Habitat-based density model for Globicephala spp. in the AFTT area

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This report documents the habitat-based density model for Globicephala spp. in the Atlantic Fleet Testing and Training Area (AFTT) area. Information on the first stage of the modeling approach, including classification of ambiguous sightings, detection function fitting and g(0) estimation can be found in individual taxon reports presented in Roberts et al. (2016) for the U.S. Atlantic and Gulf of Mexico.

Citation for this model: Mannocci L, Roberts JJ, Miller DL, Halpin PN (2016). Habitat-based density model for Globicephala spp. in the AFTT area. 2016-10-01. Marine Geospatial Ecology Lab, Duke University, Durham, NC.

Citation for the related publication: Mannocci L, Roberts JJ, Miller DL, Halpin PN. Extrapolating cetacean densities to quantitatively assess human impacts on populations in the high seas. In review in Conservation Biology.

1- Available data

Table 1: Effort (km) and sightings per surveyed region (CAR: Caribbean, EC: East coast, EU: European Atlantic, GM: Gulf of Mexico, MAR: Mid-Atlantic ridge). Details on the origin of sightings used in this study can be found in Table 1 of the associated publication.

Region	Effort	Sightings
CAR	24264.473	28
EC	1044357.704	909
EU	27526.342	57
GOM	194715.349	49
MAR	2424.421	15
All regions	1293288.288	1058

Table 2: Effort (km) and sightings per month.

Month	Effort	Sightings
January	77892.79	12
February	123591.37	27
March	117923.54	27
April	117929.72	45
May	149765.03	105
June	132713.99	145
July	162324.31	267
August	129660.43	231
September	71696.07	33
October	82560.18	80
November	69210.92	59
December	58019.93	27
All Months	1293288.29	1058

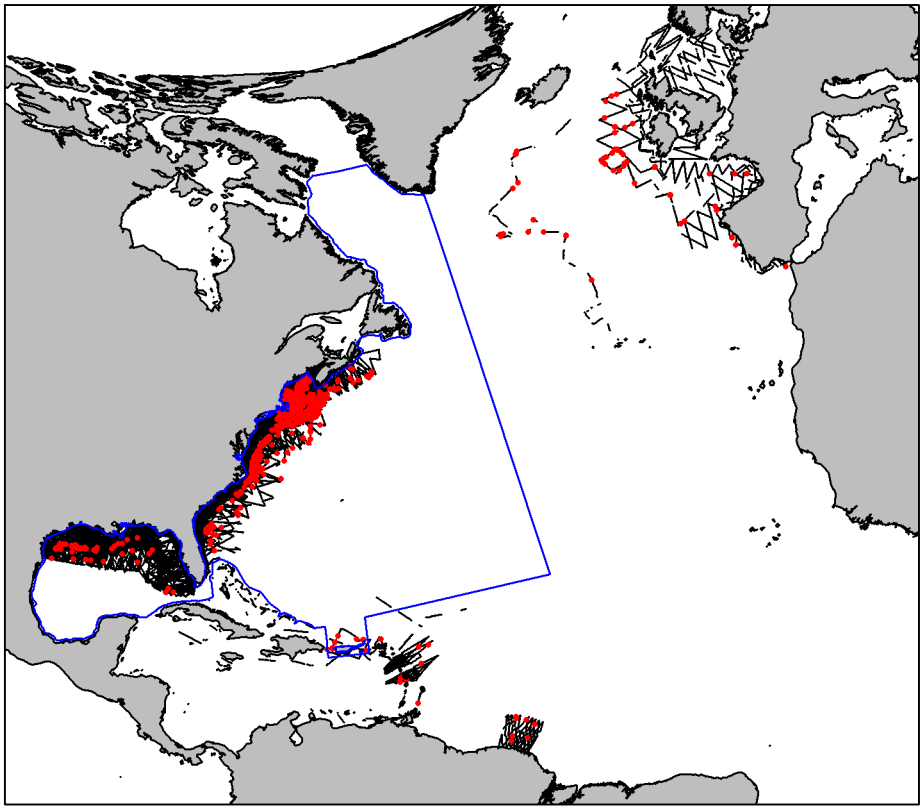


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

2- Methodological decisions

Methodological decisions reported in this section were made according to information available to us in the literature as well as feedback from a number of experts we consulted.

Modeled taxon

Globicephala spp.

Long-finned pilot whale (*Globicephala melas*) and short-finned pilot whale (*Globicephala macrorhynchus*) are not differentiable at sea, leading to a high number of ambiguous sightings in the data. In addition, these species overlap in the temperate waters of our study area (Olson 2009). We modeled the two species of pilot whales together.

Modeled season

We found no definitive evidence in the literature that pilot whales undertake extensive migrations or exhibit contrasting behaviors (e.g., feeding versus breeding) in different seasons, at the scale of our study area. Accordingly, we fitted a year-round model incorporating all available data.

Segments

In addition to segments from the western North Atlantic (east coast, Gulf of Mexico and Caribbean), we incorporated segments from the European Atlantic and the mid-Atlantic ridge to increase sighting numbers and the representativeness of offshore waters which constitute an important habitat for pilot whales (Olson 2009).

3- Best model

- **Predictors**: depth, production of epipelagic micronekton (EpiMnkPP), zooplankton production (PKPP), standard deviation of sea level anomaly (SLAStDev)
- **Model summary**:

```
##
## Family: Tweedie(p=1.471)
## Link function: log
##
## Formula:
## abundance ~ s(Depth, k = 4, bs = "ts") + s(EpiMnkPP, k = 4, bs = "ts") +
##     s(PkPP, k = 4, bs = "ts") + s(SLAStDev, k = 4, bs = "ts") +
##     offset(log(area_km2))
## <environment: 0x1ebb02ec>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -5.64723    0.07495  -75.35   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Approximate significance of smooth terms:
##               edf Ref.df      F  p-value
## s(Depth)    2.514      3 149.67  < 2e-16 ***
## s(EpiMnkPP) 1.068      3  16.40 9.48e-13 ***
## s(PkPP)     2.834      3  45.18  < 2e-16 ***
## s(SLAStDev) 2.856      3  43.57  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.00185   Deviance explained = 23.3%
## -REML = 8597.1  Scale est. = 182.94    n = 125985
```

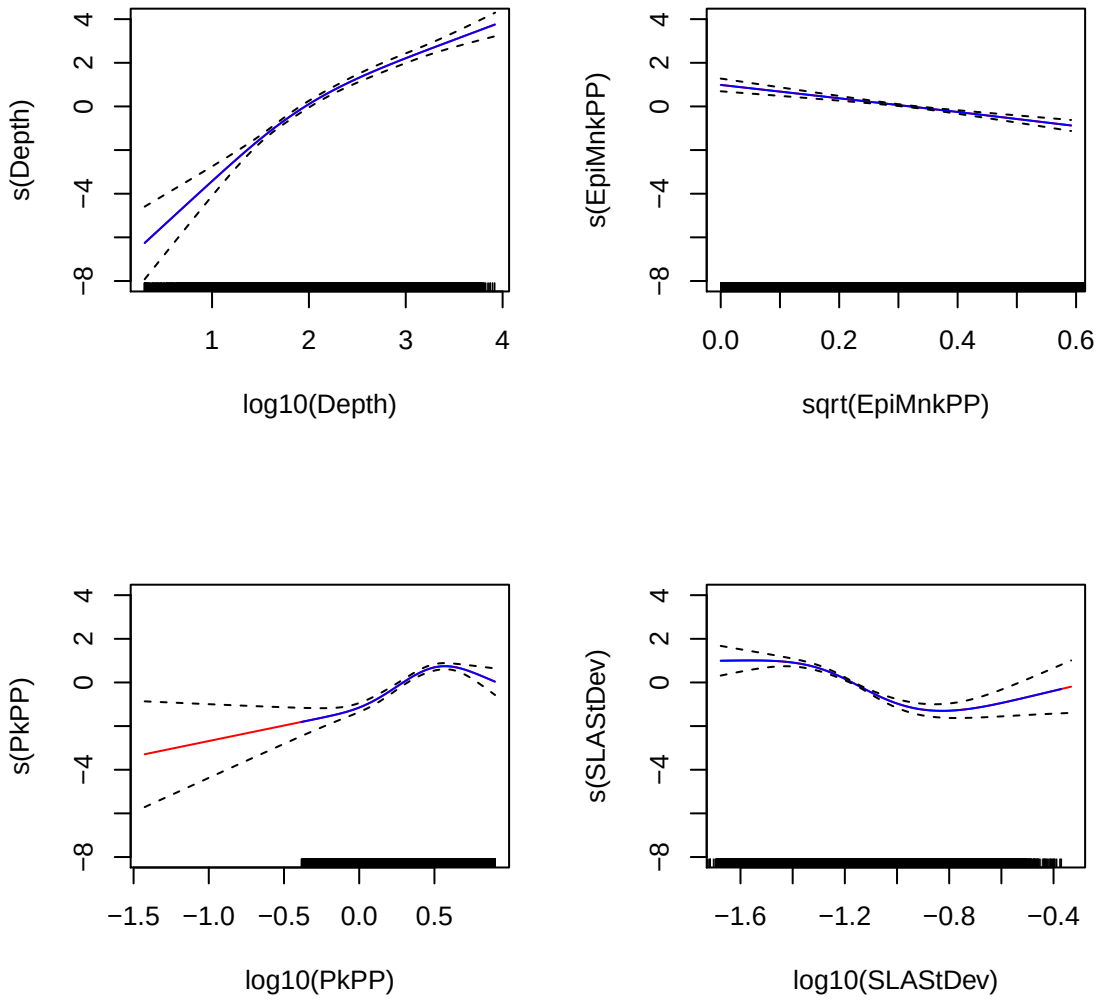


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals. The rug plot on the x-axis shows covariate values sampled in the data. Note that transformations were used for some covariates.

