Preliminary analysis of changes in spatial distribution of Antarctic minke and humpback whales in Area IV during the period of JARPA and JARPAII from 1989 to 2006

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ABSTRACT

Changes in spatial distribution of Antarctic minke whales and humpback whales in Area IV during the period of JARPA and JARPAII were examined. To elucidate temporal changes of their spatial distribution, data obtained in JARPA-JARPAII was divided into three periods: early (1989/1990, 1991/1992 and 1993/1994), middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006). Spatial distribution was estimated using generalized additive models (GAM). The presence or absence of whales was used as a response variable while seafloor depth, distance from shelf break and longitude were used as explanatory variables. Mean probabilities of the occurrence of Antarctic minke whales in the survey area in early, middle and late periods were 0.41, 0.46 and 0.41 while those of humpback whales were 0.14, 0.35 and 0.46. Occupied area indices (probabilities of the occurrence of Antarctic minke whales minus probabilities of the occurrence of humpback whales) were also calculated. If the index was 1, only Antarctic minke whales were presented in a grid cell while only humpback whales were presented if the index was -1. If the index was 0, probabilities of the presence of Antarctic minke whales and humpback whales in a grid cell were identical. Mean occupied area indices in early, middle and late periods were 0.28, 0.11 and -0.07, respectively. The spatial distribution of humpback whales was expanded during the period of JARPA and JARPAII while that of Antarctic minke whales remained stable. The results indicated that competition between humpback and Antarctic minke whales for habitat in Area IV during the period of JARPA and JARPAII was intensified as abundance of humpback whales increased.

INTRODUCTION

Humpback whales (*Megaptera novaeangliae*) in the Southern Hemisphere had been exploited commercially since the early 1900's. The International Whaling Commission (IWC) protected humpback whales from commercial whaling in the Southern Hemisphere in 1963. The Scientific Committee of the IWC (IWC/SC) now recognizes eight major breeding stocks in the Southern Hemisphere, namely Breeding Stocks A, B, C, D, E, F, G and X (IWC, 2011). The Indian sector of the Antarctic between 70°E and 130°E, also defined as Area IV of the IWC baleen whale management area (Donovan, 1992), is used by breeding stock D (BSD) as its main summer feeding ground (Pastene et al. 2013). The Breeding ground of BSD is located in Western Australia. It was reported that abundance of BSD in feeding (from 1989 to 2004: Matsuoka et al., 2011) and breeding ground (from 1999 to 2008: Hedley et al. 2011) was increased. The results of population assessment of BSD by the IWC/SC indicated the population size in 2006 was 60-80% of pre-exploitation (IWC, 2007) although further assessment is still undergoing. Habitat expansion of BSD in the feeding ground was observed qualitatively as the abundance was increased (Matsuoka et al., 2011). However, it has not been tested quantitatively.

In contrast to humpback whales, abundance of Antarctic minke whales (*Balaenoptera bonaerensis*) in Area IV did not show any significant trend from late 1980's to mid-2000's (Hakamada et al. 2014a; Okamura and Kitakado, 2012). However, it was reported that the energy storage and stomach contents weight of Antarctic minke whales in the same period were declined (Konishi and Walløe 2014a;b). The results indicated there was a possibility of competition between humpback and Antarctic minke whales for their major prey, krill.

The objectives of this paper are two folds. Firstly, it is investigated that whether habitat of humpback whales in Area IV is expanded from late 1980's to mid-2000's. Secondary, it is investigated that whether changes in overlapping spatial distribution of humpback and Antarctic minke whales in Area IV from the late 1980's to the mid-2000's have occurred. Data obtained by Japanese Whale Research Program under Special Permit in the Antarctic (JARPA) and its phase II (JARPAII) was used in the analysis.

MATERIALS AND METHODS

JARPA was conducted from the 1987/1988 to the 2004/2005 season. JARPAII has been conducted since 2005/2006. Among them, the surveys were conducted in Area IV in nine seasons (1989/1990, 1991/1992, 1993/1994, 1995/1996, 1997/1998, 1999/2000, 2001/2002, 2003/2004 and 2005/2006). A general map of the survey area is shown in Fig. 1. Sighting survey data obtained in these years were used in the analysis. Data used in the abundance estimation of humpback (Hakamada et al. 2014b) and Antarctic minke (Hakamada et al. 2014a) whales were used in this analysis. Details of survey methods and data are described in these two papers. Sighting survey efforts in the northern part of the survey area was sparse (e.g. about two transects in each 10 degree longitudinal sector) in each year. Estimation of the distribution of whales between transects is difficult by using such data sets. To deal with the difficulty, data were pooled according to time periods: early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods.

The survey areas were divided into 30×30 km grid cells in the South Pole Lambert azimuthal equal area projection with central meridian at 100°E and latitude of origin at 65°S. The effort data were separated in 1 km segments and then aggregated in the grid cells. The sighting data were allocated to 30×30 km grid cells based on the geographic coordinates of the sighting positions. Let Y_i be the number of schools 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 occurrence of humpback/Antarctic minke 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 the occurrence of humpback and Antarctic minke whales were estimated separately. Seafloor depth, distance from the shelf break (800m isobath) and longitude are used as explanatory variables. ETOPO1 Global Relief Model (Amante and Eakins, 2009) is used as seafloor depth. Original resolution of ETOPO1 is 1x1 arc minute grid cell. The location of the shelf break is identified by using this data. Mean depth in each 30x30 km grid cell and distance between the shelf break and each grid cell are calculated using a geographic information system (GIS), ArcGIS version 10.1 (ESRI, Redlands, CA, USA). Latitudinal heterogeneity of the distribution of whales can be captured by these two variables. Longitude is also used as a covariate because the environmental covariates used in this analysis might not capture longitudinal heterogeneity of the distribution of whales.

Smoothness parameters were estimated with the generalized cross-validation (GCV). For these analyses, the mgcv package (Wood, 2006) version 1.7-27 of R software version 3.0.2 (R Development Core Team 2013) was used. Probabilities of the presence of humpback and Antarctic minke whales in unsurveyed gird cells were estimated using the fitted model.

To investigate the extent of overlapping spatial distribution between humpback and Antarctic minke whales, an index, the occupied area index, was calculated as:

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

where

z_i : occupied area 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 humpback whales in the *i*-th grid cell

If the index was 1, only Antarctic minke whales were present in the *i*-th grid cell while only humpback whales were present if the index was -1. If the index was 0, probabilities of the presence of Antarctic minke and humpback whales in the *i*-th grid cell were identical.

RESULTS AND DISCUSSION

A summary of number of grid cells used in the analysis is shown in Table 1. Selected GAMs are summarized in Table 2. Smoothed fits of selected covariate modeling the probability of occurrences of humpback and Antarctic minke whales in early, middle and late periods are shown in Figs. 2-7.

