Exploration of GAM based abundance estimation method of Antarctic minke whales to take into account environmental effects: A case study in the Ross Sea

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ABSTRACT

Practicably of GAM for the abundance estimation of Antarctic minke whales was explored using data obtained by the *Kaiyo Maru*-JARPA joint survey, in the Ross Sea in austral summer in 2005. The joint survey was designed as a multi-disciplinary study combing surveys on cetacean, krill and oceanography. A hierarchical structure with three strata of spatial models is considered in this study: (1) presence and absence of Antarctic and ice krill, (2) biomass density of Antarctic and ice krill and (3) school counts of Antarctic minke whales. Three abiotic factors, distance from physical boundary (combination of coast, ice edge and shelf ice lines) and integrated temperature and salinity mean from surface to 200m (ITEM-200 and ISAM-200) as well as latitude and longitude were used as covariates for models (1) and (2). Predicted surfaces of krill were also used as covariates in the model (3). Scale of interactions between Antarctic minke whales and the environmental factors were investigated at a segment length of 5 n.miles. The distribution of ice and Antarctic krill could be related to the presence of AASW. Predicted school counts of Antarctic minke whales were low where ice krill distributed while it was high where Antarctic krill distributed. Abundance of Antarctic minke whales could relate to the biomass of Antarctic krill. School counts of Antarctic whales increased as ITEM-200 increased while they increased as ISAM-200 decreased. Abundance estimates in the Ross Sea showed large fluctuation notably between CPII and CPIII. GAM based model can contribute to evaluate the reasons of abundance fluctuation if environmental data are available. Continuation of the multi-disciplinal ecological survey like the *Kaiyo Maru*-JARPA joint survey is critically important to detect interactions between fluctuations of abundance of Antarctic minke whales and their environment.

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 if it is exist. 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 the line transect survey (Hedley et al, 1999; 2004). The technique was applied to a multi-disciplinary 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) was conducted during the austral summer every year from 1987/1988 to 2004/2005. A multi-disciplinal ecological survey, Kaiyo Maru-JARPA joint survey, was conducted in the Ross Sea in 2004/2005. Because the Ross Sea is a unique region of the Antarctic in terms of its physics and its ecology (Smith, et al., 2007), this study provided good opportunity to test whether the GAM based model can be practicable in such a unique marine ecosystem. The joint survey was designed as a multi-disciplinary study combing surveys on cetacean, krill and oceanography. In this paper, abundance estimation of Antarctic minke whales using GAM base count model was explored to take account the environmental effects.

MATERIALS 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 krill survey. Tracklines of KM was set on four longitudinal lines: 175°E, 180°, 175°W, 170°W and 165°25'W. Zigzag trcaklines were 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).

Cetacean sighting survey data

A sighting survey vessel, KS2 was engaged in the sighting survey of cetaceans. 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 KS2 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.

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). Biomass density of two species of krill, ice krill (*Euphausia crysallorophias*) and Antarctic krill (*E. superba*), were used in the analysis. 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. A quantitative echo sounder (Simrad EK500, Norway) with software version 5.30 on board 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 (g/m^2) for every 5 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 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 ($\overline{Q}_{200}$) could be used as an index of distribution patterns of Antarctic krill. The index expresses not only absolute value but also the 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 5 by 5 n.miles. To get equidistance grid, geological reference data were converted to the equidistant cylindrical projection assuming that the equator was at 77^oS 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). 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

A hierarchical structure with three strata of spatial models is considered in this study.

The presence and absence of krill

Let Y_i be the biomass density (g/m^2) of krill in the i-th segment, and X_i denote the presence or absence of krill as

$$X_i = \begin{cases} 1 & if\ Y_i > 0, \\ 0 & o.w. \end{cases}$$

Each transect was divided into 5 n.miles equidistance segments and the average biomass density was calculated for each segment. Then we consider a spatial smoother using GAM having a binomial error distribution with the logistic link function,

$$\log \frac{p_i}{1-p_i} = \theta_o^{(1)} + \sum_k f_k^{(1)}(z_{ik}^{(1)}),$$

where

$p_i = E[X_i]$: probability of presence of ice/Antarctic krill in the i-th segment

$\theta_o^{(1)}$: an intercept

$f_k^{(1)}$: a nonparametric smooth function of the k-th explanatory variable

$z_{ik}^{(1)}$: the value of the k-th covariate in the i-th segment

The presence and absence of ice and Antarctic krill was estimated separately. Environmental covariates, distance from physical boundary (*DistIce*), ITEM-200 (*ITEM.200*) and ISAM-200 (*ITEM.200*) as well as Latitude and longitude (*Lat*, *Long*) were used for the initial model. The values of covariates were taken from the nearest grids from the mid points of the segments. Terms in the parentheses were names used in the model.