4- Environmental envelopes

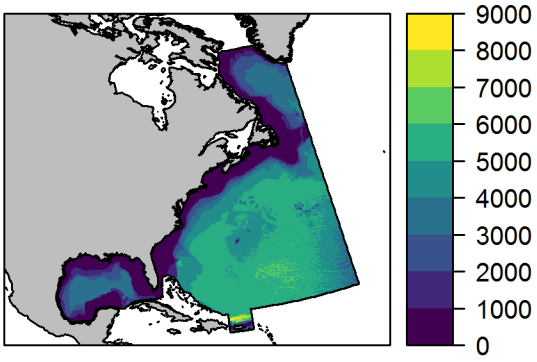
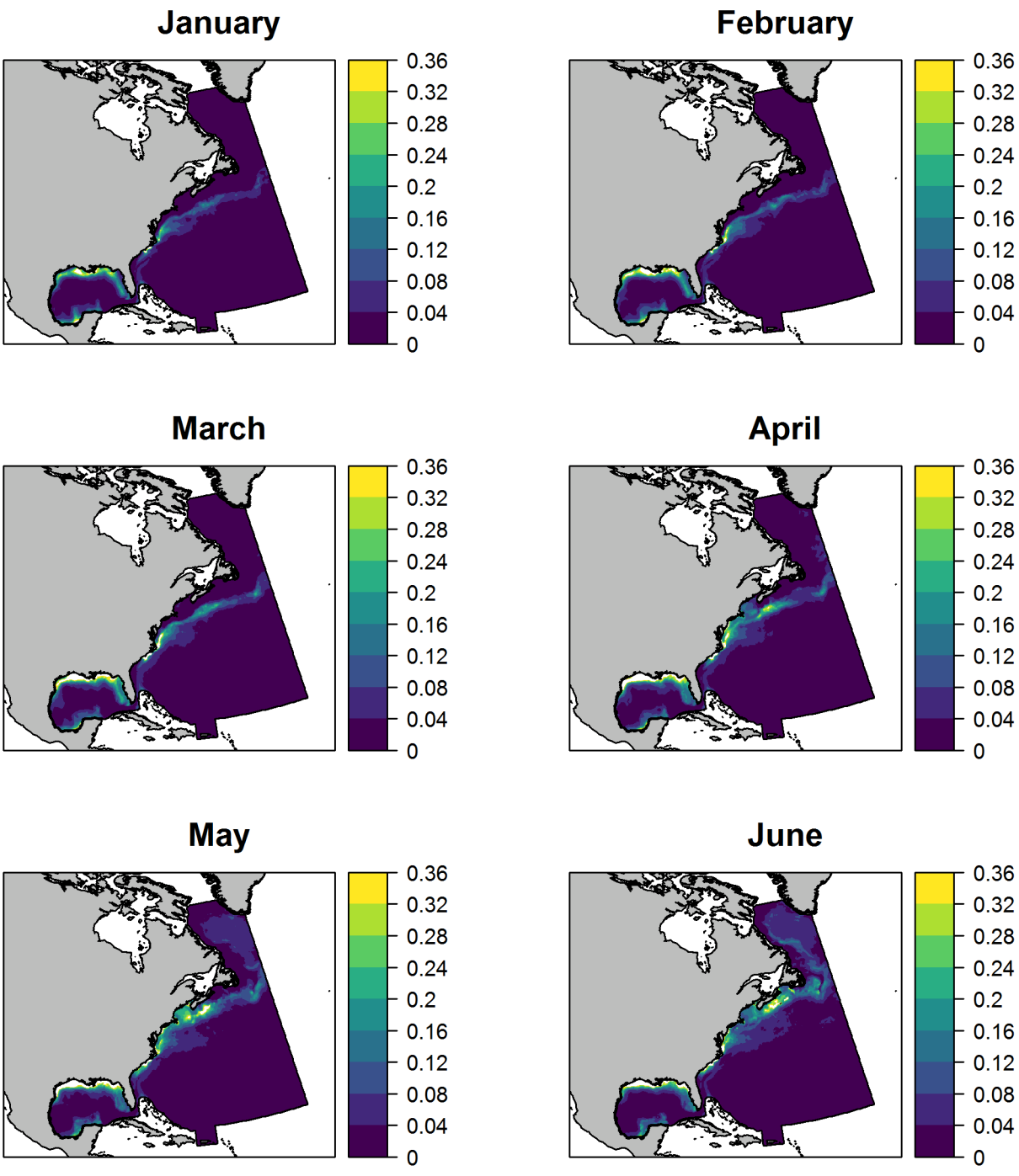


Figure 3: Environmental envelope for depth. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0

