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

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This report documents the habitat-based density model for Kogia 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 Kogia 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	24264.47	7
EC	1044357.70	31
GOM	194715.35	218
All regions	1263337.53	256

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

Month	Effort	Sightings
January	77892.79	4
February	123591.37	4
March	117923.54	13
April	117929.72	14
May	149765.03	105
June	129393.69	29
July	135693.85	55
August	129660.43	24
September	71696.07	4
October	82560.18	1
November	69210.92	3
December	58019.93	0
All Months	1263337.53	256

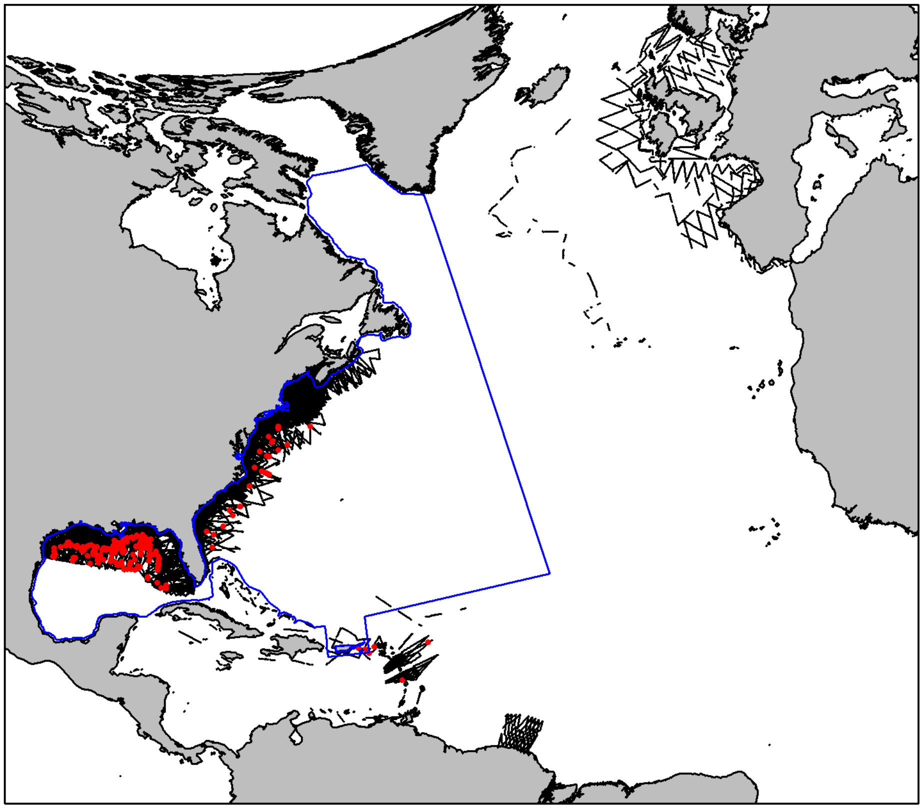


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

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

Kogia spp.

Since dwarf sperm whale (*Kogia sima*) and pygmy sperm whale (*Kogia breviceps*) are not differentiable at sea, leading to a high number of ambiguous sightings, we modeled them together within the Kogia spp. guild.

Modeled season

We fitted a year-round model as we found no definitive evidence in the literature that Kogia undertakes extensive migrations or exhibits contrasting behaviors (e.g., feeding versus breeding) in different seasons at the scale of our study area.

Segments

We incorporated segments from the east coast, Gulf of Mexico and Caribbean where sightings were reported (Table 1).

3- Best model

- **Predictors**: depth, production of epipelagic micronekton (EpiMnkPP), sea surface temperature (SST)
- **Model summary**:

```
##
## Family: Tweedie(p=1.312)
## Link function: log
##
## Formula:
## abundance ~ s(Depth, k = 4, bs = "ts") + s(EpiMnkPP, k = 4, bs = "ts") +
##     s(SST, k = 4, bs = "ts") + offset(log(area_km2))
## <environment: 0x1a61d35c>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -13.351      1.097  -12.17   <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)    2.248      3 19.665 4.43e-14 ***
## s(EpiMnkPP) 1.062      3  4.232 0.000215 ***
## s(SST)      1.697      3 21.753  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  -0.00228   Deviance explained = 41.8%
## -REML = 1986.3  Scale est. = 59.839    n = 113880
```