Biomass density of krill

The biomass density (g/m^2) of krill given presence is modeled using GAM based on a normal error distribution with the identical link function,

$$\log Y_i \,|_{Y_i>0} = \log \lambda_i + \varepsilon_i,$$

$$\log \lambda_i = \theta_o^{(2)} + \sum_k f_k^{(2)}(z_{ik}^{(2)}),$$

where

λ_i: the logarithm of the expected krill biomass density given its presence in the i-th segment

$\theta_o^{(2)}$: an intercept

$f_k^{(2)}$: a nonparametric smooth function of the k-th explanatory variable

$z_{ik}^{(2)}$: the value of the k-th covariate in the i-th segment

ε_i : an error term distributed as N(0,σ^2)

Environmental covariates, *DistIce*, *ITEM.200* and *ITEM.200* as well as *Lat* and *Long* were used for the initial model. The values of covariates were taken from the nearest grids from the mid points of the segments. Then, the biomass density surfaces for ice and Antarctic krill are estimated as the products of p_i and λ_i

School counts of Antarctic minke whales

Counts of schools of Antarctic minke whales are modeled using GAM having a Poisson error distribution with a logarithmic link function. 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 particular segment. In this analysis, each transect was divided into 5 n.miles 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 with the following count model;

$$\log E(n_i) = \ln(a_i) + \theta_0^{(3)} + \sum_k f_k^{(3)}(z_{ik}^{(3)})$$

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)

$\theta_o^{(3)}$: an intercept

$f_k^{(3)}$: a nonparametric smooth functions of the *k*-th explanatory variable

$z_{ik}^{(3)}$: the value of the *k*-th covariate for the *i*-th segment

Environmental covariates, *DistIce*, *ITEM.200* and *ITEM.200* as well as *Lat* and *Long* were used for the initial model. The values of covariates were taken from the nearest grids from the mid points of the segments. In addition, predicted biomass densities of ice and Antarctic krill (*pred.cry* and *pred.sup*) for the segements were also used as covariates. Terms in the parentheses were names used in the model. An Interaction term of latitude and Longitude (Long*Lat) was also considered in the model.

4) Estimation of smoothness parameter and model selection

Smoothness parameters were estimated with the generalized cross-validation (GCV). Model selection was also conducted using GCV scores. For this analyses, "mgcv" package (version 1.30-23) of R software (R Development Core Team, 2006) was employed.

RESULTS

Initial models for the estimation of biomass densities of ice and Antarctic krill contained latitude but it was discarded regardless of GCV score because it overestimated the biomass densities at certain longitude. Shapes of the functional forms for selected covariates to model the presence and absence of Antarctic krill were shown in Fig. 1. Shapes of the functional forms for selected covariates to model the biomass density of Antarctic krill given presence were shown in Fig. 2. Those figures suggested that distribution and biomass of Antarctic krill increased as latitude increase. The probability of presence of Antarctic krill increased as ITEM-200 decreased while peak of biomass density showed bimodal shape (at -1.5 and -0.5 °C). The shape of the functional form of ISAM-200 in the biomass prediction model was relatively flat between 34.1 and 34.4 and it levelled off below and upper side of those salinities. Shapes of the functional forms for selected covariates to model the presence and absence of ice krill were shown in Fig. 3. Shapes of the functional forms for selected covariates to model the biomass density of ice krill given presence were shown in Fig. 4. Shapes of the functional forms for latitude and distance from the physical boundary were complex. Probability of occurrence of ice krill increased as ITEM-200 decreased. The peak of functional form for ISAM-200 was salinity between 34.3 and 34.4. Predicted density surface of biomass density of ice and Antarctic krill was shown in Fig. 5. Overall, predicted density surface well capture the observed krill distribution and biomass density.

Maps of distribution patterns of covariates to model the school counts of Antarctic minke whales were shown in Fig. 6. Shapes of the functional forms for selected covariates to model the school counts of Antarctic minke whales were shown in Fig. 7. The school counts increased as the predicted biomass density of Antarctic krill increased. Shapes of the functional forms for ice krill was relatively flat and it levelled off as it increased. The school counts increased as ITEM-200 increased. In contrast, the school count increased as ISAM-200 decreased. Predicted density surface of the school counts of Antarctic minke whales was shown in Fig. 8. Overall, predicted density surface captured the actual distribution pattern of Antarctic minke whales but fitting was not so good in the northern part of the Ross Sea.

DISCUSSION

The results suggested that distribution of ice and Antarctic krill in the Ross Sea was related to the oceanographic conditions. This study was the first attempt to relate the distribution of ice and Antarctic krill and the environmental factors in the Ross Sea. There are 5 major water masses in the Ross Sea according to Jacobs and Giulivi (1999) and Russo (2000) and they are summarized in Table 1. Even though the relationships between water mass structures and, ITEM-200 and ISAM-200 is not clear at this stage, the distribution of ice and Antarctic krill could related to the presence of AASW. Because response of biomass densities to the environmental factors were complex as suggested by the shapes of functional forms of selected covariates, further study is required to adding ecologically meaningful interpretation of the results.

