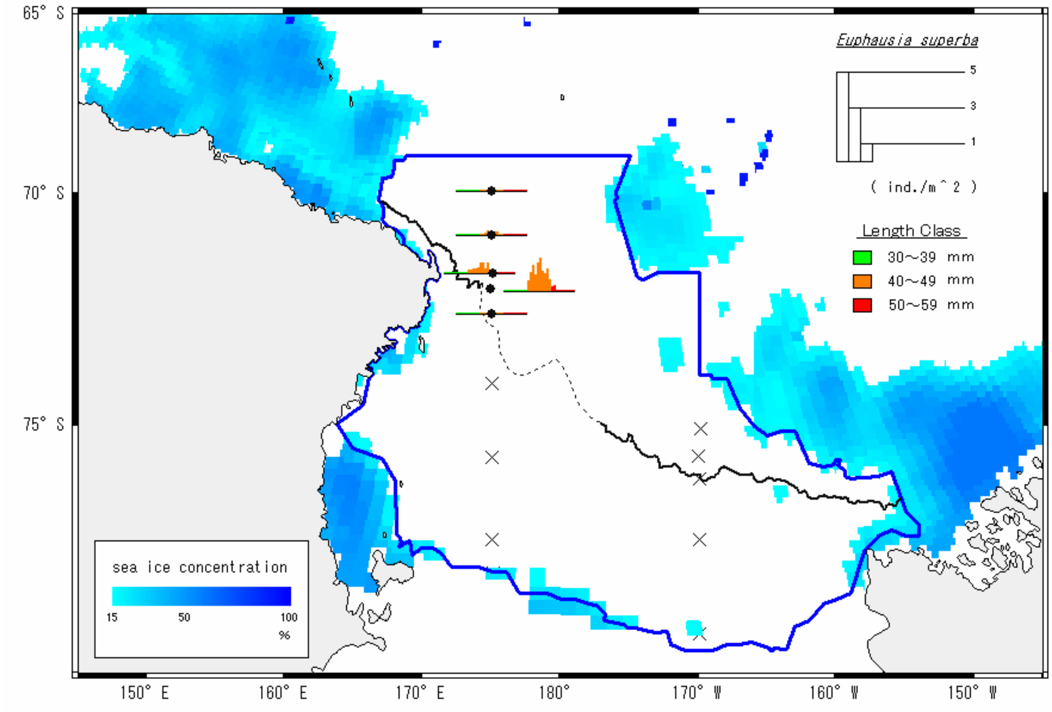
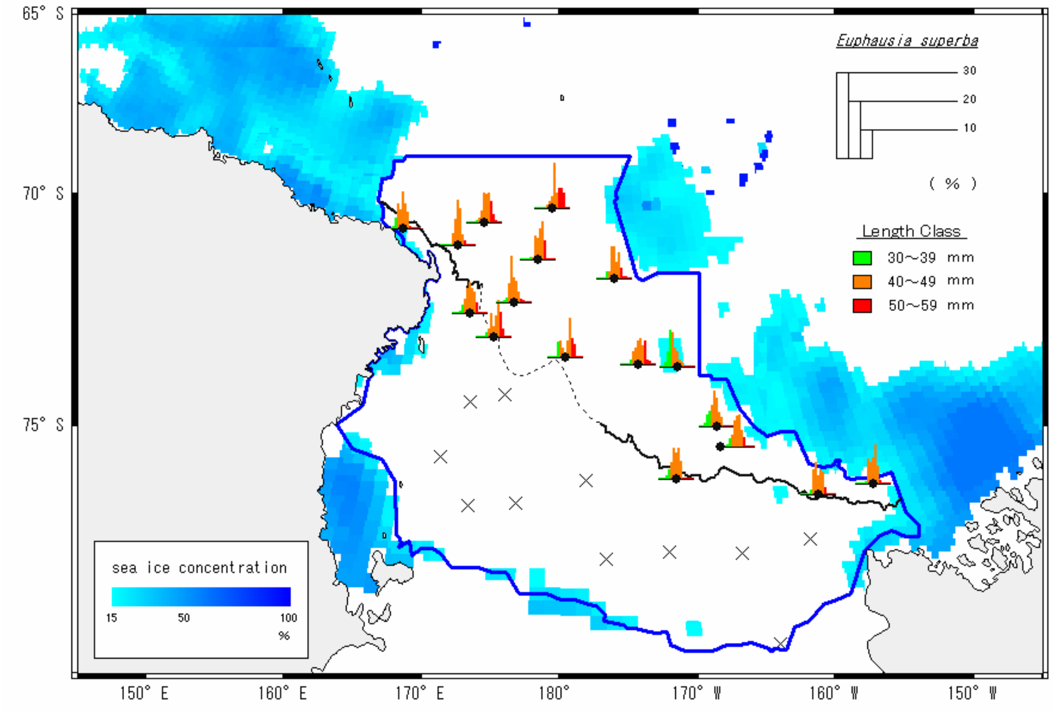


