Structure of the marine ecosystem of the Ross Sea, Antarctica —overview and synthesis of the results of a Japanese multidisciplinary study by *Kaiyo-Maru* and JARPA—

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A multidisciplinary marine ecosystem study in the Ross Sea region of the Antarctic was conducted in austral summer in 2004/05 as a Japanese national program. A fisheries research vessel, *Kaiyo-Maru*, and JARPA (the Japanese Whale Research Program under Special Permit in the Antarctic) vessels were engaged in the study. The main focus of the study was to elucidate the ecological interactions among biological organisms, especially between krill and whales. The surveys consisted of (1) oceanographic observations, (2) net sampling of planktons and fishes, (3) hydroacoustic surveys of krill (4) sighting surveys of top predators (birds and cetaceans) and (5) sampling of Antarctic minke whales. To understand the distribution pattern of various biological organisms in relation to oceanographic conditions, a simple oceanographic index, Mean TEMperature from the surface to 200 m (MTEM-200) was introduced. Species compositions changed against the north-south gradient of MTEM-200. For instance, Antarctic krill were mainly distributed in waters between 0 and −1ºC while ice krill were distributed in waters colder than −1ºC. Humpback whales were mainly distributed in the waters warmer than 0ºC. Antarctic minke whales were mainly distributed in waters around −1ºC in a continental shelf slope frontal zone. Comparison of stomach contents of minke whales and net samples as well as results of spatial modeling suggested that oceanographic conditions played an important role in defining predator-prey relationships. The data collected through this multidisciplinary study provides vital information to understand the structure of the marine ecosystem in the Ross Sea where data are still sparse.

Key words: B*alaenoptera bonaerensis*, *Euphausia superba*, *Euphausia crystallorophias*, food web, environment-prey-predator relationship

Introduction

The large embayment with a vast area of continental shelf makes the Ross Sea marine ecosystem unique among the Antarctic waters. The ecosystem on the continental shelf is relatively known (Smith et al., 2007 for review). However, there is little information on the waters adjacent to the continental shelf. Because the continental shelf and the adjacent waters are generally connected through ocean circulation (Kwok, 2005), it is ideal to conduct a multidisciplinary survey in these areas simultaneously to understand the structure of the whole ecosystem of the Ross Sea. The R/V *Kaiyo Maru* and the Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) research vessels were used to conduct a multidisciplinary ecosystem survey jointly in the Ross Sea in the austral summer of 2004/05 as a Japanese national program.

Recently, large-scale, multidisciplinary surveys were conducted in the Antarctic waters. An Australian national multidisciplinary survey, BROKE (Baseline Research on

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Oceanography, Krill and the Environment), was conducted in the Indian Ocean sector of the Antarctic in the austral summer of 1996 (Nicol et al., 2000). CCAMLR (the Commission for the Conservation of Antarctic Marine Living Resources) conducted a multinational, large scale multidisciplinary survey in the Atlantic sector in the austral summer of 2000 (Watkins et al., 2004). The SO GLOBEC (the Southern Ocean Global Ocean Ecosystems Dynamics) program also conducted a multinational, large scale multidisciplinary survey in the western Antarctic Peninsula mainly in the austral autumn and winter of 2001 (Hofmann et al., 2004). Although large scale national ecological surveys have been conducted (Ackley et al., 2003; Faranda et al., 1999), no large scale multidisciplinary survey including surveys on cetacean has been conducted in the Ross Sea region in the past. Because ecological information is still sparse in the Ross Sea, CCAMLR encouraged regional studies in the Ross Sea (CCAMLR, 2007). The IWC (International Whaling Committee) also recommended that a multidisciplinary survey in the Antarctic be conducted to elucidate the role of whales in the Antarctic marine ecosystem (IWC, 1998; Fujise et al., 2010).

The Japanese national program took a multidisciplinary approach to clarify the ecological structure of the Ross Sea marine ecosystem. The main focus of the study was to elucidate the ecological interactions among biological organisms, especially between krill and whales. The surveys consisted of (1) oceanographic observations, (2) net sampling of planktons and fishes, (3) hydroacoustic surveys on krill (4) sighting surveys of top predators (birds and cetaceans) and (5) sampling of Antarctic minke whales.

The main objective of this paper is to provide an overview of the results of the Japanese multidisciplinary ecological study conducted in the Ross Sea region in the austral summer of 2004/2005. As a synthesis of the results, the relationship between distribution patterns of biological organisms and oceanographic conditions are summarized. A simple oceanographic index, Mean TEMperature from the surface to 200 m (MTEM-200), was used in this paper.

Overview of survey methods and results

General survey strategy

The survey was conducted in the Ross Sea region of the Antarctic (Fig. 1; also see Naganobu et al., 2010). Northern and southern boundaries of the survey area were set at 60°S and the Ross Sea Ice Shelf (approximately 78°S), respectively. Western and eastern boundaries were set at 160°E and 160°W, respectively. Western and eastern boundaries of JARPA were extended to 130°E and 145°W, respectively. No survey was conducted in the area covered by sea ice because survey vessels were not icebreakers. The survey was conducted from December 2004 to February 2005.