The school counts of Antarctic minke whales increased as the biomass density of Antarctic minke whales increased while it decreased as the biomass density of ice krill increased. The results suggested that Antarctic minke whales in the Ross Sea could show the prey selection toward Antarctic krill. Comparison between stomach contents weight in Antarctic minke whales and biomass of krill should be conducted in the future research to confirm the existence of prey selection. Predicted school counts of Antarctic minke whales were low where ice krill distributed while it was high where Antarctic krill presented. Abundance of Antarctic minke whales could positively relate to the biomass of Antarctic krill. The distribution of Antarctic minke whales in the Ross Sea was related to the oceanographic condition. It seemed that the distribution of Antarctic minke whales could related to the AASW. AASW is associated with presence of melting water of sea ice. The results suggested that Antarctic minke whales could be follow the retreating ice edge. Ainley et al. (2006) reported that Antarctic minke whales were observed in the polynya in December and the distribution was decreased as season progress. It can be postulated that Antarctic minke whales could mainly distributed in the small polynya in early summer then they could propagate throughout the Ross Sea to follow the receding sea ice. 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.

The Ross Sea faced at least two extreme naturally induced ecosystem disturbances in recent years (2000/01 and 2002/03). Both disturbances were caused by calving of enormous icebergs, namely B-15 and C-19, and they caused anomalous sea ice covered hence resulted in unusual low chlorophyll-a concentrations in the Ross Sea (Arrigo, et al., 2002, Arrigo and Van Dijken, 2003). The International Whaling Commission (IWC) has conducted the Antarctic minke whale abundance assessment cruises in the Ross Sea. The surveys were conducted in 1980/81 as a part of the first circumpolar survey (CPI) in 1985/86, as a part of the second circumpolar survey (CPII) and in 2003/2004 as a part of the third circumpolar survey (CPIII). CPIII in the Ross Sea was conducted just a year after the ecological disturbance. The Ross Sea region is the part of Area V of the IWC's baleen whale management area. It was reported that abundance of Antarctic minke whales in Area V showed noticeable change from CPII (278,693 individuals) to CPIII (140,336 individuals) (Branch, 2006) though the reason of the change is not specified at this stage. Because CPIII in the Ross Sea was conducted just after the ecological disturbance due to the icebergs, low abundance estimate of Antarctic minke whales in CPIII might be related to the ecological disturbance. A phytoplankton species, the prymnesiophyte *Phaeocystis antarctica*, dominated in the south western shelf while diatoms dominated in the northern shelf (Arrigo, et al., 2003). The results of this study suggested that the area of high density of ice krill was coincided with the area of high density of *P. Antarctica*. The low *P. Antarctica* concentrations in the Ross Sea in 2002/2003 could cause low density of ice krill in 2003/2004. The difference of abundance estimate of Antarctic minke whales between CPII and CPII in the southern portion of the Ross Sea (South of 74°S) was remarkable (CPII=94,403 individuals ,CPIII=12,110 individuals in IO mode) though surveyed areas were also different (CPII=107,717 n.mile^2, CPIII=56,444 n.mile^2) (Branch, 2006). Change of the survey area was caused by the difference of sea ice extent between CPII and CPIII. Antarctic minke whales from 165°E at least to 145°W belonged to a western South Pacific stock (P-stock) (Pastene, 2006). It is feasible to hypothesize that the distribution pattern of P-stock could change within the distribution range in response to the environmental factors. The reasons of the difference of abundance of Antarctic minke whales between CPII and CPIII can be explained by the difference of environmental factors between two surveys. The effect of environmental factors on abudance estimation of Antarctic minke whales can be assessed using a GAM based model.

This preliminarily modelling work revealed that spatial modelling can be applied to study of environment-baleen whale relationship. Several points, however, should be improved in the future study. School sizes of Antarctic minke whales could also related to the environmental variables. As in the case of krill biomass density prediction method in this study, two stage model can be applied to the estimation of Antarctic minke whale abundance. The two stage model would constitute of the school density and the School size estimation models. Due to the difficulty of the interpretation of the results and the experimental modelling procedures, it could be difficult to apply a GAM based model to get absolute abundance of cetacean. Yet it is very useful tool to depict the distribution pattern using estimated surface. It can be applied to the future ecological 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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Table 1. 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

