Habitat-based density model for fin whale in the AFTT area

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This report documents the habitat-based density model for fin whale 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 fin whale 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	3
EC	1044357.704	1781
EU	27526.342	192
GOM	194715.349	1
MAR	2424.421	12
All regions	1293288.288	1989

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

Month	Effort	Sightings
January	77892.79	59
February	123591.37	41
March	117923.54	58
April	117929.72	134
May	149765.03	255
June	132713.99	370
July	162324.31	487
August	129660.43	223
September	71696.07	60
October	82560.18	132
November	69210.92	103
December	58019.93	67
All Months	1293288.29	1989

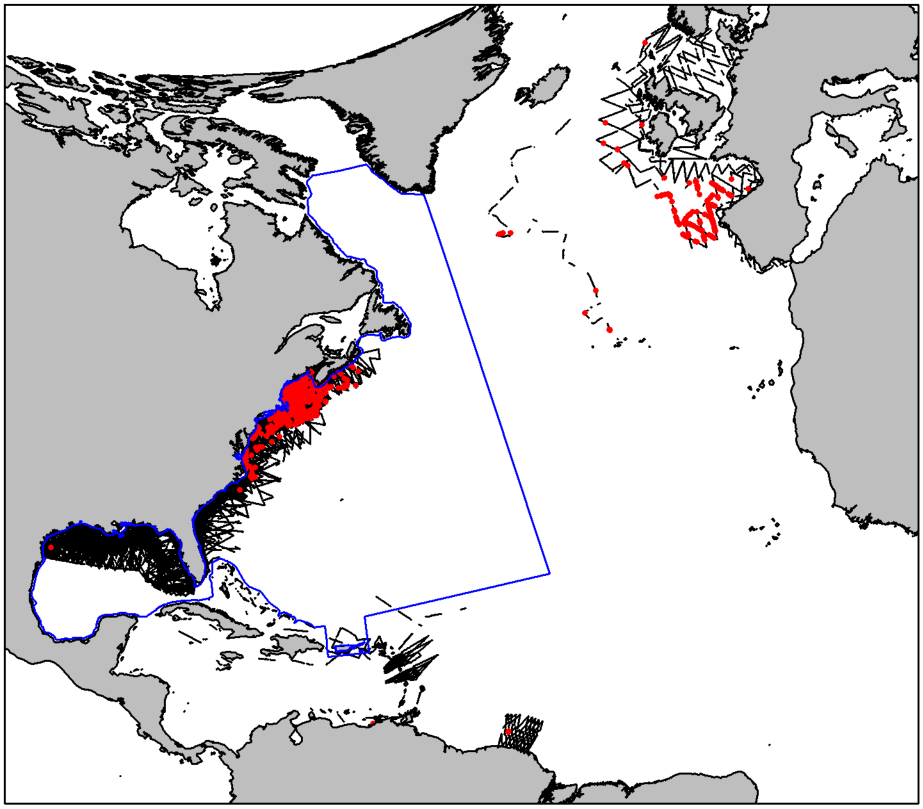


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

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

Fin whale (*Balaenoptera physalus*)

Modeled season

Contrary to humpback whales, fin whales do not undertake long-range migrations that result in distinct distributions in summer and winter (Edwards et al. 2015, Aguilar 2009). In addition, there is evidence that some fin whales remain at mid latitudes year-round, indicating that not all individuals engage in concerted migrations (Hain et al. 1992). Given this information, it seemed reasonable to fit a year-round model.

Segments

We incorporated segments from the east coast, Gulf of Mexico and Caribbean. Incorporating segments from the mid-Atlantic ridge and the European Atlantic resulted in lower predicted densities on the continental shelf and slope, and higher predicted densities in oceanic waters. This appeared inconsistent with the known affinity of fin whales for the continental shelf and slope in our study area (Hain et al. 1992, Hamazaki 2002). Sightings in the western North Atlantic were concentrated on the continental shelf, whereas they were mostly beyond the shelf on the eastern North Atlantic, suggesting that fin whales may target different prey or respond to different underlying environmental drivers in each part of the basin. Based on this presumption, we included segments from the western North Atlantic only.

Special treatment in the Gulf of Mexico

Since fin whales are described as accidental in 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**: slope, distance to SST fronts (DistToFront), production of epipelagic micronekton (EpiMnkPP), sea surface temperature (SST)
- **Model summary**:

```
##
## Family: Tweedie(p=1.186)
## Link function: log
##
## Formula:
## abundance ~ s(Slope, k = 4, bs = "ts") + s(DistToFront1, k = 4,
##     bs = "ts") + s(EpiMnkPB, k = 4, bs = "ts") + s(SST, k = 4,
##     bs = "ts") + offset(log(area_km2))
## <environment: 0x000000000c16bc48>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept)  -7.3225     0.1273  -57.54   <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(Slope)        2.479      3 57.448  < 2e-16 ***
## s(DistToFront1) 1.051      3  6.124 1.06e-05 ***
## s(EpiMnkPB)     2.942      3 65.588  < 2e-16 ***
## s(SST)          2.923      3 44.945  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.0141   Deviance explained = 22.9%
## -REML =  12188  Scale est. = 24.488    n = 120884
```