Survey effort and sighting positions of Antarctic minke whales in Area IV in early, middle and late periods is shown Fig. 8 while estimated spatial distribution is shown in Fig. 9. Overall, spatial distribution of Antarctic minke whales was consistent throughout the three periods. Densities of Antarctic minke whales were high in the western part of the survey area where Prydz Bay is located. Antarctic minke whales were mainly distributed south of the shelf break where seafloor depth is shallow. The relationship between bottom topography and the distribution of Antarctic minke whales revealed by this study is consistent with past studies (Ainley et al. 2012; Kasamatsu et al. 1996; Murase et al. 2002; 2013). Frequency distributions of probabilities of occurrence of Antarctic minke whales in the survey area in early, middle and late periods are shown in Fig. 10. Means of probabilities of occurrence of Antarctic minke whales in the survey area in early, middle and late periods were 0.41, 0.46 and 0.41, respectively. Probabilities of occurrence of Antarctic minke whales were also consistent throughout the three periods.

Survey effort and sighting positions of humpback whales in Area IV in early, middle and late periods is shown Fig. 11 while estimated spatial distribution is shown in Fig. 12. In the early period, humpback whales were mainly distributed in the northern part of the survey area between 80°E and 100°E. In the middle period, humpback whales expanded their habitat closer to the shelf break between 80°E and 120°E. In the late period, humpback whales were distributed in the entire survey area along the shelf break. Frequency distributions of probabilities of occurrence of humpback whales in the survey area in early, middle and late periods are shown in Fig. 13. Means of probabilities of occurrence of humpback whales in the survey area in early, middle and late periods were 0.14, 0.35 and 0.46, respectively. Probabilities of the occurrence of humpback whales increased from the early to late periods. Past studies using data obtained in the 1980's and early 1990's demonstrated that humpback whales were distributed in the northern part of the study area (Kasamatsu et al. 1996; Murase et al. 2002). However, results of this study suggested humpback whales expanded their habitat closer to the shelf break as their abundance rebounded. The results of this study suggested that humpback whales were rarely distributed on the shelf in the feeding season. The finding contrasted with other results in the feeding season in the North Atlantic (Paxton et al. 2007) and the nursing/breeding seasons when they were distributed in shallow seafloor depth areas (Ernst and Rosenbaum 2003; Paxton et al. 2011).

Estimated spatial distribution of occupied area indices of Antarctic minke whales and humpback whales in Area IV in early, middle and late periods is shown in Fig. 14. The figure suggested that the habitats of humpback whales expanded both in the longitudinal and latitudinal direction while that of Antarctic minke whales remained stable. Frequency distributions of occupied area indices in early, middle and late periods shifted from positive values to negative values (Fig. 15). Means of occupied area indices in early, middle and late periods were 0.28, 0.11 and -0.07, respectively. These results indicated that competition between humpback and Antarctic minke whales for habitats in Area IV during the period of JARPA and JARPAII was intensified as abundance of humpback whales increased. The results of competition for habitats could be reflected in biological parameters of Antarctic minke whales such as the energy storage and stomach contents weight.

ACKNOWLEDGEMENT

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Table 1. .Number of grid cells used in modeling.

Period	Grid cell in sruvey area	Grid cell with effort	Grid cell with minke whale	Grid cell with humpback whale
Early (1989/1990, 1991/1992, 1993/1994)	2,209	1,324	582	184
Middle (1995/1996, 1997/1998, 1999/2000)	2,207	1,286	639	455
Late (2001/2002, 2003/2004, 2005/2006)	2,345	1,134	518	565

Table 2. Results of GAM modelling. Approximate significance levels (*p*-value) and effective degrees of freedom (edf) are shown for each of the covariates.

Period	Early				Middle				Late			
Species	Minke whale		Humpback whale		Minke whale		Humpback whale		Minke whale		Humpback whale	
Family	Binomial		Binomial		Binomial		Binomial		Binomial		Binomial	
Link function	Logit		Logit		Logit		Logit		Logit		Logit	
Adjusted R^2	0.13		0.13		0.20		0.20		0.16		0.30	
Deviance explained (%)	10.1		18.6		16.0		17.8		12.7		25.7	
GCV score	1.25		0.68		1.19		1.09		1.21		1.06	
Covariates	edf	p value	edf	p value	edf	p value	edf	p value	edf	p value	edf	p value
Longitude	3.43	<0.01	7.88	<0.01	8.59	<0.01	5.71	<0.01	1.00	<0.01	7.92	<0.01
Distance from shelf break	5.05	<0.01	8.24	<0.01	1.77	<0.01	1.93	0.02	1.00	<0.01	4.06	<0.01
Seafloor depth	1.00	<0.01	6.32	0.13	3.08	<0.01	5.67	<0.01	1.00	<0.01	5.00	<0.01

