Results of the cetacean prey survey using echo sounder in JARPA from 1998/99 to 2002/2003

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ABSTRACT

Krill biomass estimation surveys using quantitative echo sounder have been conducted in JARPA since 1998/99 season to achieve one of the main objectives of JARPA which is elucidation of the role of whales in the Antarctic marine ecosystem. The survey was conducted concurrently with cetacean survey. Similar biomass estimates were obtained in Area IV in 1999/2000 (36.4 million t) and 2001/2002 (36.1 million t) season. In Area V, biomass in 2000/2001 (18.7 million t) and in 2002/2003 (21.0 million t) were similar but biomass in 1998/1999 (32.3 million t) was higher than rest of two years. Higher biomass in 1998/99 could be explained by seasonal effect and area coverage difference. Biomass in Area IV was higher than Area V. Regional krill distribution pattern difference in response to the southerly shift of the SB-ACC was observed in Area IV. Because krill biomass survey in whole Area IV and Area V were rarely conducted in the past, krill data collected by JARPA were quite important to understand krill-baleen whale relationship in the Antarctic.

INTRODUCTION

It is well known that krill is the key species in the Antarctic marine ecosystem because krill is a major link in the transfer of energy from primary producers to larger organisms such as baleen whales (Laws, 1985; Murphy et al., 1988). Krill have been known as the major food source of baleen whales other than Bryde's whales (*Balaenoptera edeni*) in the Antarctic (Kawamura, 1994). "Krill surplus" caused by intensive commercial harvesting of large whales, blue (*B. musculus*), fin (*B. physalus*) and humpback whales (*Megaptera novaeangliae*), has been central theorem of the Antarctic ecosystem study. "Krill surplus" resulted in increasing in amount of available food to other krill feeders such as Antarctic minke whales (*B. bonaerensis*) (Laws, 1977). But it appears that the situation is changed in recent years. After the ban of commercial whaling of large whales in 1987, it was reported that abundance of those species increased in recent years. For example, abundance of blue whales increase 8% per year at the circumpolar level (Branch et al., 2004) though the abundance was still low comparing with pre exploitation population size. Some stocks of humpback whales in southern hemisphere have been showed remarkable recovery even to near pre-exploitation level (Jhonston and Butterworth, 2004). To test the magnitude of interaction, preliminarily baleen whales-krill interaction model was developed but the interpretation was limited at this moment because of paucity of information including biomass estimation of krill (Mori and Butterworth, 2004). Krill density showed both short and long term changes. In short term, krill density showed large year to year fluctuation at decadal scale in response to environmental variability such as sea ice extent and oceanographic conditions (e.g. Pakhomov, 2000; Hewitt and Demer, 2003). It was reported that krill density have showed statistically significant decreasing trend in the southwest Atlantic since 1976 (Atkinson et al. 2004) though the magnitude of decrease should be studied further to draw the conclusion because wide varieties of net types were used in the analysis. Given the krill density change information, krill biomass survey should be conducted regularly in the same region. To assess the magnitude of interspecific competition among baleen whales for krill and the consequences of the competition quantitatively, conducting concurrent cetacean and krill survey is critical.

The Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) provided unique opportunity to conduct the concurrent cetacean and krill survey. 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 response to the comments, echo sounder survey to examine distribution and abundance of krill has been conducted concurrently with cetacean survey since 1998/99 season. Krill distribution data will be linked with distribution patterns of baleen whales whereas krill abundance data will allow us to examine the magnitude of the interspecific relationship among baleen whales for krill. The preliminary report of the results the echo sounder surveys of krill that were conducted in 1998/1999 and in 1999/2000 were reported to the International Whaling Commission (IWC)/Scientific Committee (SC) as SC/52/E5 (Murase et al., 2000) and published in scientific journal (Murase et al., 2002). This paper presents the echo sounder survey methodology and the results of biomass estimation of krill in JARPA from 1998/99 to 2002/2003.