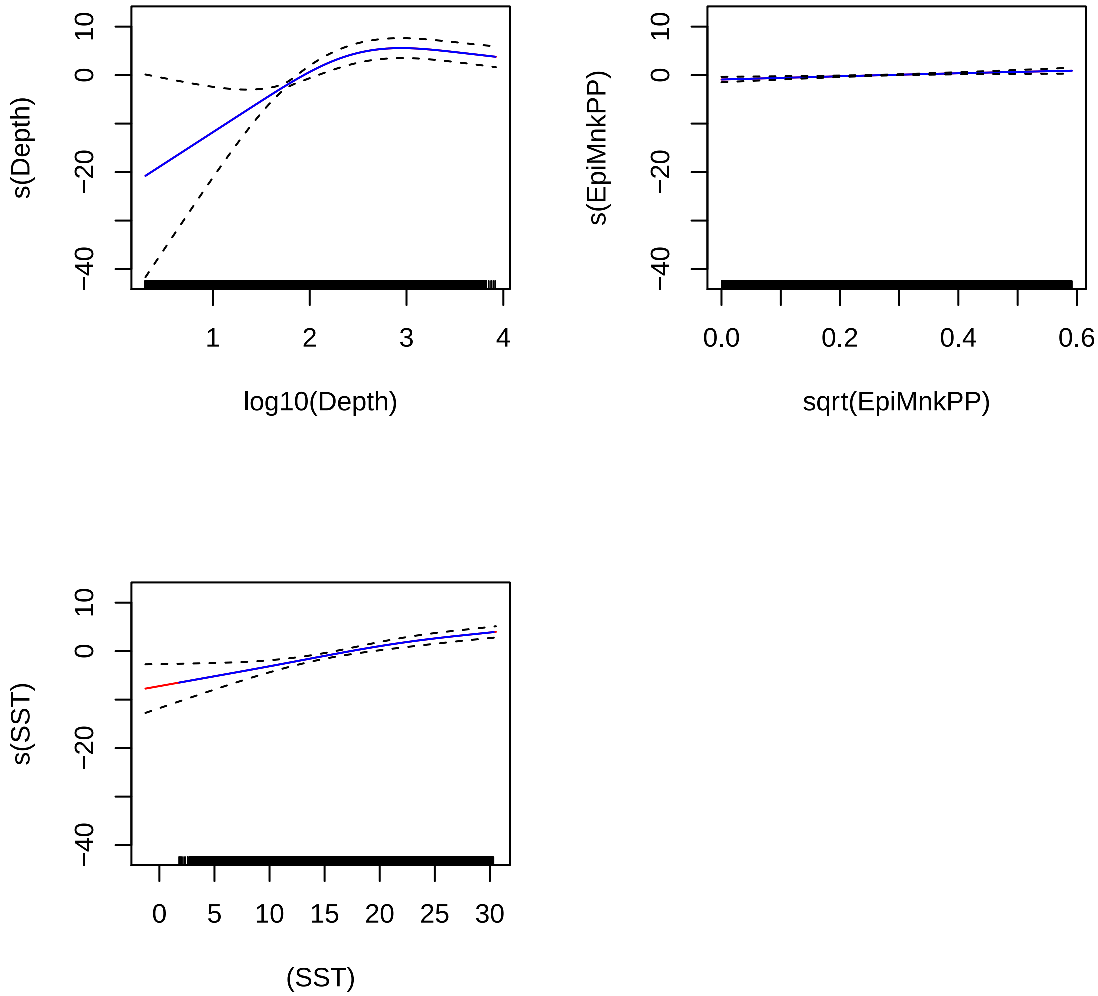


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals.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

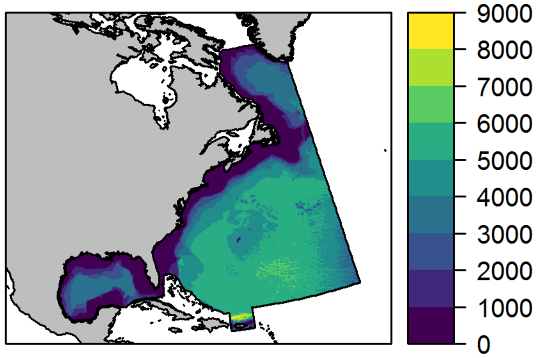
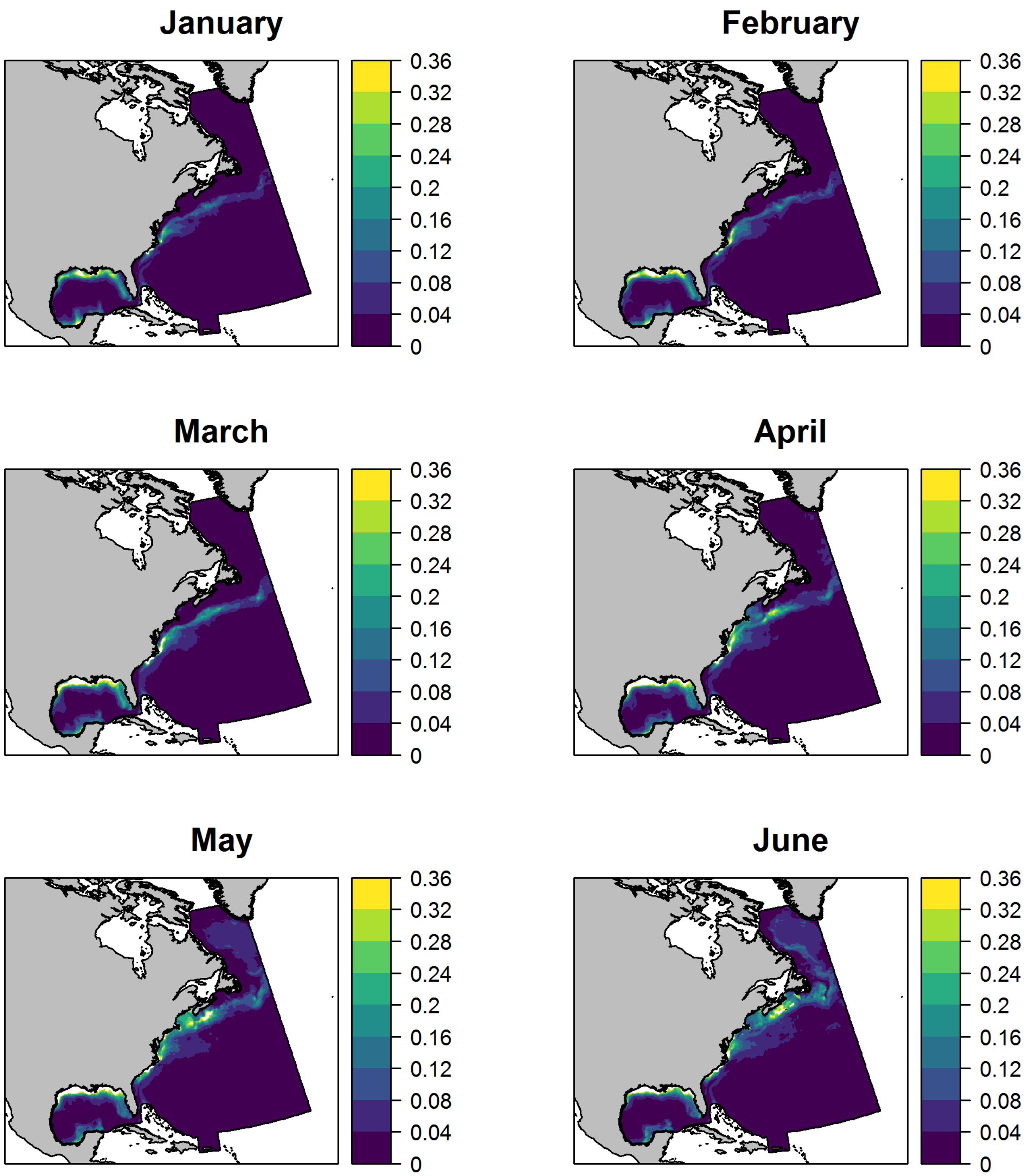


Figure 3: Environmental envelope for depth. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.



