Supporting Information for "**Dynamic species distribution models in the marine realm: predicting year-round habitat suitability of baleen whales in the Southern Ocean**" – Frontiers in Marine Science 8:802276.

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Authors

Ahmed El-Gabbas *; Ilse Van Opzeeland; Elke Burkhardt; Olaf Boebel

Ocean Acoustics Group, Alfred-Wegener Institute (AWI), Helmholtz Centre for Polar and Marine Research, 27570 Bremerhaven, Germany.

* Corresponding author: ahmed.el-gabbas@awi.de; elgabbas@outlook.com

Appendix 1: Seasonal research efforts in the Southern Ocean

Seasonal research efforts in the Southern Ocean were estimated and used to correct spatial biases in species observation data. To this end, we collected ship track data from a variety of sources. The primary data source was sailwx[1] (Hal Mueller, personal communication). Sailwx provides a global, publicly available dataset on ship locations and weather conditions (1980-now). Other data sources used include Marine Geoscience Data System[2], UK Polar Data Centre[3], Australian Antarctic Division (AAD)[4], and RV Polarstern[5].

Sailwx data processing: Sailwx data was provided in a tabular format, representing ship track points. We excluded points north of the Southern Ocean Polar Front and only extracted four columns from the original dataset: CALLSIGN: unique maritime identifier to ships and boats; TIMESTAMP: number of seconds elapsed since January 1, 1970 (Unix epoch); Latitude; and Longitude. This reduced file size from 240 GB to only 17 MB. A unique ID for each point was assigned by concatenating call sign and time stamp to make it easier later to mark and exclude spatial outliers.

Points were assigned to six ship types based on call signs (tourism, tall ships, fishing, military, buoys, and research). This was mainly performed following SCAR's (Scientific Committee on Antarctic Research) Antarctic Observing Network (AntON)[6]. Call signs not included in the AntON report were individually checked using internet search and assigned to the appropriate ship type. Call signs that cannot be assigned to a definite ship type were assigned as 'unknown'. Here, we only considered "research" ship data, as they represent the majority of the data in the Southern Ocean and are more relevant for our application.

Data points were converted into polylines (spatial lines shapefiles), one line for each call sign. The original dataset was not split into smaller chunks (sub-tracks) for independent research expeditions. Thus, converting the points into spatial lines can involve spurious segments between time-independent expeditions entering and leaving the Southern Ocean. Call sign lines were split into meaningful sub-tracks by calculating the time difference between every two subsequent points: lines were split into sub-tracks if the time difference exceeds two days. We think this is sufficient to discriminate between independent research expeditions.

[1] https://www.sailwx.info/shiptrack/ (Mobile Geographics LLC)
[2] http://www.marine-geo.org/
[3] https://www.bas.ac.uk/data/uk-pdc/
[4] https://www.antarctica.gov.au/
[5] https://www.awi.de/en/expedition/research-vessel-and-cutter/polarstern.html
[6] IP034: The Antarctic Observing Network (AntON) to Facilitate Weather and Climate Information (joint paper with WMO). Available at: https://www.scar.org/library/policy/antarctic-treaty/atcm-xxxix-and-cep-xix-2016/2749-atcm39-ip034/

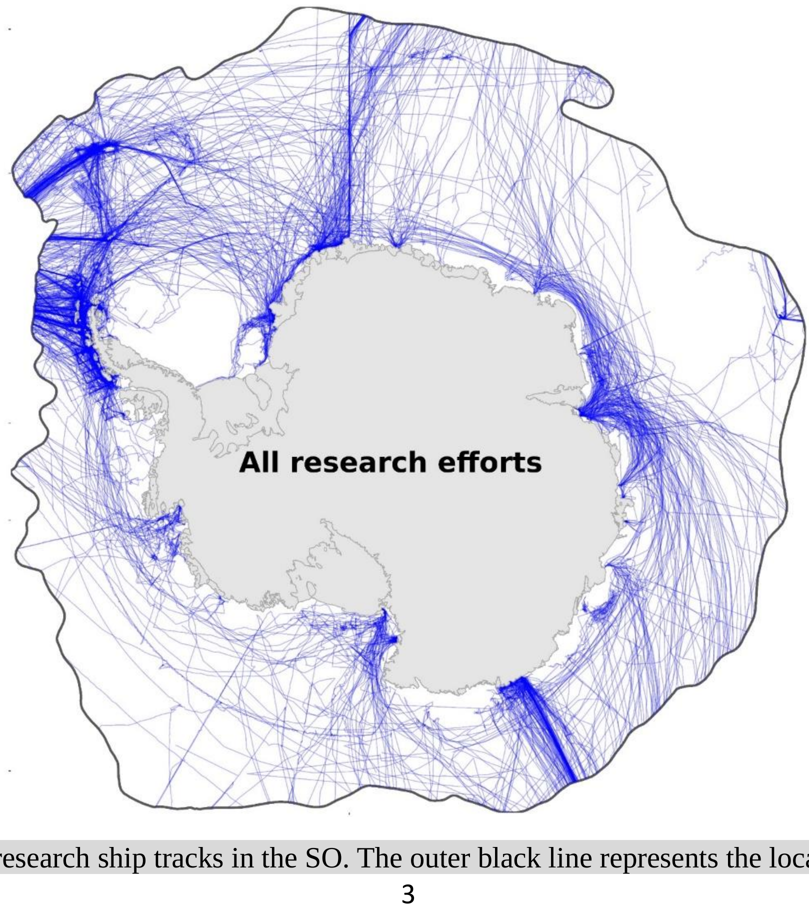
For each valid sub-track (≥ two connected points), we inspected for possible spatial errors (outliers) by calculating the speed (kmh^{-1}) at which the ship has traveled between every two subsequent points (Euclidean distance, in km, per hour). We used z-score of speed to detect outliers, calculated as: $\frac{\text{speed} - \text{mean speed of the sub-track}}{\text{standard deviation of speed of the sub-track}}$. Points with z-score ≥ three were marked as spatial outliers and were removed from the spatial line. Sub-tracks were then checked for not-yet-detected outliers by visualizing them at a circumantarctic projection.

Some of the call signs provided by the Sailwx were already available from their original sources (e.g. Polarstern). These call signs were excluded from the Sailwx data and replaced with data from their original sources:

- 6WLI – VEMA (marine-geo.org)
- 9VEZ4 - Eltanin (marine-geo.org)
- DBLK - Polarstern
- JZJF - Maurice Ewing (marine-geo.org)
- KAOU - Rover Revelle (marine-geo.org)
- KCEJ – Knorr (marine-geo.org)
- LOIO – Islasorcadas (marine-geo.org)
- UIMS - Akademik Nikolaj Strakhov (marine-geo.org)
- VNAA - Aurora Auralis (AAD)
- WBP3210 - Nathaniel B Palmer (marine-geo.org)
- WCX7445 - Laurence M Gould (marine-geo.org)
- WHBA - Robert D Conrad (marine-geo.org)
- ZDLP - James Clark Ross (UK Polar Data Centre)

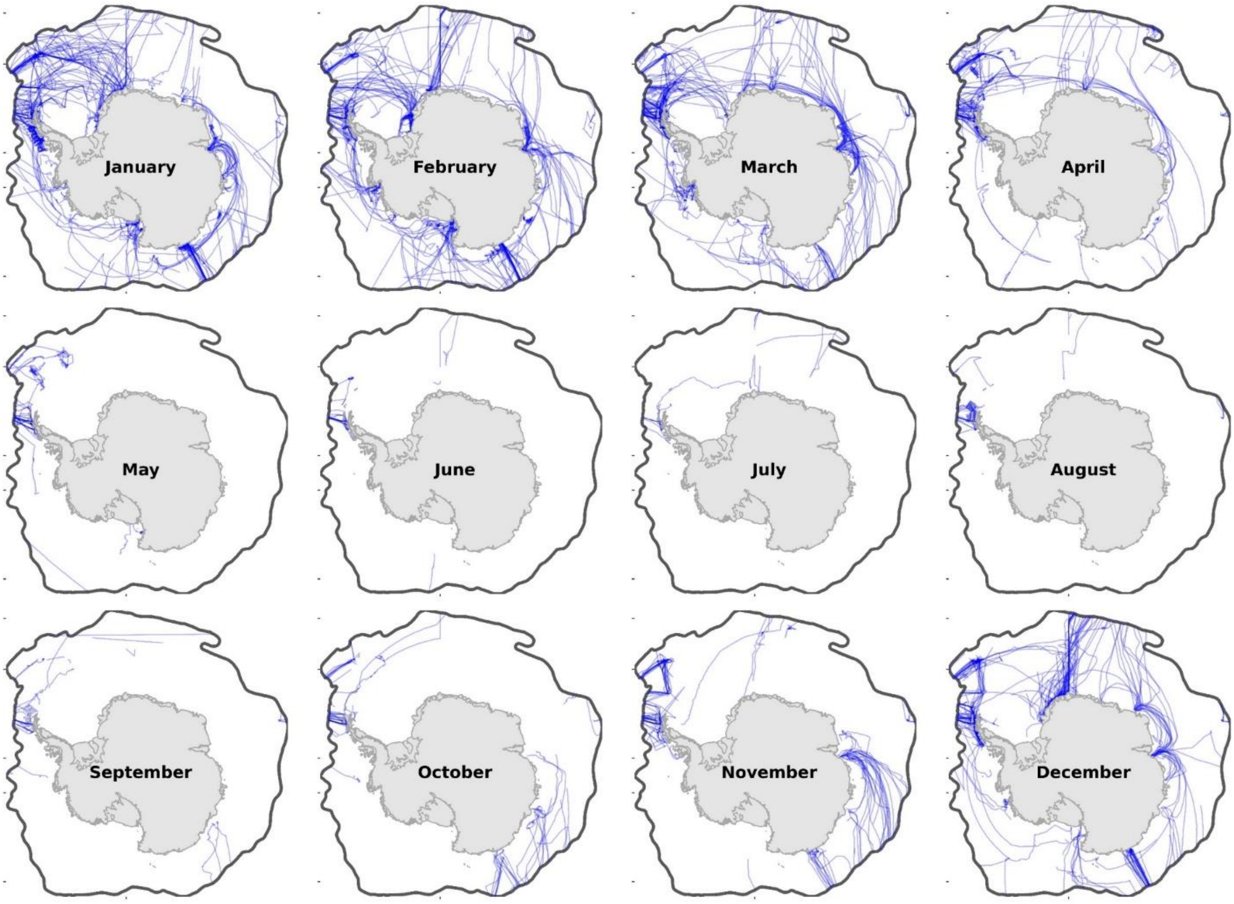
Seasonal research efforts in the Southern Ocean

Final research ship tracks from all data sources were then merged into one spatial data set. Maps below show the overall pattern of research ship tracks in the Southern Ocean (irrespective of the time), in addition to their monthly and seasonal pattern (seasons determined as a three-month interval from January).

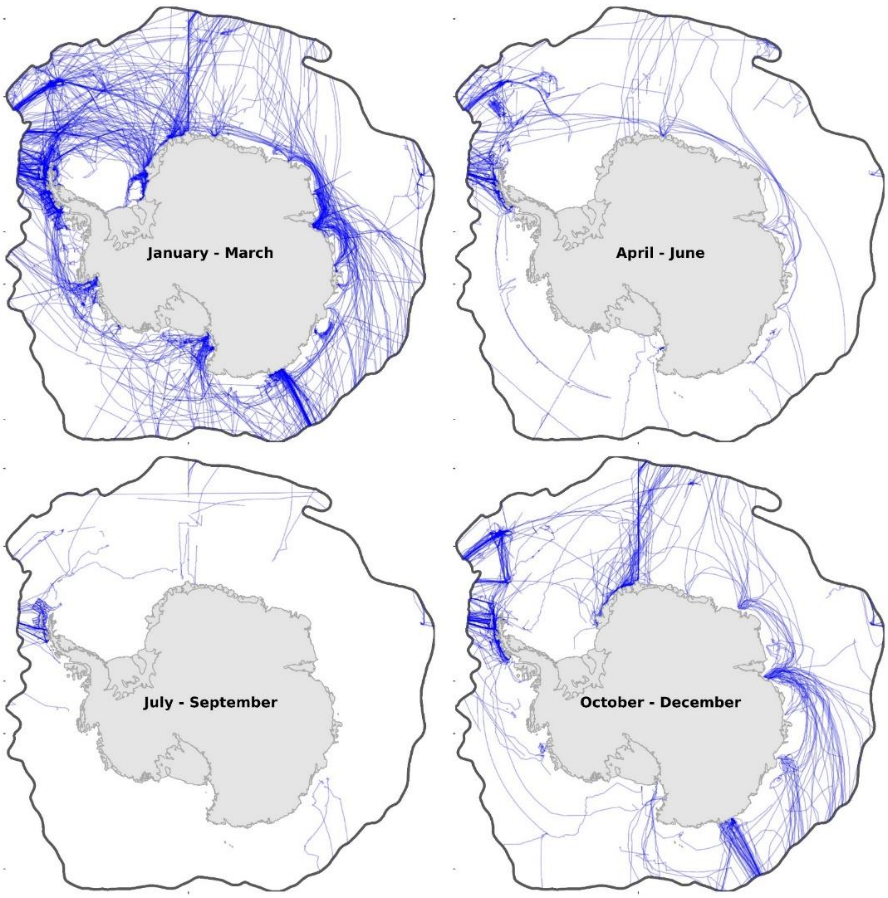


The overall pattern of research ship tracks in the SO. The outer black line represents the location of the Polar Front.

Seasonal research efforts in the Southern Ocean



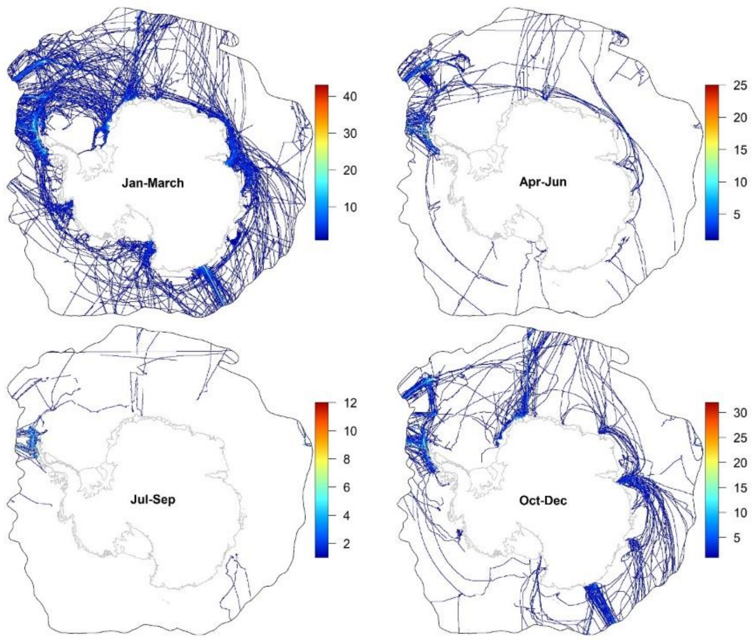
Monthly pattern of research ship tracks in the SO



Seasonal pattern of research ship tracks in the SO

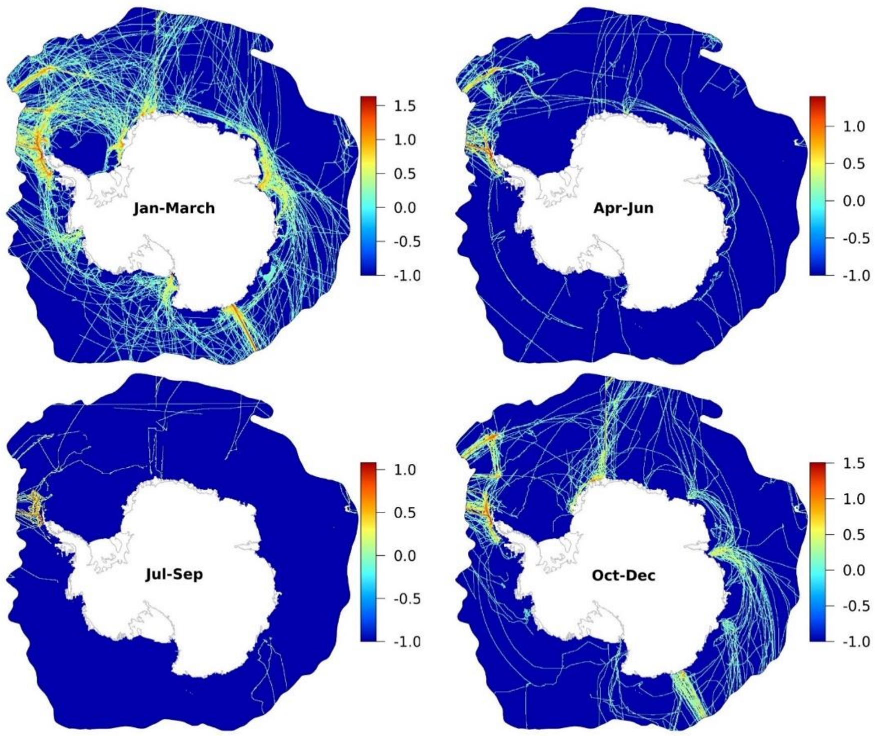
Seasonal research efforts in the Southern Ocean

Quality-controlled track lines were then rasterized into a circumpolar 10×10 km grid (the same grid used in the models): the value in each cell represents the number of research ship tracks per cell in the respective season.



Number of seasonal research ship tracks per 10×10 km grid

Seasonal research effort layers were used as probability weight during the daily sampling of background locations: cells with higher effort value in the respective season are more likely to be sampled than cells with little effort. Cells without any tracks (zero value) were filled with a small value (0.1), allowing them to be sampled, yet at a lower probability. This approach is similar to the use of bias-grid in Maxent.

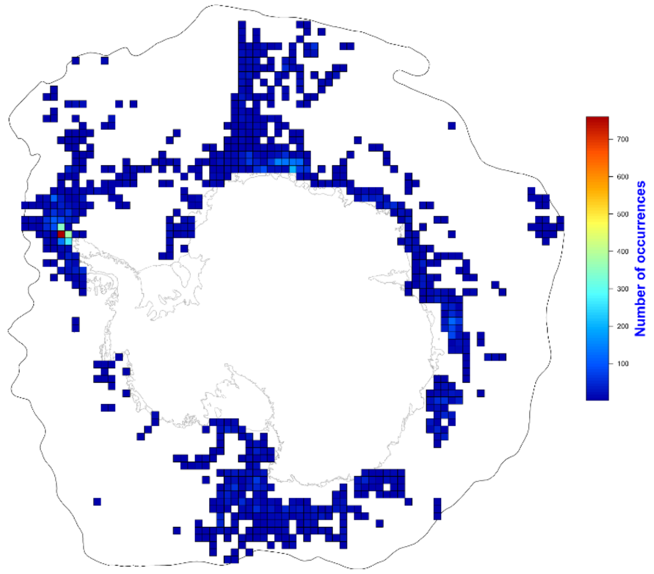


Seasonal research efforts in the Southern Ocean (plotted at log_{10} scale)

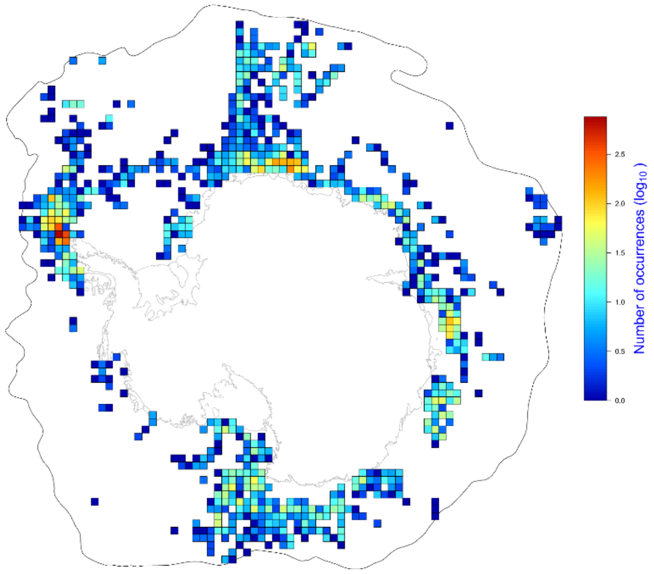
Table S1: Model evaluation results.

The table shows the values of AUC, TSS_{MaxSS}, and $TSS_{EqualSS,}$ all using independent testing datasets (testing presences and background locations) on spatial or temporal cross-validation (CV). For each model, two threshold rules were used to calculate TSS: a threshold that maximizes the sum of sensitivity and specificity (i.e., maximum TSS, TSS_{MaxSS}); and a threshold at which sensitivity and specificity are equal ($TSS_{EqualSS}$). Values represent the mean and standard deviation for the respective cross-validated model. The last column shows the total number of species sightings used in the models.

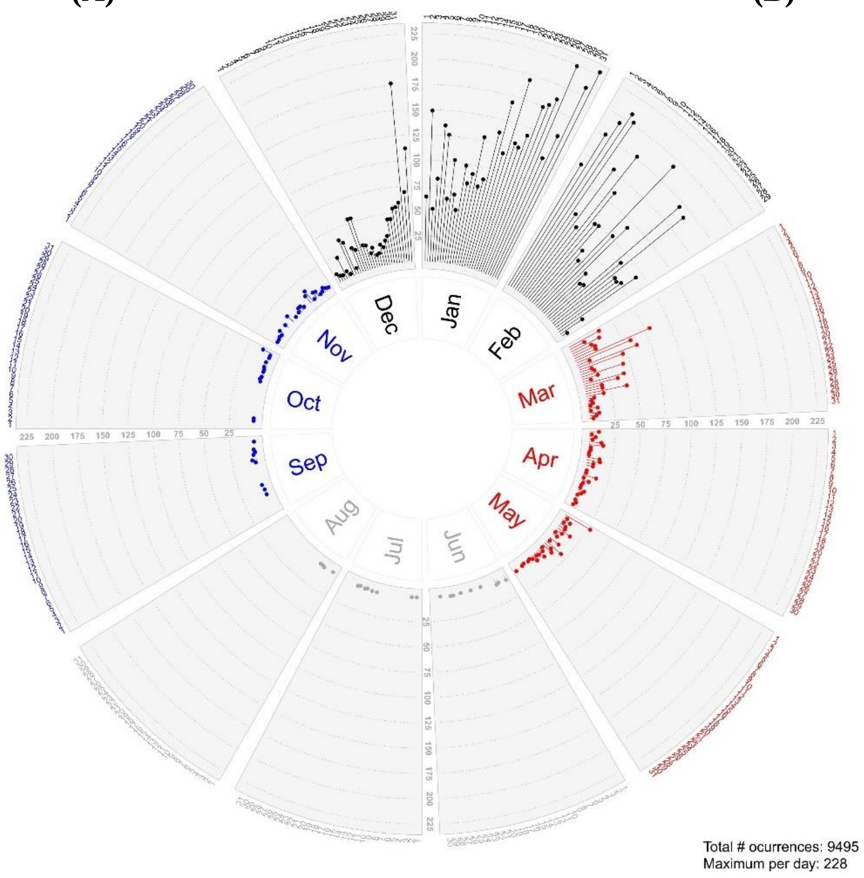
Species	Testing AUC		Testing TSS $_{MaxSS}$		Testing TSS $_{EqualSS}$		# sightings
	Spatial CV	Temporal CV	Spatial CV	Temporal CV	Spatial CV	Temporal CV	
Antarctic minke whales	0.86 ± 0.06	0.83 ± 0.03	0.60 ± 0.10	0.52 ± 0.08	0.57 ± 0.12	0.48 ± 0.11	3,597
Antarctic blue whales	0.85 ± 0.14	0.86 ± 0.08	0.68 ± 0.15	0.61 ± 0.18	0.55 ± 0.28	0.55 ± 0.22	192
Fin whales	0.82 ± 0.09	0.83 ± 0.06	0.60 ± 0.11	0.56 ± 0.10	0.50 ± 0.19	0.50 ± 0.09	730
Humpback whales	0.90 ± 0.03	0.90 ± 0.02	0.65 ± 0.06	0.63 ± 0.03	0.63 ± 0.07	0.62 ± 0.04	4,976



(A)



(B)

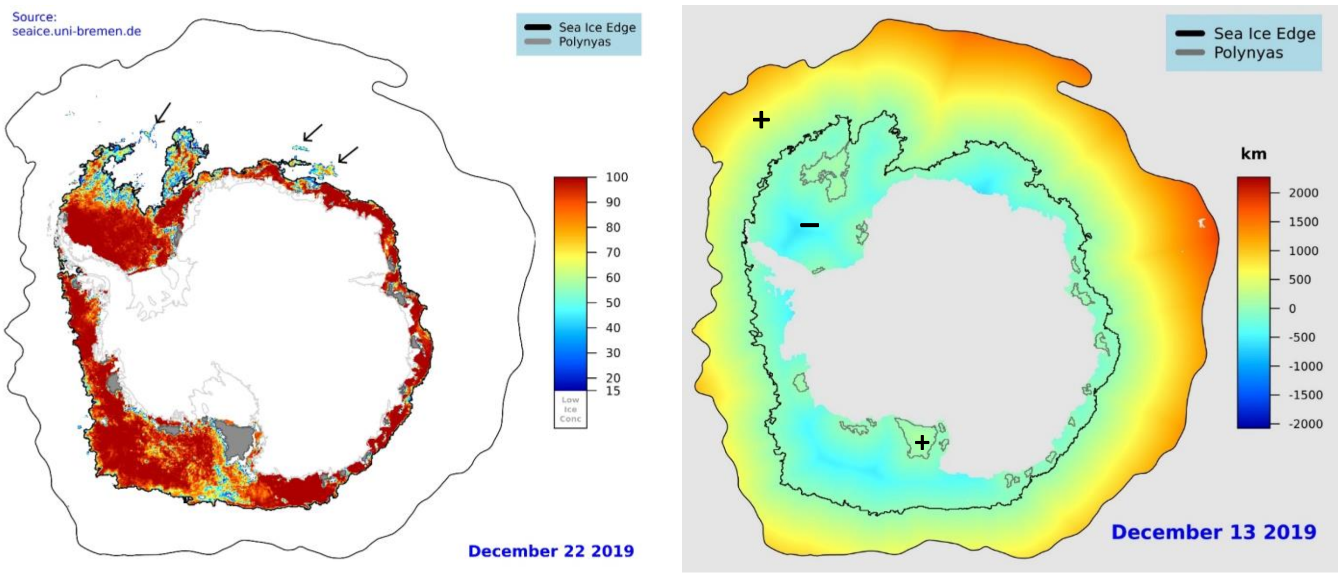


(C)

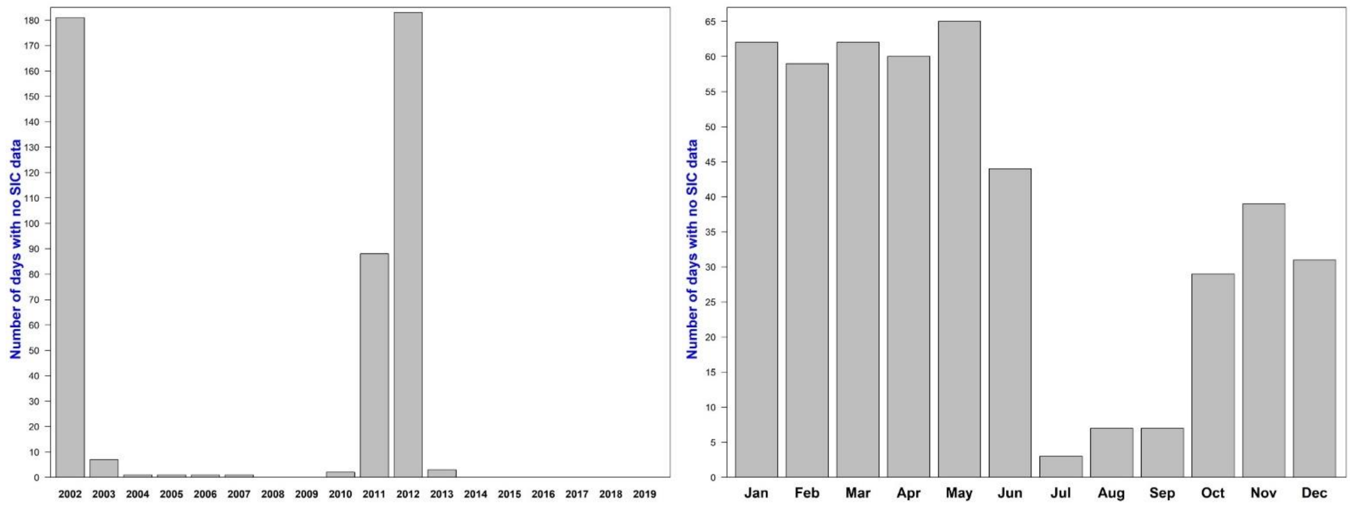
Figure S1: Spatiotemporal biases in baleen whale sighting data in the Southern Ocean.

(A) The number of species sightings per 100×100 km grid (2002-2019). **(B)** The same information as in ***a***, but on the $\log_{10}$ scale. The Antarctic Peninsula area shows an evident spatial bias, with exceptionally highest number of sightings per cell. Most humpback whale sightings (and, to a lesser extent, fin whales) were observed from this area (see Figures S19 and S27).

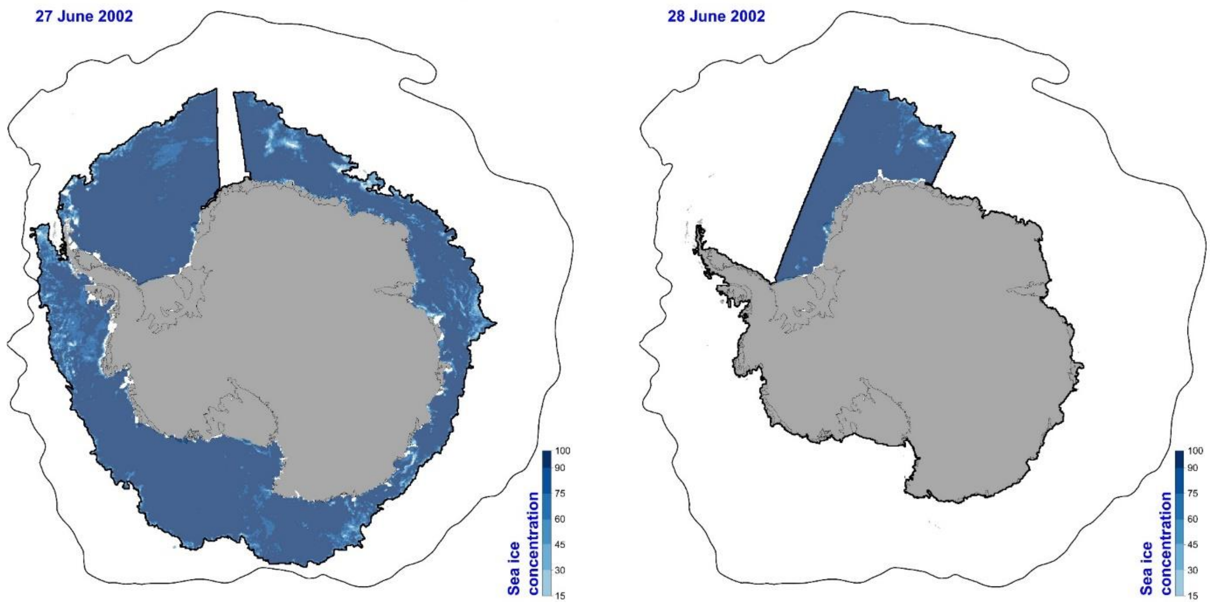
Panel **(C)** shows the total number of sightings (2002-2019) per calendar day.


Source:
seaice.uni-bremen.de
Sea Ice Edge
Polynyas
100
90
80
70
60
50
40
30
20
15
Low Ice Conc
December 22 2019
Sea Ice Edge
Polynyas
km
2000
1500
1000
500
0
-500
-1000
-1500
-2000
December 13 2019

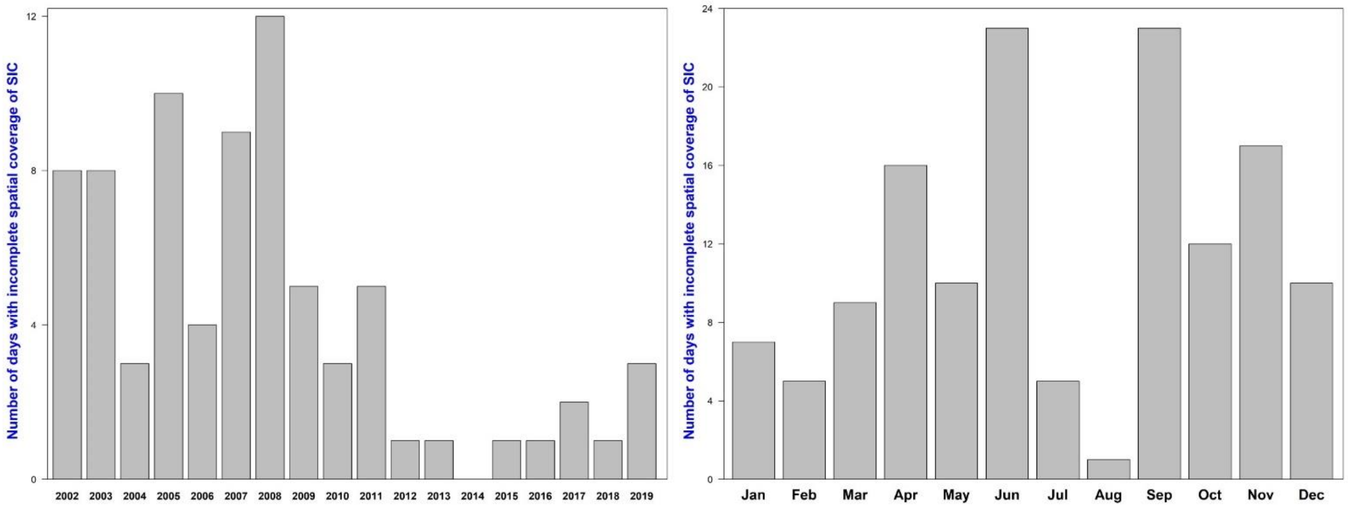
(A)


Number of days with no SIC data
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Number of days with no SIC data
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

(B)


27 June 2002
28 June 2002
Sea ice concentration
100
90
75
60
45
30
15

(C)



(D)

Figure S2: The processing of sea ice concentration data.

