Habitat-based density model for harbor porpoise in the AFTT area

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This report documents the habitat-based density model for Harbor porpoise 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 Harbor porpoise 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
EC	1044357.70	1901
EU	27526.34	280
All regions	1071884.05	2181

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

Month	Effort	Sightings
January	71406.04	11
February	96993.70	30
March	98664.69	100
April	105121.39	186
May	107303.24	369
June	117542.82	200
July	140391.18	397
August	110040.12	763
September	52584.62	46
October	57619.14	36
November	60008.94	22
December	54208.17	21
All Months	1071884.05	2181

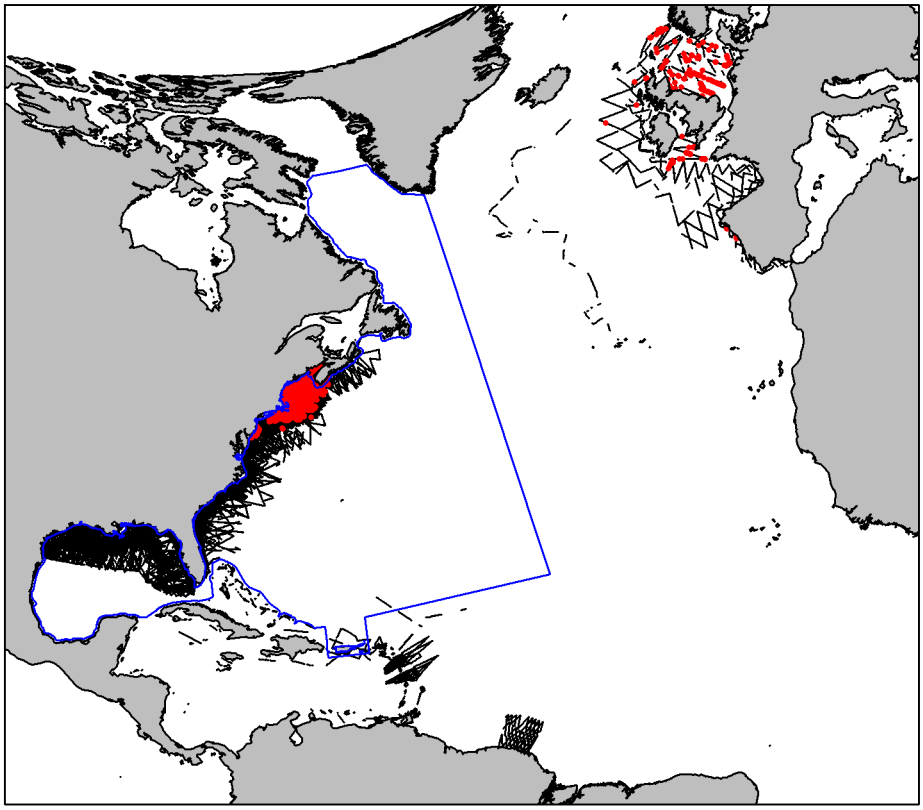


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

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

Harbor porpoise (*Phocoena phocoena*)

Modeled season

Seasonal movements of harbor porpoises have been reported for some locations (e.g., the Gulf of Maine/Bay of Fundy; Palka et al. 1996), but there is no definitive evidence that they undertake large migrations or exhibit contrasting behaviors (e.g., feeding versus breeding) in different seasons, at the scale of our study area. Therefore, we fitted a year-round model.

Segments

Because moderately rough seas can cause a dramatic decrease in harbor porpoise detections, and consistent with other density modeling studies (e.g., Hammond et al. 2013), we only used segments with a Beaufort Sea state of 2 or less to fit the model. Incorporating segments from the European Atlantic resulted in very low predicted densities in offshore waters of the AFTT area. This seemed inconsistent with the offshore occurrence of harbor porpoises suggested by numerous sightings (Teilmann and Dietz 1998) and bycatch records (Stenson and Reddin 1994, Palka et al. 1996). Accordingly, we included segments from the western North Atlantic only.

Special treatment in the Gulf of Mexico

Since there were no harbor porpoises sighted during the Gulf of Mexico surveys and the species is described as absent from the Gulf of Mexico (Jefferson and Schiro 1997), we assigned zero densities to the entire Gulf of Mexico (the model predicted very low densities).

3- Best model

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

```
##
## Family: Tweedie(p=1.394)
## Link function: log
##
## Formula:
## abundance ~ s(Depth, k = 4, bs = "ts") + s(EpiMnkPP, k = 4, bs = "ts") +
##     s(PkPB, k = 4, bs = "ts") + s(SLAStDev, k = 4, bs = "ts") +
##     offset(log(area_km2))
## <environment: 0x1b2cc6f0>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -9.9379     0.7836  -12.68   <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)    2.952      3  48.951  < 2e-16 ***
## s(EpiMnkPP) 2.781      3  15.922 4.57e-11 ***
## s(PkPB)     2.911      3 139.025  < 2e-16 ***
## s(SLAStDev) 1.962      3   9.011 3.85e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.0338   Deviance explained = 46.5%
## -REML = 8027.4  Scale est. = 41.255    n = 45539
```

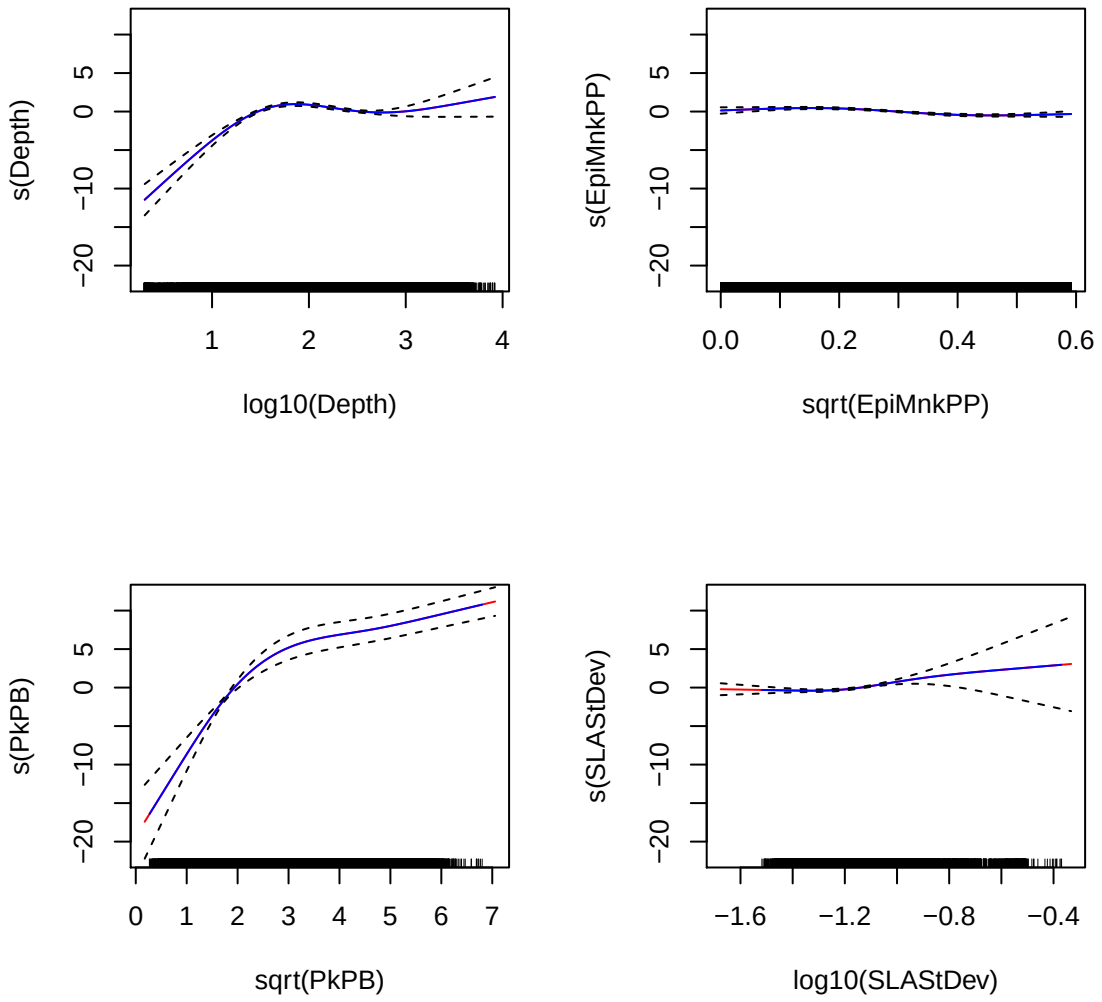


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals. 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