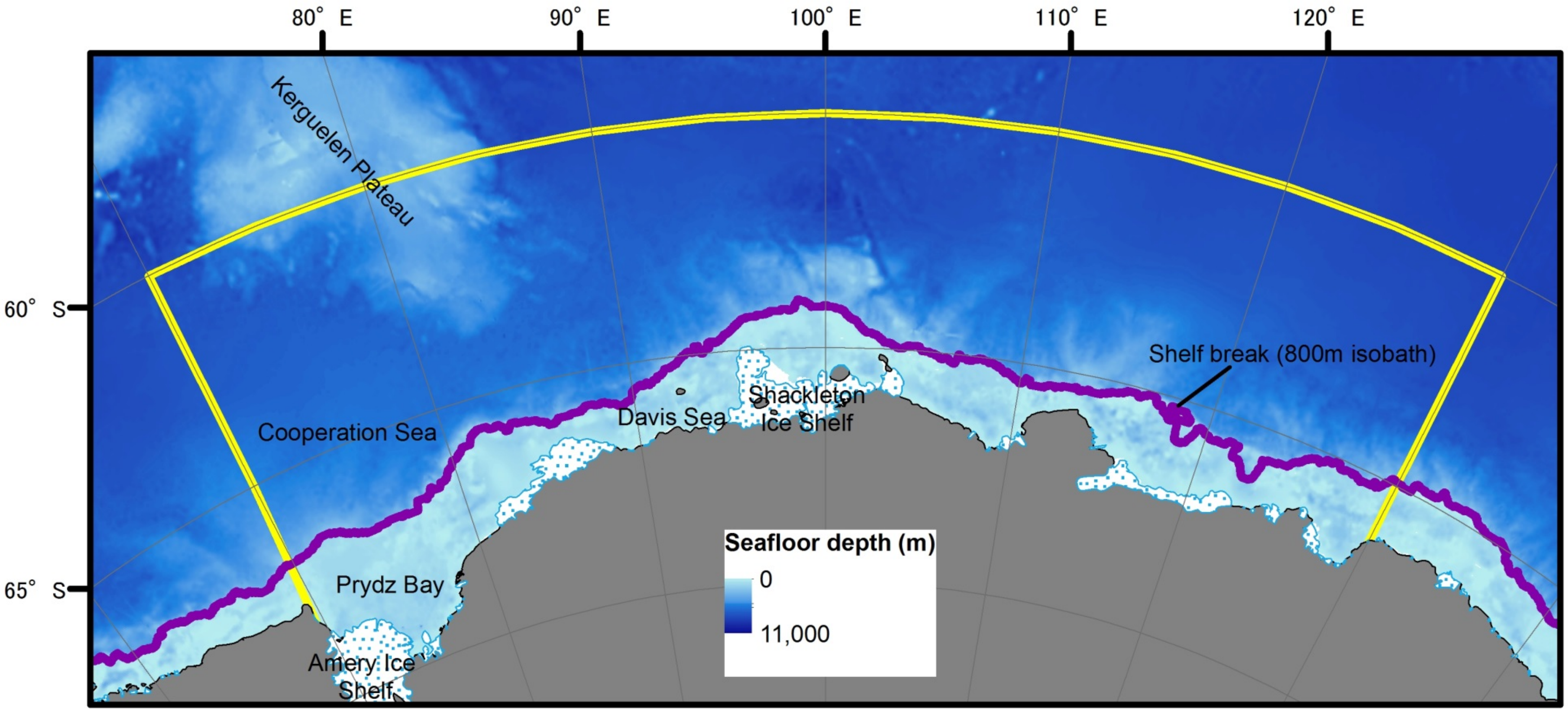

Fig. 1. General map of the survey area. Area bounded by yellow line is the survey area (Area IV of the IWC baleen whale management area). Seafloor depth and the location of shelf break (800m isobaths; purple line) are also shown.

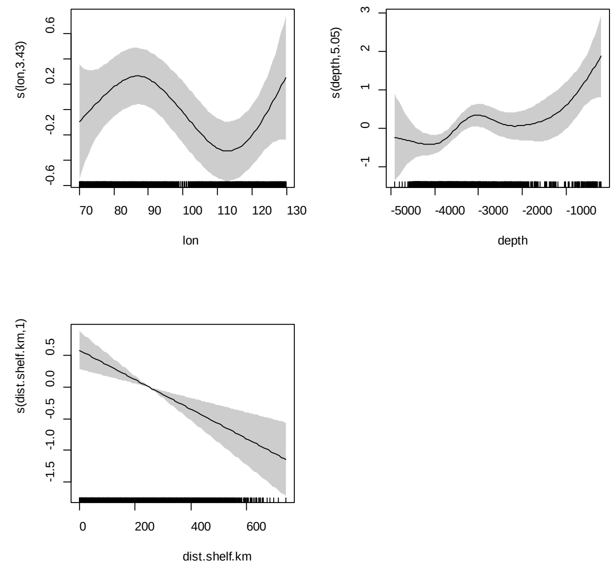

Fig. 2. Smoothed fits of selected covariate modeling the probability of occurrences of Antarctic minke whales in early period (1989/1990, 1991/1992 and 1993/1994). Tick marks on the x-axis are observed data points. The shaded areas indicate the 95% confidence bounds. lon: longitude, depth: seafloor depth (m), dist.shelf.km: distance from the shelf break (km).

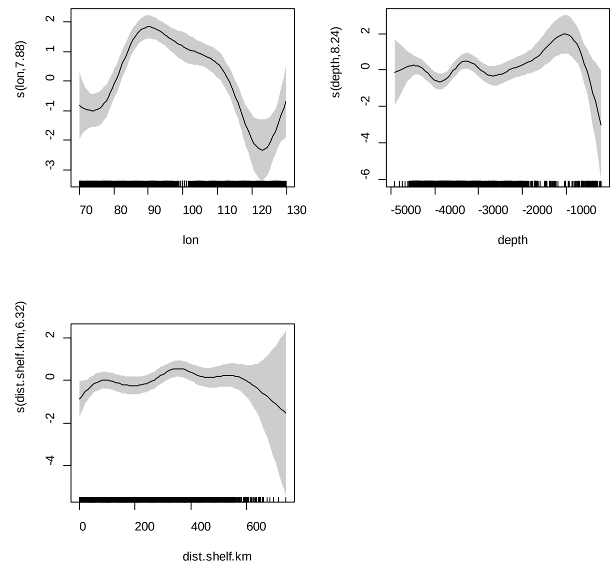

Fig. 3. Smoothed fits of selected covariate modeling the probability of occurrences of humpback whales in early period (1989/1990, 1991/1992 and 1993/1994). Tick marks on the x-axis are observed data points. The shaded areas indicate the 95% confidence bounds. lon: longitude, depth: seafloor depth (m), dist.shelf.km: distance from the shelf break (km).

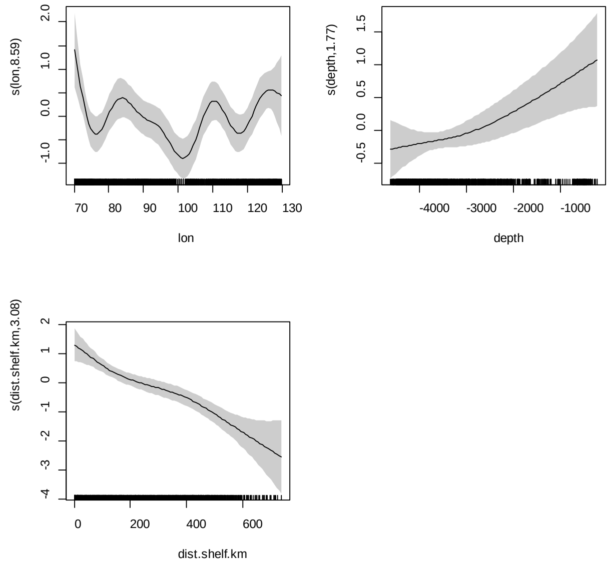

Fig. 4. Smoothed fits of selected covariate modeling the probability of occurrences of Antarctic minke whales in middle period (1995/1996, 1997/1998 and 1999/2000). Tick marks on the x-axis are observed data points. The shaded areas indicate the 95% confidence bounds. lon: longitude, depth: seafloor depth (m), dist.shelf.km: distance from the shelf break (km).

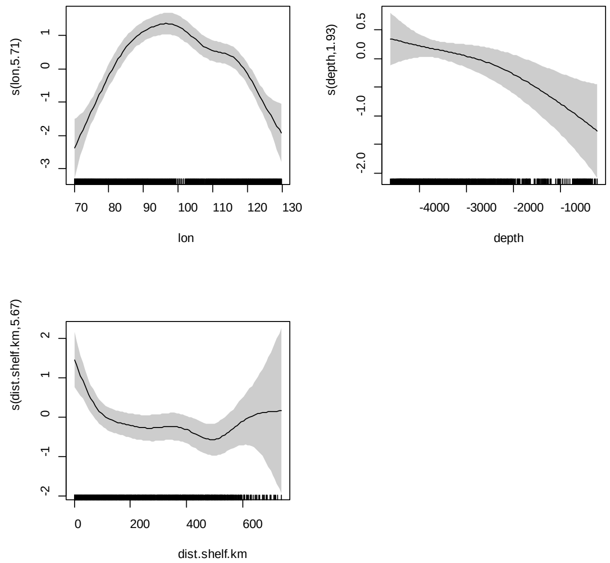

Fig. 5. Smoothed fits of selected covariate modeling the probability of occurrences of humpback whales in middle period (1995/1996, 1997/1998 and 1999/2000). Tick marks on the x-axis are observed data points. The shaded areas indicate the 95% confidence bounds. lon: longitude, depth: seafloor depth (m), dist.shelf.km: distance from the shelf break (km).

