Changes in baleen whale distribution patterns between CPII and CPIII

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ABSTRACT

Changes in spatial distribution patterns of large baleen whales (southern right, fin, sei and humpback whales) in relation to Antarctic minke whales were examined in Area I, IV and V-W using data obtained in IDCR/SOWER CPII and CPIII. Firstly, probabilities of occurrences of large baleen whales and Antarctic minke whales were estimated spatially at a scale of 10×10 km grid cell. Then occupied area index (probabilities of presence of Antarctic minke whales minus probabilities of presence of large baleen whales) were calculated. Environmental condition in Area I was different between CPII and CPIII. The 5ºC SST isotherm as proximity of the Polar Front (PF) was intruded in the survey area up to 65ºS in CPII especially in the east of 90ºW while it was remained in the northern edge of the survey area (around 60ºS) in CPIII. Probability of presence of Antarctic minke whales in CPII was high where continental shelf break and PF were close together along the Antarctic Peninsula. Such convergence of PF to the Antarctic Peninsula and high density of Antarctic minke whales were not observed in CPIII. In addition, number of sightings of fin, sei and humpback whales were increased in Area I from CPII to CPIII. Area occupied by these three whales was increased in Area I. Number of sightings of southern right, fin and humpback whales was increased in Area IV from CPII to CPIII. Area occupied by these three whales was increased in Area IV. Number of sightings of fin and humpback whales was increased in Area V-W from CPII to CPIII. Area occupied by these two whales was increased in Area V-W. The apparent decrease of abundance of Antarctic minke whales was reported in Area I, IV and V-W. It can be hypothesized that increase in number and extent of spatial distributions of large baleen whales in survey areas could results in (1) increase in number of Antarctic minke whales in the south of ice edge (2) increase in longitudinal (east-west) movement of Antarctic minke whales within stock boundaries and (3) effect on demographic parameters of Anarchistic minke whales through direct/indirect competition. In addition, changes in environmental conditions such as locations of front and sea ice edge between CPII and CPIII should also be considered. Further, the substantial change in the survey design as in the case of Area I impedes the direct comparison of abundance between CPII and CPIII. Reasons for difference of abundance estimates of Ataractic minke whales between CPII and CPIII should be combinations of above mentioned factors. Region-specific integrated approach should be taken to evaluate the reasons because it is obvious that factors affecting abundance estimates are different from region to region.

INTRODUCTION

The International Whaling Commission (IWC) conducted the Antarctic minke whale (*Balaenoptera bonaerensis*) abundance assessment cruises from 1978/79 to 2009/10 in the Antarctic in austral summer as reviewed by Matsuoka, *et al.* (2003). The names of the cruises were firstly the International Decade of Cetacean Research programme (IDCR, from 1978/79 to 1995/96) and then the Southern Ocean Whale and Ecosystem Research programme (SOWER, from 1996/97 to 2009/10). These cruises covered three circumpolar surveys for the purpose of comprehensive assessments: 1978/79-1983/84 (first circumpolar, CPI), 1984/85-1990/91 (second circumpolar, CPII) and 1991/92-2003/04 (third circumpolar, CPIII). A noticeable abundance decline from CPII to CPIII using the IWC standard abundance estimation method (Branch, 2006a) has raised questions whether the decline is true or apparent. Discussion on reasons for the difference of the estimates between CPII and CPIII is ongoing in the Scientific Committee of IWC (IWC/SC).

It was reported that number of large baleen whales such as blue, fin and humpback whales was increased in some region of the Antarctic in the period of the three circumpolar surveys (Branch, *et al.*, 2004; Matsuoka, *et al.*, 2006; Branch, *in press*). Though effect of increase in number of large baleen whales on abundance of Antarctic minke whales was pointed out (Branch, 2006b), the effect has not been examined fully. In this paper, changes in baleen whale distribution patterns between CPII and CPIII in relation to Antarctic minke whales were examined in Area I (120ºW-60ºW), IV (70ºE-130ºE) and V-W (130ºE-170ºW) where sea ice conditions in the south of the ice edges were similar between CPII and CPIII.

MATERIALS AND METHODS

Standard data set prepared by Burt (2004) was used as data of sighting effort and sighting of Antarctic minke whales. Primary sighting data of southern right (*Eubalaena australis*), fin (*B. physalus*), sei (*B. borealis*) and humpback (*Megaptera novaeangliae*) whales corresponding to the standard effort data were extracted from the IWC Database-Estimation System Software (DESS) (Strindberg and Burt, 2000). Like minke whales were not included in the analysis. Duplicate sightings were excluded in this analysis. Because the objective of this analysis was not estimation of abundance but estimation of probability of occurrence in a certain grid cell, no truncation and smearing was applied to the sighting data. Number of sightings used in the analysis is shown in Table 1.

The survey areas were divided into 10×10 km grid cells. The effort data were separated in 1 km segments and then aggregated in the grid cells. The sighting data were allocated to 10×10 grid cells based on the geographic coordinates of the sighting positions. Let Y_i be the number of school of whales in the *i*-th grid cell, and X_i denote the presence or absence of whales as

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

Then a spatial smoother using GAM having a binomial error distribution with the logistic link function is considered as,

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

where

$p_i = E[X_i]$: probability of presence of Antarctic minke/large baleen whales in the *i*-th grid cell

θ_o : an intercept

f_k : a nonparametric smooth function of the *k*-th explanatory variable

z_{ik} : the value of the *k*-th covariate in the *i*-th grid cell

The probabilities of presence of Antarctic minke and large baleen whales were estimated separately. Small number of sightings of large baleen whales in CPII limited species by species estimation of probabilities of presence. Therefore, they were treated as large baleen whales in this analysis. Number of grid cells used in the modeling is summarized in Table 1. An interaction term of latitude and longitude (latitude×longitude) and depth were used as covariates in the models in Area IV and V-W. The 2-minute gridded global relief data (ETOPO2v2) (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Center 2006) was used as depth data. It was reported that sea surface temperature (SST) in Area I in CPII was high especially in the east of 90ºW where the Antarctic Peninsula is located (Kasamatsu, *et al.*, 2000a). Therefore, an interaction term of distance from the continental shelf break (800 m isobaths) and distance from the 5ºC SST isotherm (shelf break×PF) was also used as covariates in Area I. The 5ºC SST isotherm is considered as proximity of the Polar Front in austral summer as described in Belkin and Gordon (1996). Satellite derived SST data, the AVHRR Pathfinder Version 5 (PO.DAAC, 1985) was used to identified the isotherm. January monthly daytime SST data corresponding to the survey area and years were used. Circumpolar surveys (CPII and CPIII) were used as a categorical covariate in all areas. The surveys in each Area were completed in one year in CPII while it took 2 to 3 years in CPIII for the completion (Table 1). Number of grid cells used in the modeling is summarized in Table 2. All geographically referenced data used in this analysis were converted to the South Pole Lambert azimuthal equal area projection to obtain size of area accurately as much as possible. Central meridians and latitude of origins were different in each management area (Table 3). Smoothness parameters were estimated with the generalized cross-validation (GCV). For these analyses, the mgcv package (Wood, 2006) version 1.7-2 of R software version 2.12.1 (R Development Core Team 2010) was used. Probabilities of presence of Antarctic minke and large baleen whales in unsurveyed gird cells were estimated using the fitted model.

To investigate extent of spatial distribution overlap between Antarctic minke whales and large baleen whales, an index, occupied area index was calculated as:

$$z_i = p_{x,i} - p_{y,i}$$

where

z_i : occupied index in the *i*-th grid cell

$p_{x,i}$: probability of presence of Antarctic minke whales in the *i*-th grid cell

$p_{y,i}$ probability of presence of large baleen whales in the *i*-th grid cell

If the index is 1, only Antarctic minke whales were presented in the *i*-th grid cell while only large baleen whales were presented if the index is -1. If the index is 0, probabilities of presence of Antarctic minke whales and large baleen whales in the *i*-th grid cell were identical.

