Relating the distribution patterns of Antarctic minke whales with abiotic and biotic enviromental factors in the Ross Sea in 2005 using Kaiyo Maru-JARPA joint survey data.

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ABSTRACT

Influential environmental factors on distribution patterns of Antarctic minke whales at small scale (30n.miles segment) in the Ross Sea in austral summer were examined based on *Kaiyo Maru*-JARPA joint survey data using the generalized additive model (GAM). The joint survey was designed as a multi-disciplinary study combing surveys on cetacean, krill and oceanography. Relationship between distribution patterns of krill and the environmental factors was also studied. Three abiotic factors, distance from physical boundary (combination of coast, ice edge and shelf ice lines), integrated temperature and salinity mean from surface to 200m (ITEM-200 and ISAM-200) as well as latitude and longitude were used as covariates in the study. Distribution pattern of krill was described by ITEM-200 and ISAM-200 as well as latitude and longitude. Distributions of mean krill density increased at the salinity values higher than 34.5. The results indicated that krill distribution could be related to the presence of Modified Circumpolar Deep Water (MCDW). Distributions of Antarctic minke whale schools were explained by density of krill and ISAM-200 as well as latitude and longitude. In contrast to krill, the distributions of Antarctic minke whales increased at the salinity values lower than 34.4. The presence of Antarctic minke whales could be related to Antarctic Surface Water (AASW). The peak of the number of schools of Antarctic minke whales was observed around the $1 g/m^2$ of krill density and it levelled off toward both lower and higher densities of krill. It can be hypothesized, at the scale of this study, that Antarctic minke whales could be not directly searching krill aggregations but following the retreating sea ice (low salinity water) where the ooccurrence of moderate density of krill could be found in high probability. It is promising that distribution patterns of baleen whales in relation to environmental factors can be related if good data set from a multi-disciplinary study like *Kaiyo Maru*-JARPA joint survey is available. However modelling techniques applied to this study was preliminary and much improvement is necessary.

INTRODUCTION

Dismantling the mechanism of distribution patterns of baleen whales in the highly changing marine environment is interesting and important study from the pure and applied ecological science perspective. Interests from the applied ecology perspective are three folds. First, it is important to know how distribution pattern and abundance of baleen whales at the proximate level (e.g. snap shot type sighting survey) are affected by the abiotic and biotic environmental factors and the magnitudes of the effect should be quantified. Secondary, how the change in distribution patterns would affect the stock structure of baleen whales. Finally, how cumulating environmental changes at proximate level would ultimately affect the population dynamics of baleen whales at long time scales (e.g. Leaper et al., 2006). Classically, such environment-whale relationship in the Antarctic were studied using descriptive technique such as overlay mapping (Ichii, 1990; Matsuoka et al., 2003; Murase et al., 2002) and correlation analysis (Kasamatsu et al., 2000). Recently, Generalized Additive Model (GAM) based environment-whale modeling technique was developed for data collected in line transect survey (Hedley et al, 1999; 2004). The technique was applied to a multi-dsciplinal ecological study in the Western Antarctic Peninsula Region (Friedlaender et al., 2006). Applications of such modeling techniques have been wide spreading worldwide at various spatiotemporal scales but it is still in developing stage (Redfern et al., 2006 for review).

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. There was no expectation to investigate environment-whale relationship at small spatial scale using statistical modelling at the time of the JARPA interim meeting but newly developed modelling techniques allow us to test scaling effect on cetacean ecology using data collected in line transect survey. In this paper, effect of oceanographic conditions and presence of krill on distribution patterns of Antarctic minke whales (*Balaenoptera bonaerensis*) was examined at small spatial scale (approximately 3 by 30n.miles grid) using data from Kaiyo Maru-JARPA joint survey conduced in the Ross Sea in austral summer in 2005.

MATERIALS AND METHODS

Cetacean survey data

A sighting survey vessel, *Kyoshin Maru No. 2* (KS2, 368 GT) was engaged in the sighting survey of cetaceans in the Ross Sea (south of 69°S and approximately between 165°E and 155°W). Zigzag tracklines were constructed within the survey area. The starting points of tracklines were selected randomly. The sighting survey was conducted during daylight hours. The nominal steaming speed of SV on the tracklines was 10 knot. Three and two primary observers were in the top barrel and upper bridge, respectively. Principally, KS2 conducted the survey for 8 hours per day by Passing Mode and for 4 hours per day by Closing Mode in alternative manner. When the sightings during Closing Mode (primary sightings) were thought to be Antarctic minke whales, KS2 approaching to primary sightings to confirm species as well as the number of individuals in the schools. Sightings during approaching to primary sightings were secondary sightings and those were not included in this analysis. All sightings were passed in Passing Mode and treated as primary sightings. Sightings with estimated perpendicular distances more than 1.5n.miles were excluded in the analysis as in Branch and Butterworth (2001). The effective search half widths (*esw*) were estimated using a hazard-rate-model with no adjustment term. It was assumed that probability of detection of whales on the trackline is 1 (g(0)=1). Confirmed school size sighted during Closing Mode was used to estimate the mean school size (E(s)) according to the method described in Branch and Butterworth (2001). Details of estimation methods of esw and E(s) were descried in Hakamada et al. (2006). Estimated *esw* for Closing and Passing Mode was 0.609 and 0.766, respectively. Estimated E(s) was 1.673.