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

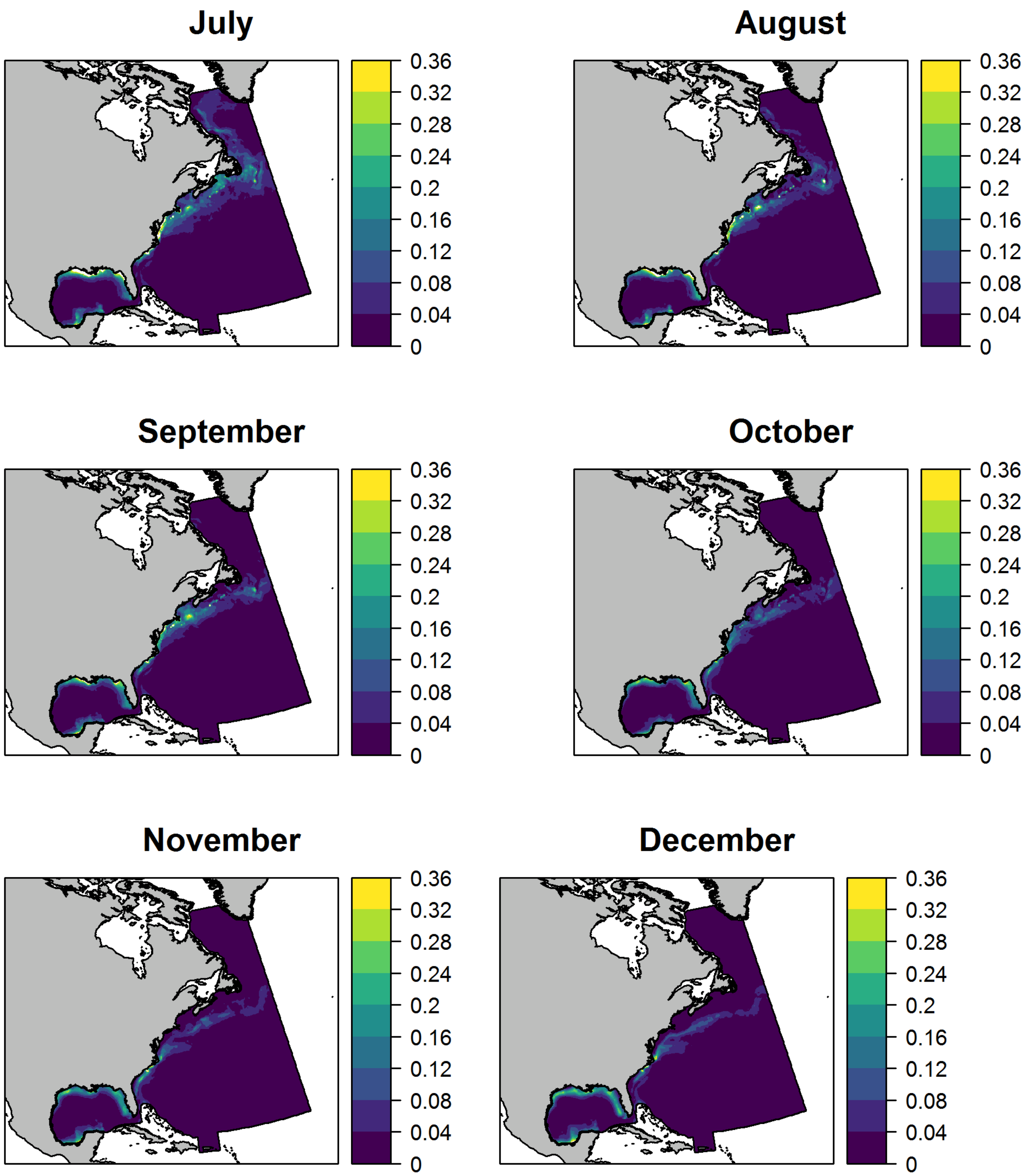
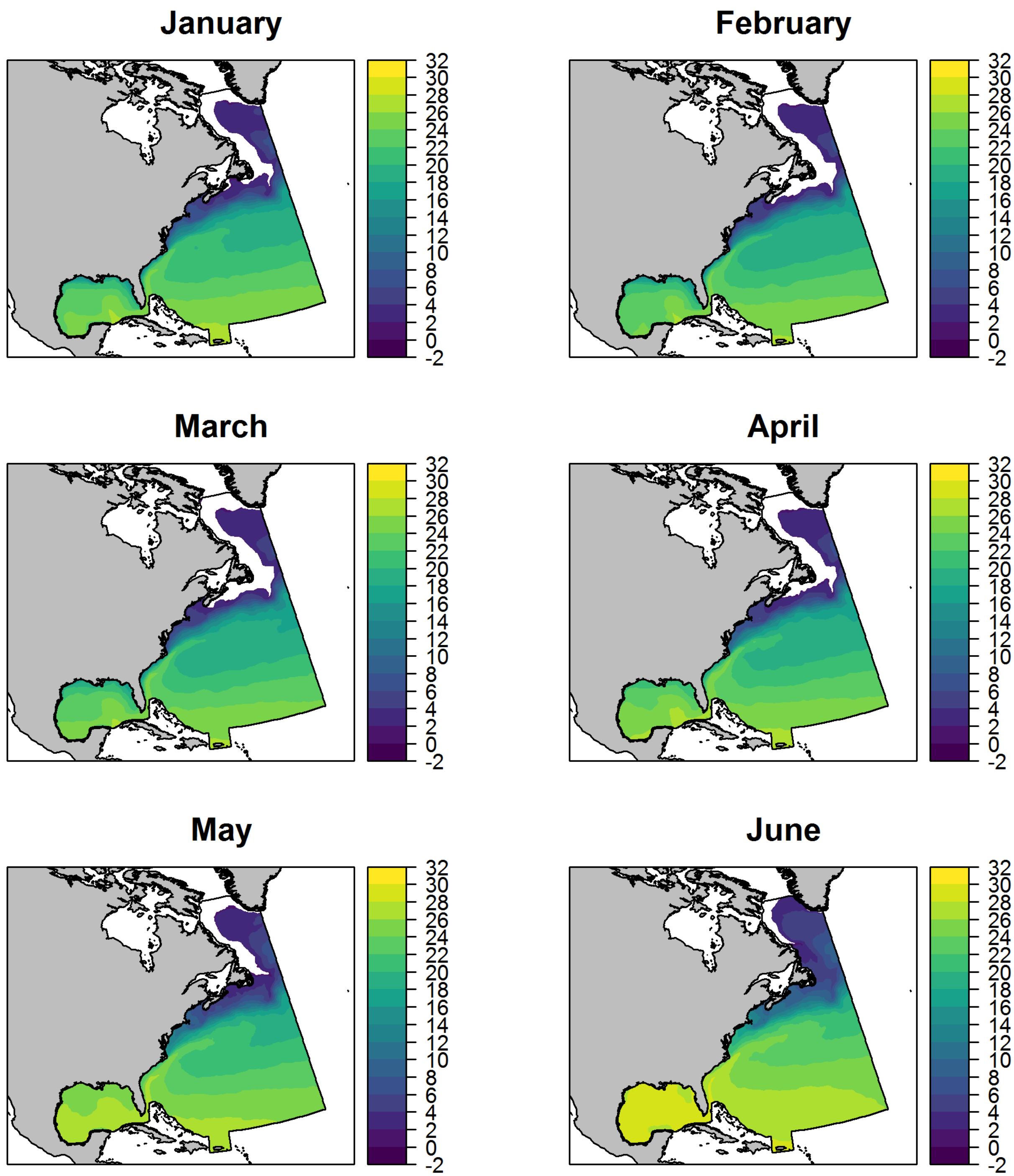


Figure 4: Monthly environmental envelopes for production of epipelagic micronekton. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0 -2
February
32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0 -2
March
32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0 -2
April
32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0 -2
May
32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0 -2
June
32 30 28 26 24 22 20 18 16 14 12 10 8 6 4 2 0 -2