Sea ice conditions at the time of survey prepared by Murase *et al.* (2011) were used in the distribution maps for illustrative purpose.

RESULTS

Area I

CPII, latitude×longitude and shelf break×PF were significant at 0.05 level in the model for Antarctic minke whales while all covariates except CPIII were significant in the model for large baleen whales (Table 4). Observed distribution patterns and estimated probabilities of presence of Antarctic minke whales in Area I in CPII and CPIII are shown in Fig. 1. Position of the 5ºC SST isotherm as proximity of PF was also shown in Fig. 1. The 5ºC SST isotherm in CPII was around 60ºS between 120ºW and 100ºW and it was abruptly intruded toward south up to 65ºS in the east of 100ºW. It should be noted that the survey design between CPII and CPIII was different. Whole area south of 60ºS was surveyed in CPIII while only south of 65ºS was surveyed in CPII. Two high density areas of Antarctic minke whales were observed in CPII. One was along the ice edge between 120ºW and 100ºW and the other was along the 5ºC SST isotherm between 95ºW and 70ºW. Position of the 5ºC SST isotherm in CPIII was remained around 60ºS and no intrusion to south was observed. One high density area of Antarctic minke whales was observed along the ice edge between 120ºW and 100ºW. Observed distribution patterns and estimated probabilities of presence of large baleen whales (fin, sei and humpback whales) in Area I in CPII and CPIII are shown in Fig. 2. Some concentrations of large baleen whales were observed between 110ºW and 90ºW in CPII and they were expanded in CPIII. In addition, Concentrations of large baleen whales were observed between 80ºW and 60ºW in CPIII where few animals were observed in CPIII. Spatial distribution patterns of occupied area indices in CPII and CPIII are shown in Fig. 3. Most of the survey area was occupied by Antarctic minke whales in CPII while large baleen whales expanded their occupied area in CPIII especially between 90ºW and 60ºW. Average occupied indices in CPII and CIII were 0.21 and 0.05, respectively.

Area IV

All covariates (CPII, CPIII, depth and latitude×longitude) were significant at 0.05 level in the models for Antarctic minke whales and large baleen whales (Table 4). Observed distribution patterns and estimated probabilities of presence of Antarctic minke whales in Area IV in CPII and CPIII are shown in Fig. 4. Overall distribution patterns were similar between CPII and CPIII but probability of presence was decreased in CPIII. Observed distribution patterns and estimated probabilities of presence of large baleen whale in Area IV in CPII and CPIII are shown in Fig. 5. Southern right, fin and humpback whales were sighted. Large baleen whales were mainly distributed northern part of the longitudinal range between 90ºE and 100ºE in CPII. Few right whales and no fin whales were sighted in CPII. In contrast, number of sightings of these three species and their extent of distribution area were increased in CPIII. Spatial distribution patterns of occupied area indices in CPII and CPIII are shown in Fig. 6. Most of Area IV was occupied by Antarctic minke whales in CPII except northern part of the longitudinal range between 90ºE and 100º E. In contrast, large whales expanded their occupied area from 80E to 120E in longitudinal direction and to the ice edge in the south. Average occupied indices in CPII and CIII were 0.11 and -0.06, respectively.

Area V-W

All covariates (CPII, CPIII, depth and latitude×longitude) were significant at 0.05 level in the models for Antarctic minke whales and large baleen whales except CPIII in the model for Antarctic minke whales (Table 4). Observed distribution patterns and estimated probabilities of presence of Antarctic minke whales in Area V-W in CPII and CPIII are shown in Fig. 7. Overall distribution patterns of Antarctic minke whales were similar between CPII and CPIII but probability of presence was decreased in CPIII. Observed distribution patterns and estimated probabilities of presence of large baleen whales in Area V-W in CPII and CPIII are shown in Fig. 8. Fin and humpback whales were sighted. Distribution of large baleen whales was scarce throughout the survey area in CPII. In contrast, number of sightings of these species and their extent of distribution area were increased especially longitudinal range between 150ºE and 170ºE in CPIII. Spatial distribution patterns of occupied area indices in CPII and CPIII are shown in Fig. 9. Occupied area of large whales in CPIII was increased between 150ºE and 170ºE and it extended to the ice edge. Average occupied indices in CPII and CIII were 0.21 and 0.08, respectively.

DISCUSSION

Area I

The results of this paper suggested change in position of the 5ºC SST isotherm could substantially affected the distribution patterns of Antarctic minke whales. It has been well documented that Antarctic minke whales are pagophilic species meaning that they are distributed along and within sea ice in the austral summer (Kasamatsu, *et al.*, 2000b; Murase, *et al.*, 2002; Kelly, *et al.*, 2009). However, high density of Antarctic minke whales was observed in the offshore of the western Antarctic Peninsula (WAP) along the 5ºC SST isotherm in CPII. In this paper, the 5ºC SST isotherm was used as proximity of PF. PF is a strong jet within the Antarctic Circumpolar Current (ACC) flowing eastward continuously around Antarctica and the position showed interannual variability (Moore, *et al.*, 1997). Antarctic minke whales almost exclusively feed on Antarctic krill (Tamura and Konishi, 2010). Habitat of Antarctic krill is limited in the south of PF (Miller and Hampton, 1989). WAP is known as breeding ground of Antarctic krill which sustain the highest densities in the South Atlantic. Intrusion of the 5ºC SST toward south up to 65ºS in the east of 100ºW and associated small scale eddies could cause high density of Antarctic krill in the offshore region of WAP. As the results, high density area of Antarctic minke whales could be formed along the 5ºC SST isotherm. In contrast, such high density area of Antarctic minke whales was not observed in CPIII when the 5ºC SST isotherm remained in the north of 60ºS. The difference of environmental condition between CPII and CPIII should be taken account to investigate reasons for the difference of the abundance estimates of Antarctic minke whales between CPII and CPIII. Abundance of humpback whales in Area I was increased from CPII to CPIII (Branch, *in press*). Though area specific abundance of fin and sei whales in CPII and CPIII has not been estimated, it is obvious that their number was increased from CPII to CPIII given number of sightings. It should be stressed that the survey design between CPII and CPIII was totally different. In such case, direct comparison of abundance estimates between CPII and CPIII is not impossible but extremely difficult.

Area IV and Area V-W

It was reported that abundance of humpback whales was increased from CPII and CPIII in Area IV and VI-W (Branch, *in press*). Analysis using JARPA data also suggested similar trend (Matsuoka, *et al.*, *in press*). Breeding stock D of humback whales is mainly distributed in Area IV while breeding stock E is mainly distributed in Area V-W. A population dynamics modelling indicated that breeding stock D and E would recover to pristine level within 2 decades (Johnston and Butterworth, 2005). Abundance estimates of southern right and fin whales in Area IV and V-W in CPII and CPIII has not been reported but it is obvious that these two species were also increased from CPII to CPIII given number of sightings. It was reported that the Indian Ocean stock (including Area IV) of fin whales were increased recently based on JARPA data (Matsuoka, *et al.*, 2005). As suggested by the analysis in this paper, these large baleen whales expanded their distribution area along with their abundance increase.

Recommendation for the future study

It can be hypothesized that increases in number and extent of spatial distributions of large baleen whales in survey areas could results in (1) increase in number of Antarctic minke whales in the south of ice edge (2) increase in longitudinal (east-west) movement of Antarctic minke whales within stock boundaries and (3) effect on demographic parameters of Anarchistic minke whales through direct/indirect competition. In addition, changes in environmental conditions such as locations of front and sea ice edge between CPII and CPIII should also be considered. Further, the substantial change in the survey design as in the case of Area I impedes the direct comparison of abundance between CPII and CPIII. Reasons for difference of abundance estimates of Ataractic minke whales between CPII and CPIII should be combinations of above mentioned factors. Region-specific integrated approach should be taken to evaluate reasons because it is obvious that factors affecting abundance estimates are different from region to region.