MATERIALS AND METHODS

Survey area

Two baleen whale management area defined by the International Whaling Commission (IWC), Area IV (70°E-130°E) and Area V (130°E-170°W), were surveyed alternative years. The areas between south of 60°S and the ice edge line were surveyed. Each area were further divided into two, east and west, at 100°E in Area IV and at 165°E in Area V. Each sector further divided into two strata, north (between the 60°S latitude line to the line of 45 n.miles from ice edge) and south (between the line of 45 n.miles from ice edge and ice edge). Exceptions were the Prydz Bay region (south of 66°S between 70°E and 80°E) and the Ross Sea region (South of 69°S between 165°E and 170°W). The Ross Sea region was defined as south-east stratum of Area V whereas the Prydz Bay region was called as it was. In addition to two Areas, eastern part of Area III and western part of Area VI were also surveyed alternative years. No specific stratification was set in those Areas. Following acronyms were used to describe strata name;

III-E-F	Eastern half of Area III, first period
III-E-S	Eastern half of Area III, second period
IV(or V)-NE	North-East stratum in Area IV (or V)
IV(or V)-NW	North-West stratum in Area IV (or V)
IV(or V)-SW	South-West stratum in Area IV (or V)
IV(or V)-SE	North-East stratum in Area IV (or V)
IV-PB	Prydz Bay region in Area IV
VI-W-F	Western half of Area VI, first period
IV-W-S	Western half of Area VI, second period

Timing of surveys

Surveys were conducted during austral summer (December-March). Detailed survey dates were summarized in Table 1 and 2.

Trackline designs

Sawtooth type zigzag lines were used in each survey. Details of the trackline designs were reviewed in Nishiwaki et al. (2005).

Survey vessel

The cetacean sighting vessel, *Kyoshinmaru No.2* (368 GT) was engaged in the sighting survey of cetaceans as well as echo sounder and oceanographic surveys. The nominal steaming speed of SV on the track line was 10.5 knots.

Data acquisition and storage system

An EK500 scientific echo sounder (Simrad, Norway) with software version 5.30 operating frequency at 38 and 120 kHz on board Kyoshin-maru No.2 was used to collect data for the acoustic survey from 1998/99 to 2003/04. The transducers were hull-mounted at the depth of 4.3 m from the surface. Each transducer was covered with a 40 mm polycarbonate acoustic window to minimize the damage on the transducer surface from contacting sea ice. The hydraulic oil filled the space between the transducer surfaces and the acoustic windows. Data were stored and interpreted with the aid of a BI500 post processing system (Simrad, Norway) from 1998/99 to 2003/04. BI500 was software operated under the UNIX operation system. BI500 had three major function; 1) recording echo sounder data, 2) analyzing echogram data and 3) outputting the analysis results.

Data analysis system

BI500 was used in 1998/99 and in 1999/2000. Echoview version 3.00.74.01 (SonarData Pty Ltd, Australia) was used from 2000/01 to 2003/04. Major function of Echoview was same as BI500 but it allowed more detailed analysis than BI500. Echoview was software operated under the Microsoft Windows. Echoview was capable to analyze BI500 data file.

Calibrations

The copper sphere technique that described in EK 500 operation manual (Simrad, 1997) was applied for the calibrations. Calibrations were conducted in Antarctic water every year. In 2002/03 and 2003/04, calibrations were attempted but the results weren't applied to the analysis because those were conducted in unsuitable conditions for calibration. For those years, the result of the calibration in 2001/02 was applied for analysis.

Data recording methodology

The survey was conduced during diurnal hours from an hour after sunrise to an hour before sunset. Maximum survey time per day was 12 hours. Data were recorded continuously while the vessel steamed on predetermined trackline. The data were not used in the analysis when the vessels deviated from the trackline such as during cetacean species confirmation.

Data analysis methodology

We applied the acoustic data analysis described by Hewitt and Demer (1993) and Demer and Hewitt (1995). The following procedures came from those papers. Mean backscattering area per square n. mile of survey transect (s_A) attributed to krill for every 1 n. mile of survey transect over 10 to 250 m depth was calculated by following formula;

$$s_A = 4\pi r_0^2 1852^2 \int_{r_1=10}^{r_2=250} s_V dr \left(\frac{m^2}{n.mi^2}\right)$$

where, r is depth from the surface, r_0 = 1m representing the reference range for backscattering strength and $s_V = 0$ if $10 \log (s_V) \leqq -80$dB, because threshold backscattering was set at –80dB. Because direct sampling method (e.g. net sampling) to identify species was not available, the difference between the mean volume backscattering strength (ΔMVBS) of 120 and 38 kHz fell between 2 and 12 dB is classified as krill (Madureira et al., 1993). Because BI500 didn't have capability to calculate ΔMVBS, the differences were visually identified using the echogram in 1998/99 and 1999/2000. For the lest of year, ΔMVBS was calculated quantitatively using Echoview.

