Alternative estimation of Antarctic minke whale abundance taking account of possible animals in the unsurveyed large polynya using GAM-based spatial analysis: A case study in Area II in 1997/98 IWC/SOWER

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ABSTRACT

An Antarctic baleen whale management area, Area II (0°-60°W), was surveyed by the IWC/IDCR-SOWER in 1986/87 as the second circumpolar survey (CPII) and, in 1996/97 and 1997/98 as the third circumpolar survey (CPIII). The whole area of Area II was covered in 1986/87. In CPIII, the area was separated into two at 25°W. The sector between 0° and 25°W was surveyed in 1996/97 and the rest (25°W-60°W) was surveyed in 1997/98. Sea ice extent in the southeastern Weddell Sea was unusually large in the summer of 1996/97. Unusual extensive sea ice free area, polynya, adjacent to southeastern side of Antarctic Peninsula was observed in the 1997/98. Such a large polynya wasn't observed during satellite observation period (1979-2002) except in 1997/98. The survey vessels could not conduct survey in the polynya because sea ice prevented the access to there. The area of the polynya was estimated as 89,602 n.mile^2 using satellite derived data. It was 29.2% of the surveyed area in 1997/98. Abundance estimate of Antarctic minke whale in the polynya was extrapolated using a GAM based spatial model to assess the impact of unsurveyed polynya on the abundance estimate in CPIII. Environmental variables, satellite derived SST and chlorophyll-*a* concentration, bottom depth and distance from ice edge were used in the model. It was reported that abundance estimates using the IWC standard method in Area II in CPII and CPIII were 131,177 and 43,592 individuals, respectively. Abundance of Antarctic minke whale in the Ronne Polynya was estimated as 63,364 individuals using the spatial model. Abundance estimates using GAM-based spatial modeling in CPII and CPIII were 144,793 and 110,859 individuals, respectively including the estimate in the polynya in 1997/98. The result suggested that abundance estimate in the CPIII would be underestimated because of presence of the large polynya.

KEYWORD: ANTARCTIC MINKE WHALE; SEA ICE; POLYNYA; ABUNDANCE ESTIMATE; ANTARCTIC

INTRODUCTION

The International Whaling Commission (IWC) has conducted the Antarctic minke whale abundance assessment cruises since 1978/79 in the Antarctic in austral summer (Matsuoka *et al*., 2003, for review). The name of the cruises were called as the International Decade of Cetacean Research programme (IDCR) from 1978/79 to 1995/96 and then changed to the Southern Ocean Whale and Ecosystem Research programme (SOWER) from 1996/97to 2003/04. The cruises covered three circumpolar surveys. Abundance estimation was made using each circumpolar data set; 1978/79-1983/84 (first circumpolar, CPI), 1984/85-1990/91 (second circumpolar, CPII) and 1991/92-1997/98 (third circumpolar, CPIII). Though the abundance estimate of the third circumpolar set has not been completed, a noticeable decline in abundance estimates from CPII (766,000) to CPIII (268,000) (Branch and Butterworth, 2001) brought question whether the decline is true or apparent. Several hypotheses that might affect the apparent abundance change were pointed out (IWC, 2005). One of the factors is proportion of Antarctic minke whales population south of the ice edge where survey vessels can not enter.

In the past, the IWC conducted the sighting survey of Antarctic minke whale between 0° and 60°W (Area II) in 1986/87 as CPII and 1996/97 and 1997/98 as CPIII. Whole Area was surveyed in CPII whereas Area was separated into two at 25^{o}W and surveys were conducted in two separate years (1996/97 and 1997/98) in CPIII. The 1996/97 SOWER was conducted in eastern half (0°-25°W) of Area II. It was reported that amount of sea ice in the southeastern Weddell Sea was unusually large (Hegseth and Von Quillfeldt, 2001). The 1997/98 SOWER was conducted in western half (25°W-60°W) of Area II. Though the large sea ice free area, polynya, was observed adjacent to southeastern side of Antarctic Peninsula during the cruise, the vessels could not conducted survey in the area because sea ice prevented the vessels accessing (Ensor *et al.*, 1998). The polynya was called as the Ronne Polynya and it had largest extent in 25 years satellite observation periods (Ackley *et al.*, 2001). In Area II, there is outstanding difference in abundance estimates between CPII (131,177 individuals) and CPIII (43,592 individuals) (Branch and Butterworth, 2001) and the unusual large polynya could contribute the lower abundance estimates in CPIII. Murase and Shimada (2004) estimated the abundance of Antarctic minke whale in the Ronne Polynya assuming that the density in the polynya was same as adjacent surveyed strata. Abundance estimates in CPIII increased to 86,264 individuals after adding estimates in the polynya (Murase and Shimada, 2004) though the method was crude. Spatial models based on the Generalize Additive Model (GAM) have been developed to estimate the abundance of cetaceans in unsurveyed area (e.g. Hedley *et al*., 2004). In this paper, abundance estimation of Antarctic minke whale in the polynya was carried out using GAM-based spatial model. The implications of unusual sea ice conditions in CPIII for the interpretation of the abundance difference between CPII and CPIII in Area II were discussed.