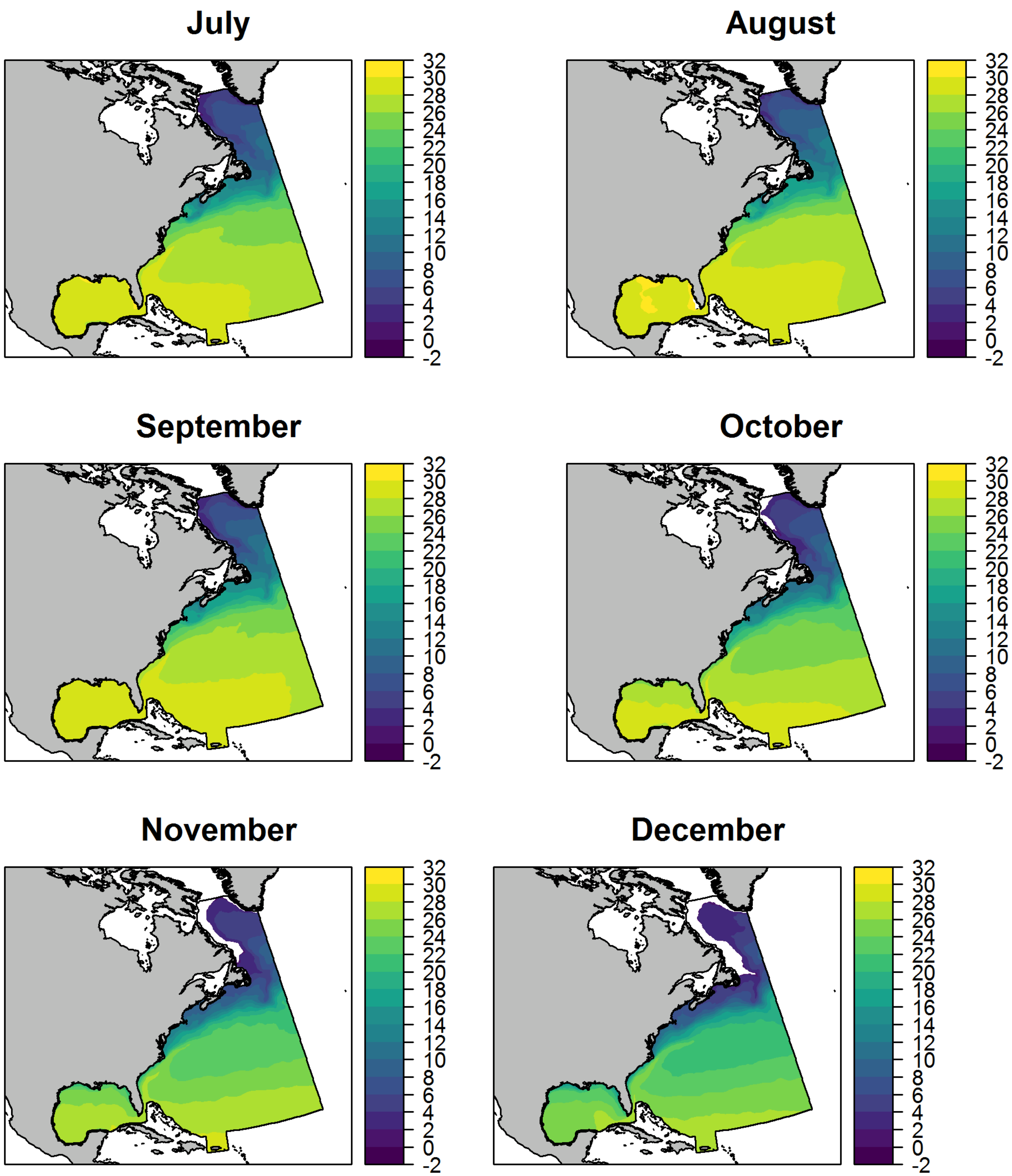


Figure 5: Monthly environmental envelopes for sea surface temperature. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