Krill density data

Details of the survey and the analysis methods for the estimation of krill biomass density were described in Murase et al. (2006). A quantitative echo sounder (Simrad EK500, Norway) with software version 5.30 on board the KS2 was used to collect data for the analysis. Data collected at 120 kHz were used. The data were not used in the analysis when the vessels deviated from the trackline such as during cetacean species confirmation. Distribution patterns and length frequency information for two species were collected from RMT and stomach contents of Antarctic minke whale. All data were analyzed using Echoview version 3.00 (SonarData, Australia). 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 krill (Hewitt et al., 2004). Mean biomass density (ρ, g/m^2) for every 30 n.mile of survey transect from 10 to 250m was used in this study.

Oceanographic observations

Oceanographic observations were conducted in the survey area by *Kaiyo Maru* (KM, 2630 GT) 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 ($\overline{Q}_{200}$) could be used as an index of distribution patterns of Antarctic krill. The index expresses not only absolute value but also gradient of temperature reflecting seasonal change in surface layer. Recently, ITEM-200 was used as an indicator of macorzooplankton community in the Antarctic (Hosie et al., 2000). In addition to ITEM-200, Integrated SAlinity Mean water depth from surface to 200m (ISAM-200) was calucuated as an indicator of water mass in the Ross Sea. ITEM-200 and ISAM-200 were extrapolated horizontally using kriging methods using a software, Surfer 8 (Golden Software Inc. 2002). Gird resolution for kriging was set as 30 by 30 n.miles. To get equidistance grid, geological reference data were converted to the equidistant cylindrical projection assuming that the equator was at 77^{o}S and 180^o. KM and KS2 recorded water temperature and salinity 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. 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.

Other covariates

Distance from the physical boundary (a combination of coast, ice shelf and sea ice edge lines) was used as a covariate for the analysis. In addition, latitude and longitude were used as covariates.

Spatial modeling

Two spatial models were considered in this study. First, the effect of environmental factors on the distribution patterns of krill was modeled using GAM with a normal error distribution. Mean krill density in each 30 n.miles segment was estimated as;

$$\ln(\rho_i + 0.01) = \vartheta_0 + \sum_k f_k(z_{ik}) + \varepsilon_i$$

where

ρ_i : mean krill biomass density (g/m^2) in the i-th segment with 30 n.mile length

θ_0 : an intercept

.f_k : nonparametric smooths of explanatory variables

z_{ik} : the value of the k-th covariate in the i-th segment

ε_i : an error term normally distributed

Here, a correction factor, 0.01, was used for the mean krill density because some of density took value of 0. Environmental covariates, original latitude, longitude (Original.Long, Original.Lat), distance from physical boundary (DistIce), ITEM-200 (Water.temp.Aveg.200m) and ISAM-200 (PSU.aveg.200m) were used for the initial model for krill distribution. A total of 5 terms in the parentheses were names used in the model. Same segments as sighting data were used in the model. Methods of transect segmentation were described below. Segments with no survey effort distance were omitted in the analysis.

Secondary, the effect of environmental factors on the distribution patterns of Antarctic minke whales schools was modeled. We used counts of schools in a segment as objective variables rather than abundance estimates themselves. In the GAM-based spatial model, shorter sighting effort distance in a segment is problematic for the model fitting because it could result in higher abundance estimates in the segment. In this analysis, each transects was divided into 30n.mile equidistance segments and the sighting effort data were pooled in each segment. By this way, Closing Mode data could be used in analysis instead of using only Passing Mode data because it could avoid short effort distance in a segment. Segments with no sighting effort distance were omitted in the analysis. The number of school of Antarctic minke whales in each segment was estimated as;

$$\log E(n_i) = \ln(a_i) + \theta_0 + \sum_k f_k(z_{ik})$$

where

n_i = the number of school in the ith segment

a_i = the offset variable (the area of the i-th segment calculated as 2 times *esw* times sighing effort distance)

θ_0 = an intercept

f_k = nonparametric smooths of explanatory variables

z_{ik} = the value of the k-th covariate for the i-th segment

Environmental covariates, original latitude, longitude (Original.Long, Original.Lat), mean krill density (mean.dens.kr.ln.001), distance from physical boundary (DistIce), ITEM-200 and ISAM-200 were used for the initial model. Terms in the parentheses were names used in the model. We assumed a Poisson distribution with overdispersion for the distribution of counts.

For both models, smoothness parameters were estimated with the generalized cross-validation (GCV). Model selection was also conducted using GCV scores. For this analyses, "mgcv" package (version 1.30-21) of R software (R Development Core Team, 2006) was employed.