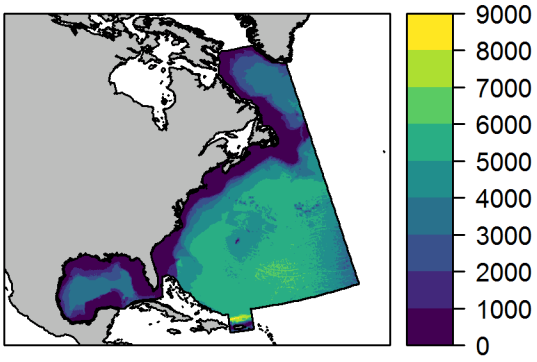
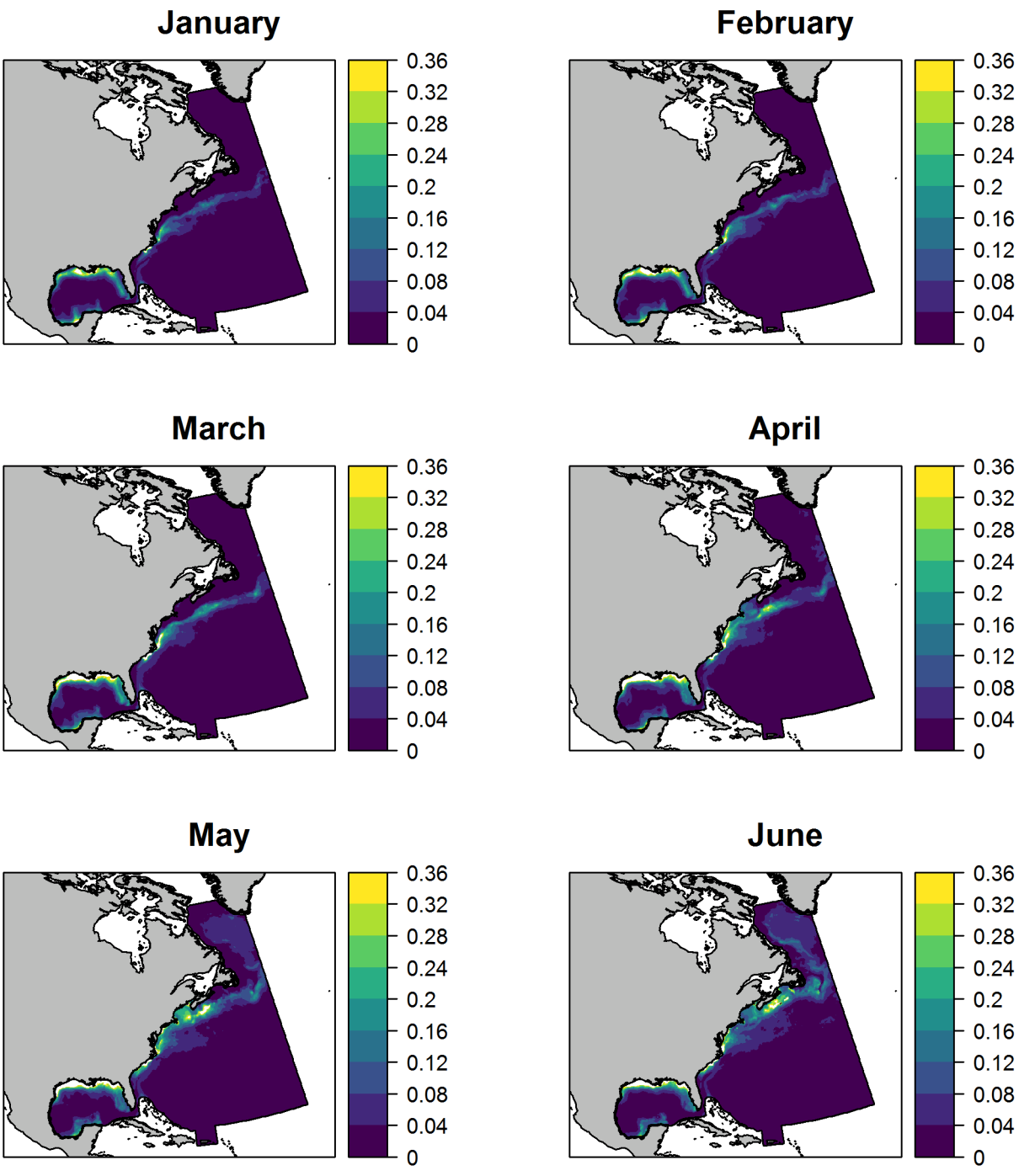


Figure 3: Environmental envelope for depth. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