Fig.1. Map of Integrated TEMperature Mean water depth from surface to 200m (ITEM-200) based on CTD and XCTD casts in the Ross Sea and adjacent region. CTD and XCTD stations used in the analysis were shown. Pink thick line (—) represented -1°C isothermal line of ITEM-200. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the map.

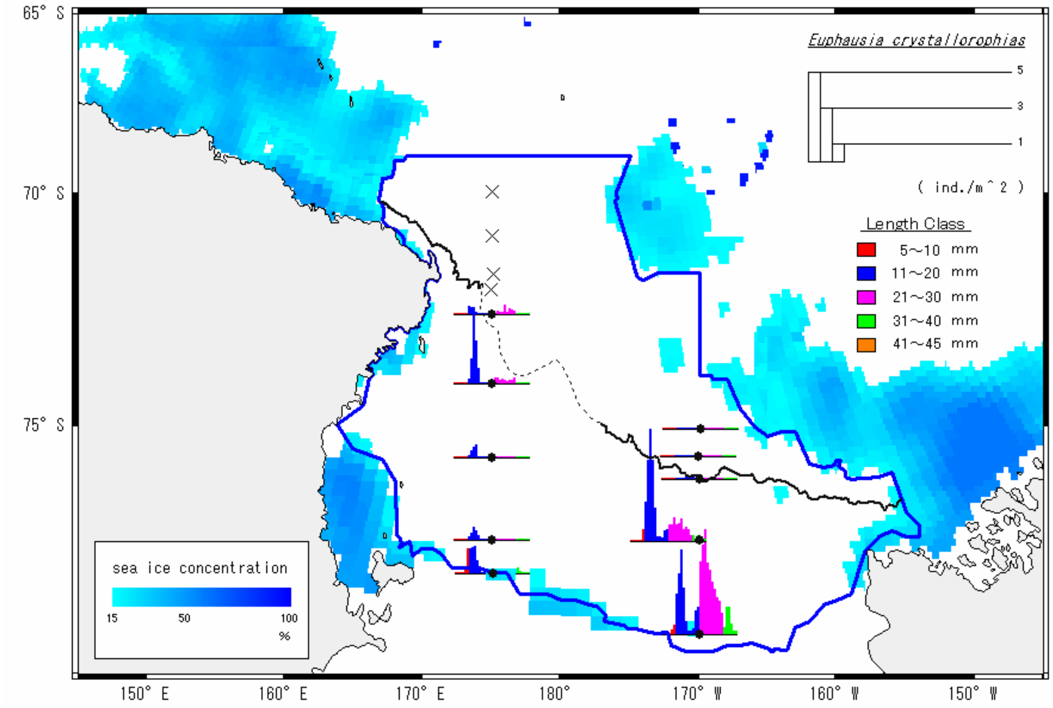


(a)