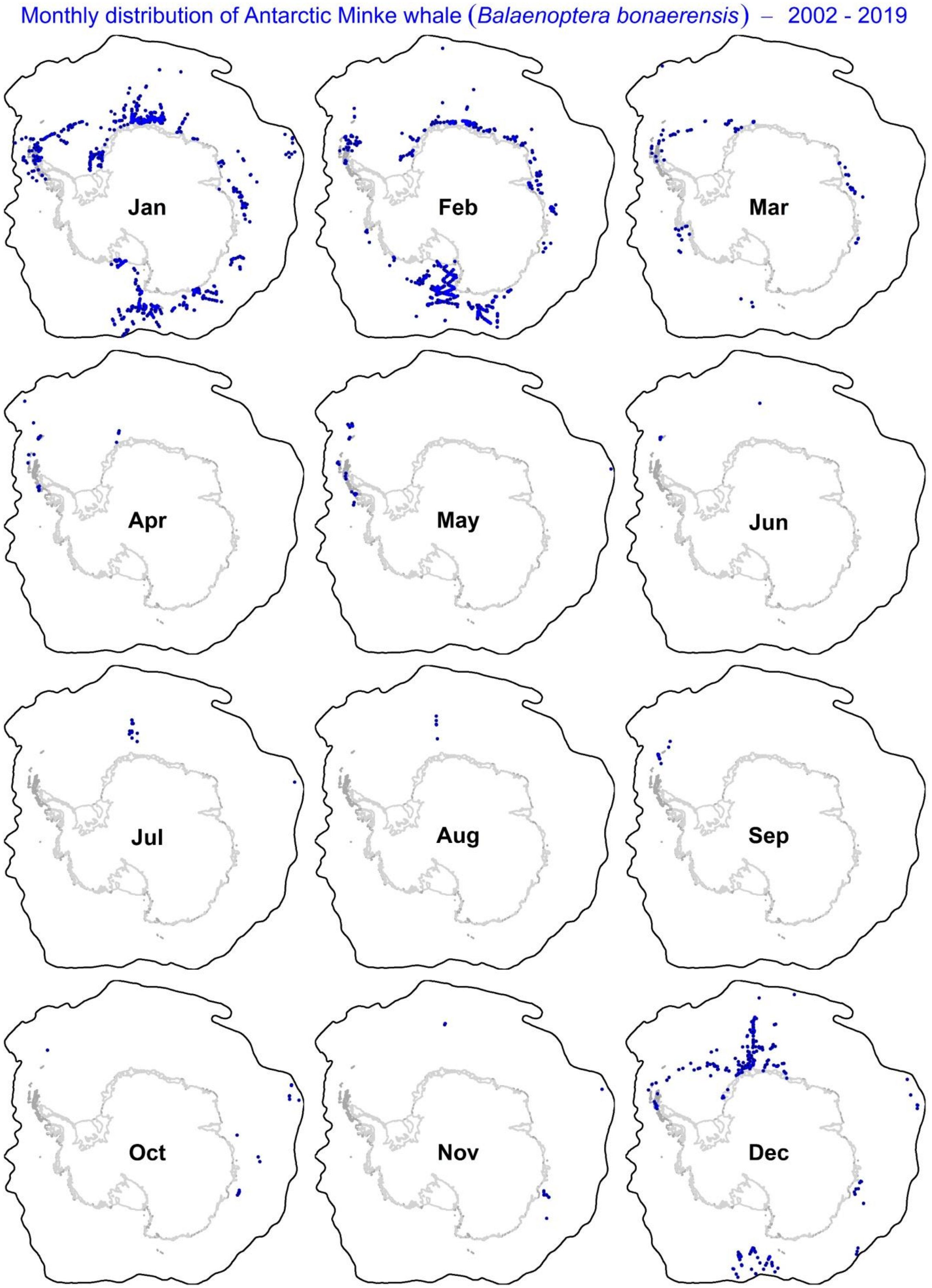
(A) The estimation of daily sea ice edge (SIE). The map to the left shows the estimated location of SIE on 22nd December 2019 (black line), with colors represent only cells with SIC >15%. The determination of the SIE has trade-offs, and some cells with SIC >15% can still be located north of SIE (e.g., areas marked with arrows). Dark grey areas south of the SIE represent polynyas on that day. We only considered areas south of the SIE of more than 20 connected cells with <15% SIC that persist for five consecutive days as polynyas (here: persistent low SIC from 20-24 December 2019). The map to the right shows an example of how we estimated the distance to SIE (13th December 2019). The black line represents SIE, while the light grey polygons south of it represent polynyas. Cells intersected with SIE or polynyas borders were assigned a value of zero, positive north of SIE (+), and negative south of it (−), except for polynyas which were given a positive value.

(B) Number of days without SIC data per year (left) or per month (right). Note the large number of days without SIC data in 2002, 2011, and 2012. These years were excluded from the background sampling to get balanced temporally cross-validated models.

(C) Two examples of days with incomplete SIC coverage. Only SIC >15% are shown in the maps. On these days, we cannot estimate the SIE correctly, and then days with such issues were excluded from background sampling.

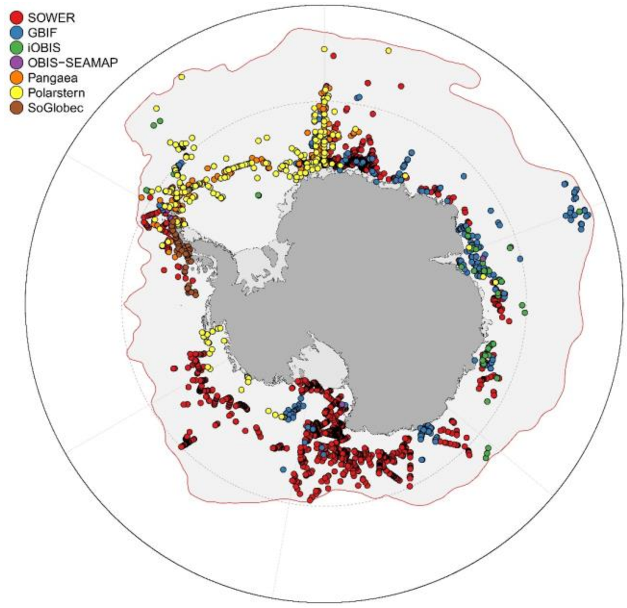
(D) The number of days with incomplete SIC spatial coverage per year or month.

Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)

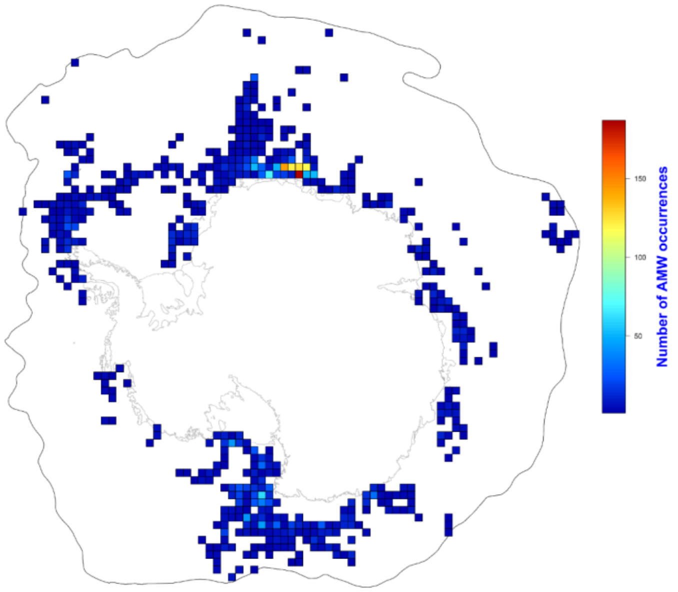


(A)

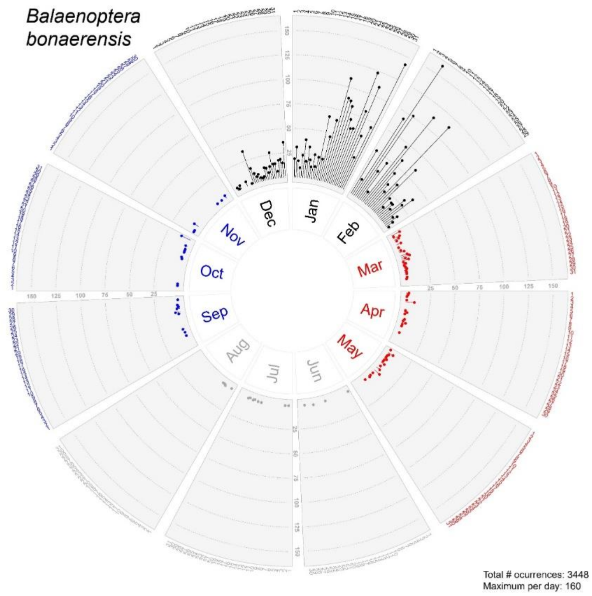
Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)



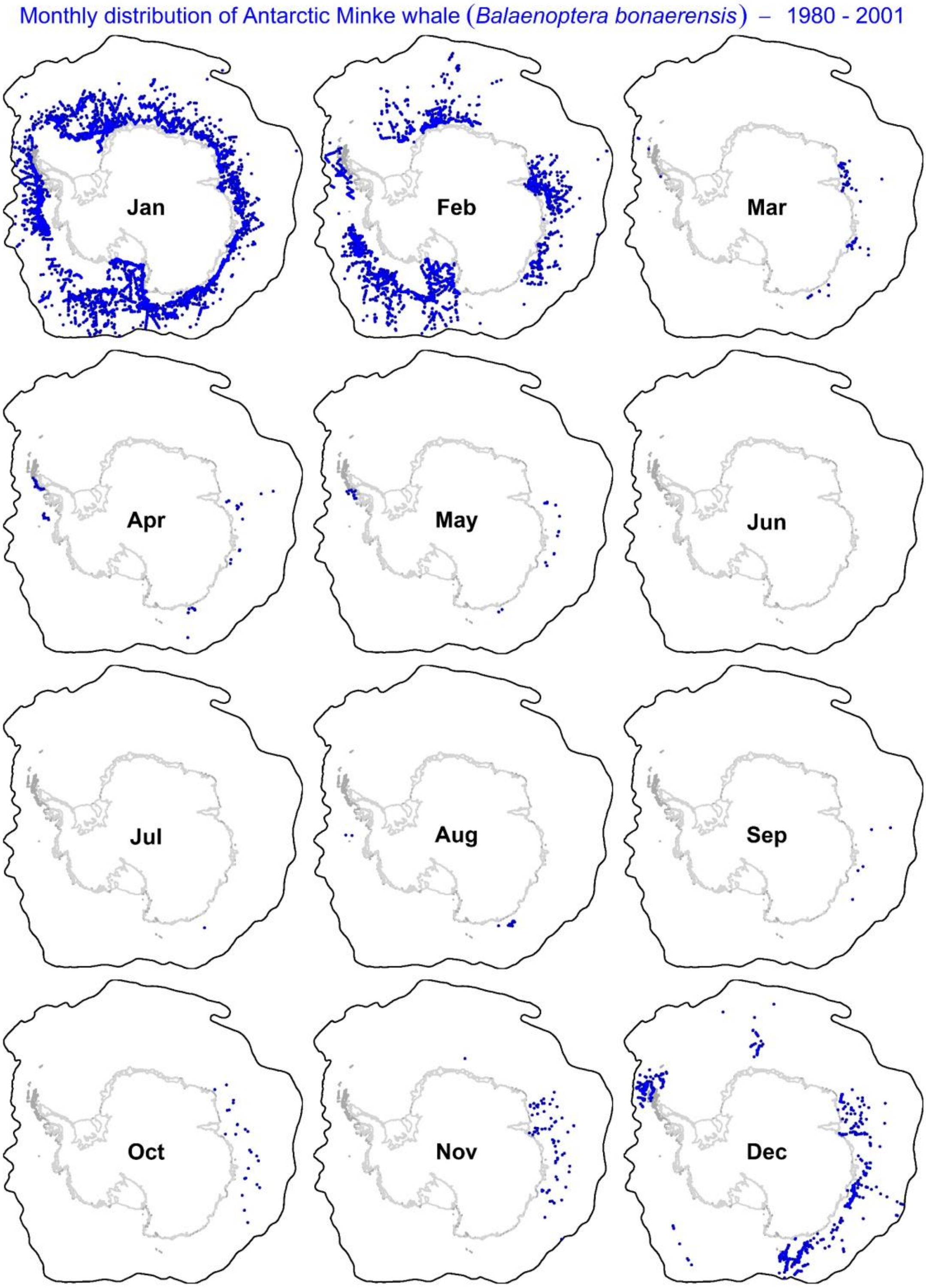
(B)



(C)



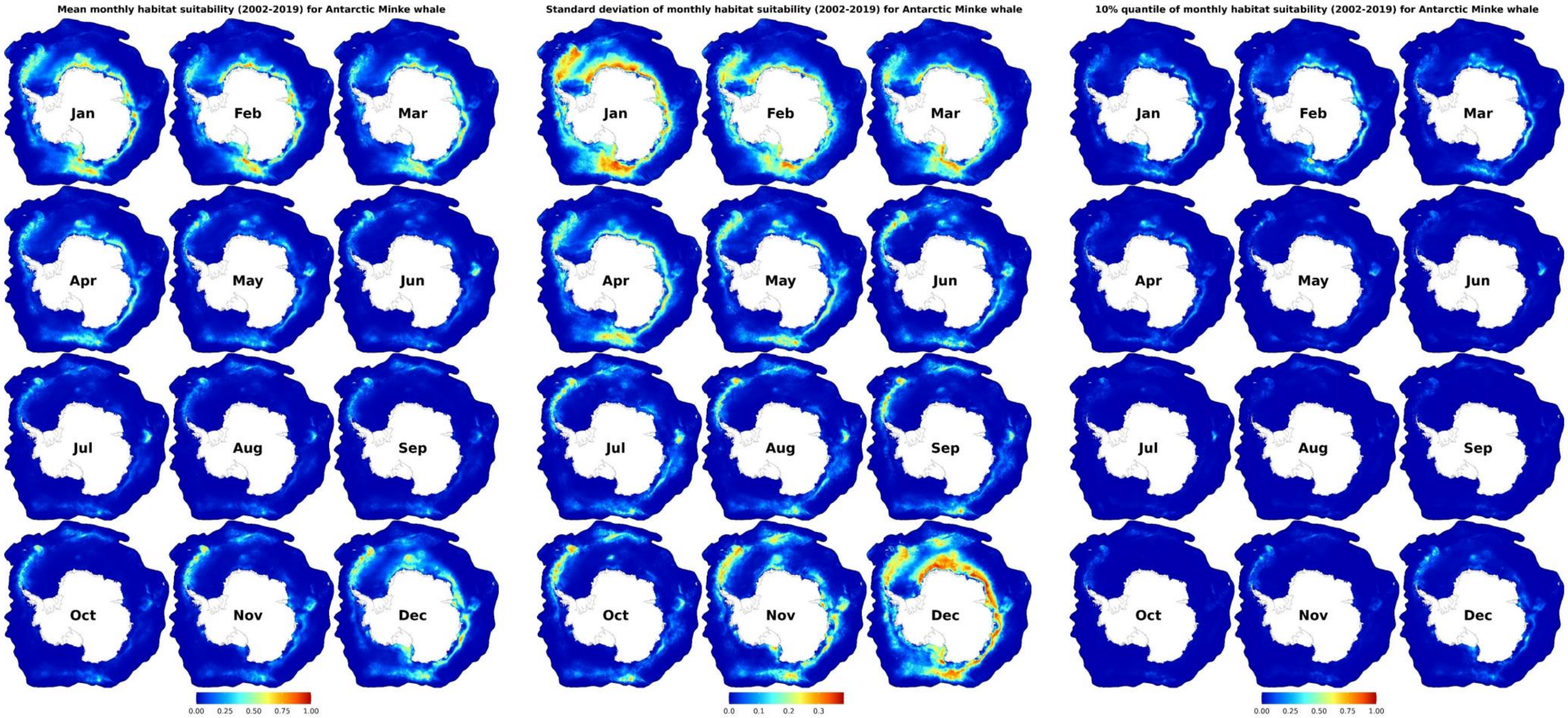
(D)



(E)

Figure S3: Spatiotemporal distribution of Antarctic minke whale sightings. Maps shown in **(A)** represent the monthly spatial distribution of observations used in this study (2002-2019), with the source of the data shown in **(B)**. Panel **(C)** indicates the number of sightings per 100×100 km grid, while **(D)** shows the total number of sightings per calendar day for the same period. Maps in **(E)** are for the monthly distribution of sightings between 1980 and 2001 (excluded in the current study due to the lack of sea ice data before 2002).

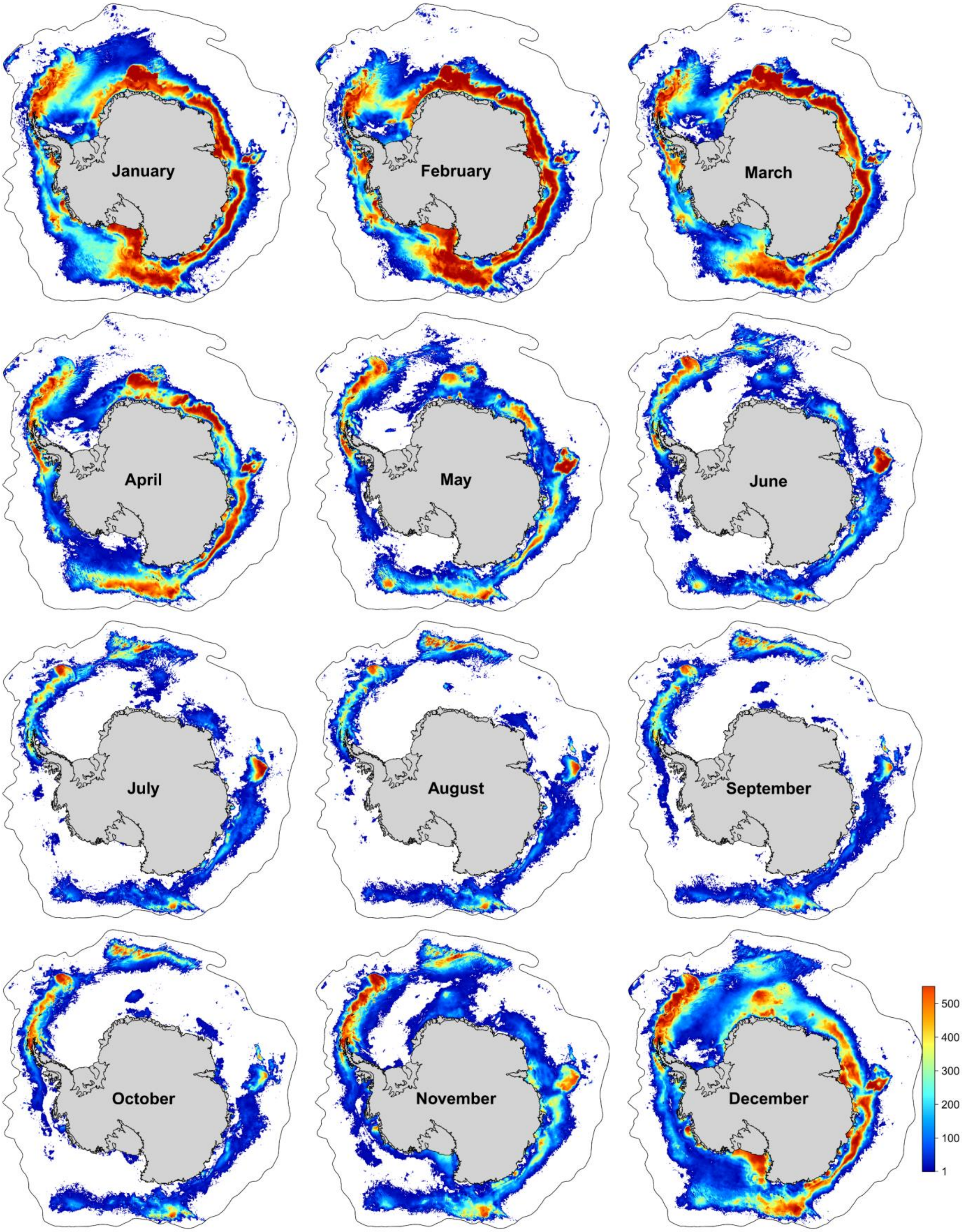
Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)



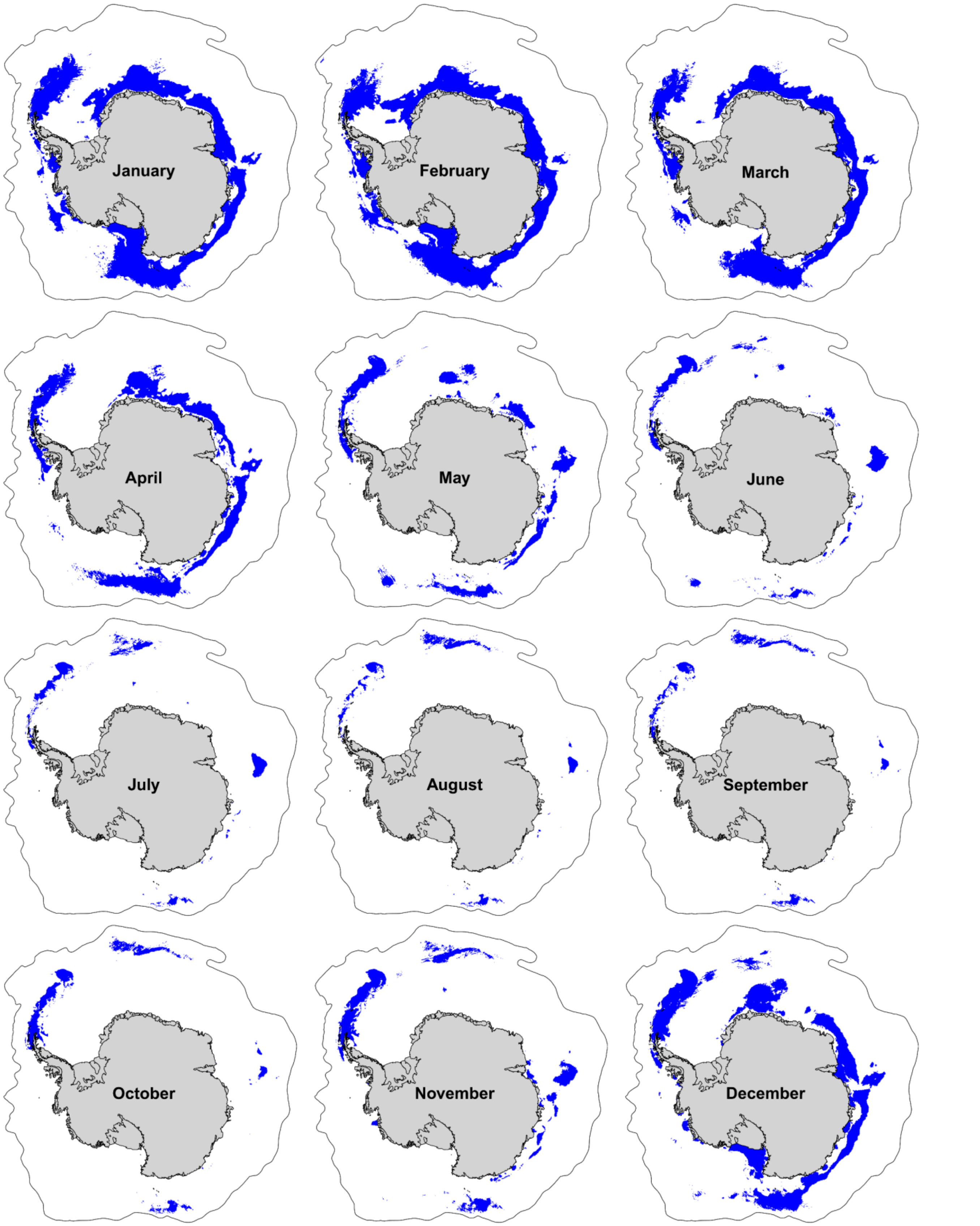
(A) Mean **(B) Standard deviation** **(C) 10% quantile**

Figure S4: Monthly predicted habitat suitability for Antarctic minke whales. Each map represents a long-term summary of habitat suitability from 2002 to 2019 for the respective month: A) mean; B) standard deviation; C) 10% quantile. Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)



(A)



(B)

Figure S5: Monthly suitable habitats for Antarctic minke whales. **(A):** the number of days (2002 to 2019) each cell was predicted suitable in the respective month. White areas represent cells not suitable at a single day in the respective month. **(B)** shows the final monthly binary map: areas marked with blue show cells predicted suitable in at least 50% of days in the respective month.

Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)

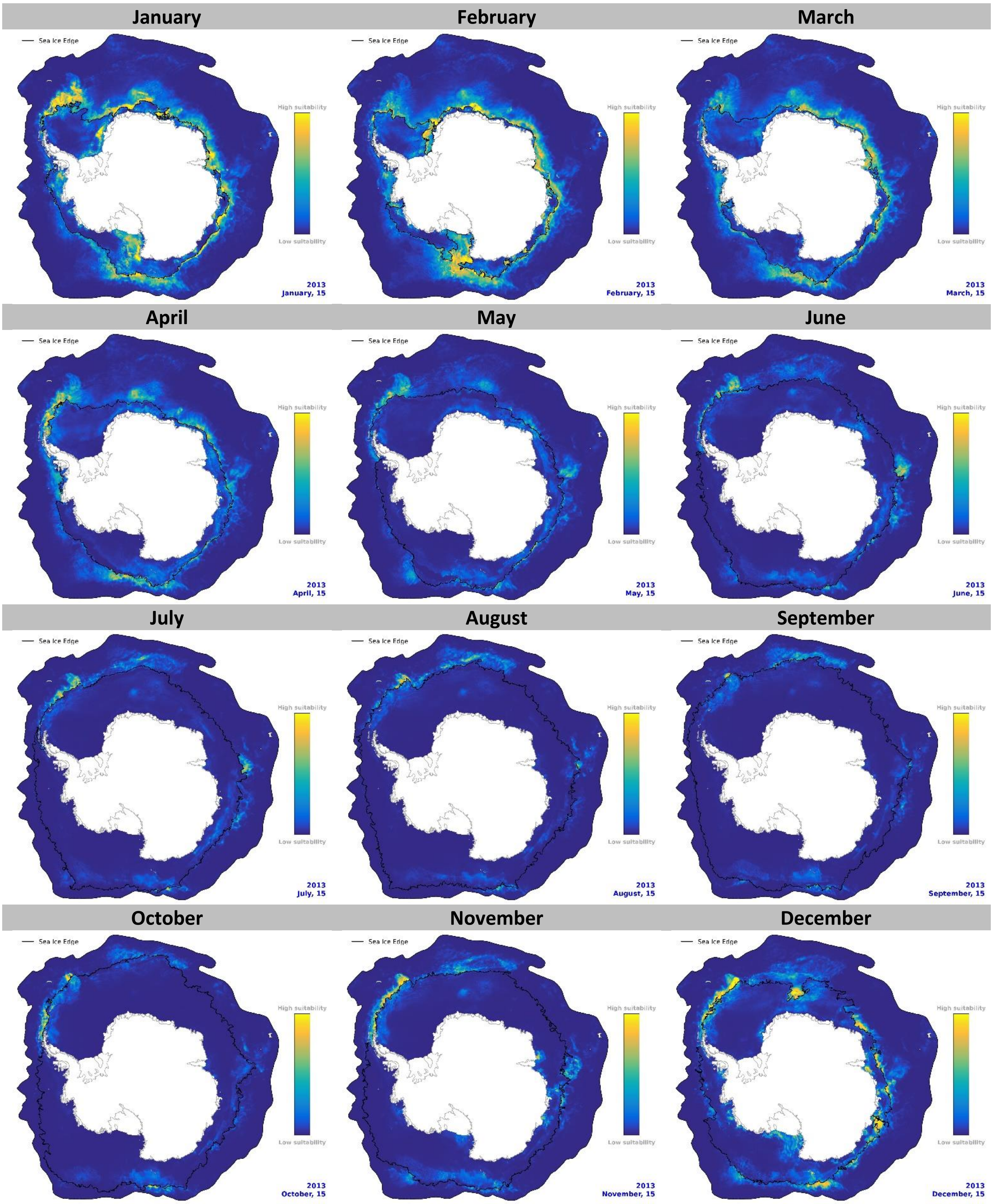
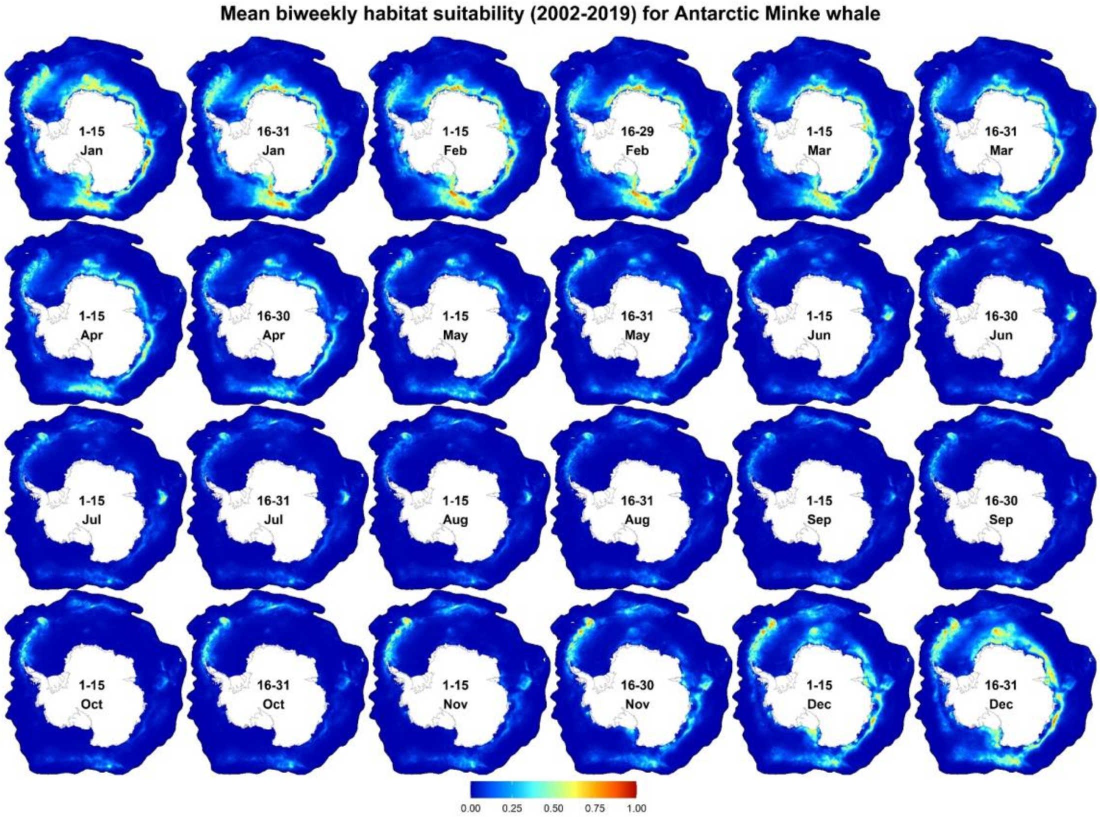
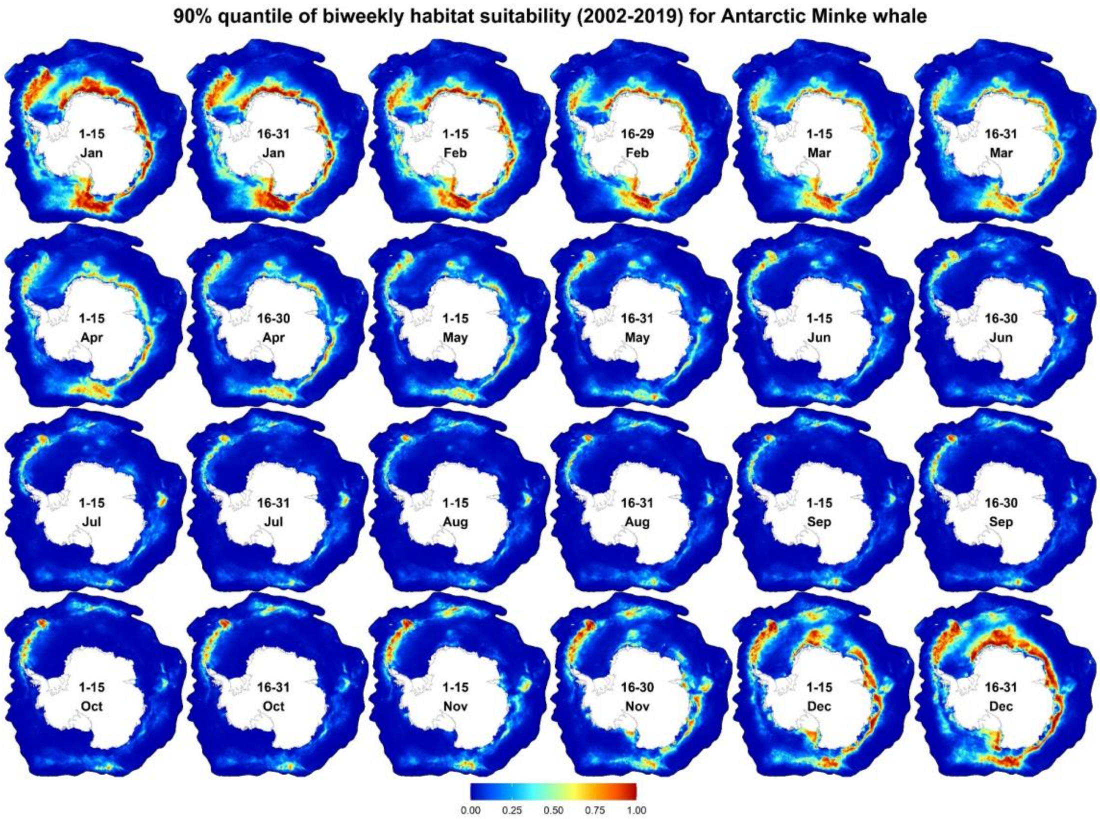


Figure S6: Examples of daily habitat suitability maps for Antarctic minke whales. Each panel shows predicted habitat suitability on the 15th of each month in 2013.

Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)



(A)



(B)

Figure S7: Biweekly predicted habitat suitability for Antarctic minke whales. Each map represents the mean **(A)** or 90% quantile **(B)** of daily predictions from 2002 to 2019 in c.a. two weeks intervals (from the 1st - 15th and 16th – 31st day of the respective month). Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)

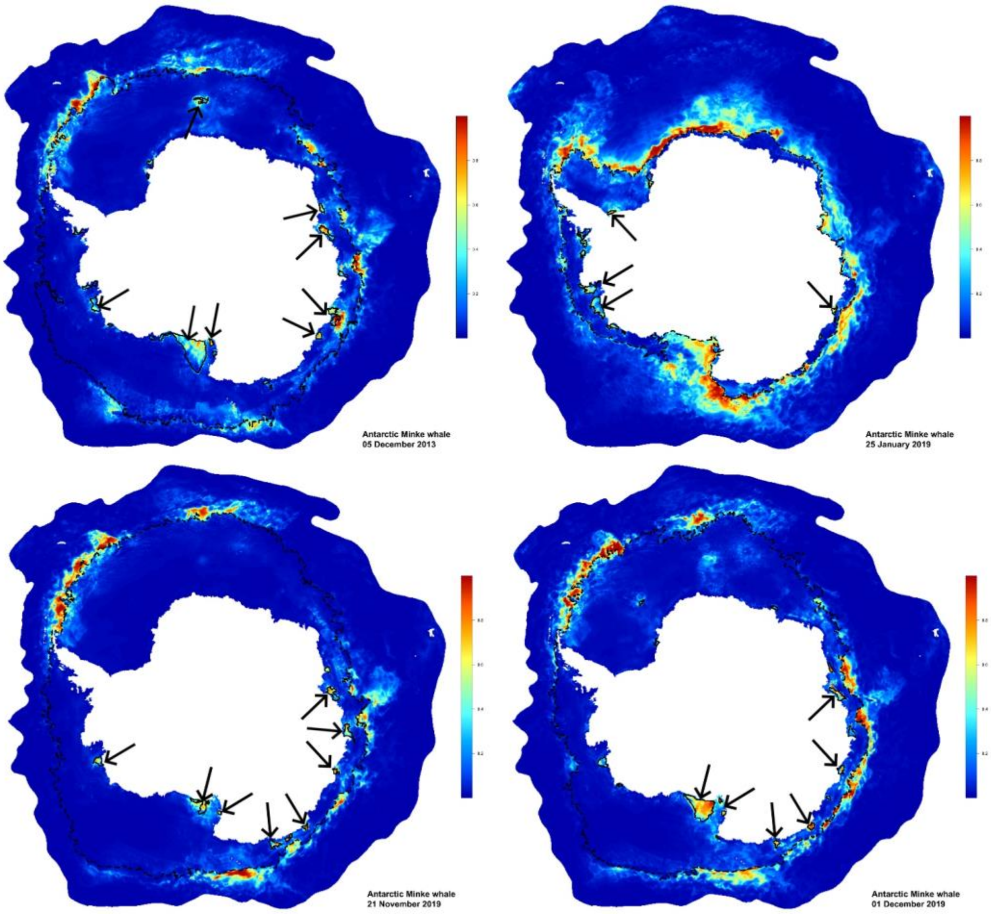
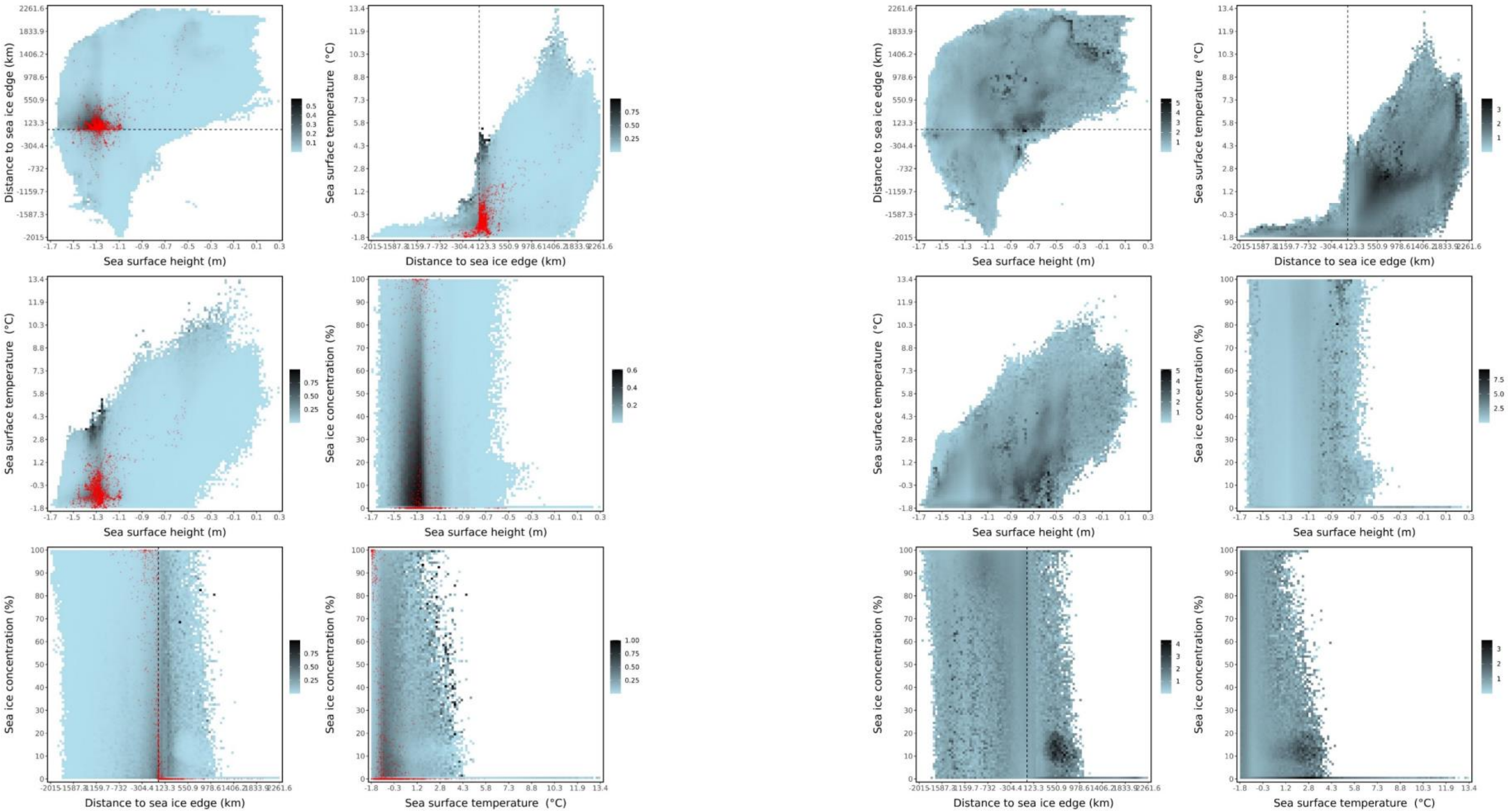


Figure S8: Example days with high Antarctic minke whale habitat suitability in coastal polynyas (arrows) south of the daily estimated SIE (black line).

Results of dynamic SDMs for the Antarctic minke whales (Figures S3-S10)



(A) **(B)**

Figure S9: Mean (A) and standard deviation (B) of habitat suitability of Antarctic minke whales (cloglog scale) in pairwise environmental space of the four most important predictors (see Figure 6 in the main text for more details). In each plot, predicted values from the full model (calibrated without cross-validation) at year-round environmental combinations were estimated (~27M spatiotemporally sampled backgrounds, 2003-2010 and 2013-2019). Predictions at each combination of two predictors (represented as 100×100 pixels) were summarized to represent the mean (A) or standard deviation (B) of habitat suitability per combination. In contrast to marginal response curves (Figure S16), we allow here all other predictors to vary together to represent mean suitability at all other possible combinations. The frequency at which each combination is available in the background information used is shown in Figure S35. Higher mean or standard deviation values are represented in darker colors (white areas are for non-existing combinations). Spatiotemporally-matched environmental conditions at species observations are shown as red points (A).

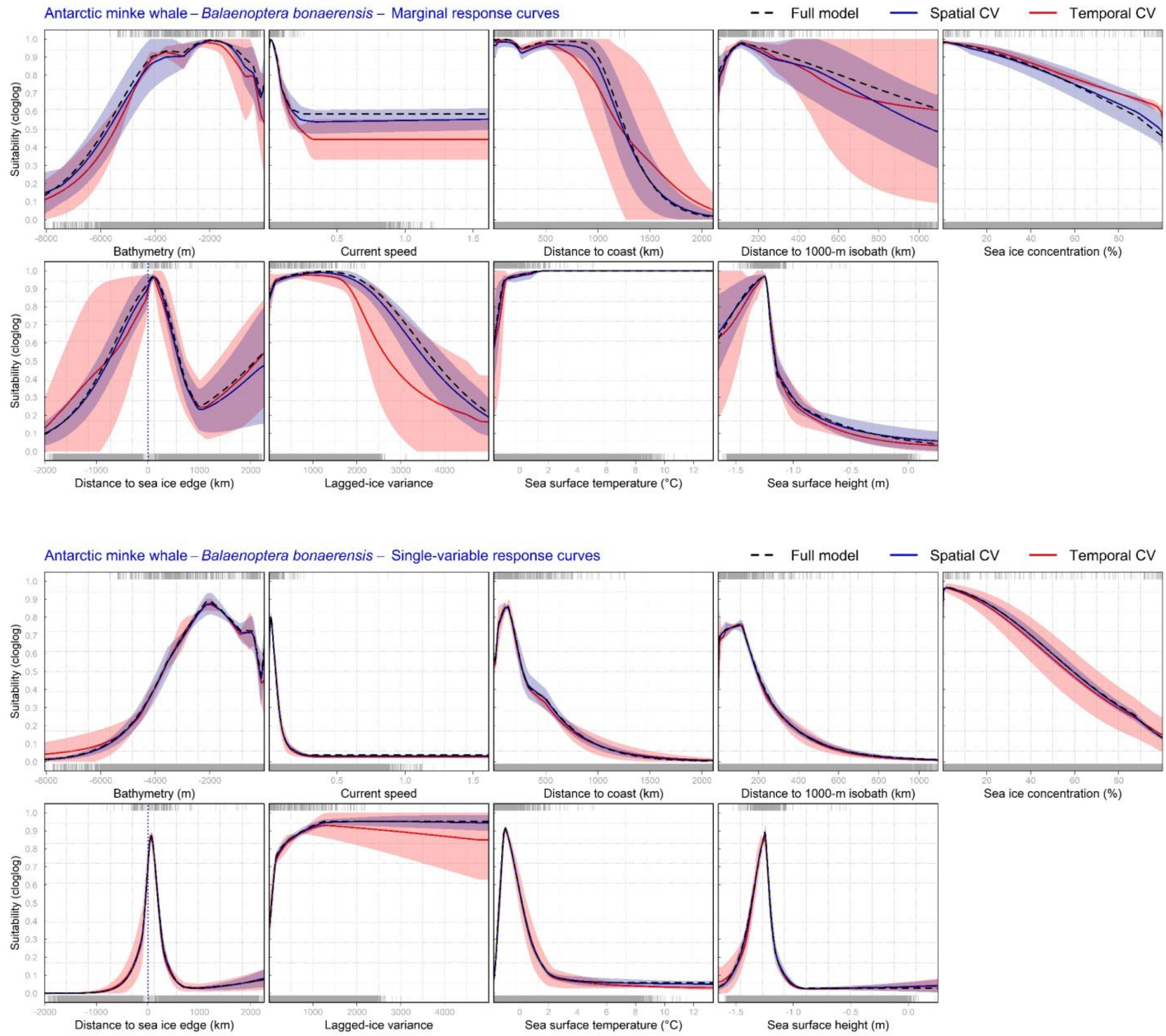
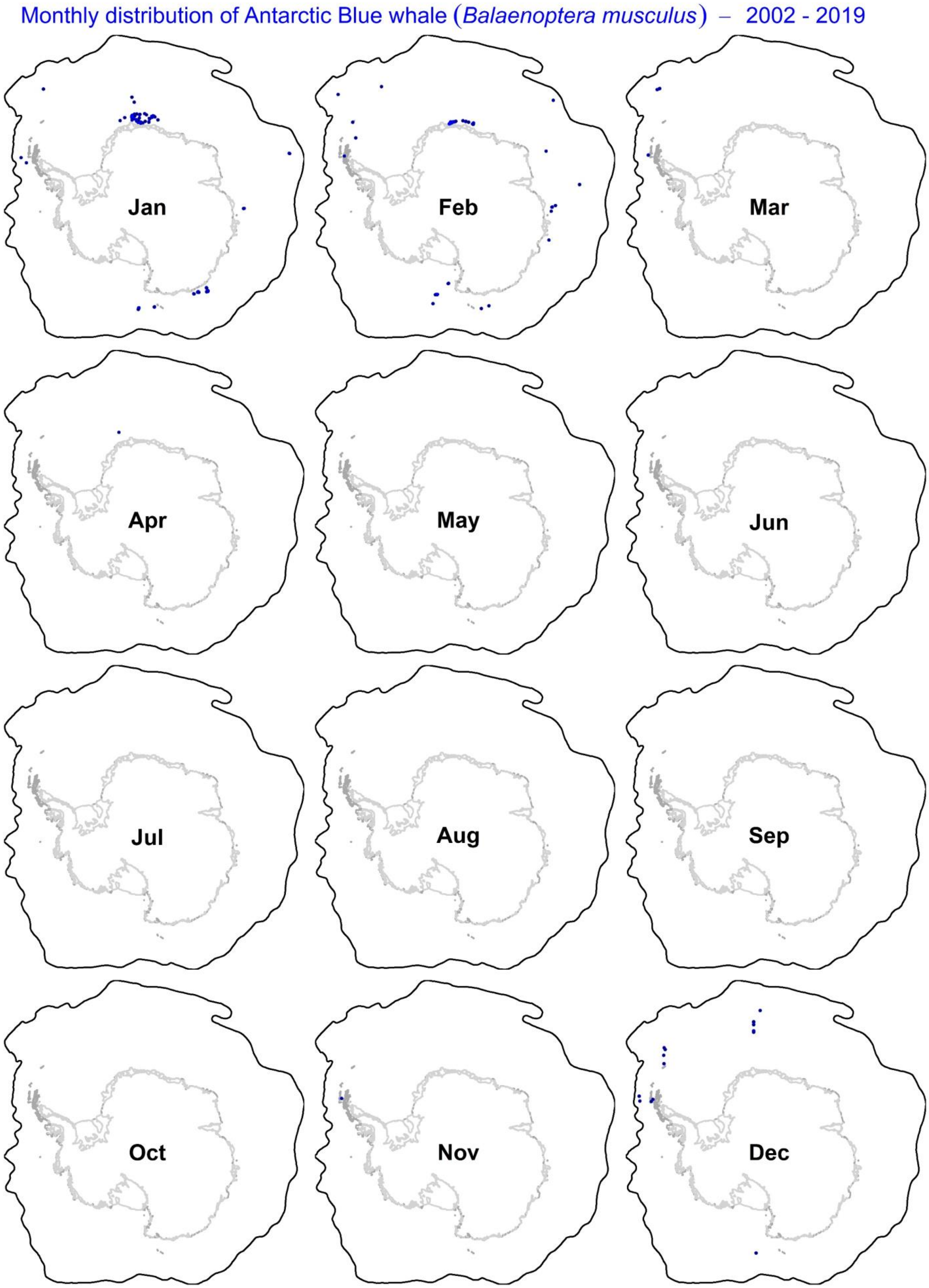


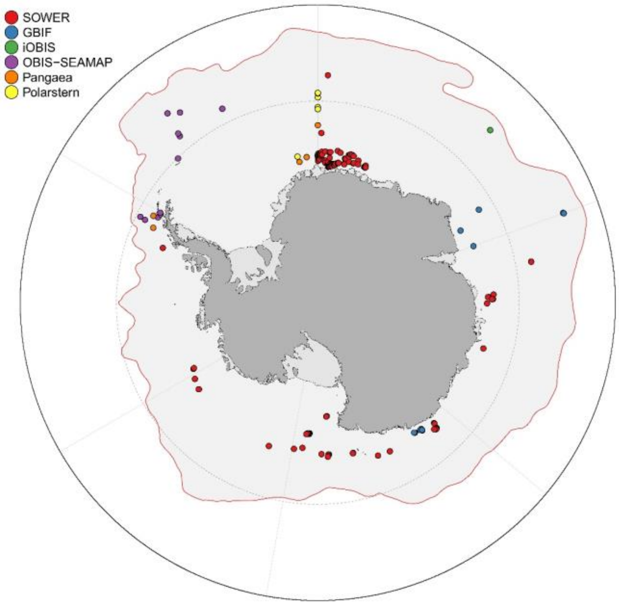
Figure S10: Response curves for Antarctic minke whale models. The first set of plots shows marginal response curves, in which models were run using all predictors, then each predictor's response curve is drawn by fixing all other predictors at their mean value at training presences. In the second set of plots, an additional set of models was run only using one predictor in turn. Blue lines and shaded areas represent the mean and standard deviation of response curves of spatially cross-validated models; red for temporally cross-validated models. The black dashed line is for a full model calibrated with all sightings (no cross-validation). In each plot, the top grey rug shows spatiotemporally matched conditions at species observations, while the bottom grey rug shows values at spatiotemporally sampled 20K locations.

Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)

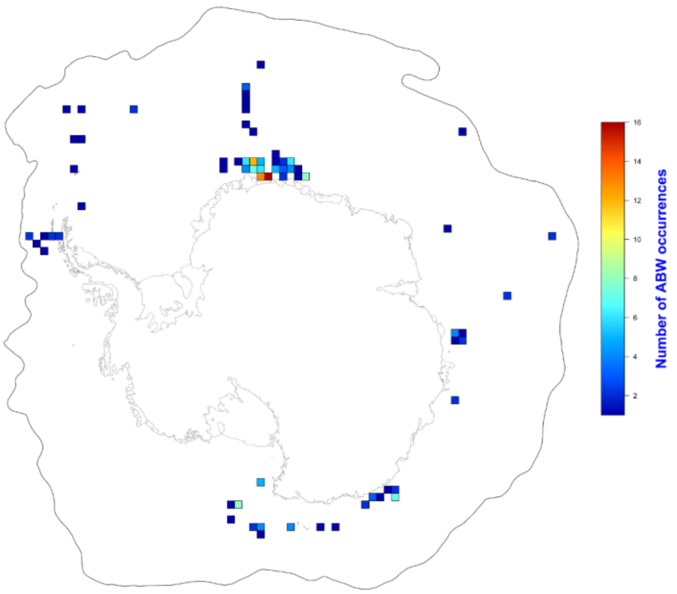


(A)

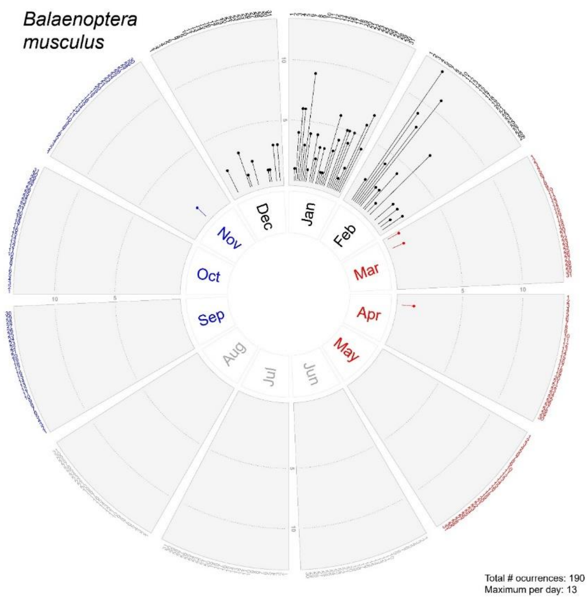
Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)



(B)

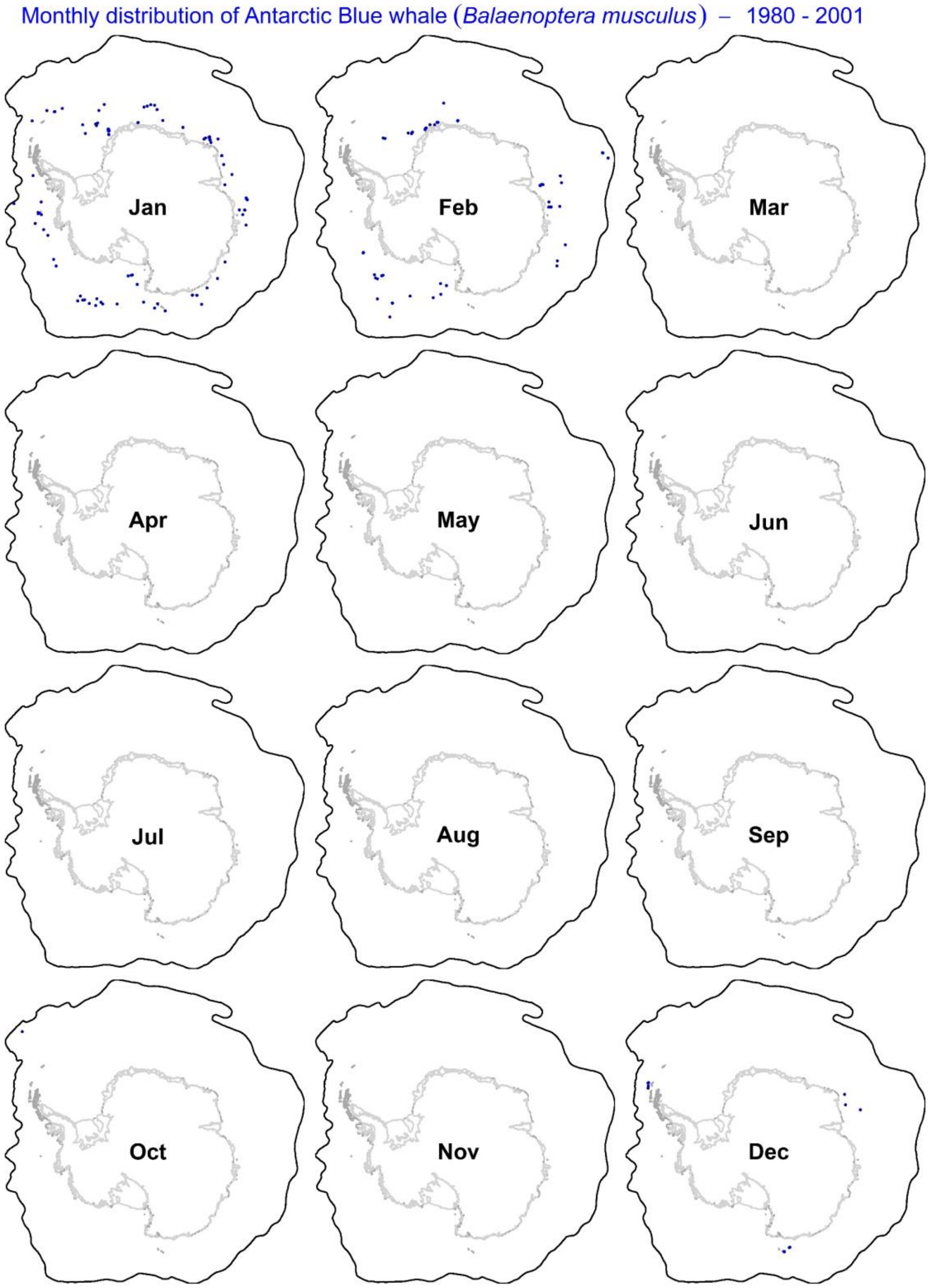


(C)



(D)

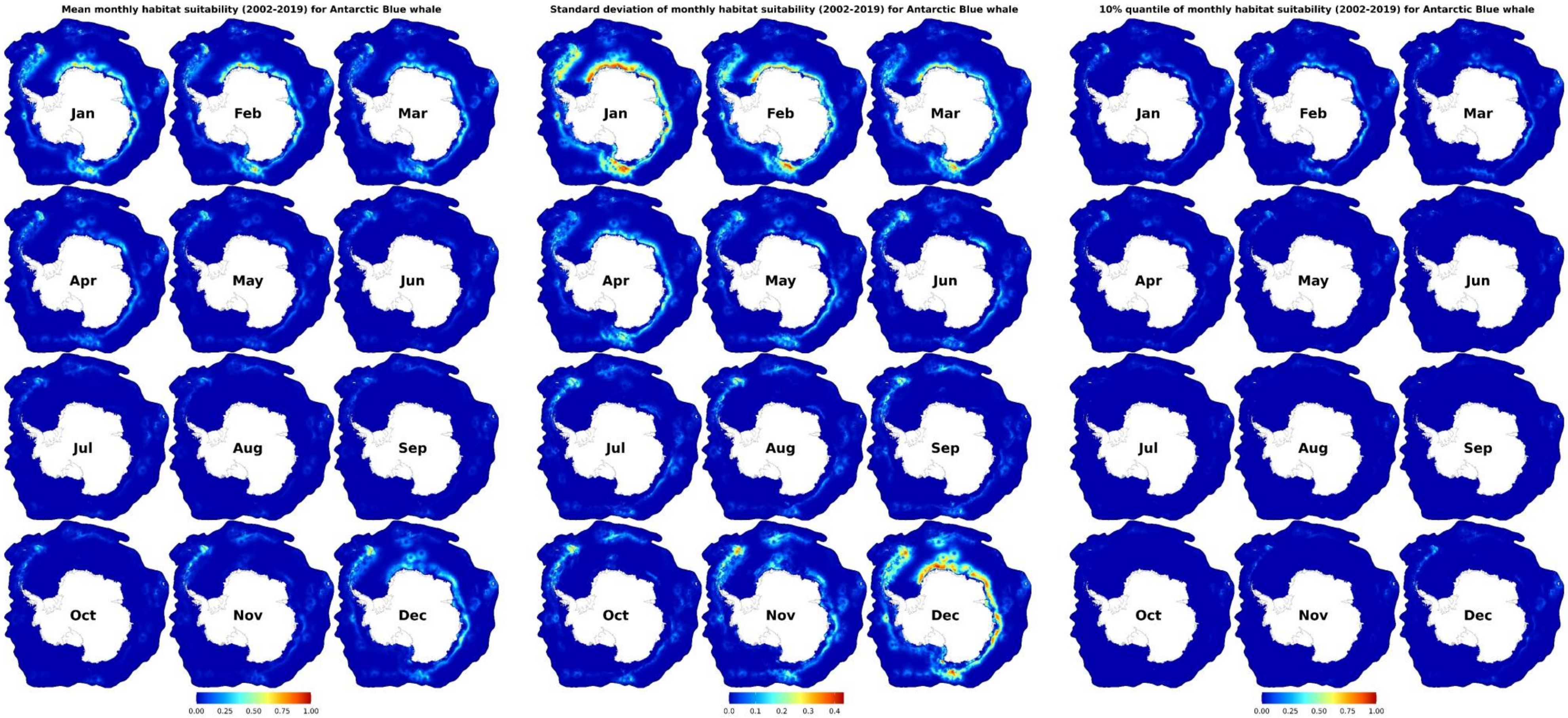
Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)



(E)

Figure S11: Spatiotemporal distribution of Antarctic blue whale sightings. Maps shown in **(A)** represent the monthly spatial distribution of observations used in this study (2002-2019), with the source of the data shown in **(B)**. Panel **(C)** indicates the number of sightings per 100×100 km grid, while **(D)** shows the total number of sightings per calendar day for the same period. Maps in **(E)** are for the monthly distribution of sightings between 1980 and 2001 (excluded in the current study due to the lack of sea ice data before 2002).

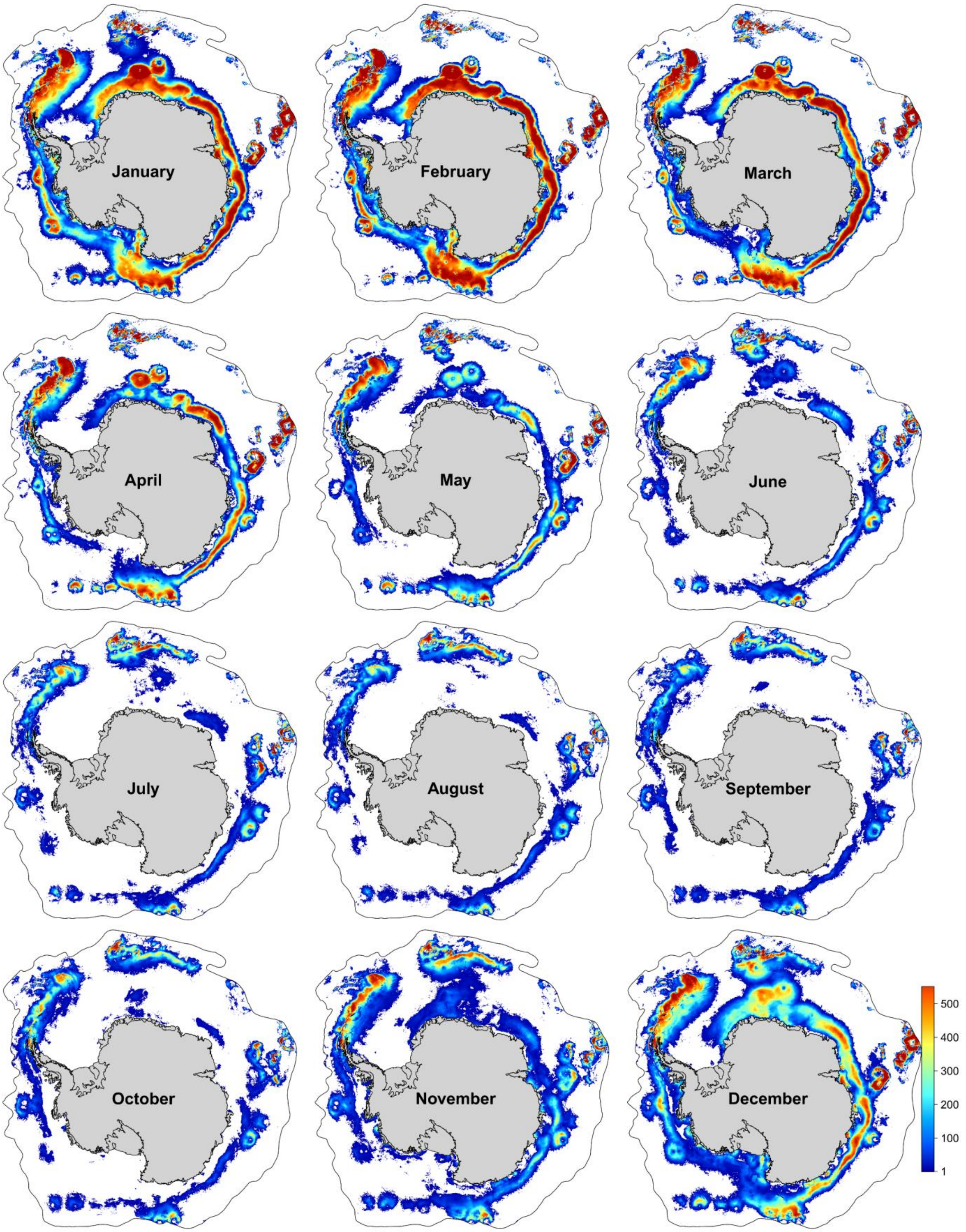
Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)



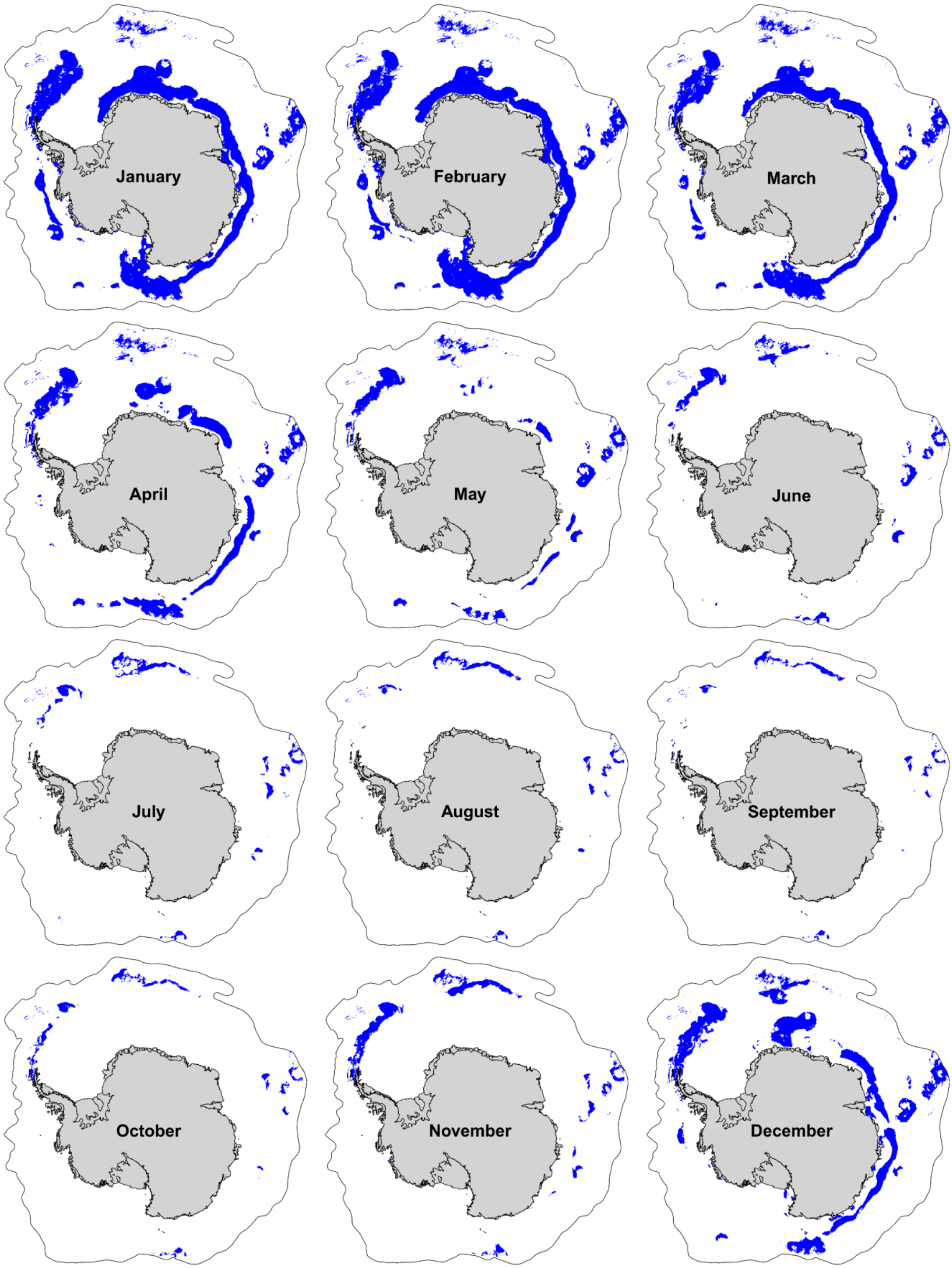
(A) Mean **(B) Standard deviation** **(C) 10% quantile**

Figure S12: Monthly predicted habitat suitability for Antarctic blue whales. Each map represents a long-term summary of habitat suitability from 2002 to 2019 for the respective month: A) mean; B) standard deviation; C) 10% quantile. Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)



(A)



(B)

Figure S13: Monthly suitable habitats for Antarctic blue whales. **(A):** the number of days (2002 to 2019) each cell was predicted suitable in the respective month. White areas represent cells not suitable at a single day in the respective month. **(B)** shows the final monthly binary map: areas marked with blue show cells predicted suitable in at least 50% of days in the respective month.

Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)

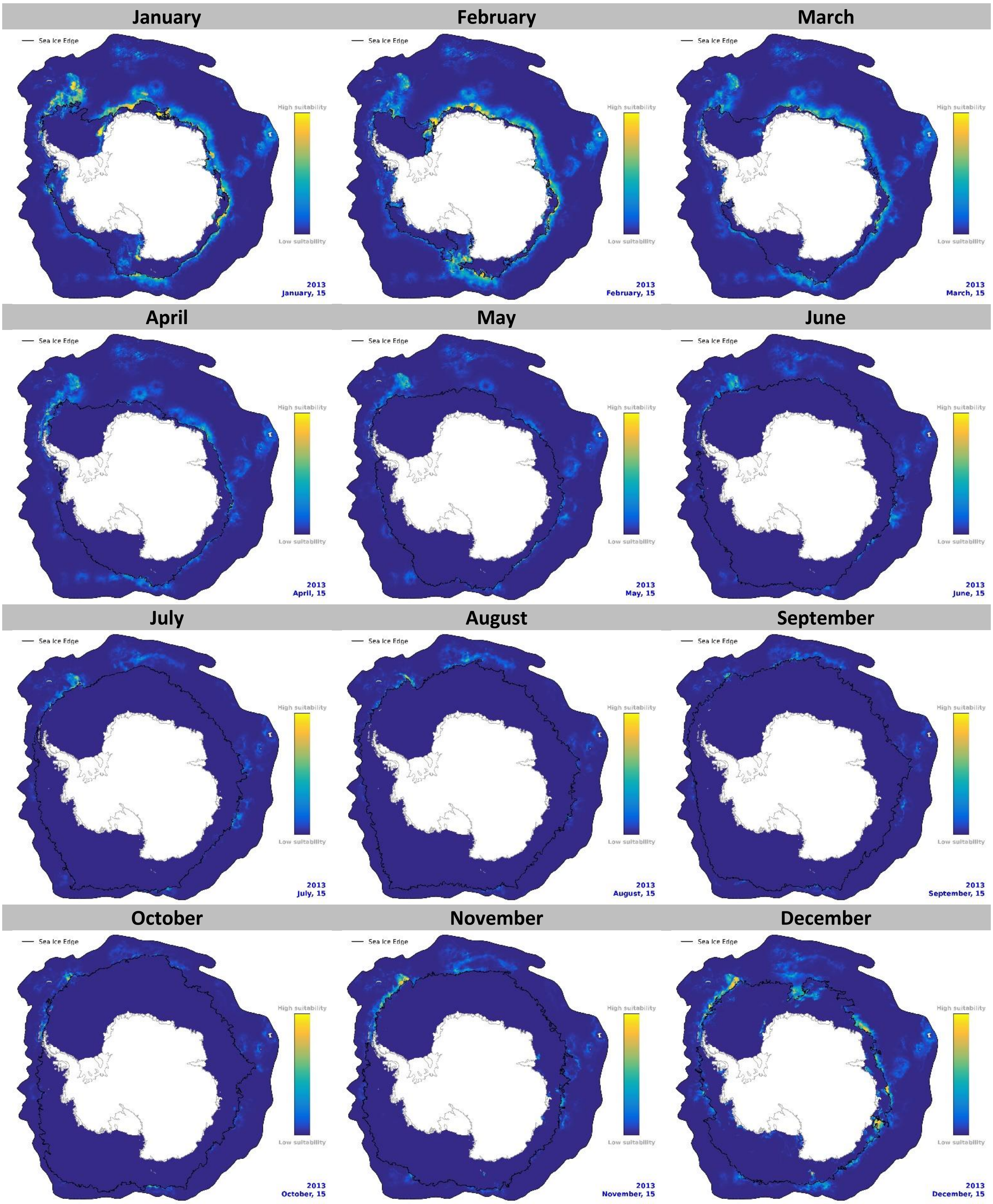
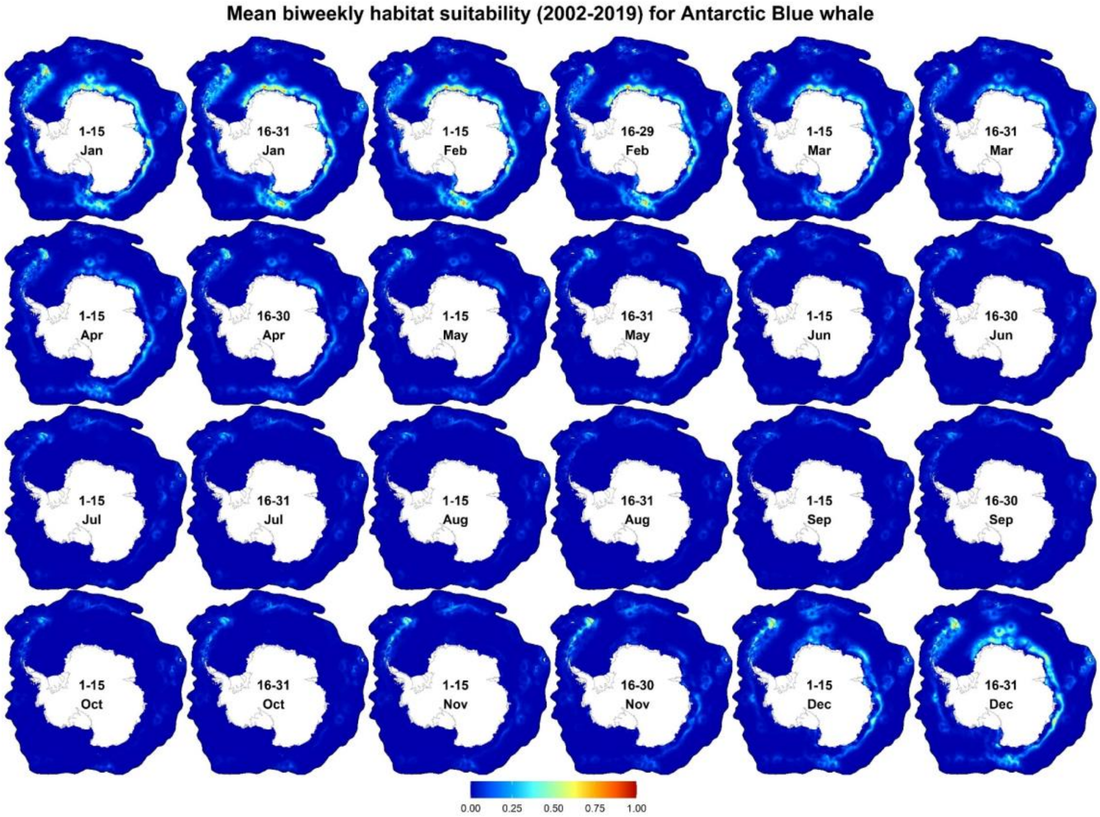
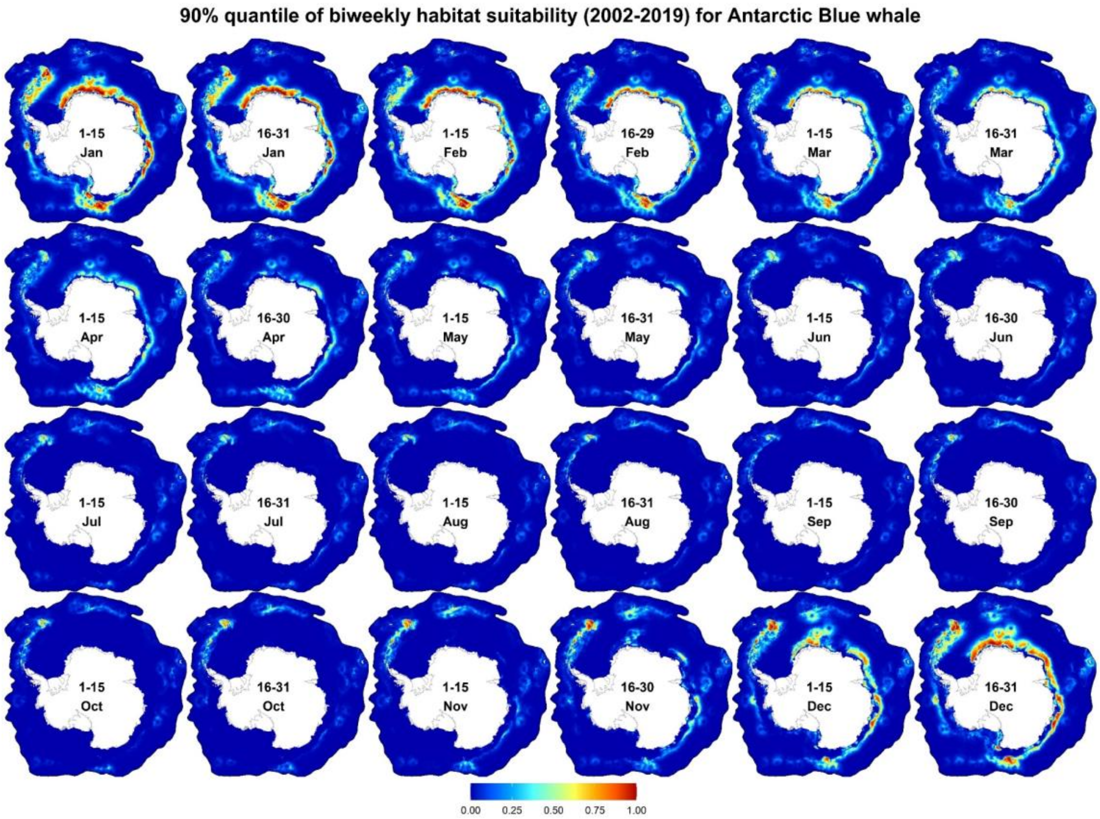


Figure S14: Examples of daily habitat suitability maps for Antarctic blue whales. Each panel shows predicted habitat suitability on the 15th of each month in 2013.

Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)



(A)



(B)

Figure S15: Biweekly predicted habitat suitability for Antarctic blue whales. Each map represents the mean **(A)** or 90% quantile **(B)** of daily predictions from 2002 to 2019 in c.a. two weeks intervals (from the 1st - 15th and 16th – 31st day of the respective month). Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)

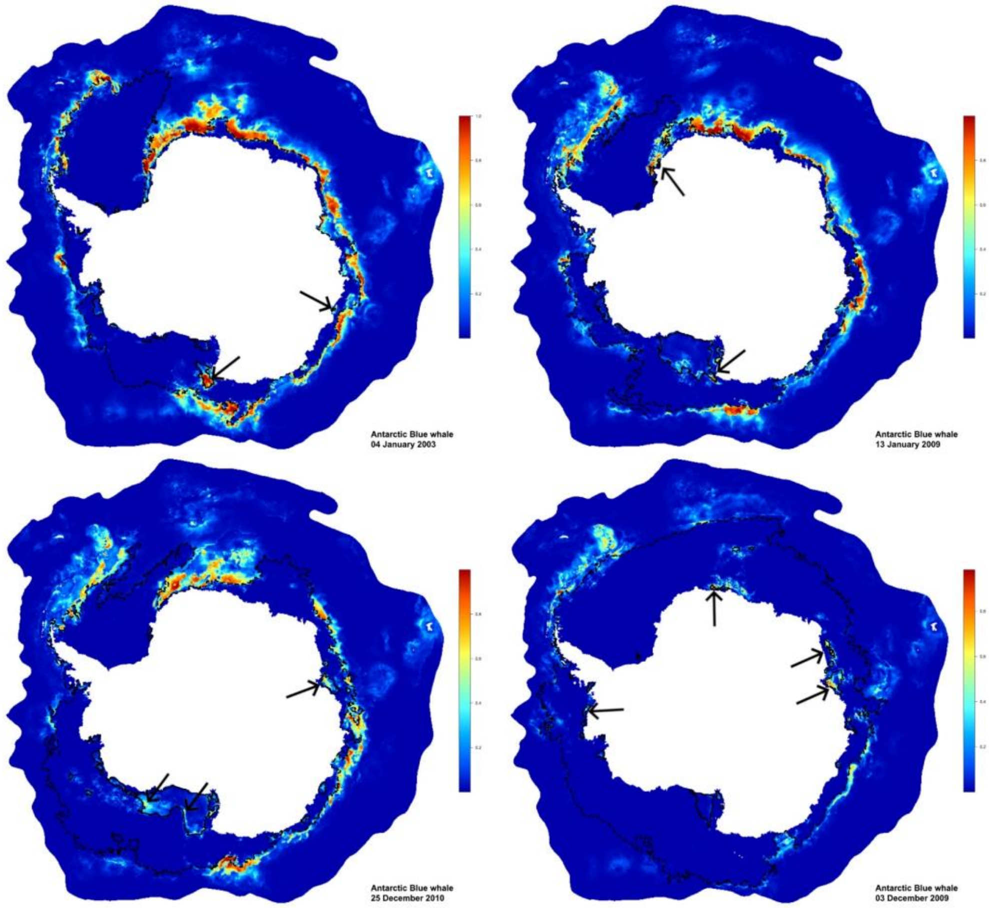
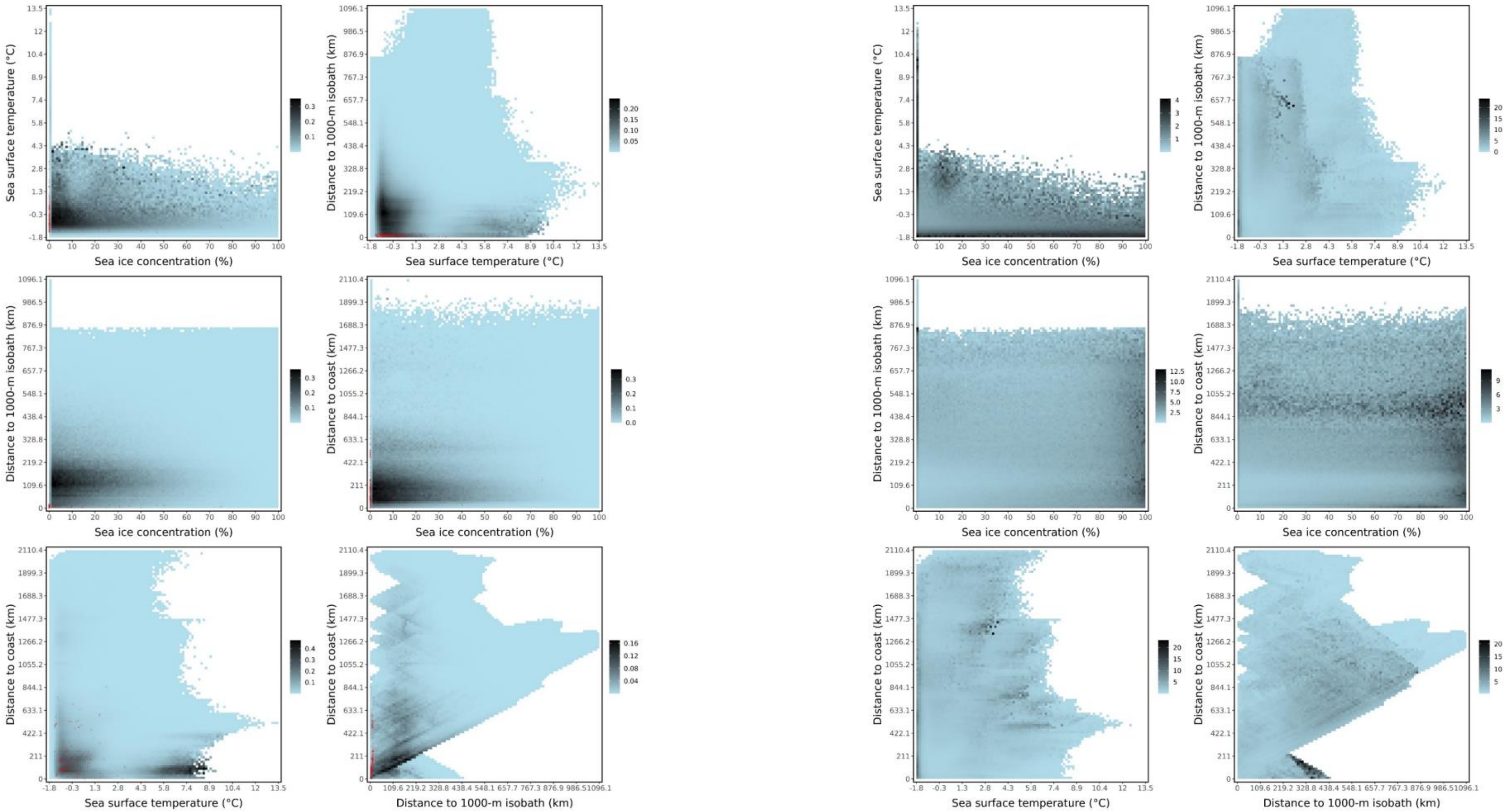


Figure S16: Example days with high Antarctic blue whale habitat suitability in coastal polynyas (arrows) south of the daily estimated SIE (black line).

Results of dynamic SDMs for the Antarctic blue whales (Figures S11-S18)



(A) **(B)**

Figure S17: Mean (A) and standard deviation (B) of habitat suitability of Antarctic blue whales (cloglog scale) in pairwise environmental space of the four most important predictors (see Figure 6 in the main text for more details). In each plot, predicted values from the full model (calibrated without cross-validation) at year-round environmental combinations were estimated (~27M spatiotemporally sampled backgrounds, 2003-2010 and 2013-2019). Predictions at each combination of two predictors (represented as 100×100 pixels) were summarized to represent the mean (A) or standard deviation (B) of habitat suitability per combination. In contrast to marginal response curves (Figure S18), we allow here all other predictors to vary together to represent mean suitability at all other possible combinations. The frequency at which each combination is available in the background information used is shown in Figure S35. Higher mean or standard deviation values are represented in darker colors (white areas are for non-existing combinations). Spatiotemporally-matched environmental conditions at species observations are shown as red points (A).

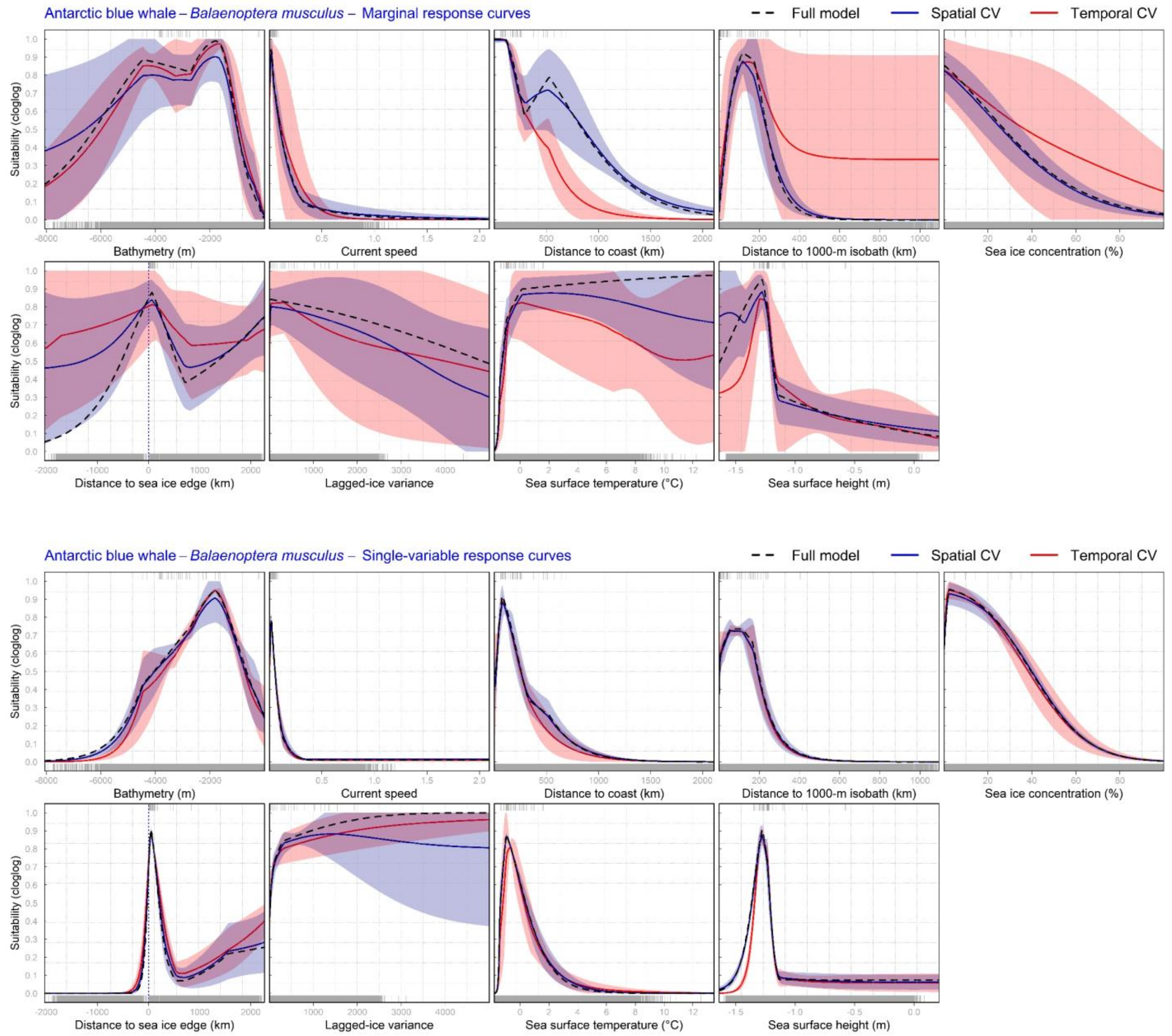
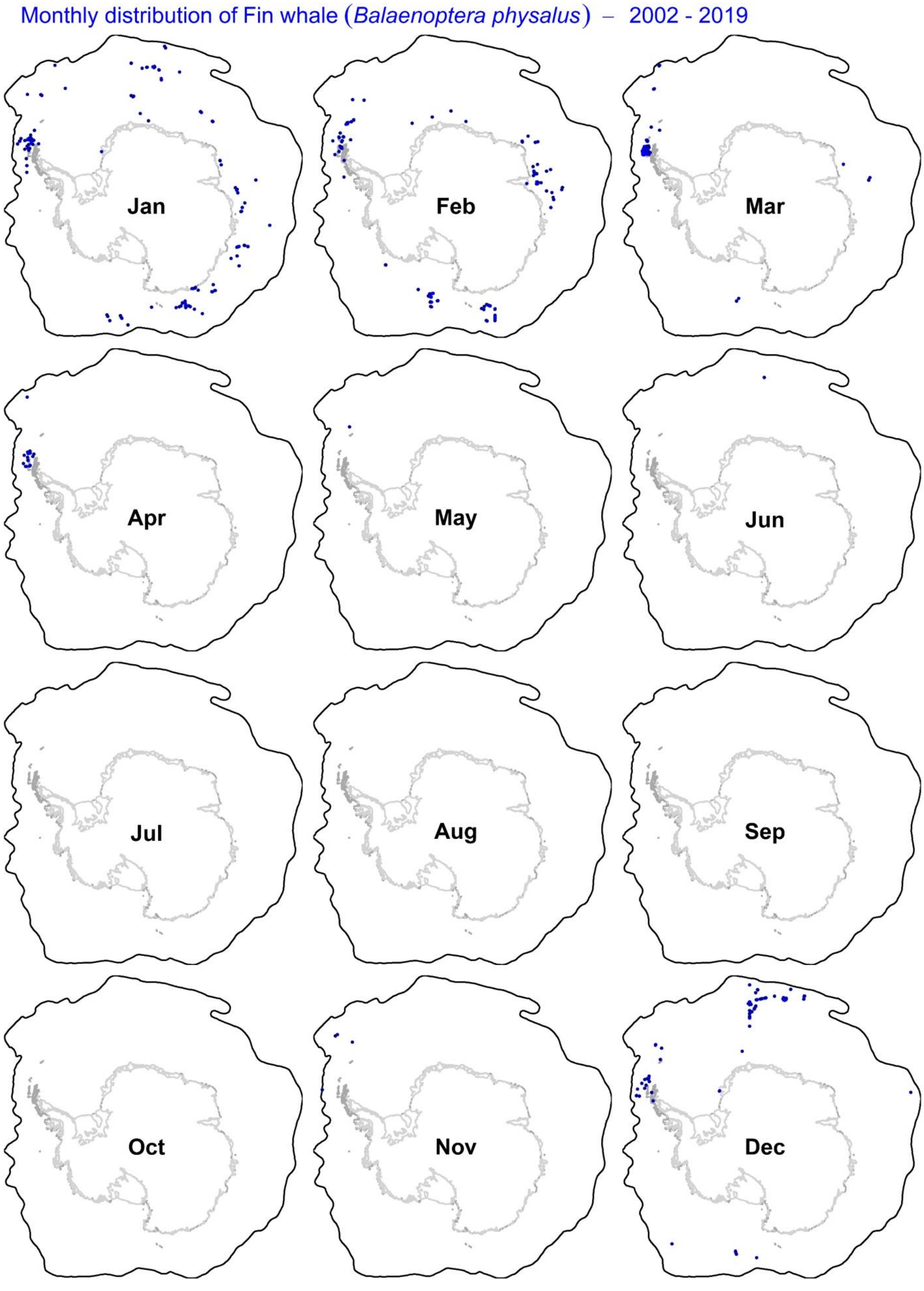


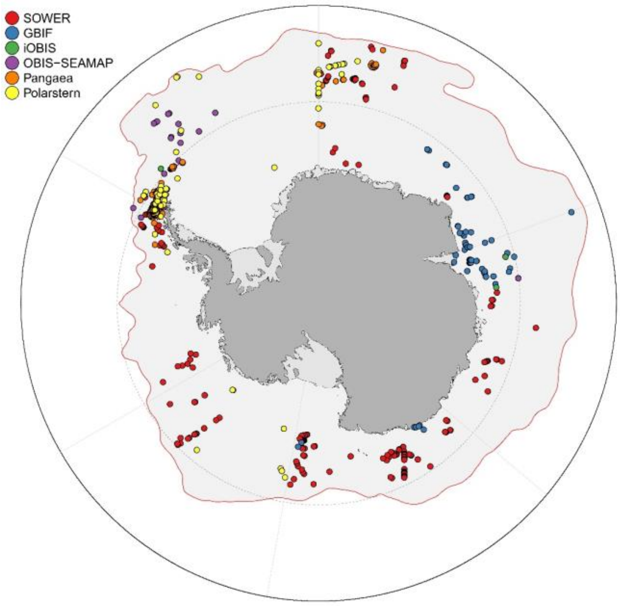
Figure S18: Response curves for Antarctic blue whale models. The first set of plots shows marginal response curves, in which models were run using all predictors, then each predictor’s response curve is drawn by fixing all other predictors at their mean value at training presences. In the second set of plots, an additional set of models was run only using one predictor in turn. Blue lines and shaded areas represent the mean and standard deviation of response curves of spatially cross-validated models; red for temporally cross-validated models. The black dashed line is for a full model calibrated with all sightings (no cross-validation). In each plot, the top grey rug shows spatiotemporally matched conditions at species observations, while the bottom grey rug shows values at spatiotemporally sampled 20K locations.

Results of dynamic SDMs for the fin whales (Figures S19-S26)

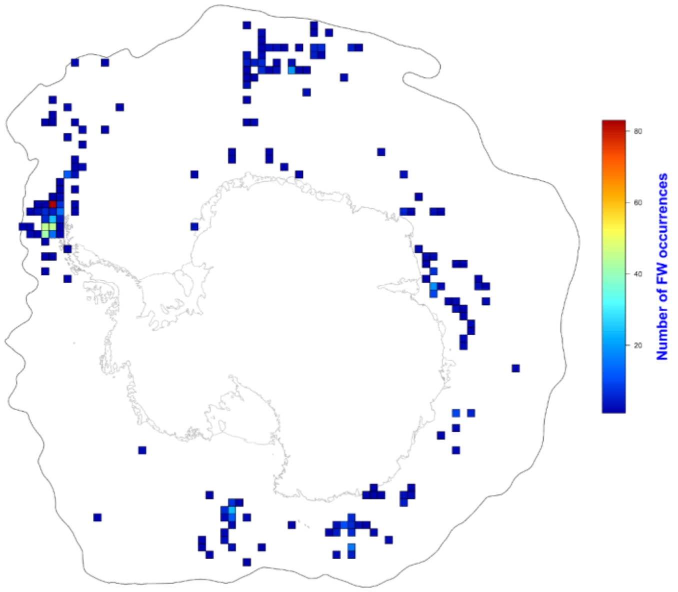


(A)

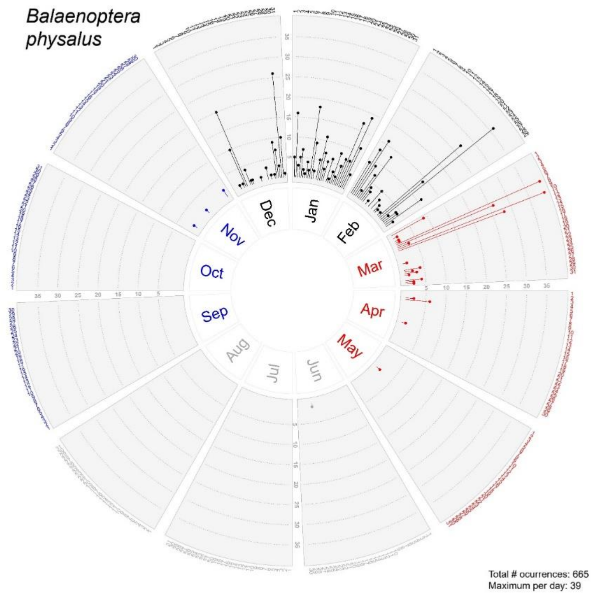
Results of dynamic SDMs for the fin whales (Figures S19-S26)



(B)

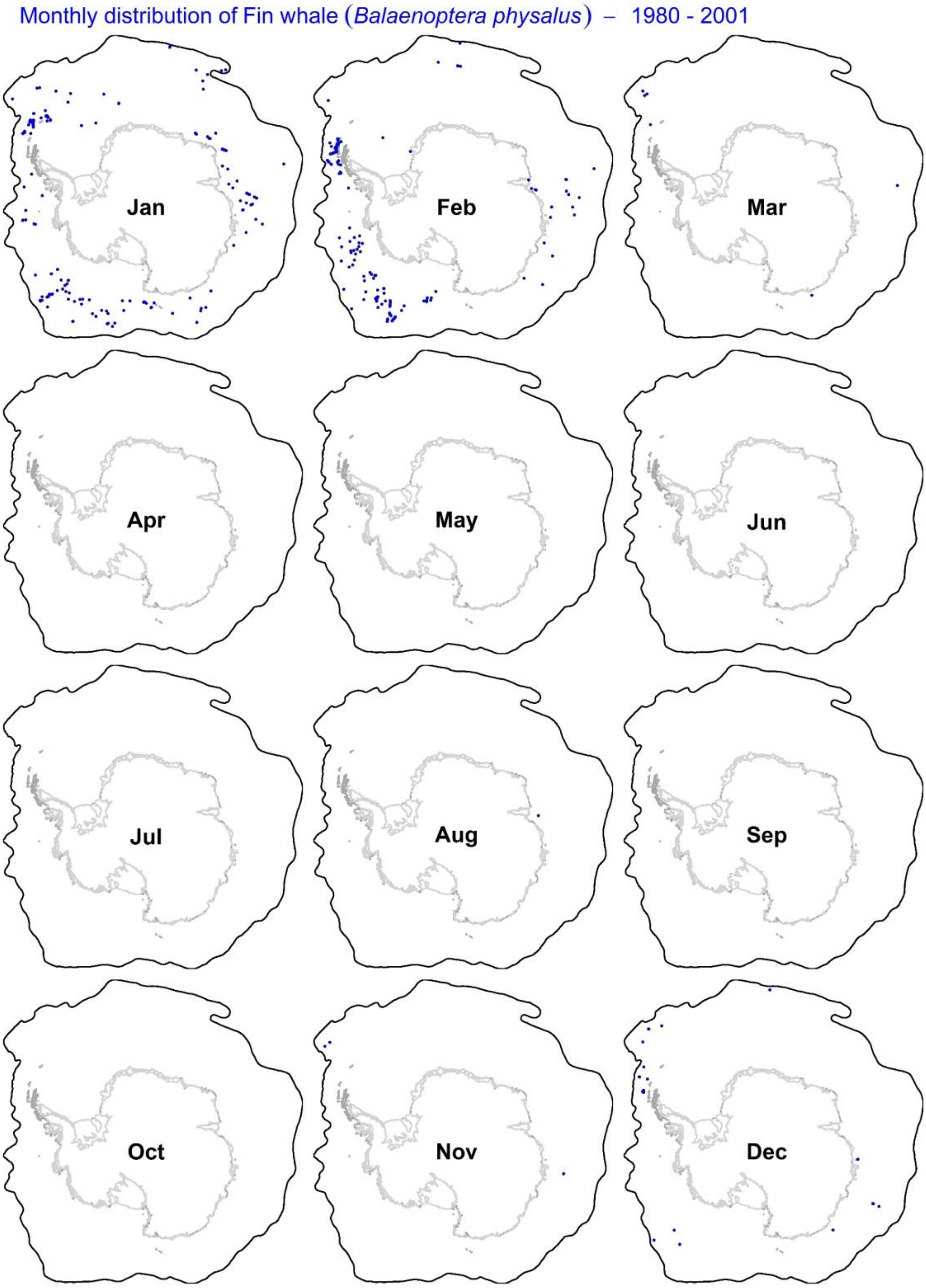


(C)



(D)

Results of dynamic SDMs for the fin whales (Figures S19-S26)



(E)

Figure S19: Spatiotemporal distribution of fin whale sightings. Maps shown in **(A)** represent the monthly spatial distribution of observations used in this study (2002-2019), with the source of the data shown in **(B)**. Panel **(C)** indicates the number of sightings per 100×100 km grid, while **(D)** shows the total number of sightings per calendar day for the same period. Maps in **(E)** are for the monthly distribution of sightings between 1980 and 2001 (excluded in the current study due to the lack of sea ice data before 2002).