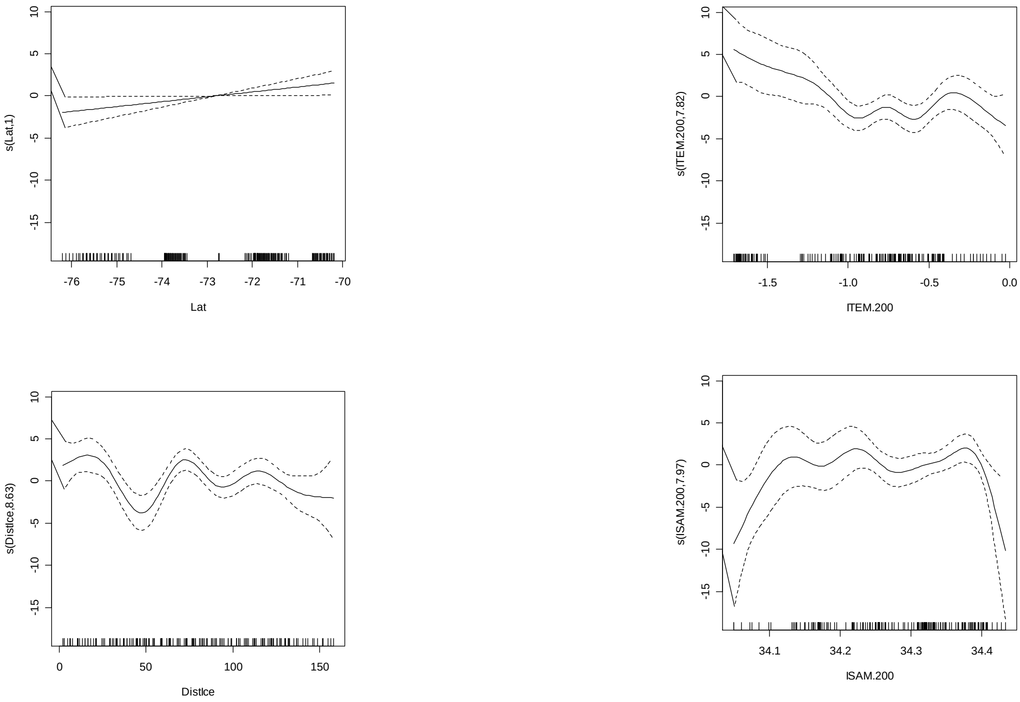

Fig. 1. Shapes of the functional forms for selected covariates to model the presence/absence of Antarctic krill.

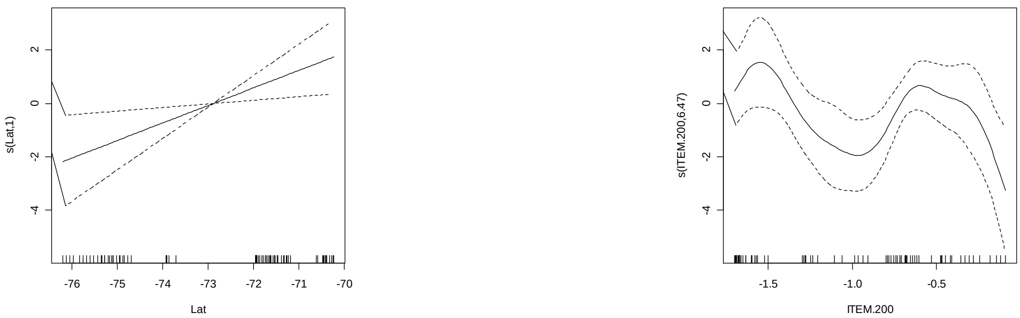

Fig. 2. Shapes of the functional forms for selected covariates to model the density of Antarctic krill.

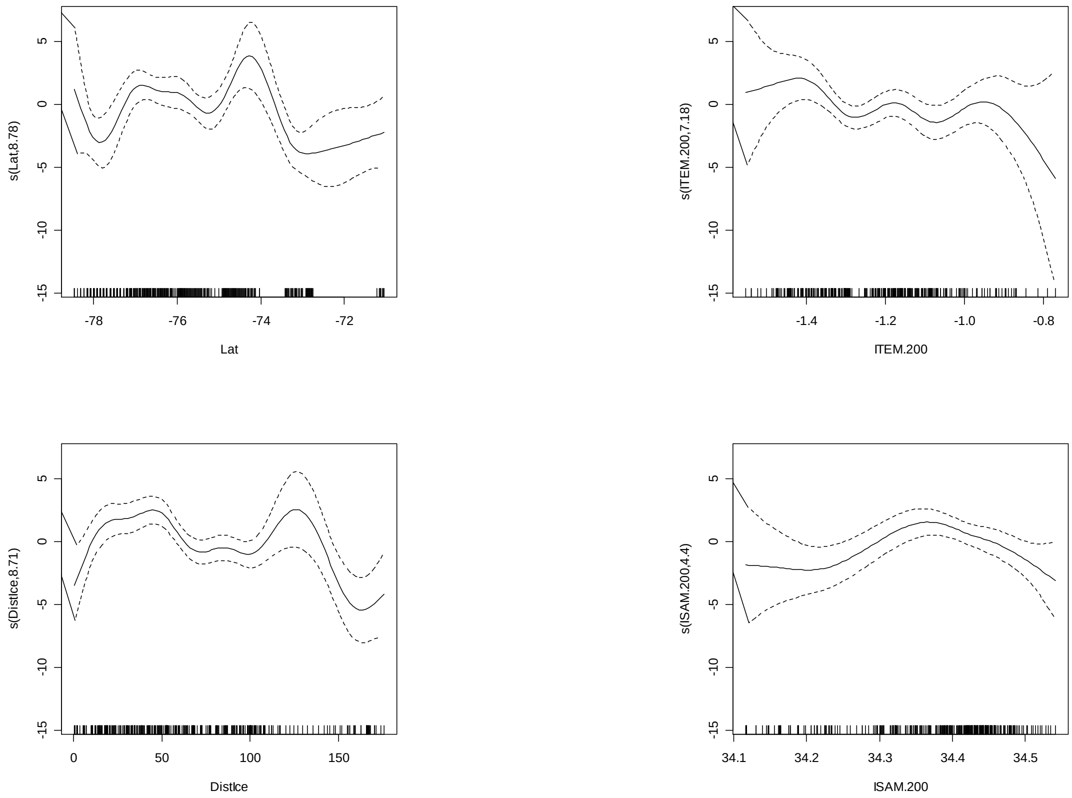

Fig. 3. Shapes of the functional forms for selected covariates to model the presence/absence of ice krill.