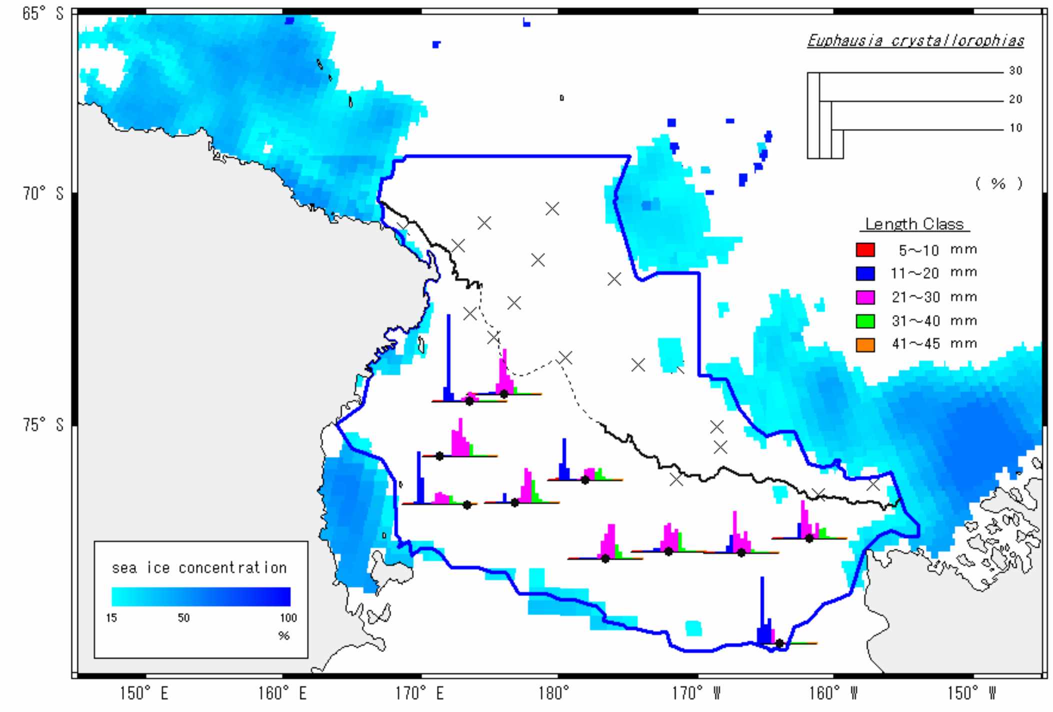


(b)

Fig.2. Distribution patterns and length frequencies of Antarctic krill: (a) sampled by RMT8+1 and (b) samples from stomach contents of Antarctic minke whales. Notes that units of histograms were diffrencent (ind/m^2 for RMT8+1 and % for stomach contents). "X" denoted sampling locations without Antarctic krill. Thick blue line (▬) represented survey area boundary. Thick black solid line (▬) and dotted line (- -) represented bottom depth contour lines at 1000 m and -1°C isothermal line of ITEM-200, respectively. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the map.