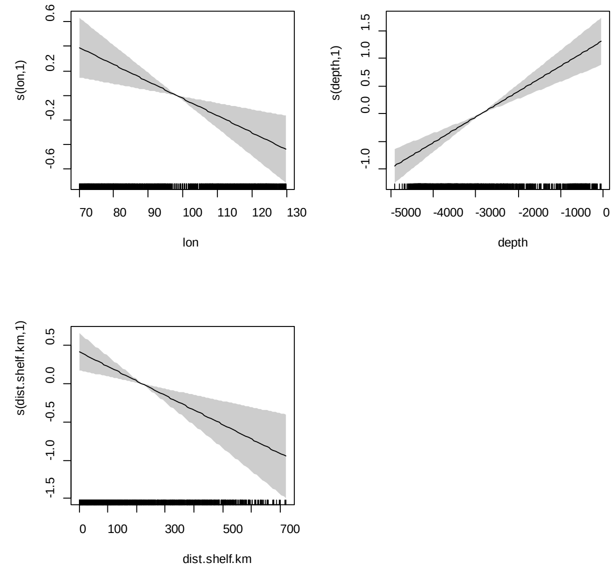

Fig. 6. Smoothed fits of selected covariate modeling the probability of occurrences of Antarctic minke whales in late period (2001/2002, 2003/2004 and 2005/2006). Tick marks on the x-axis are observed data points. The shaded areas indicate the 95% confidence bounds. lon: longitude, depth: seafloor depth (m), dist.shelf.km: distance from the shelf break (km).

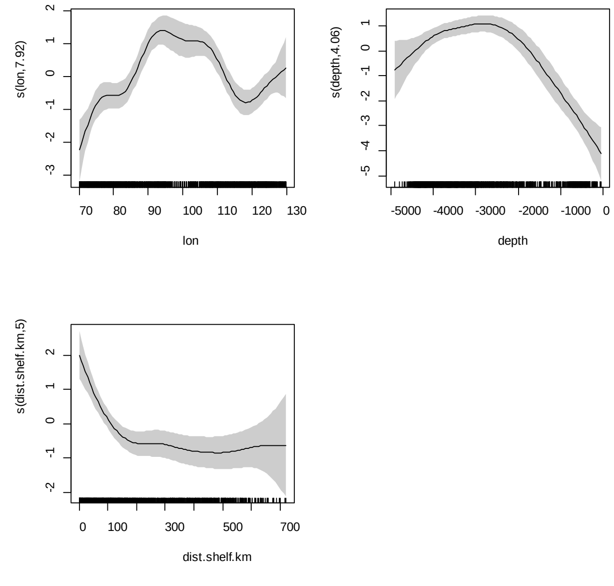

Fig. 7. Smoothed fits of selected covariate modeling the probability of occurrences of Antarctic minke whales in late period (2001/2002, 2003/2004 and 2005/2006). Tick marks on the x-axis are observed data points. The shaded areas indicate the 95% confidence bounds. lon: longitude, depth: seafloor depth (m), dist.shelf.km: distance from the shelf break (km).

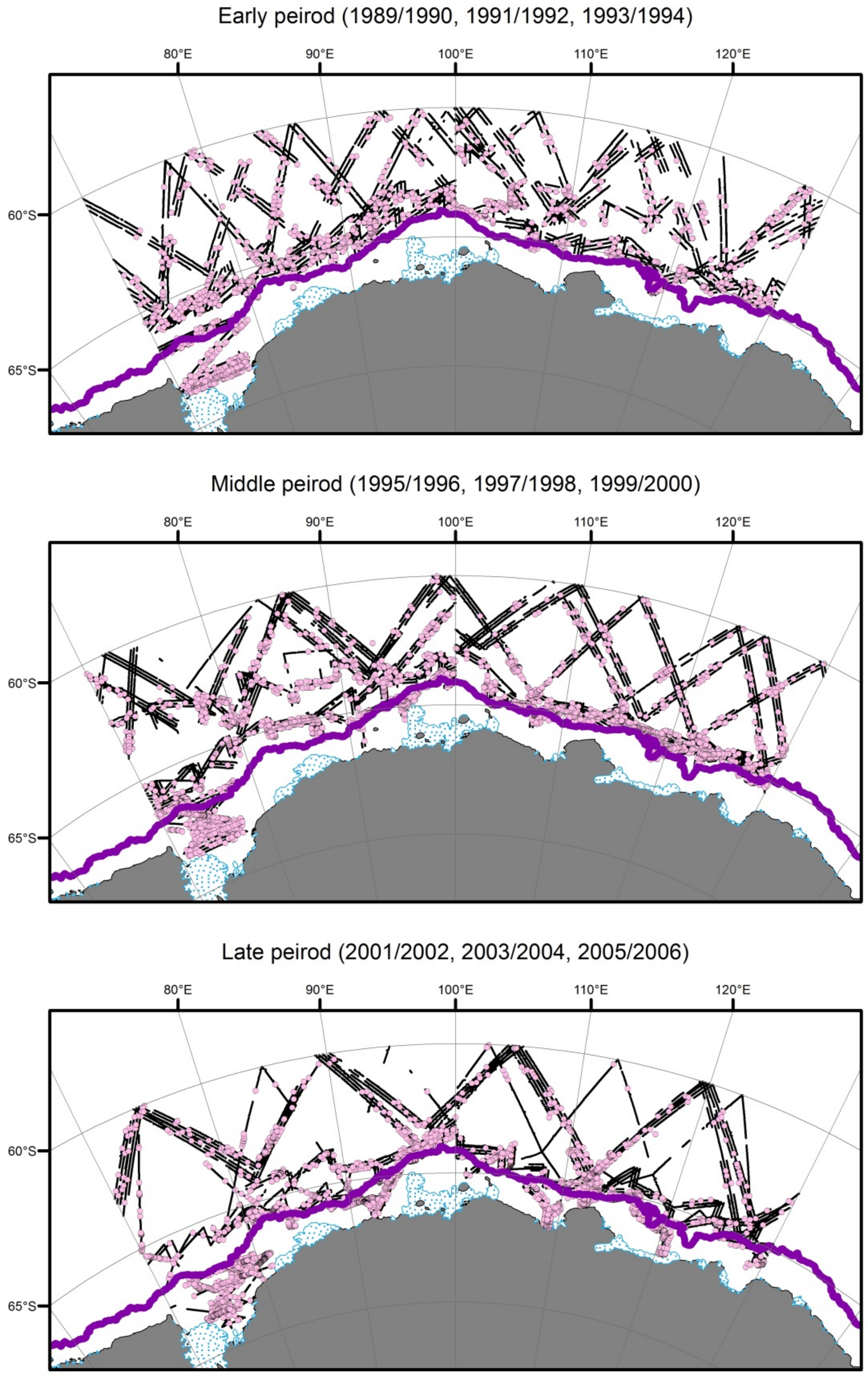

Fig. 8. Surveyed tracklines (black line) and sighting positions of Antarctic minke whales (pink circle) in Area IV in early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods. Location of the shelf break (800m isobaths; purple line) is also shown.

