Habitat-based density model for striped dolphin in the AFTT area

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This report documents the habitat-based density model for striped dolphin 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 striped dolphin 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	1
EC	1044357.704	195
EU	27526.342	36
GOM	194715.349	92
MAR	2424.421	12
All regions	1293288.288	336

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

Month	Effort	Sightings
January	77892.79	1
February	123591.37	11
March	117923.54	14
April	117929.72	19
May	149765.03	34
June	132713.99	30
July	162324.31	195
August	129660.43	23
September	71696.07	7
October	82560.18	0
November	69210.92	0
December	58019.93	2
All Months	1293288.29	336

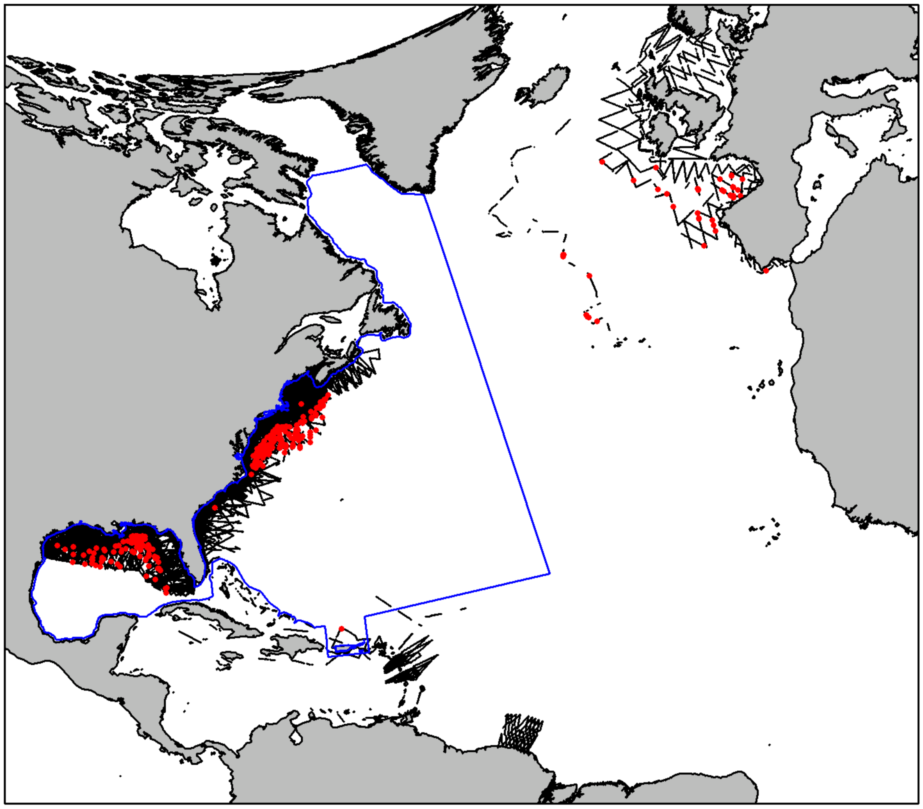


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

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

Striped dolphin (*Stenella coeruleoalba*)

Modeled season

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

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 striped dolphins (Archer & Perrin 1999; Archer 2009).

3- Best model

- **Predictors**: depth, chlorophyll concentration (Chl), distance to sea surface temperature fronts (DistToFront), production of epipelagic micronekton (EpiMnkPP)
- **Model summary**:

```
##
## Family: Tweedie(p=1.304)
## Link function: log
##
## Formula:
## abundance ~ s(Depth, k = 4, bs = "ts") + s(Chl1, k = 4, bs = "ts") +
##     s(DistToFront1, k = 4, bs = "ts") + s(EpiMnkPP, k = 4, bs = "ts") +
##     offset(log(area_km2))
## <environment: 0x1ebd1284>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -8.2060     0.2818  -29.12   <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)        1.741      3 122.142  < 2e-16 ***
## s(Chl1)         2.453      3  15.998 8.35e-12 ***
## s(DistToFront1) 1.159      3   7.512 1.04e-06 ***
## s(EpiMnkPP)     2.095      3  22.881  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.0392   Deviance explained = 57.2%
## -REML = 3173.2  Scale est. = 178.59    n = 116739
```

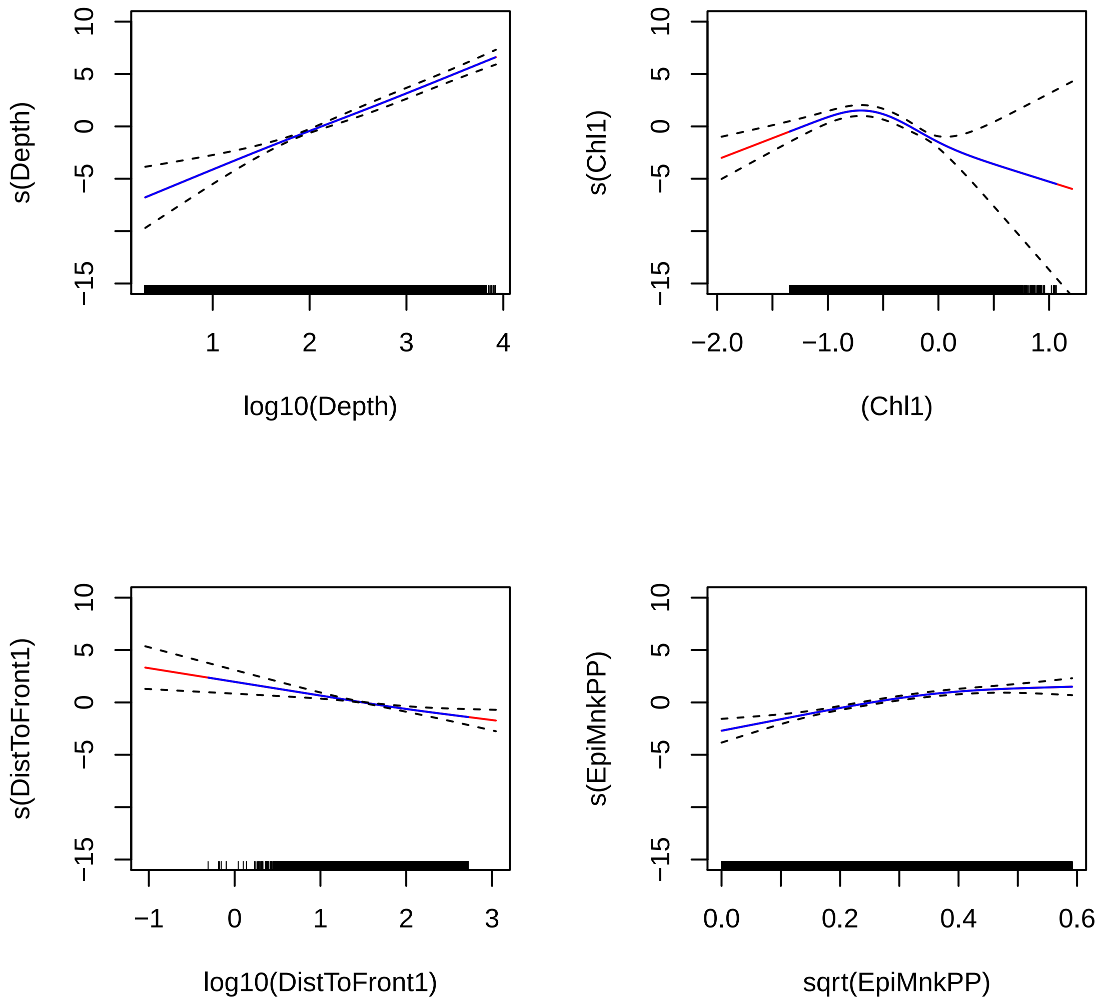


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals.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