RESULTS

GAM-based spatial models considered in this study and their GCV scores were summarize in Table 1. Initial model including latitude, longitude, distance from physical boundary, ITEM-200 and ISAM-200 had lowest GCV value (3.566) to predict mean krill density. Other two models either considering only latitude and longitude or environmental factors had higher GCV scores (4.3412 and 4.7648). The results suggested that combination of geological reference and environmental factors well described the distribution pattern of krill in the Ross Sea. General shapes of the functional forms for covariates were same for three models to predict mean krill density (Figs. 1-3). Two peaks in latitude (76-78°S and 70-72°S) suggested habitat segregation of two krill species, ice *(Euphausia crytallorophia*) and Antarctic krill (*E. superba*). Southern peak was related to the distribution of ice krill while northern peak was related to the distribution of Antarctic krill. Longitudinal distribution of krill was centered between 180° and 170°W. Mean krill density increased as ITEM-200 decreased. Mean krill density increased as ISAM-200 increased. Abrupt increase of mean krill density was observed at the salinity values higher than 34.5.

The model including interaction term of latitude and longitude, mean krill density and ISAM-200 had lowest GCV value (1.2765). General shapes of the functional forms for covariates were same between the selected model and the initial model (Figs. 4-5). Relationship between distribution of krill and Antarctic minke whales was not constant manner. Peak of the distribution of Antarctic minke whales were observed around the mean krill density of 1.0g/m^2 and it levelled off toward both low and high mean krill density sides. Then the distribution of Antarctic minke whales increased toward mean krill density 0g/m^2. In contrast to krill, the distributions of Antarctic minke whales increased at the salinity values lower than 34.4. The distributions of Antarctic minke whales were high in north central part of the Ross Sea.

DISCUSSION

Though the distribution pattern of Antarctic minke whales was partially explained by the presence of krill, the response was not monotonic increase with the increase of krill. Non liner relationship between the distribution of Antarctic minke and humpback whales, and acoustic volume backscattering levels as an index of presence of krill were reported in the Western Antarctic Peninsula Region in austral autumn (Friendlaender et al., 2006). In the Western Antarctic Peninsula Region in austral autumn, the distribution of Antarctic minke and humpback whales, and krill were increased and then stabilizing at Plateau. In contrast, the distribution of Antarctic minke whales was leveled off beyond the certain level of mean krill density in this study. Results from Friendlaender et al., (2006) and this study suggested that certain type of thresholding foraging behavior was existing as reported by Piatt and Methven (1992). Piatt and Methven (1992) reported that no minke whales were observed until capelin school density reached certain level in Witless Bay, Canada. The shape of the functional form for mean krill density in this study was different from the result in the Western Antarctic Peninsula Region. Few high mean krill densities were observed in the Ross Sea in 2005. Because of low encounter rate of high mean krill density, the distributions of Antarctic minke whales could decrease beyond the certain level of mean krill density in this study.

Though ISAM-200 was selected as an explanatory variable to predict krill and Antarctic minke whale distribution, responses were different between them. Distributions of krill increased at the salinity values higher than 34.5 whereas distribution of Antarctic minke whales increased at the salinity values lower than 34.4. There are 5 major water masses in the Ross Sea according to Jacobs and Giulivi (1999) and Russo (2000) and their characteristics were summarized in Table 2. The salinity values higher than 34.5 could be related to presence of Modified Circumpolar Deep Water (MCDW). It was reported that distribution of krill was associated with the presence of MCDW in the Ross Sea (Sala et al., 2002) and in the Western Antarctic Peninsula Region (Lawson et al, 2004). Although few clear relationship between environmental factors and krill have been demonstrated (Sigel, 2005), association between MCDW and krill in embayed area of the Antarctic could be existed. The salinity values lower than 34.4 could be related to the presence of Antarctic Surface Water (AASW). AASW is associated with presence of melting water of sea ice. The results suggested that Antarctic minke whales could be not searching high density area of krill but simply follow the retreating ice edge where probability of encounter rate to optimal krill density could be high. Such hypothesis should be tested using moving behavior of Antarctic minke whales. Satellite tag was attached to common minke whales (*B. acutorostrata*) in the North Atlantic to monitor their movement (Heide-Jorgensen et al, 2001). Study of movement of Antarctic minke whales should be conducted using satellite tag in the future study. The results of this study indicated that ISAM-200 could be used as an index of presence of certain types of water masses but actual relationship between ISAM-200 and water masses should be investigated in the future study.

This preliminarily modelling work revealed that spatial modelling can be applied to study of environment-baleen whale relationship as well as environment-krill relationship. Several points, however, should be improved in the future study. In this study, only the number of schools of Antarctic minke whales was considered. More individuals of Antarctic whales may concentre around the certain level of mean krill density. Therefore, direct analysis for the number of individuals or two-stage analysis (spatial distribution of whales school and school size) would be employed in the future analysis. Such a two-stage distribution can also be applied to the analysis for krill density. Mean krill density of 0 g/m^2 was recorded in some segments. To handle this, we used an ad-hoc way that a small value was added to the density. However, two-stage models such as delta-lognormal may be promising and therefore be considered in the future. Because geological feature was complex in the Ross Sea, handling of data around edge of the study area should be considered in the future study.

The results of this study indicated distribution patterns of baleen whales in relation to environmental factors can be related if good data set from a multi-disciplinary study like *Kaiyo Maru*-JARPA joint survey is available. Spatial modelling at global scale to map the distribution of marine mammals was attempted in recent year (Kaschner et al, 2006) but the model overlooked the small local scale processes. More local specific study of environment-baleen whale relationship should be conducted to construct accurate large scale spatial model.