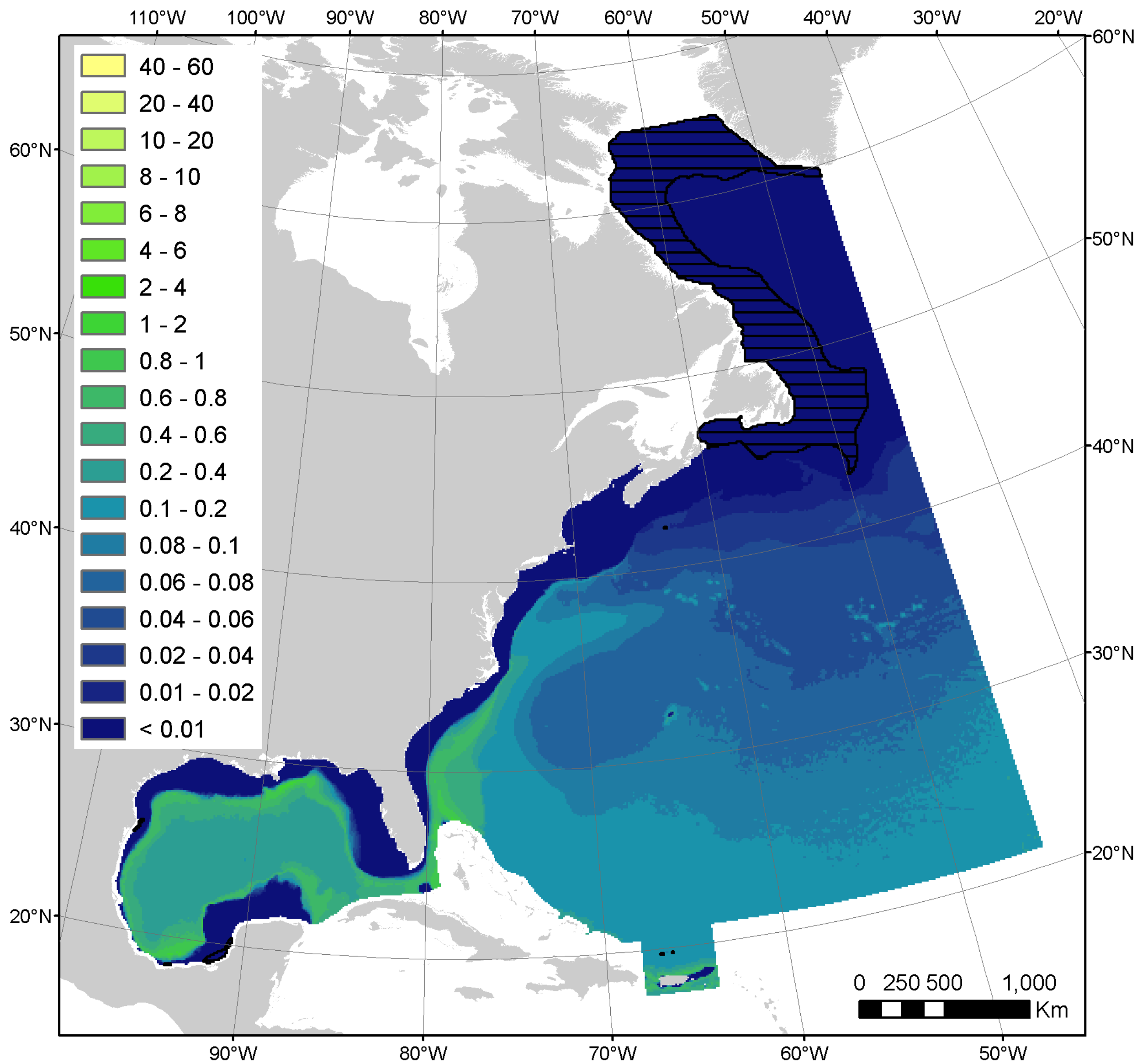


Figure 6: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

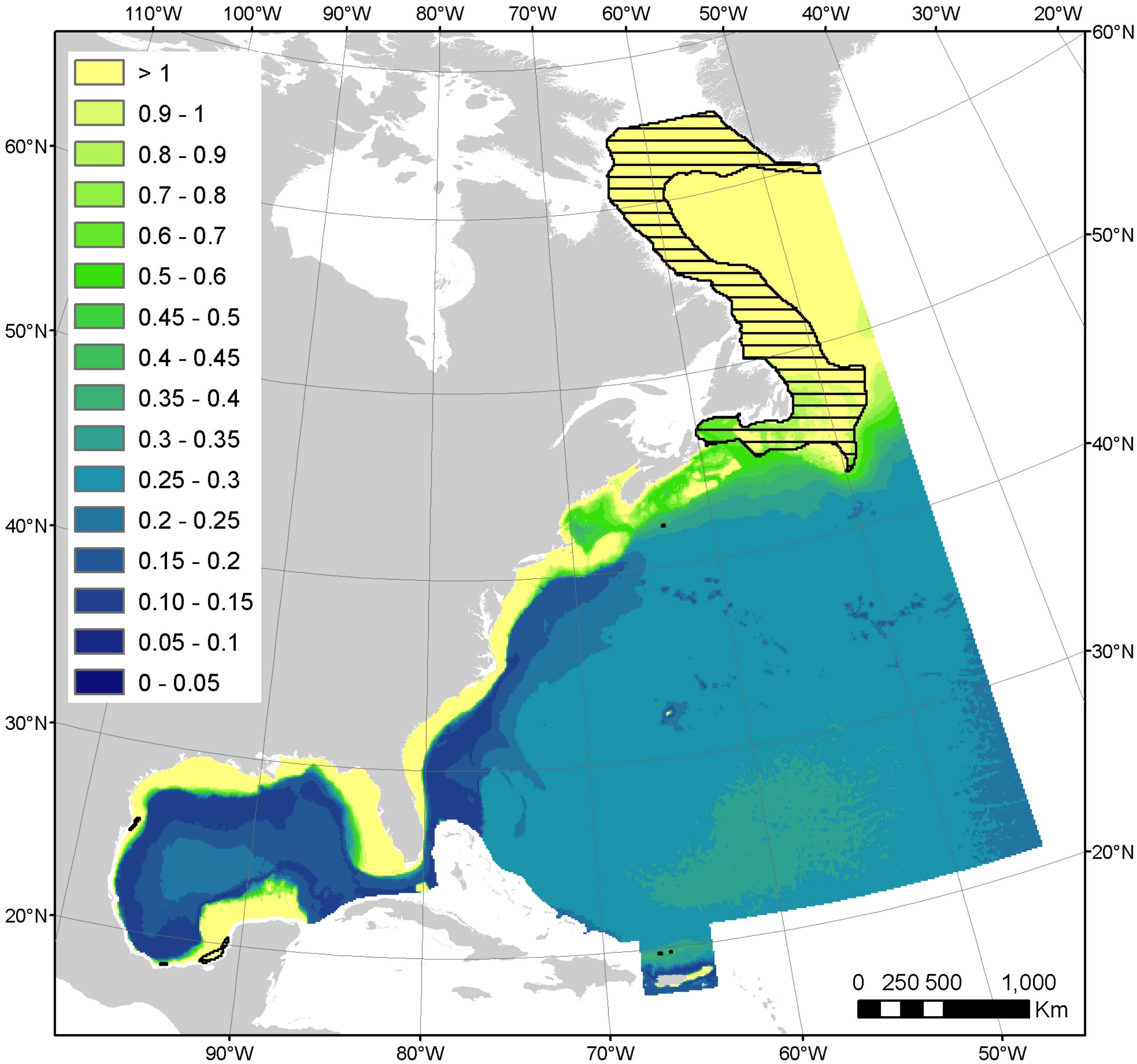


Figure 7: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

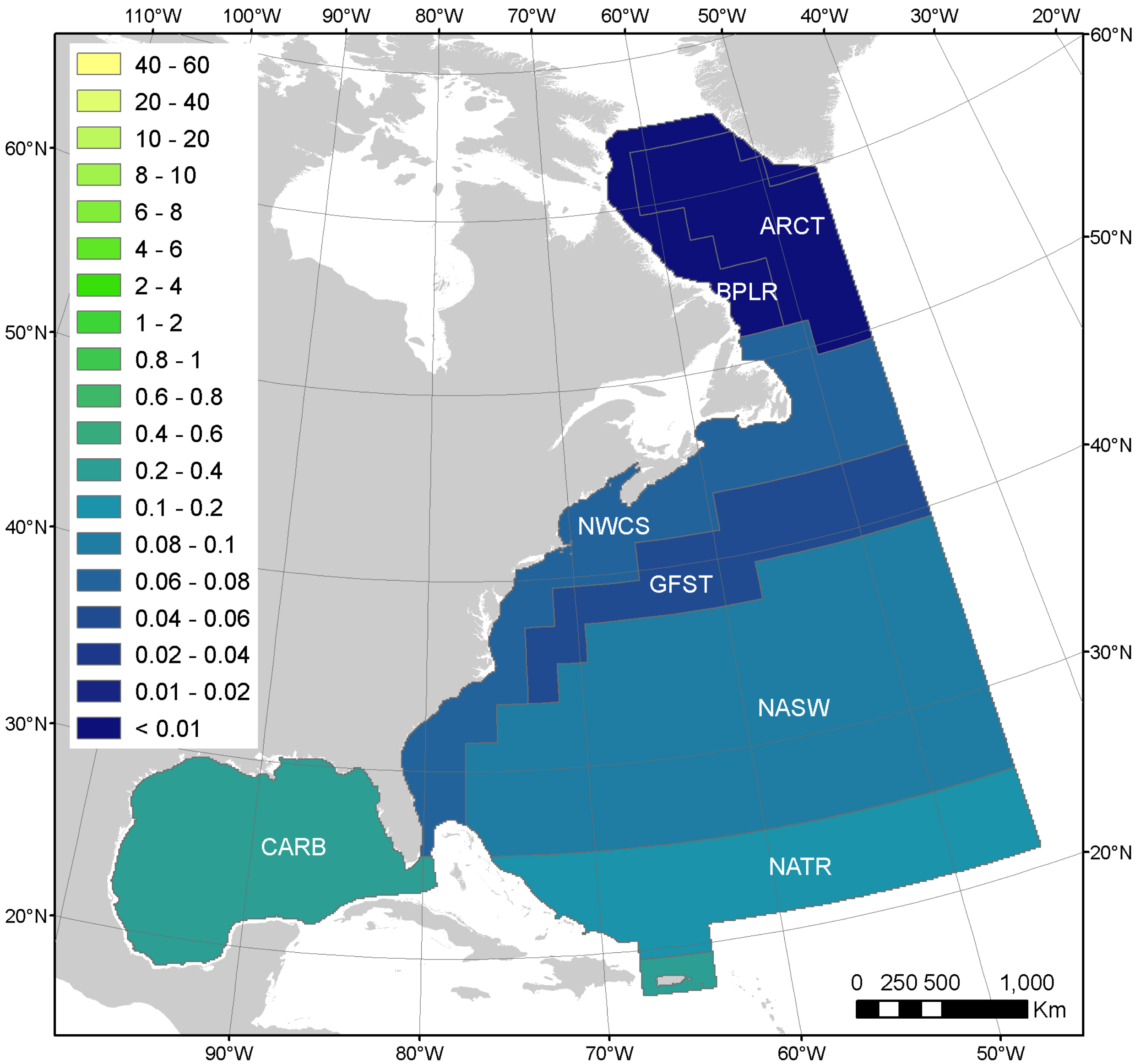


Figure 8: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic Tropical Gyral Province; NASW: North Atlantic Subtropical Gyral Province (West); NWCS: North West Atlantic Shelves Province.