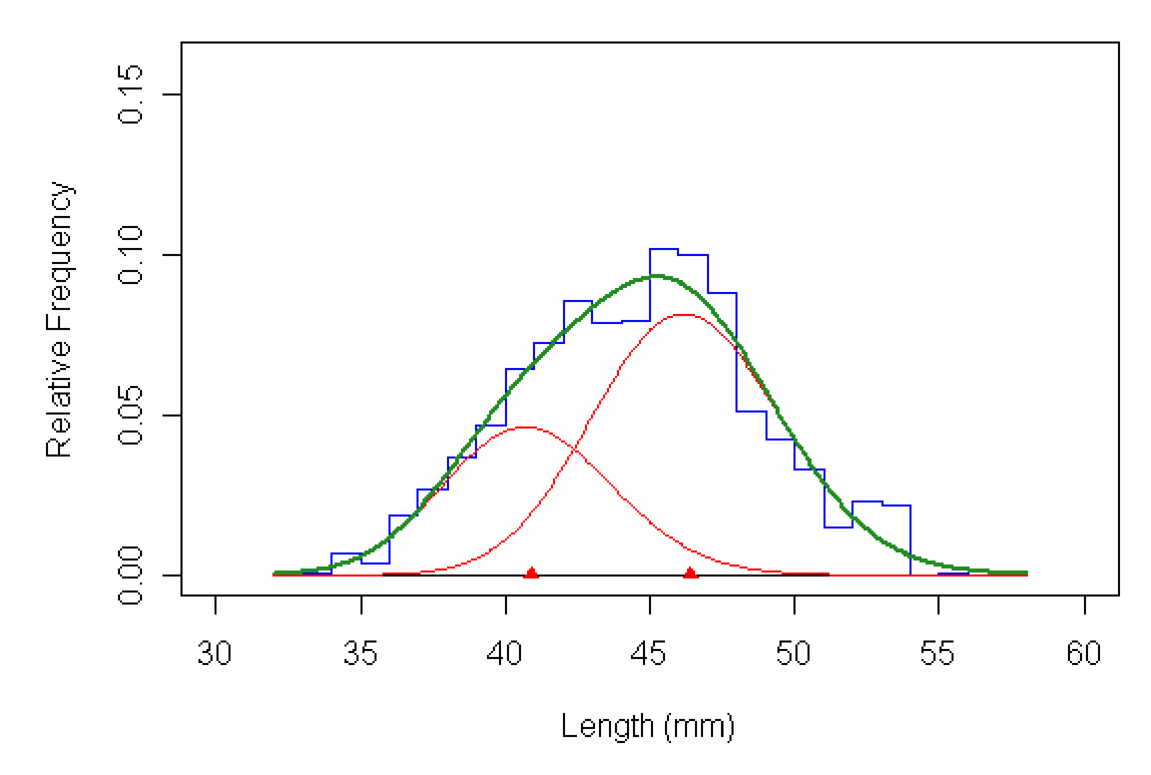


(a)