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REFERENCES

Branch, T. A. and Butterworth, D. S. 2001. Southern Hemisphere minke whales: standardised abundance estimates from the 1978/79 to 1997/98 IDCR-SOWER surveys. J. Cetacean Rea and Manage. 3:143-174.

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.

Hakamada, T., Matsuoka, K. and Nishiwaki, S. 2006. An update of Antarctic minke whales abundance estimate based on JARPA data. Paper SC/D06/J6 presented to the JARPA Review Meeting, December 2006 (unpublished).

Hedley, S. L., Buckland, S. T. and Borchers, D. L. 1999. Spatial modelling from line transect data. J. Cetacean Rea and Manage. 1:255-264.

Hedley, S. L., Buckland, S. T. and Borchers, D. L. 2004. Spatial distance models. In Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L. and Thomas, L. (Eds.), Advanced distance sampling. Oxford University Press, Oxford, pp.48-70.

Heide-Jorgensen, M. P., Nordoy, E. S., Oien, N., Folkow, L. P., Kleivane, L., Blix, A . S., Jensen, M. V. and Laidre, K. L. 2001. Satellite tracking of minke whales (*Balaenoptera acutorostrata*) off the coast of northern Norway. J. Cetacean Rea and Manage. 3:175-178.

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.

Ichii, T. 1990. Distribution of Antarctic krill concentrations exploited by Japanese krill trawlers and minke whales. Proceedings of the NIPR Symposium on Polar Biology 3; 36-35.

Jacobs S.S. and Giulivi C.F. 1999. Thermohaline data and ocean circulation on the Ross Sea continental shelf. In: Spezie, G. and Manzella, G. M. R. (eds). Oceanography of the Ross Sea, Antarctic. Springer Verlag, Berlin, Heidelberg pp.3-16.

Kasamatsu, F., Ensor, P., Joyce, G. G. and Kimura, N. 2000. Distribution of minke whales in the Bellingshausen and Amundsen Seas (60°W-120°W), with special reference to environmental/physiographic variables. Fish. Oceanogr. 9:214-223.

Kaschner, K., Watson, R., Trites, A. W. and Pauly, D. 2006. Mapping world-wide distributions of marine mammals species using relative envriomental suitability (RES) model. Mar. Ecol. Prog. Ser. 316:285-310.

Lawson, G. L., Wiebe, P. H., Ashjian, C. J., Gallager, S. M., Davis, C. S. and Warren, J. D. 2004. Acoustically-inferred zooplankton distribution in relation to hydrography west of the Antarctic Peninsula. Deep Sea Res. II. 51:2041-2072.

Leaper, R., Cooke, J., Trathan, P., Reid, K., Rowntree, V. and Payne, R. 2006. Global climate drives southern right whale (Eubalaena australis) population dynamics. Biol. Lett. 2:289-292.

Matsuoka, K., Watanabe, T., Ichii, T., Shimada, H. and Nishiwaki, S. 2003. Large whale distributions (south of 60S, 35E-130E) in relation to the southern boundary of the ACC. In Antarctic Biology in a Global Contest, ed. by Huiske, A.H.L., Gieskes, W.C.C., Rozema, J., Schrno, R.M.L., van der Vies, S.M. and Wolff, W.J. Backhuys Publishers, Leiden, The Netherlands: 26-30.

Murase, H., Matsuoka, K., Ichii, T. and Nishiwaki, S. 2002. Relationship between the distribution of euphausiids and baleen whales in the Antarctic (35°E-145°W). Polar Biol., 2002. 25: 135-145.

Murase, H., Tamura, T., Matsuoka, K., Nishiwaki, S., Yasuma, H., Matsukura, R., Yabuki, T., Takao, Y., Taki, T., Hayashi, T. and Naganobu, M. 2006. 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 2004/05 using Kaiyo Maru-JARPA joint survey data. SC/D06/J24 presented to the JARPA Review Meeting, December 2006 (unpublished).

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.

Piatt, J. F. and Methven, D. A. 1992. Threshold foraging behavior of baleen whales. Mar. Ecol. Prog. Ser. 84:205-210.

Redfern, J. V., Ferguson, M. C., Becker, E. A., Hyrenbach, K. D., Good, C., Barlow, J., Kaschner, K., Baumgartner, M. F., Forney, K. A., Balance, L.T., Fauchald, P., Halpin, P., Hamazaki, T., Pershing, A. J., Qian, S. S., Read, A., Reilly, S. B., Torres. L. and Werne, F. 2006. Techniques for cetacean-habitat modelling. Mar. Ecol. Prog. Ser. 310:271-295.

Russo, A. 2000. Water mass characteristics during the ROSSMIZE cruise (Western Sector of the Ross Sea, November-December 1994). In: Faranda, F., Guglielmo, L. and Ianora, A. (eds.) Ross Sea ecology. Springer Verlag, Berlin, Heidelberg. pp.83-93.

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.

Siegel, V. Distribution and population dynamics of *Euphausia superba*: summary of recent findings. Polar Biol. 29:1-22.

Table 1. GAM based models considered in this study: (a) models for mean krill density and (b) models for number of school of Antarctic minke whale. Initial model was marked with “*”.