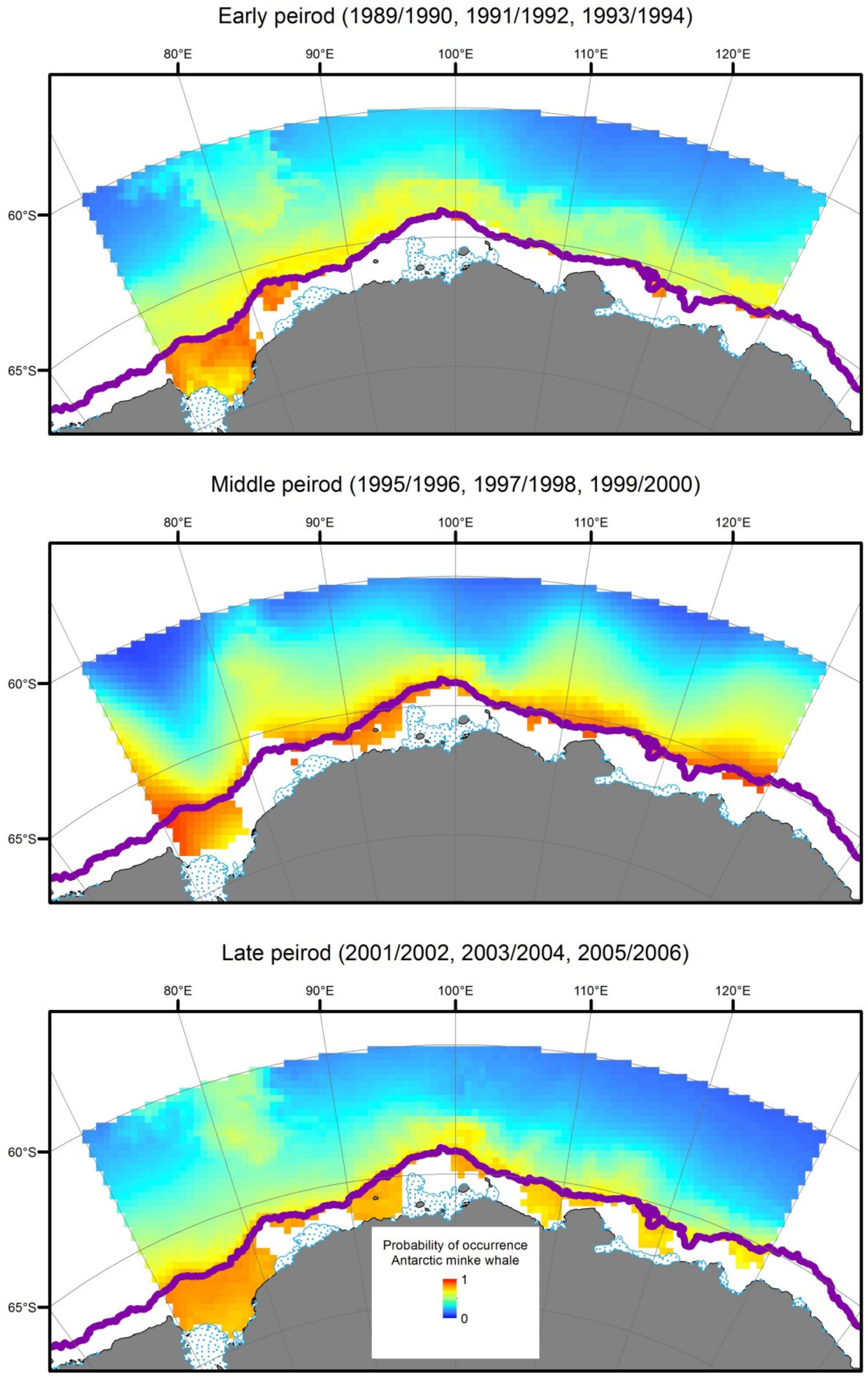

Fig. 9. Estimated probabilities of occurrence of Antarctic minke whales in Area IV in early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods. Location of the shelf break (800m isobaths; purple line) is also shown.

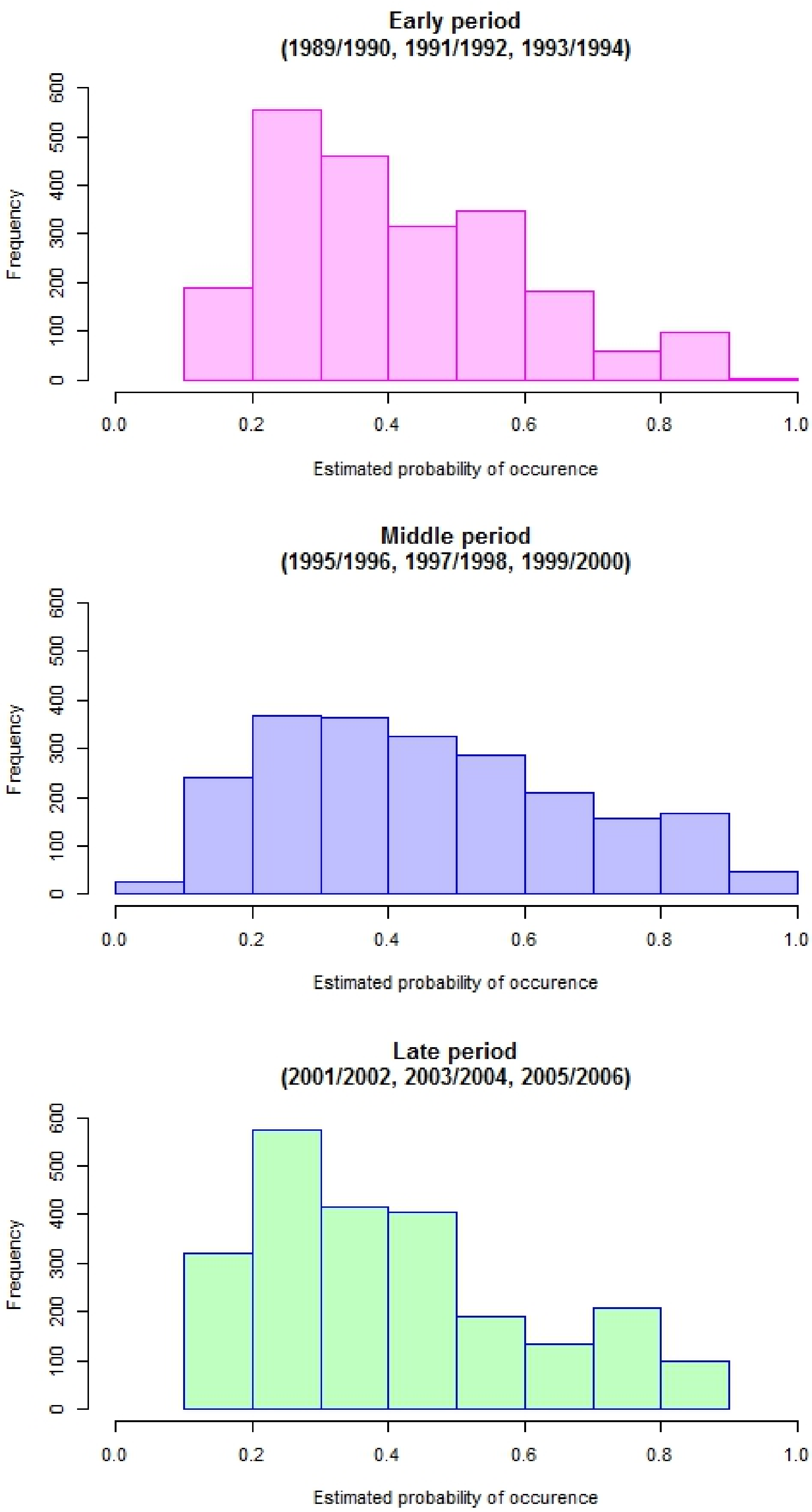

Fig. 10. Frequency distributions of probabilities of occurrence of Antarctic minke whales in Area IV in early, middle and late periods.