MATERIALS AND METHODS

Cetacean survey data

IWC divided southern ocean into six areas for the management of baleen whales (Donovan, 1991). Area II is set between 0^o and 60^{o}W (Fig. 1). Sighting survey for the abundance estimation of Antarctic minke whale was conducted in austral summer. CPII survey was conducted from December 28, 1986 to February 4, 1987. Full longitudinal coverage was made in 1986/87 cruise. In CPIII, Area II was divided into two at 25°W. Eastern half (0^o-25^{o}W) was surveyed in 1996/97 cruise (January 16-February 14, 1997) whereas western half (25^{o}W-60^{o}W) was survey in 1997/98 cruise (January 18-February 14, 1998). Latitudinal coverage was basically south of 60^{o}S to ice edge except 0^o-20^{o}W of CPII where the northern limit was set at 61^{o}S-63^{o}S. In addition, the northern limit of latitudinal coverage was extended up to 58°S in western portion of Area II because sea ice was extended far north. Sighting effort data, sighting data of Antarctic minke whales, boundary lines of strata, waypoint and ice edge data stored in the IWC Database-Estimation Software System (DESS) version 3.4 (Strindberg and Burt, 2004) were used. Three sighting vessels, Kyo Maru 27 (K27), Shonan Maru (SM1) and Shonan Maru 2 (SM2) conducted the survey in CPII whereas two vessels, SM1 and SM2 engaged in the survey in CPIII. The sighting surveys were conducted in two mode: closing and IO. Both closing and IO mode data were used in the analysis. In closing mode, two observers were stationed in top barrel while no observer was stationed in independent observation platform (IOP). Once a sighting was made, the ship approached to the sighting to confirm species and school size. In the IO mode, two observers were stationed in top barrel while an observer was stationed in IOP. No approach was made to sightings. Detailed explanation of survey modes is given in Branch and Butterworth (2001). Sightings with estimated perpendicular distance more than 1.5 n.miles were excluded in the analysis. The ice edge is defined by a level of ice cover that prevents the survey from being conducted at normal survey speed (11.5 knots) (IWC, 2003). The ice edge was obtained by the dedicated ice edge survey vessel in CPII whereas it was estimated using the sea ice chart published by the National Ice Center (US) except around the waypoints. Because the sea ice chart was published weekly, the estimated ice edge using it lacked precision of CPII though the data were comparable (Ensor *et al.*, 1997; Ensor *et al.*, 1998).

Satellite sea ice data

Satellite derived daily sea ice data, Bootstrap Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I (Comiso, 1999) from 1978 to 2002 was used to map the see ice concentration and extent south of the ice edge. Sea ice observation using the satellite passive microwave sensors was started with the launch of Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 in 1978. The sensor was changed to Special Sensor Microwave/Imager (SSM/I) in 1987 and the data collection is still on going. The data were collected every other day for the SMMR whereas those were collected every day for the SSM/I. The daily satellite data corresponding to midday of the surveyed period in each 5-10 latitudinal and longitudinal degree sectors were integrated into a map using geographic information system (GIS), Marine Explorer (Environmental Simulation Laboratory Co. LTD, Japan). Because the most of the ice edge was estimated using the weekly charts in CPIII, they were referred to determine the appropriate date of the satellite data. The area of the polnya was calculated using the map. The polynya was defined as 0% sea ice concentration area south of the ice edge in this paper. Monthly mean sea ice satellite data in January from 1979 to 2002 were used to investigate long term sea ice configuration change in Area II.

Environmental covariates in the model

Following environmental variables as well as distance from ice, latitude and longitude were used as covariates in the GAM-based spatial model. Because data used in the analysis had different map projections, they were converted to same projections. To get equidistance grid, geological reference data were converted to the equidistant cylindrical projection assuming that the equator was at 65^{o}S and 30^{o}W. In addition, because original resolutions of the data were also different from data to data, all data were converted to 30 n.miles by 30 n.miles grid (900 n.mile^{2}) data based on Kriging method using software, Surfer (Golden Software Inc., 1997).

Satellite chlorophyll-a concentration data

To see the chlorophyll-*a* concentration in Area II in winter of 1998, The SeaWiFS (Sea-viewing Wide Field-of-view Sensor) Level-3 winter averaged chlorophyll-*a* concentration 9km mapped data (Feldman and McClain, 2005) was used. Because the SeaWiFS image is available after September, 1997, there is no satellite chlorophyll-*a* concentration image for the 1986/87 and 1996/97 cruise.

Satellite sea surface temperature data

Satellite derived sea surface temperature (SST) data, AVHRR Oceans Pathfinder global 4km equal-angle all SST v5 (NOAA,NASA) (*Kearns et al.*, 2004), were used in the analysis. January monthly mean data in 1987, 1997 and 1998 were used as the representative SST in each survey years. Accuracy of the data was ±0.3-0.5^{o}C.

Digitized bottom depth data

Digitized bottom depth data, 2-Minute Gridded Global Relief Data (ETOPO2) published by National Geophysical Data Center, NOAA/NGDC were used.