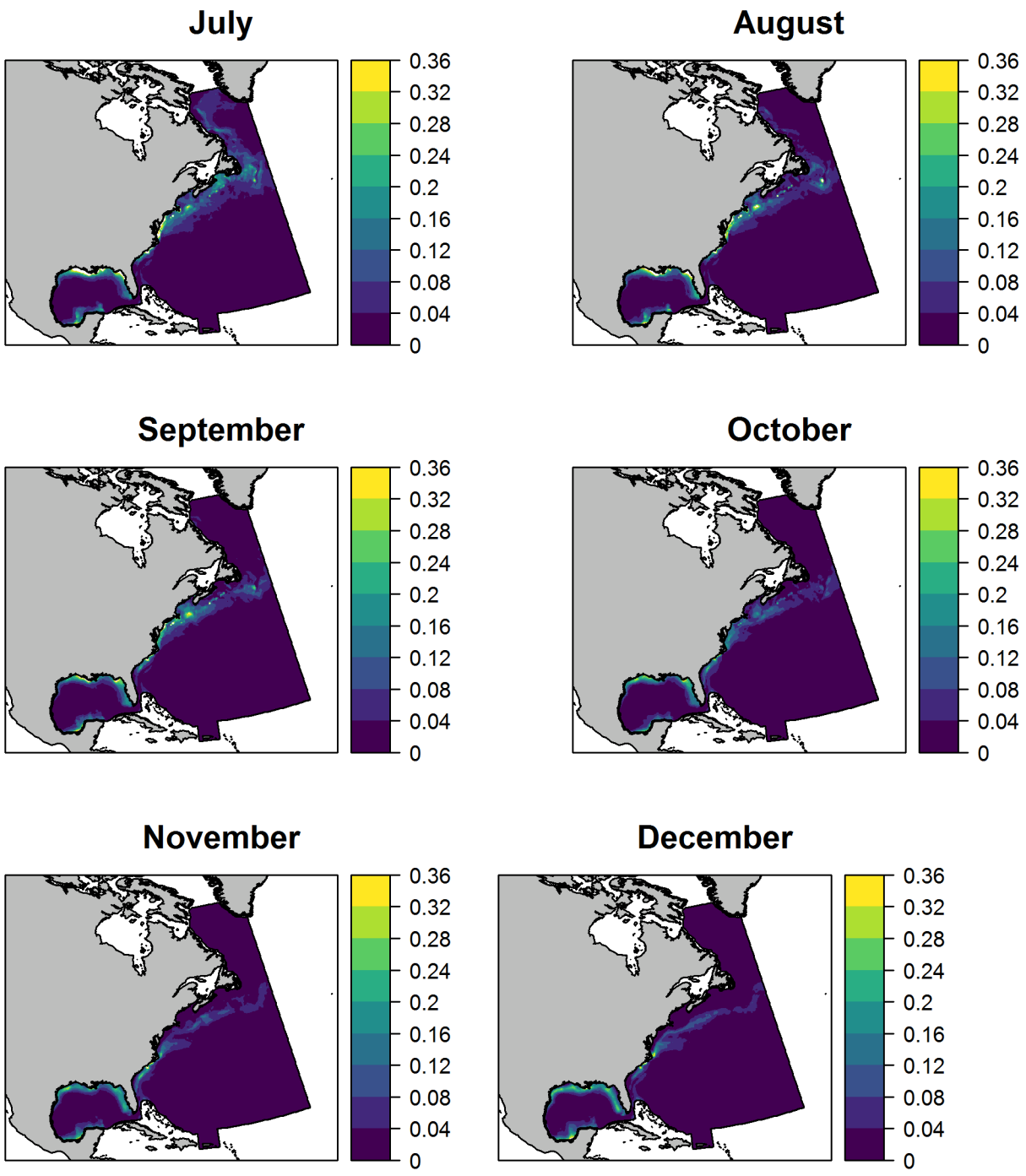
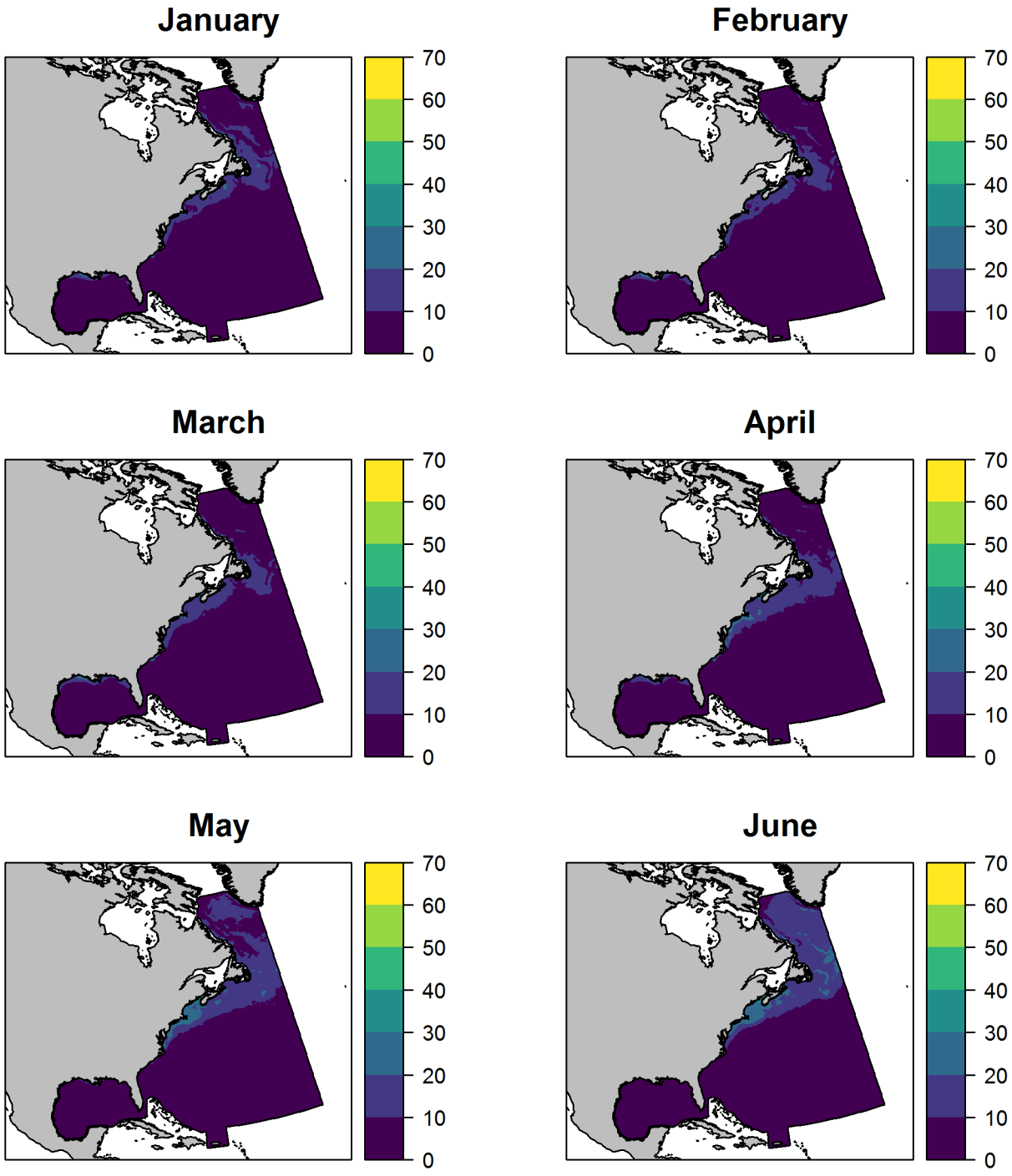


Figure 4: Monthly environmental envelopes for production of epipelagic micronekton. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
70
60
50
40
30
20
10
0