Krill backscattering cross section area (σ) was calculated with the following formula based on krill target strength described by Greene et al. (1991):

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

where, l was standard length of krill. Krill wet weight (w) was calculated with the following formula based on Siegel (1986):

$$w = 0.00193 l^{3.325} .$$

Average area krill biomass density ($\overline{\rho}$) was calculated as follows;

$$\overline{\rho} = S_A \frac{w}{\sigma} = 0.249 l^{-0.16} S_A .$$

Then, frequency distribution of euphausiids standard length (f_i) was applied to the following formula;

$$\overline{\rho} = 0.249 \sum_{i=1}^{n} f_i (l_i)^{-0.16} S_A .$$

Because minor variation in the frequency distribution of krill length did not affect the krill biomass estimate, a combined distribution data based on Loeb and Siegel (1992) was used (Demer and Hewitt, 1995) as follows;

$$\sum_{i=1}^{n} f_i (l_i)^{-0.16} \cong 0.562 .$$

With this formula mean krill biomass of each transect in each stratum was calculated. Following procedures were adopted from Jolly and Hampton (1990). Weighted mean of S_A of each block was;

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

where, $\overline{S_{Ak}}$ = mean S_A in kth block, N_k = number of transects in kth block, $\overline{S_{Aki}}$ = mean S_A on the ith transect in kth block and n_{k_i} = number of 1 n. mile averaging intervals on the ith transect in kth 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 $\overline{\rho}$ using above motioned formula. Biomass was estimated as;

$$B_k = A_k \rho_k$$

where, B_k is density biomass in kth block and A_k is area of kth 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;

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

Biomass (B_0) in each Area was calculated as;

$$B_0 = \sum_{k=1}^{N} B_k .$$

Overall survey variance of B_0 was;

$$Var(B_0) = \sum_{k=1}^{N} \mathrm{var}(B_k) .$$

Coefficient of variation of B_0 was calculated as;

$$CV(B_0) = \frac{\sqrt{Var(B_0)}}{B_0} .$$

RESULTS

Area IV and eastern part of Area III

Surveys were conducted in Area IV and eastern part of Area III in 1999/2000 and 2001/2002. Density and biomass in each stratum in each year were summarized in Table 1. Distribution patterns were shown in Fig. 1. Timings of surveys were almost same for two years. Density and biomass in IV-SW in 2001/2002 were remarkably higher than 1999/2000. It should be noted that survey effort in Northern strata in Area IV in 2001/2002 was lower than that of in 1999/2000 because of poor weather conditions for the echo sounder survey.

Area V and western part of Area VI

Surveys were conducted in Area V and western part of Area VI in 1998/1999, 2000/2001 and 2002/2003. Density and biomass in each stratum in each year were summarized in Table 2. Distribution patterns were shown in Fig. 2. Timing of survey in 1998/1999 was different from other years. Because the mouth of the Ross Sea was closed in 1998/1999, the Ross Sea region was not surveyed. In addition, V-NE was not surveyed.

Biomass estimation by Area

Results of biomass estimation of krill by area by year were summarized in Table 3. Overall, year to year differences of biomass estimations and CVs were small except 1998/1999, though each stratum in each area showed year to year biomass and CV variations. It should be noted that the survey timing and coverage in Area V in 1998/1999 were different from other years.