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Table 1. Number of schools used in the analysis.

Area	CP	Year	Longitude	Minke whale	Right whale	Fin whale	Sei whale	Humpback whale
Area I	CPII	1989/1990	120ºW-60ºW	698	-	2	3	23
	CPIII	1993/1994	110ºW-80ºW	223	-	0	0	12
		1999/2000	80ºW-60ºW	62	-	21	0	49
		2000/2001	120ºW-110ºW	46	-	5	8	15
		Sub total		331	-	26	8	76
Area IV	CPII	1988/1989	70ºE-130ºE	434	1	0	-	53
	CPIII	1994/1995	70ºE-80ºE	85	0	0	-	3
		1998/1999	80ºE-130ºE	121	22	13	-	223
		Sub total		206	22	13	-	226
Area V West	CPII	1985/1986	130ºE-170ºE	344	0	4	-	4
	CPIII	2001/2002	130ºE-150ºE	89	-	0	-	14
		2002/2003	150ºE-170ºE	142	-	36	-	74
		Sub total		231	-	36	-	88

Table 2.Number of grid cells used in model fitting.

Area	CP	Grid cell With effort	Grid cell with minke whale	Grid cell with large baleen whale
Area I	CPII	1,359	350	26
	CPIII	1,597	215	83
Area IV	CPII	1,482	270	39
	CPIII	1,394	141	175
Area V West	CPII	911	205	7
	CPIII	954	152	95

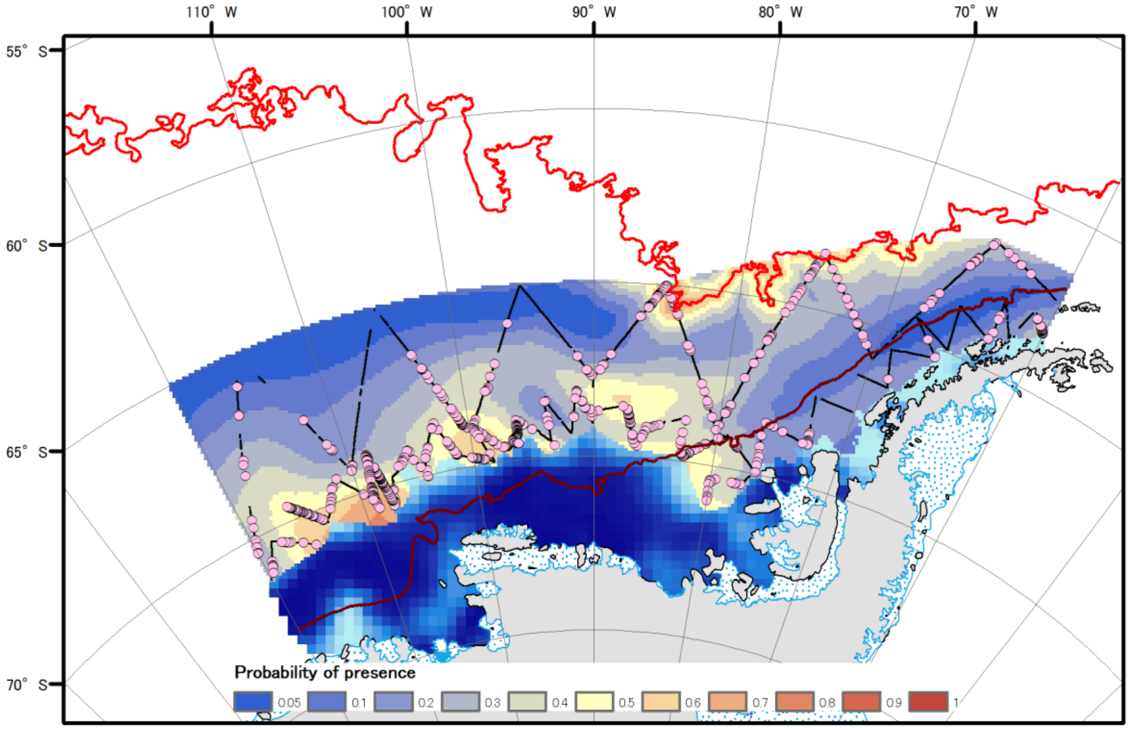
Table 3. Central meridians and latitude of origins used in the the South Pole Lambert azimuthal equal area projection.

Area	Central meridians	latitude of origins
I	90W	66S
IV	100E	65S
V	165E	69S

Table 4. Results of GAM modelling. Approximate significance levels (p-value) and degrees-of-freedom (df) are shown for each of the covariate.

Area	Area I				Area IV				Area V West			
Speices	Minke whale		Large baleen whale		Minke whale		Large baleen whale		Minke whale		Large baleen whale	
Adjusted R^2	0.15		0.16		0.13		0.17		0.11		0.21	
Deviance explained (%)	17.0 %		30.6 %		15.4 %		27.7 %		13.1 %		33.7 %	
GCV score	0.84		0.23		0.71		0.39		0.88		0.29	
	df	p-value	df	p-value	df	p-value	df	p-value	df	p-value	df	p-value
Covariates												
CPII	-	<0.01	-	<0.01	-	<0.01	-	<0.01	-	<0.01	-	<0.01
CPIII	-	0.03	-	0.14	-	<0.01	-	<0.01	-	0.03	-	<0.01
Depth	0.35	0.56	10.86	<0.01	3.78	<0.01	3.22	<0.01	3.54	<0.01	7.10	<0.01
Latitude×longitude	2.29	<0.01	8.73	<0.01	5.19	<0.01	14.23	<0.01	3.83	<0.01	7.75	<0.01
Shelf break × PF	28.10	<0.01	28.86	<0.01	-	-	-	-	-	-	-	-