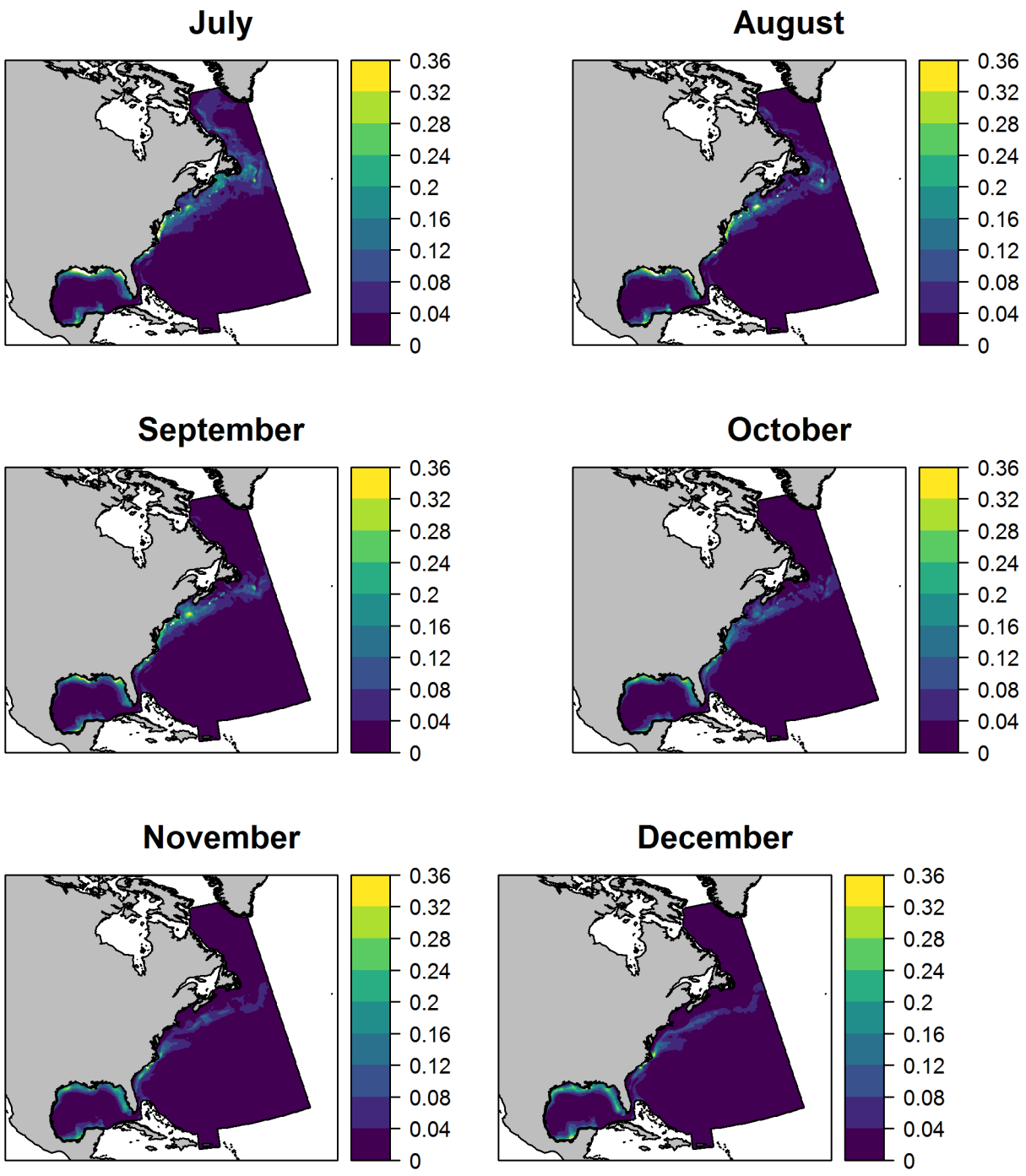
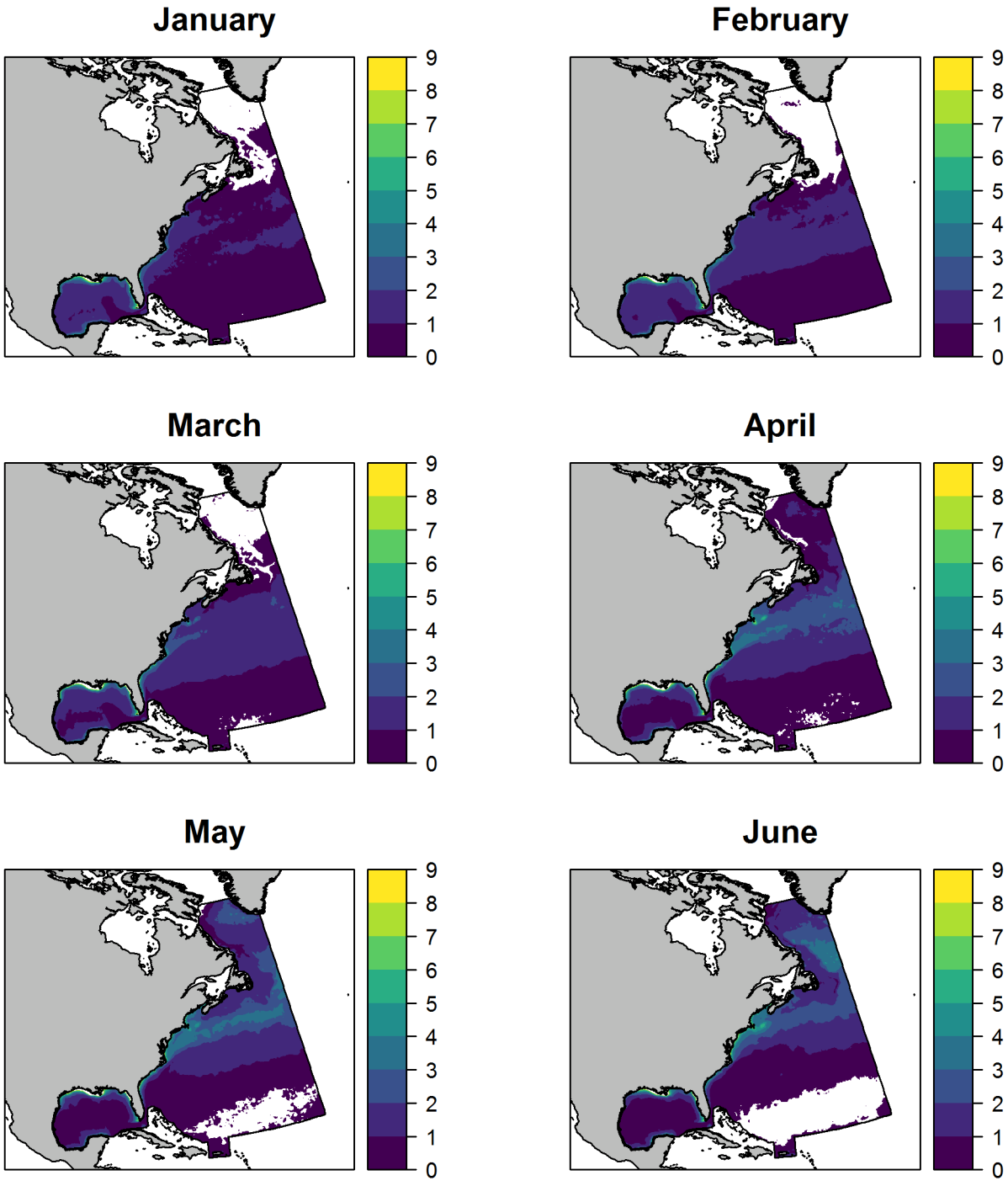


Figure 4: Monthly environmental envelopes for production of epipelagic micronekton. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
9
8
7
6
5
4
3
2
1
0

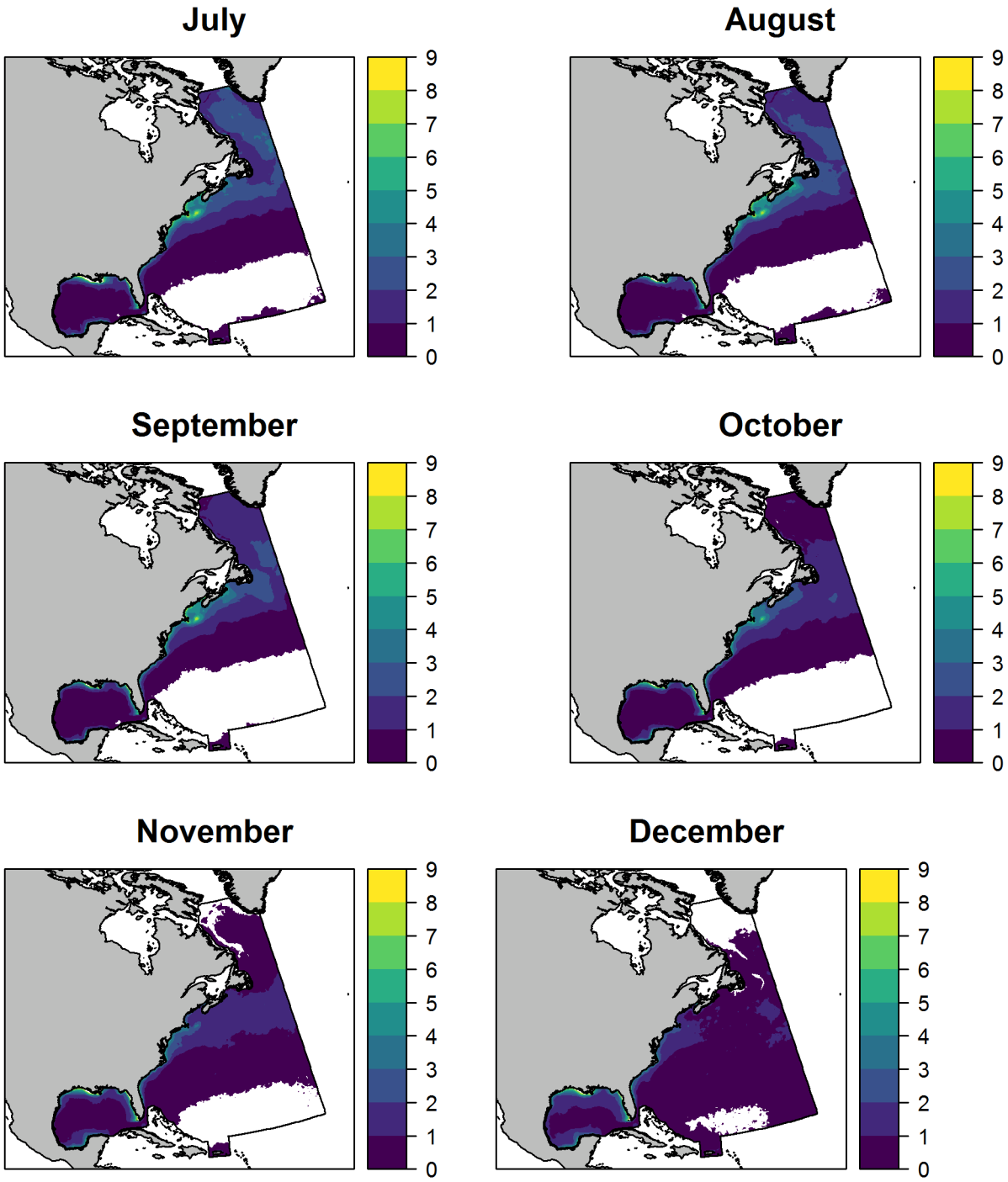
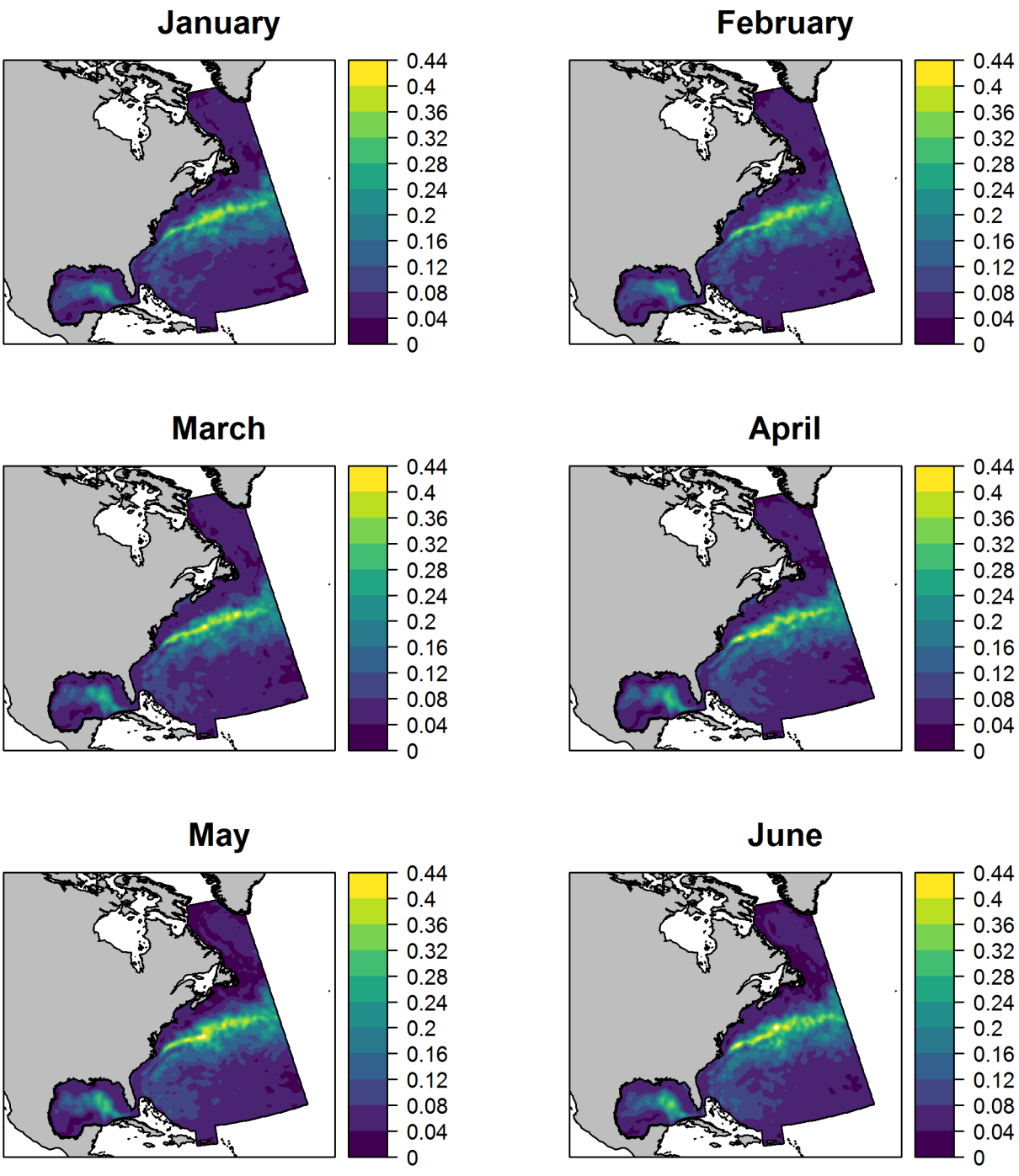