Spatial abundance estimation modelling

Essentially, a GAM-based spatial model, the count model, developed by Hedley *et al*. (1999) was used but several points were different. 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 IO mode data because it could avoid above mentioned problem. Segments with zero sighting effort distance were omitted in the analysis. In some cases in closing mode, sightings with no sighting effort distance were recorded. Individual density of Antarctic minke whale in each segment was estimated as;

$$D_i = \frac{m_i E[S]}{2 w_s L_i} \quad ,$$

where

D_i= the whale individual density of the ith segment (individuals/n.mile^2)

m_i= the number of whale schools in the ith segment

$E[S]$ = the estimated mean school size

w_s = the effective search half-width for schools (n.miles)

L_i = the length of the ith segment (n.miles).

Estimated mean school size and effective search half width for schools reported in Branch and Butterwroth (2001) were used in the analysis and they were summarized in Table 1. Ideally, survey area should be gridded as same resolution of the segmented area (i.e. L_i times w_s) to estimate the abundance in each segment but because it was technically difficult, the survey areas were divided into 30 n.miles by 30 n.miles grids as approximately same size of segmented areas. Abudance in each 30 n.miles by 30 n.miles grid (N_i) was estimated using the D_i.

To model the response as a function of spatial environmental covariates, we use a GAM with spatially referenced environmental covariates, with the following general formulation:

$$E\left[N_i\right] = \exp\left[\beta_0 + \sum_{j=1} s_j(z_{ij})\right],$$

where

N_i = the abuandace in the ith grid (D_i*900n.mile^2, individuals)

β_0 =an intercept

s_j = nonparametric smooths of explanatory variables

z_{ij} = the value of the jth covariates in the ith grid.

A GAM with a logarithmic link function and overdispersed Poison error distribution was used. Environmental covariates, original latitude, longitude (Original.Long, Original.Lat), distance from ice edge (Ice.Dist), SST

(SST.degree.Celsius.), chlorophyll-*a* concentration (Ch.a.mg.m.3.), water bottom depth (Depth.m.) were used for the initial model. Terms in the parentheses were names used in the model. Each grid had unique values of the environmental variables. Details of environmental covariates were descried in the previous section. Models were selected using mgcv package (version 1.2-4) (Wood, 2001) of R software (R Development Core Team, 2005). At first, models were fitted within survey area then extrapolated to the polynya to estimate the abundance in there.

RESULTS

Comparisons of survey area, survey distance and number of schools used in Branch and Butterworth (2001) and this study were summarized in Table 2. Differences in survey area and distance between surveys could be caused by the conversion of the map projections. It should be noted that because values of 1996/97 in Branch and Butterworth (2001) were longitudinal coverage between 0^{o} and 30^{o}W whereas those in present study were between 0^{o} and 25^{o}W, direct comparison could not be made. Also, smearing was applied to the number of schools in Branch and Butterworth (2001) whereas no smearing was applied to data used in this study. January monthly averaged sea ice extent image in the Area II in January from 1979 to 2002 was shown in Fig. 2. No large polynya was observed during the satellite observation period except 1998. Sighting survey trackline, sighting positions of Antarctic minke whale, ice edge line defined by the survey vessels and satellite derived sea ice concentration data in CPII and CPIII were overlaid in Fig. 3. Positions of ice edge defined by the satellite and the vessel had good agreement though there was some discrepancy between them, especially in 1986/87. The reason of discrepancy in 1986/87 was due to the data recoding interval (every other day) of the satellite. The sea ice extent in the southern part of the 1996/97 cruise was larger than that in the 1986/87 cruise. In 1997/98 cruise there was a large polynya which were not observed in the 1986/87 cruise. The area of the polynya was estimated as 89,602 n.mile^2. The total surveyed area in the 1997/98 was 306,981 n.mile^2. The area of the polynya was 29.2% of the surveyed area.

Selected GAM-based spatial model and their GCV score in each survey year was shown in Table 3. Selected covariates were different among each year. Shapes of the functional forms for covariates used in the models were shown in Figs. 4-6. Those figures suggested that the habitat choice of Antarctic minke whales in Area II would be quite complex manner because there was neither constant decreasing nor increasing trend along the environmental covariates. Chlorophyll-*a* concentration was not selected in the any model. Comparison of abundance estimates between standard methods reported in Table 3 of Branch and Butterworth (2001) and spatial modelling methods in this study were summarized in Table 4. Though no CV estimate was provided in this study, abundance estimates within survey area showed quiet good agreement between the standard method and the GAM-based spatial modelling. The abundance of Antarctic minke whale in the Ronne Polynya was estimated as 63,394 individuals using the GAM-based spatial model in 1997/98. Difference of abundance estimates between CPII and CPIII were reduced from 97,297 to 33,933 individuals once the abundance in the polynya was included.