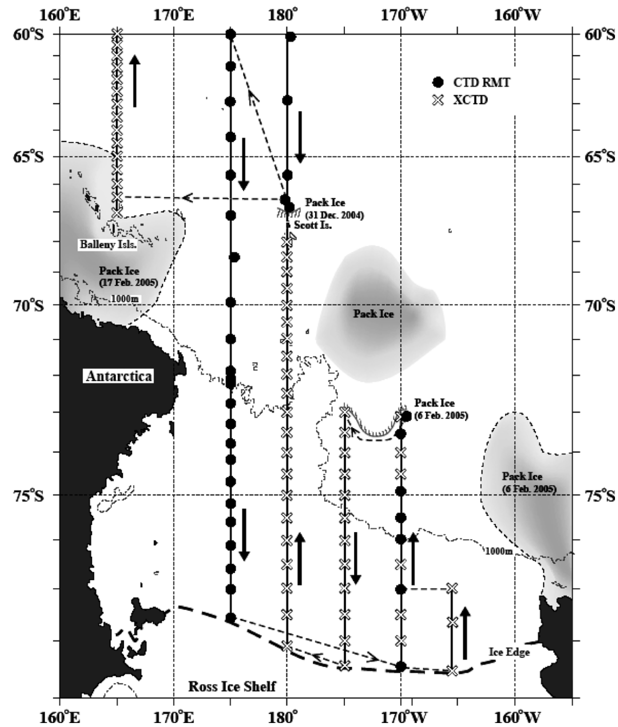

Figure 1. Transect lines and stations by research items of the R/V *Kaiyo Maru* during 26 December 2004 and 24 February 2005. The survey area was bounded on the west and east by 160°E and 160°W and the south of 60°S and north of approximately 78°S. The dashed line: 1000 m depth.

A total of six research vessels engaged in the survey. A stern trawl type fisheries research vessel, *Kaiyo Maru* (2630 GT, Fisheries Agency of Japan), conducted the following survey items: (1) oceanographic observations, (2) net sampling of planktons and fishes, (3) hydroacoustic surveys on krill (4) sighting surveys of birds. The JARPA fleet consisted of five research vessels dedicated to the cetacean surveys. One dedicated sighting vessel (SV), *Kyoshin-maru No. 2* (372GT), three sighting/sampling vessels (SSVs) namely *Yushin Maru* (720GT), *Yushin Maru No. 2* (747GT) and *Kyo Maru No. 1* (812.08GT), and one research base ship, *Nisshin Maru* (NM, 8030GT), were engaged in the cetacean surveys. These six vessels operated concurrently in the Ross Sea region so that a variety of data could be obtained for ecological studies. *Kaiyo-Maru* surveyed on longitudinal tracklines set on 165°E, 175°E, 180°, 175°W, 170°W and 165°W. Tracklines of JARPA were zigzag shape with starting points selected randomly. Further details of survey methods of the *Kaiyo-Maru* and JARPA were described in Anonymous (2006) and Nishiwaki et al. (2005; 2006), respectively.

Oceanographic observation

The oceanographic observations were conducted onboard the *Kaiyo-Maru* and the *Kyoshin-Maru No. 2* (Yabuki et al., 2010). The conductivity-temperature-depth profilers (CTD) and the expendable conductivity-temperature-depth profilers (XCTD) were used to investigate the structure of water mass characteristics and circulation features. All of the CTD data were collected with Sea Bird Electronics Co. (SBE) CTDs (SBE-9plus) while all of the XCTD data was sampled with Tsurumi Seiki Co. (TSK) XCTDs. Twenty-four 10-liter Niskin bottles were set for water sampling. Detailed observations of physical, chemical and biological parameters including phytoplankton (Furuya et al., 2010) were conducted especially along the 175°E trackline.

Various water masses were identified in the survey area (Fig. 1). Based on data in the literature (e.g., Carmack, 1990; Russo, 2000) the main water masses that occurred in the present survey were generalized as follows: Seasonal Summer Water with warm temperature and low salinity over the summer seasonal thermocline (SSW), Winter Water (WW) marked by a temperature minimum layer less than 0°C, Circumpolar Deep Water (CDW) indicating a high temperature and salinity maximum below the Antarctic Surface Water (ASW) and WW, Shelf Water (SW) specially designated as the Antarctic continental shelf such as the Ross Sea, and Antarctic Bottom Water (ABW) indicating low temperature and high salinity above the bottom.

A simple oceanographic index, the Mean TEMperature structure from the surface to 200 m in depth (MTEM-200) was also used to examine the relationships between oceanographic conditions and distribution patterns of biological organisms. MTEM-200 can be used to summarize the stratified water masses. Using MTEM-200 for the T-S diagram, we showed separations of T-S lines with colors (Fig. 1). Black lines (<1°C of MTEM-200) distributed in the Antarctic Circumpolar Current zone. Red color lines (1°C≧MTEM-200>0°C) distributed around the SBACC (Southern Boundary of the Antarctic Circumpolar Current) zone. Green color lines (0°C≧MTEM-200>−1°C) were located in the Antarctic Surface Water zone (ASW) stratified by SSW, WW and partly CDW. Blue color lines (−1°C≧MTEM-200>−2°C) were located in continental SW.

A vertical section of temperature is shown along the 175°E trackline from the surface to near the bottom (Fig. 2). The deepest area (4000 m) extended from 60°S to the Ross Ice Shelf located at around 78°S (Fig. 3). SBACC was located at around 64°S. The Antarctic slope front (ASF) was located at around 72°S.

Low salinity water of less than 33.8 and lower density water of less than 27.2 $kg \cdot m^{-3}$ occurred between 66°S–70°S probably because of ice melt water. Salinity higher than 34.2 and density higher than 27.6 $kg \cdot m^{-3}$ occurred in the surface layer (0–100 m) at the Antarctic Divergence