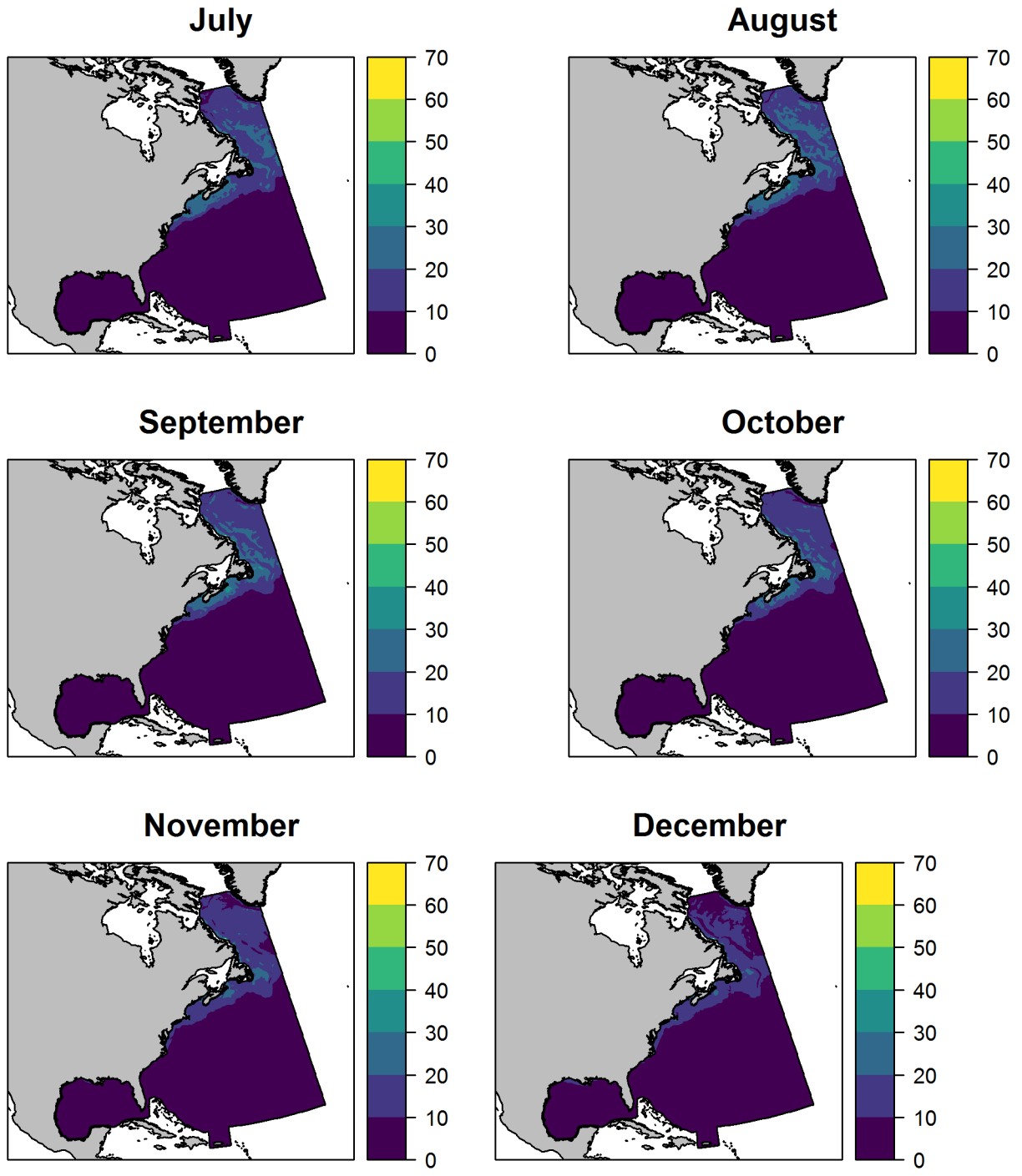
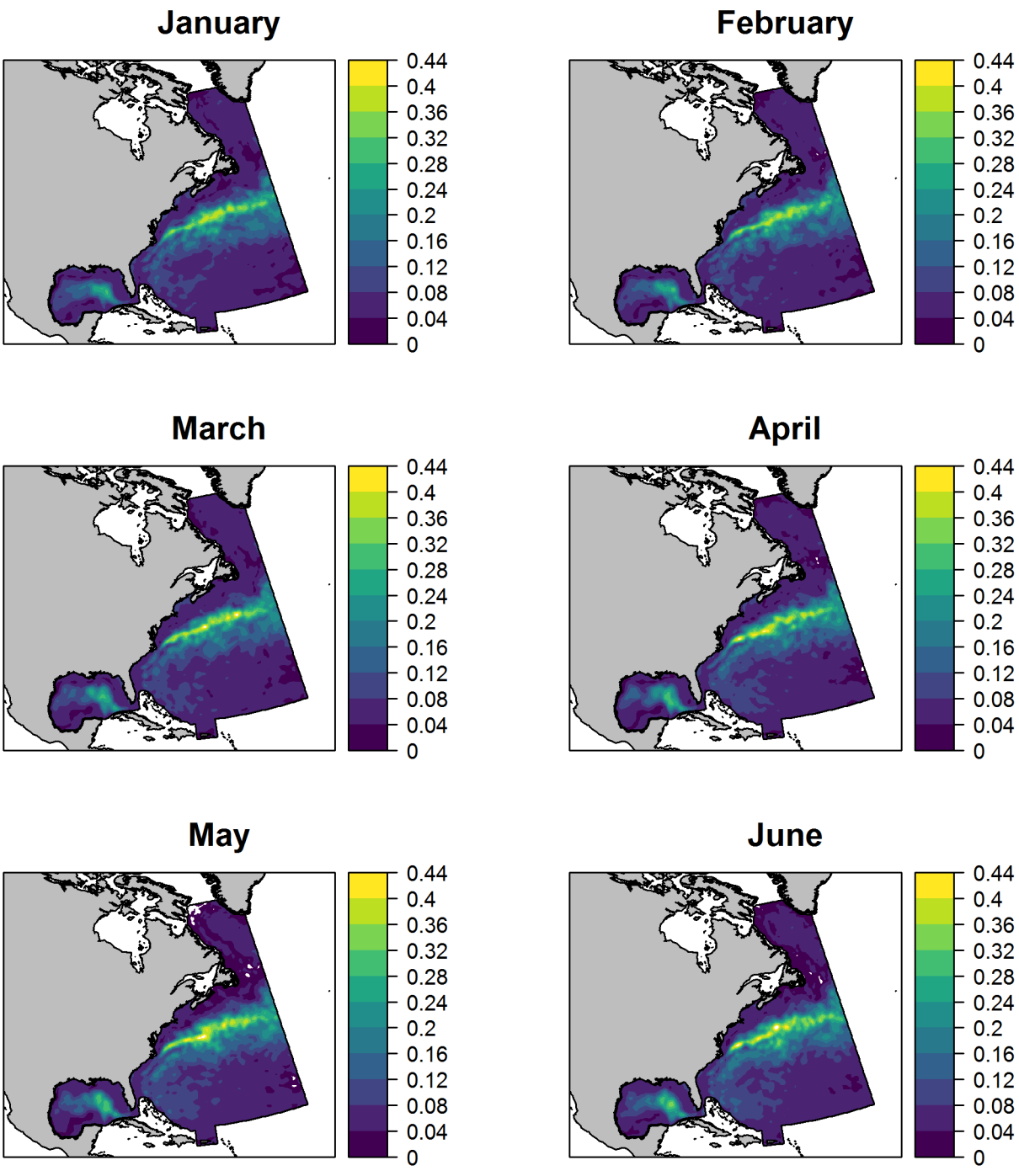


Figure 5: Monthly environmental envelopes for zooplankton biomass. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

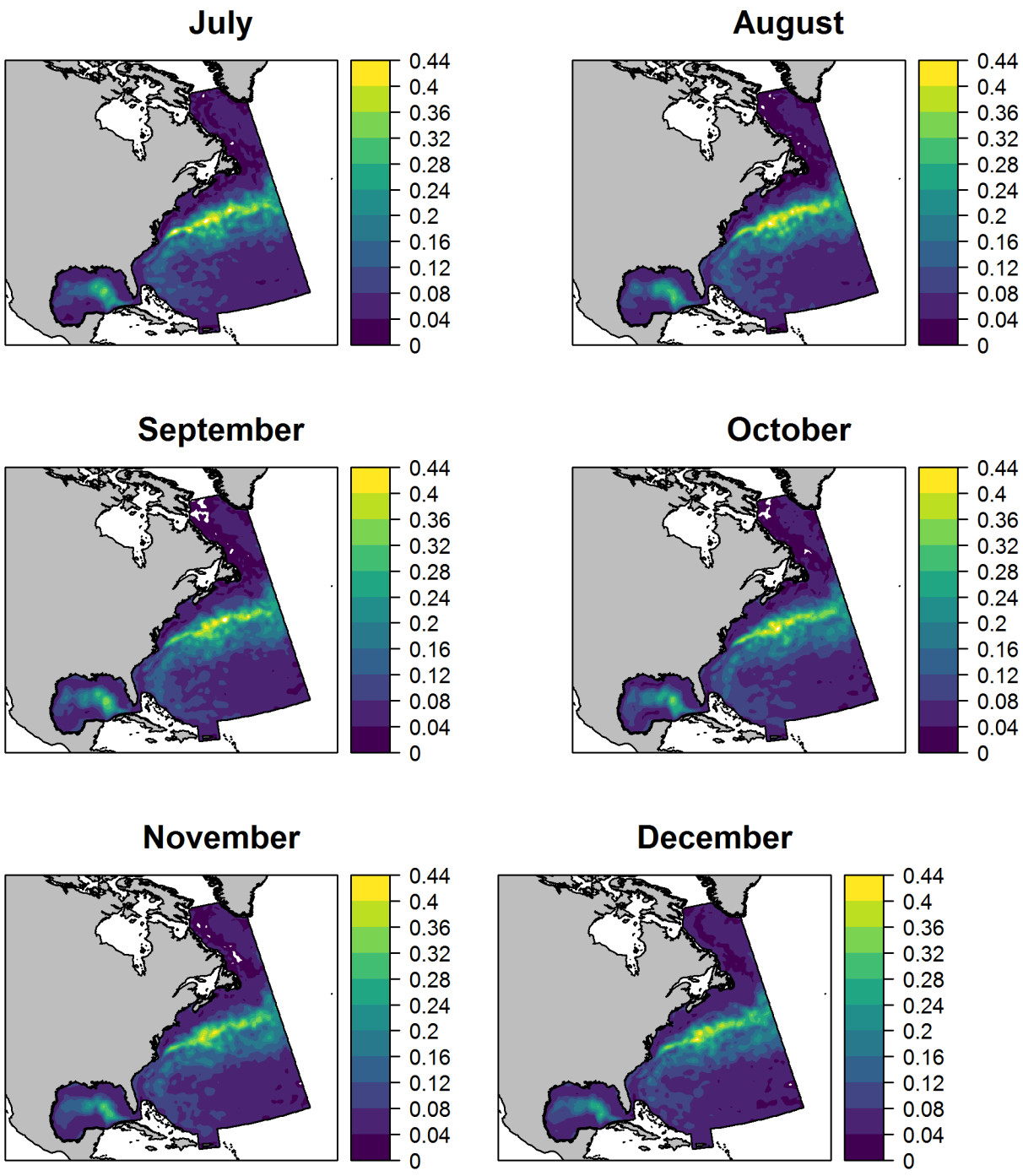


Figure 6: Monthly environmental envelopes for standard deviation of sea level anomaly. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