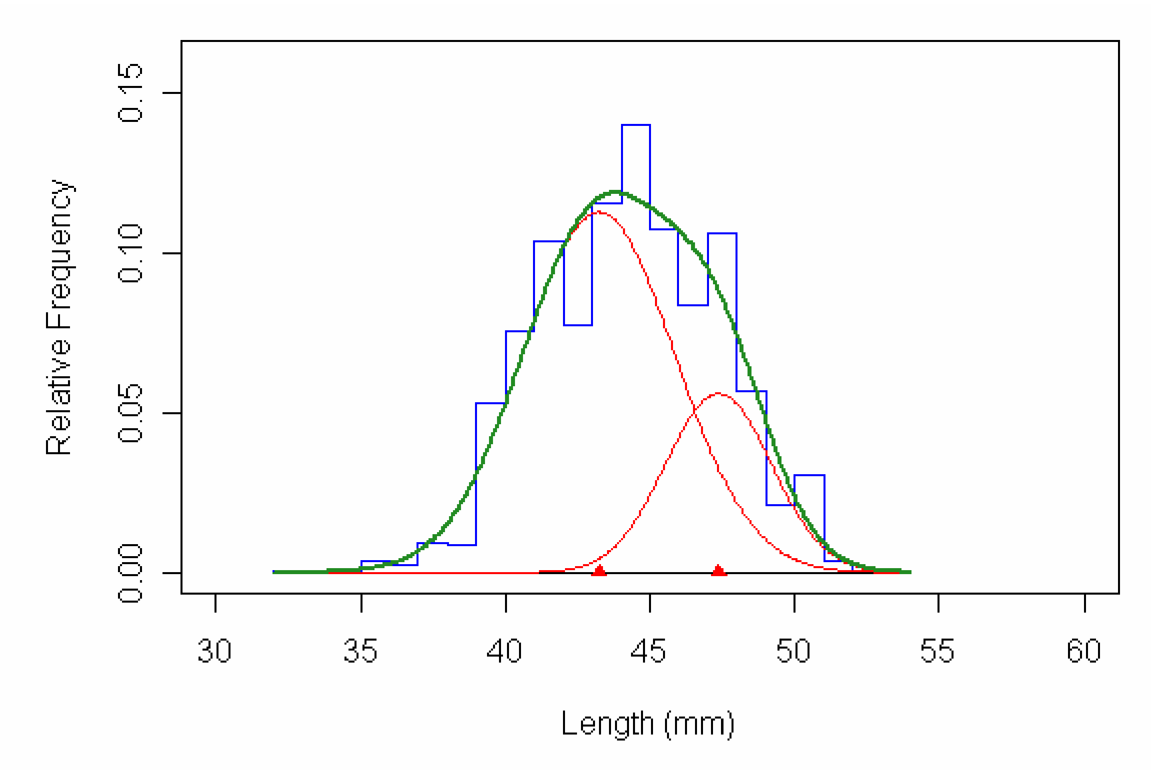


(b)

Fig.3. Distribution patterns and length frequencies of ice krill: (a) sampled by RMT8+1 and (b) samples from stomach contents of Antarctic minke whales. Notes that units of histograms were diffrencent (ind/m^2 for RMT8+1 and % for stomach contents). "X" denoted sampling locations without ice krill. Thick blue line (—) represented survey area boundary. Thick black solid line (—) and dotted line (- -) represented bottom depth contour lines at 1000 m and -1°C isothermal line of ITEM-200, respectively. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the map.

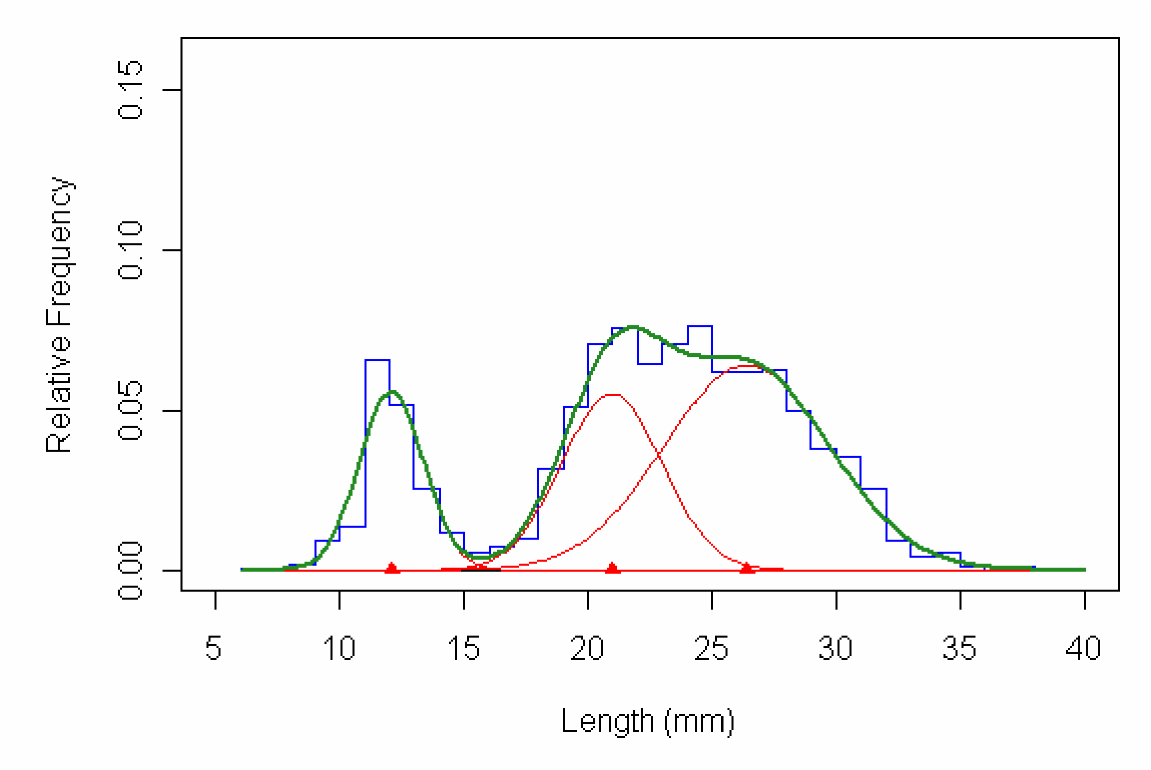


(a)