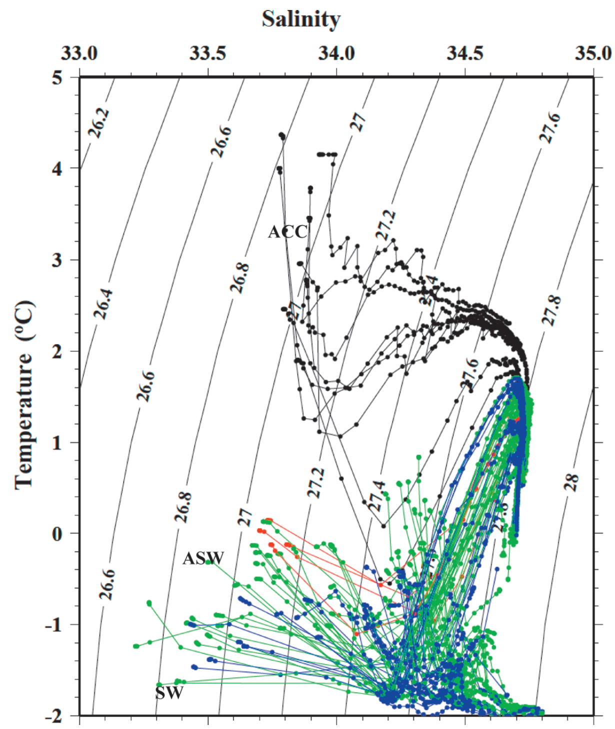

Figure 2. Temperature-Salinity diagram using all oceanographic stations by the *Kaiyo-Maru* survey. Color lines classification: black >1°C of MTEM-200, 1°C≧red>0°C, 0°C≧green>−1°C and −1°C≧blue>−2°C, respectively.

zone between 71°30′S–73°S. High salinity and density water suggested strong upwelling of CDW. Water in the Ross Sea was also of higher salinity and density suggesting upwelling to the surface layer between 75°S–76°S. Salinity higher than 34.7 and density higher than 27.9 $kg \cdot m^{-3}$ occurred on the shelf bottom.

Net sampling of planktons and fishes

Zooplankton, krill, micronekton and fishes were sampled by a Rectangular Midwater Trawl (RMT) with nominal mouth opening of 8 and 1 m^2 (1+8) and mesh size of 4.5 and 0.22 mm respectively (Roe and Shale, 1979). Sampling was conducted at 26 stations along the three longitudinal lines of 175°E, 180° and 170°W (Iwami et al., 2010; Taki et al., 2008; Taki et al., 2010; Watanabe et al., 2008: Watanabe et al., 2010). All stations were towed during the daytime and/or nights with the midnight sun except 4 stations which were towed during night time with the same daytime positions. The RMT8 nets were obliquely towed at approximately 2 knots and at 0.3 $m \cdot s^{-1}$ hoisting speed. Nets were mainly down to 1000 m or near the sea bottom where the depth was shallower than 1000 m. In this paper, samples collected from the upper 200 m water column were considered. Collected samples were kept in 10% formalin

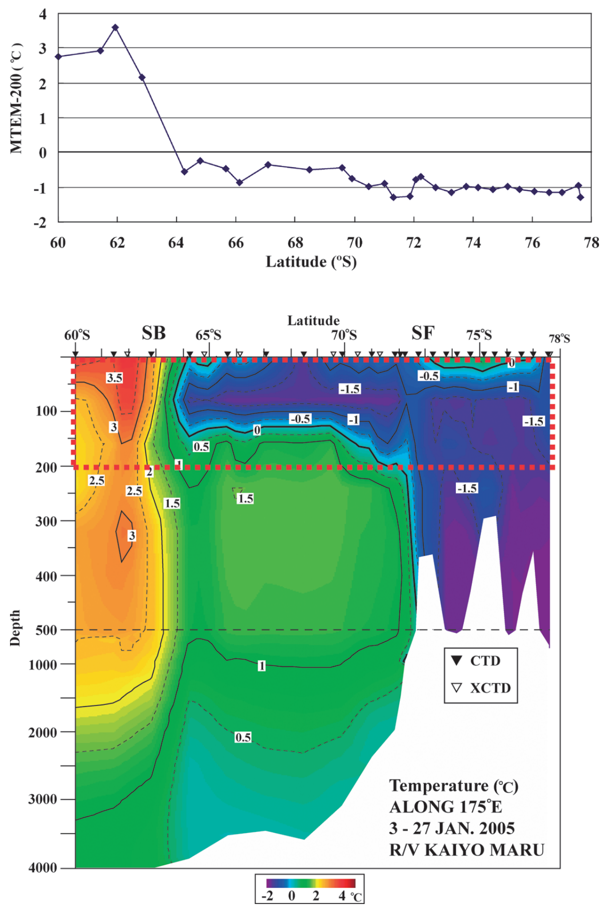

Figure 3. Vertical section of temperature along 175°E from the surface to near bottom between 60°S and the Ross Ice Shelf. The upper graph shows the mean of integrated temperature between the surface and 200 m as an environmental index (MTEM-200; a dotted line frame in the bottom graph). SB: the Southern Boundary of the Antarctic Circumpolar Current. SF: Shelf Front.

buffered seawater. In the laboratory, the samples were measured for wet weight, sorted into 17 taxonomic groups and enumerated. Gelatinous forms, salps and jellyfish, which were measured separately, were removed before measuring the wet weight. The biomass and abundance were expressed in numbers per 1000 m^3 of water filtered.

Chaethognaths (17%), Copepoda (62%), Euphausiaccea (9%) and Pteropoda (7%) were dominant taxa groups by number in the survey area. A total of 33 fish species belonging to 14 families, Nemichthyidae, Bathylagidae, Gonostomatidae, Stomiidae, Paralepididae, Scopelarchidae, Myctophidae, Muraenolepididae, Macrouridae, Melamphaidae, Nototheniidae, Artedidraconidae, Bathydraconidae and Channichthyidae, were identified. Bathylagidae and Paralepididae were grouped into “mesopelagic fishes” and the latter four families into Notothenioidei (Iwami et al., 2010).