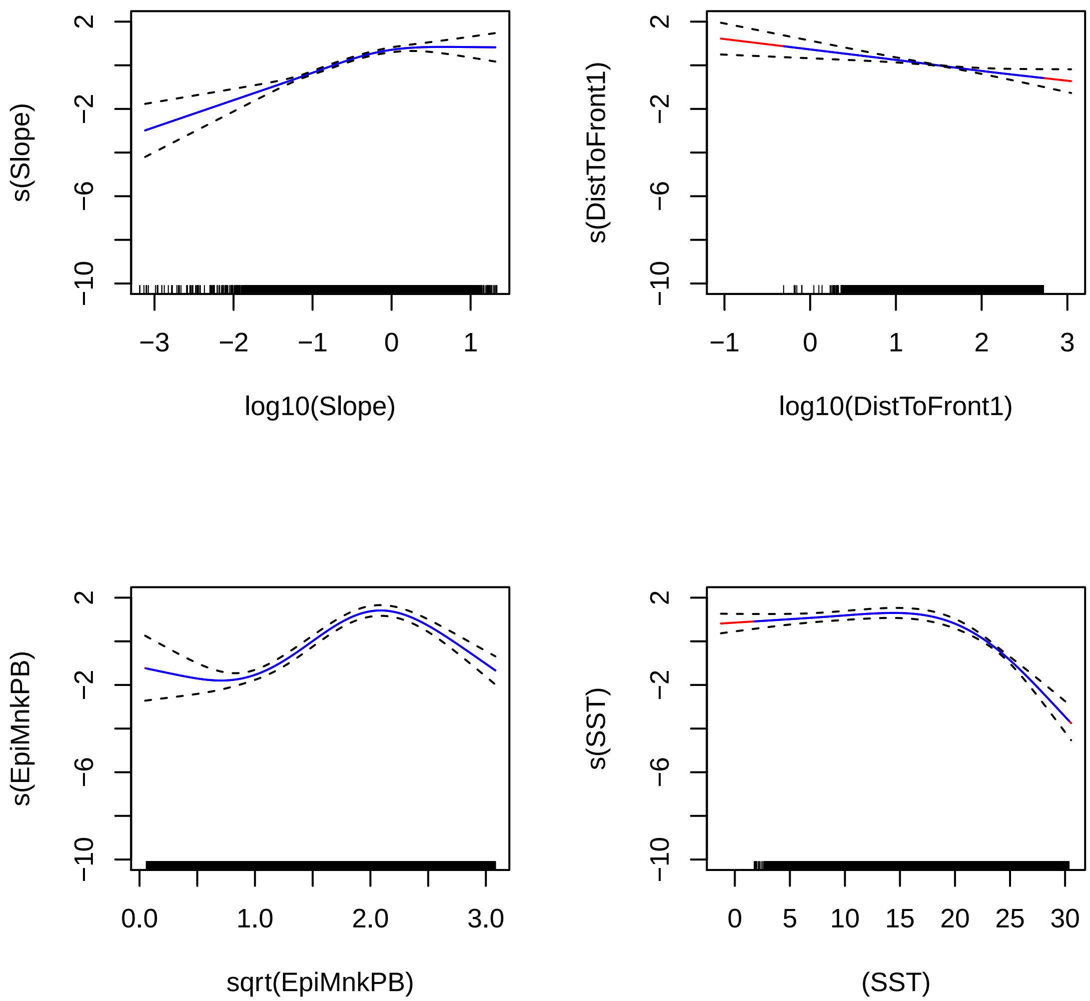


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals.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

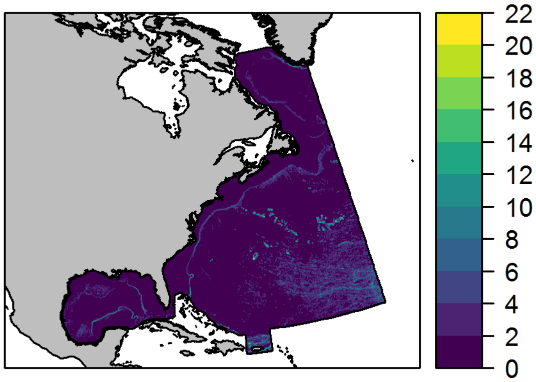
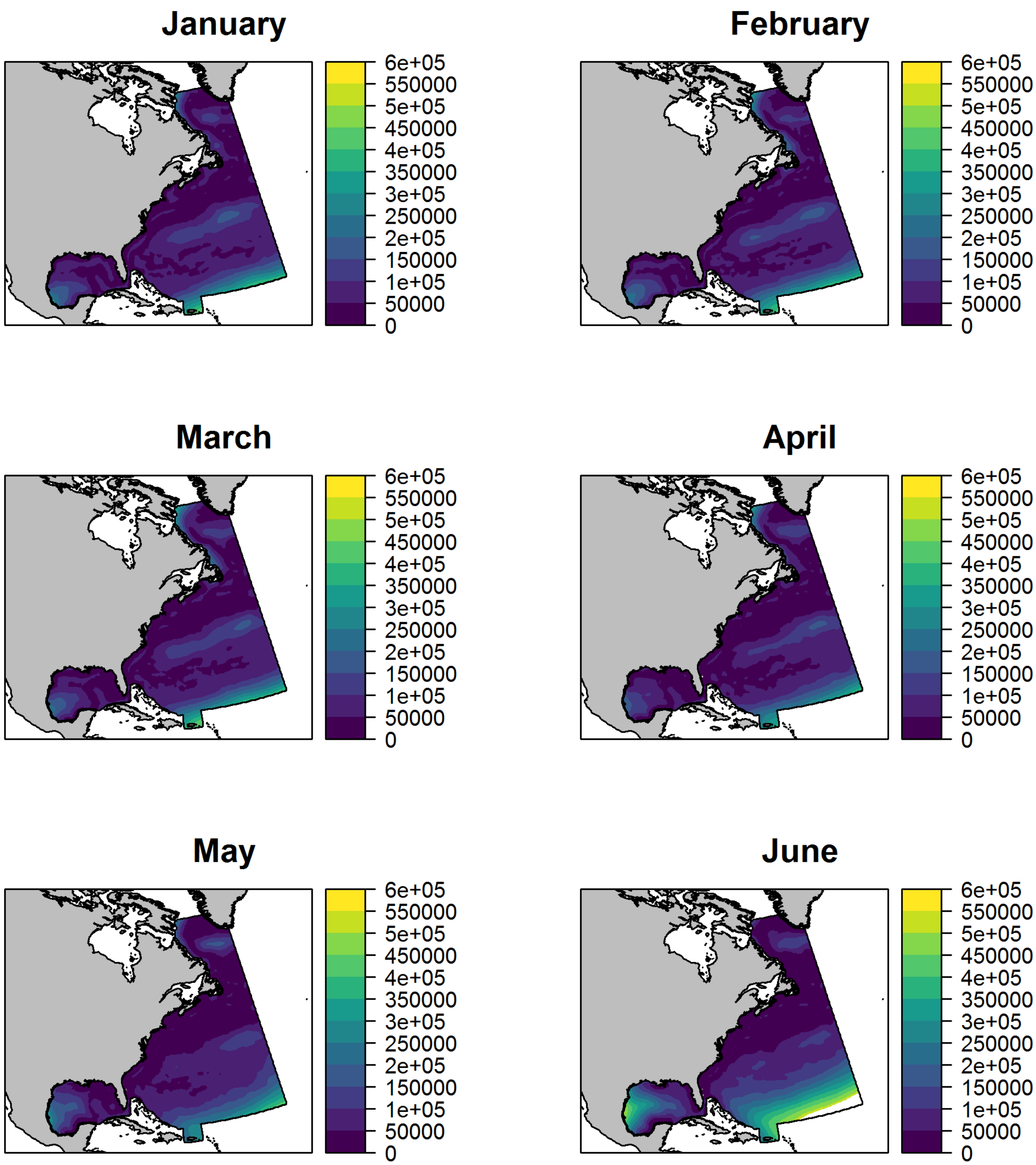