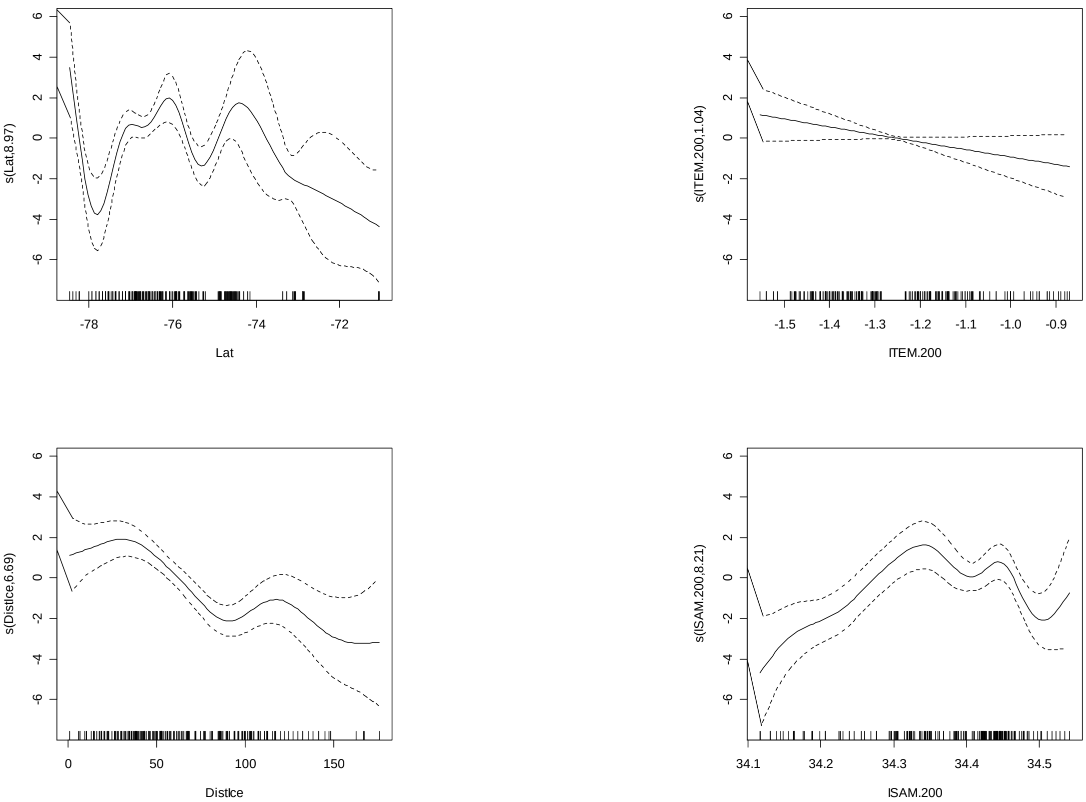

Fig. 4. Shapes of the functional forms for selected covariates to model the density of ice krill.