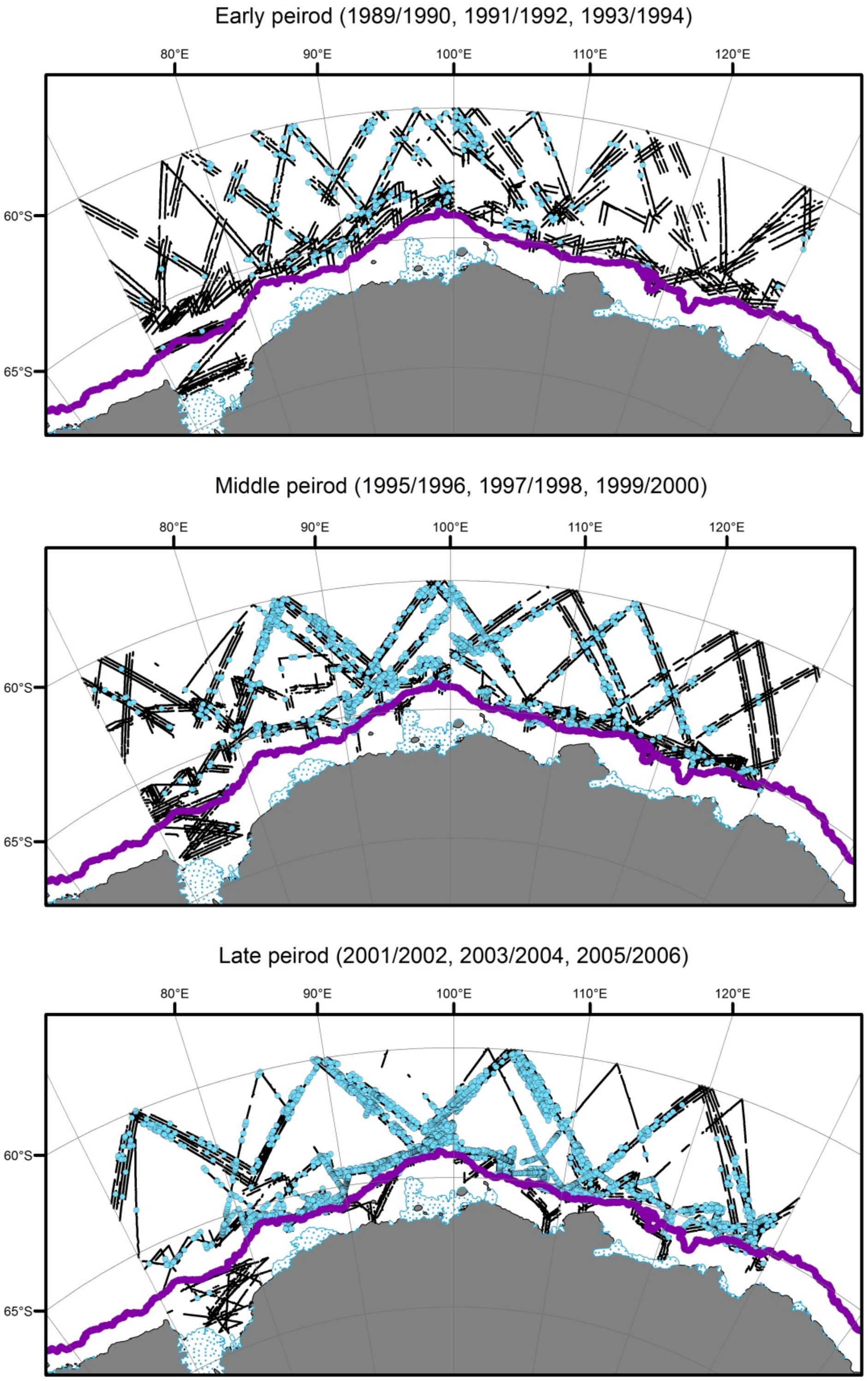

Fig. 11. Surveyed tracklines (black line) and sighting positions of humpback whales (sky blue circle) in Area IV in early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods. Location of the shelf break (800m isobaths; purple line) is also shown.