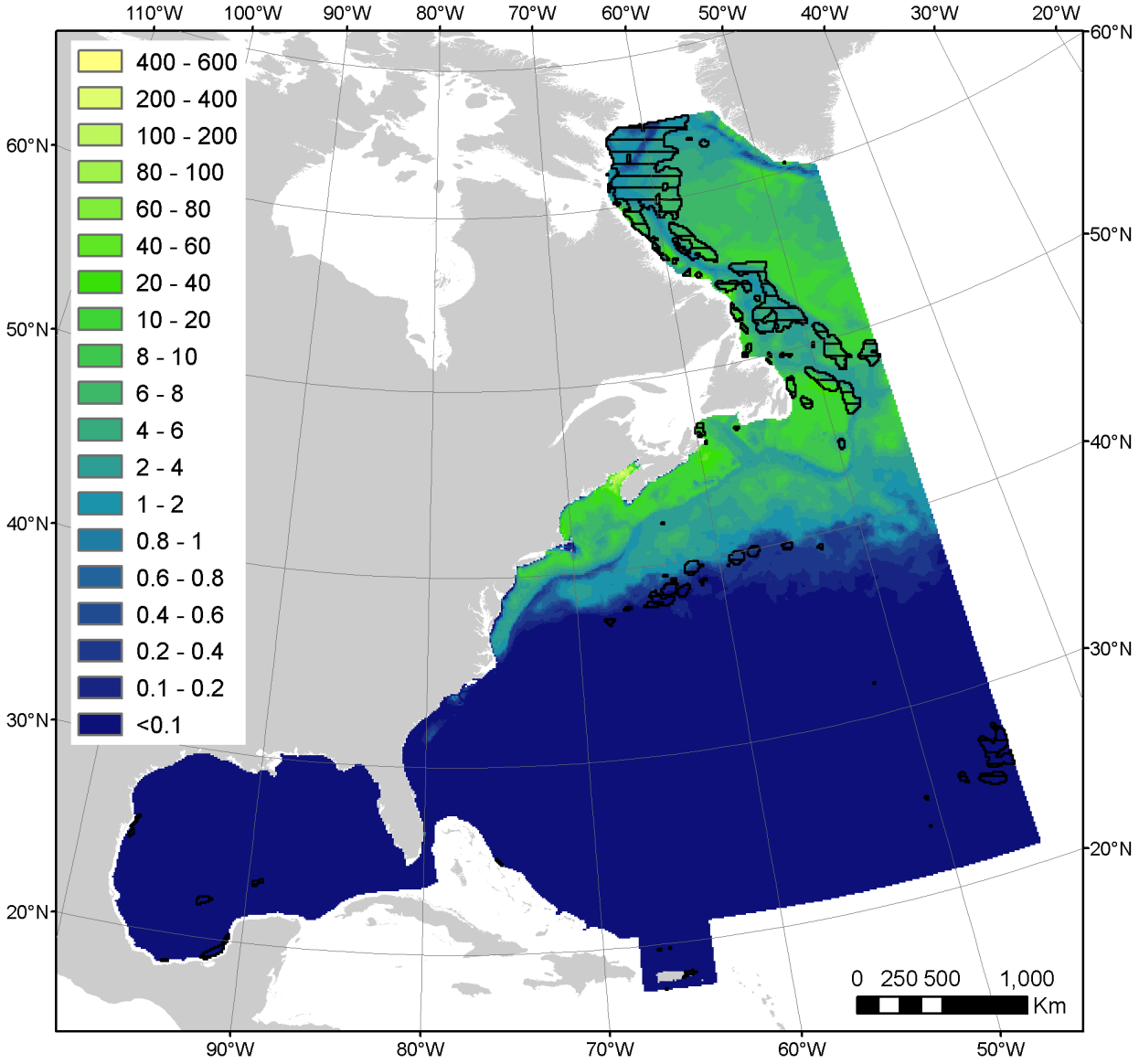


Figure 7: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

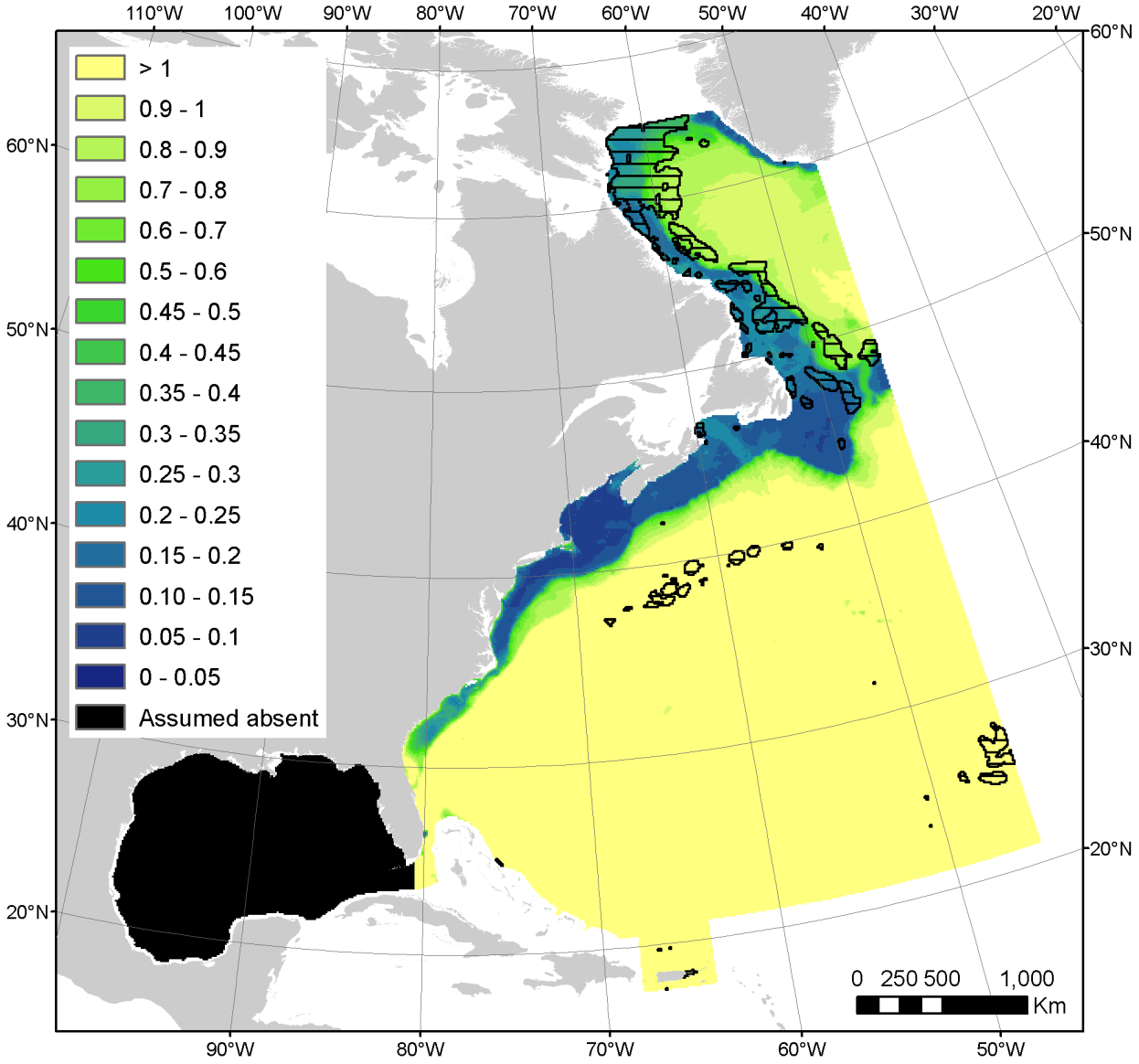


Figure 8: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

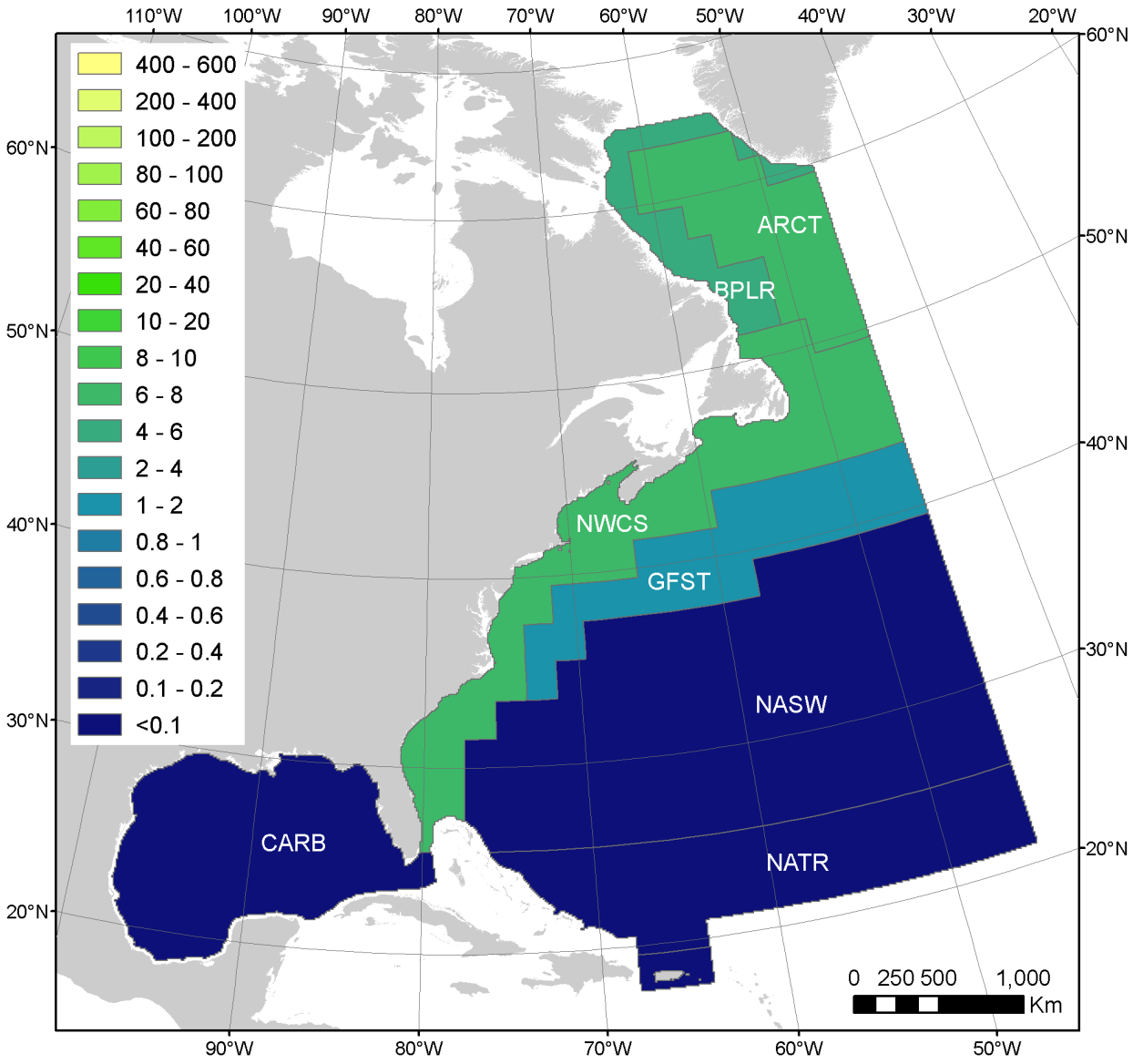


Figure 9: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic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

8- Alternate models