DISCUSSION

Southern portion of the 1996/97 survey area (0^{o}-25^{o}W) had a larger amount of sea ice than the 1986/87 survey. Because the heavy sea ice condition in this area shortened the growth season of the phytoplankton, biomass of the phytoplankton was low in this area in the summer of 1997 (Hegseth and Von Quillfeldt, 2001). Antarctic krill (*Euphausia superba*), the dominant prey species of Antarctic minke whale (Ichiii and Kato, 1991), fed predominantly on the phytoplankton (Miller and Hampton, 1989). If the biomass of the phytoplankton was low, growth and sexual development of Anarchistic krill was negatively affected. In the case of the food scarcity, Antarctic minke whales could change the feeding area in response to it. The western Weddell Sea was also covered with high concentration of sea ice in the 1996/97 survey. Because Antarctic minke whales were move across the IWC baleen whale management area boundary (Wada, 1984), some proportion of the population in Area II could move to adjacent areas, such as Area III. Migration behavior in response to the food availability could affect the change in apparent abundance estimation between CPII and CPIII.

In contrast, there was a large polynya in the 1997/98 survey. SeeWiFS satellite image suggested that the chlorophyll-*a* concentrations in the polynya was high. The size of the polynya increased from November and reached maximum about on 1 March (Ackley *et al.*, 2001). The prolonged open water period in the polynya could enhance the primary production. It was reported that the Ross Sea and the Prydz Bay showed high chlorophyll-*a* concentrations in summer (Arrigo and van Dijken, 2003). Those two regions were reported as high Antarctic minke whale density areas around the Antarctica (Kasamatsu *et al*., 1996; Kasamatsu *et al*. 1998b). Given the information, high density of Antarctic minke whales could be expected in the polynya. Though the chlorophyll-*a* concentrations was not selected in 1997/98 model in this study, this was due to low chlorophyll-*a* concentrations within the survey area. Because the difference of the chlorophyll-*a* concentrations between inside and outside of the polynya was remarkably large, it appeared that the chlorophyll-*a* was not appropriate environmental covariates in this case. This was the limitation of using GAM-based spatial modeling to extrapolate the abundance estimate to the unsurveyed region.

Abundance estimates of Antarctic minke whales using GAM-based spatial model were conducted in Area I (60^{o}W-120^{o}W) (Stahl and Borchers, 2001) and Area III (0^{o}-70^{o}E) (Hedley *et al*., 1999). Those studies indicated that school densities of Antarctic minke whales showed a relatively consistent trend along distance from ice edge in both studies. In contrast, distribution pattern of Antarctic minke whales in this study showed quite complex and inconsistent trends along the environment covariates. Kasamatsu *et al*. (1998a) postulated that the oceanographic conditions associated with the Weddell Gyre might influence the distribution pattern of Antarctic minke whales instead of sea surface temperature and sea ice extent alone. The presence of Weddell Gyre could results in complex and inconsistent relationship between distribution of Antarctic minke whales and environmental covariates. Because oceanographic conditions other than SST could not be obtained from satellite in the high latitude region of Area II, it is difficult to assess the influence of the Weddell Gyre. In such a region, direct measurement of oceanographic conditions such as CTD cast must be conducted in future survey to clarify the relationship between the distribution pattern of Antarctic minke whales and the oceanographic conditions.

The results of this study suggested again that the abundance estimate in the 1997/98 reported in Branch and Butterworth (2001) would be underestimated because of presence of the large polynya. The effect of the polynya on the CPIII abundance estimates in Area II must be taken account though it is difficult to estimate Antarctic minke whale in the south of the ice edge where the sighting vessels can not conduct the survey (IWC, 2002). Without considering the effect of the large polynya, the direct comparison of abundance estimates between CPII and CPIII is invalid. Field studies, such as sighting survey within pack ice using ice breaker (e.g. Shimada and Kato, 2005) and biotelemetry survey to monitor the movement of Antarctic minke whale within and outside of pack ice will enhance the understanding of distribution patterns of Antarctic minke whales in polynya and they should be conducted in the future survey.

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Table 1. Summary of the estimated mean school size (*E[S]*) and the effective search half-width for schools (w_s, n.miles) used in this study. Values were reported in the Branch and Butterworth (2001).

		Closing mode		IO mode	
Year	Vessel	w_s	$E[S]$	w_s	$E[S]$
1986/87	K27	0.369	2.82	0.367	2.82
	SM1	0.551	2.23	0.663	2.23
	SM2	0.526	1.92	0.571	1.92
1996/97	SM1	0.835	1.72	0.637	1.72
	SM2	0.306	2.06	0.468	2.06
1997/98	SM1	0.612	1.79	0.878	1.79
	SM2	0.881	1.81	0.672	1.81

Table 2. Comparisons of survey area, survey distance and number of schools used in Branch and Butterworth (2001, B&B) and this study (M&S&K). It should be noted that because values of 1996/97 in B&B were longitudinal coverage between 0° and 30°W whereas those in M&S&K were between 0° and 25°W direct comparison could not be made. Also, smearing was applied to the number of schools in B&B whereas no smearing was applied to M&S&K.