Figure 5: Monthly environmental envelopes for zooplankton production. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
0.44
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0

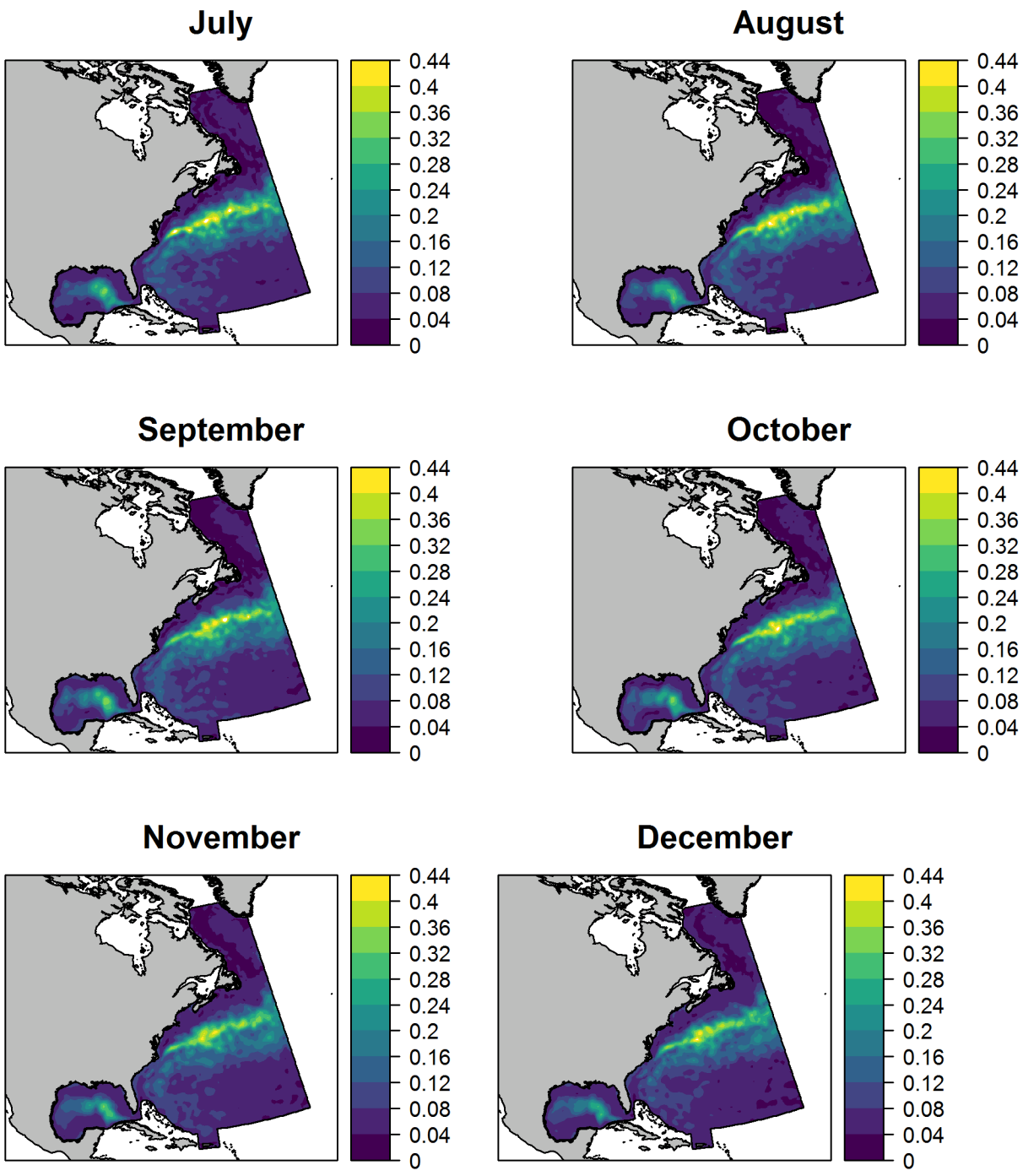


Figure 6: Monthly environmental envelopes for standard deviation of sea level anomaly. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