Hydroacoustic survey

A multifrequency quantitative echosounder (EK 500, Simrad, Norway) was used to investigate the distribution and abundance of Antarctic krill (*Euphausia superba* and ice krill (*E. crystallorophias*) (Murase et al., 2008; Yasuma et al., 2010). EK 500 a quantitative echosounder with operation frequencies of 38, 120 and 200 kHz were used by the *Kaiyo Maru* survey. The same echosounder was also used onboard the *SV* to record acoustic data. Data were recorded and stored using Echoview (SonarData, Australia). The ship steamed on track lines at the nominal speed of 10 knots. The ship carried out calibrations in the survey area. All data were analyzed using Echoview. Echoes from euphausiids were 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 were classified as euphausiid (Hewitt et al., 2004). Although the acoustic properties of ice krill have not been well studied, it has been reported that the mean of ΔMVBS ice krill in the Ross Sea was 16.33 dB (Azzali et al., 2006). Therefore it was considered that ΔMVBS values reported by Hewitt et al. (2004) were appropriate to identify echoes from euphausiid. Because acoustical discrimination between Antarctic and ice krill was difficult, species allocation of acoustic data was based on the samples from a RMT. Though the depth interval for the *Kaiyo Maru* survey were set from 15 to 500 m, effective Nautical-area-backscattering coefficients (s_A) values attributed to euphausiids came from the upper 250 m depth. Nautical-area-backscattering coefficient (s_A) by species for every 1 n.mile of survey transect over the defined depth interval was calculated. Nautical-area-backscattering coefficients (s_A) were converted to indivisuals densities by using target strength (TS). Biomasses were then calculated by using wet weight of an individual. Preliminary estimates of the biomasses of Antarctic and ice krill south of 69°S were 1.40 (CV=0.32) and 0.60 (CV=0.18) million t, respectively (Murase et al., 2008).

Seabird sighting survey

The seabird sighting survey was conducted onboard the *Kaiyo-Maru* (Kokubun et al., 2010). The survey was conducted every hour in daytime while the vessel was steaming on the trackline. The duration of each observation was 15 minutes. The number of seabird by species within 300 m strip width on one side of the vessel was counted in each observation period. A total of 5,861 individuals consisting of 21 species were observed. The most dominant seabirds were *Pachyptila* spp., (24%) followed by Antarctic petrels (*Thalassoica antarctica*, 21%), slender-billed prions (*Pachyptila belcheri*, 19%) and snow petrels (*Pagodroma nivea*, 7%). Distribution patterns differed between species.

For example, slender-billed prions and snow petrel were distributed in the northern and southern parts of survey area, repetitively while Antarctic petrels were distributed in the middle part.

Cetacean sighting survey

Four cetacean sighting survey vessels were operated in the survey area (Nishiwaki et al., 2005; Matsuoka et al., 2010). The survey was conducted in daytime. The standard sighting survey method used for the IWC Antarctic cruises (Matsuoka et al., 2003) was adopted. Principally, the survey was conducted in closing mode. The *SV* conducted passing mode survey in addition to closing mode survey. When the sightings during Closing Mode (primary sightings) were thought to be Antarctic minke whales, the vessels approached to primary sightings to confirm species as well as the number of individuals in the schools. All sightings were passed in Passing Mode and treated as primary sightings. All sightings within 3.0 n.mile strip width on both sides of the vessels were recorded. Antarctic minke whale (B*alaenoptera bonaerensis*) was dominant over other baleen whales: blue (*B. musculus*), fin (*B. physalus*) and humpback (*Megaptera novaeangiae*) whales. Killer whale (*Orcinus orca*) was dominant over other toothed whales: sperm (*Physeter macrocephalus*), Arnoux's beaked (*Barardius arnuxii*) and aouthern bottlenose (*Hyperoodon planifrons*) whales. Two dolphins, specacled porpoise (*Australophocaena dioptrica*) and hourglass dolphin (*Lagenorhynchus cruciger*), were sighted though numbers were few. Antarctic minke and killer whales were mainly distributed in waters south of 69ºS though they were found throughout the survey area. Other cetaceans were mainly distributed in the northern part of the survey area.

Preys of Antarctic minke whales

Antarctic minke whales were sampled randomly by SSVs and their stomach contents were sampled and preserved for laboratory analysis on NM (Tamura et al., 2010). Species identification and the length measurement of the stomach contents were conducted in the laboratory. Antarctic minke whales fed on ice krill in the continental shelf area while they fed on Antarctic krill north of continental break as previously reported by Ichii et al. (1998). The geographical distribution patterns of two krill species based on the stomach contents coincided well with the samples from the RMT. Stomach content mass was high around the shelf break (1000–3000 m bottom depth) in waters west of 180°. Geographical distribution patterns of Antarctic and ice krill and length distribution patterns of the two krill species in the stomach contents were similar to those in the samples from the RMT.

Synthesis: distributional ecology with reference to oceanographic conditions

To investigate the effect of the oceanographic structure on distribution patterns of various biological organisms, an oceanographic index, Mean TEMperature from the surface to 200 m in depth (MTEM-200), was used (Murase et al., 2010; Naganobu and Murase, 2010). In general, sea surface temperature (SST) is used as an index to describe distribution patterns of biological organisms worldwide. However, it is difficult to use SST as an environmental indicator in the Antartic because the gradient of SST is limited to a narrow range. Because krill fisheries are conducted mainly in the 0–200 m water column, MTEM-200 could be an appropriate environmental index to describe krill distribution. The relationship between distribution patterns of krill and MTEM-200 was initially considered by Naganobu and Hirano (1982, 1986). In fact, variation of macrozooplankton community structure in the Indian Ocean sector of Antarctic (Hosie et al., 2000) and distribution of krill in the entire Antarctic Ocean (Naganobu et al., 2008) were described by MTEM-200.