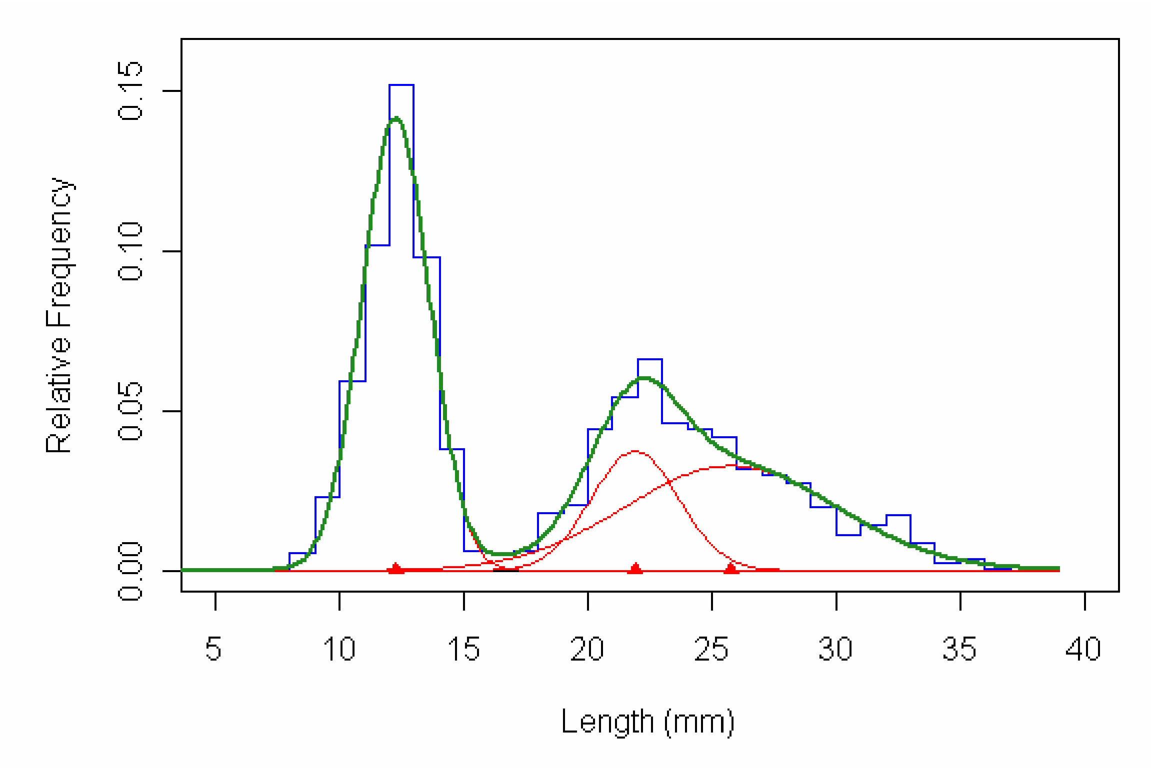


(b)

Fig.4. Length frequencies of Antarctic krill using stomach contents of Antarctic minke whales (a) and RMT8+1 samples. Green line represented overall fitting curve while red lines represented fitting curve of each age group. Red triangle represented mean length of each age group.