Results of dynamic SDMs for the fin whales (Figures S19-S26)

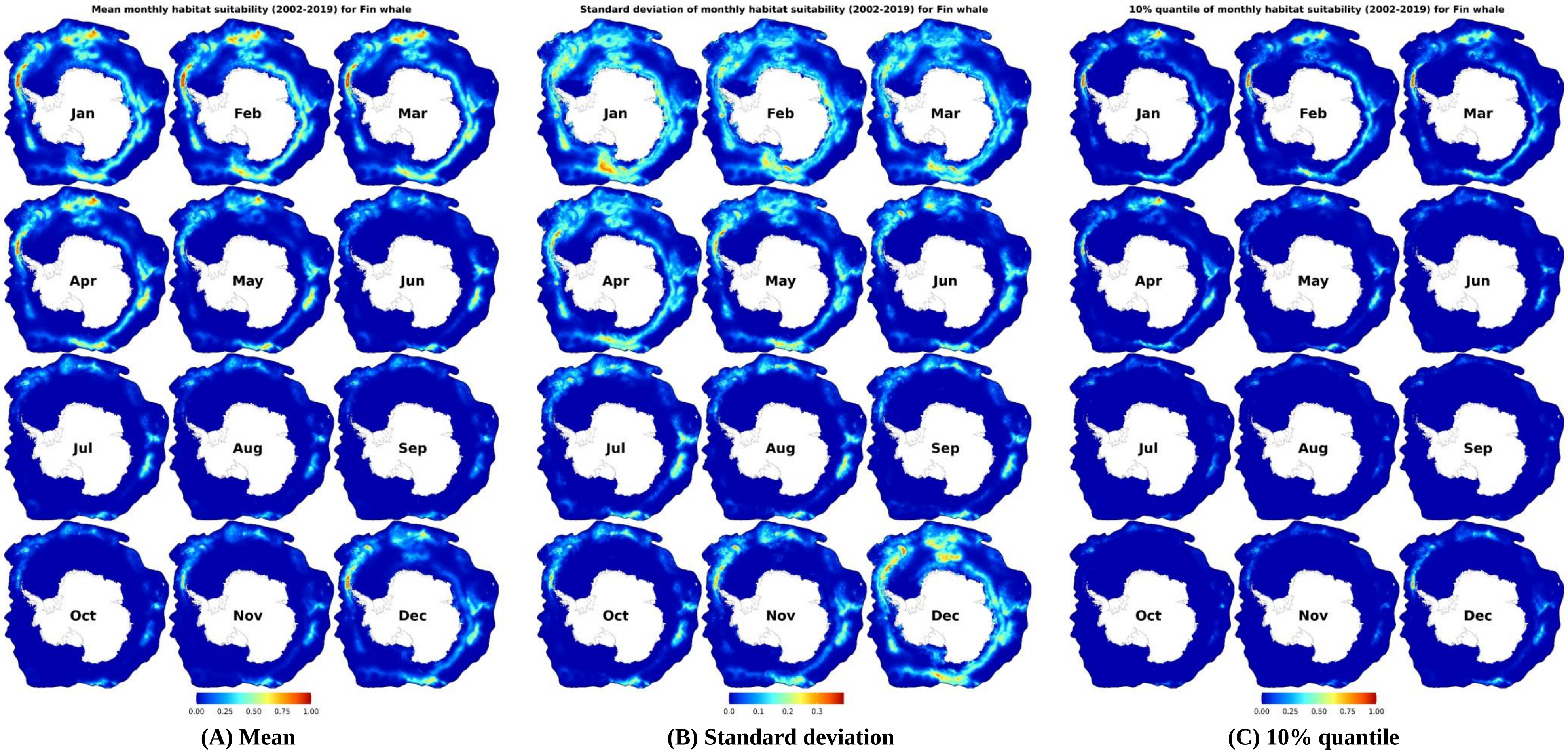
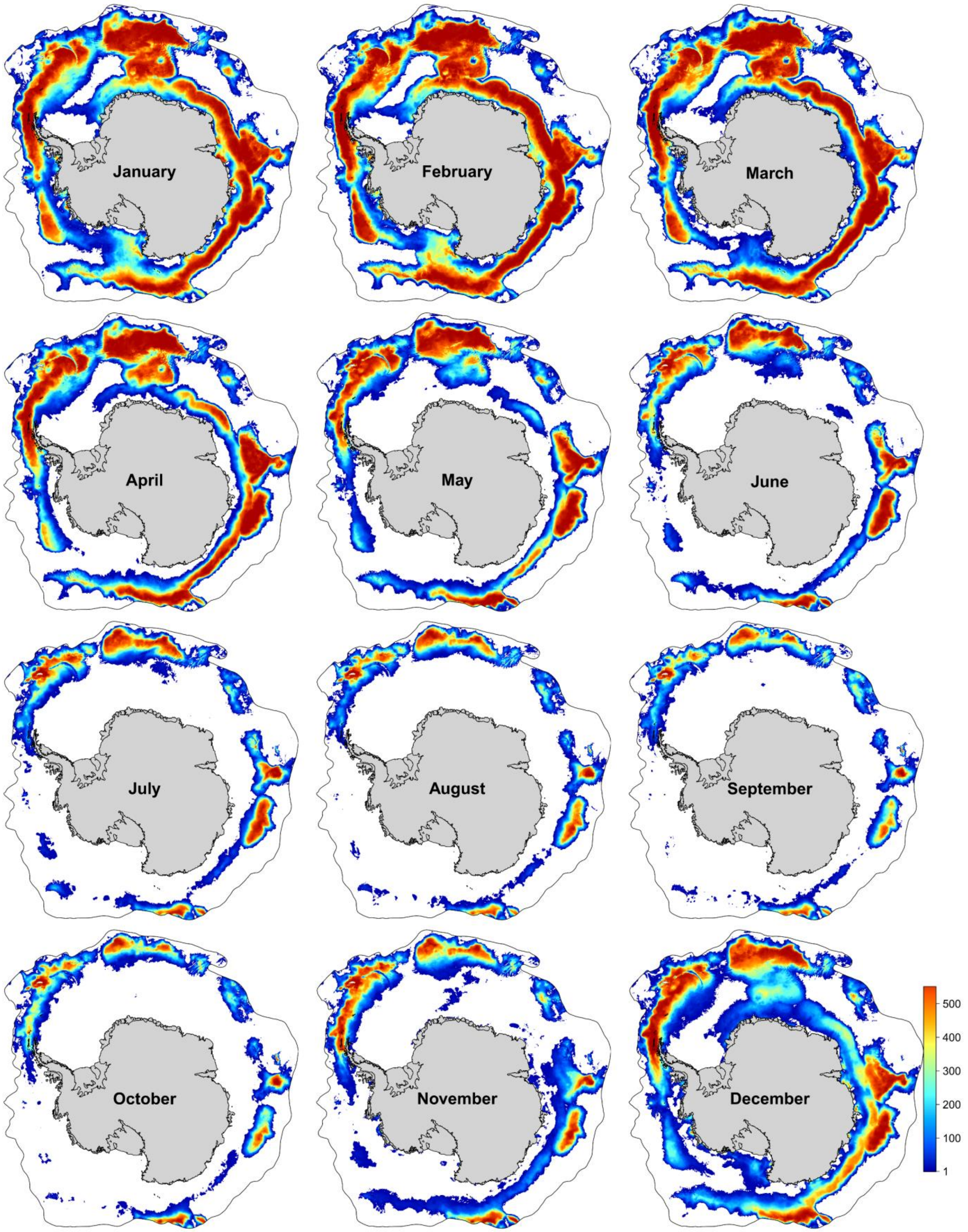
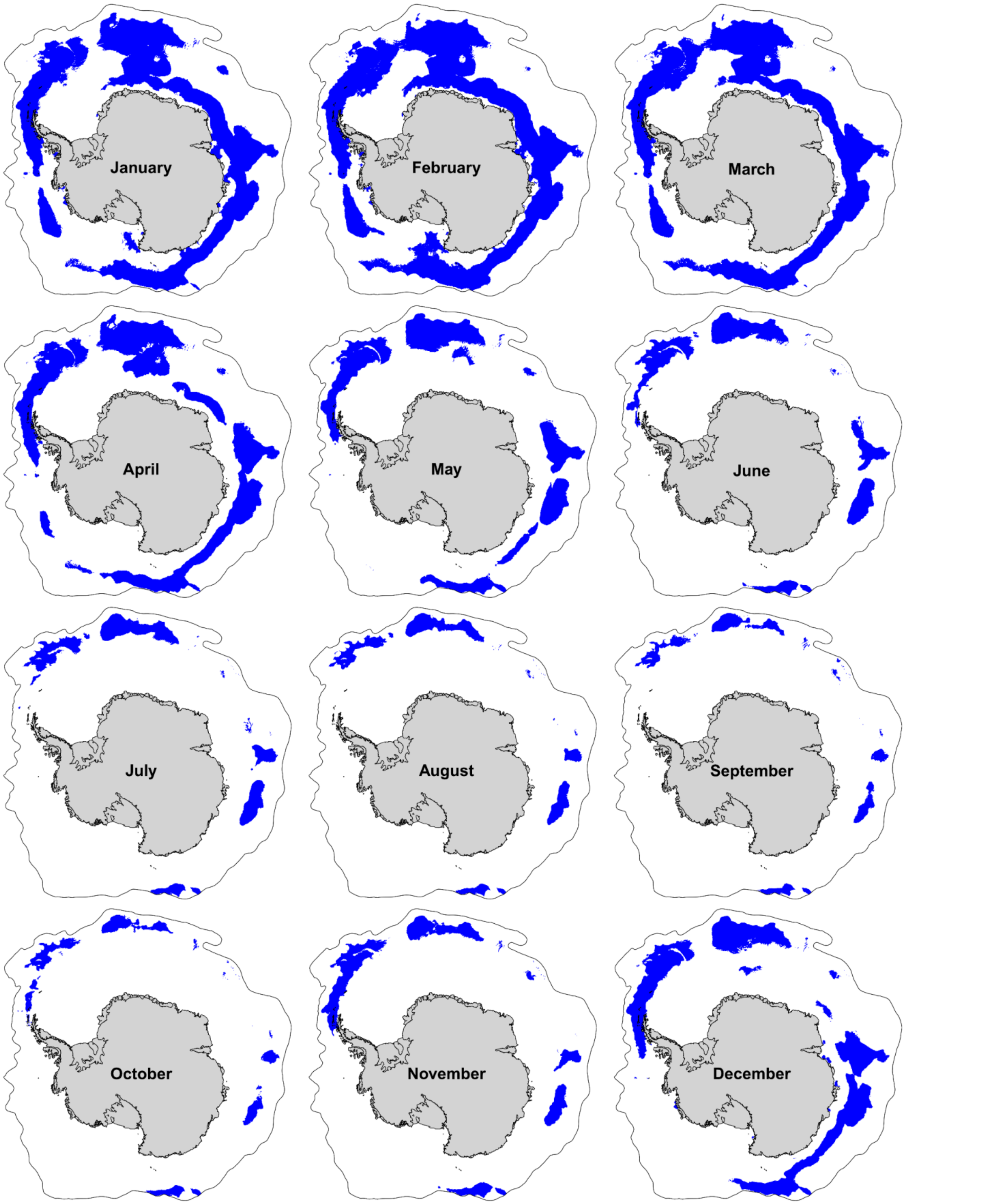


Figure S20: Monthly predicted habitat suitability for fin whales. Each map represents a long-term summary of habitat suitability from 2002 to 2019 for the respective month: A) mean; B) standard deviation; C) 10% quantile. Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the fin whales (Figures S19-S26)



(A)



(B)

Figure S21: Monthly suitable habitats for fin whales. **(A):** the number of days (2002 to 2019) each cell was predicted suitable in the respective month. White areas represent cells not suitable at a single day in the respective month. **(B)** shows the final monthly binary map: areas marked with blue show cells predicted suitable in at least 50% of days in the respective month.

Results of dynamic SDMs for the fin whales (Figures S19-S26)

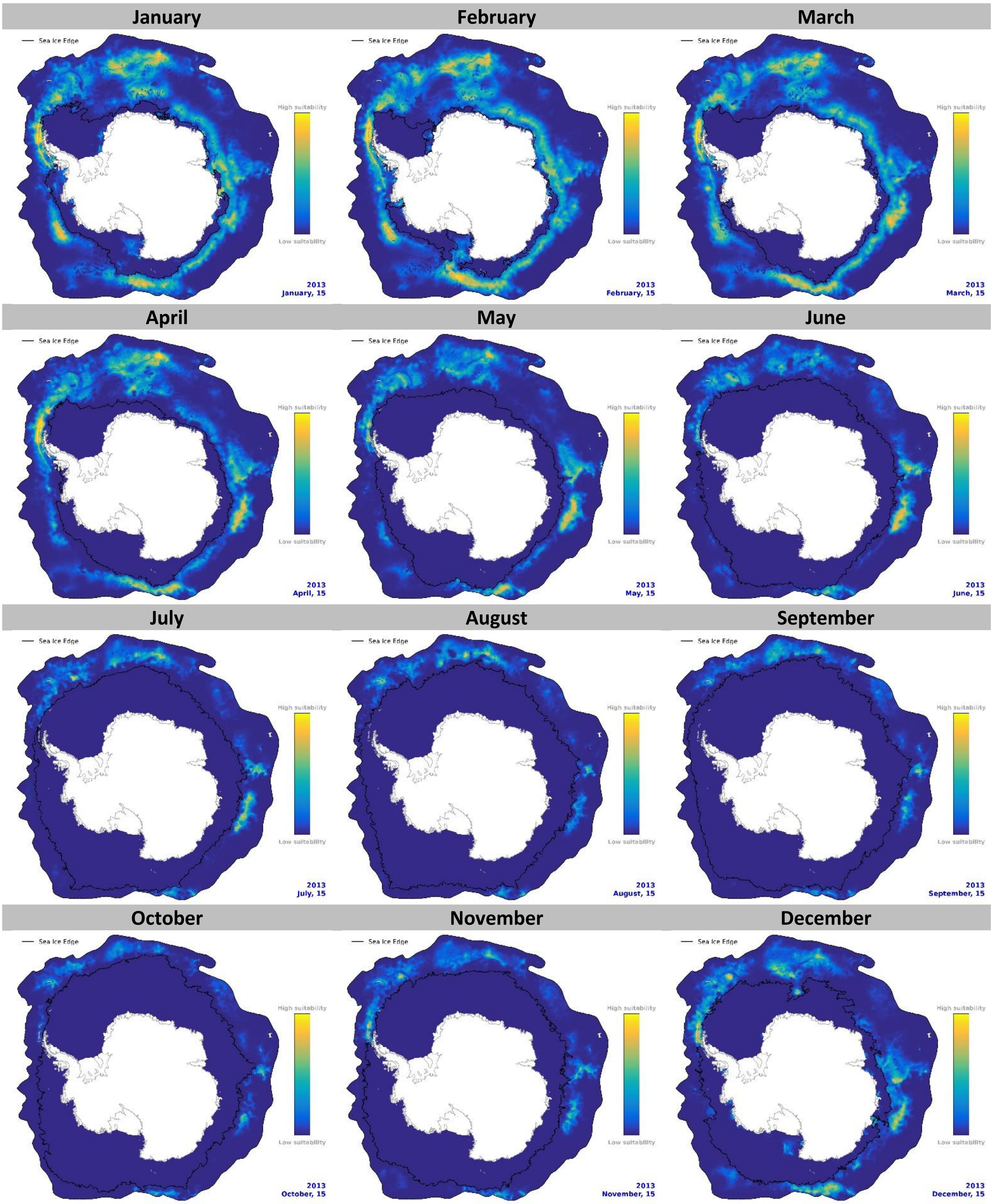
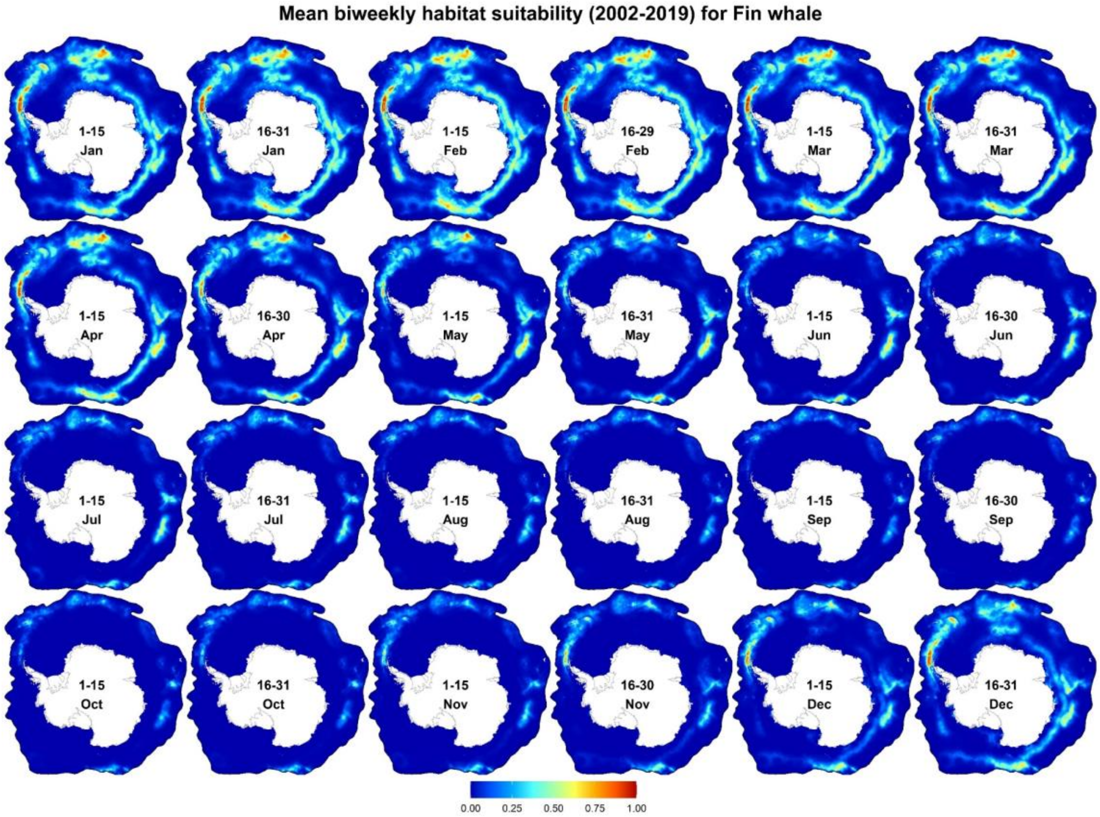
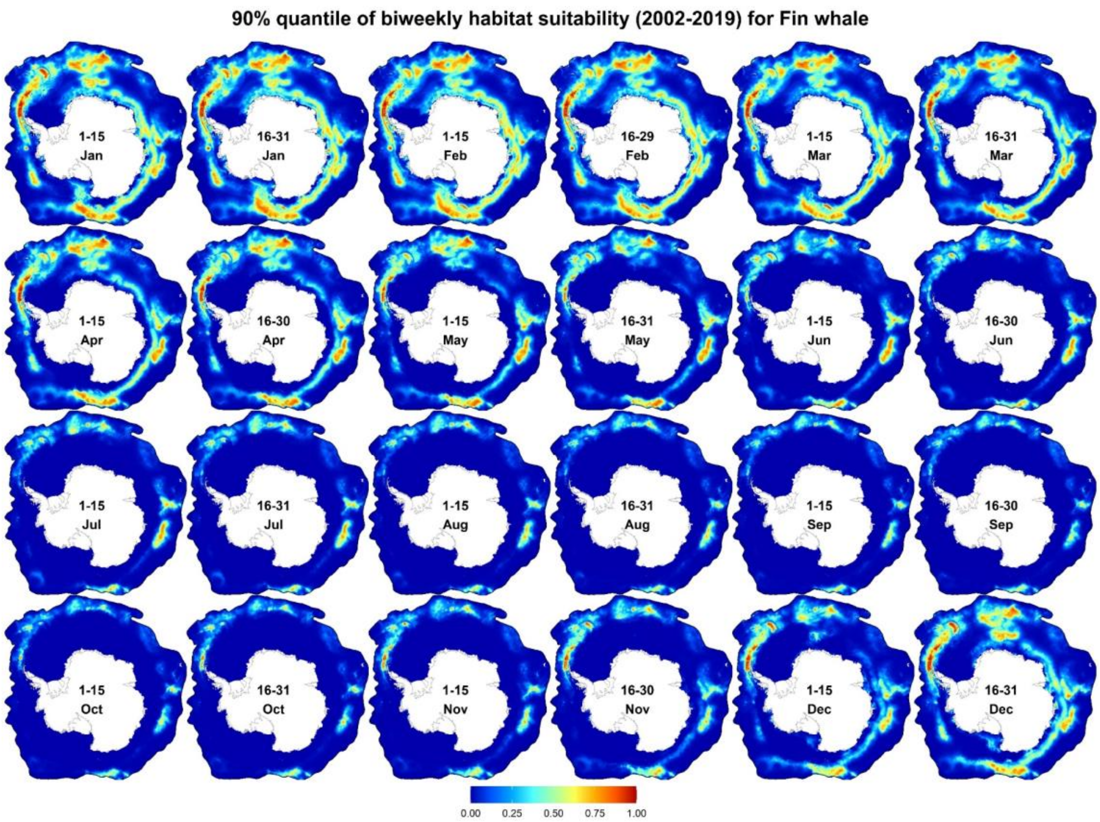


Figure S22: Examples of daily habitat suitability maps for fin whales. Each panel shows predicted habitat suitability on the 15th of each month in 2013.

Results of dynamic SDMs for the fin whales (Figures S19-S26)



(A)



(B)

Figure S23: Biweekly predicted habitat suitability for fin whales. Each map represents the mean **(A)** or 90% quantile **(B)** of daily predictions from 2002 to 2019 in c.a. two weeks intervals (from the 1st - 15th and 16th – 31st day of the respective month). Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the fin whales (Figures S19-S26)

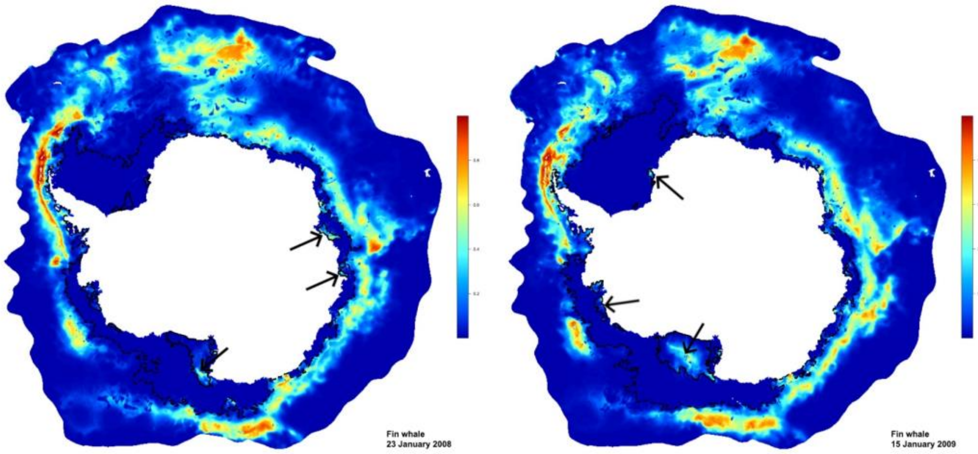


Figure S24: Example days with high fin whale habitat suitability in coastal polynyas (arrows) south of the daily estimated SIE (black line).

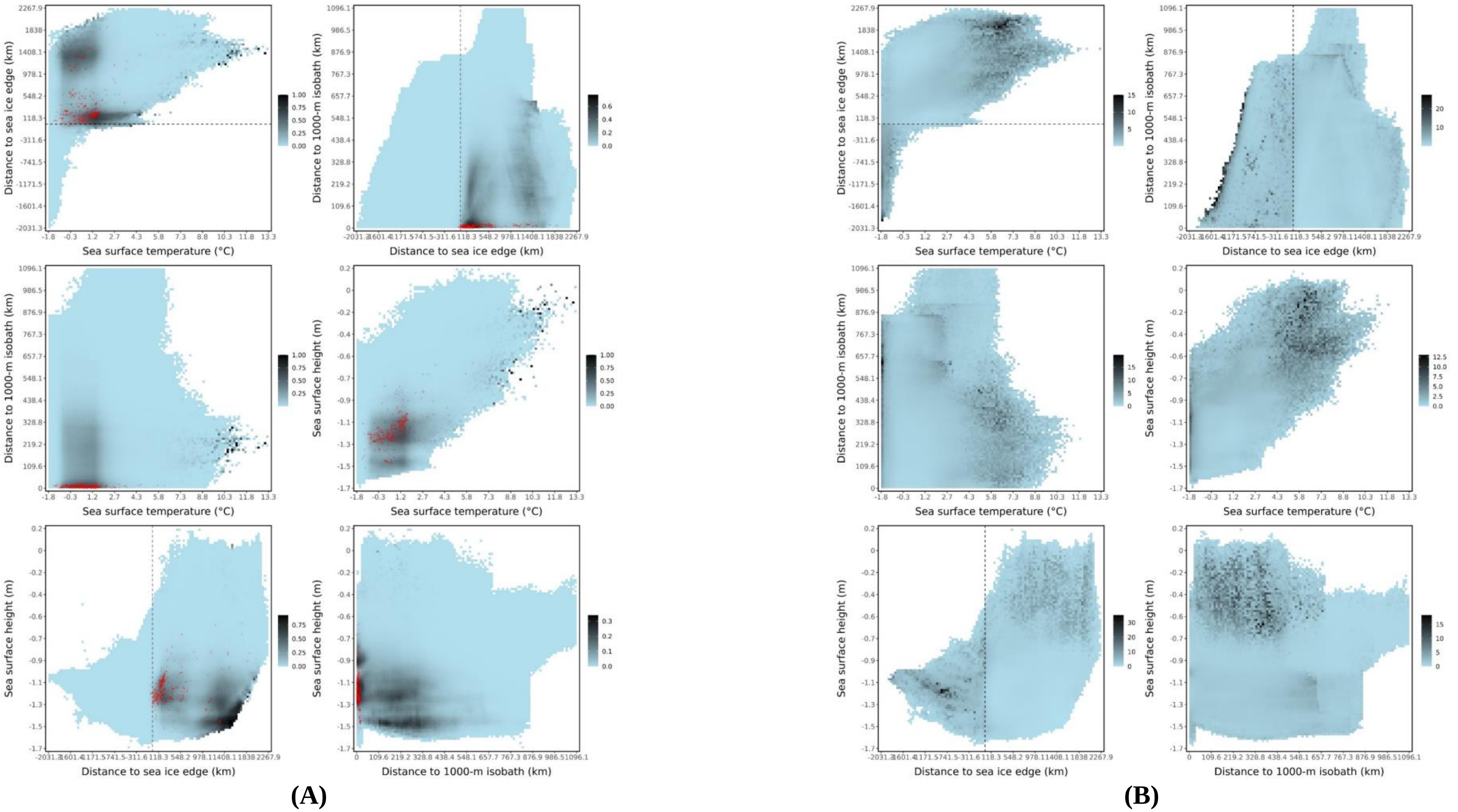


Figure S25: Mean (A) and standard deviation (B) of habitat suitability of fin whales (cloglog scale) in pairwise environmental space of the four most important predictors (see Figure 6 in the main text for more details). In each plot, predicted values from the full model (calibrated without cross-validation) at year-round environmental combinations were estimated (~27M spatiotemporally sampled backgrounds, 2003-2010 and 2013-2019). Predictions at each combination of two predictors (represented as 100×100 pixels) were summarized to represent the mean (A) or standard deviation (B) of habitat suitability per combination. In contrast to marginal response curves (Figure S26), we allow here all other predictors to vary together to represent mean suitability at all other possible combinations. The frequency at which each combination is available in the background information used is shown in Figure S35. Higher mean or standard deviation values are represented in darker colors (white areas are for non-existing combinations). Spatiotemporally-matched environmental conditions at species observations are shown as red points (A).