Figure 3: Environmental envelope for slope. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

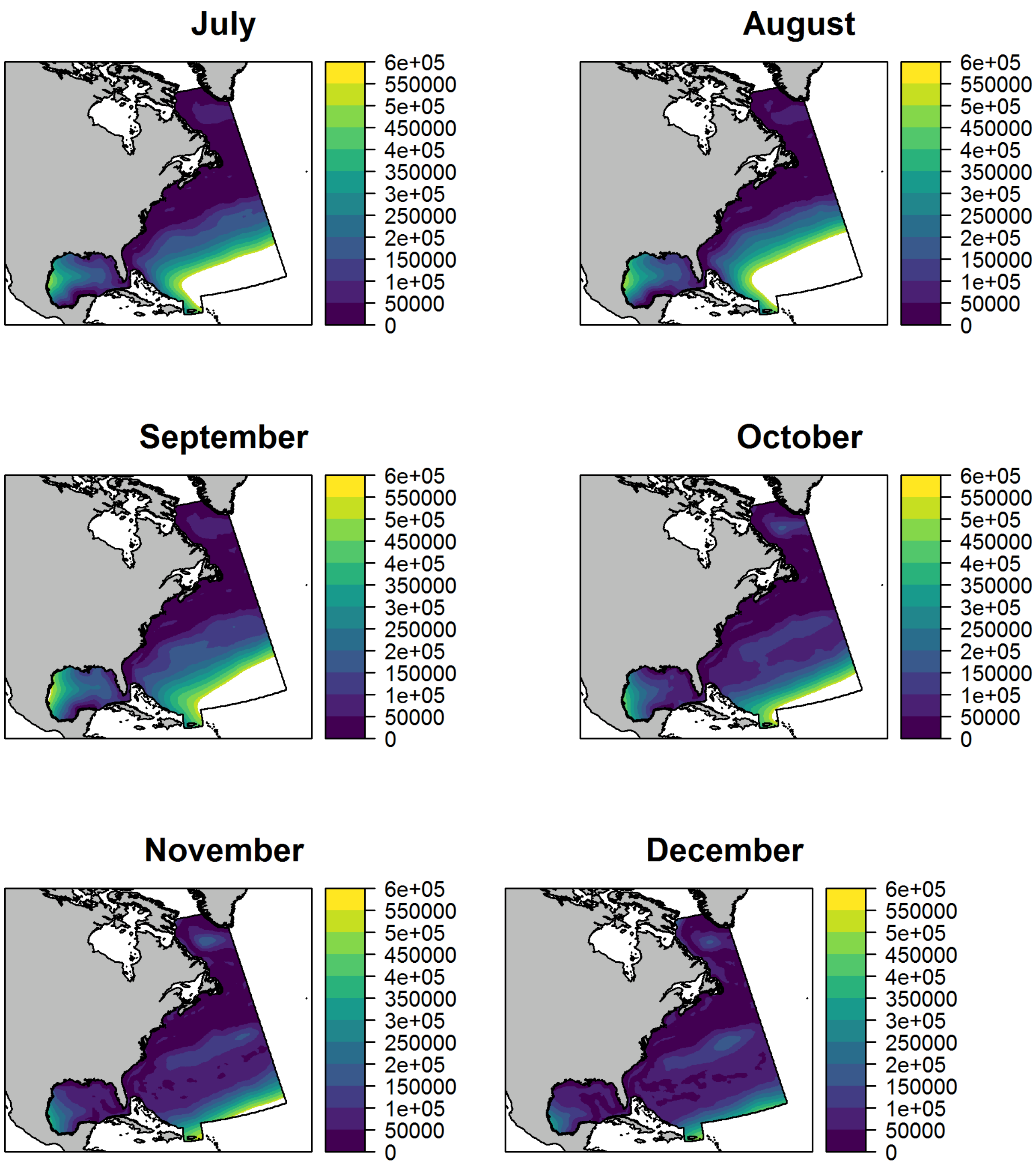
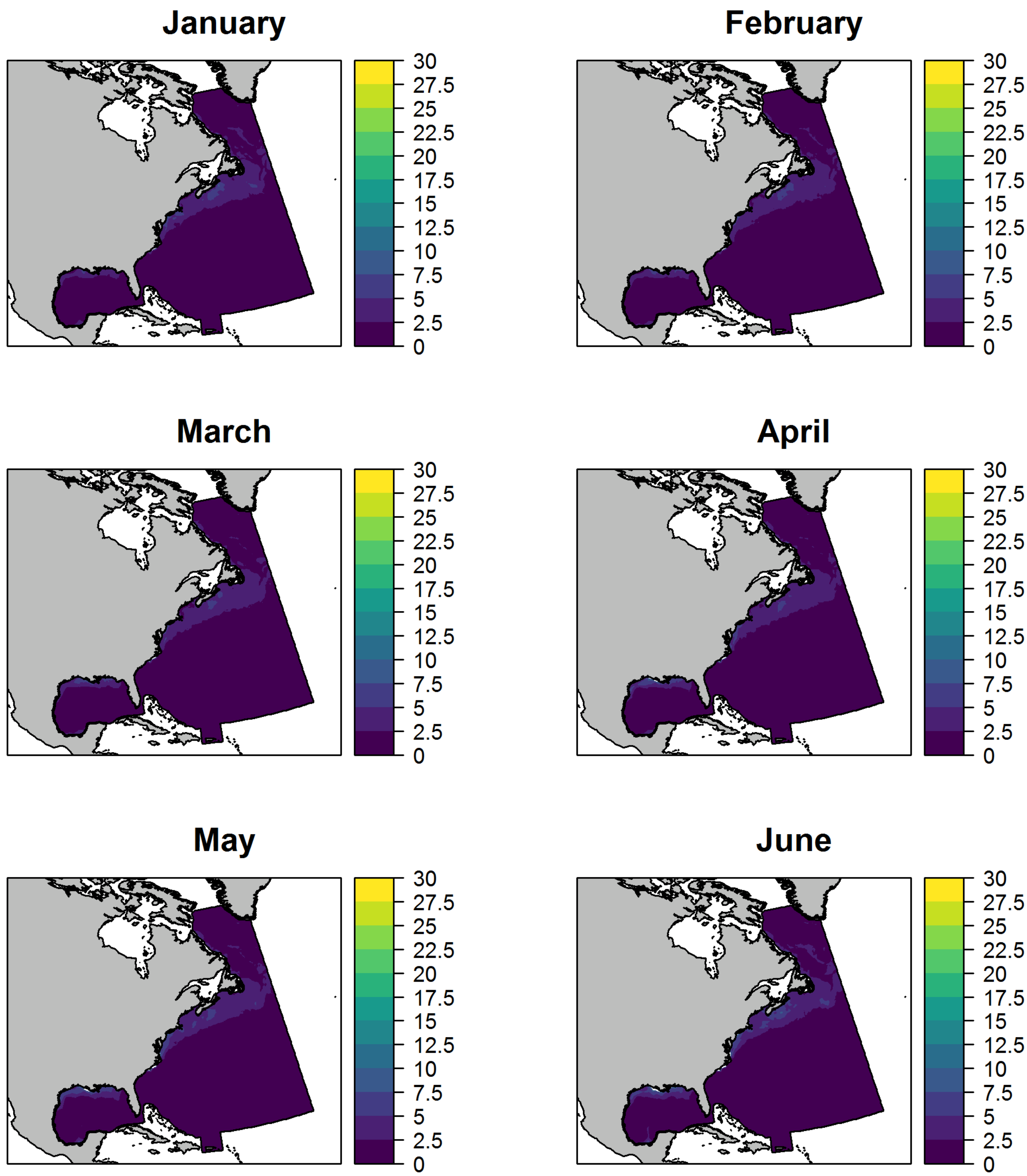