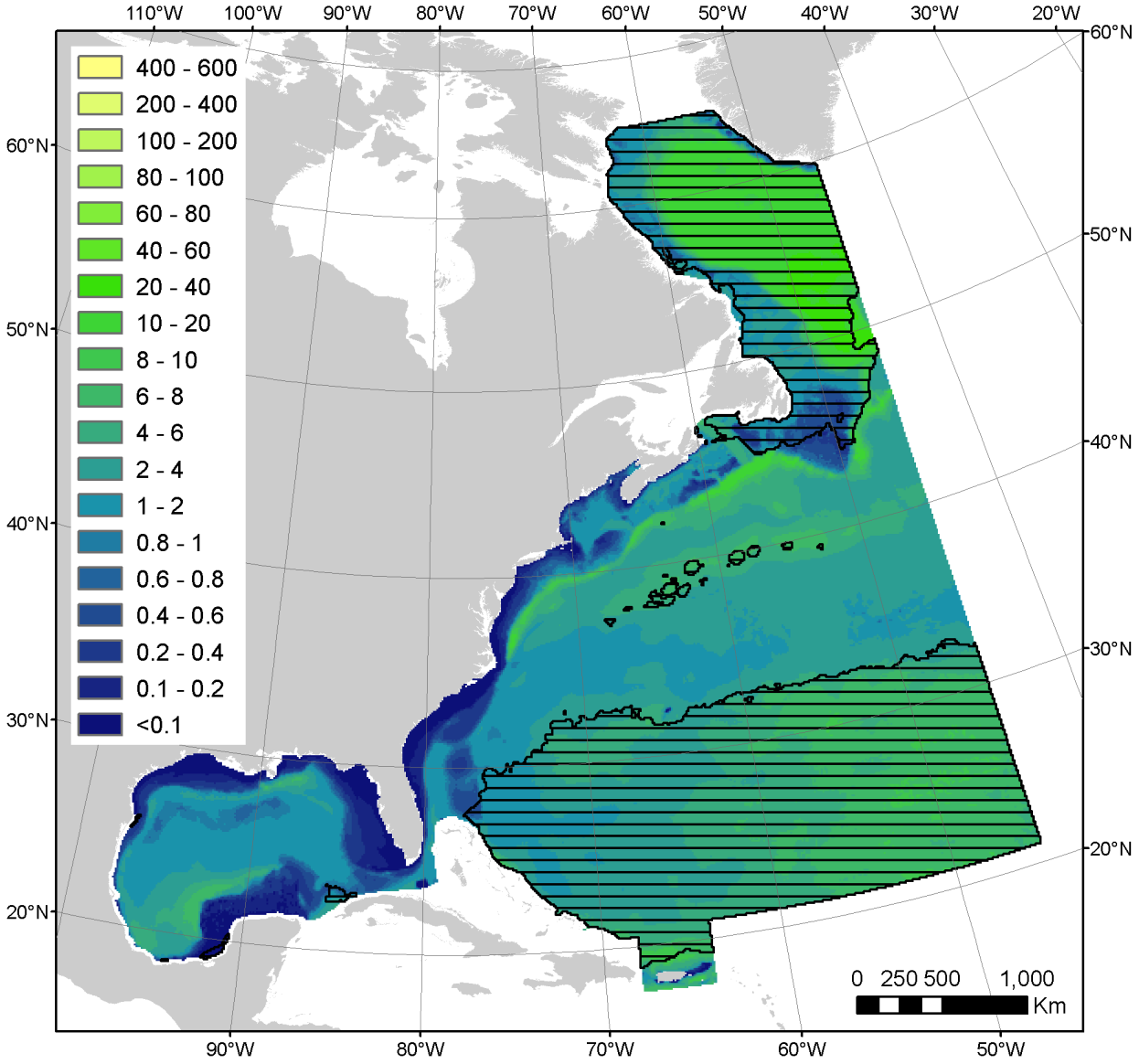


Figure 7: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

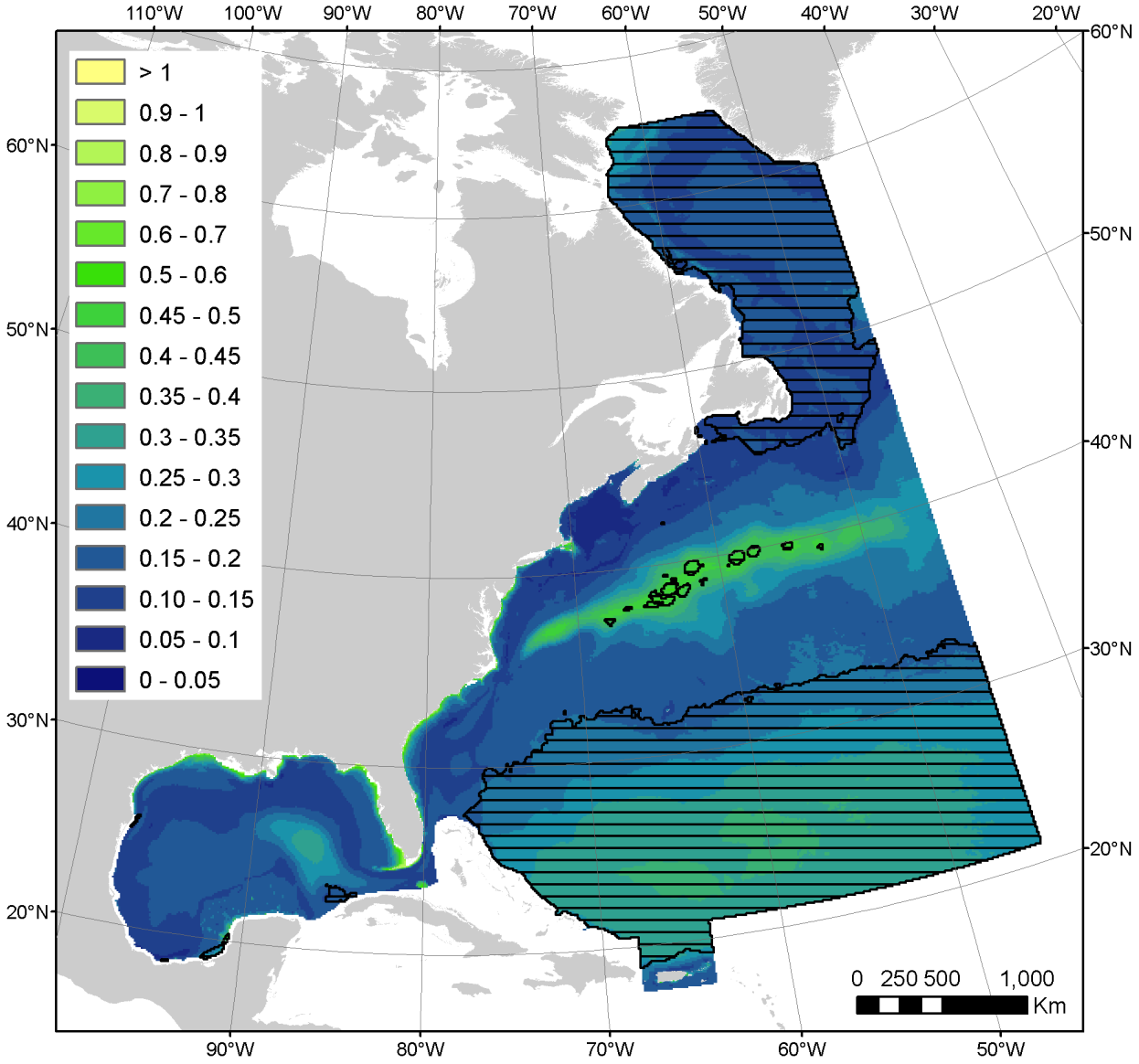


Figure 8: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

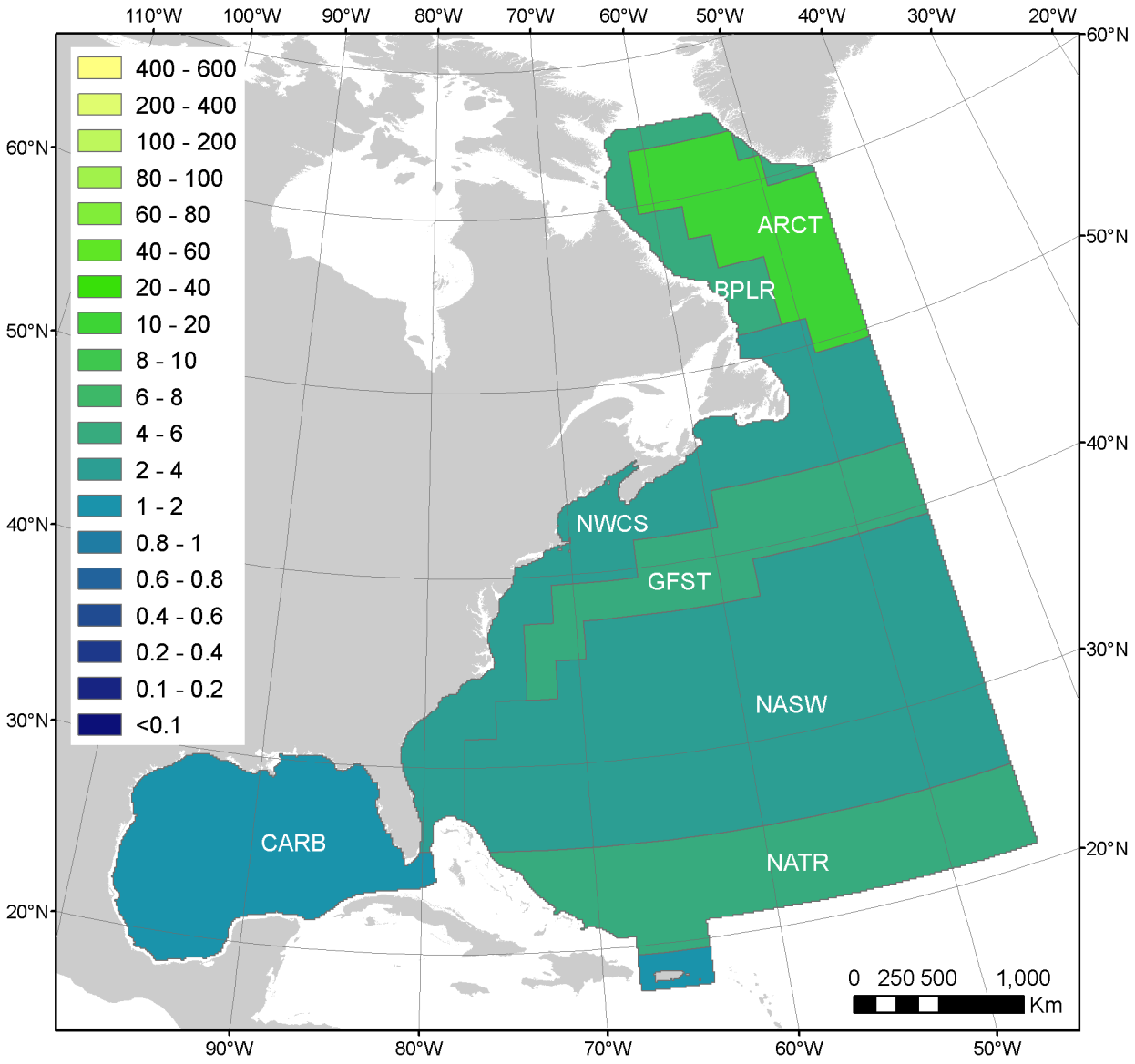


Figure 9: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic Tropical Gyral Province; NASW: North Atlantic Subtropical Gyral Province (West); NWCS: North West Atlantic Shelves Province.

8- Alternate models

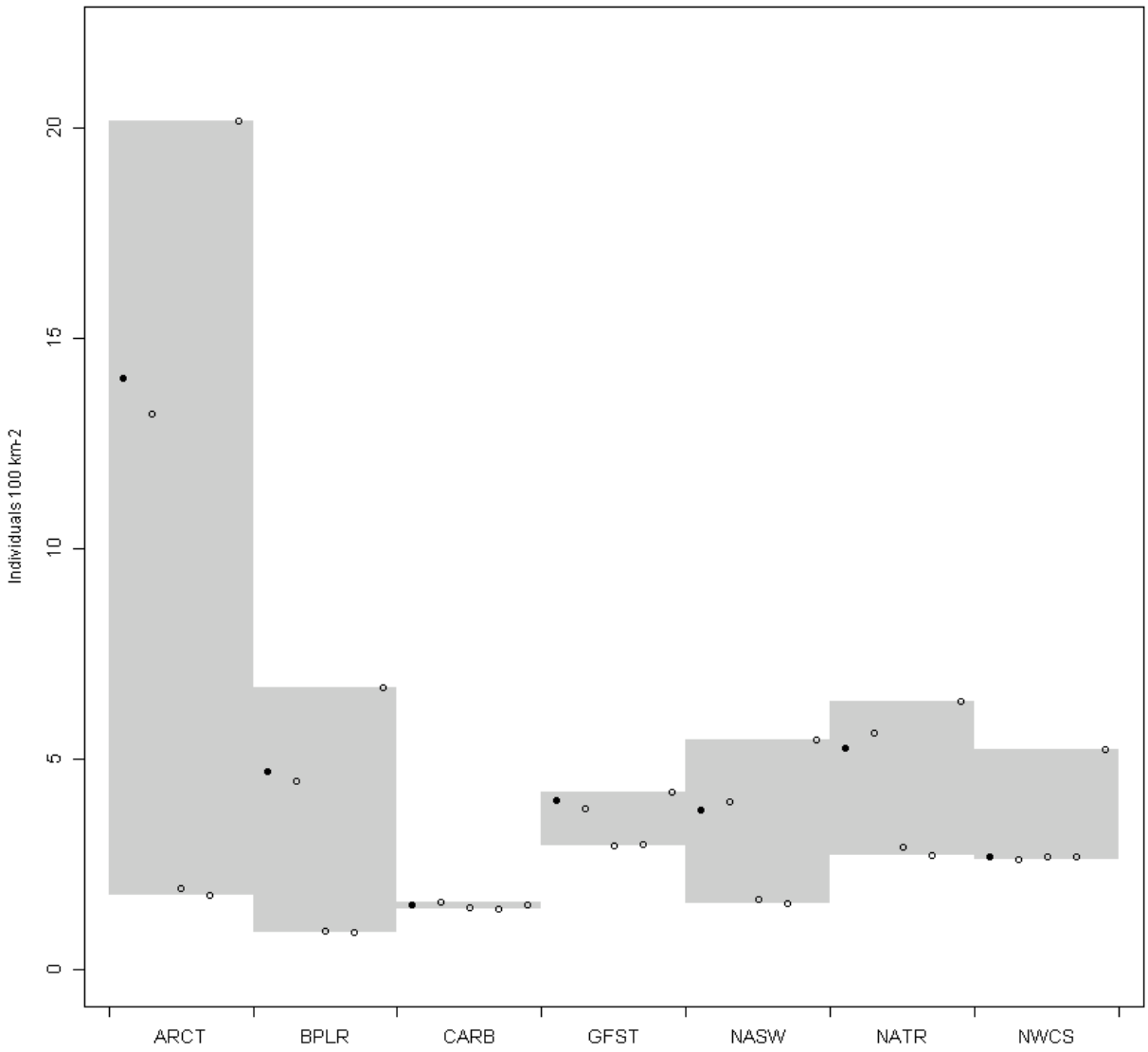


Figure 10: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to models with some support (sensu Burnham and Anderson (2002), i.e., delta AIC < 2) while hollow points correspond to models with little support (i.e., delta AIC > 2). The shaded areas indicate the range of densities predicted by the five top models for each province. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic Tropical Gyral Province; NASW: North Atlantic Subtropical Gyral Province (West); NWCS: North West Atlantic Shelves Province.

Table 3: List of the five top models with lowest AIC values. Ns: non-significant. Predictor variables: EKE: eddy kinetic energy, SLAStDev: standard error of sea level anomaly, SST: sea surface temperature, PkPP: zooplankton production, PkPB: zooplankton biomass, EpiMnkPP: epipelagic micronekton production, EpiMnkPB: epipelagic micronekton biomass, VGPM: vertically generalized production model, CHL: chlorophyll-a concentration.