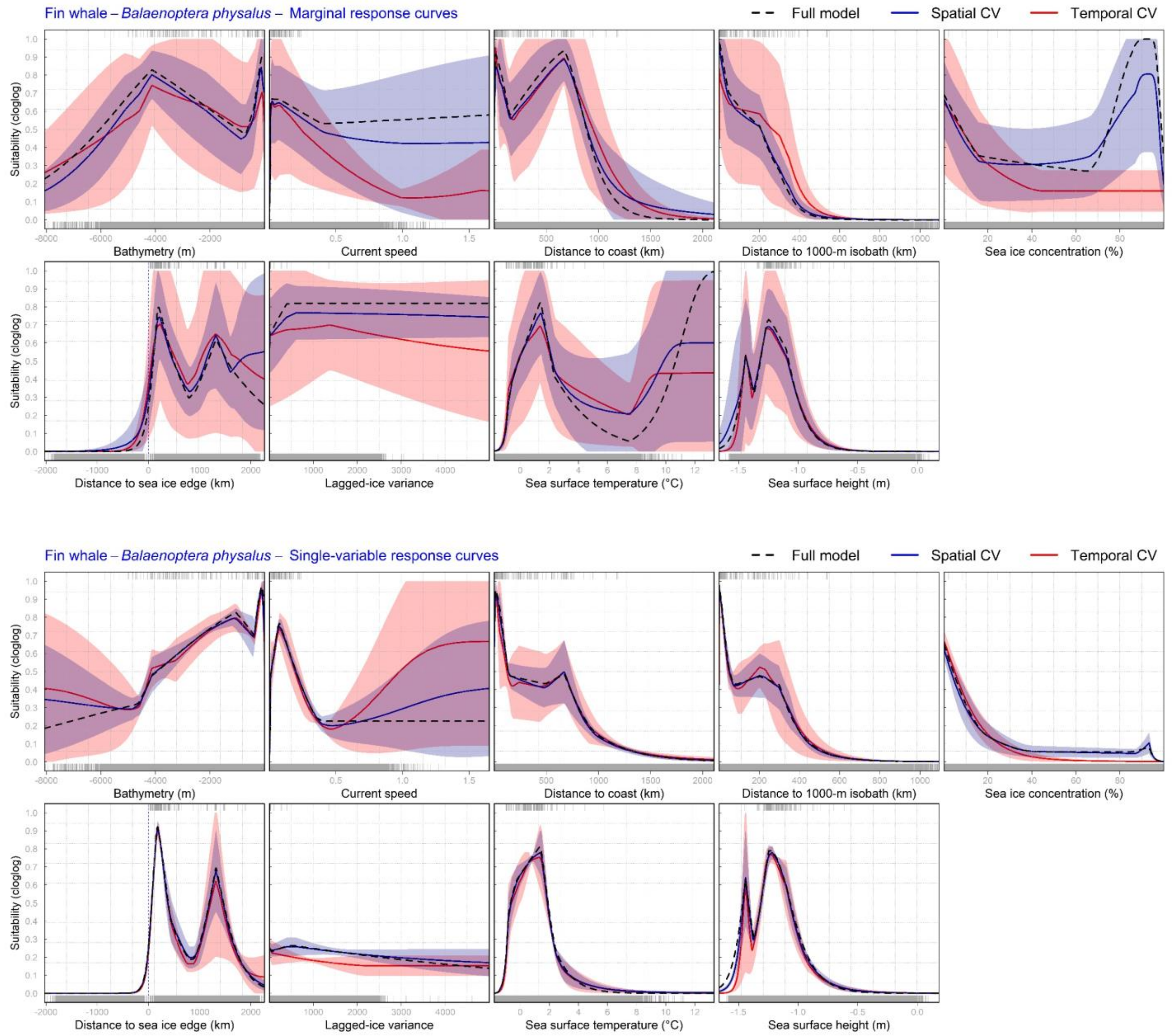
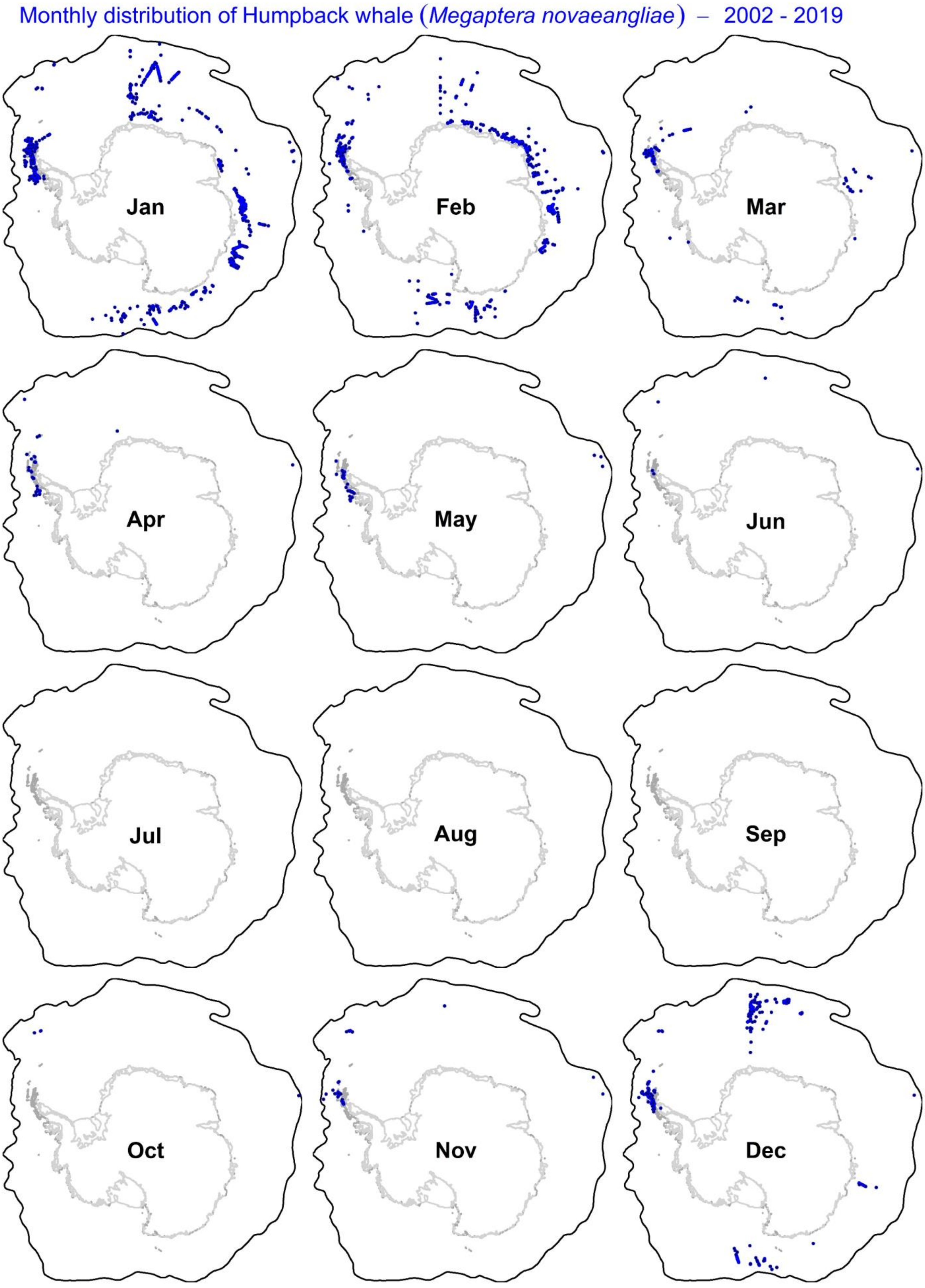


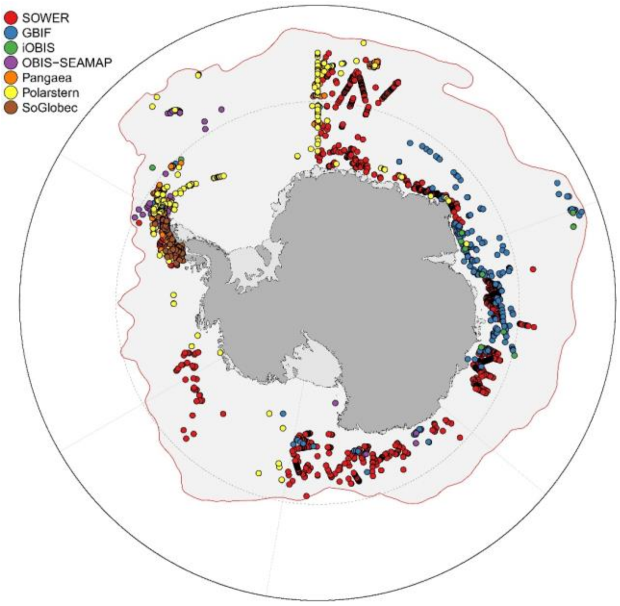
Figure S26: Response curves for fin whale models. The first set of plots shows marginal response curves, in which models were run using all predictors, then each predictor's response curve is drawn by fixing all other predictors at their mean value at training presences. In the second set of plots, an additional set of models was run only using one predictor in turn. Blue lines and shaded areas represent the mean and standard deviation of response curves of spatially cross-validated models; red for temporally cross-validated models. The black dashed line is for a full model calibrated with all sightings (no cross-validation). In each plot, the top grey rug shows spatiotemporally matched conditions at species observations, while the bottom grey rug shows values at spatiotemporally sampled 20K locations.

Results of dynamic SDMs for the humpback whales (Figures S27-S34)

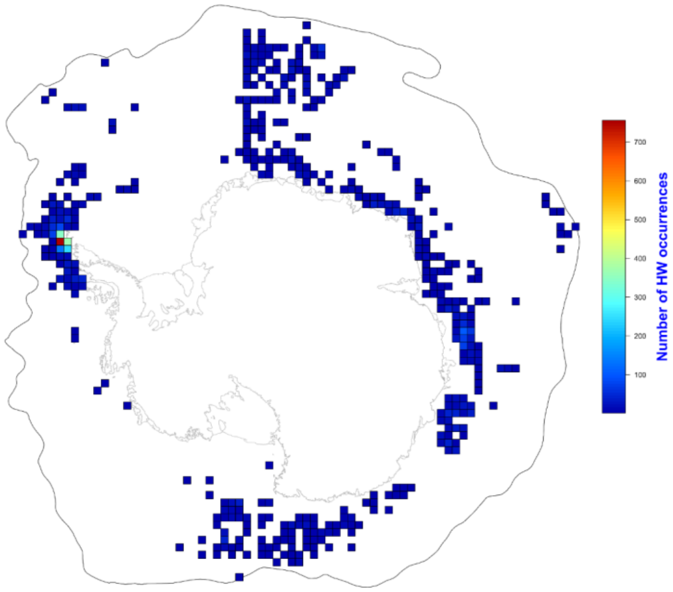


(A)

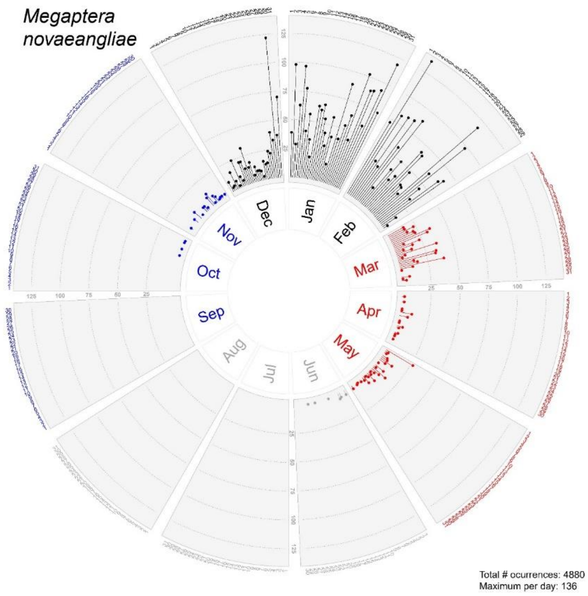
Results of dynamic SDMs for the humpback whales (Figures S27-S34)



(B)

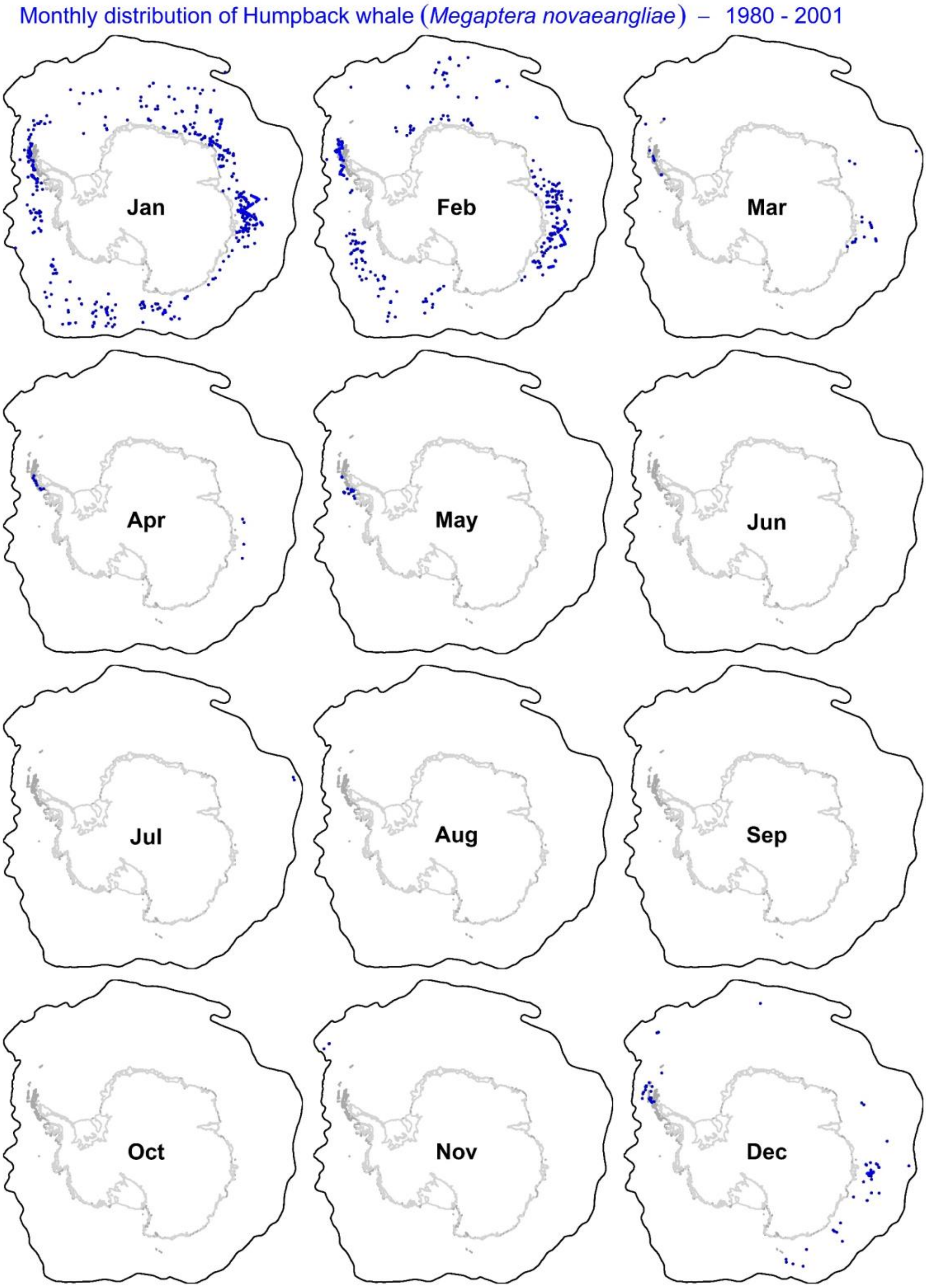


(C)



(D)

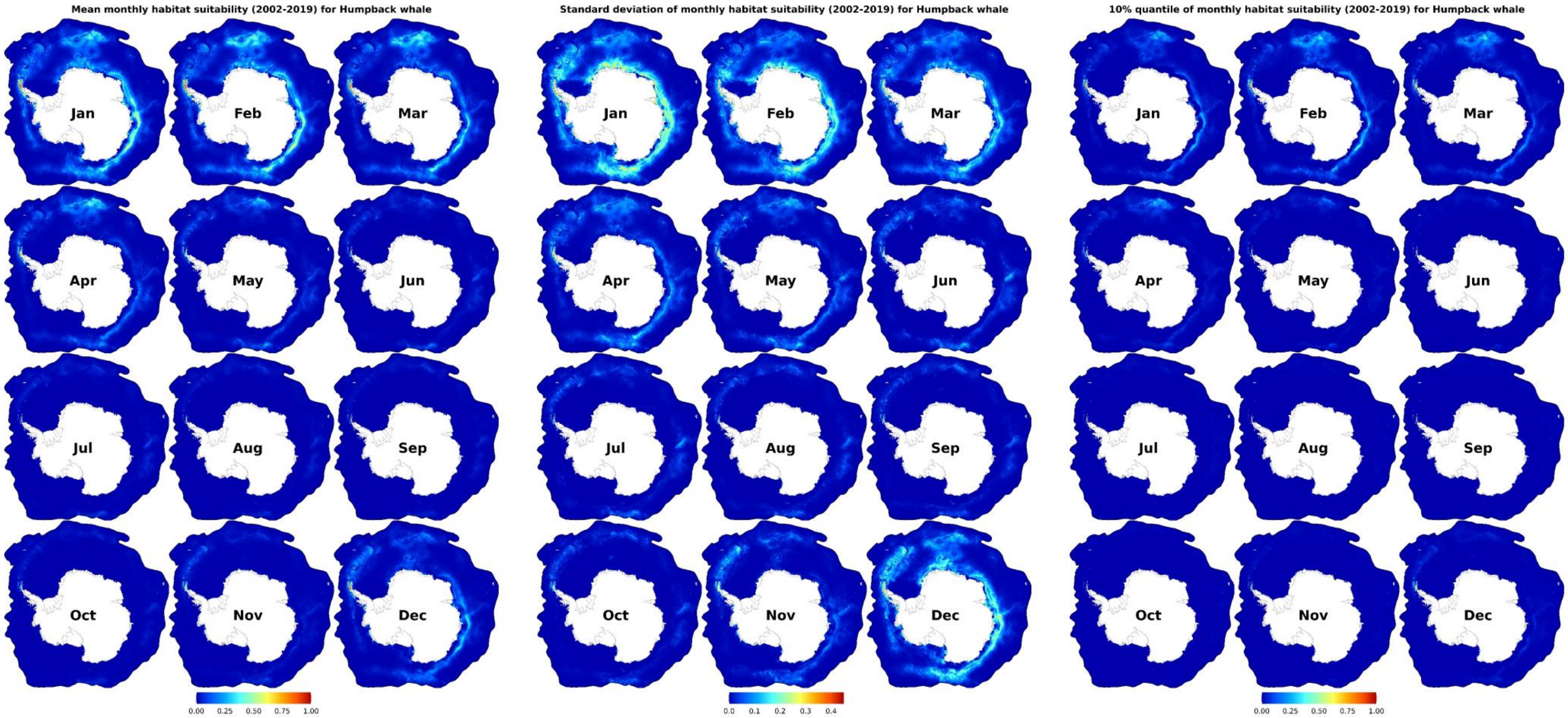
Results of dynamic SDMs for the humpback whales (Figures S27-S34)



(E)

Figure S27: Spatiotemporal distribution of humpback whale sightings. Maps shown in **(A)** represent the monthly spatial distribution of observations used in this study (2002-2019), with the source of the data shown in **(B)**. Panel **(C)** indicates the number of sightings per 100×100 km grid, while **(D)** shows the total number of sightings per calendar day for the same period. Maps in **(E)** are for the monthly distribution of sightings between 1980 and 2001 (excluded in the current study due to the lack of sea ice data before 2002).

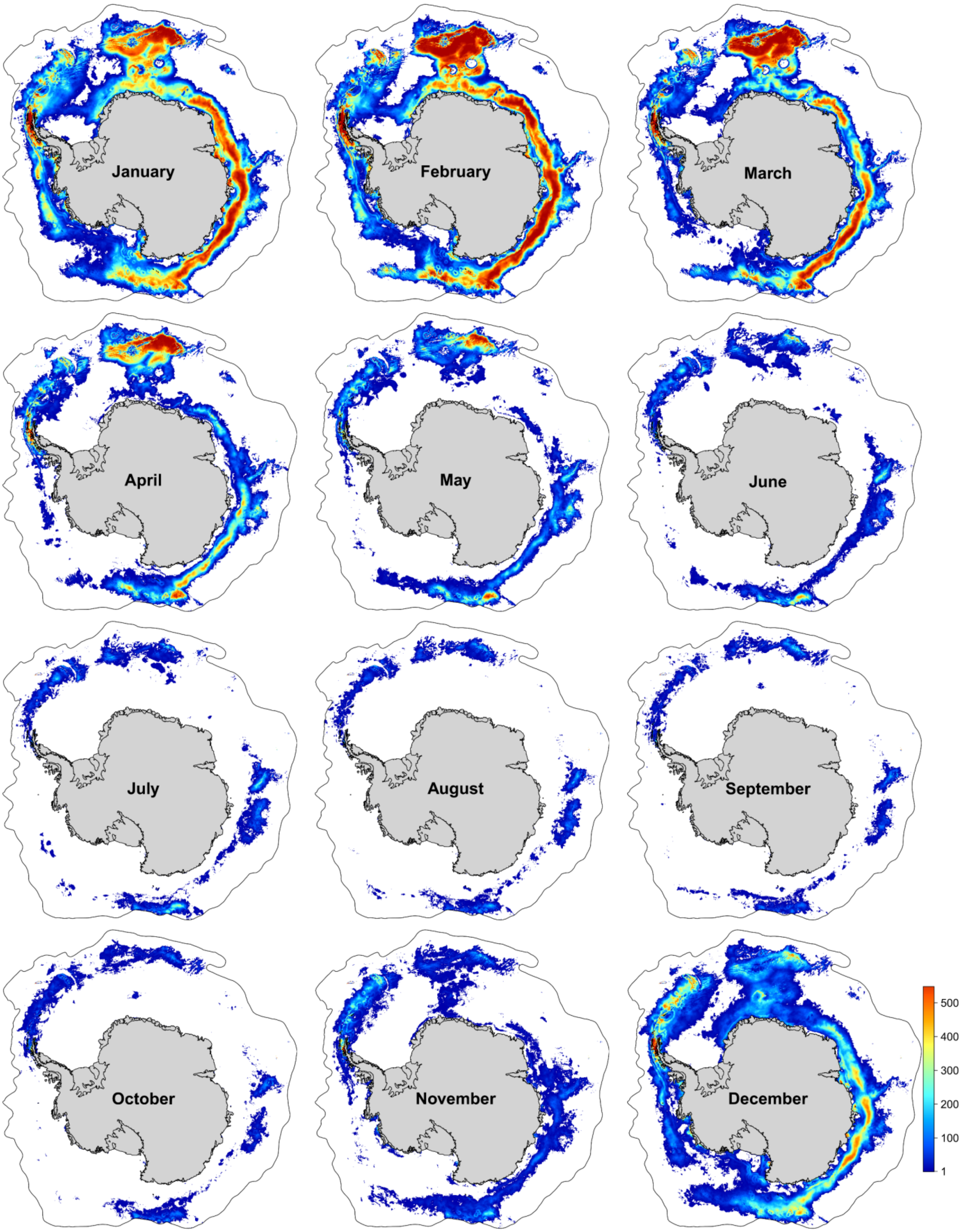
Results of dynamic SDMs for the humpback whales (Figures S27-S34)



(A) Mean **(B) Standard deviation** **(C) 10% quantile**

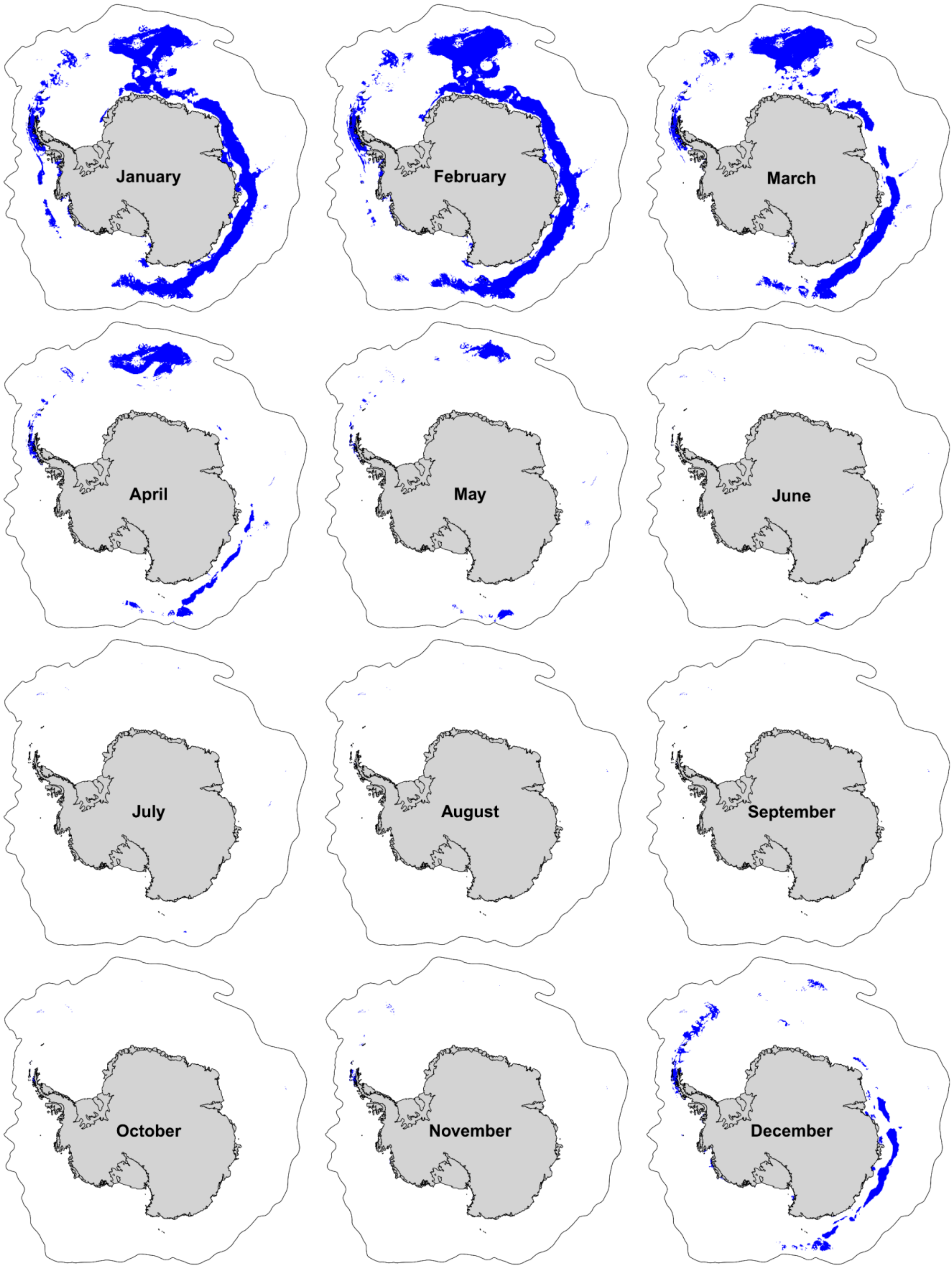
Figure S28: Monthly predicted habitat suitability for humpback whales. Each map represents a long-term summary of habitat suitability from 2002 to 2019 for the respective month: A) mean; B) standard deviation; C) 10% quantile. Warmer colors represent higher mean habitat suitability.

Results of dynamic SDMs for the humpback whales (Figures S27-S34)



(A)

Results of dynamic SDMs for the humpback whales (Figures S27-S34)



(B)

Figure S29: Monthly suitable habitats for humpback whales. **(A):** the number of days (2002 to 2019) each cell was predicted suitable in the respective month. White areas represent cells not suitable at a single day in the respective month. **(B)** shows the final monthly binary map: areas marked with blue show cells predicted suitable in at least 50% of days in the respective month.

Results of dynamic SDMs for the humpback whales (Figures S27-S34)

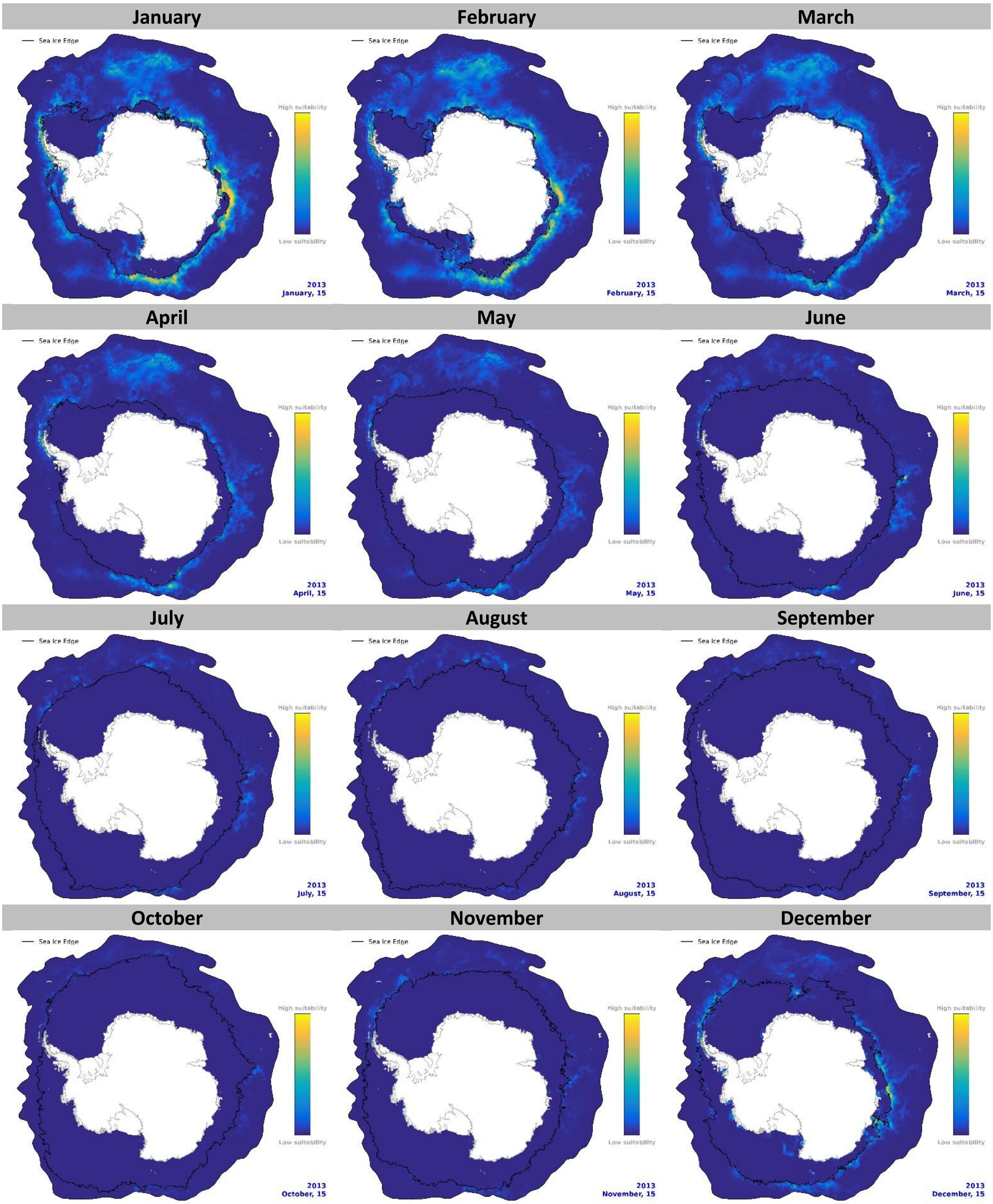
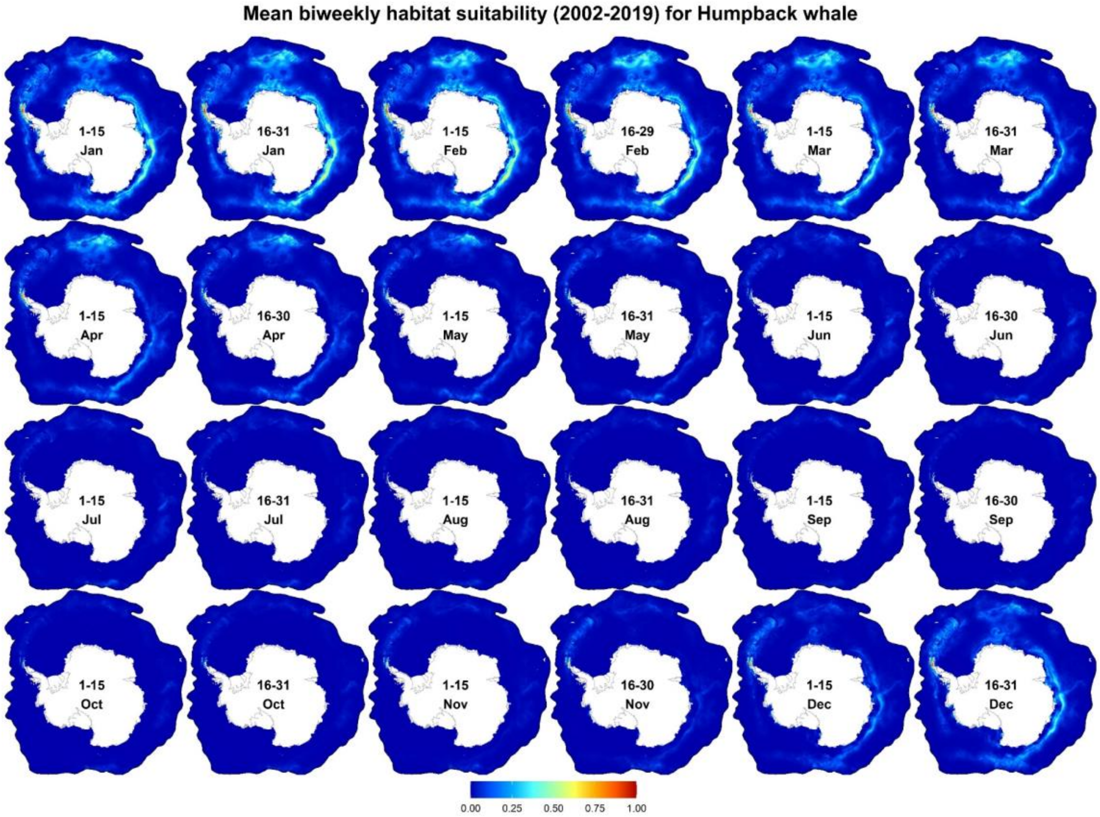
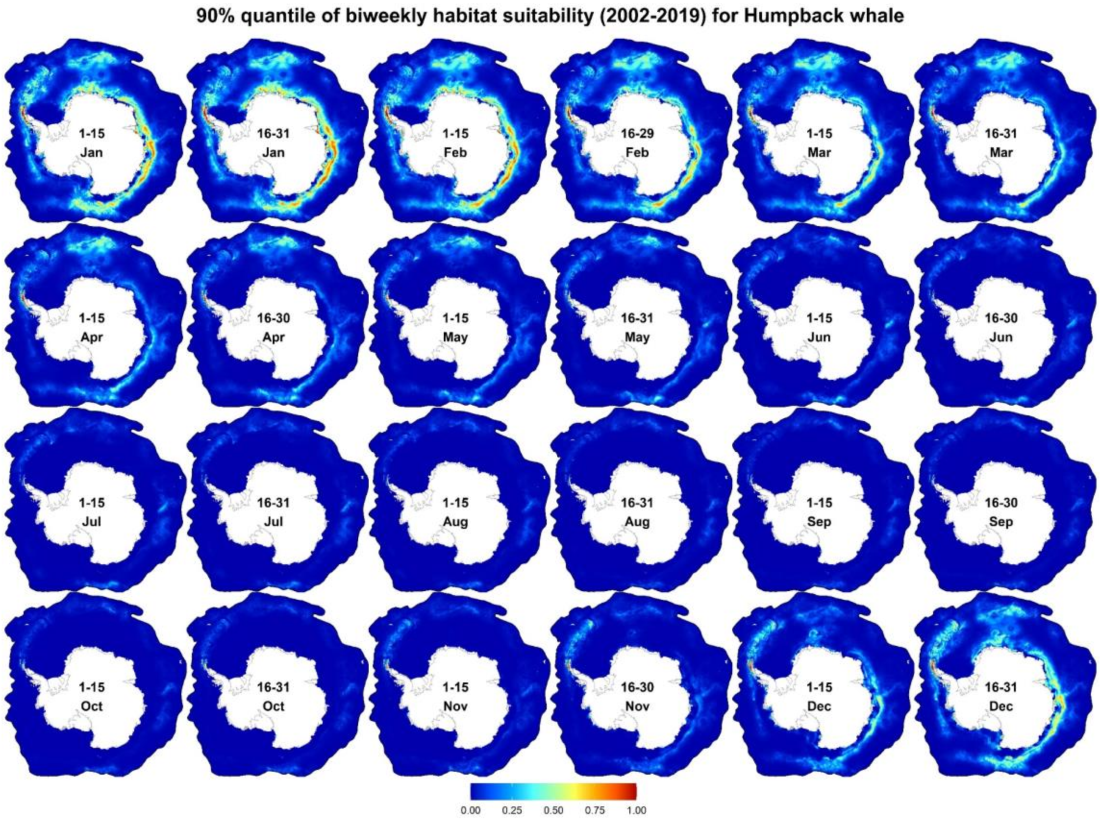


Figure S30: Examples of daily habitat suitability maps for humpback whales. Each panel shows predicted habitat suitability on the 15th of each month in 2013.

Results of dynamic SDMs for the humpback whales (Figures S27-S34)



(A)



(B)

Figure S31: Biweekly predicted habitat suitability for humpback whales. Each map represents the mean **(A)** or 90% quantile **(B)** of daily predictions from 2002 to 2019 in c.a. two weeks intervals (from the 1st - 15th and 16th – 31st day of the respective month). Warmer colors represent higher habitat suitability.