(a)

	Model	GCV Score
*	mean.dens.kr.ln.001~s(Original.Lat)+s(Original.Long)+s(DistIce)+s(Water.temp.Aveg.200m)+s(PSU.aveg.200m)	3.566
	mean.dens.kr.ln.001~s(Original.Lat)+s(Original.Long)	4.3412
	mean.dens.kr.ln.001~s(DistIce)+s(Water.temp.Aveg.200m)+s(PSU.aveg.200m)	4.7648

(b)

	Model	GCV Score
*	SumAllSchool~offset(log(2*esw*Effort.dist))+s(Original.Lat)+s(Original.Long)+s(mean.dens.kr.ln.001)+s(DistIce)+s(Water.temp.Aveg.200m)+s(PSU.aveg.200m)	1.2842
	SumAllSchool~offset(log(2*esw*Effort.dist))+s(Original.Long,Original.Lat)+s(mean.dens.kr.ln.001)+s(PSU.aveg.200m)	1.2765

Table 2. Characteristics of major water masses in the Ross Sea based on Jacobs and Giulivi (1999) and Russo (2000). Names in parenthesis are defined by Russo (2000).

Water Mass	Acronym	Potential Temprature (C°)	Salinity (PSU)	Depth (m)	Main location in the Ross Sea
High Salinity Shelf Water	HSSW	<-1.91	34.6<	100<	Subsurface western sector
Low Salinity Shelf Water	LSSW	-1.8~-1.5	34.4~34.6	100<	Subsruface eastern sector
Ice Shelf Water	ISW	<-1.92	34.6<	50<	West-central and Southwestern sector
Modified Circumpolar Deep Water (Warm Core)	MCDW (WMCO)	-1.5~1.0	34.4~34.6	100~400	Near the continental shelf
Antarctic Surface Water (Ross Sea Surface Water)	AASW (RSSW)	-1.9~2.0	<34.5	<50	Whole area