Distributions and the abundance and composition of zooplankton at each station were compared with MTEM-200 (Fig. 4). Overall, two groups were separated by the −1°C isopleth. One group located offshore in water warmer than −1°C was characterized by high abundance (>1000 individuals per 1000 m^3) and the dominance of copepods (52–93%; mean 68%) and chaetognaths (5–42%; mean 22%), while the other group located in the Ross Sea in water colder than −1°C was characterized by low abundance (<500 individuals per 1000 m^3) and the dominance

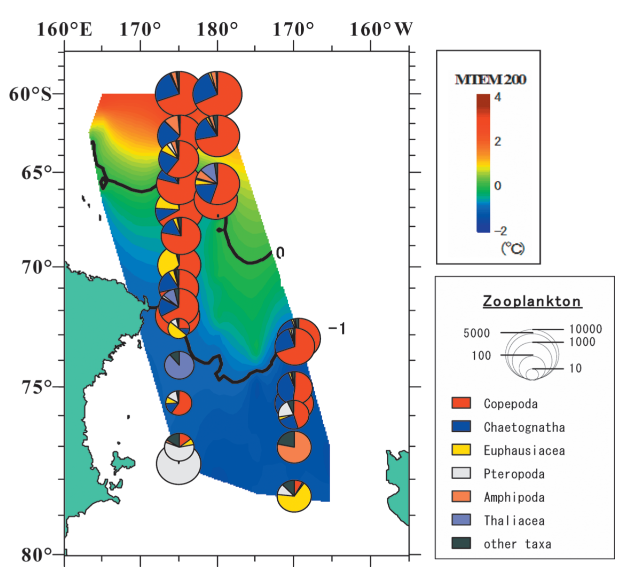

Figure 4. Distribution of the integrated abundance of zooplankton (individuals per 1000 m^3) in the water column (0–200 m) and percent composition of major taxa with MTEM-200.

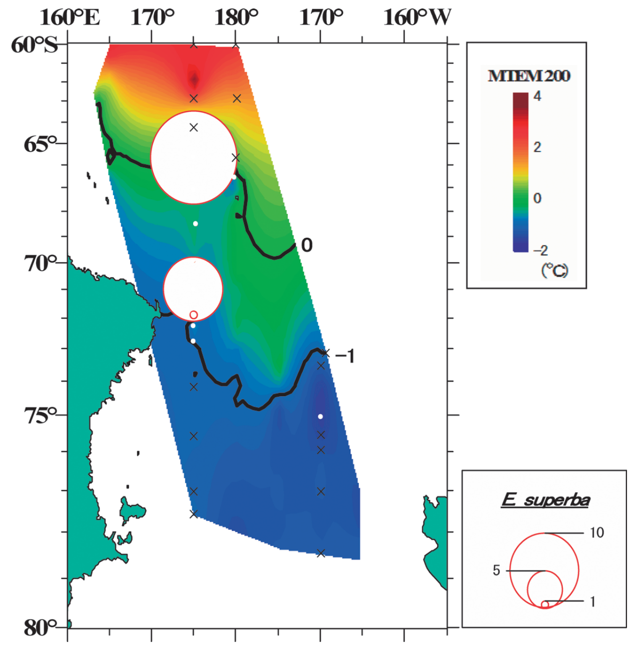

Figure 5. Distribution of Antarctic krill in routine trawls n the water column (0–200 m) with MTEM-200. Abundance circles are proportional in area to density (individuals per 1000 m^3). ×sampling sites where no specimens were caught.

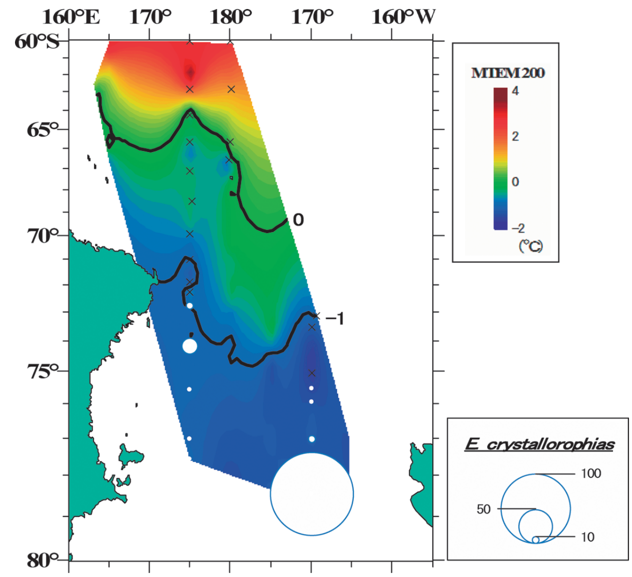

Figure 6. Distribution of ice krill in routine trawls in the water column (0–200 m) with MTEM-200. Abundance circles are proportional in area to density (individuals per 1000 m^3). ×sampling sites no specimens where were caught.

of pteropods (11–93%; mean 35.5%) and euphausiids (0–66%; mean 25%). At the stations near the edge of the Ice Shelf, pteropods were dominated (93%) with a very high abundance at the southernmost station along the 175°E trackline. Pteropods and other taxa occurred with low abundance at southernmost station along the 170°W trackline.

The results of routine oblique trawls of RMT8 (0–200 m) suggested that Antarctic krill was distributed in the waters between the MTEM-200 of 0°C and −1°C (the ASW zone) except a station in the waters of −1.5°C on the Ross Sea continental shelf (Fig. 5). On the other hand, geographical distribution of ice krill was limited to waters lower than −1°C on the continental shelf (the SW zone) (Fig. 6). No occurrences were found in the warmer waters north of the −1°C isopleth. Maximum density appeared near the Ross Ice Shelf at 78°30′S in the southeast part.