8- Alternate models

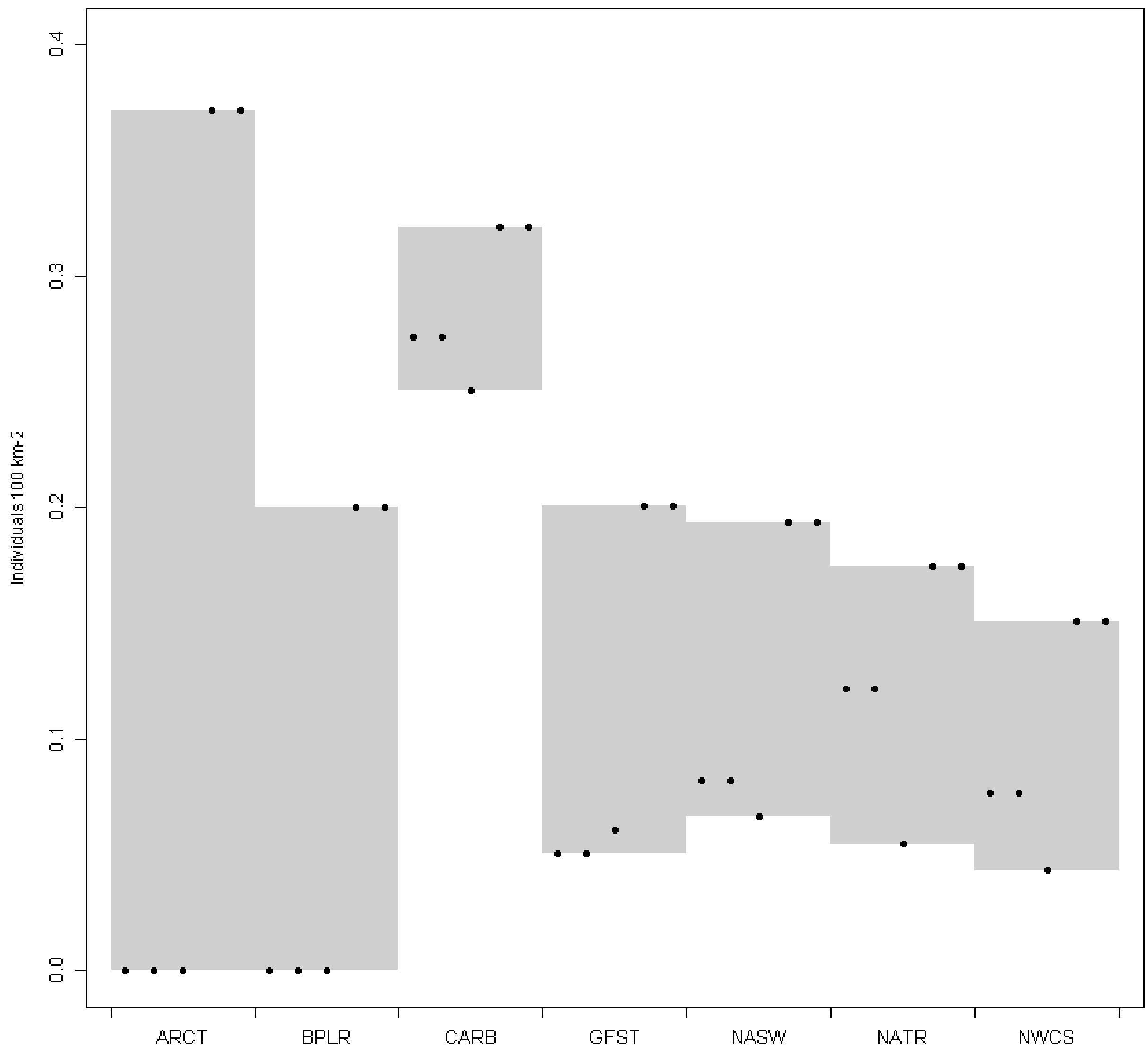


Figure 10: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to 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	SST	EpiMnkPP	ns	113959.3	0.0
Depth	SST	EpiMnkPB	ns	113960.8	1.5
Depth	DistToFront1	EpiMnkPB	ns	113961.0	1.7
Depth	SST	EpiMnkPB	SLAStDev	113961.7	2.4
Depth	SST	EpiMnkPP	SLAStDev	113962.5	3.2