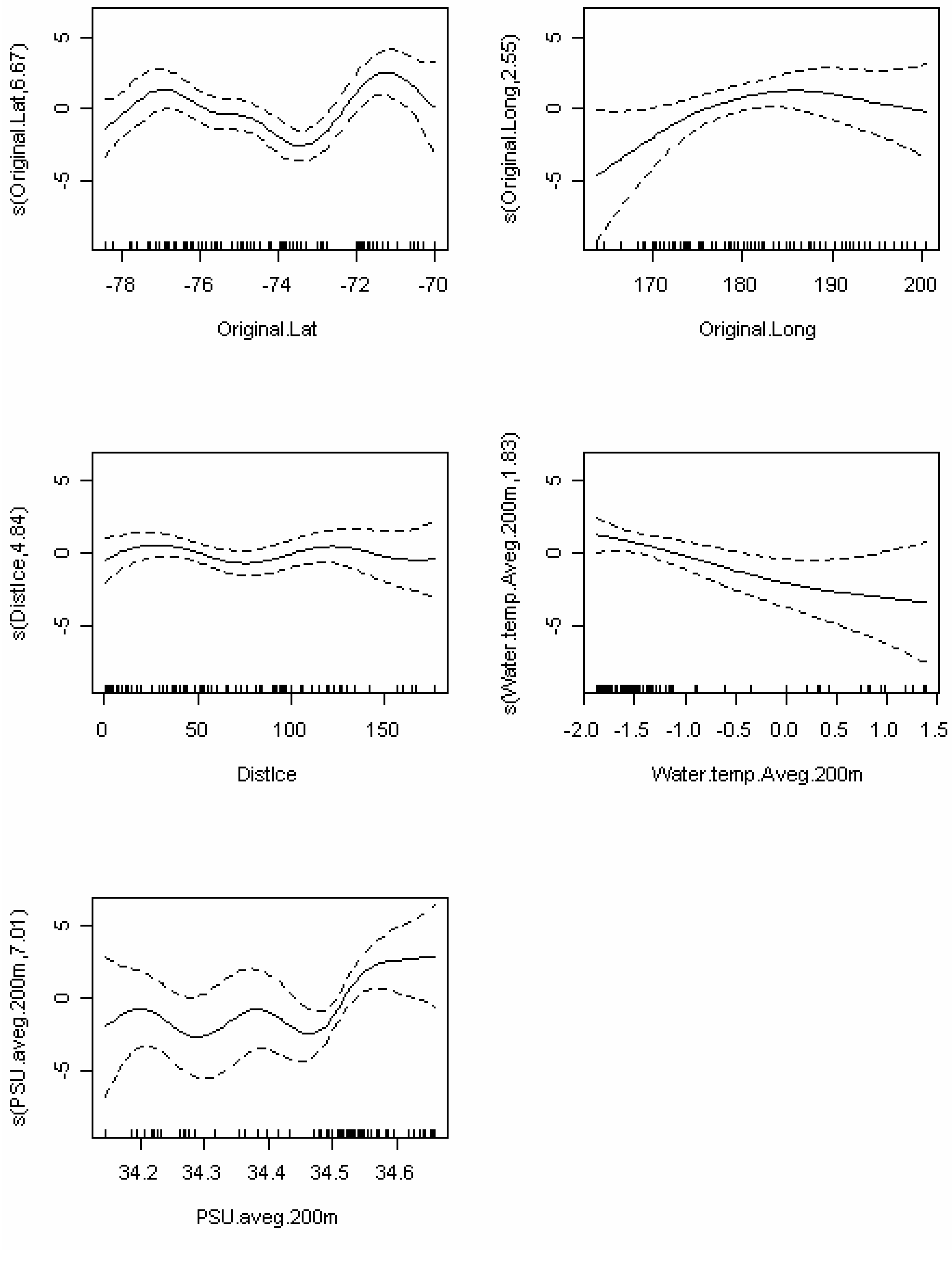

Fig. 1. Shapes of the functional forms for covariates to model the distribution pattern of krill. All covariates considered in this study were shown.

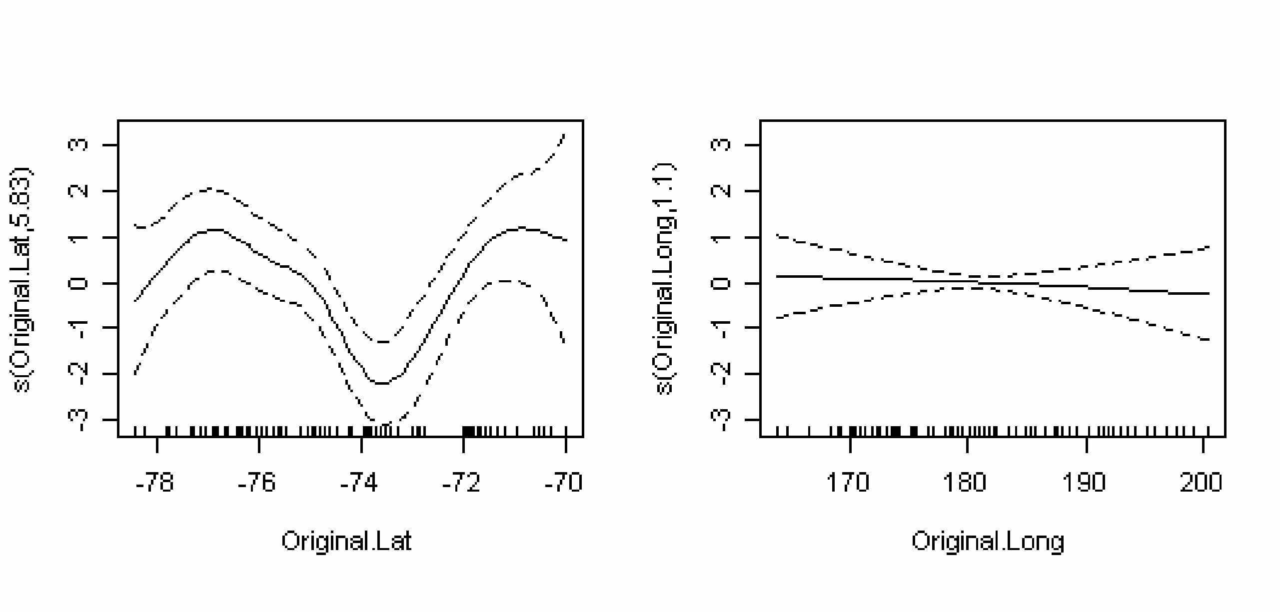

Fig.2. Shapes of the functional forms for covariates to model the distribution pattern of krill. The result of model only including latitude and longitude was shown.