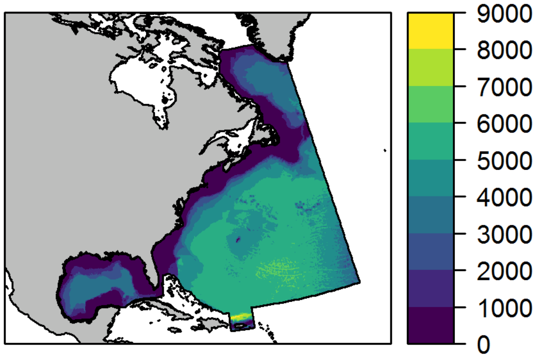
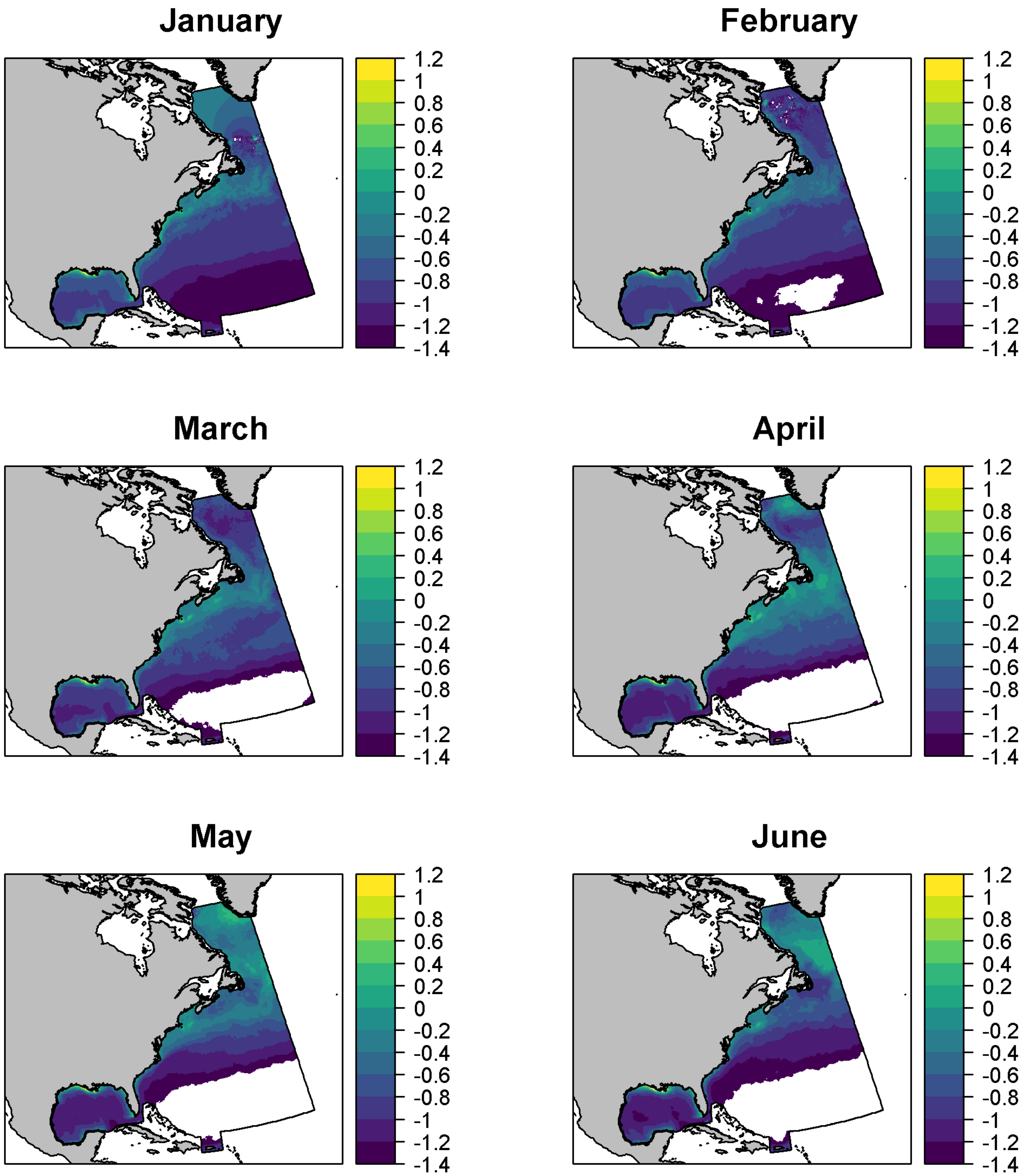


Figure 3: Environmental envelope for depth. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4