Predictors				AIC	delta AIC
SLAStDev	Depth	EpiMnkPP	PkPP	122740.4	0.0
SLAStDev	Depth	EpiMnkPP	VGPM	122743.9	3.5
SLAStDev	Slope	SST	VGPM	122748.7	8.3
SLAStDev	Slope	SST	PkPP	122749.4	9.0
SLAStDev	Depth	SST	DistToFront1	122749.6	9.2

9- Residual diagnostics

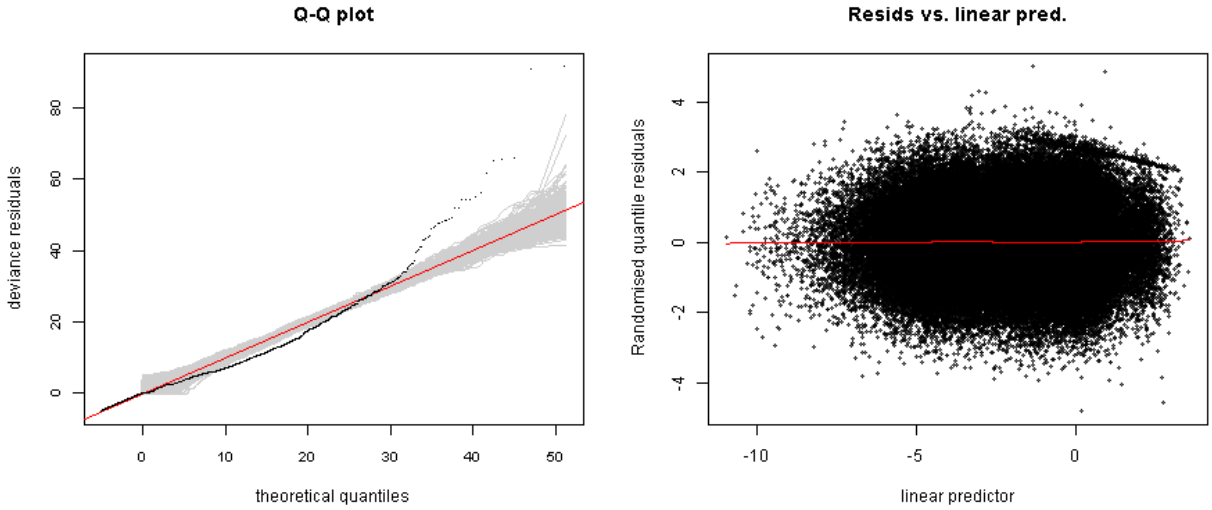


Figure 11: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates perfect agreement between residual and theoretical residual distributions. Points lying away from the red line suggest poor model fit for the corresponding quantiles. Zeros appear to the left of the Q-Q plot in alignment with the reference line. Because, by design, models were not tightly fitted to the data (see discussion of the paper), deviations from the red line may be observed. Specifically, points far above the red line for large quantiles indicate that the model underestimates high abundances observed on some segments. Right: randomized quantile residuals vs. linear predictor. A LOWESS regression is shown as a red line to illustrate any trend in the points. This plot should be generally free of any pattern. Expanding y-range indicates non-constant variance (heteroskedasticity) in the model.