DISCUSSION

The position of the Southern Boundary of the Antarctic Circumpolar Current (SB-ACC) in 2001/2002 shifted to south in comparison with that in 1999/2000 (Watanabe et al., 2005). The SB-ACC was corresponded to high primary production and hence to distribution of whales (Tynan, 1998). It was postulated that krill would be coastally constrained when the position of the SB-ACC shows southerly shift (Nicol et al., 2000(a)). Higher density and biomass in VI-SW in 2001/02 than in 1999/2000 could be related to the southerly shift in position of the SB-ACC. This is the first time to confirm the hypothesis proposed by Nicol et al. (2000(a)) in this region. Few echo sounder surveys were conducted between 35°E to 170°W in the past except the Prydz Bay region. Survey of distribution and abundance between 80°E and 150°E from south of 63°S to ice edge was conducted by Australian research vessel in 1995/96 austral summer (Pauly et al. 1997). They reported krill densities of 5.5 g/m^2, 6.7 g/m^2, 4.2 g/m^2 and 9.2 g/m^2, in whole survey area, west area (80°E-115°E), east area (115°E-150°E) and shelf break area, respectively. Those densities were significantly lower than those reported in this paper, though it was difficult to compare the two results directly because survey coverage, design and timing were totally different from each other. Quite significant inter annual variability of biomass densities caused by environmental factors were reported in the Cooperation Sea (50°E-85°E) (Pakhomov, 2000) and in the South Shetland Islands region (Hewitt and Demer, 2003). Such inter-annual variability could explain the differences but frequent surveys in this area should be conducted in future to clarify the existence of the inter-annual variability and the causes of variability. Acoustic survey in the Ross Sea region was conducted in December to January in 1989/1990 austral summer (Azzali and Kalinowski, 1997). They reported krill biomass densities as 9 g/m^2 (≈ 32 t/n.mile^2) in the end of December and at beginning of January, and 11 g/m^2

(≈ 39 t/n.mile^2) in January. Those densities were similar to values reported in this paper except 2000/2001 austral summer (6.8g/m^2). It was reported that primary productivity in the mid December in 2000 was mach lower than previous years based on the satellite observation, because presence of the large ice berg inhibited normal drift of pack ice resulting in heavier spring/summer pack ice cover (Arigo, et al., 2002). Lower primary production in the Ross Sea in 2000/2001 could reduce the biomass density of krill.

It should be noted that highest biomass recorded in Area V in 1998/1999 especially in V-NW and V-SW. In 1998/99, those two strata were surveyed earlier about a moth than latter two years (2000/2001 and 2002/2003). V-NW and V-SW were surveyed in mid January to mid February which in 1998/1999 while they were surveyed in mid February to at beginning of March in latter two years. Intra-annual variability in krill abundance was reported around South Georgia (Brierley, et al., 2002). They reported that krill abundance late (March) austral summer was significantly lower than that in January. Such intra-annual variability of krill abundance could explain the abundance difference among three survey years in V-NW and in V-SW. Effect of intra-annual variability of krill abundance should be considered in data from III-E and VI-W where surveys were conducted in either December or March. The reasons of the seasonal differences of krill biomass could be either or combination of 1) onshore migration of krill in autumn to winter (Siegel et al., 1997) and 2) depletion of krill by predators (Brierley et al. 2002).

There were two main categories of limitations to interpret the result of this analysis. First category of limitation was applied to acoustic survey of krill in general. Those general limitations were 1) background krill which could not be detected by echo sounder because of low density, 2) krill refuge which meant that krill could distribute where the survey vessel could not enter such as under sea ice and 3) surface krill which meant that krill could distribute shallower than the transducers (Nicol et al., 2000(b)). Those three general limitations of abundance estimation of krill using echo sounder would contribute to underestimation of krill biomass. The other category of limitation was applied specifically to this analysis. Though krill identification using ΔMVBS between 120kHz and 38kHz have been well established, there was some uncertainty associated species identification of mark on echogram because no net sampling was conducted in the analysis presented here. Along with this, there was no in situ length frequency and weight data of krill to convert acoustic backscattering to biomass. This was also the source of bias. Poor sea condition for echo sounder survey in Northern Stratum of Area IV in 2000/2001 resulted in poor survey coverage. Calibration of echo sounder is very important because subtle parameter setting change will results in large effect on biomass estimation of krill. Because there was no calibration result in 2002/03, interpretation of the result in that year may need caution.

Over all, the results presented here provided general distribution and biomass patterns in the survey area. Following points should be considered to improve the echo sounder survey in future: 1) survey should be conducted in peak abundance season of krill (January and February) to minimize seasonal effect on abundance estimation, 2) survey should be conducted in same area in same survey timing to interpret yearly changes, 3) target net sampling should be conducted to identify species compositions of marks detected by the echo sounder so that appropriate amount of backscattering can allocate to krill and 4) calibration must be conducted every year to set appropriate parameters in the echo sounder.