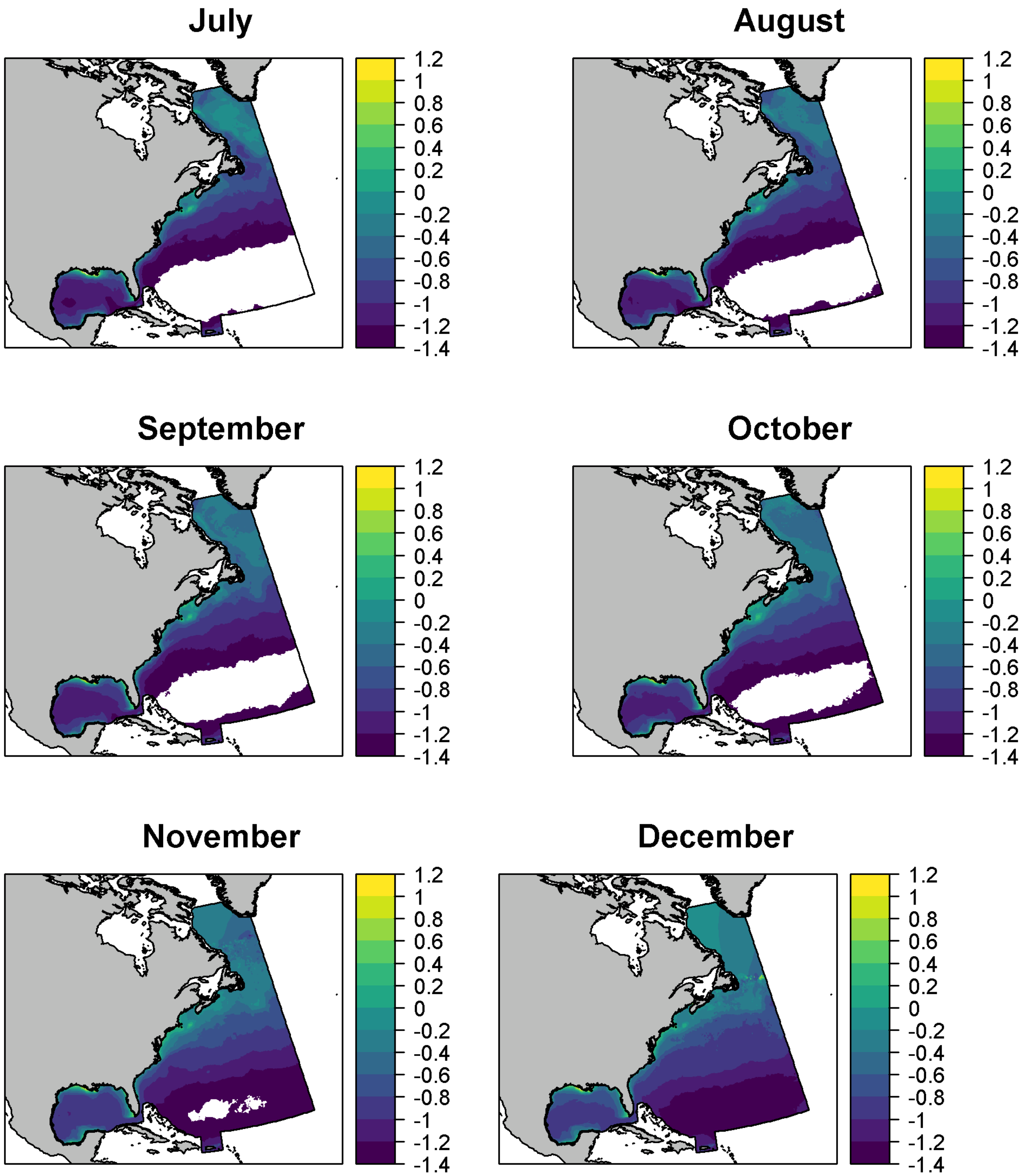
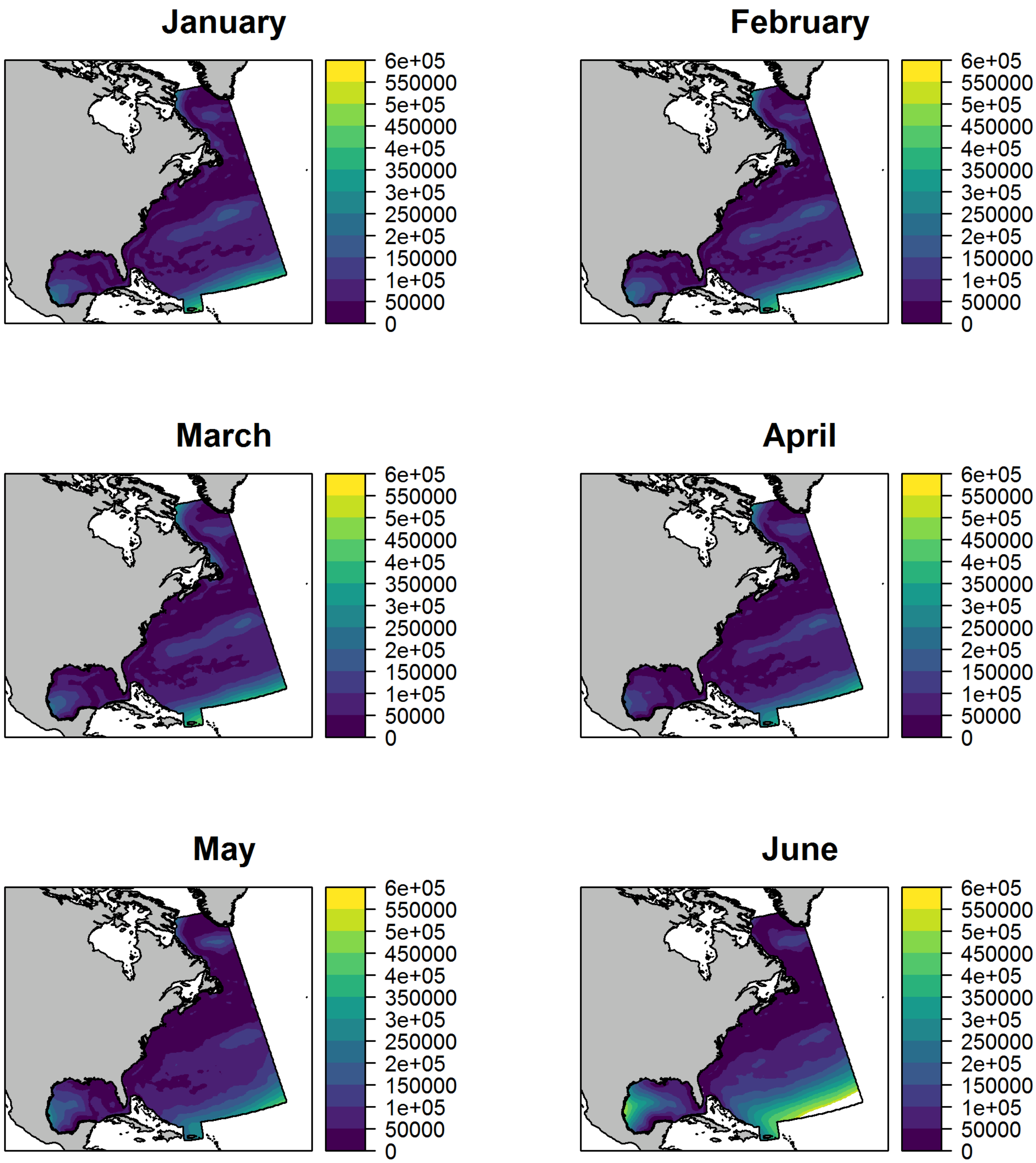


Figure 4: Monthly environmental envelopes for chlorophyll concentration. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
6e+05
550000
5e+05
450000
4e+05
350000
3e+05
250000
2e+05
150000
1e+05
50000
0