Area I CPII Antarctic minke whales



Area I CPIII Antarctic minke whales

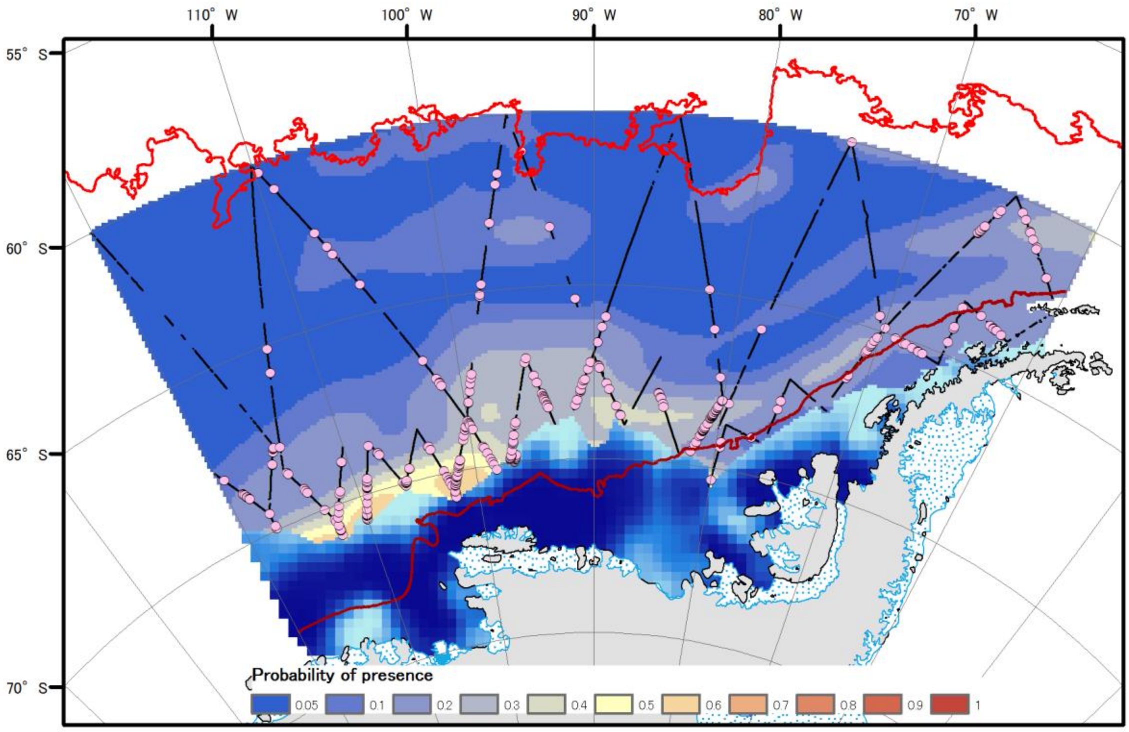
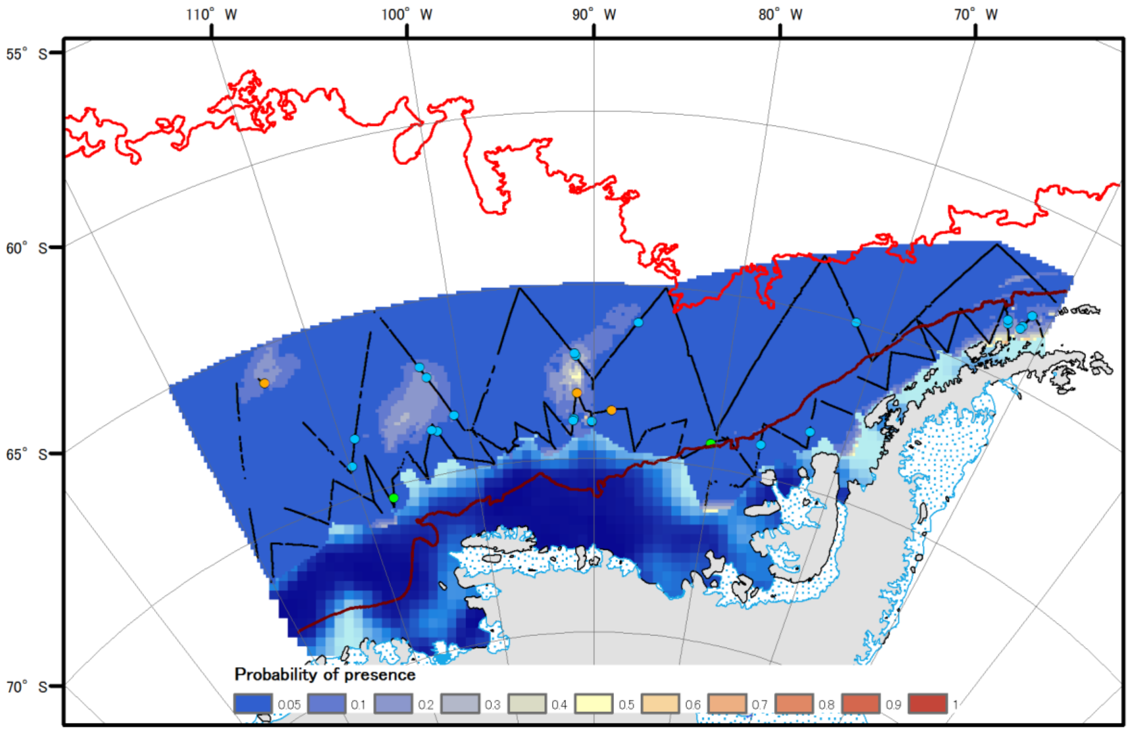


Fig 1 Estimated probabilities of presence of Antarctic minke whales in Area I in IDCR/SOWER CPII (top) and CPIII (bottom). Surveyed tracklines (black line), sighting positions of Antarctic minke whales (●) and sea ice conditions in the south of the ice edge are also shown. Continental shelf break (800 m isobath, brown line) and 5ºC SST isotherm as proximity of the Polar Front (red line) are also shown.

Area I CPII large baleen whales (fin ●, sei ● and humpback ● whales)



Area I CPIII large baleen whales (fin ●, sei ● and humpback ● whales)

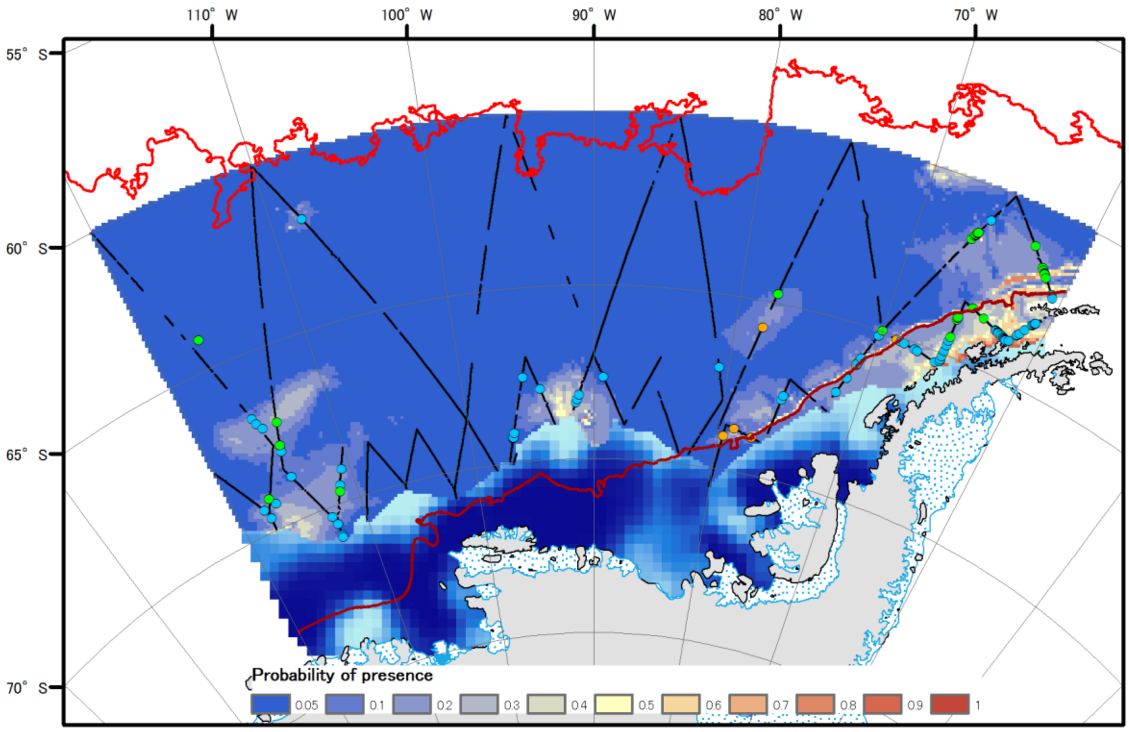
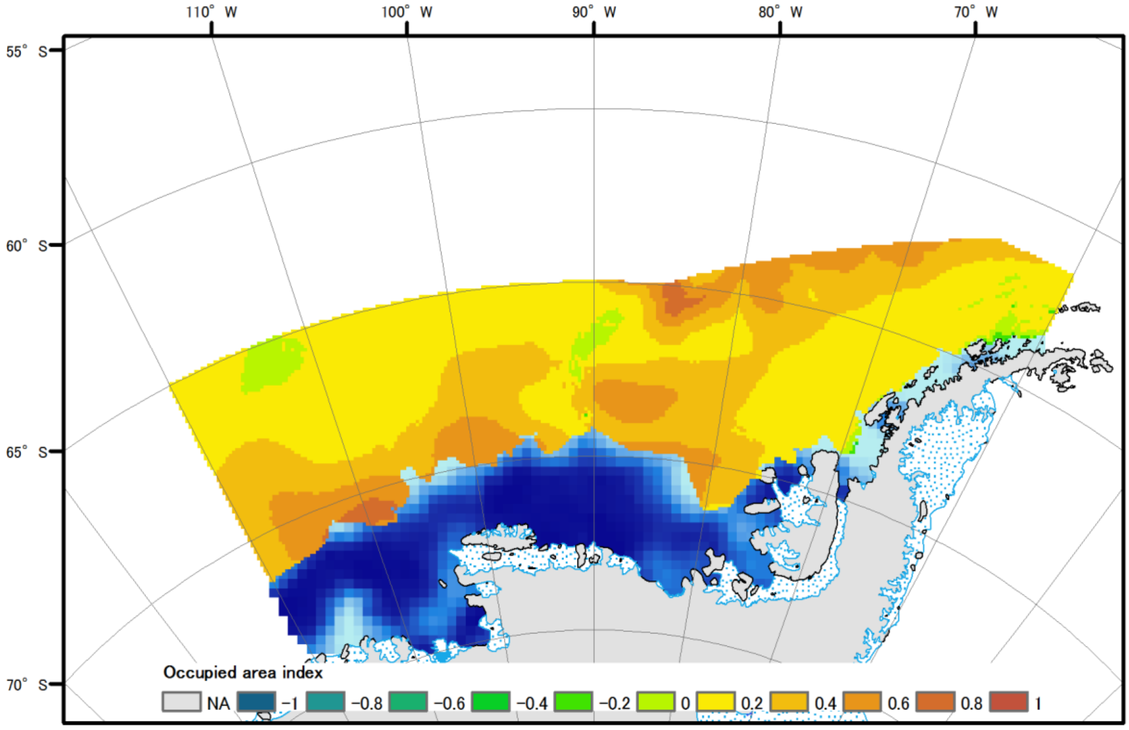