Year	B&B(2001)	M&S&K	Diff. B&B and M&S&K (%)
Survey area (n.mile^2)			
1986/97	495,208	462,600	7%
1996/97	445,715	321,300	28%
1997/98	306,981	295,200	4%
Survey distance (Closing, n.mile)			
1986/97	3,329.6	3,493.3	5%
1996/97	1,568.6	1,491.7	5%
1997/98	1,377.2	1,400.9	2%
Survey distance (IO, n.mile)			
1986/97	3,650.7	3,684.0	1%
1996/97*	1,769.4	1,631.1	8%
1997/98	1,688.1	1,690.6	0%
Number of schools (Closing)			
1986/97	257.3	261.0	1%
1996/97	54.4	51.0	6%
1997/98	82.9	83.0	0%
Number of schools (IO)			
1986/97	412.8	420.0	2%
1996/97	77.7	74.0	5%
1997/98	70.2	70.0	0%

Table 3. Selected GAM based model in Area II in CPII (1986/87) and CPIII(1996/97 and 1997/98).

CP	Year	Model	GCV score
CPII	1986/87	Ind.Abun~s(Original.Long,Original.Lat)+s(DistIce.n.mile.)+s(Depth.m.)	434.84
CPIII	1996/97	Ind.Abun~s(Original.Long, Original.Lat)+ s(DistIce.n.mile.)	250.68
CPIII	1997/98	Ind.Abun~s(Original.Long, Original.Lat)+s(SST.degree.Celsius.)	110.65

Table 4. Comparison of abundance estimates between Branch and Butterworth (2001) and this study.

		Standard methods (B&B, Table 3)				Spatial modeling				
	Year	Closing	IO	Pseudo-Passing	Invese-Variance weighted	Cloising+IO (without polynya)	Cloising+IO (including polynya)	Abundance in polynya	CPII-CPIII difference (without polynya)	CPII-CPIII difference (including polynya)
CPII	1986/87	110,984	128,680	134,363	131,177	144,793	-	-	-	-
CPIII	1996/97	29,228	26,913	35,385	28,158	30,386	-	-	-	-
	1997/98	21,291	12,939	25,776	15,434	17,110	80,473	63,364	-	-
Total of CPIII	1996/97 + 1997/98	50,519	39,852	61,161	43,592	47,496	110,859	63,364	97,297	33,933

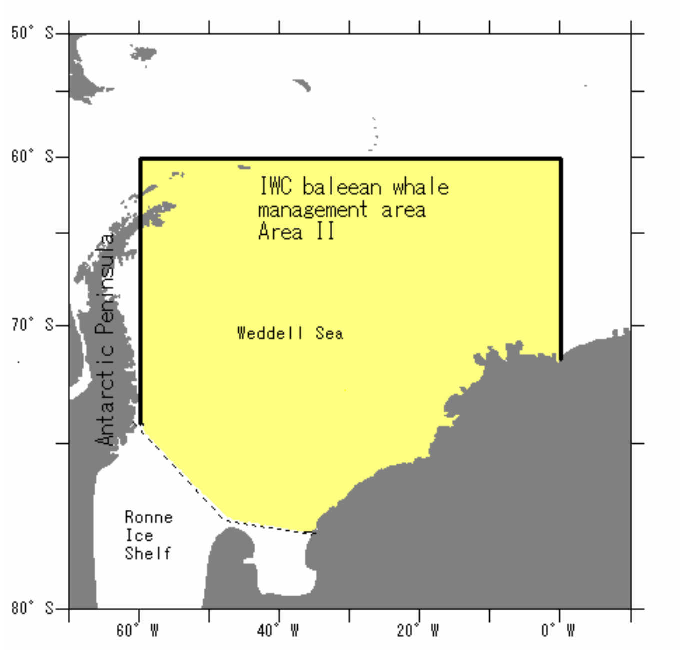


Fig. 1. Schematic map of survey area, Area II.