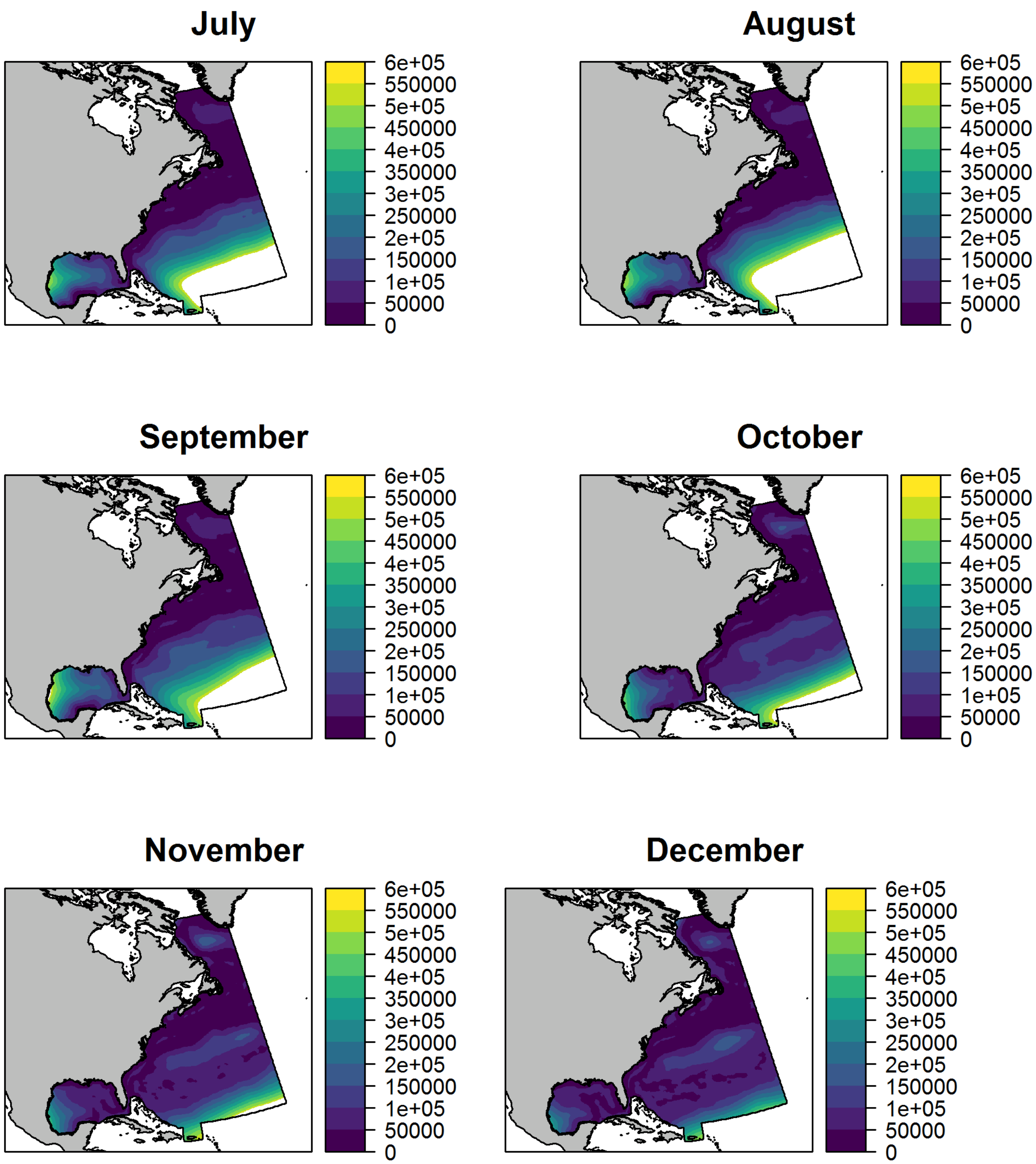
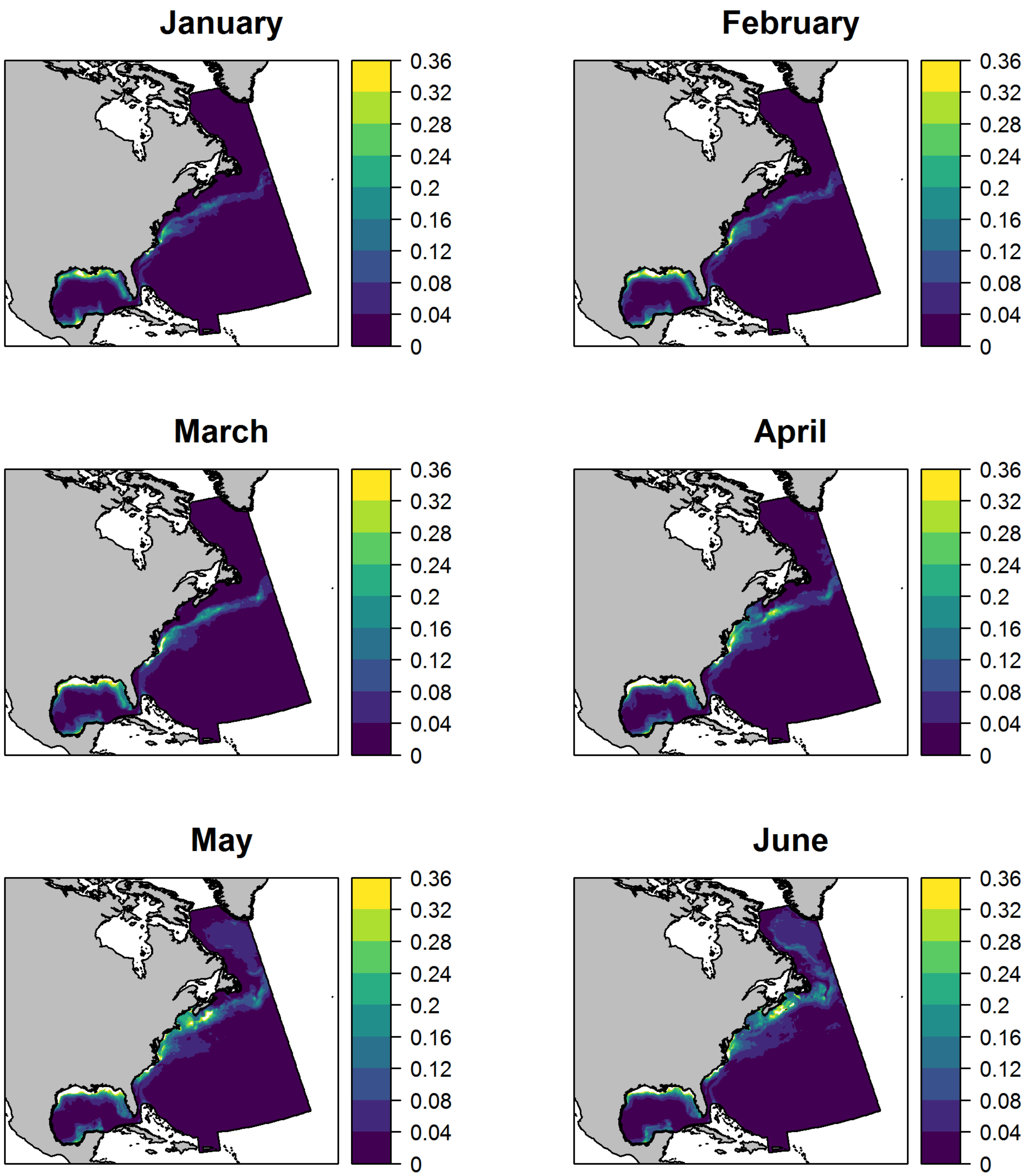


Figure 5: Monthly environmental envelopes for distance to sea surface temperature fronts. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

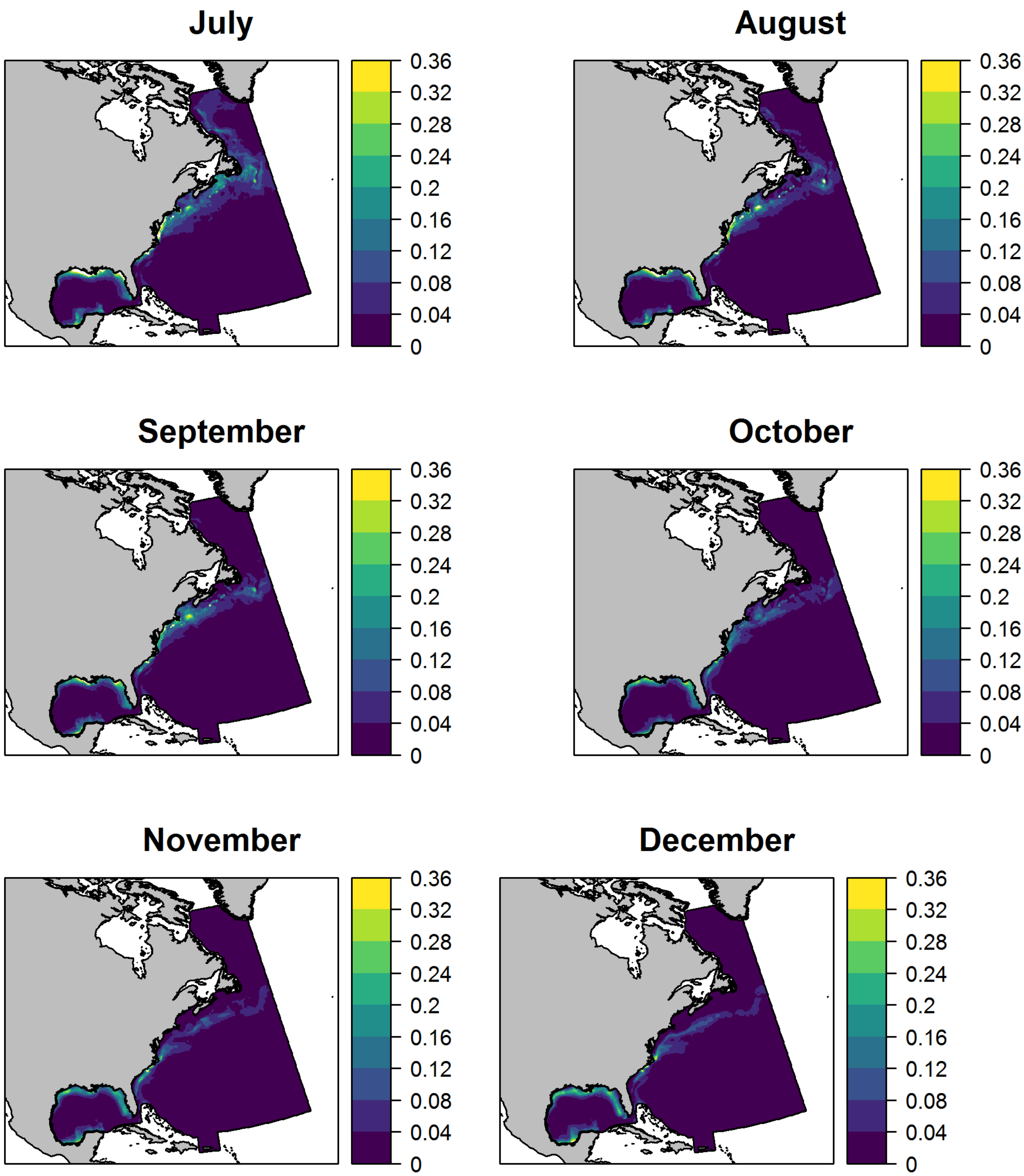


Figure 6: Monthly environmental envelopes for production of epipelagic micronekton. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