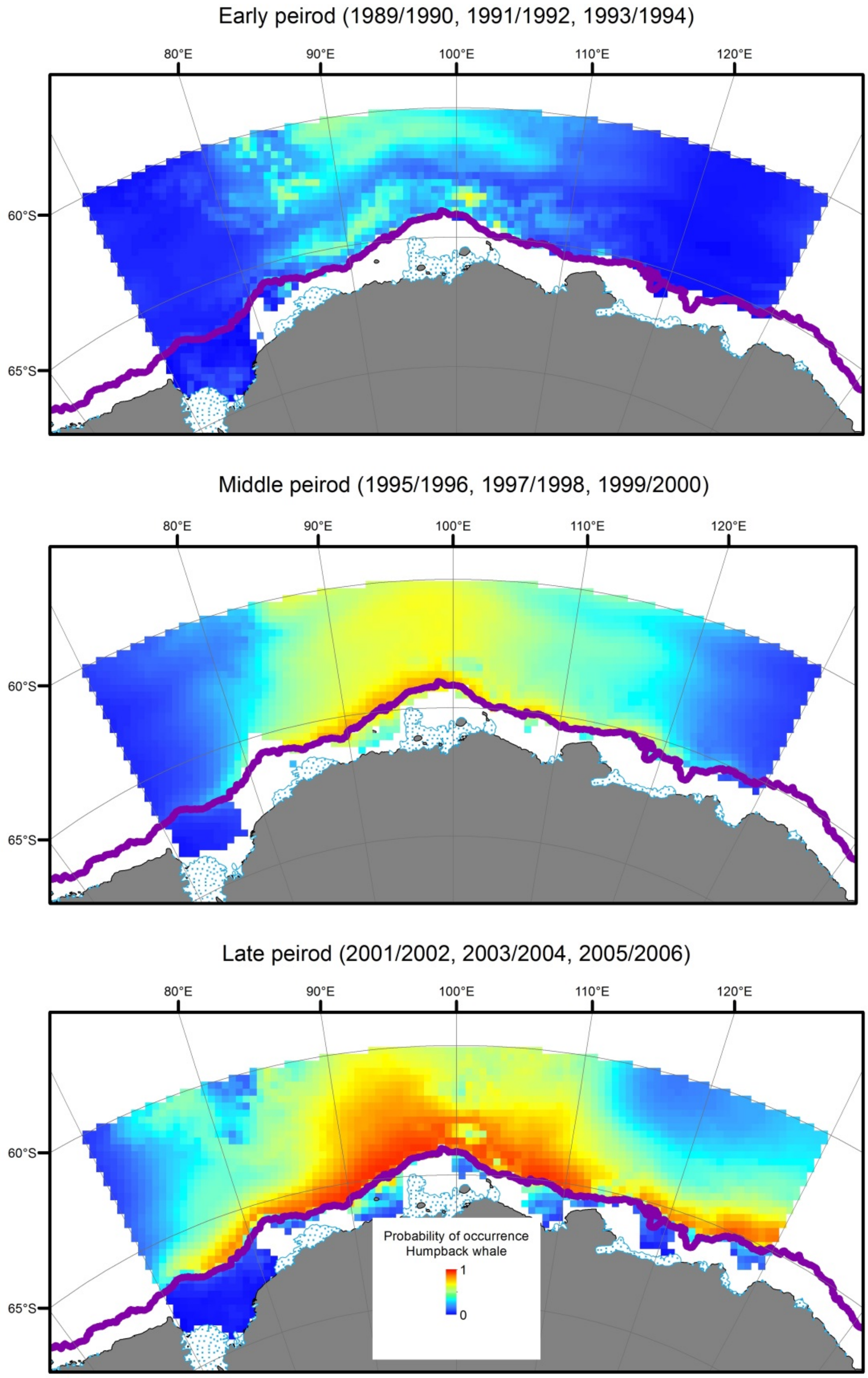

Fig.12. Estimated probabilities of occurrence of humpback whales in Area IV in early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods. Location of the shelf break (800m isobaths; purple line) is also shown.

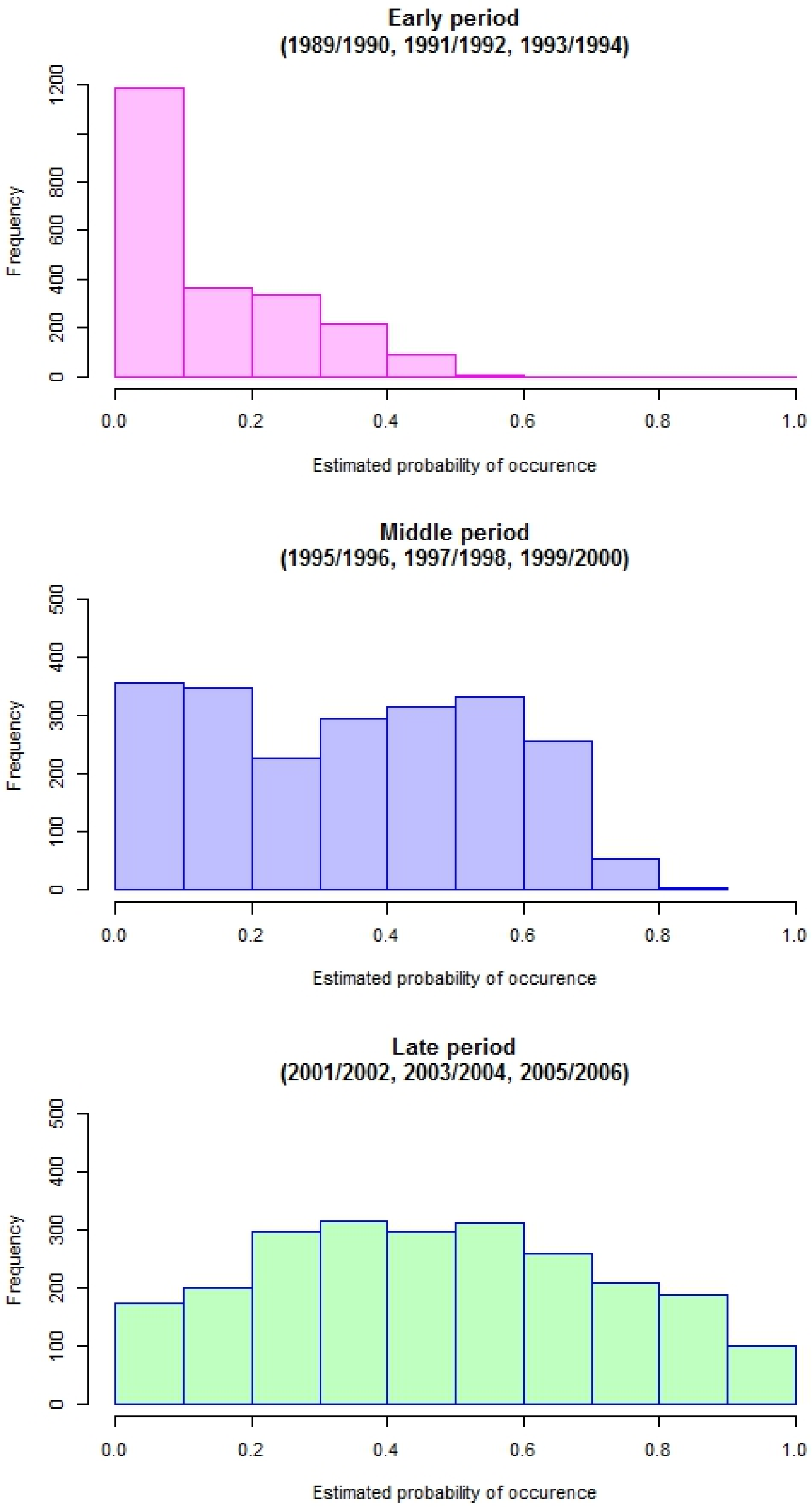

Fig. 13. Frequency distributions of probabilities of occurrence of humback whales in Area IV in early, middle and late periods.