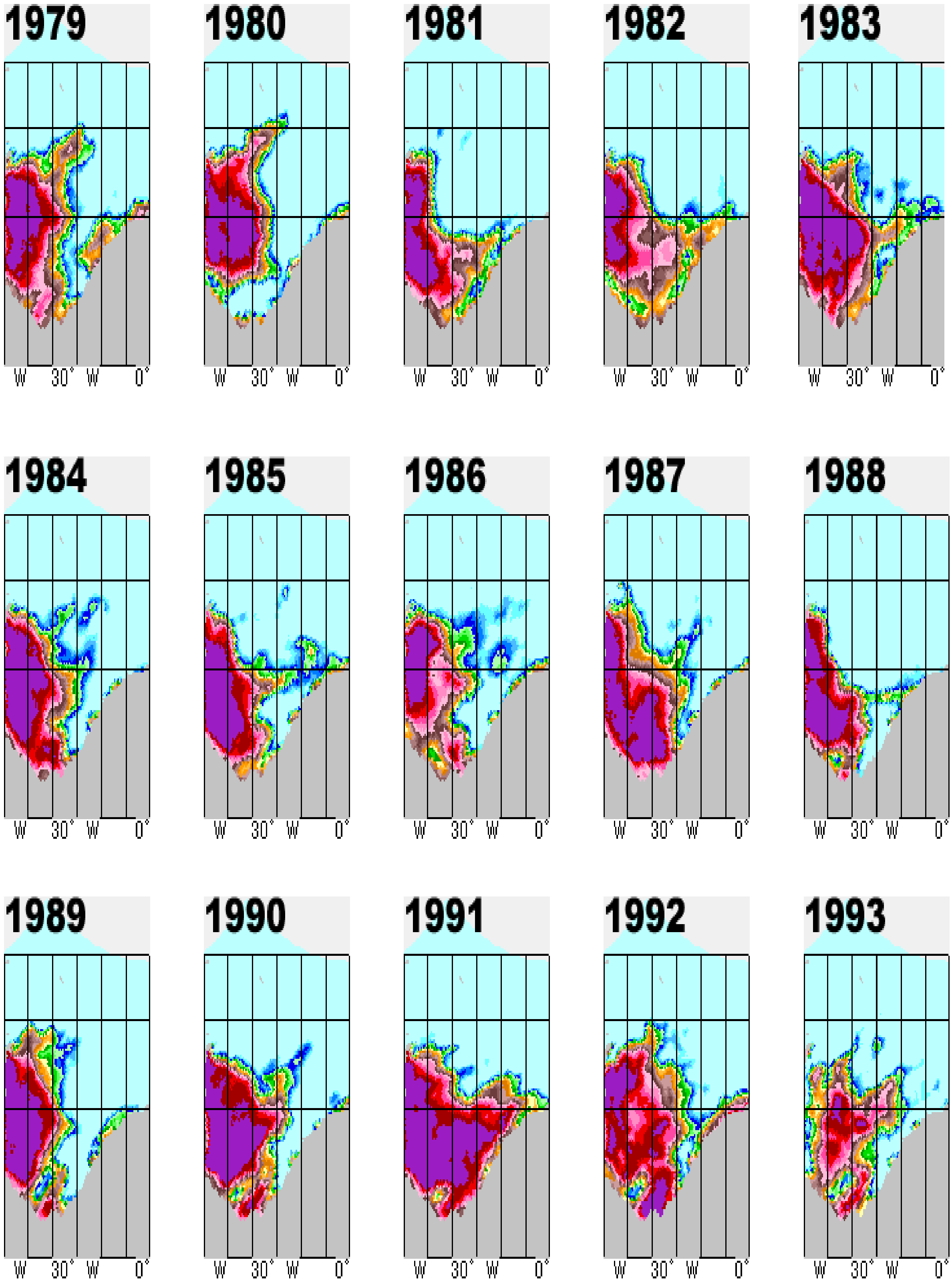


Fig. 2. January monthly mean sea ice concentration images in Area II from 1979 to 2002.