Figure 4: Monthly environmental envelopes for distance to SST fronts. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


January
February
March
April
May
June
30
27.5
25
22.5
20
17.5
15
12.5
10
7.5
5
2.5
0

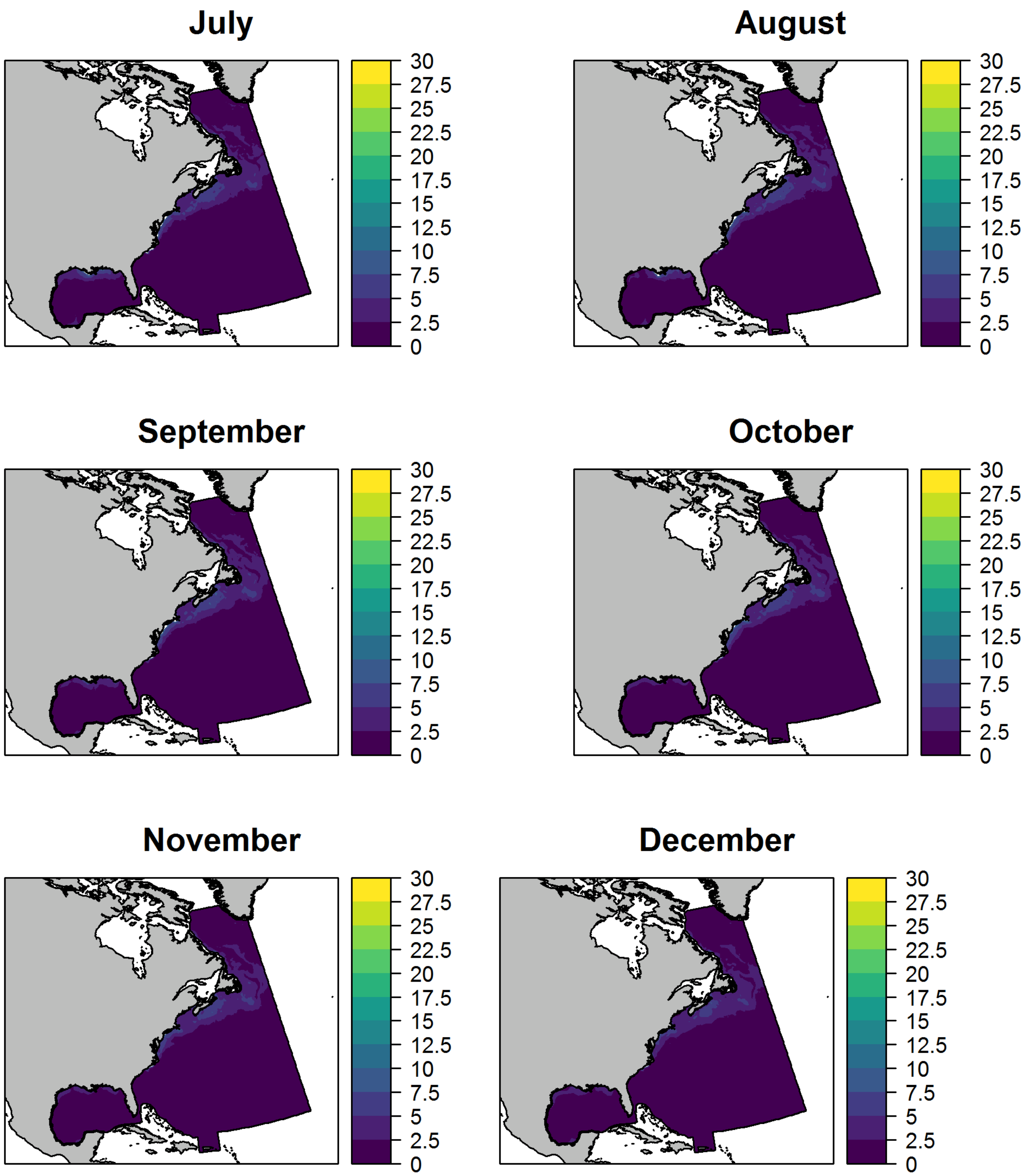
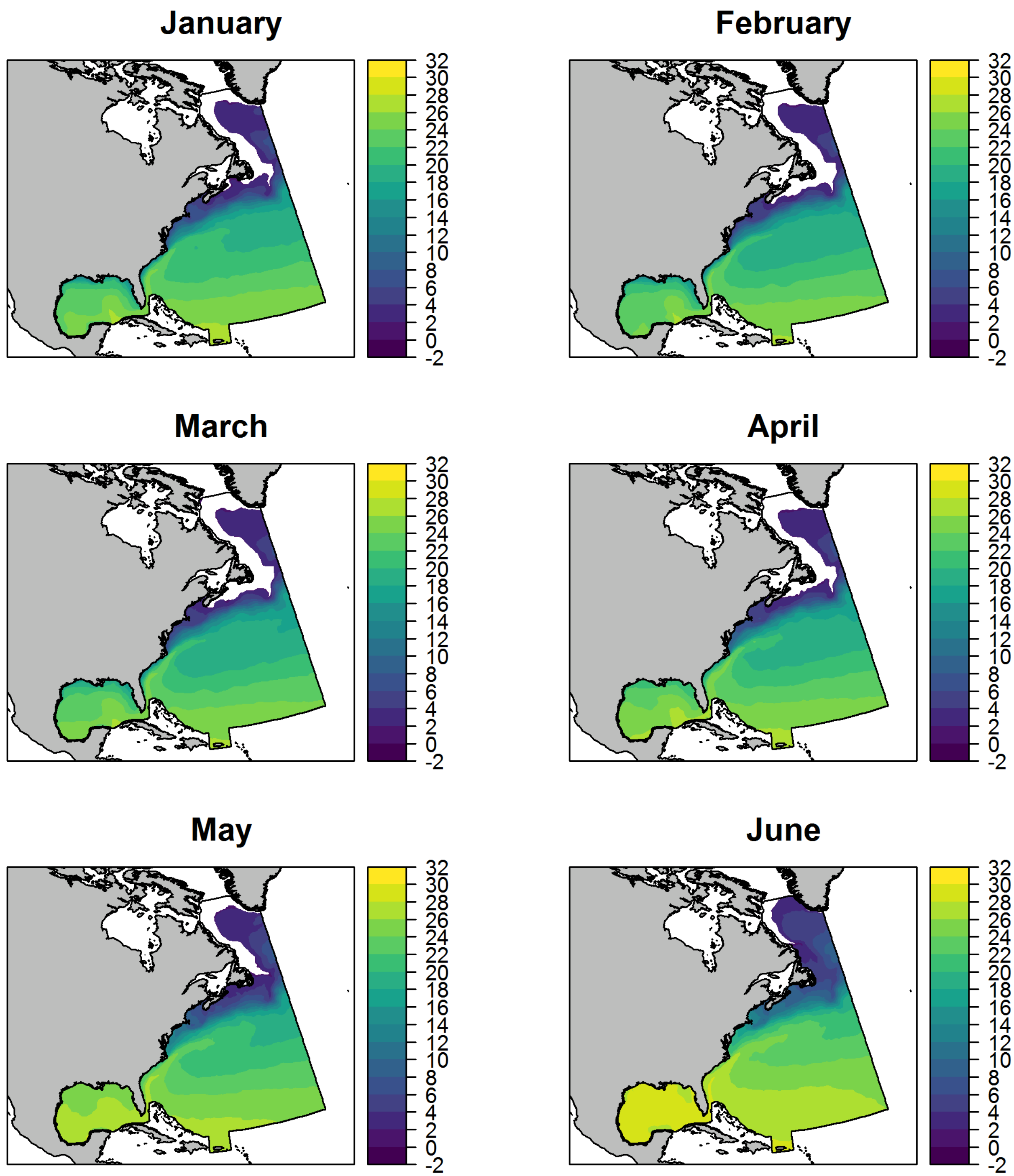