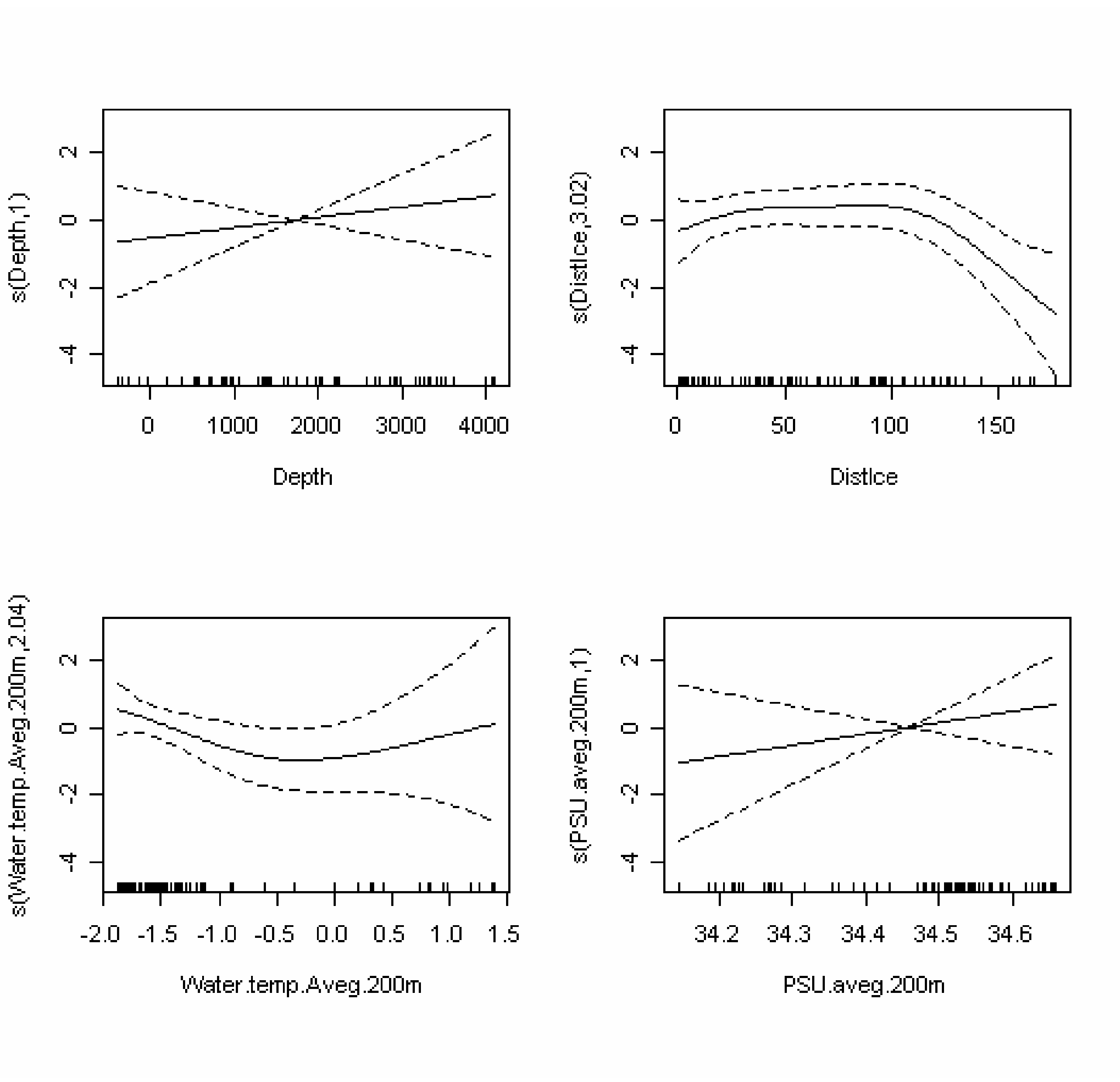

Fig.3. Shapes of the functional forms for covariates to model the distribution pattern of krill. The result of model only including environmental factors was shown.