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Table 1. Density and biomass in each stratum in Area IV and eastern part of Area III in 1999/2000 and 2001/2002

Stratum	Year	Date	Number of transects	Surveyed distances (n.miles)	Surveyed area (n.mile^2)	Mean density (g/m^2)	Biomass (Million t)	CV (%)
III-E-F	1999/2000	12/5/99-12/26/99	13	1,749	356,046	13.232	16.160	29.9
	2001/2002	11/29/01-12/24/01	8	1,116	354,965	34.519	42.027	30.2
IV-NW	1999/2000	12/27/99-1/11/00	5	1,117	236,307	19.014	15.411	54.1
	2001/2002	12/25/01-1/8/02	2	165	200,738	18.283	12.588	49.3
IV-NE	1999/2000	1/11/00-1/26/00	5	1,257	229,576	20.285	15.973	33.7
	2001/2002	1/9/02-1/25/02	5	582	223,108	14.191	10.860	50.9
IV-SE	1999/2000	1/28/00-2/18/00	15	1,061	33,129	16.288	1.851	28.9
	2001/2002	1/26/02-2/8/02	17	1,092	66,790	20.275	4.645	27.7
IV-SW	1999/2000	2/18/00-2/29/00 3/6/00-3/9/00	17	926	34,825	13.711	1.638	21.8
	2001/2002	2/10/02-2/21-02	14	975	61,517	41.016	8.654	15.9
IV-PB	1999/2000	3/1/00-3/6/00	4	428	27,000	16.736	1.550	22.6
	2001/2002	2/22/02-2/27-02	3	432	29,155	13.738	1.374	44.0
III-E-S	1999/2000	-	-	-	-	-	-	-
	2001/2002	2/28/02-3/8-02	3	300	525,715	56.754	102.337	57.8

Table 2. Density and biomass in each stratum in Area V and western part of Area VI from 1998/1999 to 2002/2003.

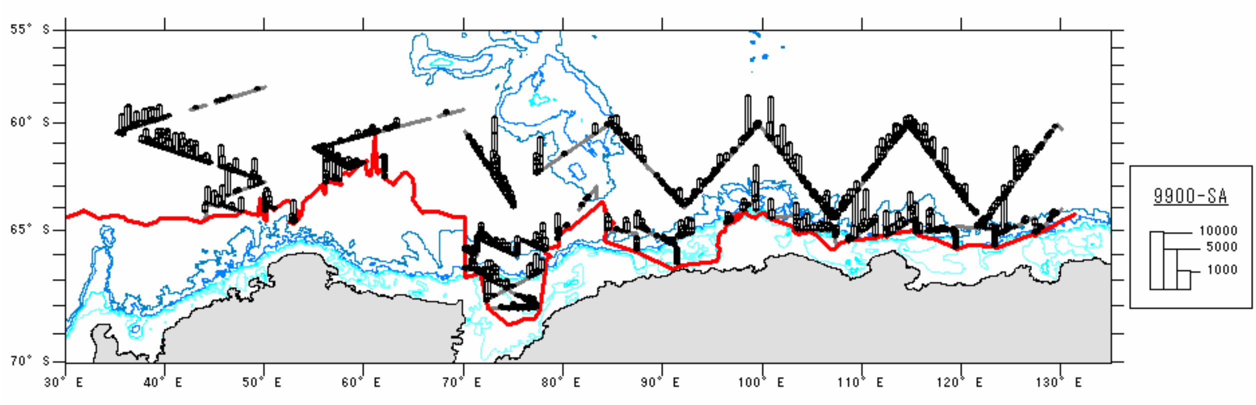
Stratum	Year	Date	Number of transects	Surveyed distances (n.miles)	Surveyed area (n.mile^2)	Mean density (g/m^2)	Biomass (Million t)	CV (%)
VI-W-F	1998/1999	-	-	-	-	-	-	-
	2000/2001	12/11/00-12/31/00	5	658	290,908	3.386	3.379	60.6
	2002/2003	12/3/02-12/30/02	14	1,810	309,998	1.514	1.610	34.2
V-NE	1998/1999	-	-	-	-	-	-	-
	2000/2001	1/1/01-1/23/01	5	896	334,377	11.617	13.324	27.4
	2002/2003	1/5/03-1/25/03	9	1,329	338,026	5.717	6.628	27.3
V-NW	1998/1999	1/14/99-2/2/99	5	1,405	321,375	21.713	23.934	20.0
	2000/2001	2/10/01-2/23/01	4	565	249,712	1.273	1.090	19.4
	2002/2003	2/11/03-2/20/03 3/5/03-3/7/03	5	805	257,084	10.146	8.947	25.4
V-SW	1998/1999	2/3/99-2/21/99	17	1,152	45,455	25.326	3.948	33.5
	2000/2001	2/25/01-3/19/01	13	857	64,854	8.557	1.903	49.4
	2002/2003	2/21/03-3/5/03	5	377	65,671	16.844	3.794	20.0
V-SE	1998/1999	2/22/99-3/13/99	13	541	52,553	24.679	4.448	36.0
	2000/2001	1/24/01-2/9/01	15	1,401	105,458	6.498	2.350	30.5
	2002/2003	1/27/03-2/9/03	10	775	58,424	8.337	1.671	27.8
VI-E-S	1998/1999	3/14/99-3/28/99	12	590	316,727	0.210	0.229	67.0
	2000/2001	-	-	-	-	-	-	-
	2002/2003	-	-	-	-	-	-	-