Results of dynamic SDMs for the humpback whales (Figures S27-S34)

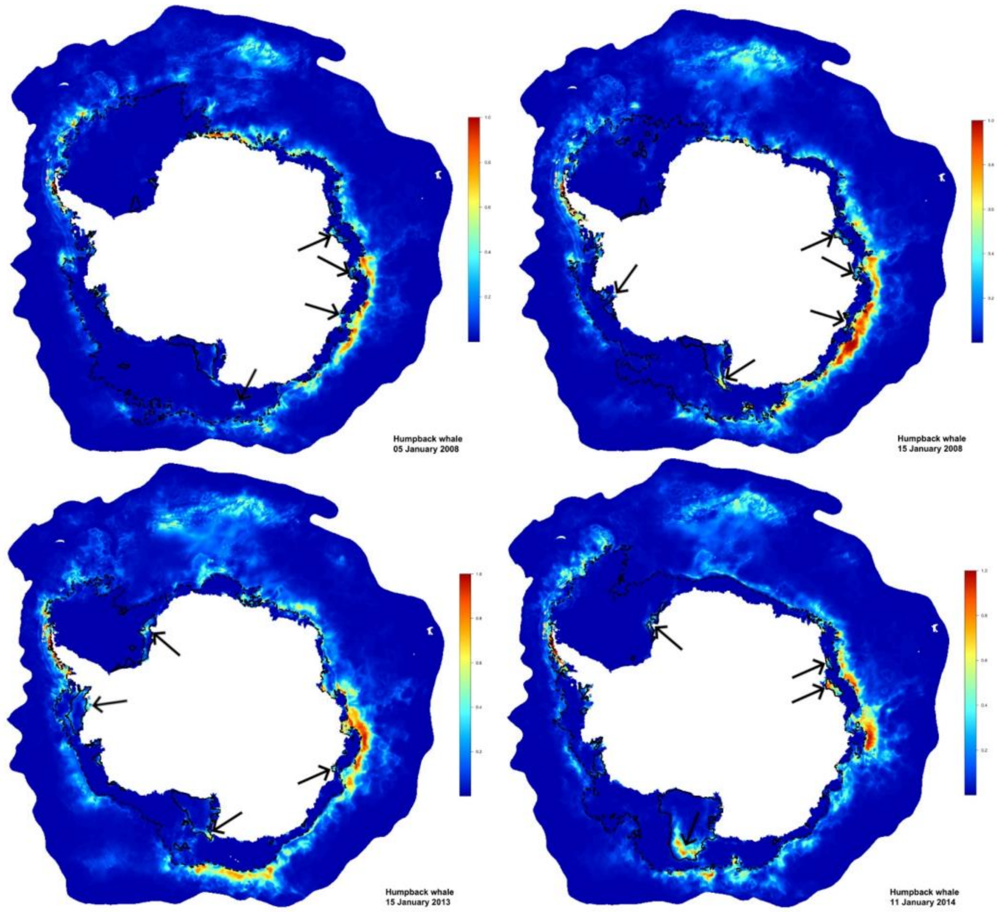
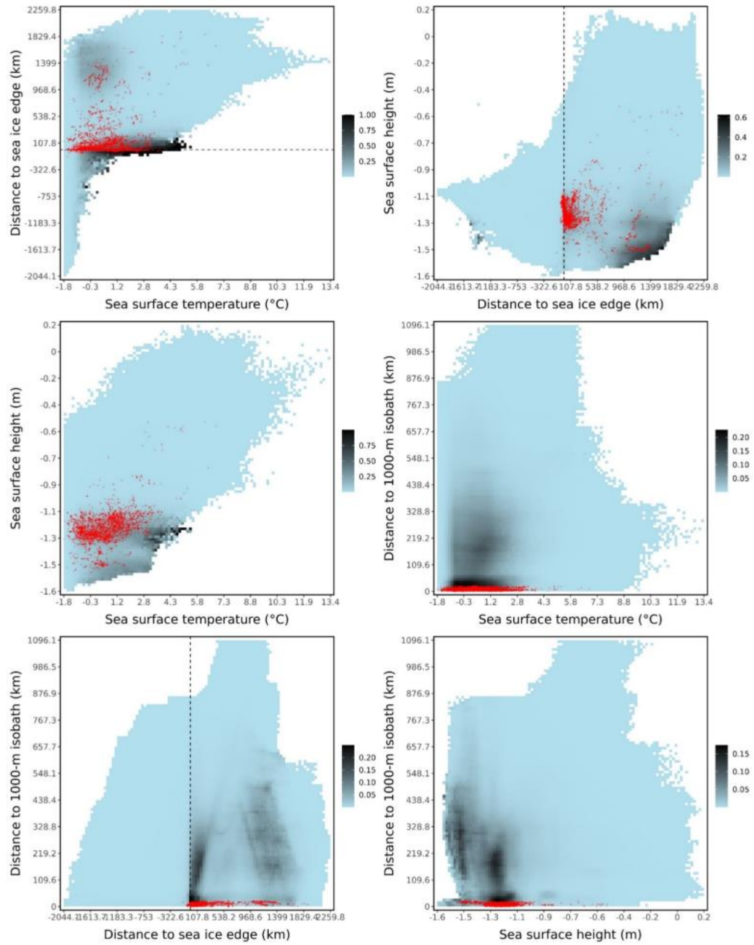
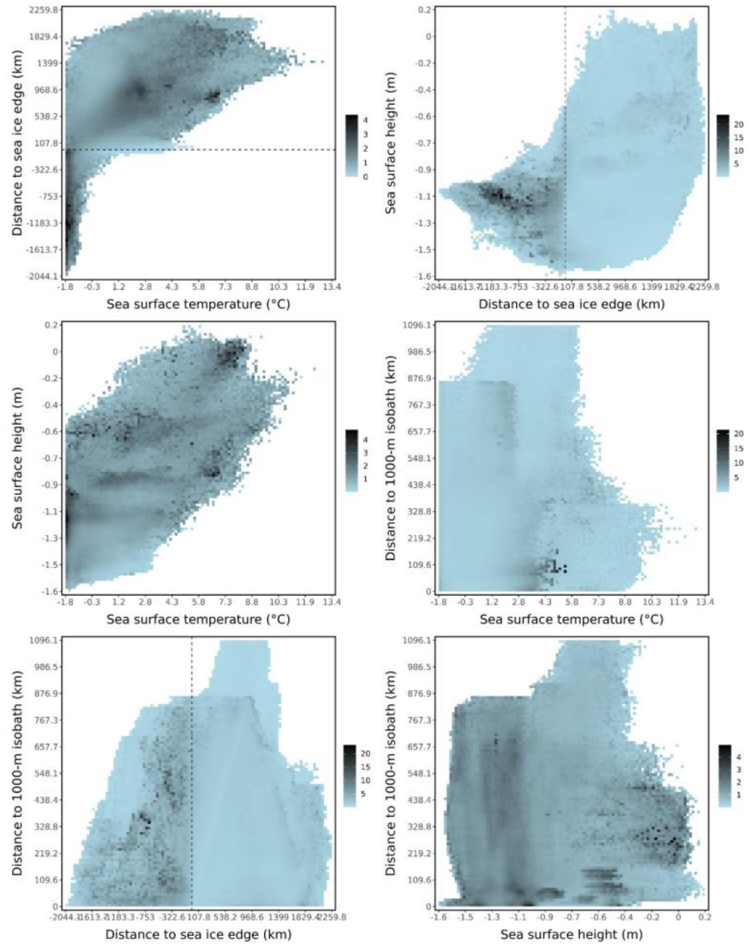


Figure S32: Example days with high humpback whale habitat suitability in coastal polynyas (arrows) south of the daily estimated SIE (black line).

Results of dynamic SDMs for the humpback whales (Figures S27-S34)



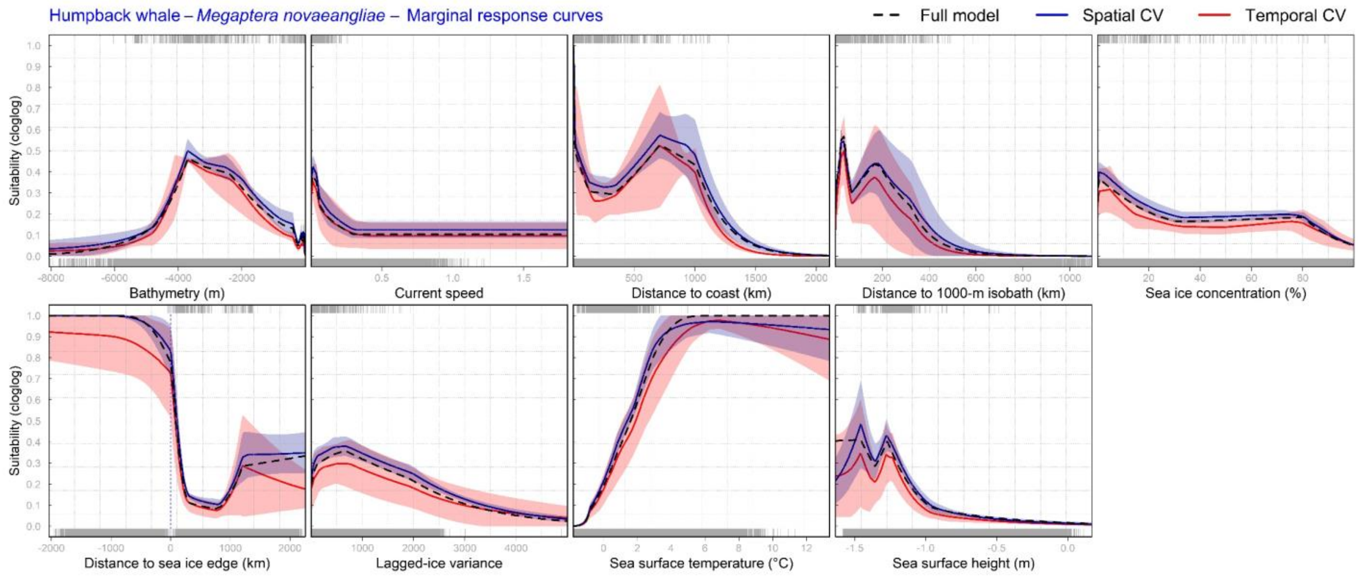
(A)



(B)

Figure S33: Mean (A) and standard deviation (B) of habitat suitability of humpback whales (cloglog scale) in pairwise environmental space of the four most important predictors (see Figure 6 in the main text for more details). In each plot, predicted values from the full model (calibrated without cross-validation) at year-round environmental combinations were estimated (~27M spatiotemporally sampled backgrounds, 2003-2010 and 2013-2019). Predictions at each combination of two predictors (represented as 100×100 pixels) were summarized to represent the mean (A) or standard deviation (B) of habitat suitability per combination. In contrast to marginal response curves (Figure S34), we allow here all other predictors to vary together to represent mean suitability at all other possible combinations. The frequency at which each combination is available in the background information used is shown in Figure S35. Higher mean or standard deviation values are represented in darker colors (white areas are for non-existing combinations). Spatiotemporally-matched environmental conditions at species observations are shown as red points (A).

Results of dynamic SDMs for the humpback whales (Figures S27-S34)



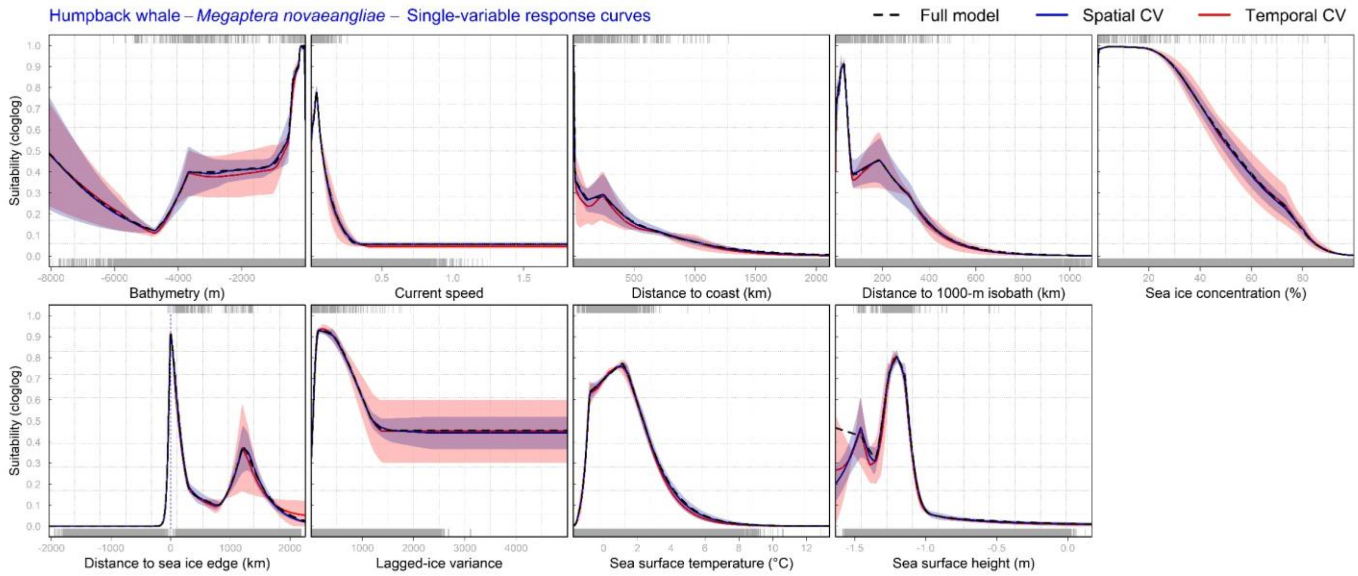


Figure S34: Response curves for humpback whale models. The first set of plots shows marginal response curves, in which models were run using all predictors, then each predictor's response curve is drawn by fixing all other predictors at their mean value at training presences. In the second set of plots, an additional set of models was run only using one predictor in turn. Blue lines and shaded areas represent the mean and standard deviation of response curves of spatially cross-validated models; red for temporally cross-validated models. The black dashed line is for a full model calibrated with all sightings (no cross-validation). In each plot, the top grey rug shows spatiotemporally matched conditions at species observations, while the bottom grey rug shows values at spatiotemporally sampled 20K locations.

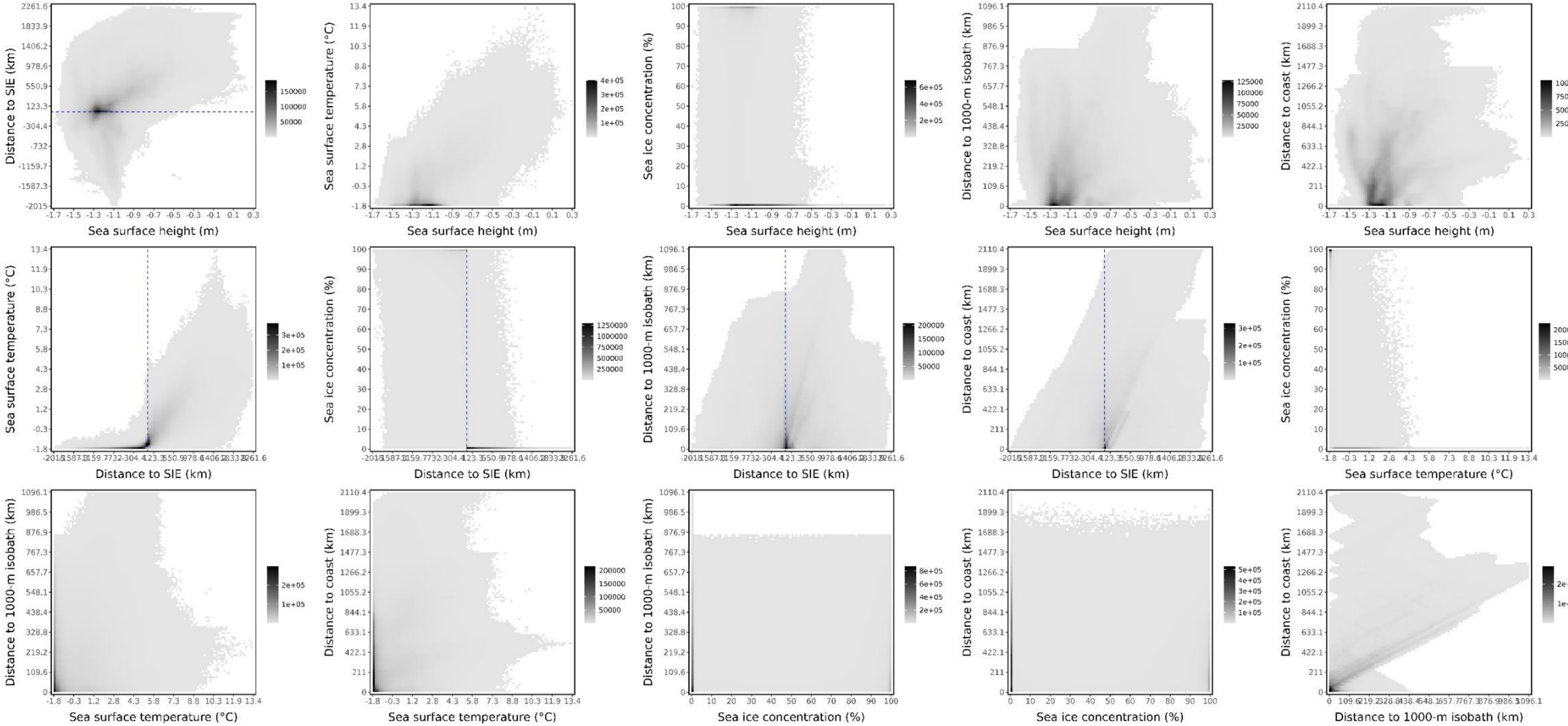
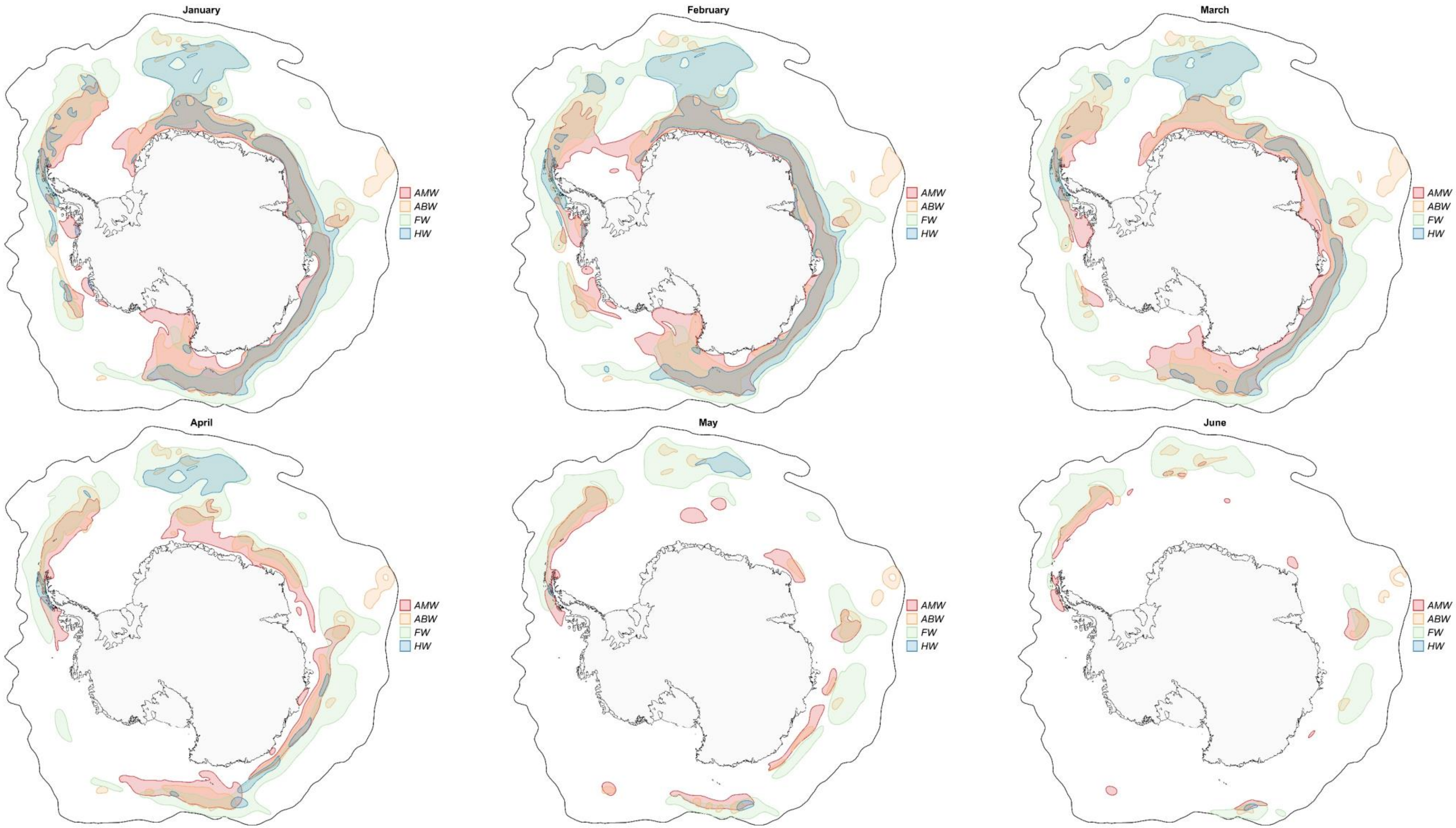


Figure S35: Pairwise environmental space of the most important six predictors. Each plot shows the frequency at which each combination exists in background information; the darker, the more frequent is the combination (white areas are for non-existing combinations).


January
February
March
April
May
June
AMW
ABW
FW
HW

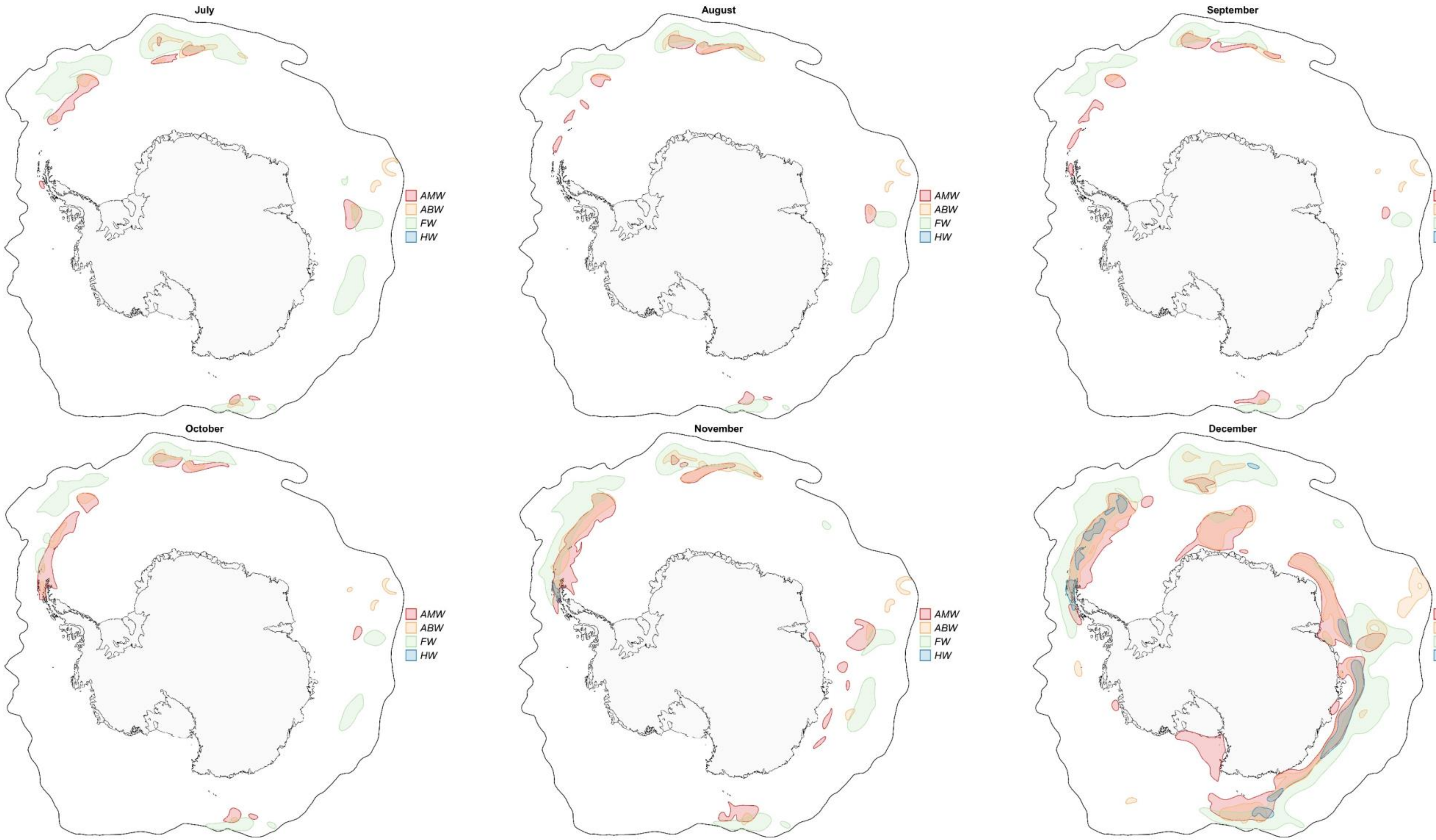
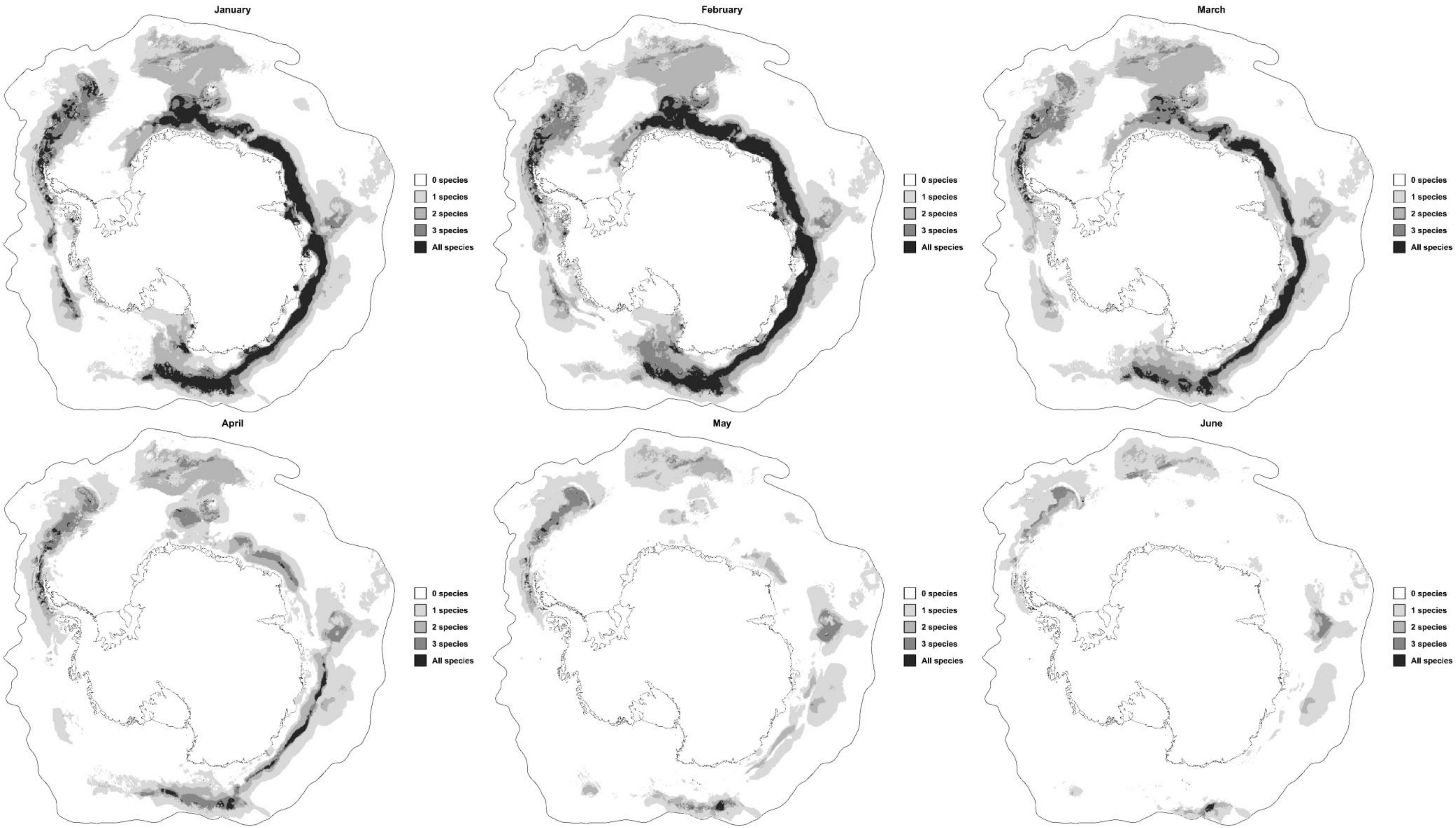


Figure S36: Overlap of monthly predicted suitable habitats of baleen whales in the SO. Colors represent possible combinations of species' suitable habitats (AMW: Antarctic minke whales; ABW: Antarctic blue whales; FW: Fin whales; HW: Humpback whales). Species-specific monthly suitable habitats are shown in Figures S5, S13, S21, and S29. Pairwise overlap between species' suitable habitats is shown in Figures S38.