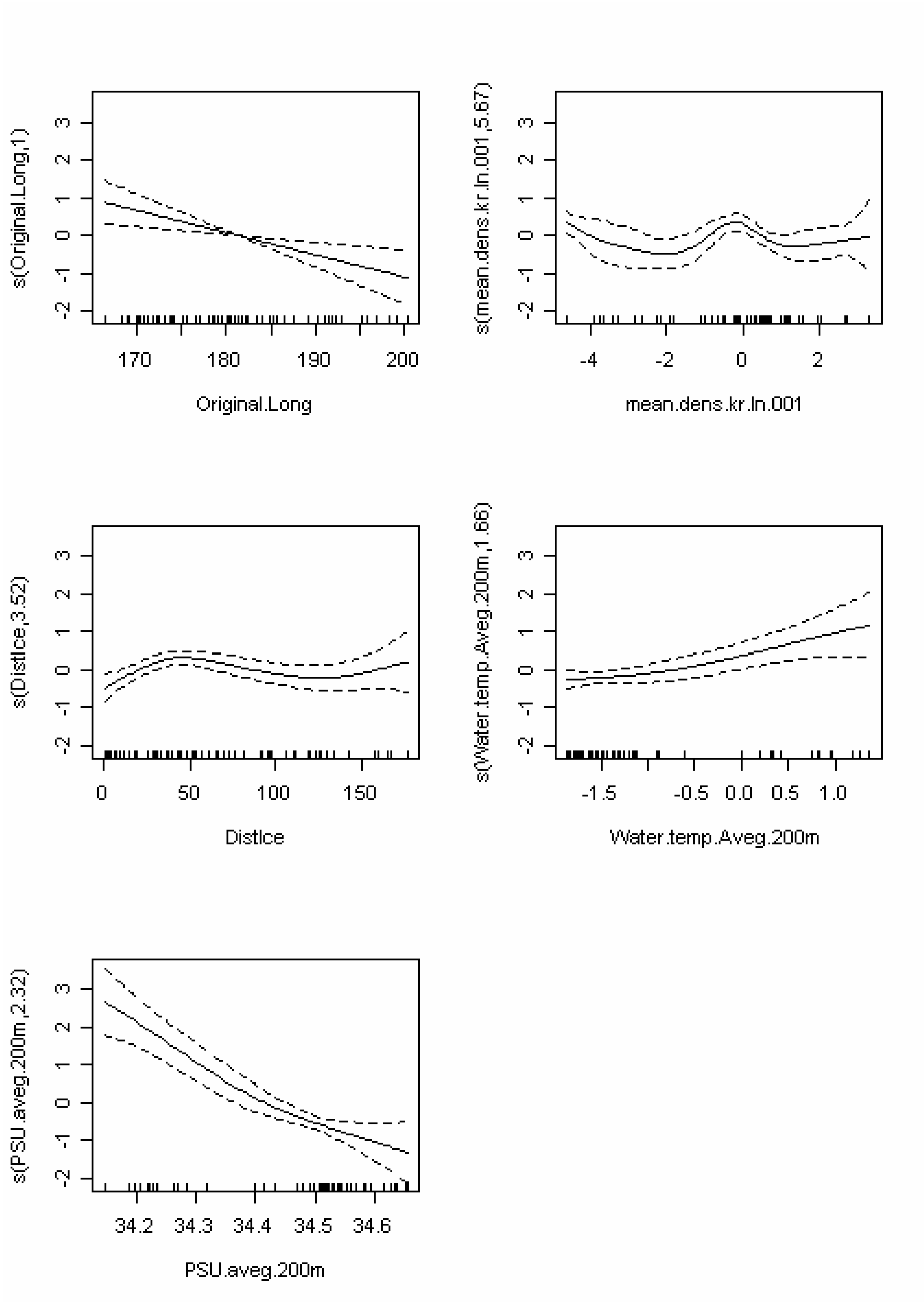

Fig. 4. Shapes of the functional forms for covariates to model the distribution pattern of Antarctic minke whales. All covariates considered in this study were shown.

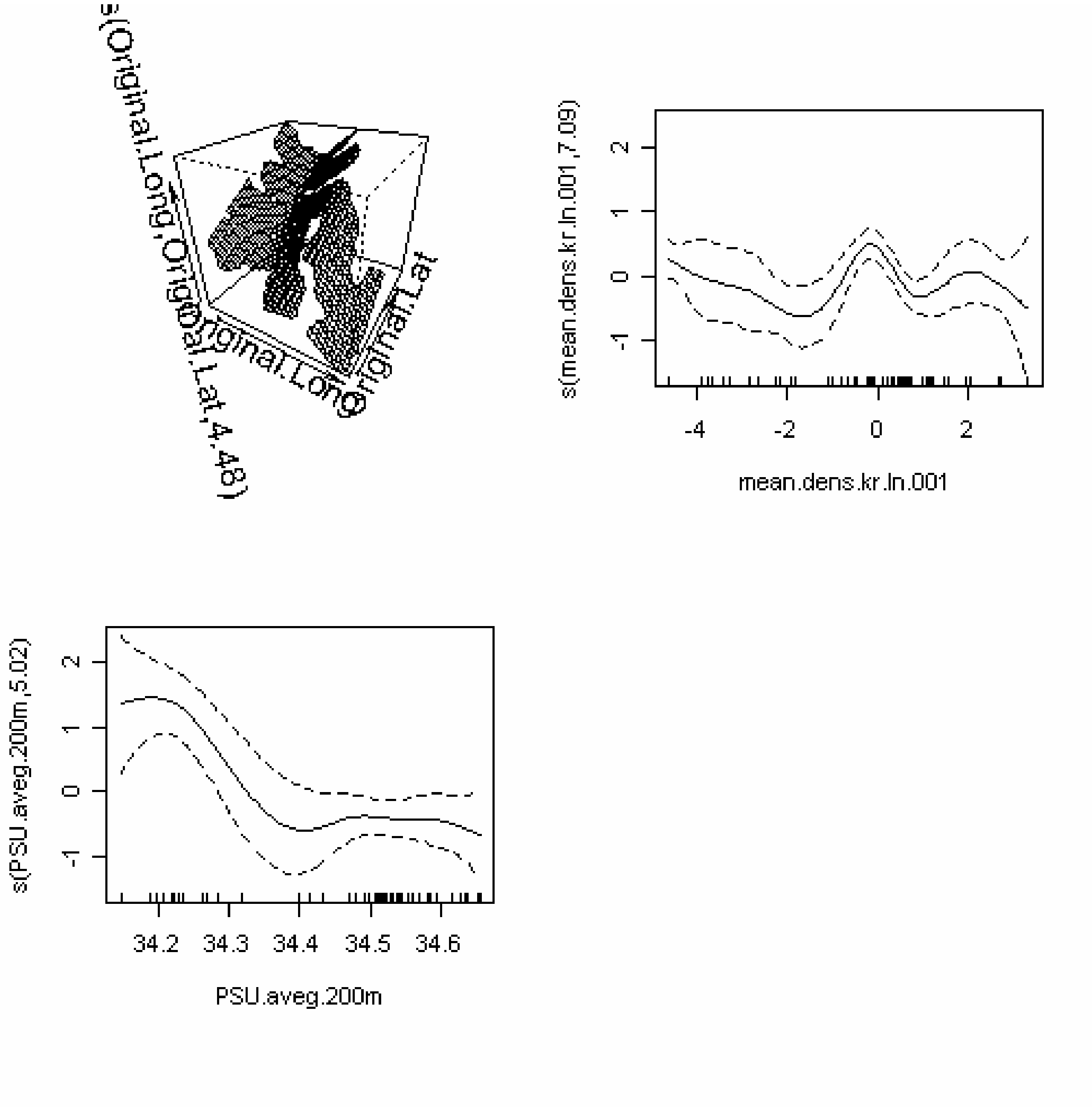

Fig. 5. Shapes of the functional forms for covariates selected to predict the distribution pattern of Antarctic minke whales.