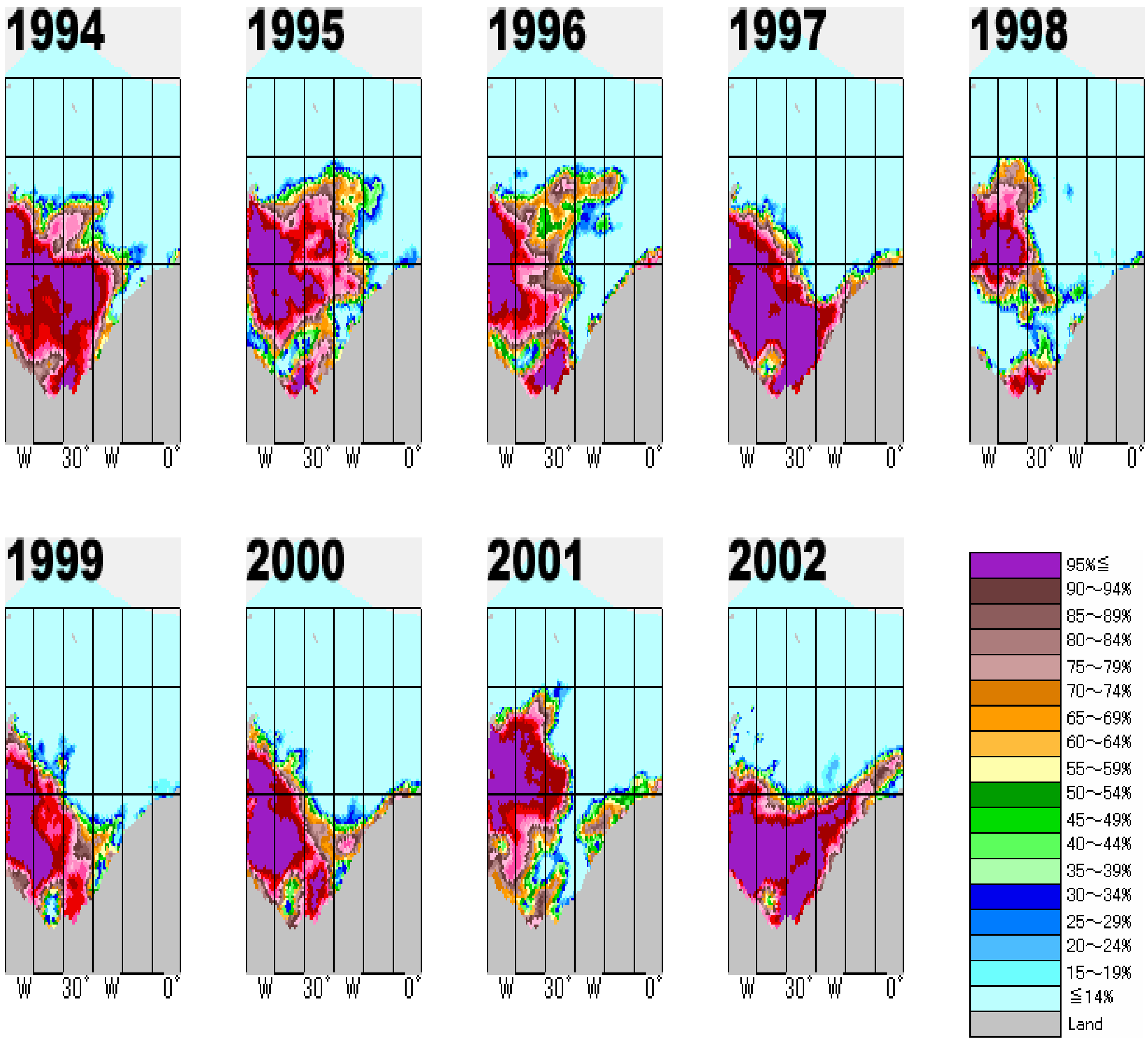
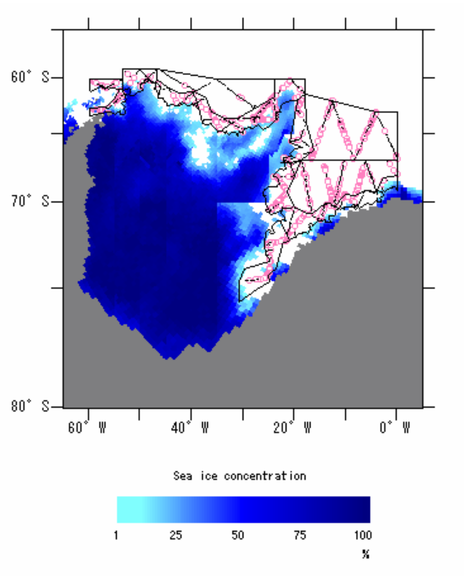
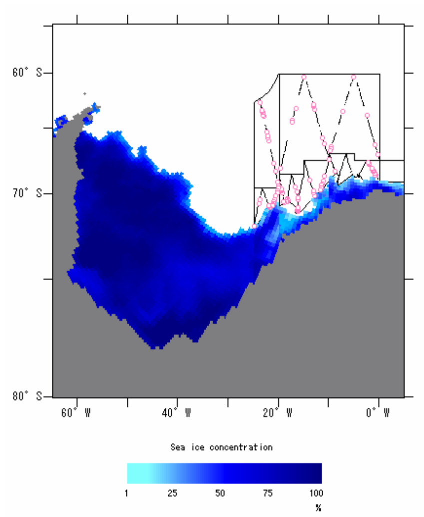


Fig. 2. (Continued)

1986/87 (CPII)



1996/97 (CPIII)



1997/98 (CPIII)

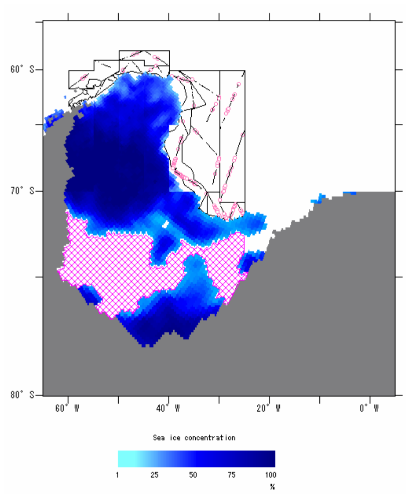
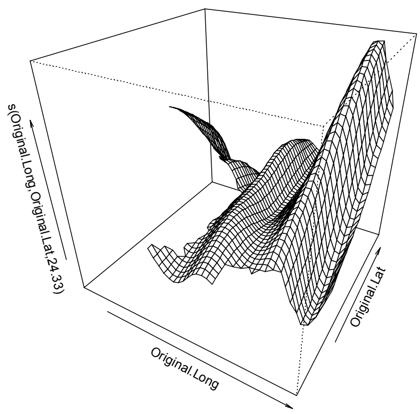
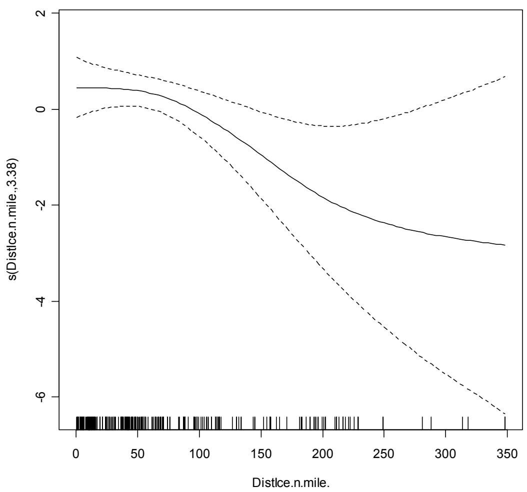