9- Residual diagnostics

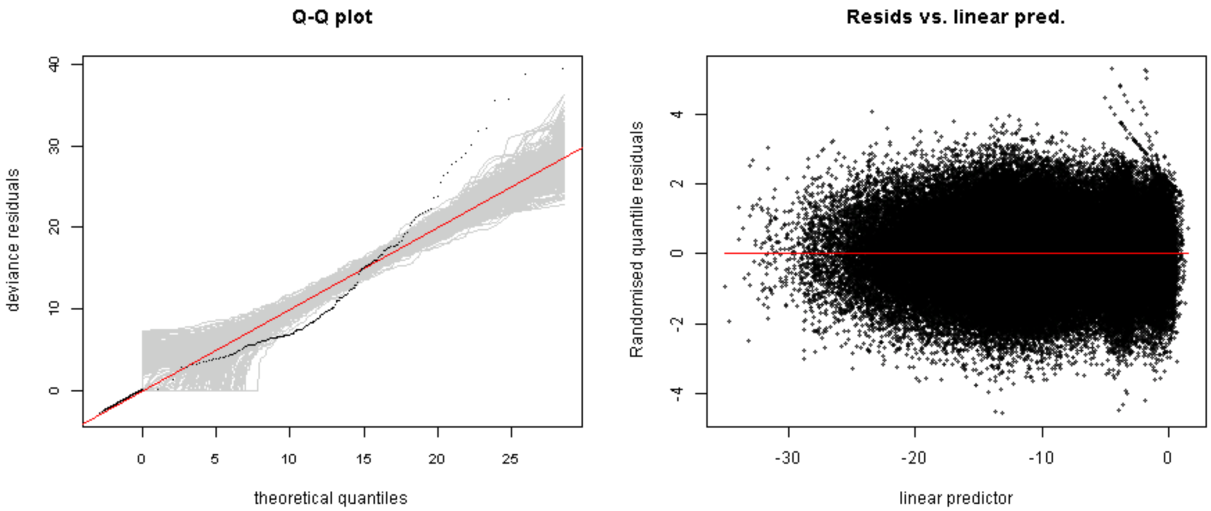


Figure 10: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates 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.

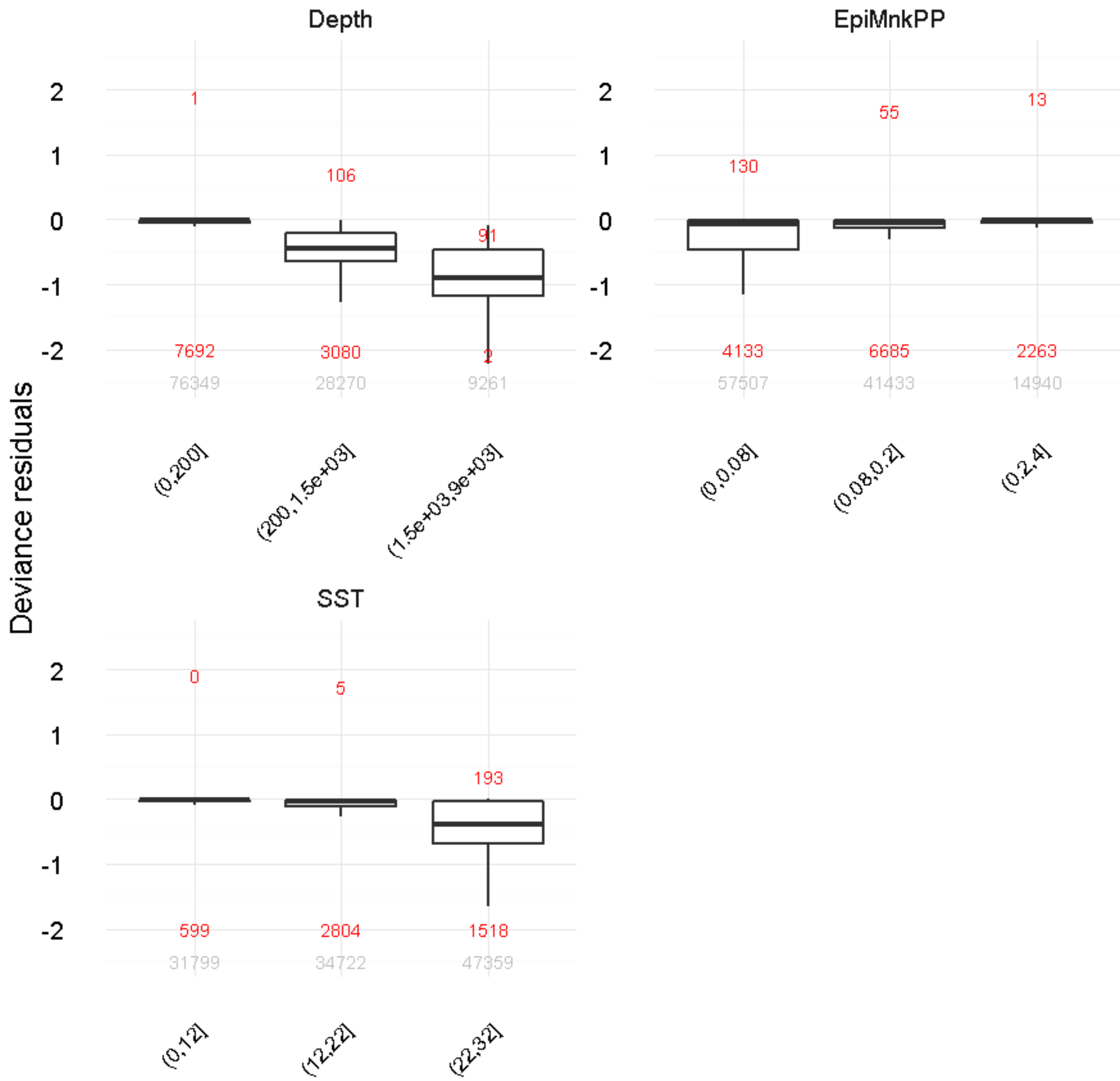


Figure 11: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers 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.