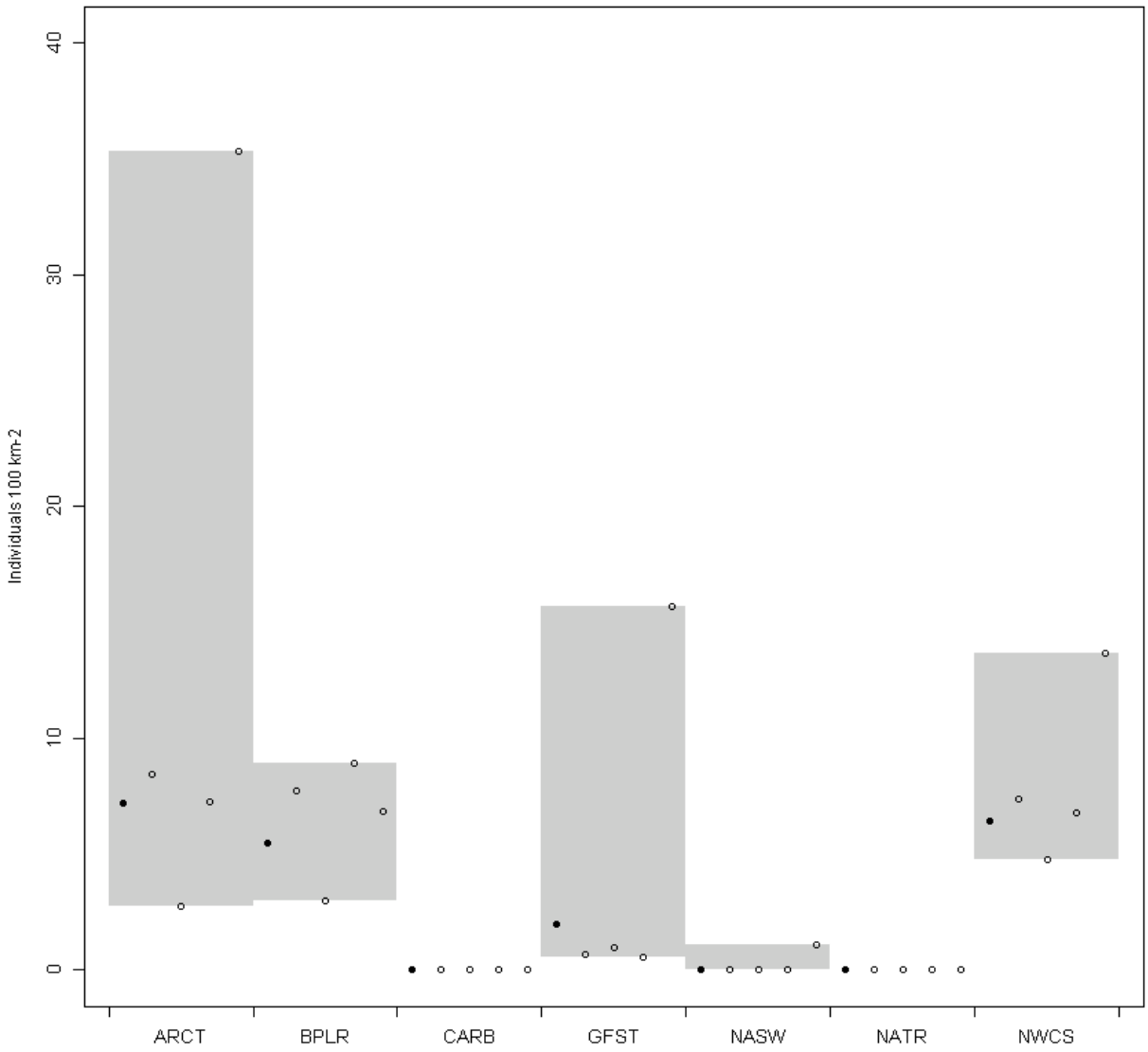


Figure 10: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to 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
Depth	EpiMnkPP	PkPB	SLAStDev	52242.03	0.00
Depth	EpiMnkPP	PkPB	DistToFront1	52246.63	4.60
Depth	SLAStDev	PkPB	DistToFront1	52247.99	5.96
Slope	EpiMnkPP	PkPB	DistToFront1	52271.51	29.48
Depth	EpiMnkPP	EKE	SST	52276.55	34.52