Distributions, abundance and composition of fishes at each station are shown with MTEM-200 on a map (Fig. 7). Horizontal distribution patterns of many species seem to be clearly correlated to hydrographic features and different water masses, although the quantitative analysis has not been completed yet. Three groups were separated by MTEM-200 of 0 and −1°C. Occurrences of notothenioid fishes were limited to the waters lower than −1°C on the Ross Sea continental shelf except for one station in the waters between 0 and −1°C. Myctophidae were distributed in

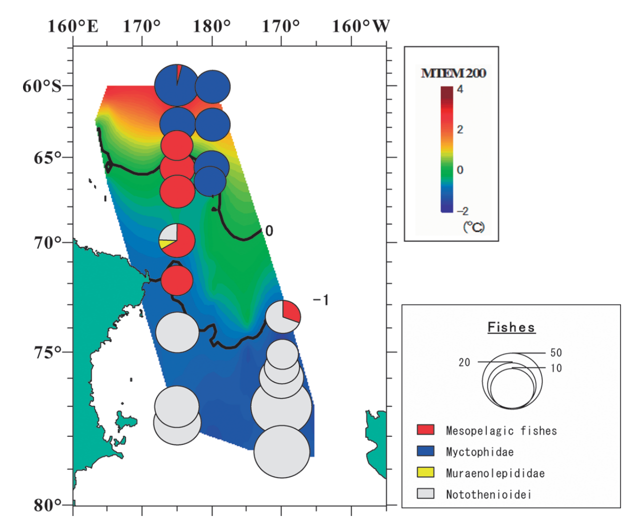

Figure 7. Distribution of the integrated abundance of fishes (individuals per 1000 m^3) in the water column (0–200 m) and percent composition of major taxa with MTEM-200.

the oceanic waters higher than 0°C and mesopelagic fish groups were mostly limited to the waters between 0 and −1°C in the ASW zone. Among these, *Pleuragramma antarcticum* of Nototheniidae was dominant both in terms of abundance and frequency. In the waters colder than −1°C on the shelf, *P. antarcticum* was characterized by a high abundance (max 100%, mean 66%). The distribution pattern of the fish taxa generally corresponds with MTEM-200.

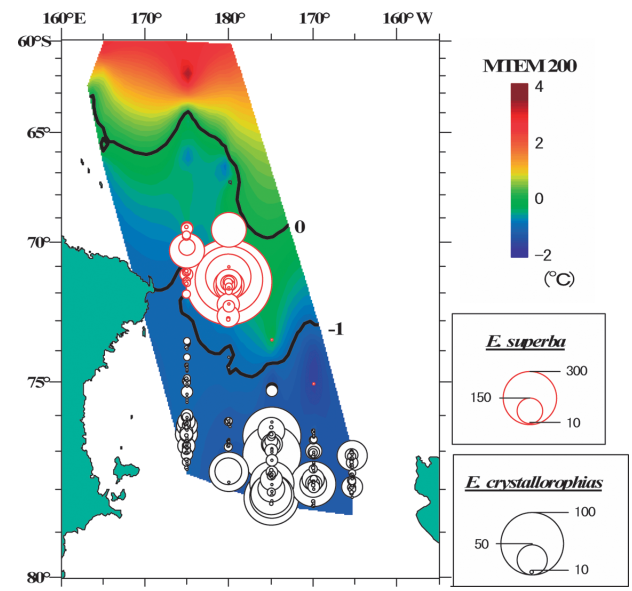

Figure 8. Distribution and density (g/m^2) of krill; Antarctic krill (*Euphausia superba*) and ice krill (*E. crystallorophias*) by the acoustic survey by *Kaiyo Maru* with MTEM-200.

We compared the results of krill distribution by acoustic measurement with MTEM-200 (Fig. 8). High density of Antarctic krill was observed in the northwestern waters in the survey area. The high density areas of Antarctic krill approximately coincided with the sharp gradient waters of MTEM-200 around −0.5°C, which indicated a frontal zone between southward warmer advection and northward colder waters. On the other hand, ice krill was observed in the shelf waters of MTEM-200 less than −1°C on the continental shelf. The high density areas of ice krill tended to distribute in small clockwise eddies and near the ice shelf along 175°W.

Figure 9 shows the distribution of Antarctic minke whales (number of schools sighted per 100 n. miles) with MTEM-200. The distribution of Antarctic minke whales ranged through south of 1°C. Relatively high density index of Antarctic minke whales was concentrated at the steep gradient around 0°C and south of −1°C. In addition, the density index was higher in the tongue-shaped southward advection along 175°W between 0 and −1°C and the tongue-shaped northward advection along 170°W. The relative high density occurred in the same area as the tongue-shaped advection with a north-south meander. High density indexes were especially concentrated in the waters with eddies around 75°S along 170°W. Figure 10 shows the distribution humpback whales (number of schools sighted per 100 n. miles) with MTEM-200. The distribution of humpback whale mainly ranged through north of 0°C. The high density indexes were concentrated at the frontal zone around 0°C.

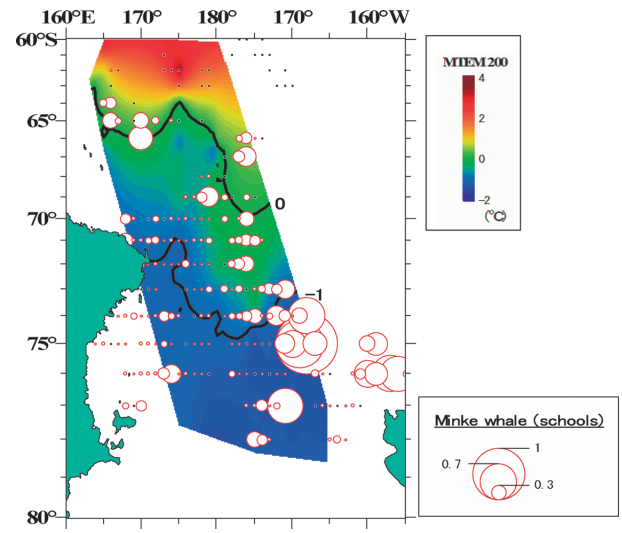

Figure 9. Distribution of Antarctic minke whale with MTEM-200. Abundance circles are proportional in area to density (number of schools sighted per 100 n. miles). A black mark (·) indicates no sighting.