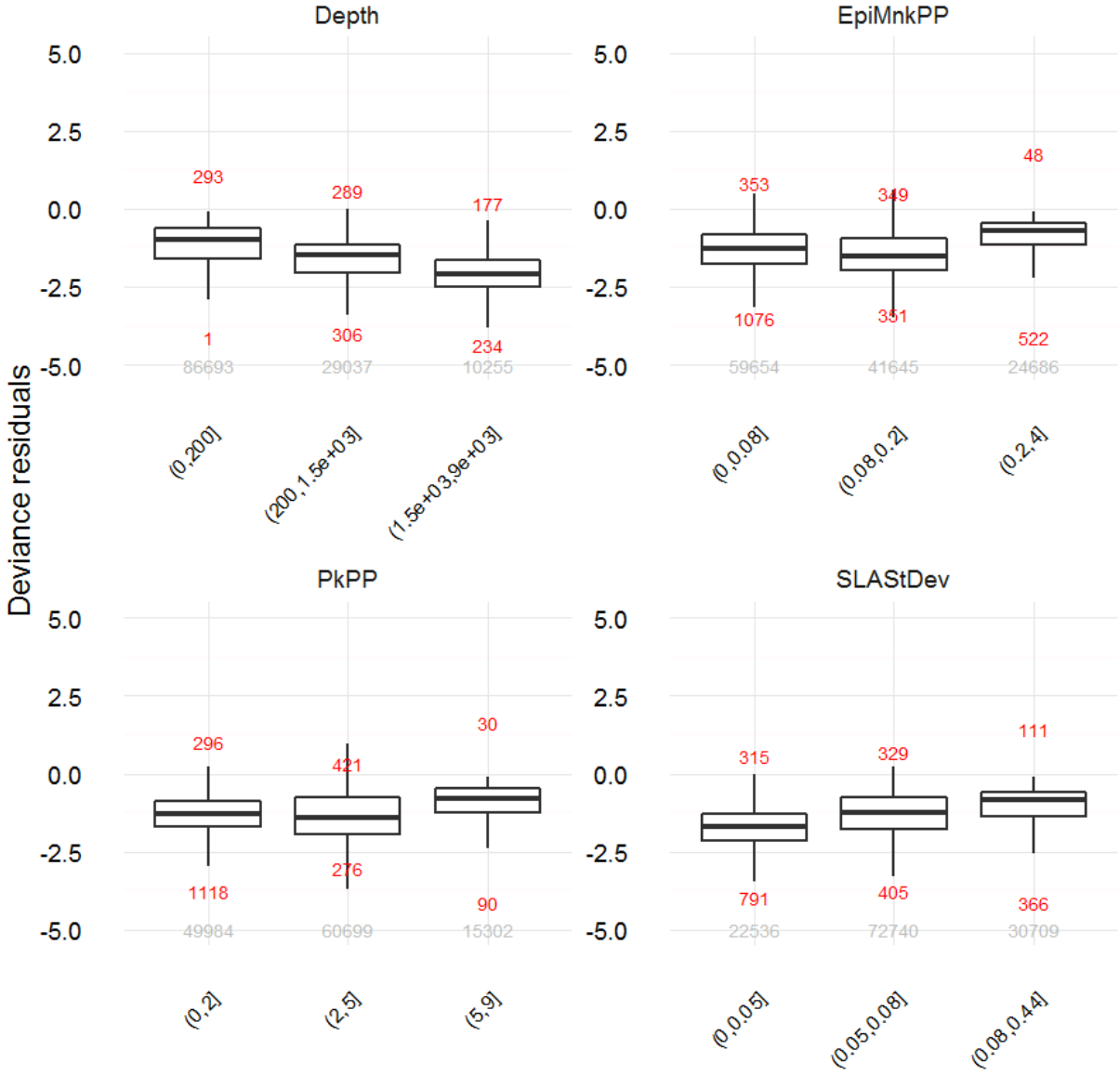


Figure 12: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers beyond the whiskers are indicated in red. Numbers of segments per bin are indicated in grey. Boxplots for the different bins of predictors should generally overlap. A boxplot having its median away from zero indicates poorer model fit for that predictor bin. Boxplots often have their medians close to zero and fewer outliers for predictor bins characterized by low abundances of the species, suggesting that model fit is generally better in low abundance areas. We believe this is an inherent feature of models applied to count data with numerous zeros.

10- Brief discussion and overall confidence in predictions

Description of confidence levels

We group taxa in three categories reflecting our relative level of confidence in predicted densities.

Level 1

This category includes tropical and warm temperate taxa for which survey data were available within most of the distributional range in the AFTT area. High/intermediate densities predicted beyond surveyed areas were supported by sightings available from OBIS-SEAMAP and the scientific literature. Very low densities predicted at northern latitudes were consistent with the described absence of these taxa. We have a reasonable confidence in predicted densities for these taxa.

Level 2

This category encompasses taxa for which a large part of the distributional range is in cold temperate and sub-polar waters. Models fitted to available survey data and extrapolated to cold temperate and sub-polar waters successfully predicted their occurrence, but predicted densities were largely speculative. The incorporation of line transect survey data from Canada and Greenland would be extremely useful to increase the reliability of predicted densities at northern latitudes. Unfortunately we were unable to obtain permission for using these data in our models. We remain hopeful that collaborations can be established in the future, and that the Canadian and Greenlandic surveys may be incorporated into a new version of our models. We have medium or low confidence in predicted densities for these taxa.

Level 3

This category includes taxa that are not known to primarily occur in cold temperate and sub-polar waters but were predicted in low/intermediate densities at higher latitudes. For these taxa, we believe predicted densities were likely overestimated at higher latitudes. However, predicted densities were supported by sightings available from OBIS-SEAMAP and the scientific literature within their core distributional range. The incorporation of line transect survey data from Canada and Greenland would be extremely useful to help correct the probable overestimation of densities at northern latitudes. We remain hopeful that collaborations can be established in the future, and that the Canadian and Greenlandic surveys may be incorporated into a new version of our models. We have medium or low confidence in predicted densities for these taxa.