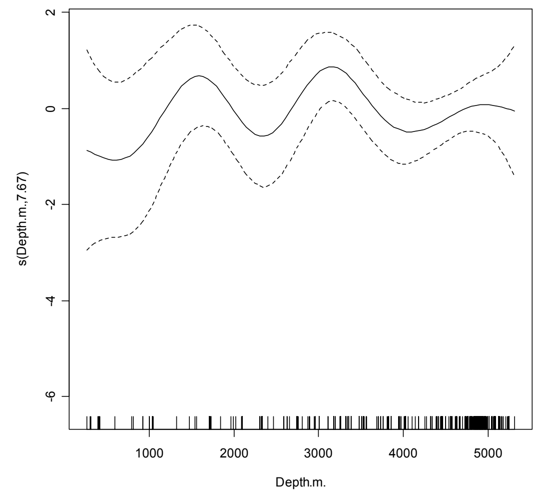
Fig. 3. Maps of sighting survey trackline, boundary lines of strata (black line), sighting positions of Antarctic minke whale (pink open circle), and satellite derived sea ice concentration in 1986/87 (above), 1996/97 (middle) and 1997/98 (bottom) in Area II. Pink hatched area in 1997/98 was defined as the Ronne Polynya in this study.



(a)

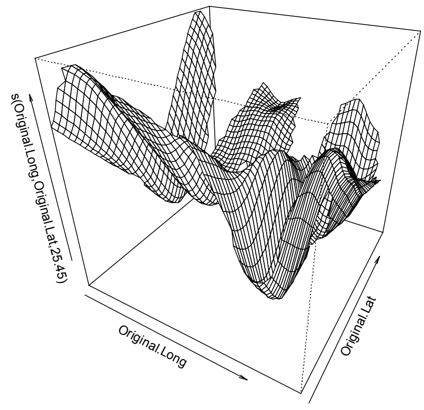


(b)

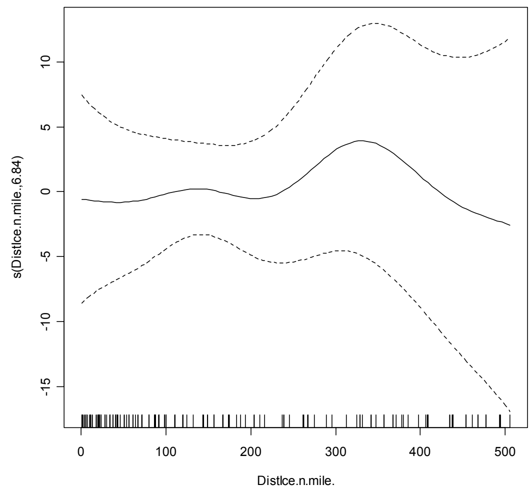


(c)

Fig. 4. Shapes of the functional forms for covariates selected for 1986/87 data: (a) 2 dimensional perspective plot of longitude and latitude, (b) distance from ice edge and (c) water bottom depth.

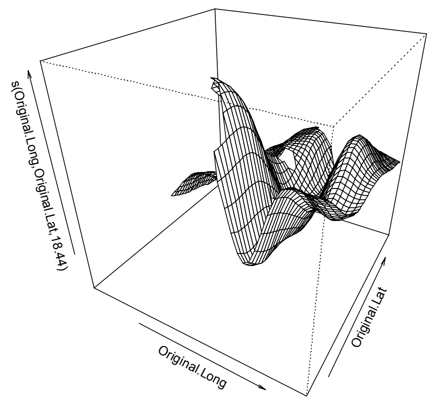


(a)

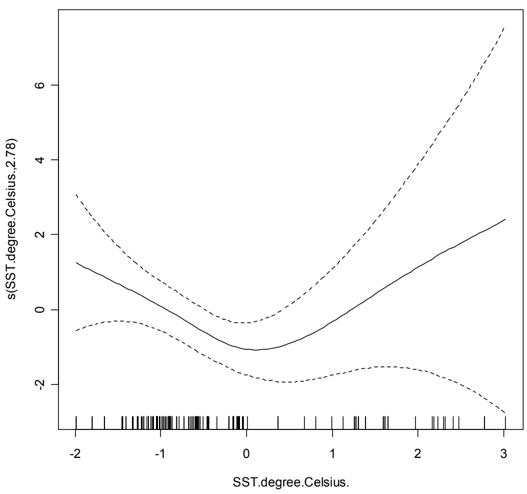


(b)

Fig. 5. Shapes of the functional forms for covariates selected for 1996/97 data: (a) 2 dimensional perspective plot of longitude and latitude and (b) distance from ice edge.



(a)



(b)

Fig. 6. Shapes of the functional forms for covariates selected for 1997/98 data: (a) 2 dimensional perspective plot of longitude and latitude and (b) SST.