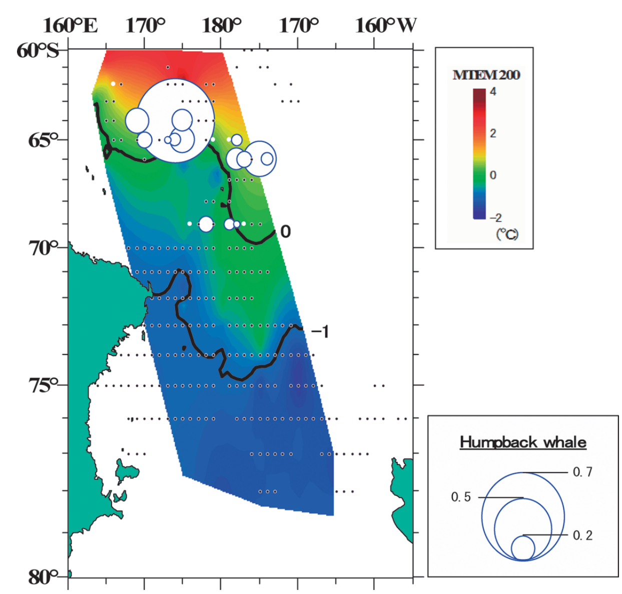

Figure 10. Distribution of humpback whale with MTEM-200. Abundance circles are proportional in area to density (number of schools sighted per 100 n. miles). A black mark (·) indicates no sighting.

Krill-cetacean distributional relationship with reference to oceanographic conditions in the waters south of 69°S was investigated by using a generalized additive model based spatial model (Murase et al., 2010). MTEM-200 was selected as a covariate in the model to describe the distribution pattern of Antarctic minke whales. The results indicated that the density of Antarctic minke whales related to MTEM-200 positively within the range of MTEM-200 between −1.5 and 1°C. Latitude, longitude, mean salinity from 0–200 m in depth (MSAM-200) and density of two krill species were also selected to model the number of schools of Antarctic minke whales. The results showed that predicted school counts of Antarctic minke whales were low where ice krill was distributed while they were high where Antarctic krill was distributed.

Discussion

The Japanese multidisciplinary ecosystem survey in the Ross Sea in 2004/2005 collected numerous data sets to understand the components of the ecosystem (e.g. oceanographic conditions and distribution patterns of biological organisms). The findings will deepen the understanding of each field of science especially in the data sparse area, the Ross Sea. In addition, the multidisciplinary data set allowed us to understand the distributional ecology in the Ross Sea. The findings were summarized in a conceptual map (Fig. 11). The oceanographic conditions generally indicated three water types; the ACC zone with MTEM-200 warmer than 0°C, the ASW zone between 0 and −1°C and the SW zone below −1°C. The eastward arrow indicates a strong eastward flow in the ACC. A north-south meandering shape was indicated as shown with MTEM-200 0 and −1°C isopleths. Southward arrows indicate putative flows in the ASW. Clockwise and anticlockwise arrows suggest regional eddies with upwelling and downwelling in the SW. Recent oceanographic results of Picco et al. (2000) and Russo (2000) for current patterns in the SW near the ice shelf were inferred in the figure.

Figure 11 shows that Antarctic krill were mainly distributed in the waters with MTEM-200 between 0 to −1°C, which approximated with the area of the ASW zone, and slightly extended into the waters of less than −1°C, Shelf Water in the SW zone. Ice krill were mainly distributed in the waters less than −1°C (SW) but not more than −1°C (ASW). Distributions of other zooplankton and fishes also showed segregated patterns with MTEM-200. Humpback whales were mainly distributed in the waters more than 0ºC, approximating with the ACC zone, with high density around 0ºC near the SBACC (Orsi et al., 1995). Antarctic minke whales were mainly distributed in the ASW and SW zones with a high density around −1°C in the continental shelf slope frontal zone. The relationship between distributions of Antarctic and ice krill, and Antarctic minke whales with MTEM-200 was also detected in the spatial model (Murase et al., 2010). The results suggested that MTEM-200 can be used as an environmental index along with traditional water mass/front classification to describe the structure of the Antarctic marine ecosystem.

As sophisticated survey equipment has been developed, it seems that use of a simple oceanographic index such as MTEM-200 is not necessary because more detailed data can be obtained using such equipment. However, as in the case of Hosie et al. (2000) in the BROKE survey, MTEM-200 is useful to understand the distribution pattern of biological organisms qualitatively in relation to water temperature gradients in both longitudinal and latitudinal directions. MTEM-200 can also be used as an environmental index in quantitative analyses. Murase et al. (2008) used MTEM 200 to identify the boundary of the distribution of Antarctic krill and ice krill for biomass estimations using acoustic data in our cooperative surveys.