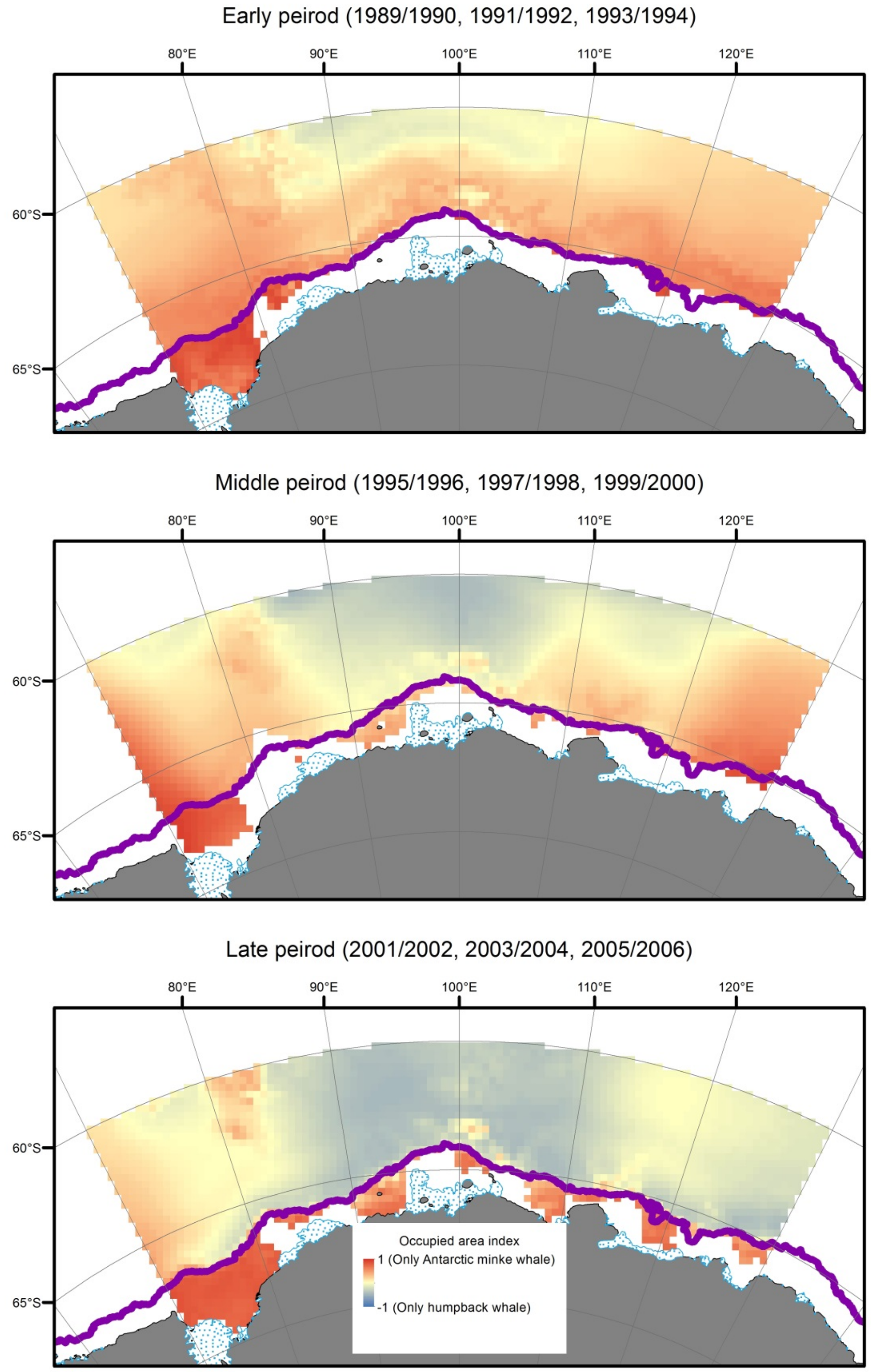

Fig. 14. Occupied area indices of Antarctic minke and humpback whales in Area IV in early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods. If the index was 1, only Antarctic minke whales were present in a grid cell while only humpback whales were present if the index was -1. If the index was 0, probabilities of the presence of Antarctic minke and humpback whales in a grid cell were identical.

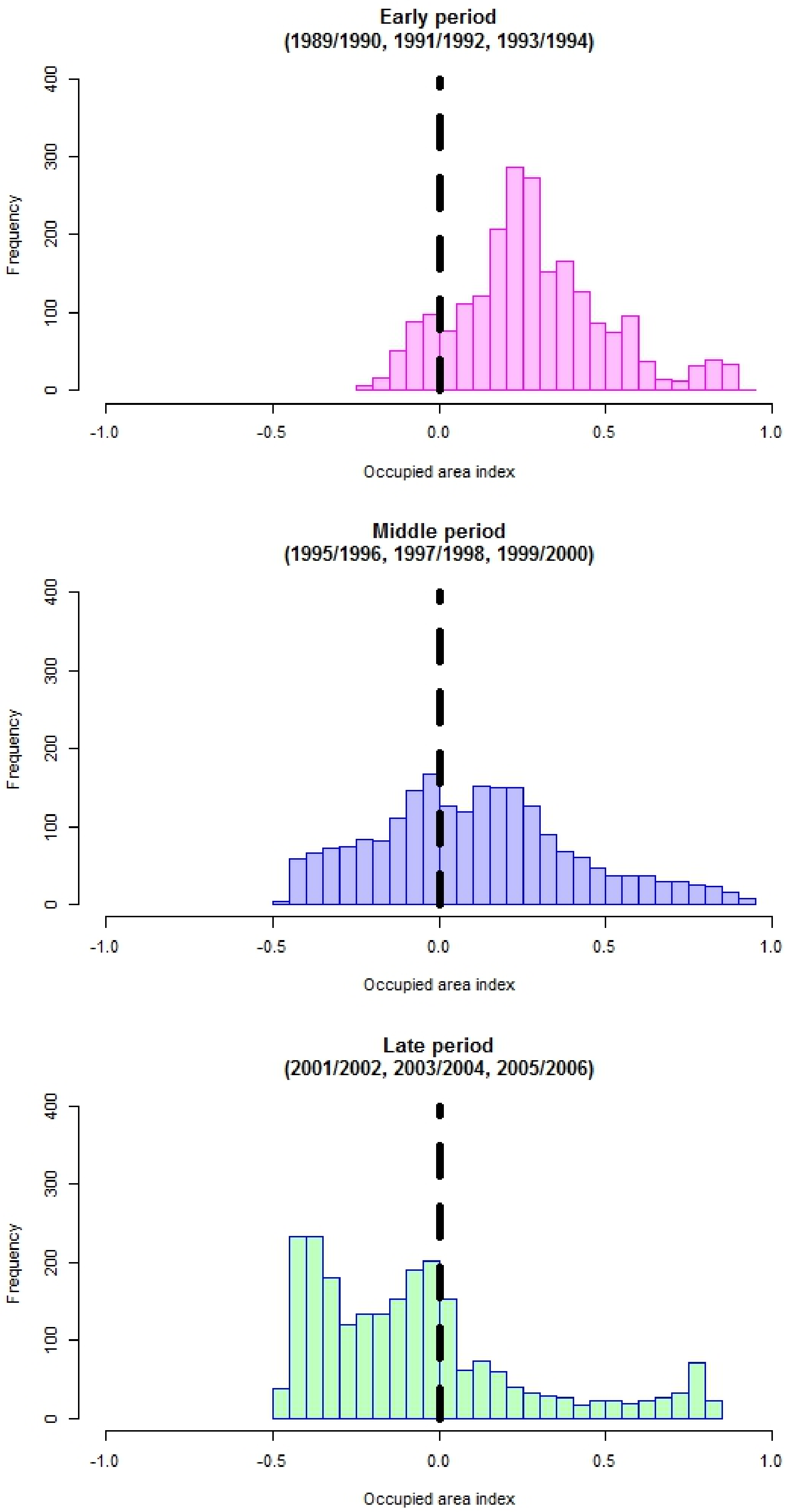

Fig. 15. Frequency distributions of occupied area indices of Antarctic minke and humpback whales in Area IV in early (1989/1990, 1991/1992 and 1993/1994) middle (1995/1996, 1997/1998 and 1999/2000) and late (2001/2002, 2003/2004 and 2005/2006) periods. If the index was 1, only Antarctic minke whales were present in a grid cell while only humpback whales were present if the index was -1. If the index was 0, probabilities of the presence of Antarctic minke and humpback whales in a grid cell were identical.