Fig 2. Estimated probabilities of presence of large baleen whales in Area I in IDCR/SOWER CPII (top) and CPIII (bottom). Surveyed tracklines (black line), sighting positions of fin (●), sei (●) and humpback (●) whales and sea ice conditions in the south of the ice edge are also shown. Continental shelf break (800 m isobath, brown line) and SST 5ºC isotherm as proximity of the Polar Front (red line) are also shown.

Area I CPII Occupied area index



Area I CPIII Occupied area index

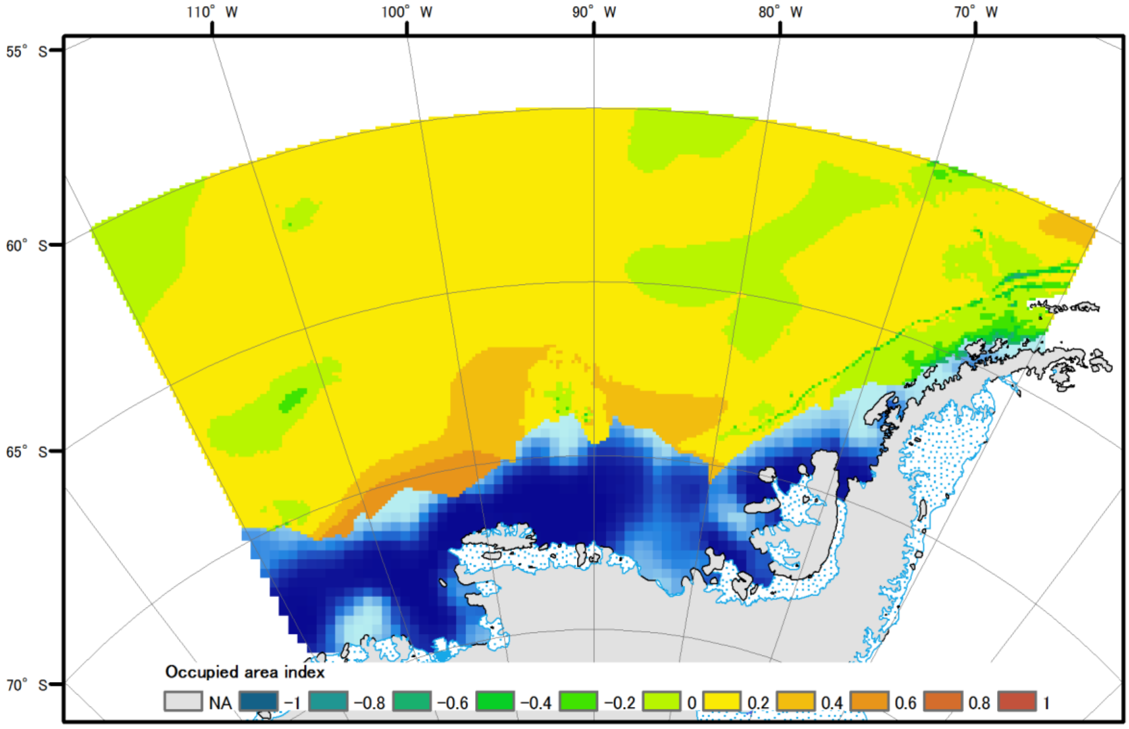
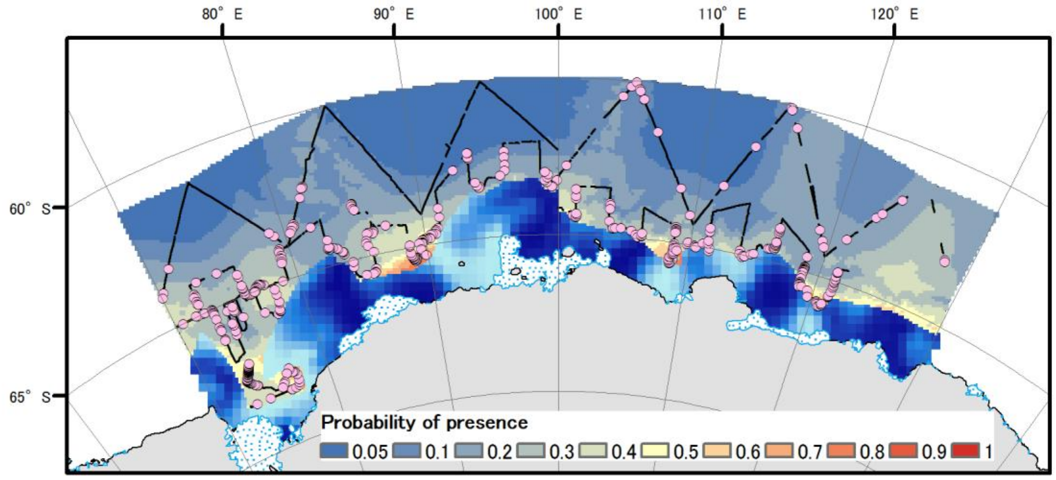


Fig 3. Occupied area indices of Antarctic minke whales and large baleen whales in Area I in IDCR/SOWER CPII (top) and CPIII (bottom). If the index is 1, only Antarctic minke whales were presented in a grid cell while only large baleen whales were presented if the index is -1. If the index is 0, probabilities of presence of Antarctic minke whales and large baleen whales in a grid cell were identical. Sea ice conditions in the south of the ice edge are also shown.