Though some modeling work was conducted by using the data obtained through our survey (e.g. Murase et al., 2010), the ecological interactions among biological organisms in the Ross Sea have not been fully investigated quantitatively at this stage. The results of this study suggested

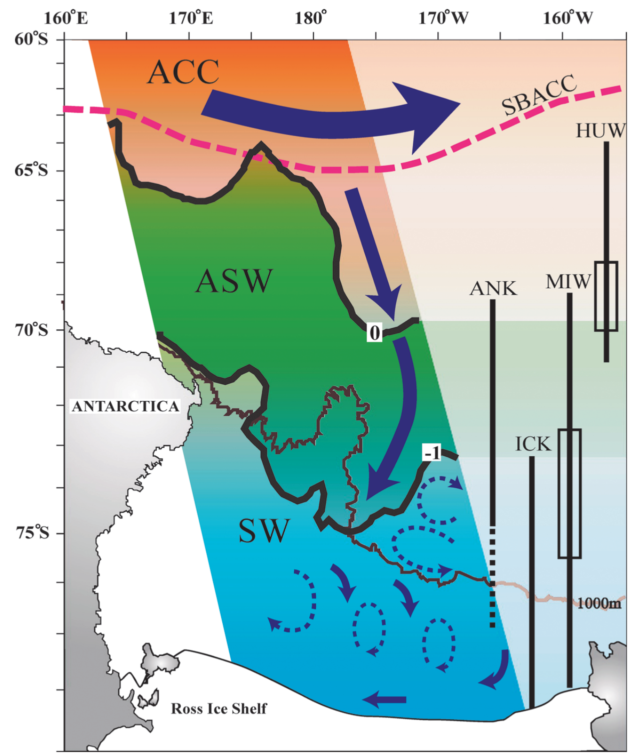

Figure 11. A summarized image relating water mass and circulation pattern of the oceanic surface layer, the distribution and abundance of krill and baleen whales. Each line on the map indicates the Southern boundary (of Antarctic Circumpolar Current) and MTEM-200=0 and −1 (°C). The 1000 m depth contour is shown. Arrows show the flow pattern. ACC: Antarctic Circumpolar Current zone. ASW: Antarctic Surface Water zone. SW: Shelf Water zone. SBACC: Southern Boundary of ACC (Orsi et al., 1995). ANK: Antarctic Krill. ICK: Ice Krill. MIW: Antarctic Minke Whale. HUW: Humpback Whale.

that habitats of predators overlapped each other. It has been reported that the presence of Antarctic minke whale near the colonies of Adélie penguins (*Pygoscelis adeliae*) could be the driving force of the prey switching from ice krill to *P. antarcticum* of Adélie penguin because feeding of Antarctic minke whales could cause local depletion of ice krill (Ainley et al., 2006). Many notothenioid fishes in the Ross Sea relied on Antarctic and ice krill as food in the Ross Sea shelf waters (Mesa, 2004). However, the magnitude of these interactions with prey has not been investigated quantitatively. The concept of Ecosystem approach to fisheries (EAF) has attracted interest from the international community in recent years. The term, EAF, was adopted by the FAO Technical Consultation on Ecosystem-based Fisheries Management held in Reykjavik in 2002 (FAO, 2003). Ecosystem models play an important role as operating models to test the management strategies of EAF. The modeling of the southern ocean ecosystem has a long history (Hill et al., 2006 for review). The CCAMLR has tried to develop ecosystem models for the purpose of krill fisheries management in the in the Scotia Sea-Antarctic Peninsula region though they have not yet been applied to management (Hill et al., 2007). No ecosystem model for fisheries management is available in other regions of the Antarctic at this stage largely because of lack of data. Ecosystem models require species interaction sub-models such as the functional responses of predators (amount of prey consumed per unit area per unit time by predators). To estimate functional response, biomass of prey and amount of prey consumed by predators must be obtained simultaneously. Data obtained through our survey allows us to construct ecosystem models and their sub-models. Therefore efforts in future research should focus in this direction. The Japanese multidisciplinary study by *Kaiyo-Maru* and JARPA serves as a starting point toward EAF for the Antarctic. Continuation of the program is crucial to collect data for ecosystem models.

Changes in oceanographic/climatic conditions in the Antarctic have been reported in recent years. There are many oceanographic papers on the variability and/or warming of the surface layer of the Indian Ocean sector (Aoki et al., 2005), the surface layer of the Antarctic Peninsula waters (Marshall et al., 2006) and the whole scale of the Antarctic/Southern Ocean (Gille, 2002). Freshening of the Antarctic Bottom Water in the Ross Sea (Jacobs et al., 2002) and the Indian and Pacific Ocean (Rintoul, 2007; Ozaki et al., 2009) has also been reported. Although the long term relationship between krill and oceanographic/climatic conditions was investigated (e.g. Atkinson et al., 2004; Brandon et al., 2004; Kawaguchi et al., 2006; Loeb et al., 1997; Murphy et al., 2007; Naganobu et al., 1999), the effort was concentrated mainly in the data rich region, the Antarctic Peninsula region. To assess the impact of oceanographic/climatic conditions on the Ross Sea ecosystem in long time scales for monitoring purposes, multidisciplinary surveys should be conducted on a regular basis.

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南極ロス海の海洋生態系構造
—開洋丸／JARPA共同による生態系総合調査の概要と結果総括—

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2004/05年南半球夏季に南極ロス海域において，特にオキアミと鯨類の関係解明を目的とした，生態系総合調査を実施した．水産庁開洋丸と南極海鯨類捕獲調査（JARPA）船団が共同して調査を行った．（1）海洋観測，（2）RMTによるプランクトンと魚類採集，（3）計量魚探によるオキアミ現存量調査，（4）高次捕食者（鳥類と鯨類）の目視調査，及び（5）クロミンククジラ標本採集の5項目を調査対象とした．多様な生物群集の分布と海洋条件との関係を理解するために，海洋学的指数として表面から200 mまでの水温平均値（MTEM-200）を用いた．南北の水温傾度に沿って，プランクトン，魚類，鳥類及び鯨類それぞれの種組成が変化することが明らかとなった．生態系総合調査を通して得られたデータは，未知が多いロス海の海洋生態系の構造を理解するための基礎となる．

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