9- Residual diagnostics

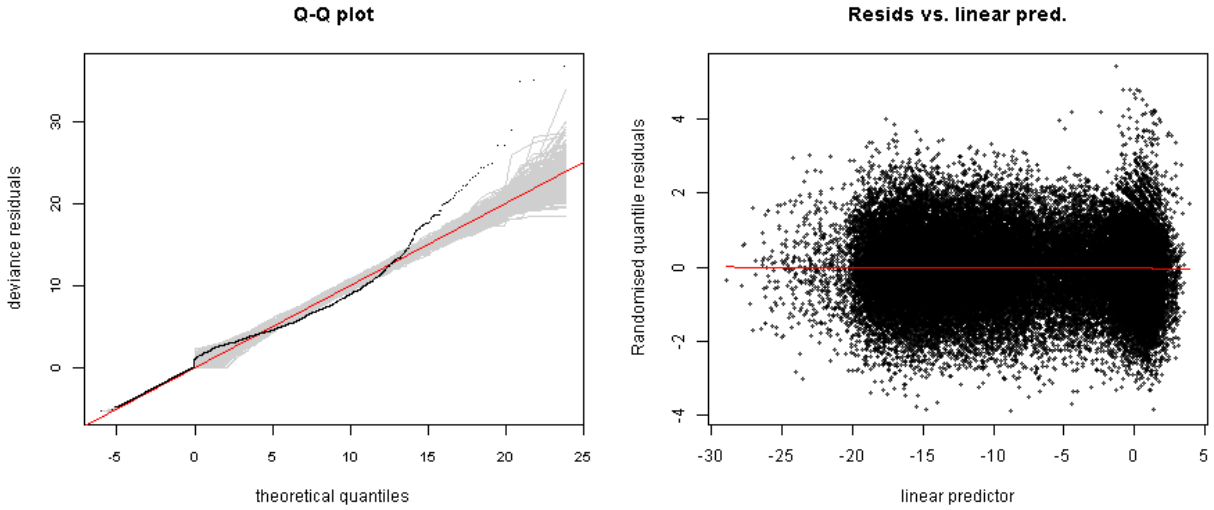


Figure 11: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates 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.

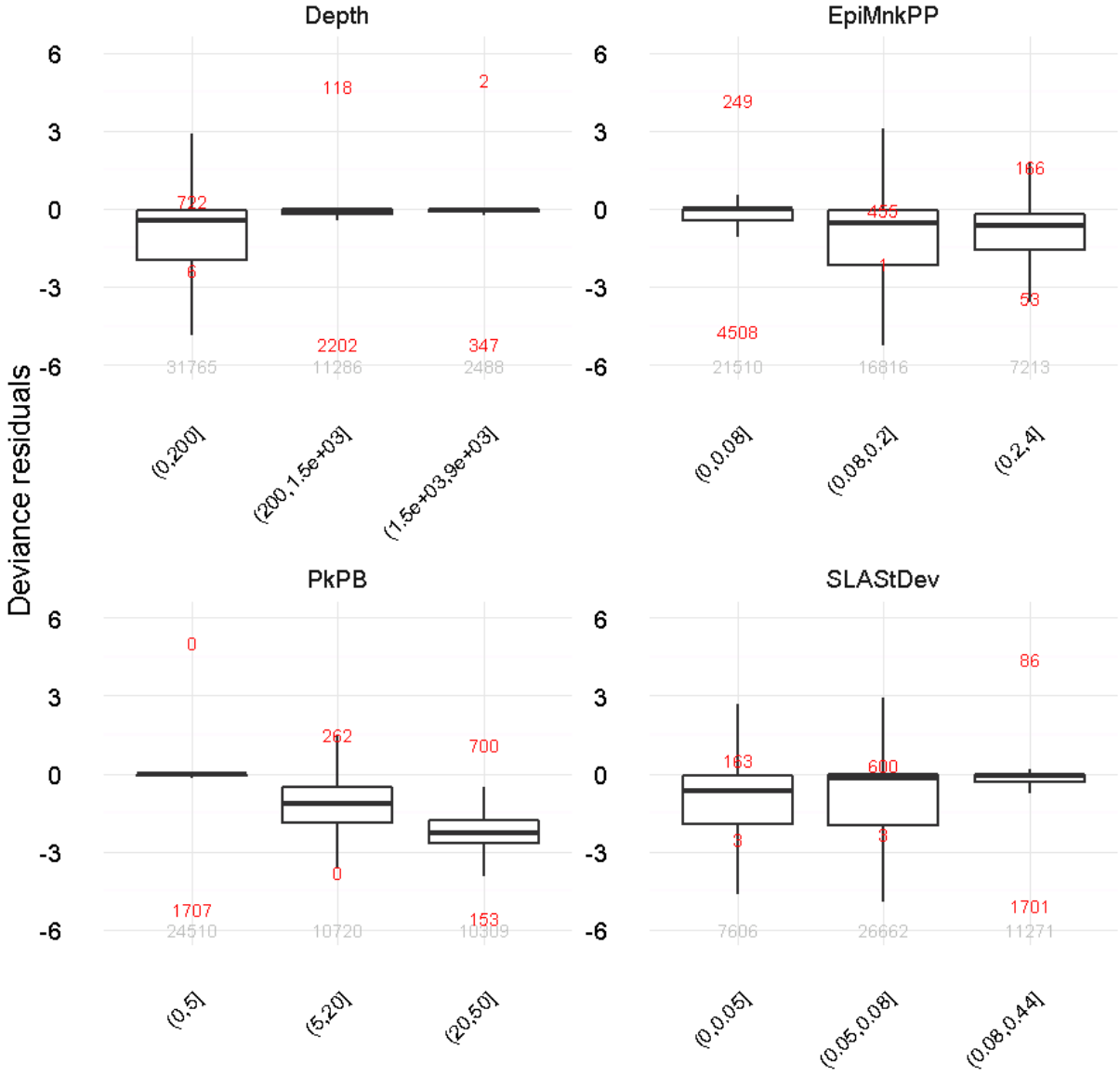


Figure 12: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers 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.