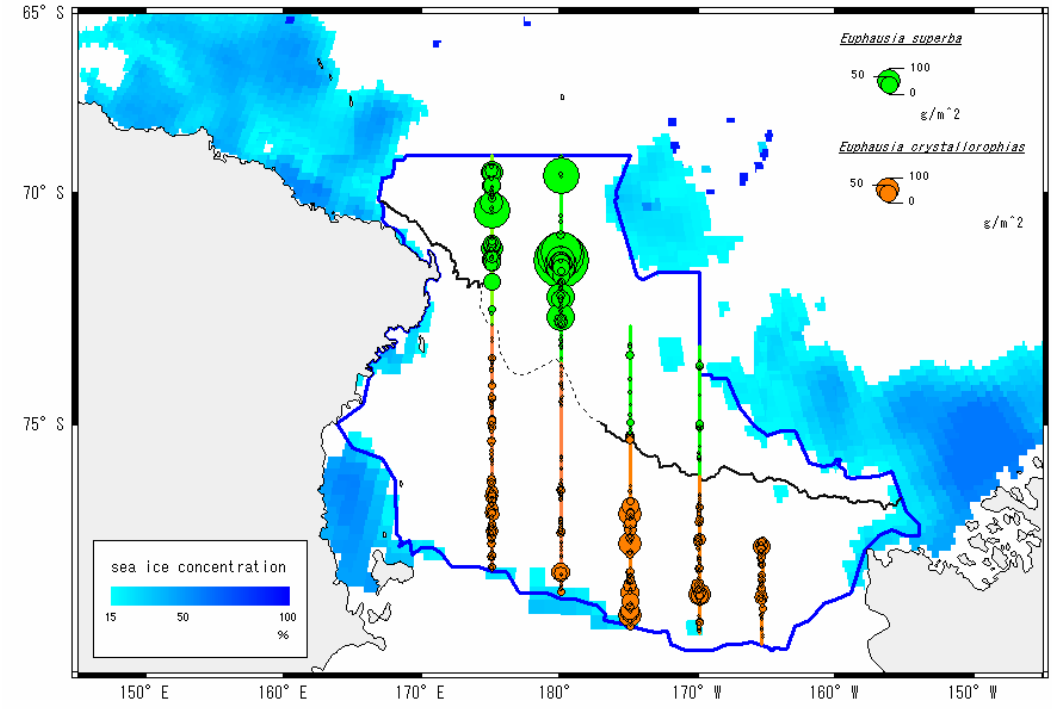


(a)

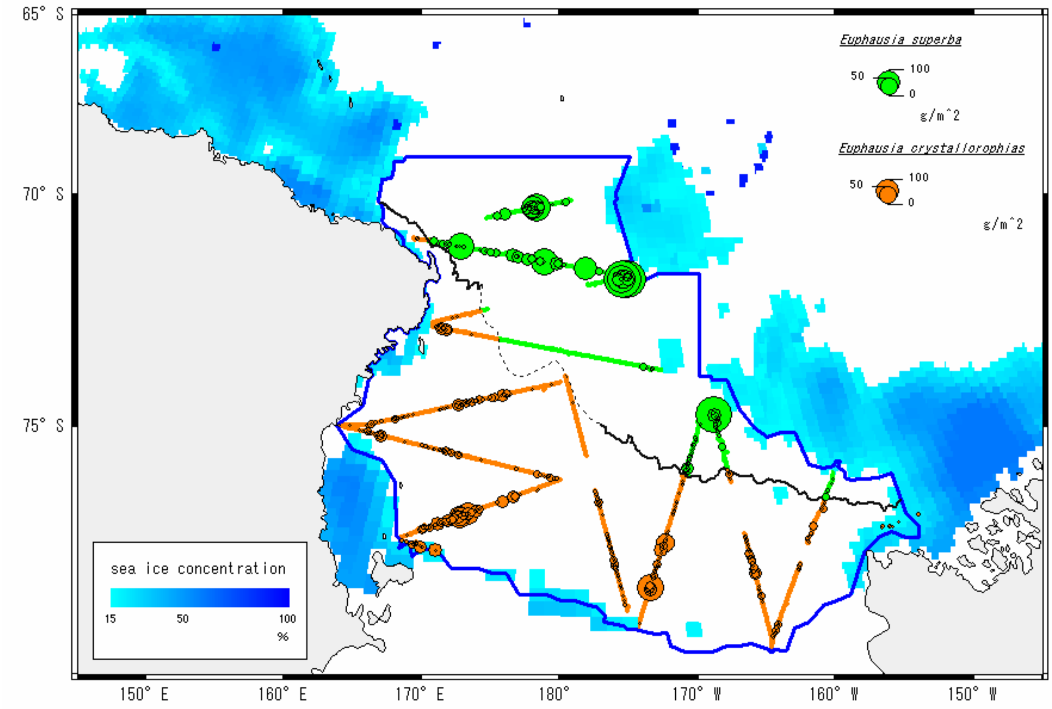


(b)