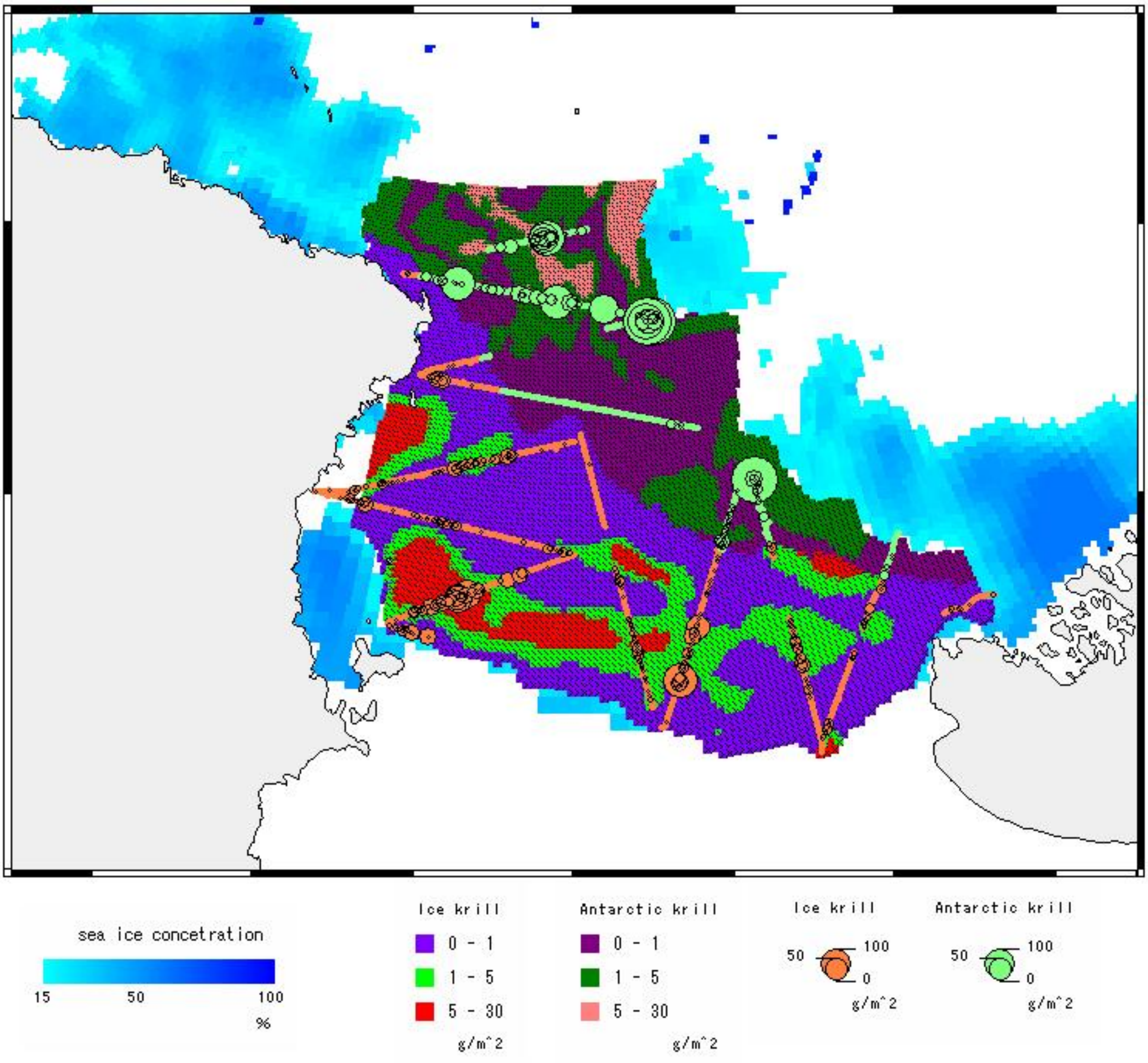

Fig.5. Predicted densitiy surface of biomass densities of ice and Antarctic krill. Surveyed tracklines and obserbed density (g/m^2) were overlaid on the map. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the map.