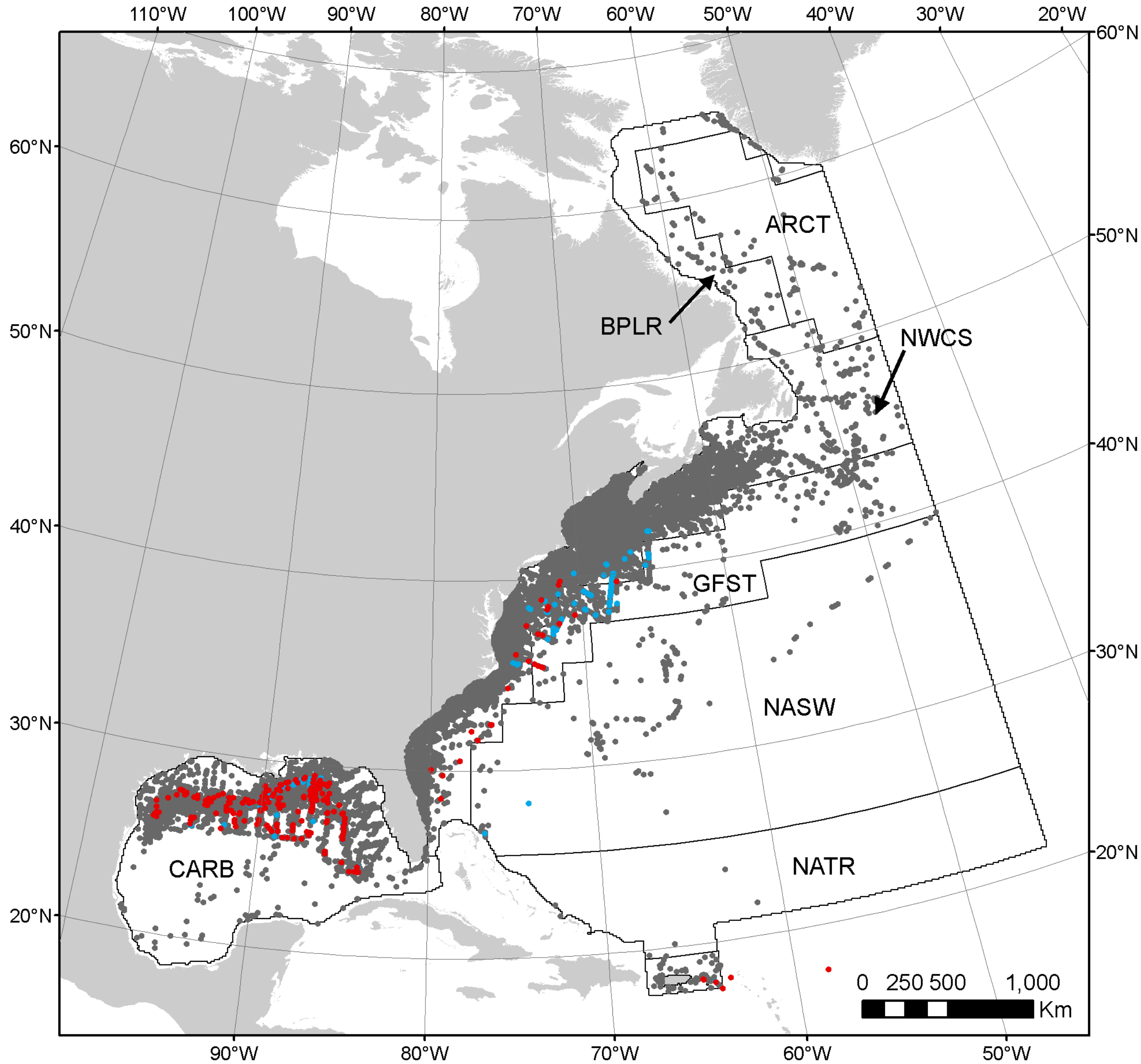


Figure 12: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other 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 256 sightings, mostly from surveys in the northern Gulf of Mexico, were available to fit the habitat-based density model. The first or lowest AIC model included sea surface temperature, depth and epipelagic micronekton production (listed in decreasing order of importance according to F-scores) and had an explained deviance of 41.8%. All top five models included depth (Table 3). All but the third model included sea surface temperature. The second and third models had a delta AIC < 2, indicating some statistical support sensu Burnham and Anderson (2002). The fourth and fifth models had comparatively little support. Predicted densities from the top five models were quite variable in the different provinces (Figure 9). The third model was largely responsible for this variation, predicting consistently higher densities than the other models. In the ARCT and BPLR provinces, well beyond the northern distribution range of Kogia spp. (Bloodworth & Odell 2008; McAlpine 2009), all models predicted densities near zero except the third model. Despite having some statistical support, the third model led to unrealistically high predicted densities so we decided to exclude it. Predicted densities from the first and second statistically supported models were overall similar in all provinces. The first model had a lower AIC and explained more deviance compared to the second model, suggesting it was slightly more suitable for modeling Kogia spp. densities.

Model predictions appeared generally consistent with the described range of Kogia spp. in offshore tropical and temperate waters (there is some evidence that dwarf sperm whale prefers warmer waters than pygmy sperm whale) (Bloodworth & Odell 2008; McAlpine 2009). The higher predicted densities along the continental slope appeared in line with habitat preferences of Kogia spp. inferred from diet analyses of stranded animals (McAlpine et al. 2009). The scarcity of sightings reported beyond well surveyed waters is likely due to the cryptic behavior and difficulty in identifying these species at sea.

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

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

Low predicted densities in the BPLR province, the ARCT province and the northern part of the NWCS province (approx. north of 42°N) seemed consistent with the described distribution of Kogia spp. in tropical and temperate waters (Bloodworth & Odell 2008; McAlpine 2009). We note that a few extralimital records exist in eastern Canada (McAlpine et al. 1997) and the northernmost sighting reported in OBIS-SEAMAP was 43°N. We caution that extrapolation to colder waters occurred in the BLPR, ARCT and northern part of the NWCS province, potentially leading to unreliable predictions. Nevertheless, we believe the low predicted densities in these northern waters are in line with the ecology of Kogia spp.

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

Predicted densities were the highest in offshore waters south of Cape Hatteras, North Carolina, where Kogia were recorded by multiple surveys. North of Cape Hatteras, Kogia were also recorded by surveys and numerous sightings were available in OBIS-SEAMAP (Figure 12), but predicted densities were lower. We think there is a possibility that our model underestimates Kogia densities north of Cape Hatteras.

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

The model predicted medium densities in the NATR and NASW provinces. Only one offshore sighting was reported in the NASW province and no sighting was reported in the NATR province, but observation effort in these provinces was extremely sparse (Figure 12). Predictions near the Bahamas (edge of the NASW province) appeared consistent with sightings of dwarf sperm whales east of Great Abaco where they occur at relatively low depths community (MacLeod et al. 2004) (Figure 12).

Until they are validated with additional sightings, predictions in offshore waters of the NATR and NASW provinces will remain largely speculative.

Caribbean (CARB) province

The CARB province was the province where predicted density was the highest on average.

In the Gulf of Mexico, predicted densities were the highest on the continental slope. Pygmy and dwarf sperm whales are considered common species within the offshore cetacean fauna of the Gulf of Mexico (Ortega-Ortiz 2002). Little information exists for Kogia spp. in the southern Gulf of Mexico. Ortega-Ortiz (2002) reported 2 sightings from an opportunistic cruise and 15 strandings on the Mexican coast. Given the numerous sightings in offshore waters of the northern Gulf of Mexico, we believe predicted densities in offshore waters of the southern Gulf of Mexico are not unrealistic.

We note that 13 strandings of Kogia spp. were reported for Puerto Rico and the Virgin Islands (Cardona-Maldonado and Mignucci-Giannoni 1999).

Overall confidence: level 1

Large amounts of survey data were available within the core distributional range of Kogia spp. and predicted densities seemed compatible with their described pelagic ecology. Few sightings were available to support predicted densities beyond surveyed areas but we believe this paucity of sightings is largely due to the cryptic behavior characterizing this taxon. The model predicted very low densities in northern waters, consistent with the described absence of Kogia spp.

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