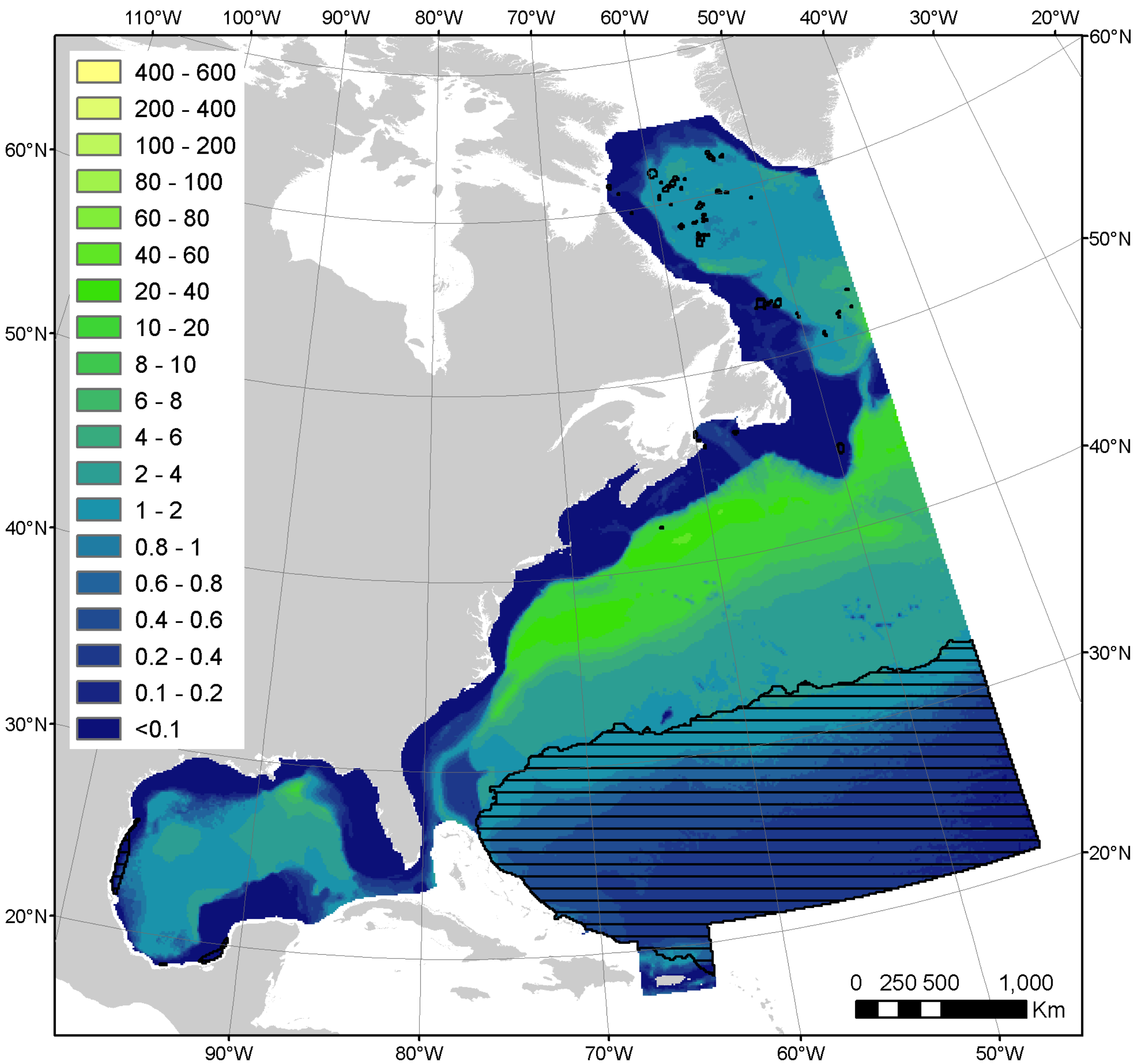


Figure 7: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

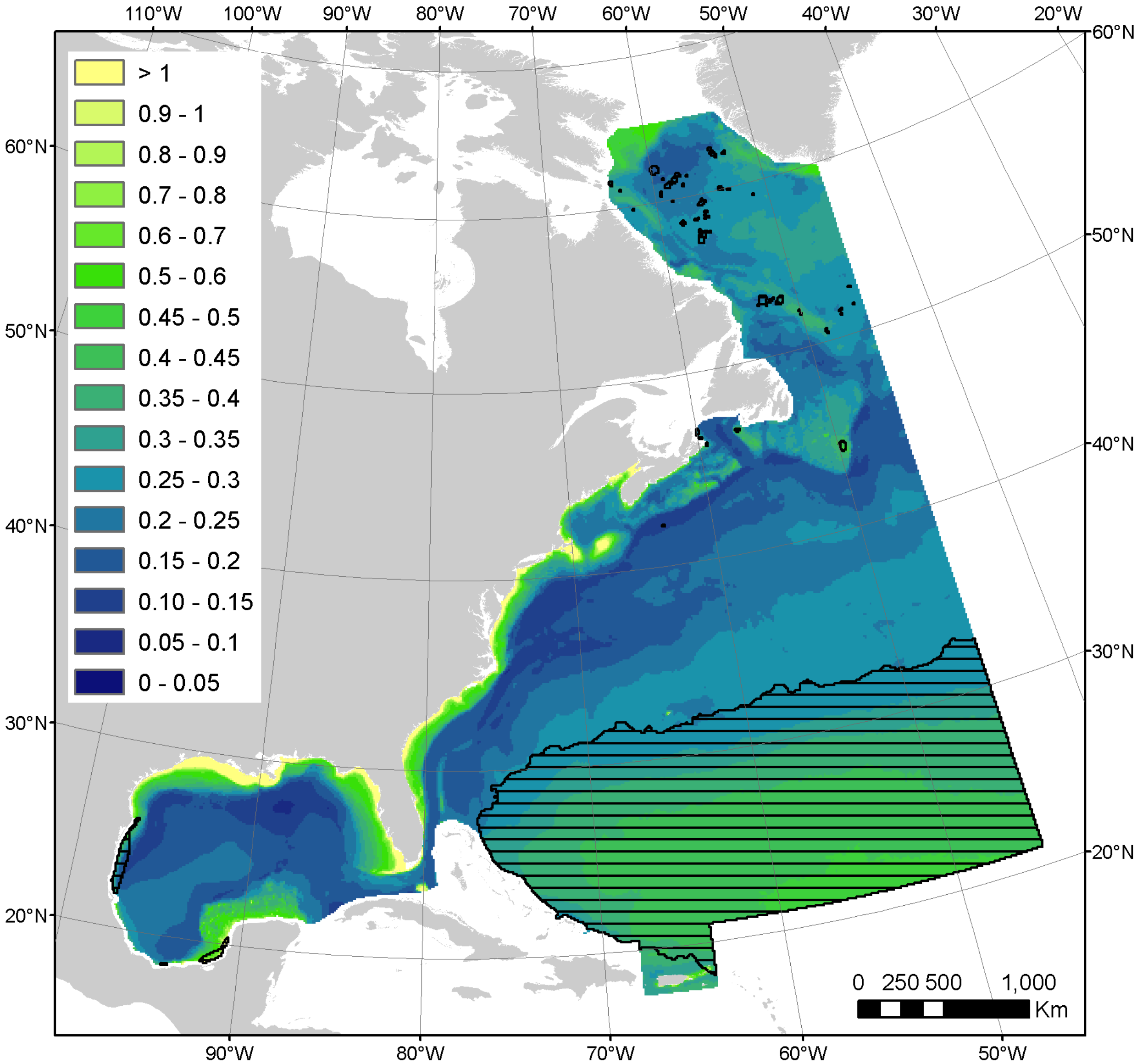


Figure 8: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

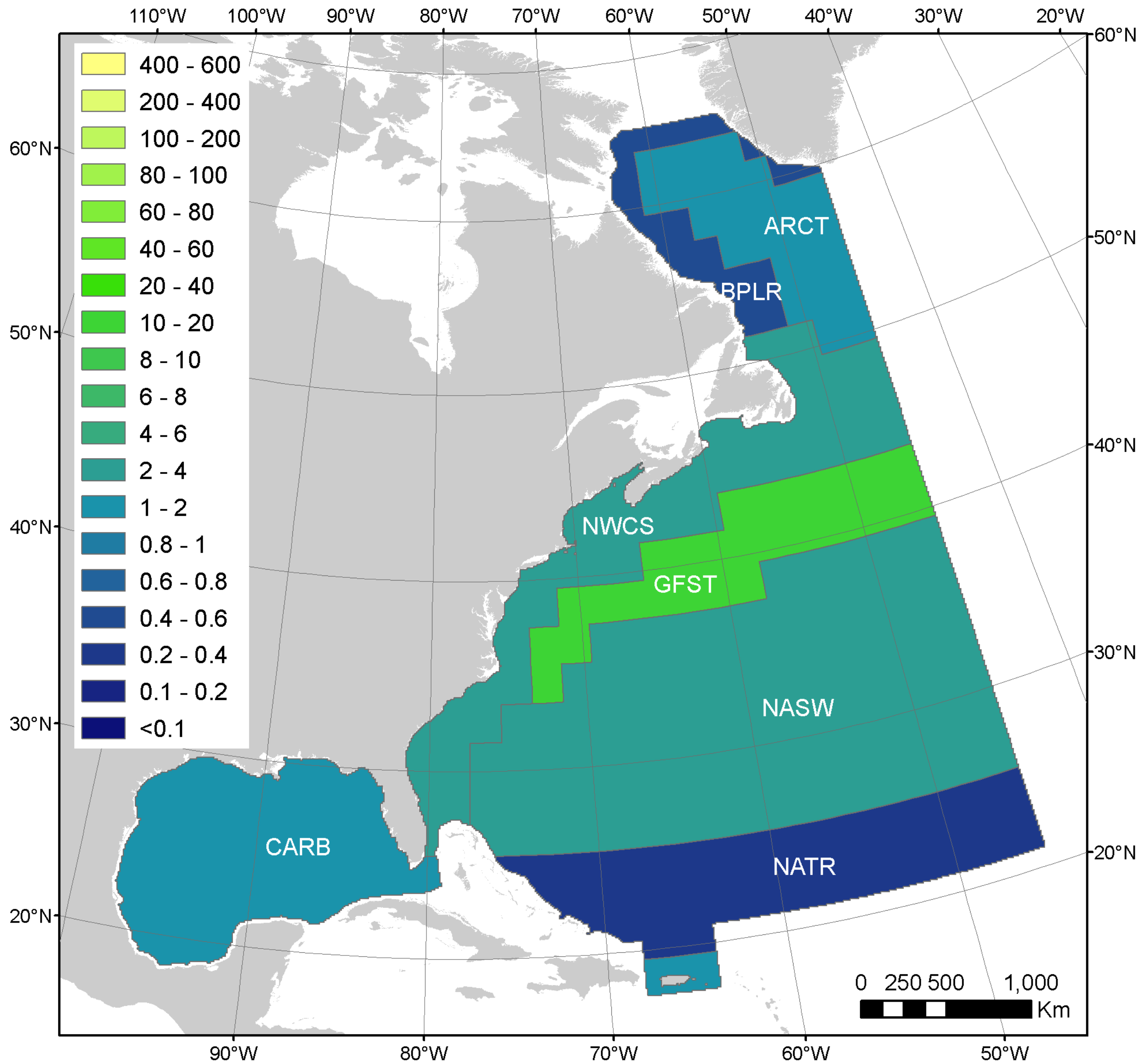


Figure 9: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic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

8- Alternate models