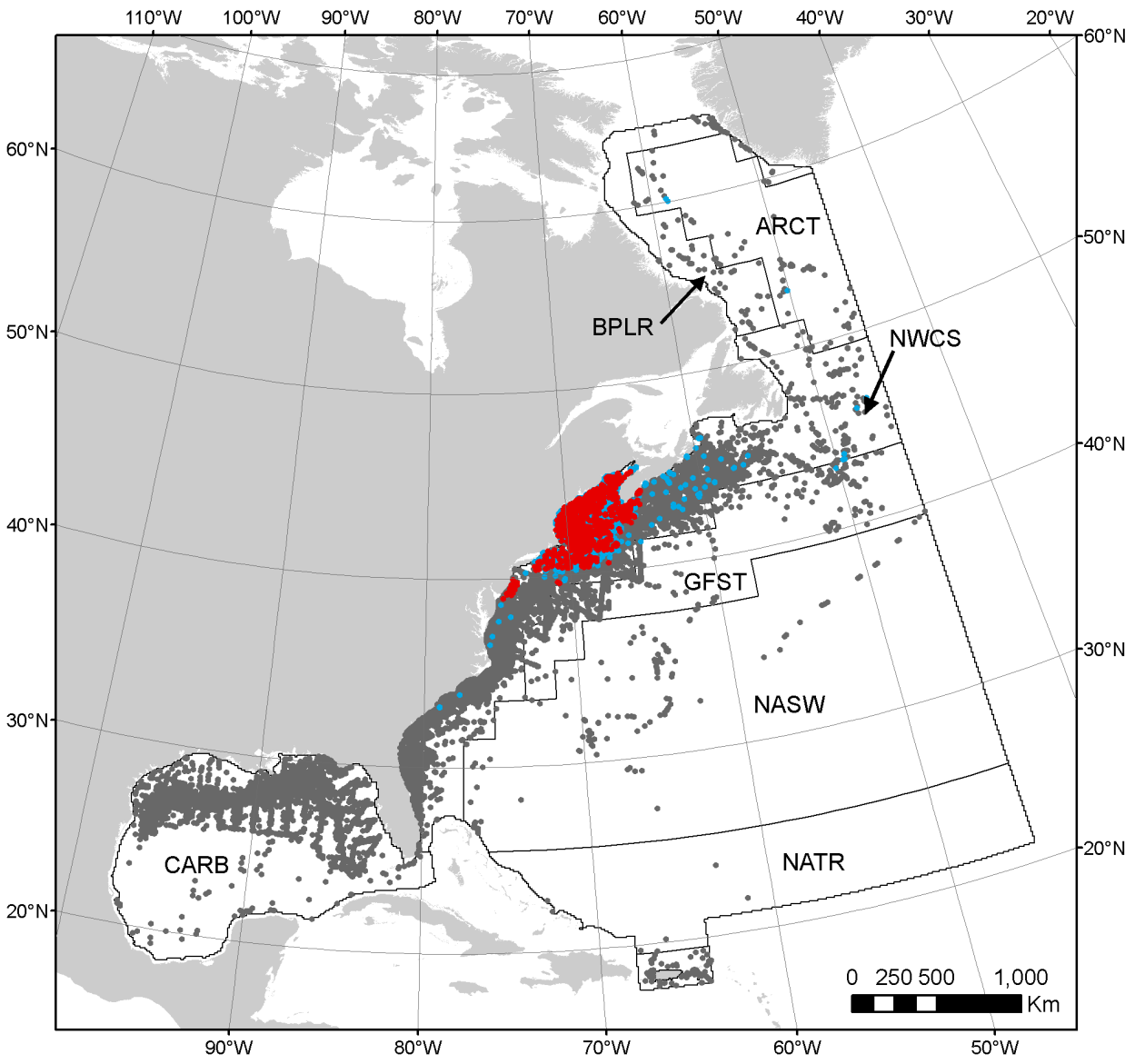


Figure 13: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other 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 total of 1901 sightings was available to fit the habitat-based density model. The first or lowest AIC model included zooplankton biomass, depth, micronekton production and standard error of sea level anomaly (listed in decreasing order of importance according to F-scores) and had an explained deviance of 46.5%. It was the only supported model sensu Burnham & Anderson (2002) (Table 3). Predicted densities from all top five models were zero in the CARB and NATR provinces and very low in the NASW province (Figure 10). Predicted densities differed roughly by a factor of 3 in the BPLR and NWCS provinces. They differed by factor of respectively 11 and 15 in the ARCT and GFST province (most of the variation was due to the fifth model which predicted much higher densities). When examining these results, it should be kept in mind that the second, third, fourth and fifth models had a large delta AIC and therefore little statistical support sensu Burnham and Anderson (2002).

Predictions were consistent with the distribution of harbor porpoises in temperate and boreal waters, primarily on the continental shelf, but also in deep offshore waters, as suggested by numerous bycatch and sighting records (Stenson and Reddin 1994, Palka et al. 1996, Bjorge and Tolley 2009, Teilmann and Dietz 1998). At least three distinct populations or stocks (Gulf of Maine/Bay of Fundy, East Newfoundland and Labrador and West Greenland) occur within the AFTT area (Palka et al. 1996; Andersen 2003) (most of the survey data available to us presumably sampled the Gulf of Maine/Bay of Fundy population). Harbor porpoises are known to undertake seasonal movements at a fairly local scale (e.g., in the Gulf of Maine/Bay of Fundy; Palka et al. 1996), but modeling these movements was beyond the scope of the present study.

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

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

The model predicted harbor porpoises to the northern extent of the AFTT area. These predictions seemed plausible as harbor porpoises were recorded as far north as 70°N in Canada (Palka et al. 1996) and 74°N in Greenland (Teilmann and Dietz 1998). Predicted densities were slightly higher in the offshore waters of the ARCT province than in the BPLR province. Little survey effort was available to support these predictions, but they did not seem incompatible with sightings reported in OBIS-SEAMAP and documented in the scientific literature.

In Greenland, where harbor porpoises are still hunted, all sightings and the majority of catches were recorded in summer and fall, suggesting highest densities in these seasons (Teilmann and Dietz 1998). During winter, harbor porpoises are thought to migrate offshore to avoid ice (Teilmann and Dietz 1998). Teilmann and Dietz (1998) reported harbor porpoises in offshore waters beyond the continental shelf, notably in the Davis Strait and the Labrador Sea, supporting the relatively high densities predicted by our model. A few sightings were also available in OBIS-SEAMAP in offshore waters of the ARCT province (but observation effort was very sparse) (Figure 13).

Numerous sightings of harbor porpoises were reported during an aerial survey in West Greenland in summer (Hansen and Heide-Jørgensen 2013). Harbor porpoises were most frequently seen in shallow coastal waters but were also observed in deeper waters as far as 200 km from the coast. We believe predictions in West Greenland are not incompatible with these survey results.

In Canada, harbor porpoises are distributed in coastal waters off Labrador and along the eastern and southern coast of Newfoundland during the spring, in Baffin Bay and in deeper waters of the Labrador Sea during the summer. They are presumed to disperse offshore during winter (Palka et al. 1996). Harbor porpoises were not seen during the Canadian TNASS survey in summer 2007 off Labrador (Lawson and Gosselin 2009) and no sightings were reported in OBIS-SEAMAP in the BPLR province (Figure 13).

We warn that extrapolation beyond predictor ranges occurred in the BPLR province and that predictions in this province remain largely speculative.

North West Atlantic shelves (NWCS) province

Palka et al. (1996) described movements of harbor porpoises within the Gulf of Maine/Bay of Fundy in spring, summer and fall. Their winter distribution is vastly unknown and offshore dispersion is a plausible hypothesis.

Predicted densities were the highest on the continental shelf. During the TNASS survey, harbor porpoises were sighted on the continental shelf south of Newfoundland (39 sightings), east of Newfoundland (1 sighting) and on the Scotian shelf (4 sightings) (Lawson and Gosselin 2009). Numerous sightings on the Scotian shelf as well as a few sightings on the continental slope southeast of Newfoundland were reported in OBIS-SEAMAP (Figure 13).

The southernmost harbor porpoise sighting recorded by surveys was just south of New Jersey. The model predicted medium densities of harbor porpoises as far south as North Carolina. In our opinion, these predictions are not unrealistic as numerous strandings were reported in North Carolina from 1997-2008, mostly in winter (Hohn et al. 2013, Byrd et al. 2014), and sightings were available in OBIS-SEAMAP as far south as 34°N (Figure 13).

Gulf Stream (GFST) province

No sightings were available to support the overall low predicted densities in offshore waters of the GFST province. We believe these predictions are not unrealistic as harbor porpoises are suspected to range offshore during the winter (Palka et al. 1996). We warn that extrapolation beyond predictor ranges occurred in some parts of the Gulf Stream and therefore predictions should be considered with extreme caution.

North Atlantic subtropical gyral (NASW), North Atlantic tropical gyral (NATR) and Caribbean (CARB) provinces

Low predicted densities in the NASW, NATR and CARB provinces appeared consistent with the absence of sightings in OBIS-SEAMAP (Figure 13) and the species preference for cold temperate waters (Bjorge and Tolley 2009).

Overall confidence: level 2

Large numbers of sightings were available for this species but they were mostly concentrated in the southern part of its wide range throughout temperate and boreal waters. The model successfully predicted its occurrence in northern latitudes but predicted densities remain largely speculative. In our opinion, the relatively high densities predicted beyond the continental shelf are not unrealistic given increasing evidence that harbor porpoises occur in deep offshore waters (notably in the wintertime). The incorporation of line transect survey data from Canada and Greenland would be extremely useful to increase the reliability of predicted densities in northern waters. 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.

11- References

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