Area IV CPII Antarctic minke whales



Area IV CPIII Antarctic minke whales

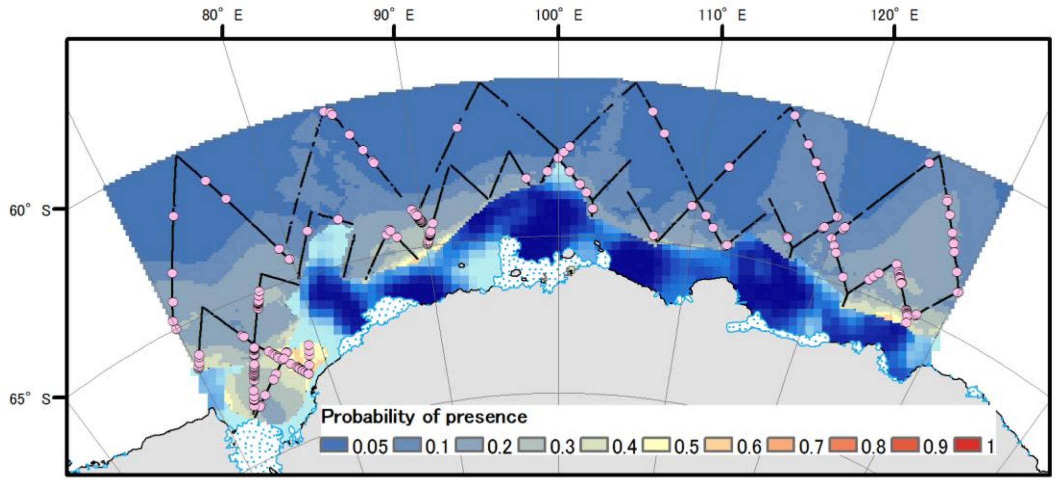
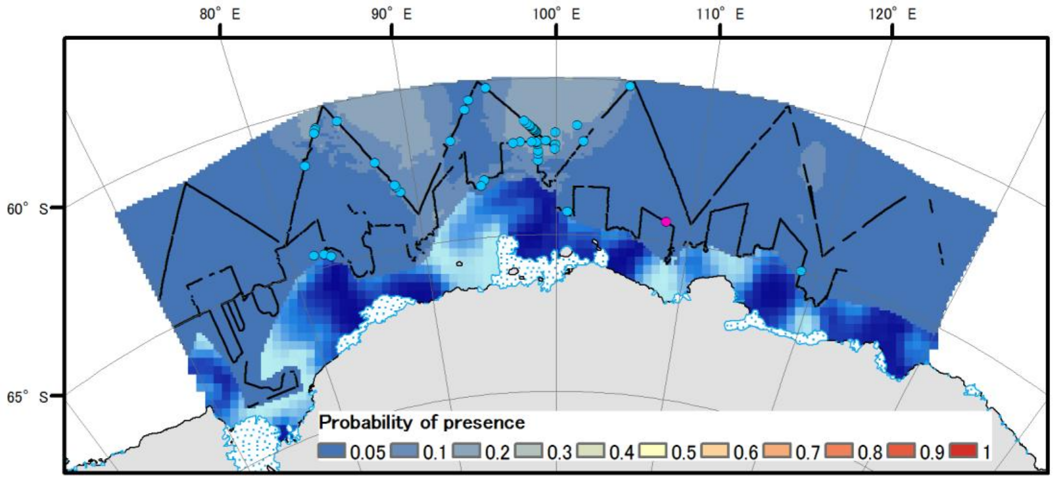


Fig 4. Estimated probabilities of presence of Antarctic minke whales in Area IV in IDCR/SOWER CPII (top) and CPIII (bottom). Surveyed tracklines (black line), sighting positions of Antarctic minke whales (●) and sea ice conditions in the south of the ice edge are also shown.

Area IV CPII large baleen whales (southern right ●, fin ● and humpback ● whales)



Area IV CPIII large baleen whales (southern right ●, fin ● and humpback ● whales)

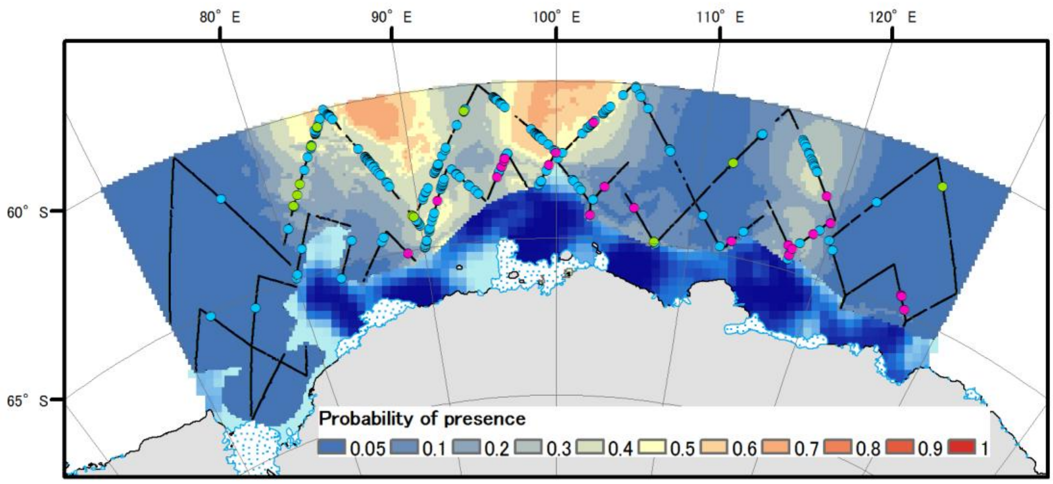
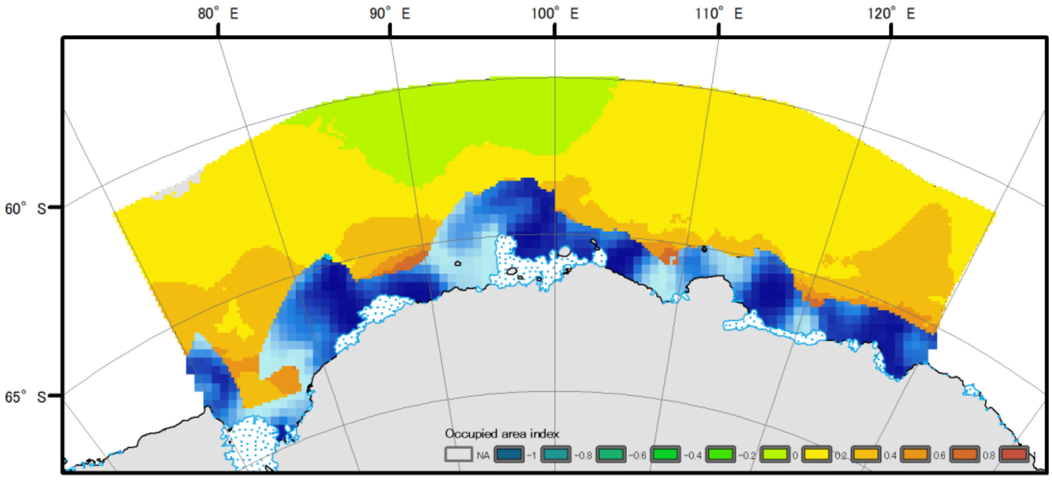


Fig 5. Estimated probabilities of presence of large baleen whales in Area IV in IDCR/SOWER CPII (top) and CPIII (bottom). Surveyed tracklines (black line), sighting positions of southern right (●), fin (●) and humpback (●) whales and sea ice conditions in the south of the ice edge are also shown.