January
February
March
April
May
June
0 species
1 species
2 species
3 species
All species

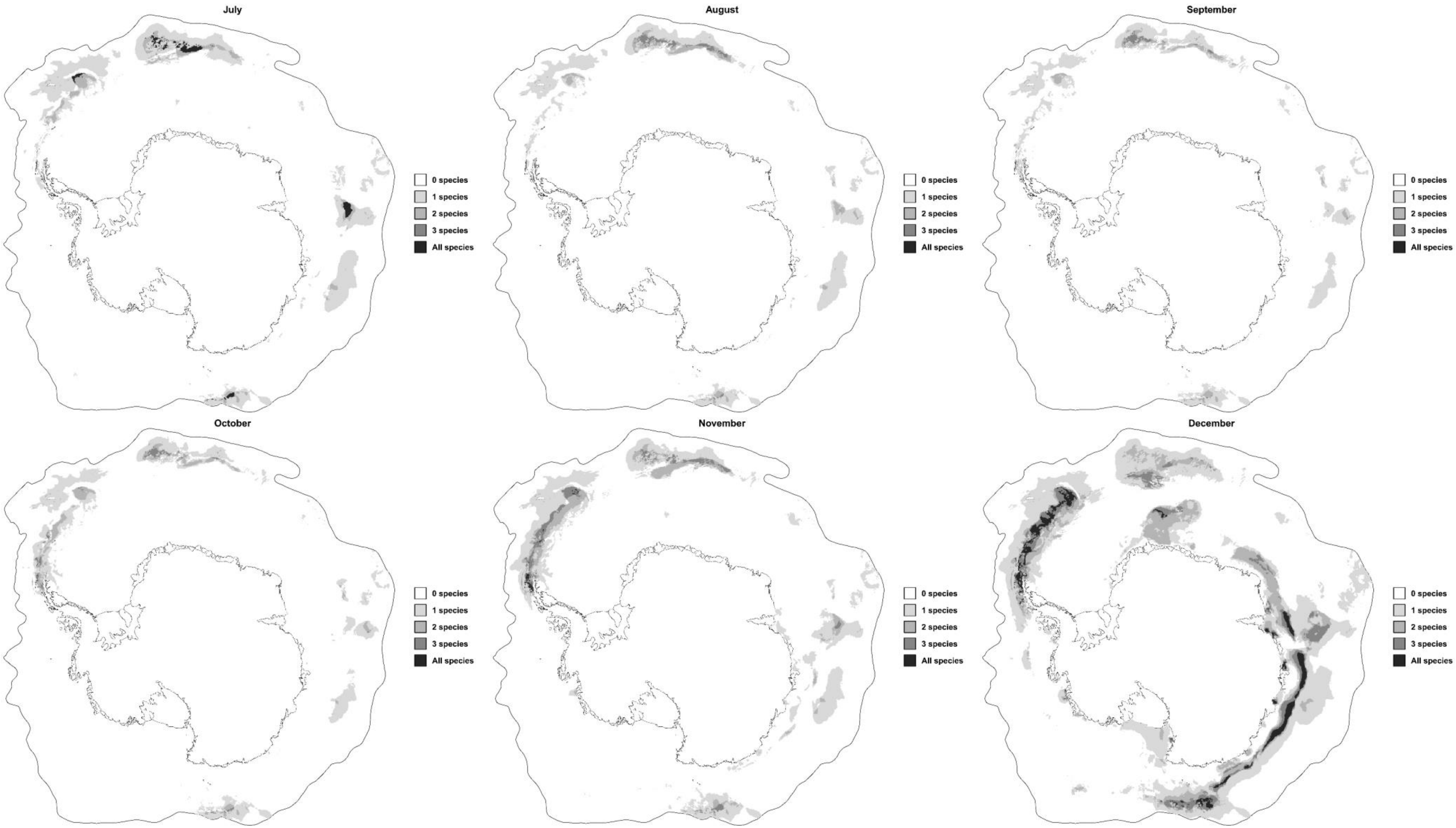
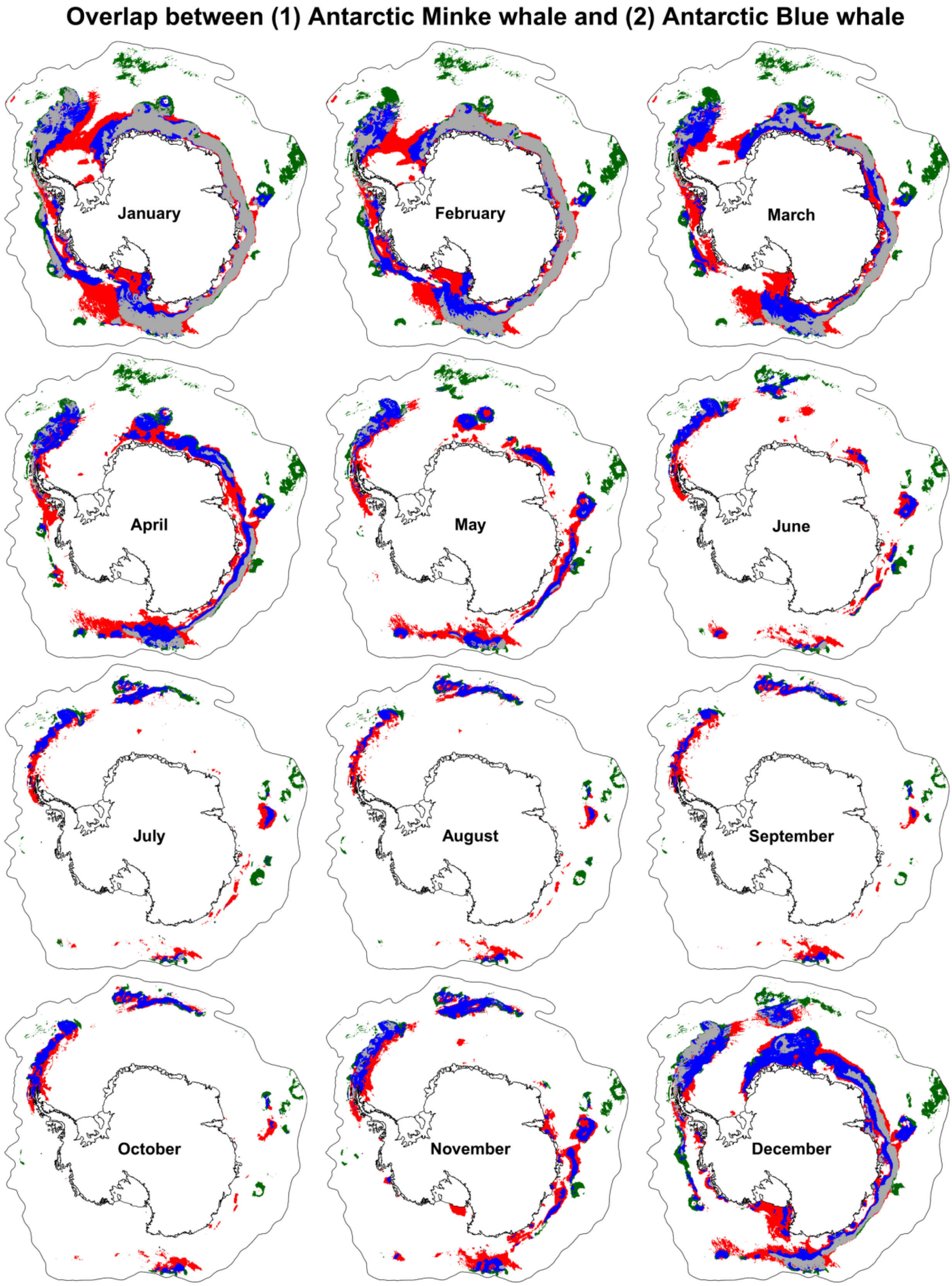
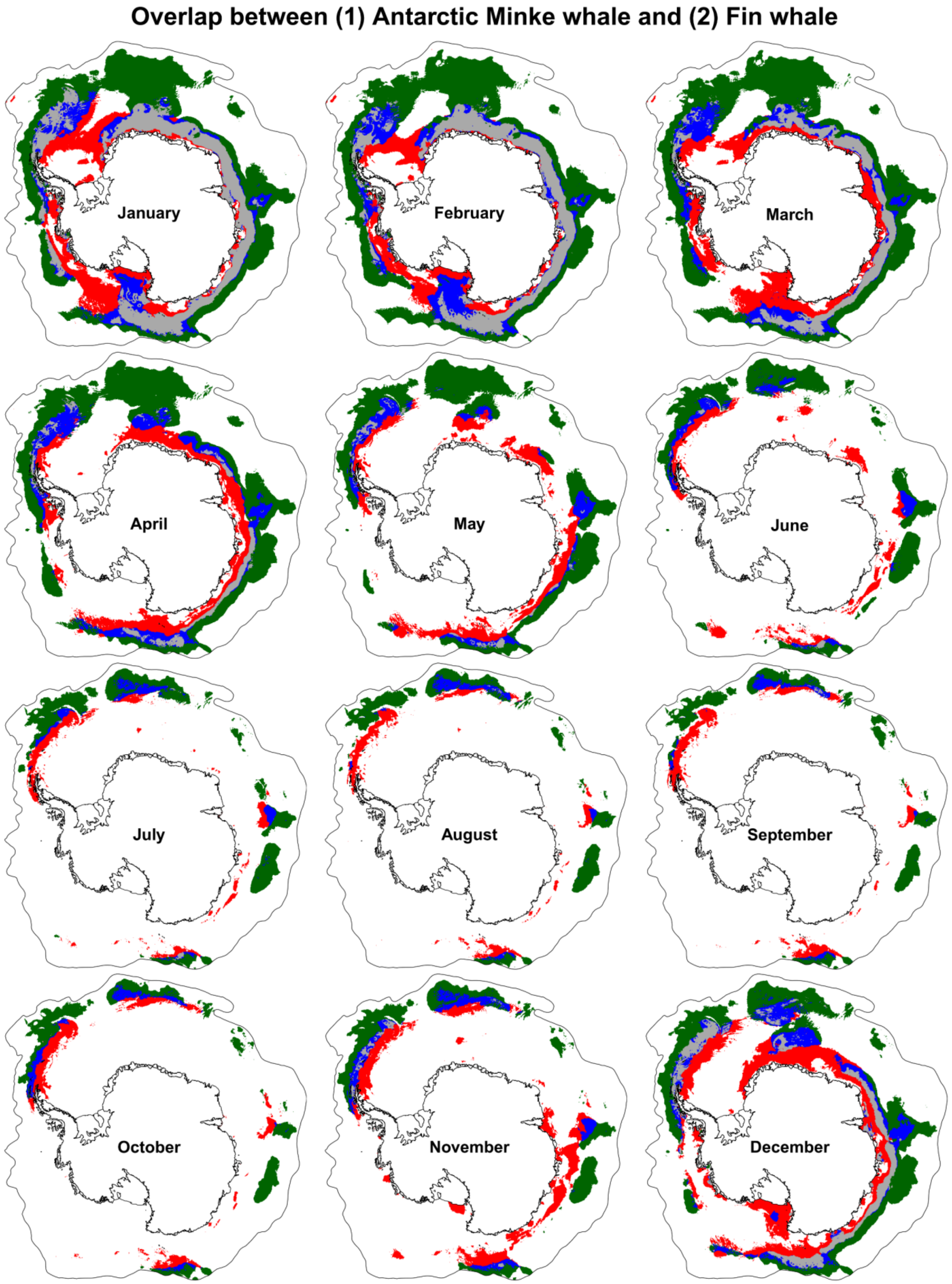


Figure S37: Overlap of monthly predicted suitable habitats of baleen whales in the SO. Colors represent the number of overlapping species. Species-specific monthly suitable habitats are shown in Figures S5, S13, S21, and S298. Pairwise overlap between species' suitable habitats is shown in Figures S38.



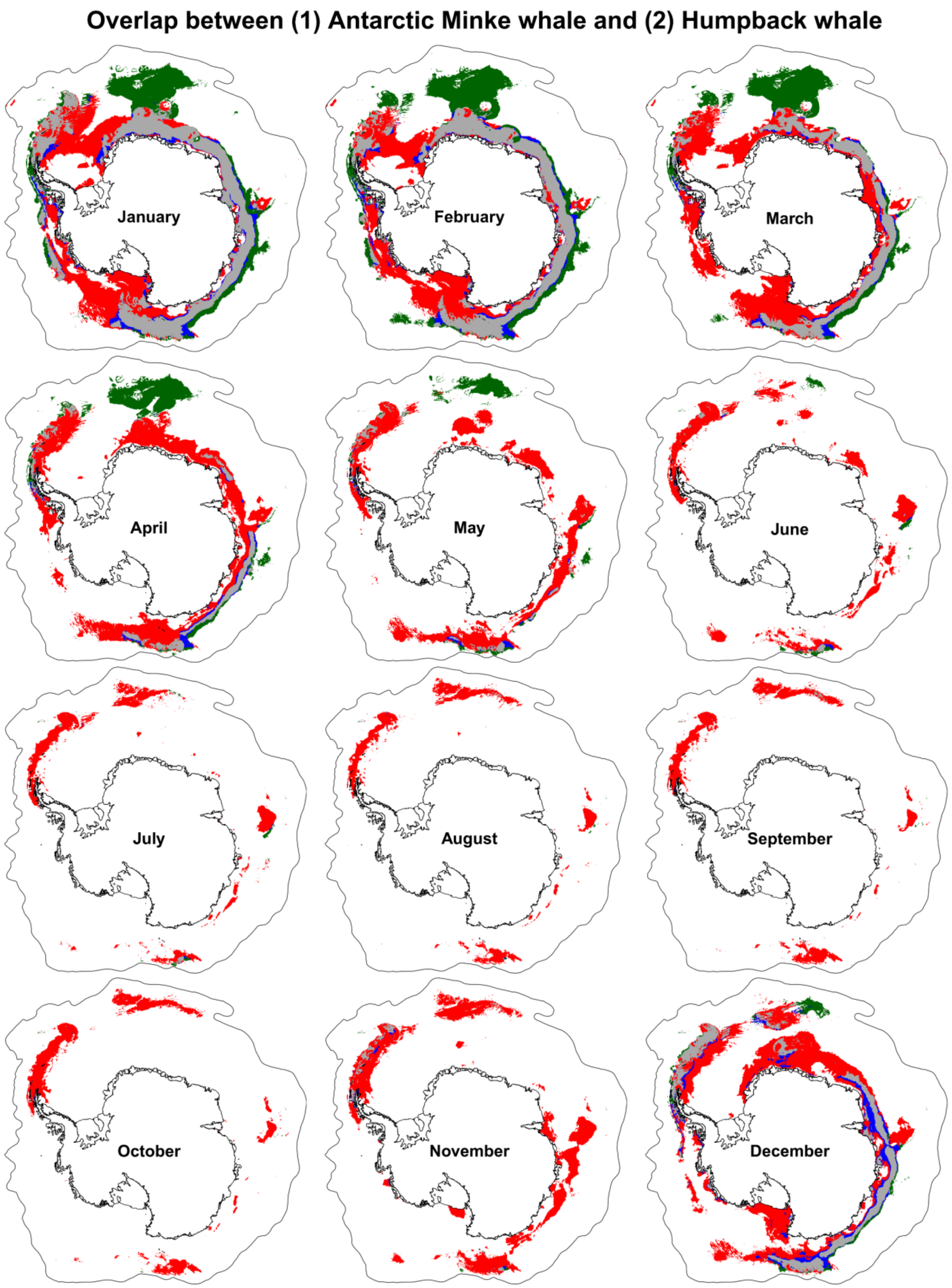
Blue: areas suitable for AMW and ABW, not overlapping with the two other species' suitable habitats; **dark grey**: areas suitable for the four baleen whale species; **red**: areas suitable for AMW, but not for ABW; **green**: areas suitable for ABW, but not for AMW.

Figure S38 (A)



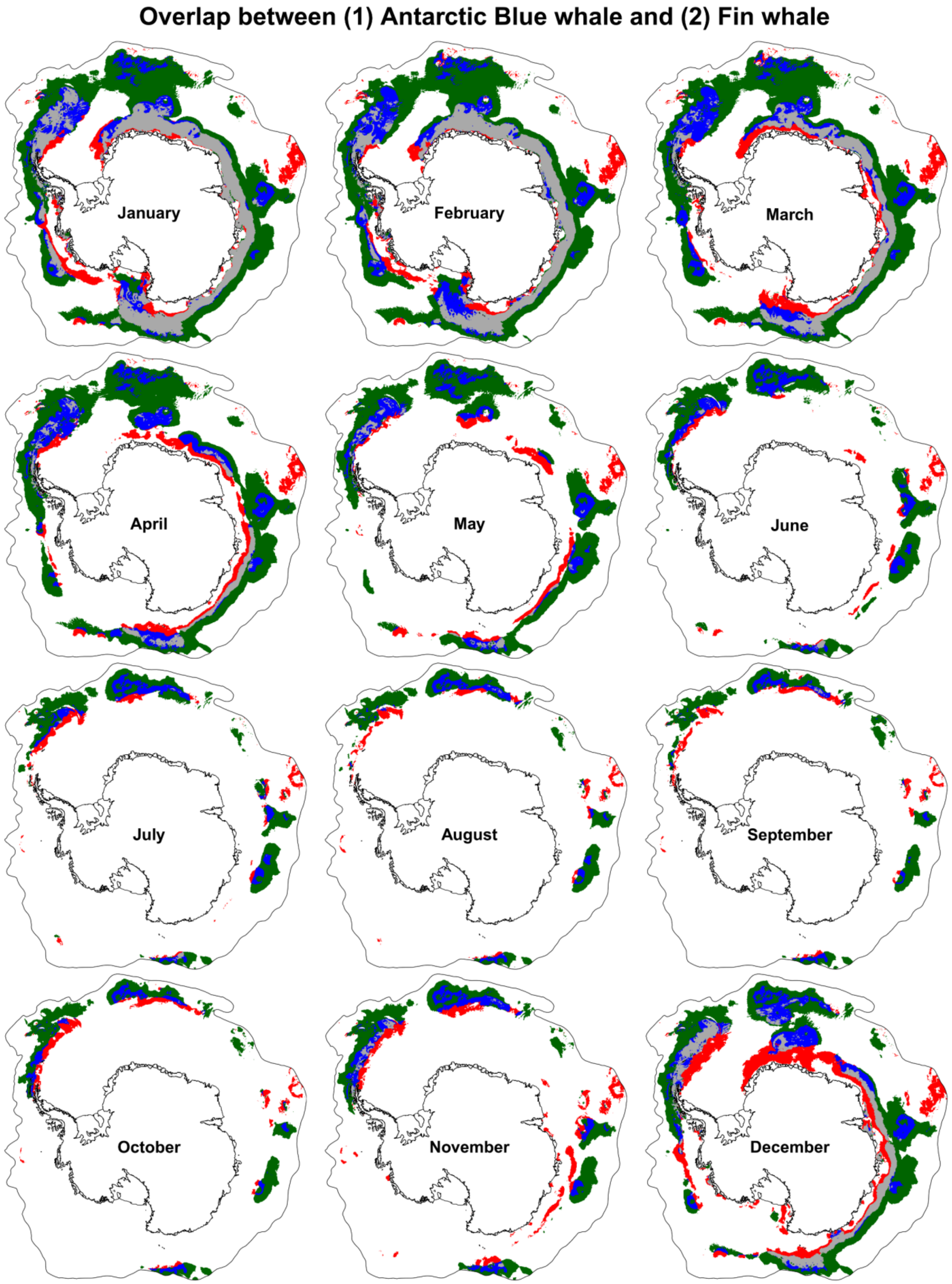
Blue: areas suitable for AMW and FW, not overlapping with the two other species' suitable habitats; **dark grey**: areas suitable for the four baleen whale species; **red**: areas suitable for AMW, but not for FW; **green**: areas suitable for FW, but not for AMW.

Figure S38 (B)



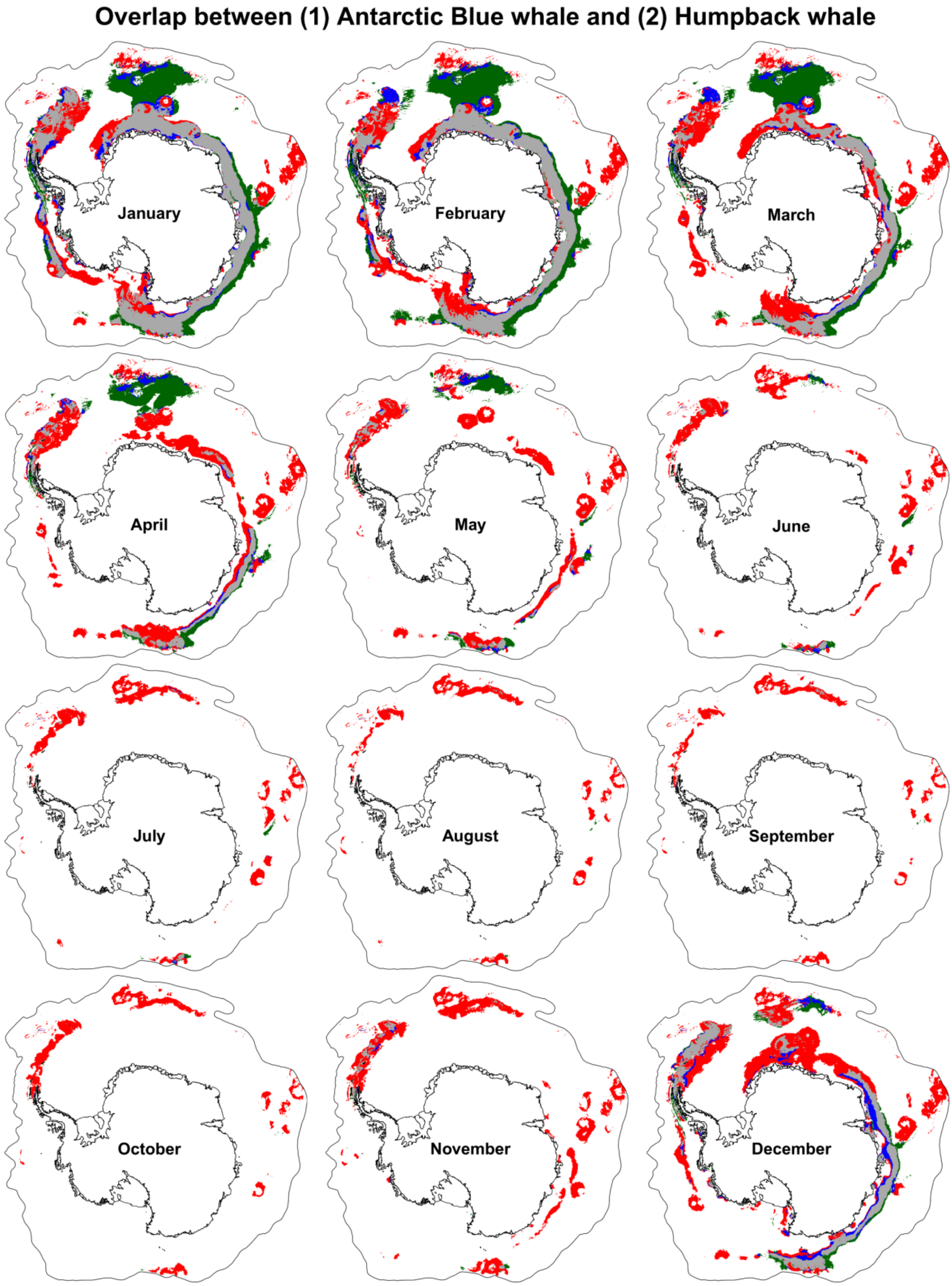
Blue: areas suitable for AMW and HW, not overlapping with the two other species' suitable habitats; **dark grey**: areas suitable for the four baleen whale species; **red**: areas suitable for AMW, but not for HW; **green**: areas suitable for ABW, but not for HW.

Figure S38 (C)



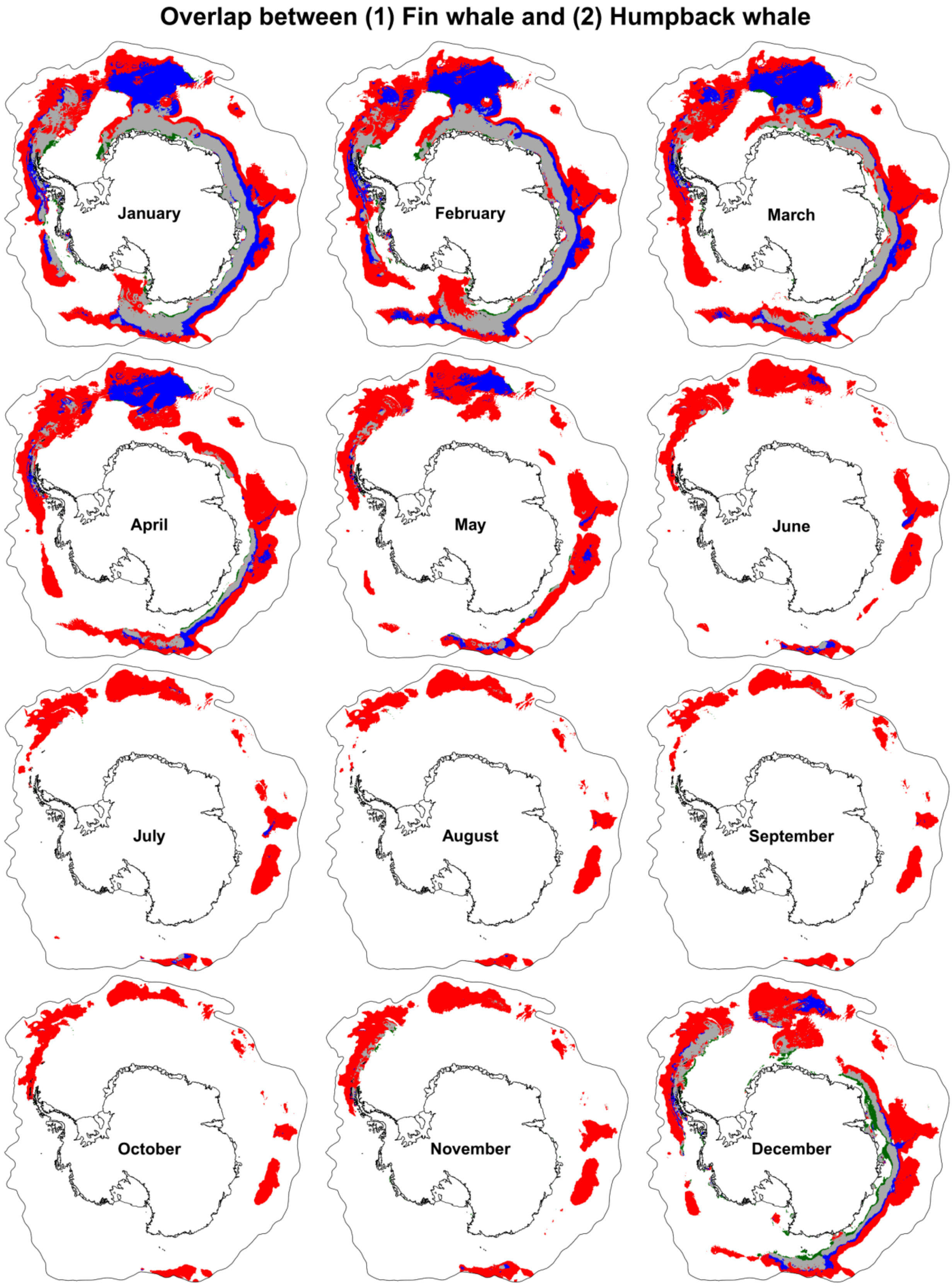
Blue: areas suitable for ABW and FW, not overlapping with the two other species' suitable habitats; **dark grey**: areas suitable for the four baleen whale species; **red**: areas suitable for ABW, but not for FW; **green**: areas suitable for FW, but not for ABW.

Figure S38 (D)



Blue: areas suitable for ABW and HW, not overlapping with the two other species' suitable habitats; **dark grey**: areas suitable for the four baleen whale species; **red**: areas suitable for ABW, but not for HW; **green**: areas suitable for HW, but not for ABW.

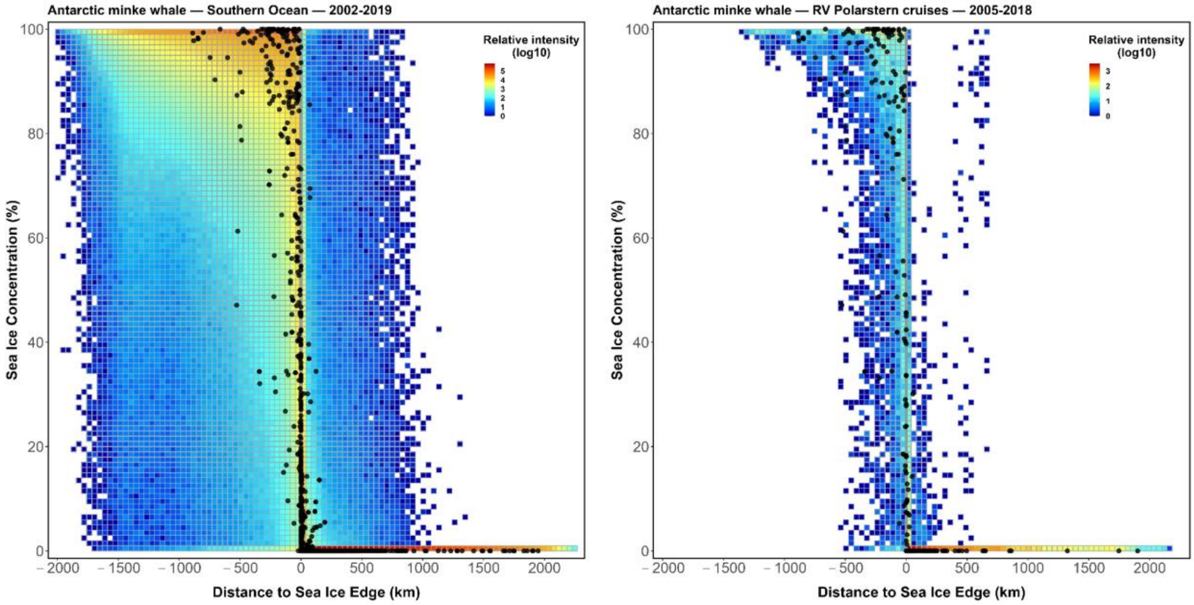
Figure S38 (E)



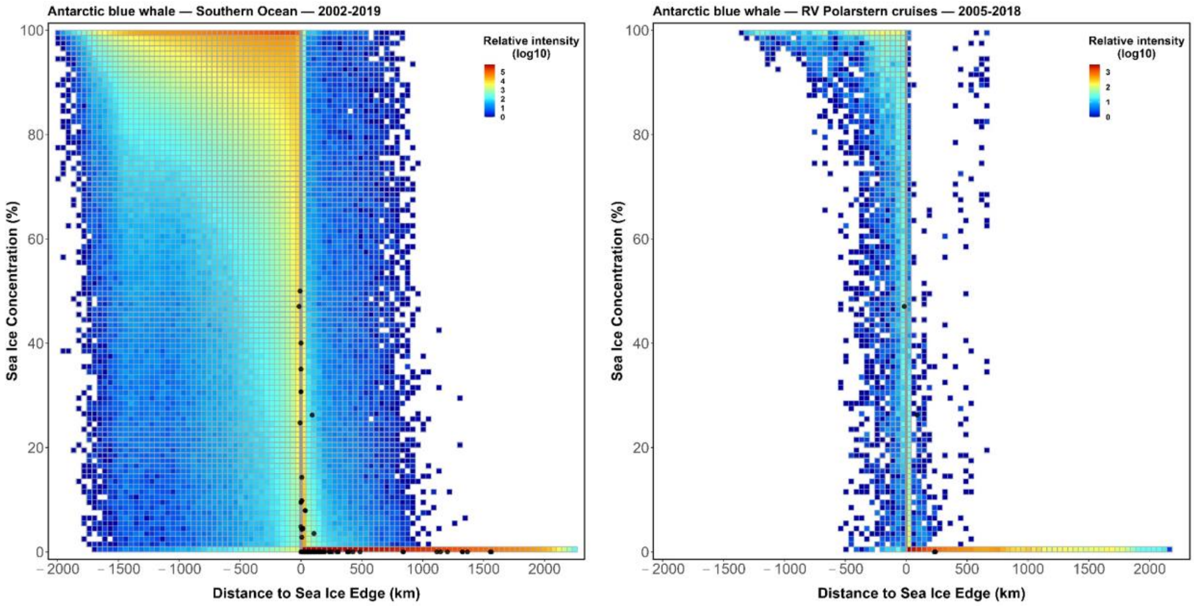
Blue: areas suitable for FW and HW, not overlapping with the two other species' suitable habitats; **dark grey**: areas suitable for the four baleen whale species; **red**: areas suitable for FW, but not for HW; **green**: areas suitable for HW, but not for FW.

Figure S38 (F)

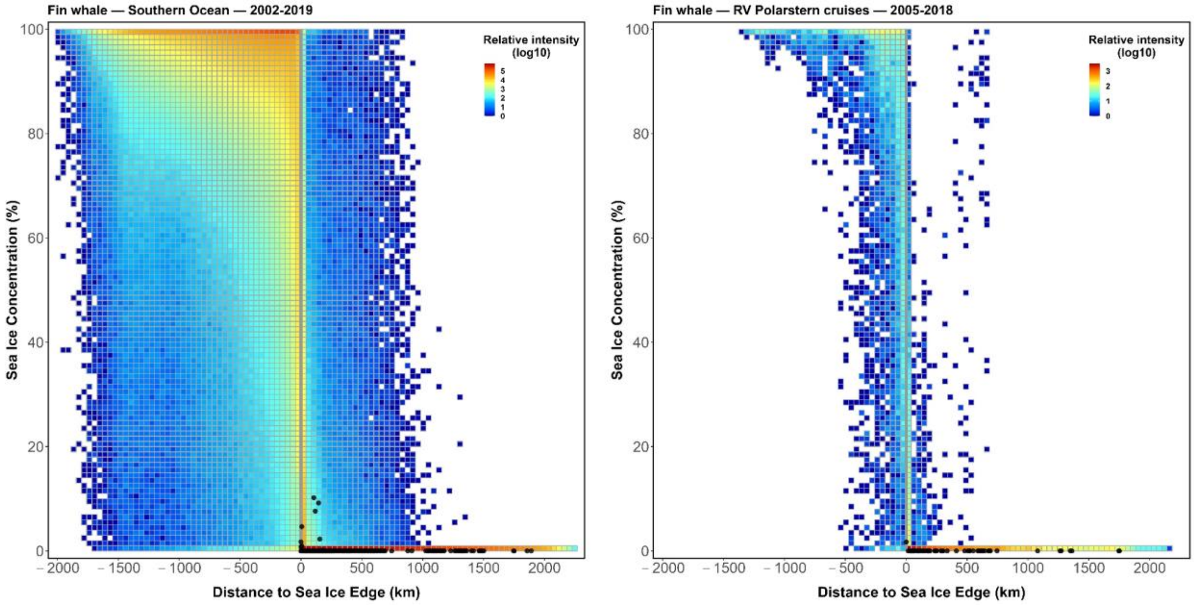
Figure S38 Monthly pairwise overlap between species suitable habitats. Each map shows the pattern of suitable habitats of each pair of species in the respective month. Blue: areas suitable for both species, but not overlapping with the two other species' suitable habitats; dark grey: areas suitable for the four baleen whale species; red: areas suitable for first, but not for the second; green: areas suitable for the second, but not for the first.



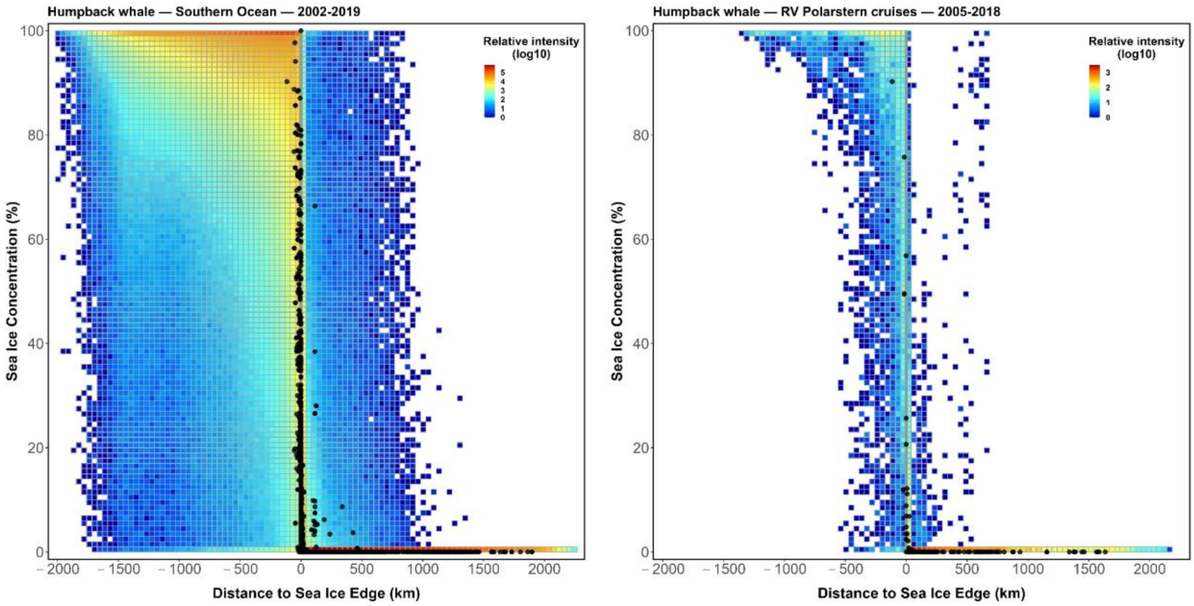
(A) Antarctic minke whales



(B) Antarctic blue whales



(C) Fin whales



(D) Humpback whales

Figure S39: Combinations of environmental conditions in the Southern Ocean (SO) for daily distance to sea ice edge (SIE; x-axis) and daily sea ice concentration (SIC; y-axis). The left panel shows combinations at daily sampled 5,000 cells (2003-2010 and 2013-2019), while the right panel shows combinations on RV Polarstern expedition tracks (2005-2018). The grid color indicates the number of cells (log scale) at each combination, representing the relative intensity of environmental conditions in both datasets (white areas are for non-existing combinations). Black points represent environmental conditions at sightings of Antarctic minke (A), Antarctic blue (B), fin (C), and humpback (D) whales: data used in this study in the left panels (including Polarstern data) and only Polarstern data in the right panels. The vertical grey line shows the location of the SIE (distance to SIE = 0 km). Background information only from limited cruise tracks (right plots) does not well represent combinations of long-term, year-round environmental conditions in the SO and is inevitably spatiotemporally biased towards the near/north of SIE, low SIC, and environmental conditions in summer. In contrast, the spatiotemporally sampled background information from the whole SO (left plot) shows less biases and broader coverage of environmental combinations. Polarstern sightings (black points) cover only part of the range of environmental conditions suitable for the species (right), while the use of crowdsourced data from other sources (left) covers a more comprehensive range of suitable environmental conditions. This disparity of environmental coverage is more evident for *HW* sightings (D).