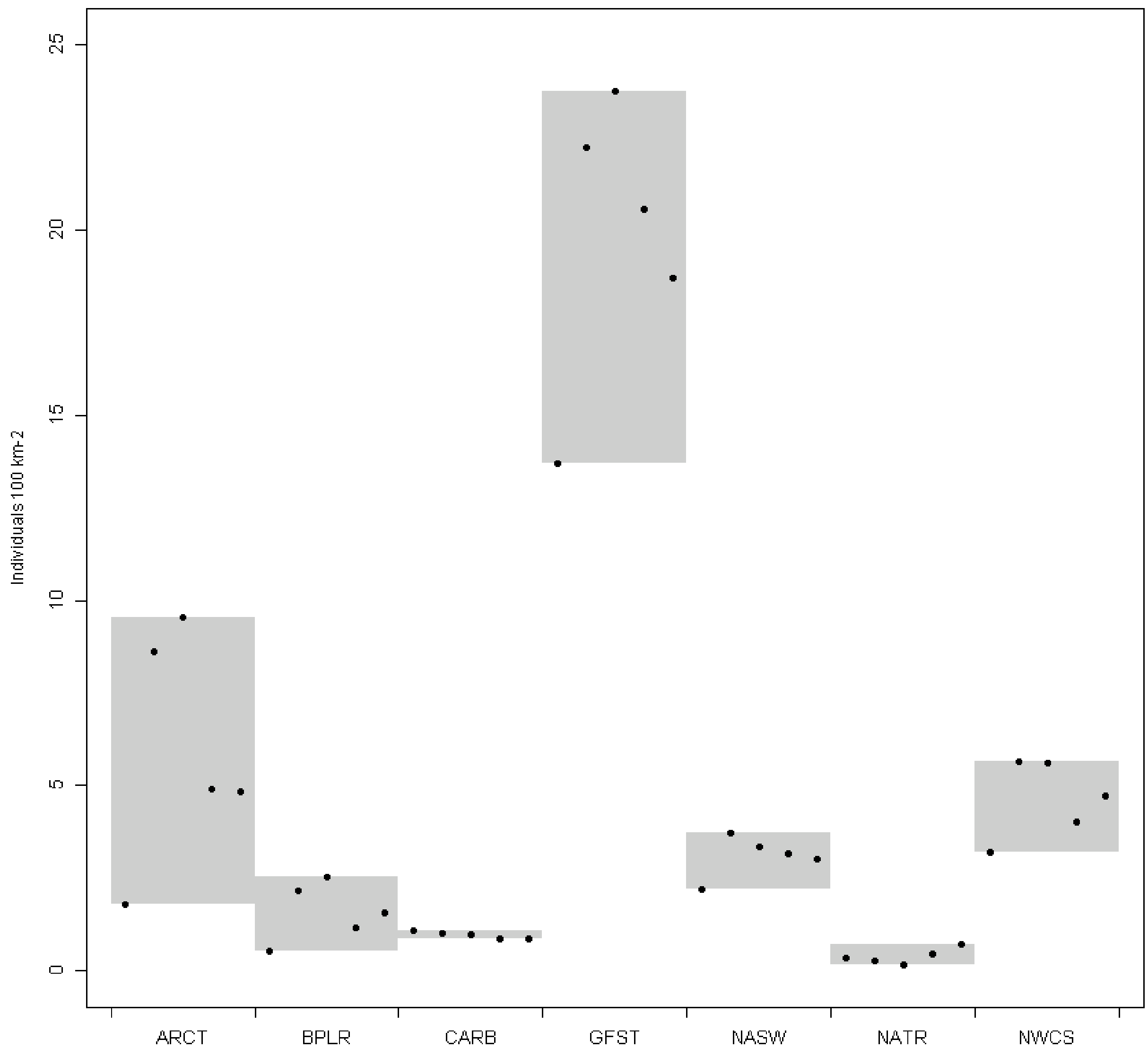


Figure 10: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to 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	DistToFront1	EpiMnkPP	Chl1	118194.6	0.0
Depth	DistToFront1	EpiMnkPB	PkPP	118195.5	0.9
Depth	DistToFront1	EpiMnkPB	VGPM	118195.5	0.9
Depth	SLAStDev	EpiMnkPP	PkPB	118195.7	1.1
Depth	DistToFront1	EpiMnkPP	PkPB	118196.5	1.9