Area IV CPII Occupied area index



Area IV CPIII Occupied area index

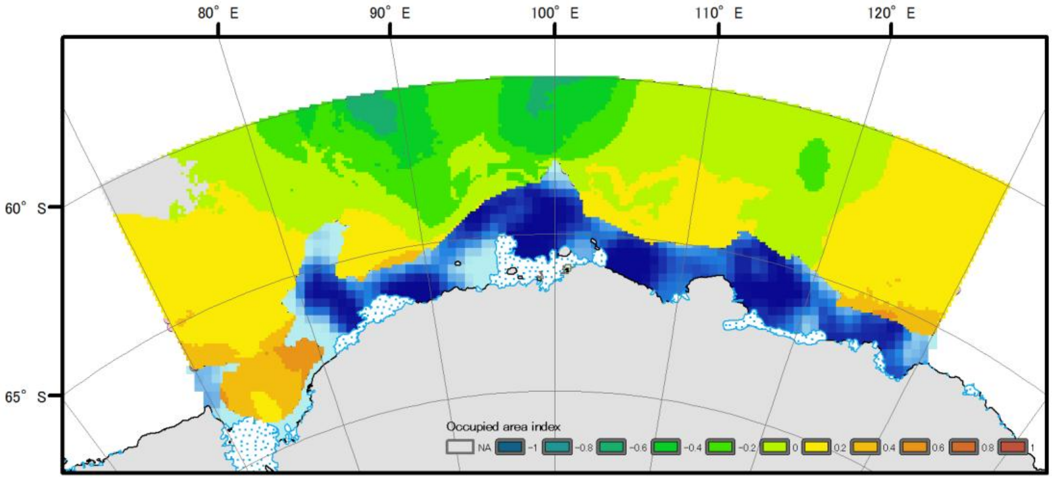
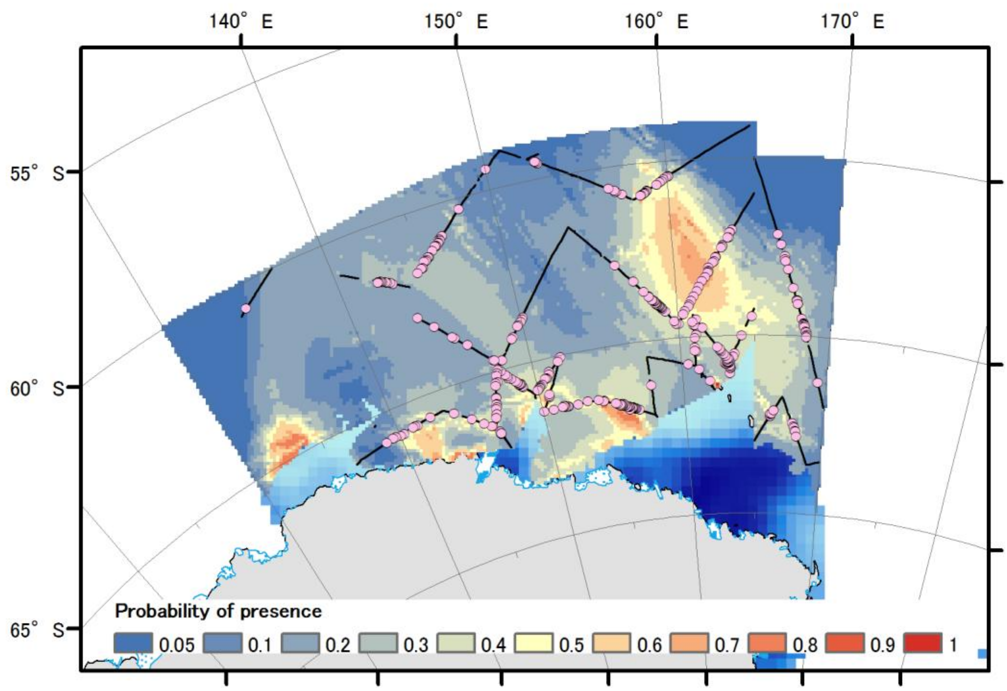


Fig 6. Occupied area indices of Antarctic minke whales and large baleen whales in Area I in IDCR/SOWER CPII (top) and CPIII (bottom). If the index is 1, only Antarctic minke whales were presented in a grid cell while only large baleen whales were presented if the index is -1. If the index is 0, probabilities of presence of Antarctic minke whales and large baleen whales in a grid cell were identical. Sea ice conditions in the south of the ice edge are also shown.

Area V-W CPII Antarctic minke whales



Area V-W CPIII Antarctic minke whales

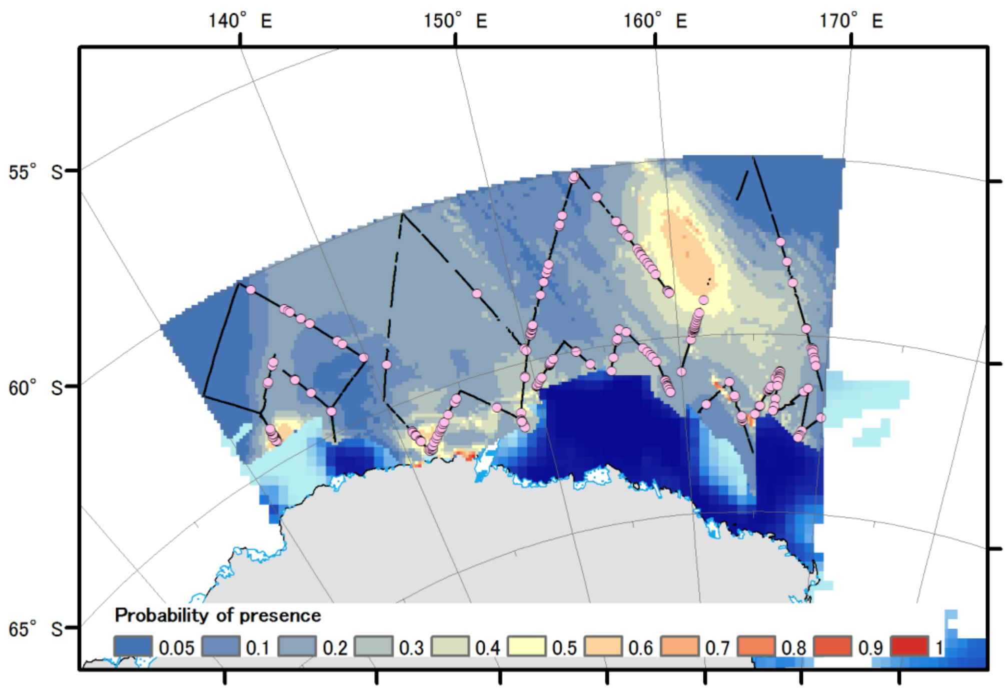
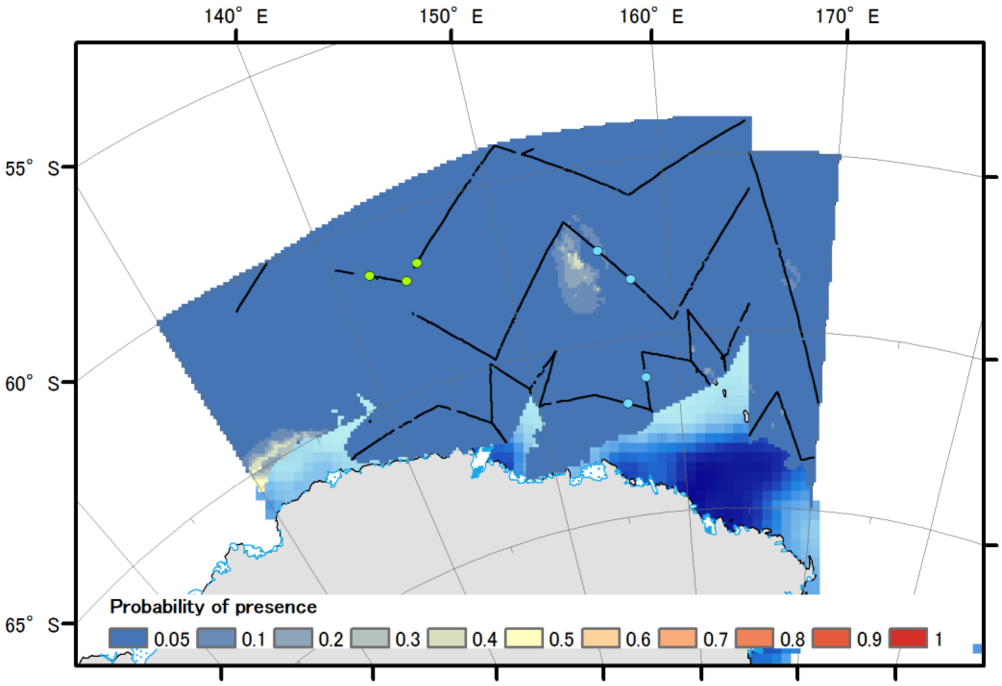


Fig 7. Estimated probabilities of presence of Antarctic minke whales in Area V-W in IDCR/SOWER CPII (top) and CPIII (bottom). Surveyed tracklines (black line), sighting positions of Antarctic minke whales (●) and sea ice conditions in the south of the ice edge are also shown.