Figure 5: Monthly environmental envelopes for production of epipelagic micronekton. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

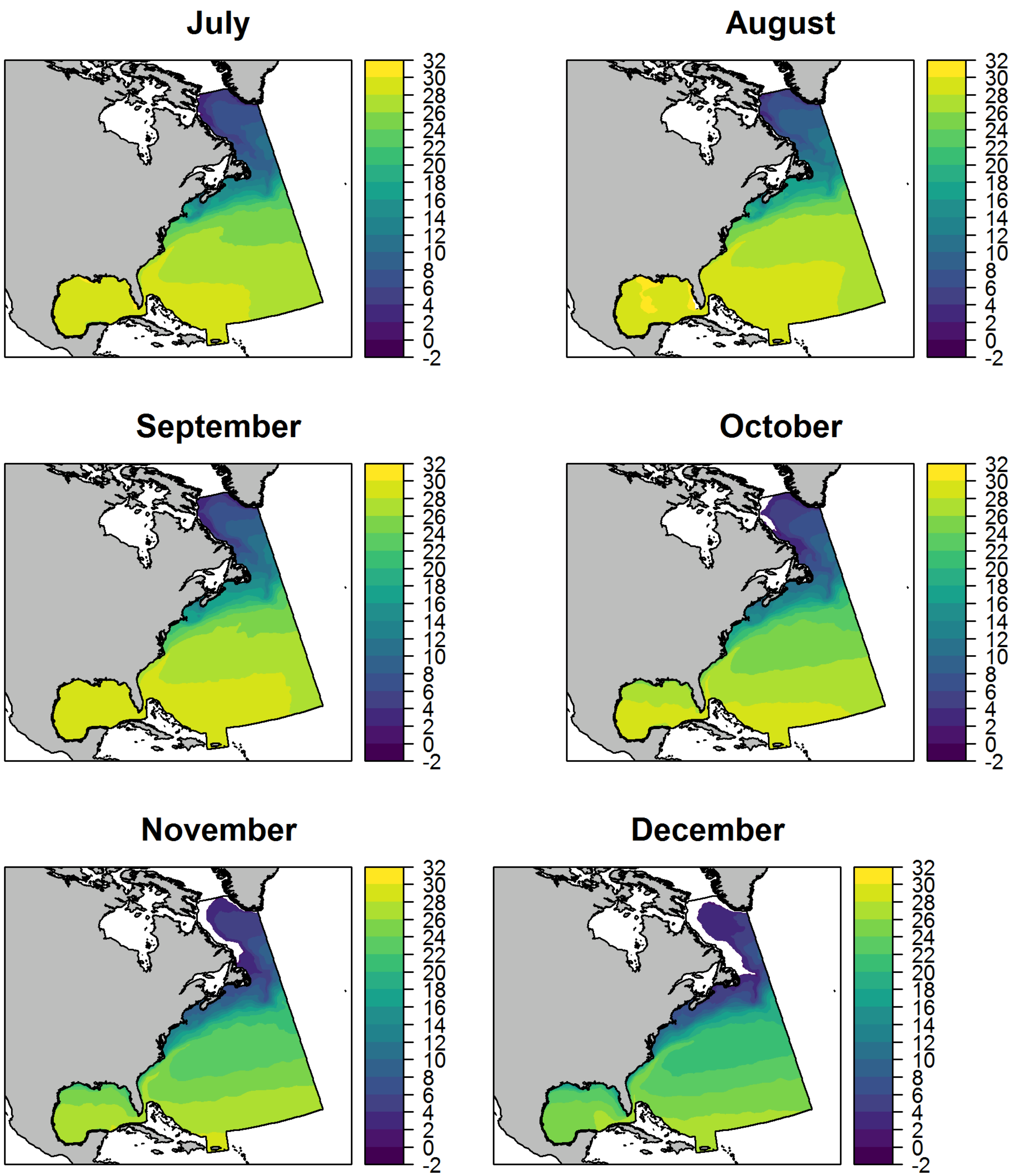


Figure 6: Monthly environmental envelopes for sea surface temperature. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