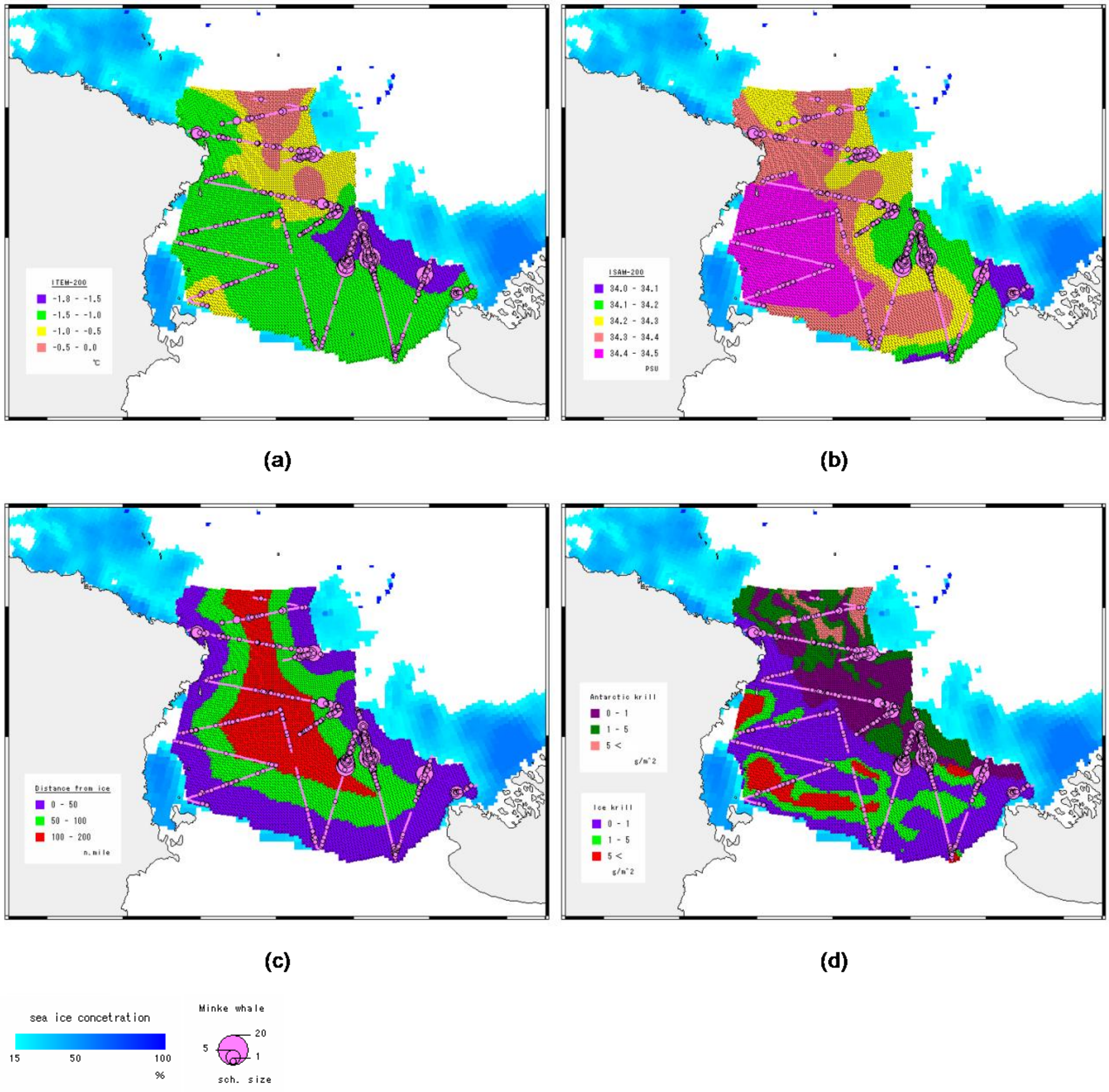

Fig. 6. Maps of covariates used in the school count model of Antarctic minke whales: (a) ITEM-200, (b) ISAM-200, (c) distance from physical boundary and (d) densities of ice and Antarctic krill. Surveyed tracklines and positions of sightings of Antarctic minke whales and their school sizes are overlaid on the maps. 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.