Area V-W CPII large baleen whales (fin ●and humpback ● whales)



Area V-W CPIII large baleen whales (fin● and humpback● whales)

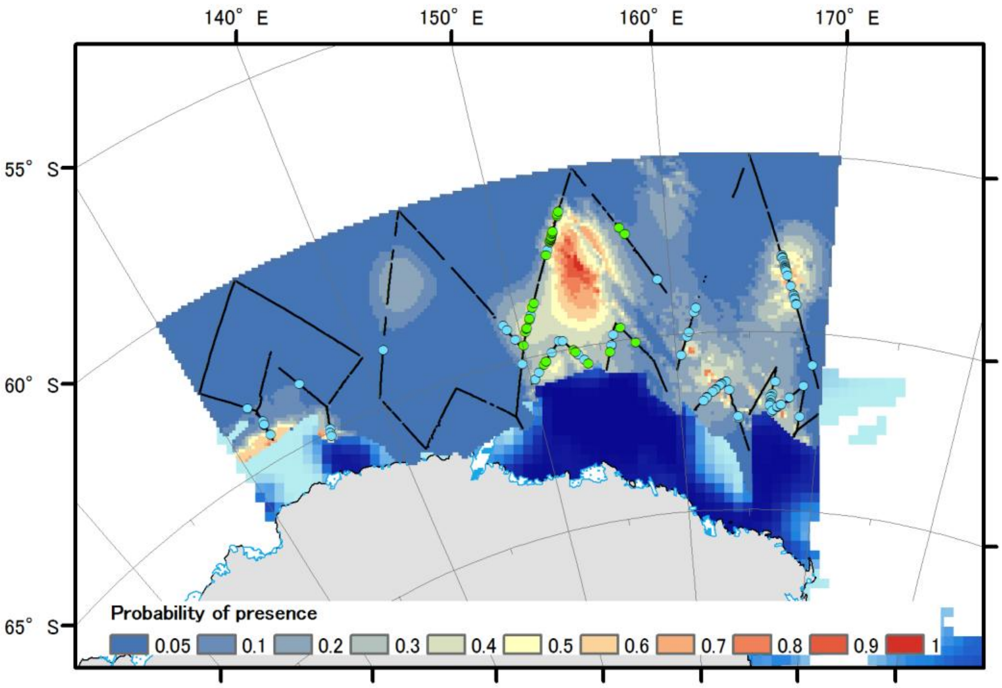
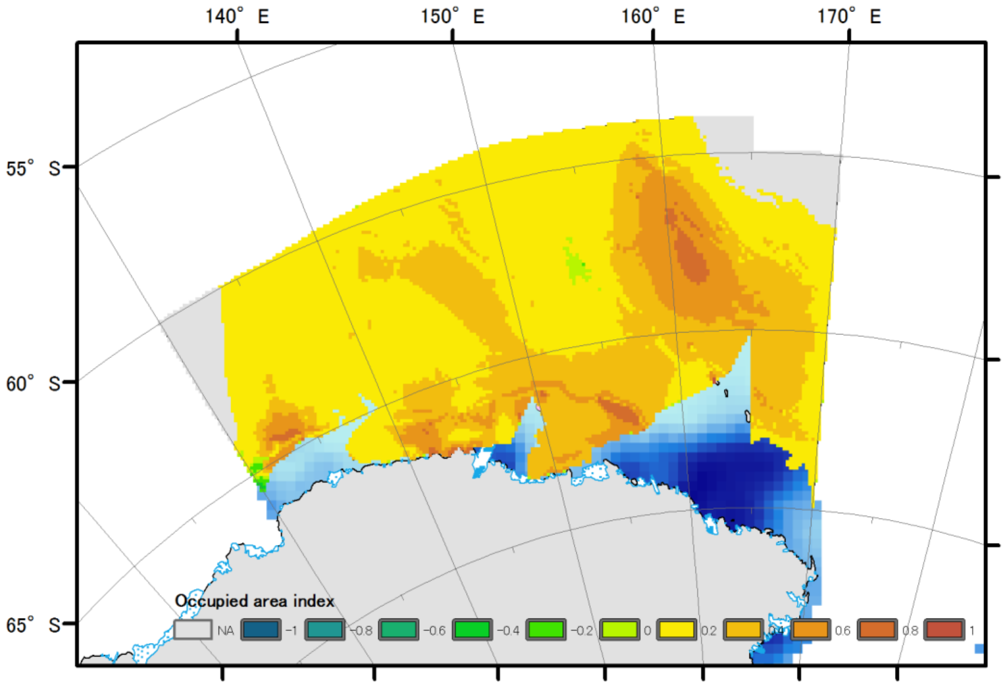


Fig 8. Estimated probabilities of presence of large baleen whales in Area V-W in IDCR/SOWER CPII (top) and CPIII (bottom). Surveyed tracklines (black line), sighting positions of fin (●) and humpback (●) whales and sea ice conditions in the south of the ice edge are also shown.

Area V-W CPII Occupied area index



Area V-W CPIII Occupied area index

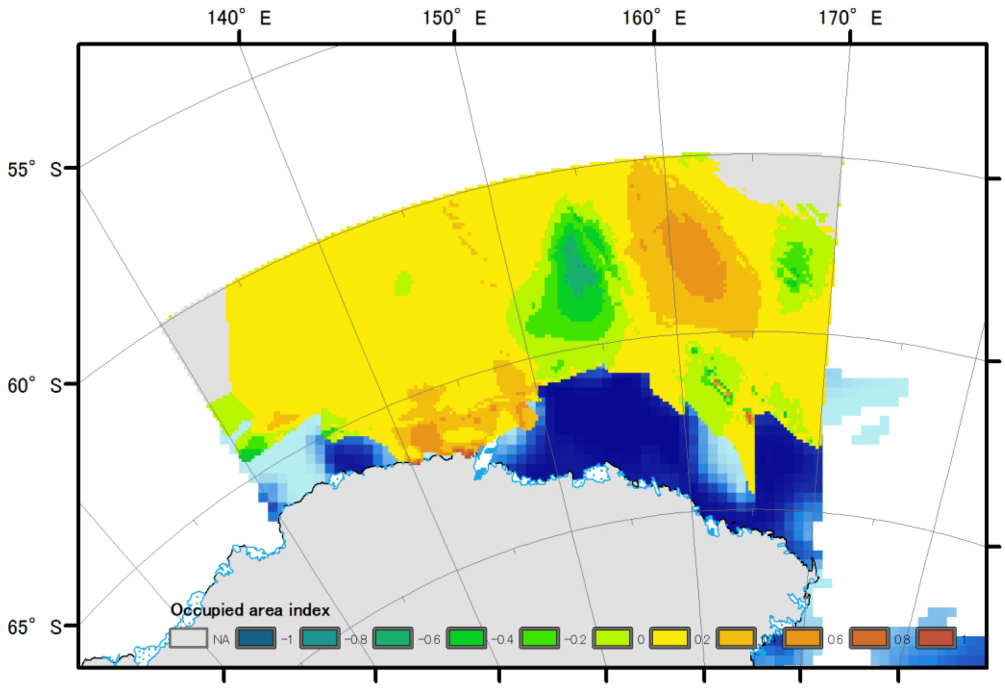


Fig 9. Occupied area indices of Antarctic minke whales and large baleen whales in Area V in IDCR/SOWER CPII (top) and CPIII (bottom). If the index is 1, only Antarctic minke whales were presented in a grid cell while only large baleen whales were presented if the index is -1. If the index is 0, probabilities of presence of Antarctic minke whales and large baleen whales in a grid cell were identical. Sea ice conditions in the south of the ice edge are also shown.