9- Residual diagnostics

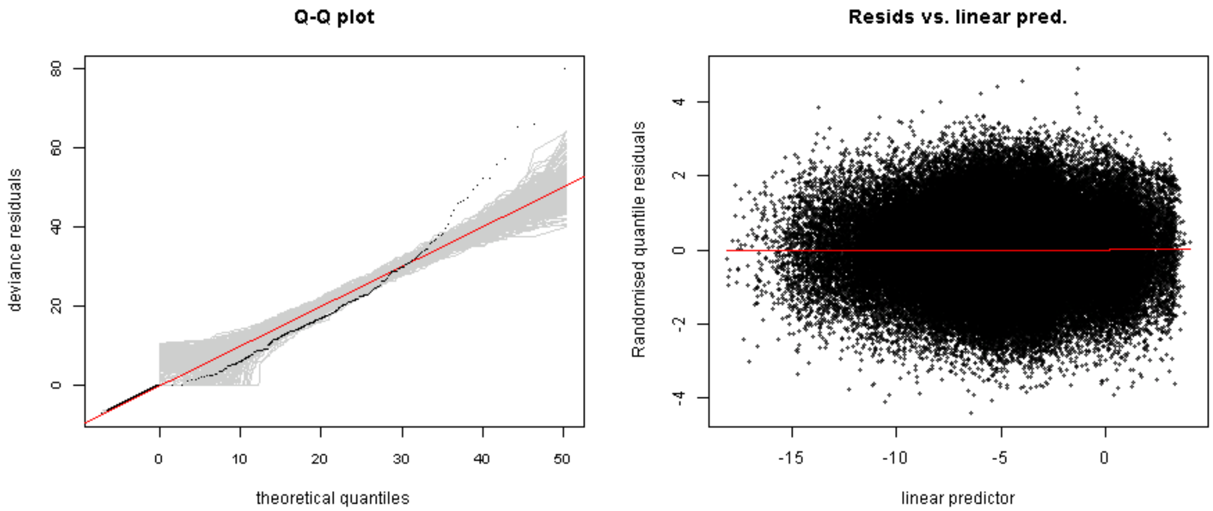


Figure 11: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates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

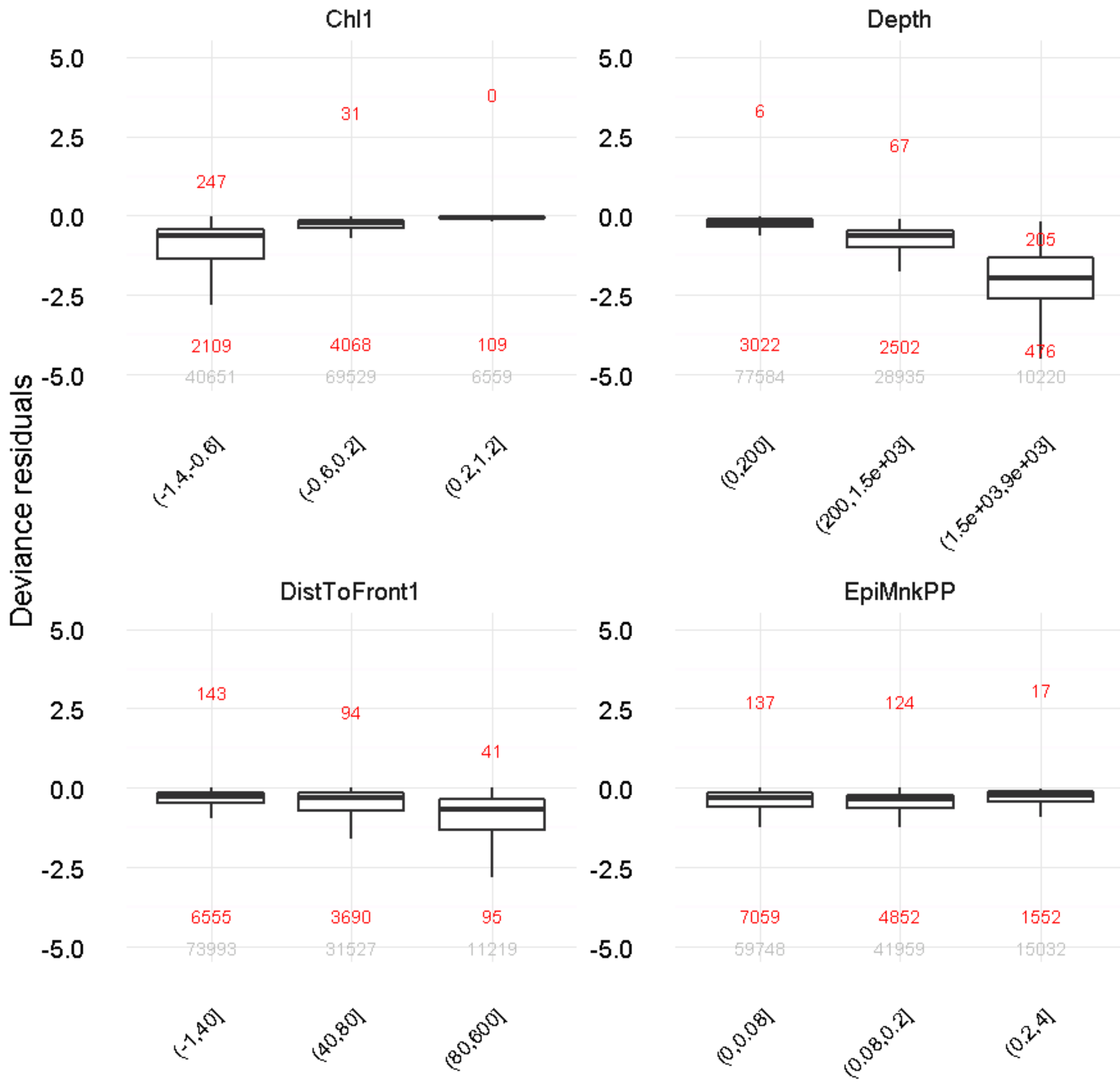


Figure 12: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers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