Table 2. Densities of krill in Area IV and V from 1998/1999 to 2002/2003.

Area	Year	Surveyed area (n.mile^2)	Biomass (Million t)	CV (%)
IV	1999/2000	560,837	36.422	27.3
	2001/2002	581,308	38.121	22.4
V	1998/1999	419,383	32.331	16.1
	2000/2001	754,401	18.668	20.6
	2002/2003	719,205	21.039	14.5

Fig. 1. Distributions and densities of krill in Area IV and eastern part of Area III in 1999/2000 and 2001/2002. Densities were shown as mean backscattering area per square n. mile of survey transect (S_A) in square root scale. Bottom depth contour lines: (500m), (1000m), (1500m) and (2000m). Ice edge line: .

1999/2000



2001/2002

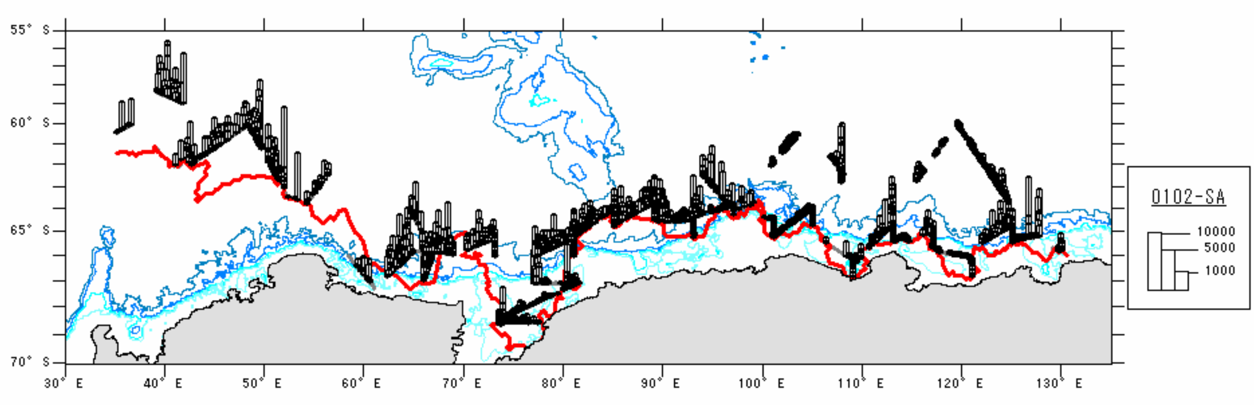


Fig. 2. Distributions and densities of krill in Area V and western part of Area VI from 1998/1999 to 2002/2003. Densities were shown as mean backscattering area per square n. mile of survey transect (S_A) in square root scale. Bottom depth contour lines: (500m), (1000m), (1500m) and (2000m). Ice edge line: .