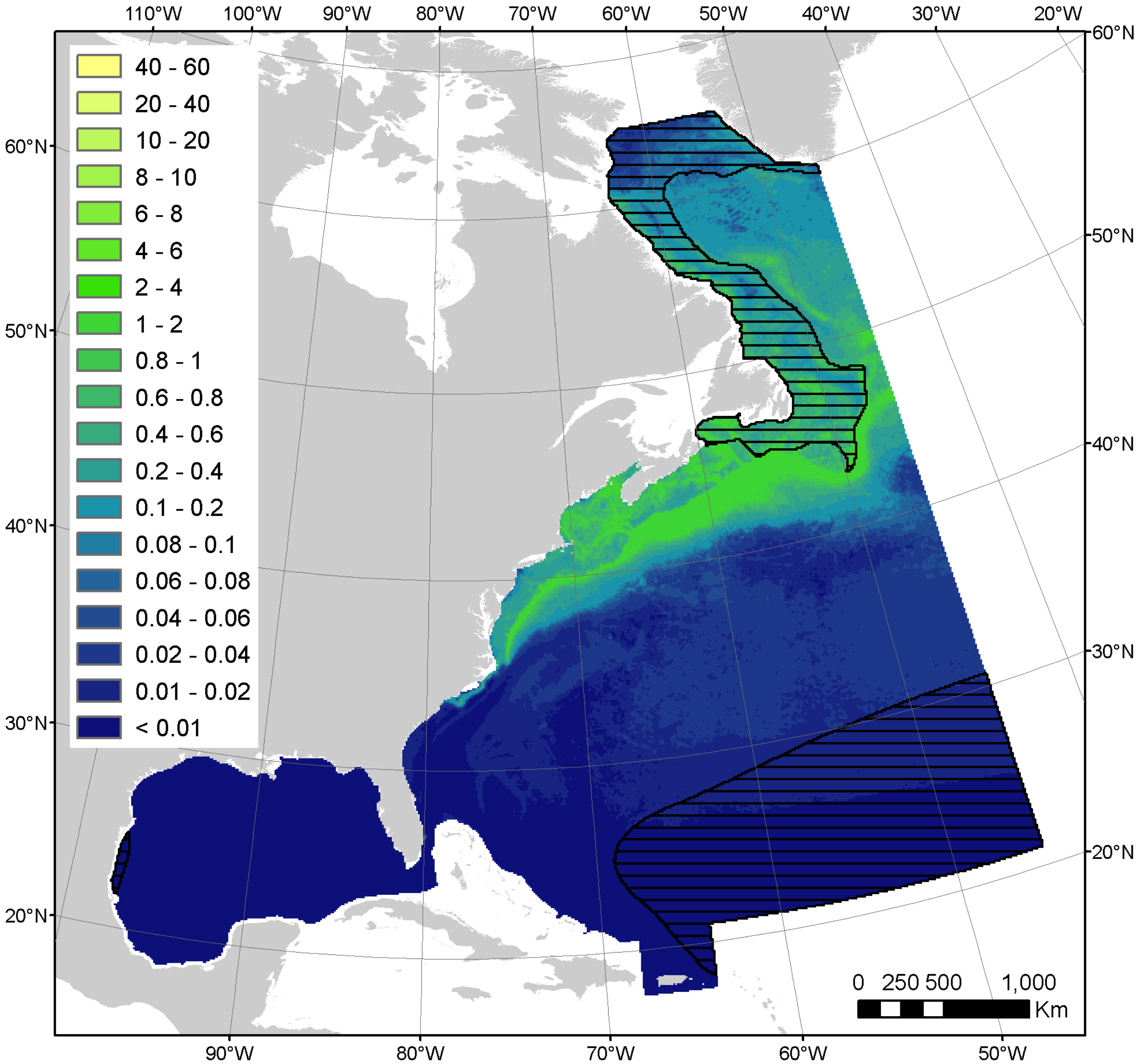


Figure 7: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

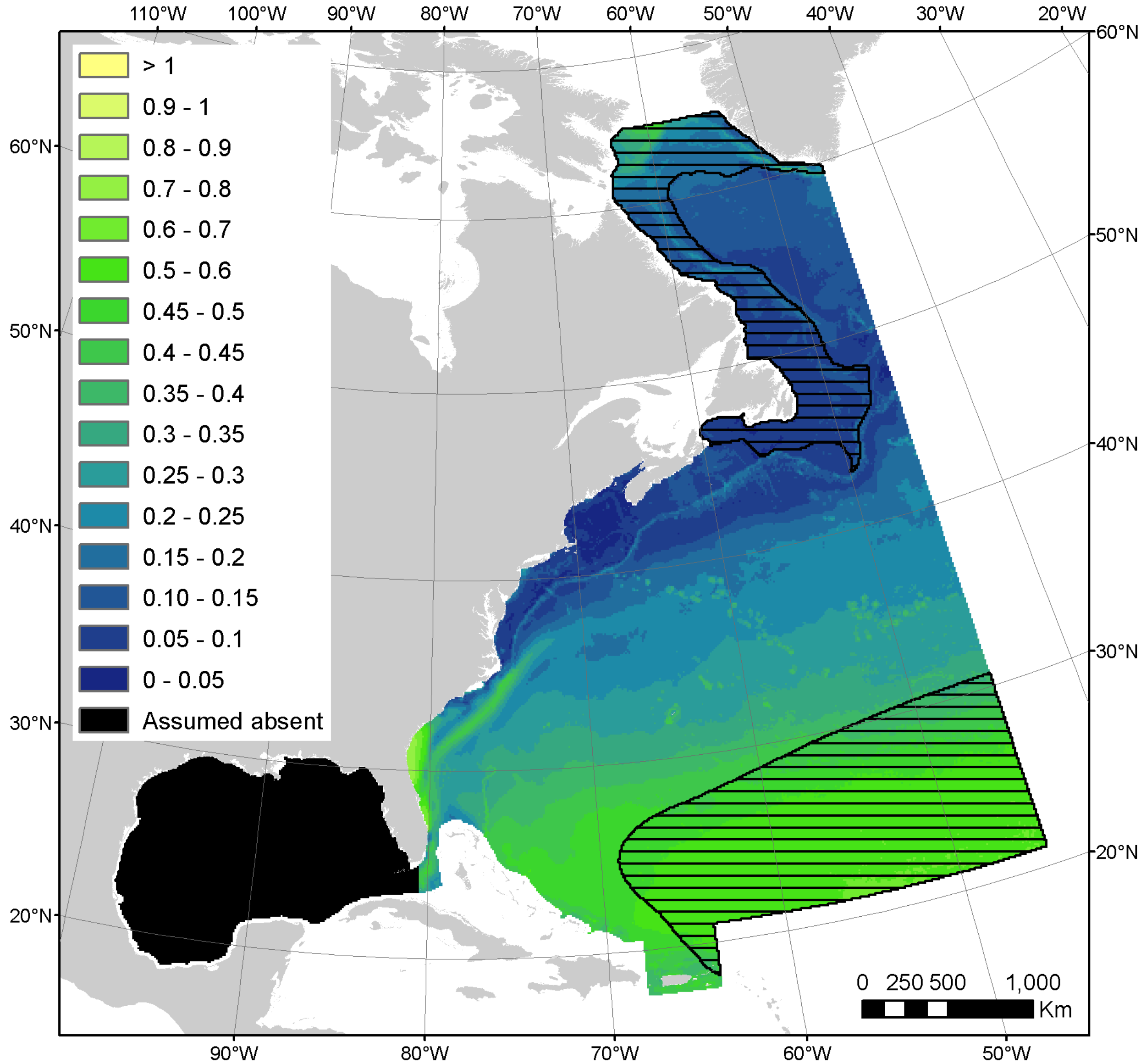


Figure 8: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