Fig.5. Length frequencies of ice krill using stomach contents of Antarctic minke whales (a) and RMT8+1 (b) samples. Green line represented overall fitting curve while red lines represented fitting curve of each age group. Red triangle represented mean length of each age group.



(a)



(b)

Fig. 6. Distribution patterns of Antarctic and ice krill based on quantitative echo sounder data: (a) *Kaiyo Maru* and (b) *Kyoshin Maru No.2*. Thick blue line (▬) represented survey area boundary. Thick black solid line (▬) and dotted line (- -) represented bottom depth contour lines at 1000 m and -1^{o}C isothermal line of ITEM-200, respectively. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the map.

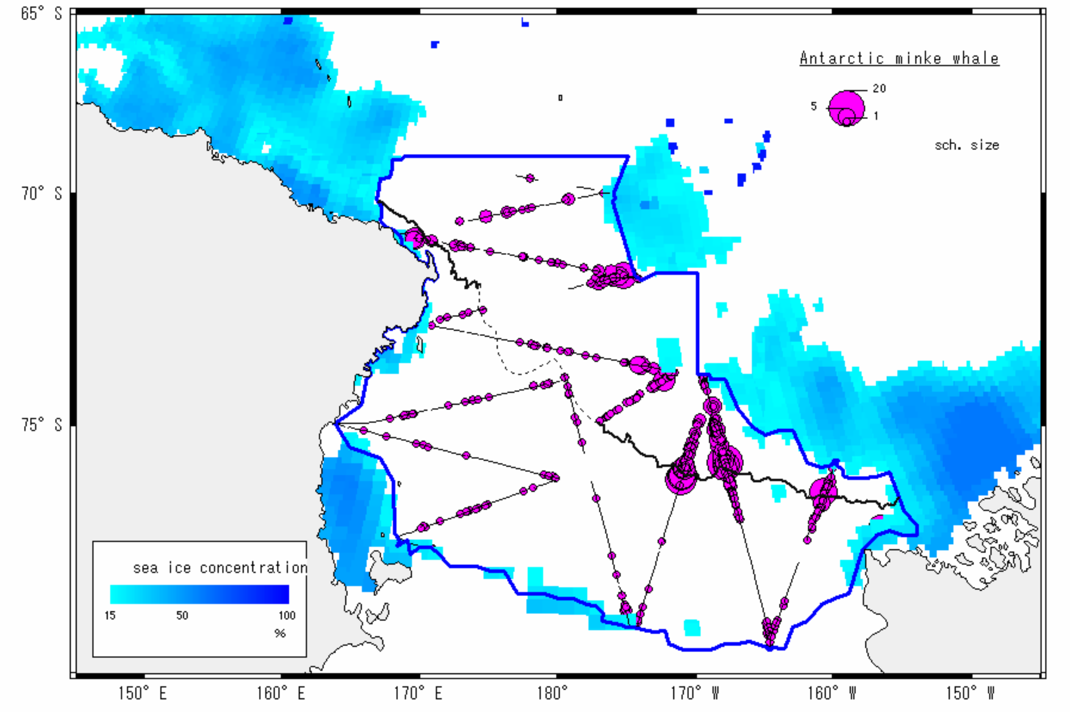


Fig. 7. Primary sighting positions and school sizes of Antarctic minke whales. Thin black line (-) represented sighting survey tracklines. Thick blue line (**—**) represented survey area boundary. Thick black solid line (**—**) and dotted line (- -) represented bottom depth contour lines at 1000 m and -1°C isothermal line of ITEM-200, respectively. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the map.