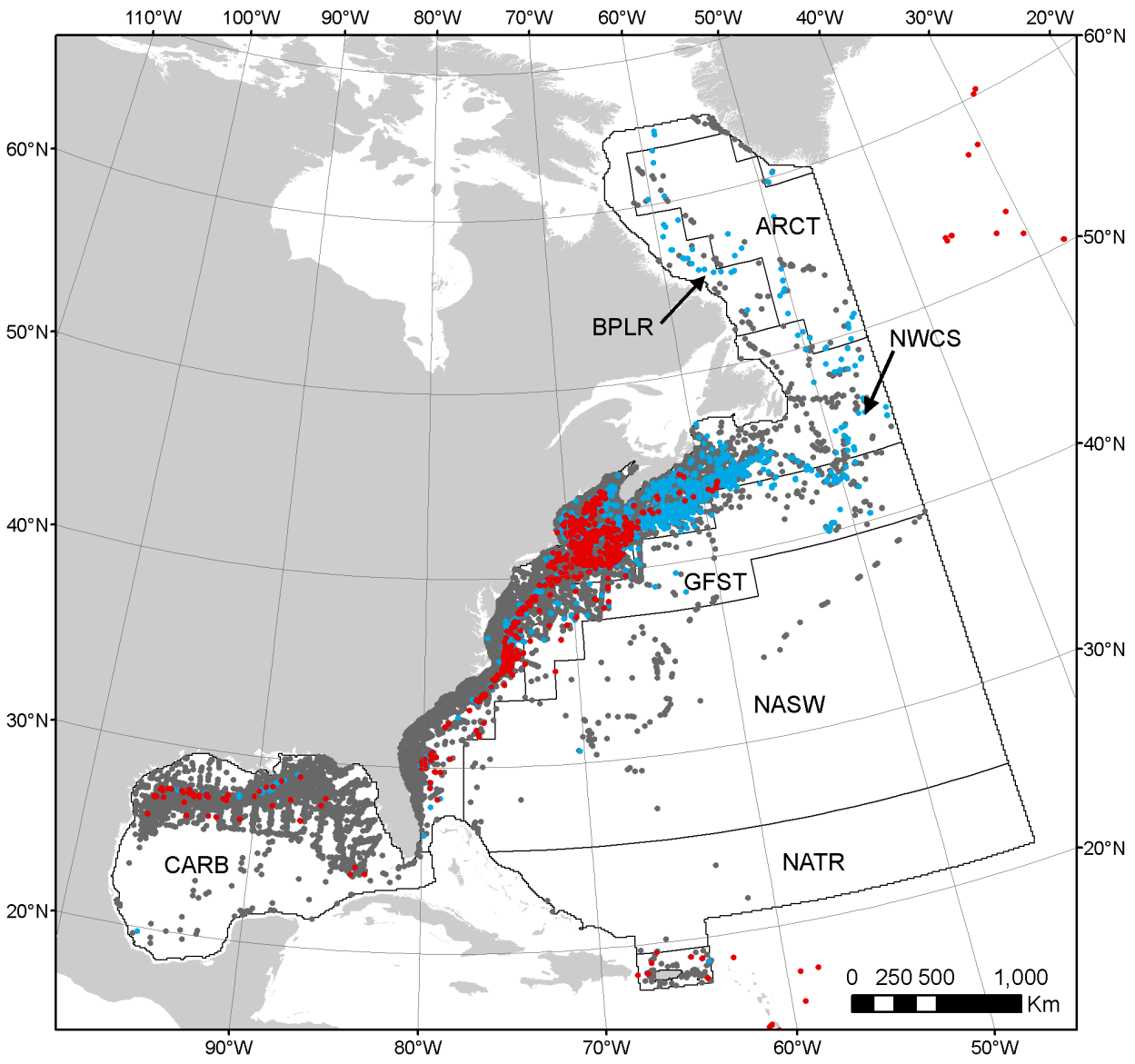


Figure 13: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other cetacean species, taken from these other datasets. Blue and grey points were extracted from OBIS-SEAMAP (accessible at http://seamap.env.duke.edu/) (Halpin et al. 2009); citations for individual datasets are provided at the end of this report. Longhurst's biogeographical provinces are shown as polygons. Dense patches of grey points without red or blue points suggest locations where the taxon of interest may be absent, under the presumption that observers who reported other cetacean taxa would have reported this one if sighted. However, important caveats apply: the map does not quantify observation effort, which was not available for all datasets and was very difficult to standardize across disparate sources (e.g., scientific surveys, whale watching logs, opportunistic sightings). The spatial distribution of effort was highly heterogeneous in both space and time. Only openly accessible datasets were considered; other cetacean datasets are known to exist for the AFTT area but have not been released for public use (e.g., the 2007 Trans North Atlantic Sightings Survey (TNASS) in Canada). The presumption that grey dots imply absence may not always hold; for example, if effort conducted in that area was directed towards particular species, sightings of our taxon of

interest may not have been recorded.

General

A relatively large sample size of 1058 sightings was available to fit the habitat-based density model (we note that 85% of the sightings were from surveys in the east coast region). The lowest AIC model included depth, zooplankton production, standard error of sea level anomaly and micronekton production (listed in decreasing order of importance according to F-scores) and had an explained deviance of 23.3%. This model was the only supported model sensu Burnham and Anderson (2002) (Table 3). All top five models included standard error of sea level anomaly. Predicted densities from the top five models were very similar in the CARB and GFST provinces (Figure 10). They differed by factors 2-3 in the NASW, NATR and NWCS provinces. Predicted densities were the most variable in the ARCT and BPLR provinces where they roughly differed by factors 10 and 7 respectively. When examining these results, it should be kept in mind that the second, third, fourth and fifth models had a delta AIC >2 and therefore little statistical support sensu Burnham and Anderson (2002).

Predictions appeared consistent with the wide geographic range of pilot whales with an occurrence in both nearshore and pelagic waters (Olson 2009). Short-finned pilot whales generally inhabit tropical and subtropical waters whereas long-finned pilot whales are typically found in cold temperate waters. Both species overlap in temperate waters (approximately between 35 and 40°N) within our study area (Olson 2009).

We now discuss the quality of predictions per biogeographic province by comparing them with available literature and observations from OBIS-SEAMAP.

Boreal polar (BPLR) and Atlantic Arctic (ARCT) provinces

Little survey effort was available to support the relatively high predicted densities in the ARCT province and the intermediate predicted densities in the BPLR province. Nonetheless, predictions were compatible with sightings from OBIS-SEAMAP and the scientific literature.

Sightings of long-finned pilot whales were reported in OBIS-SEAMAP off Canada and West Greenland as far north as 62°N (Figure 13). Long-finned pilot whales were sighted on 3 occasions off Labrador during the Canadian TNASS line transect survey in summer 2007 (Lawson and Gosselin 2009) (sightings not contributed to OBIS-SEAMAP and therefore, not shown on Figure 13).

Despite a sparse observation effort, several dozens of sightings were reported in OBIS-SEAMAP in offshore waters of the ARCT province (Figure 13). Numerous sightings of long-finned pilot whales have also been recorded during summer surveys in Greenland where they are known to prefer deep offshore waters (Heide-Jørgensen et al. 2008, Hansen and Heide-Jørgensen 2013). Together, these results seemed to support the high predicted densities in the ARCT province.

We warn that extrapolation beyond predictor ranges occurred throughout the BPLR and ARCT provinces. Consequently, predicted densities are largely speculative and should be interpreted with extreme caution.

North West Atlantic shelves (NWCS) and Gulf Stream (GFST) provinces

Highest densities of pilot whales were predicted on the continental slope from North Carolina to Newfoundland.

Medium to high predicted densities on the Scotian shelf and continental slope, where survey effort was limited compared to further south, seemed corroborated by large amounts of sightings reported in OBIS-SEAMAP (Figure 13). High predicted densities on the continental slope southeast of Newfoundland were also supported by a concentration of sightings (Figure 13). During the Canadian TNASS survey, long-finned pilot whales were sighted on 36 occasions on the Scotian shelf and on 7 occasions southeast of Newfoundland (Lawson and Gosselin 2009) (sightings not shown on Figure 13). Long-finned pilot whales were regularly seen in summer near the Gully canyon, on the Scotian shelf edge (Hooker et al. 1999).

Extrapolation beyond predictor ranges occurred in the central part of the GFST province and therefore, predicted densities should be viewed with due caution. We believe predictions in the Gulf Stream are not unrealistic as they were supported by multiple pilot whale sightings shown on Figure 13.

North Atlantic tropical gyral (NATR) and North Atlantic subtropical gyral (NASW) provinces

Extrapolation to lower zooplankton production occurred throughout the NATR and NASW provinces, leading to predicted densities that are largely speculative. One sighting was reported in OBIS-SEAMAP in the NASW province and none was reported in the NATR province (but observation effort was extremely sparse) (Figure 13).

Wells et al. (2013) released a short-finned pilot whale equipped with a satellite tag near the Florida Keys. The animal travelled north to the Blake Plateau, then to offshore waters of the North Atlantic gyre, before moving south to the Greater Antilles

In our opinion, predictions in these provinces are not totally unrealistic since pilot whales have pelagic habitats and presumably range throughout the North Atlantic Ocean (Olson 2009).

Caribbean (CARB) province

Predicted densities were on average lower in the CARB province compared to other provinces.

In the Gulf of Mexico, highest pilot whale densities were predicted in offshore waters beyond the continental shelf. The short-finned pilot whale is considered a common cetacean species in the offshore Gulf of Mexico (Jefferson and Schiro 1997). Twenty six opportunistic sightings of short-fined pilot whales were reported in the southwestern Gulf of Mexico, mainly on the outer continental shelf and the slope, roughly corresponding to an area where the model predicted relatively high densities (Ortega-Ortiz 2002). A sighting in the southwestern Gulf of Mexico was also reported in OBIS-SEAMAP (Figure 13).

Model predictions near Puerto Rico and the Virgin islands appeared compatible with opportunistic sightings of short-finned pilot whales both on the shelf and in offshore waters (Mignucci-Giannoni 1998).

Overall confidence: level 2

Available survey data did not span the wider range of pilot whales (specifically, long-finned pilot whales) in cold temperate waters. The model successfully predicted their occurrence in northern waters but predicted densities were largely speculative as they were derived from extrapolation beyond predictor ranges. Nevertheless, predicted densities in northern offshore waters did not seem implausible given the numerous offshore sightings and the described pelagic habits of long-finned pilot whales. Incorporating line transect survey data from Canada and Greenland would be critical to increase the reliability of predicted densities in northern waters of the AFTT area. Unfortunately, we were unable to obtain permission for using these data in our model. We remain hopeful that collaborations can be established in the future, and that the Canadian and Greenlandic surveys may be incorporated into a new version of our models. We re-iterate that extrapolation beyond predictor ranges occurred at high latitudes and in the North Atlantic gyre and that predicted densities should be interpreted with extreme caution.

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