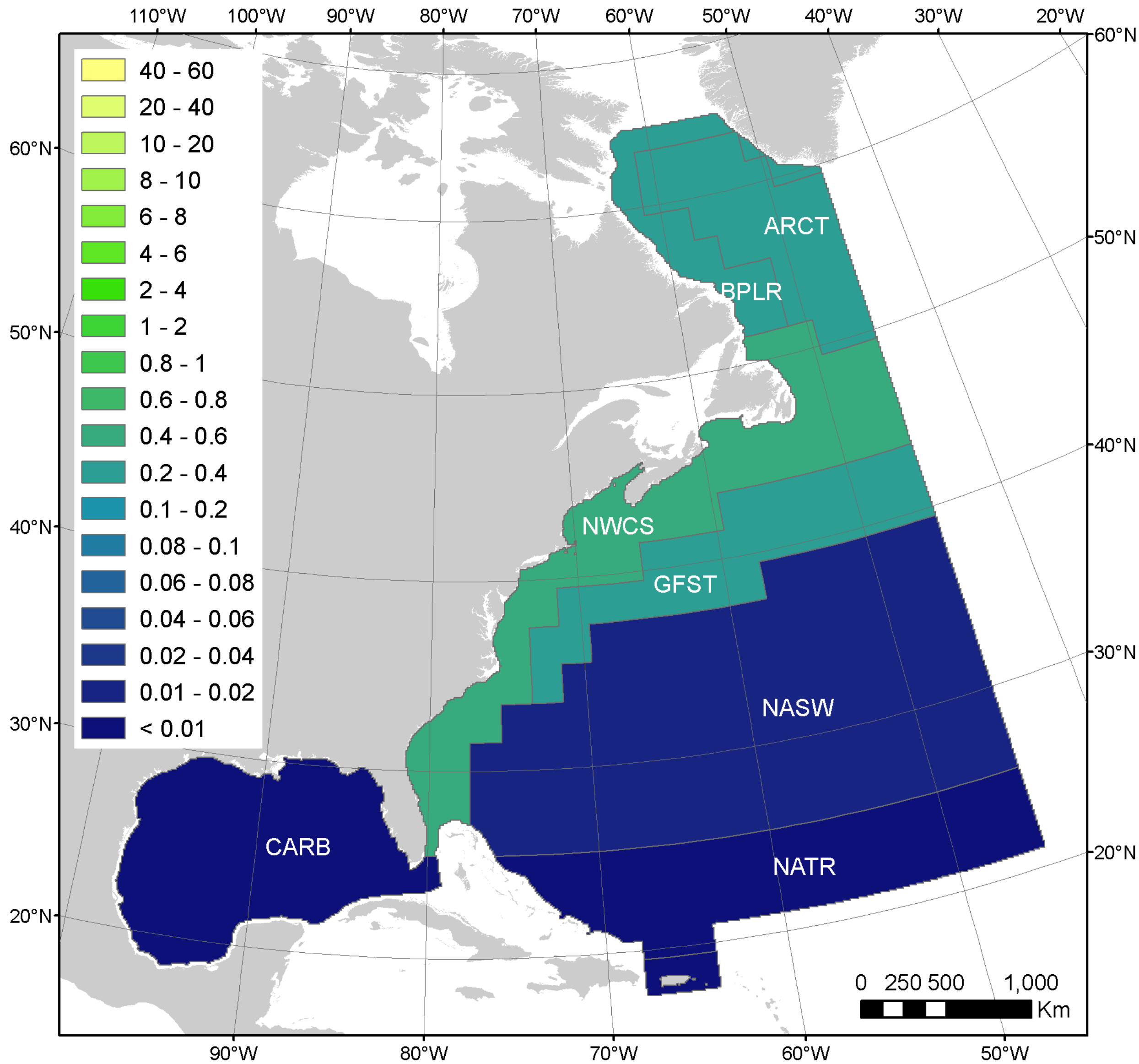


Figure 9: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic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