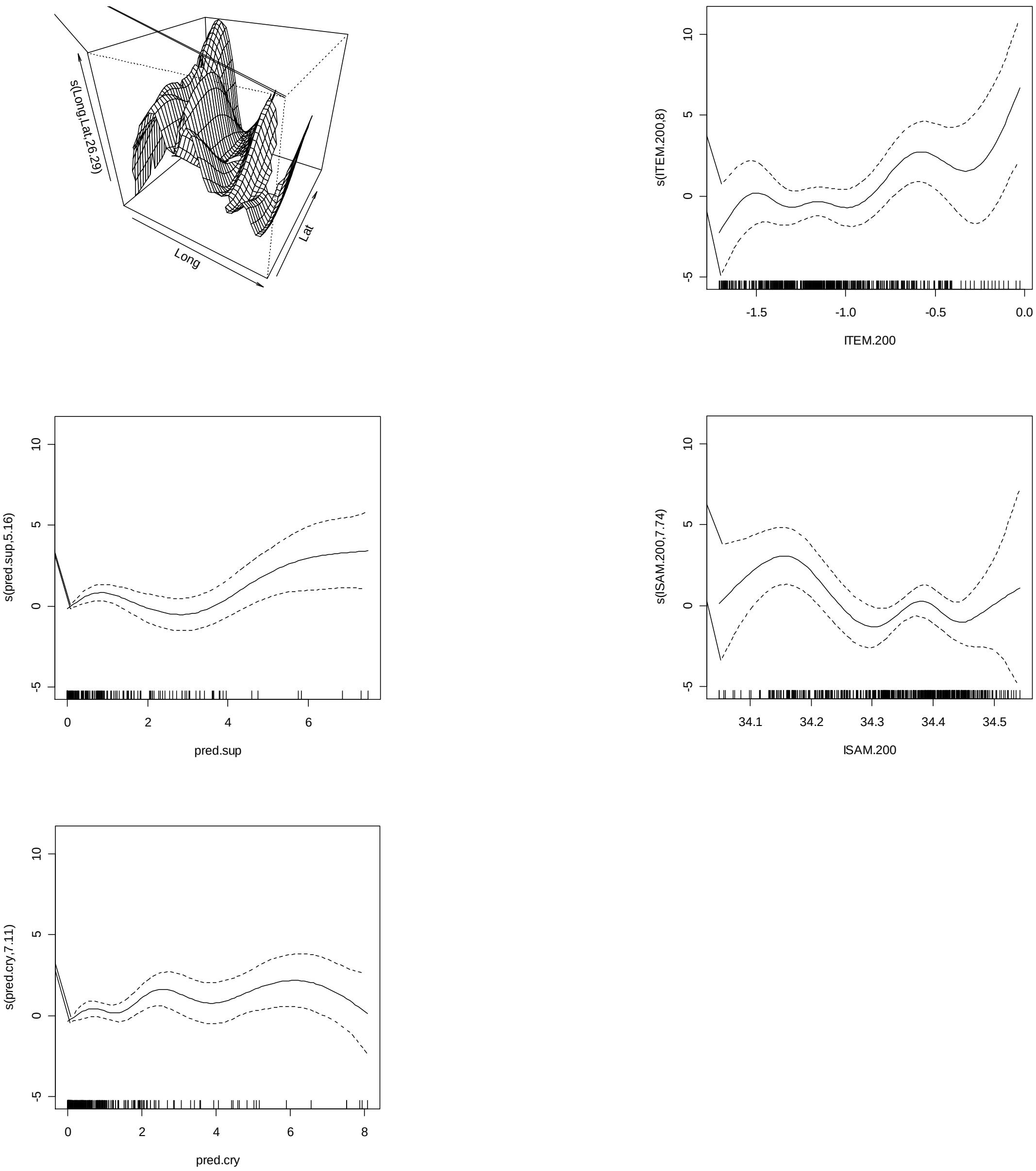

Fig. 7. Shapes of the functional forms for selected covariates to model the number of school of Antarctic minke whale.

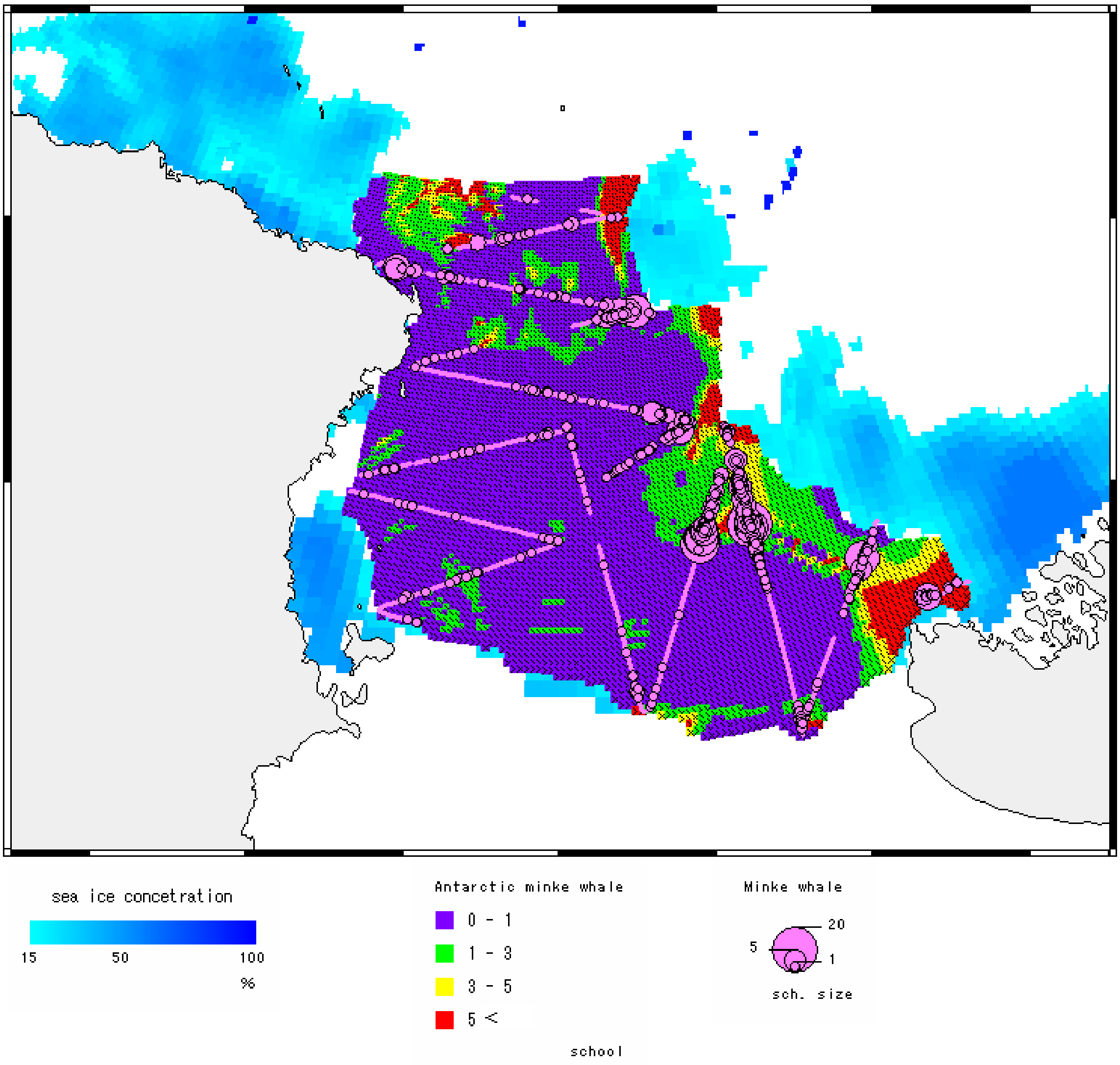

Fig. 8. Predicted density surface of the school counts of Antarctic minke whales. Surveyed tracklines and positions of sightings of Antarctic minke whales and their school sizes are overlaid on the maps. Sea ice concentration data, DMSP SSM/I Daily and Monthly Polar Gridded Sea Ice Concentrations, at the time of the survey were overlaid on the maps.