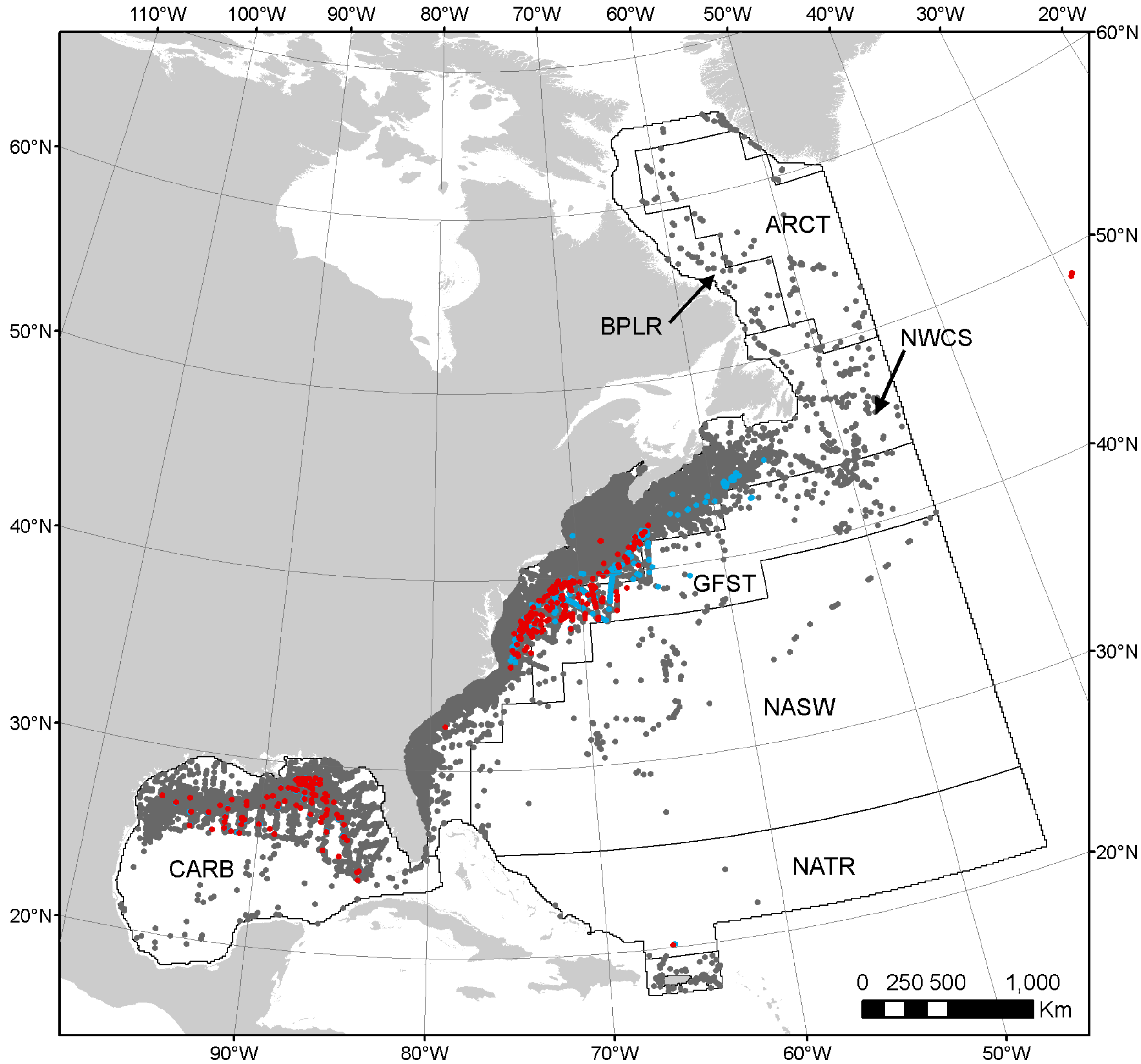


Figure 13: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other 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 336 sightings was available to fit the habitat-based density model (we note that most sightings were from summer months). The first or lowest AIC model included depth, micronekton production, chlorophyll concentration and distance to fronts (listed in decreasing order of importance according to F-scores) and had an explained deviance of 57.2%. All top five models included depth; all but the fourth model also included distance to fronts. All top five models had a delta AIC < 2 indicating some statistical support sensu Burnham and Anderson (2002) (Table 3). Predicted densities from the top five models were very similar in the CARB and NATR provinces and relatively similar in the BPLR, NASW and NWCS provinces. They differed by a factor 4.5 in the ARCT and a factor 1.8 in the GFST province (in both provinces, the first model predicted lower densities than the other four models) (Figure 10). The first model had the lowest AIC and explained slightly more deviance than the other four models, suggesting it was more suitable for modeling striped dolphin densities.

Predictions appeared consistent with the described distribution of striped dolphins in continental slope and oceanic waters (Archer & Perrin 1999; Archer 2009). Although striped dolphins are typically reported in warm temperate to tropical waters, the model predicted them in relatively low densities in cold temperate waters. We note that the northern range of the species is not well-established, with some studies reporting that the northern limit is a function of water temperature (Bloch et al. 1996) or affected by processes such as meanderings of the Gulf Stream (Archer and Perrin 1999). Given this lack of a clear northern limit, we believe predictions are not unrealistic (although more data would be needed to corroborate them).

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

In these provinces, the model predicted overall low densities off the continental shelf. No sightings were reported in OBIS-SEAMAP (but observation effort was very sparse). As already mentioned above, we believe the low predicted densities are not completely unrealistic. Indeed, a few extralimital records exist (mostly strandings) for Canada and Greenland (Archer & Perrin 1999) and striped dolphins were sighted as far north as 48°N at the mid- Atlantic ridge (Waring et al. 2008) (Figure 13). We warn that extrapolation beyond predictor ranges occurred in parts of the ARCT and BPLR provinces and predictions in these areas should be considered with caution. Model uncertainty was also the highest in the ARCT province, resulting in a relatively large range of predicted densities (we believe the lowest densities predicted by the best supported model were probably the most realistic).

North West Atlantic shelves (NWCS) province

Highest densities were predicted in continental slope and offshore waters, consistent with striped dolphin's habitat preferences described in the literature (Archer & Perrin 1999; Archer 2009). Striped dolphins were reported on the continental slope off Nova Scotia (Figure 13) and sighted on 4 occasions on the Scotian shelf during the Canadian TNASS 2007 survey (Lawson & Gosselin 2009) (sightings not contributed to OBIS-SEAMAP and therefore not shown on Figure 13). Most records from eastern Canada are sightings concentrated in deep waters of the Gully canyon (Baird et al. 1993, Gowans and Whitehead 1995, Hooker et al. 1999).

Lower densities were predicted south of 33°N where few sightings were reported (Figure 13).

Gulf Stream (GFST) province

The Gulf Stream was the province where highest striped dolphin densities were predicted. We note that the best supported model predicted lower densities compared to the other four models. Surveys off the continental shelf in the western part of the GFST province reported numerous sightings of striped dolphins (Figure 13). However, predicted densities in the eastern part of the GFST province were supported by very sparse effort and only a few available sightings reported in OBIS-SEAMAP (Figure 13). Striped dolphins have been reported to associate with the north wall of the Gulf Stream and warm core rings (Waring et al.

1992). In other parts of the world, they are also known to associate with strong currents (e.g., the Kuroshio Current) (Miyazaki et al. 1974; Archer & Perrin 1999).

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

Our model predicted overall low densities in the NASW and NATR provinces. No sighting was reported in the NASW province and only one sighting was reported in the NATR province, as far south as 20°N during a NOAA line transect survey included in this study, but these provinces received very little observation effort (Figure 13). We note that extrapolation to waters of lower chlorophyll concentration occurred in the southern part of the NASW province and throughout the NATR province; therefore, predicted densities should be considered with due caution.

Caribbean (CARB) province

In the Gulf of Mexico, striped dolphins were mainly predicted off the continental shelf, with higher densities in the northeastern Gulf of Mexico where numerous sightings were recorded by surveys. To our knowledge, only 2 records exist for striped dolphins in the southern Gulf of Mexico, both strandings (Ortega-Ortiz 2002).

Sightings of striped dolphins have not been documented near Puerto Rico (Mignucci Giannoni 1998), consistent with low densities predicted by the model.

Overall confidence level: 3

Predictions seemed generally in line with striped dolphin's core distribution in offshore temperate water and its described affinity for the Gulf Stream. However, we believe the low densities predicted in sub-polar waters were likely overestimated. The incorporation of line transect survey data from Canada and Greenland would help correct this possible overestimation. 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 model.

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