8- Alternate models

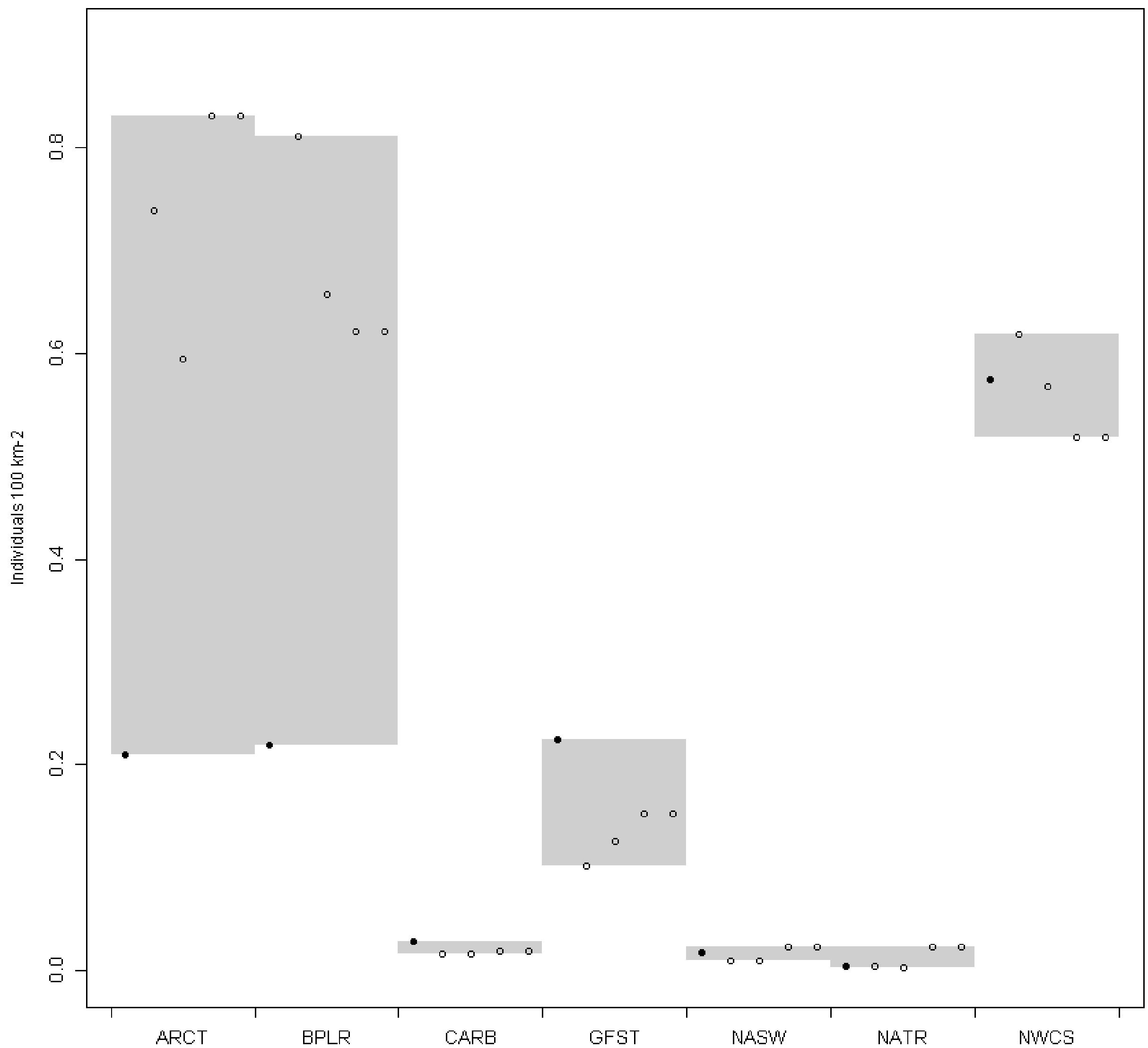


Figure 10: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to 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
DistToFront1	Slope	EpiMnkPB	SST	121288.2	0.0
DistToFront1	Slope	PkPB	SLAStDev	121291.9	3.7
DistToFront1	Slope	PkPB	EpiMnkPP	121292.9	4.7
DistToFront1	Depth	PkPB	ns	121295.1	6.9
DistToFront1	Depth	PkPB	ns	121295.1	6.9

9- Residual diagnostics

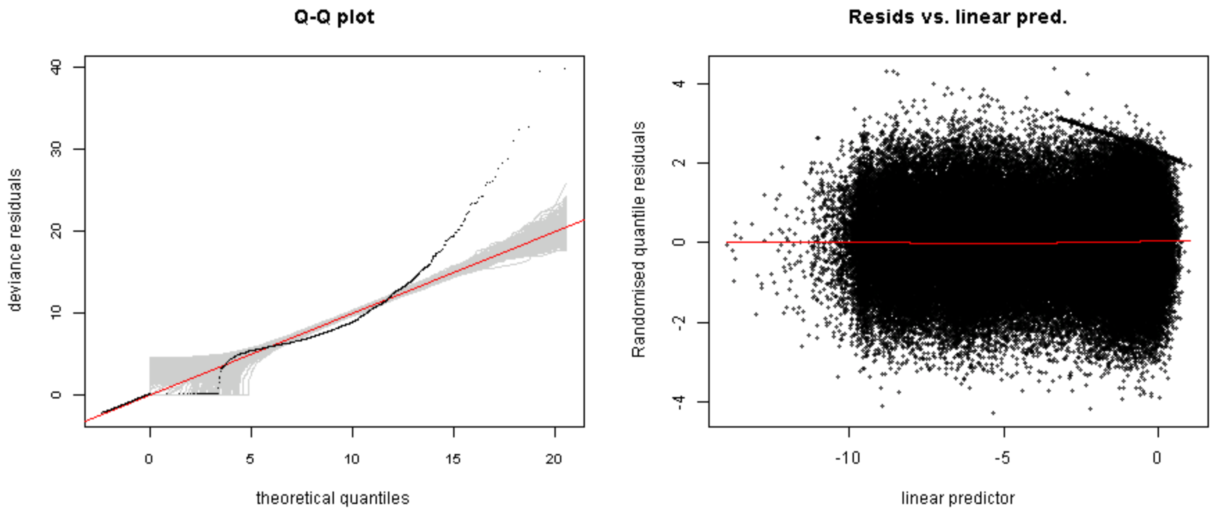


Figure 11: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates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

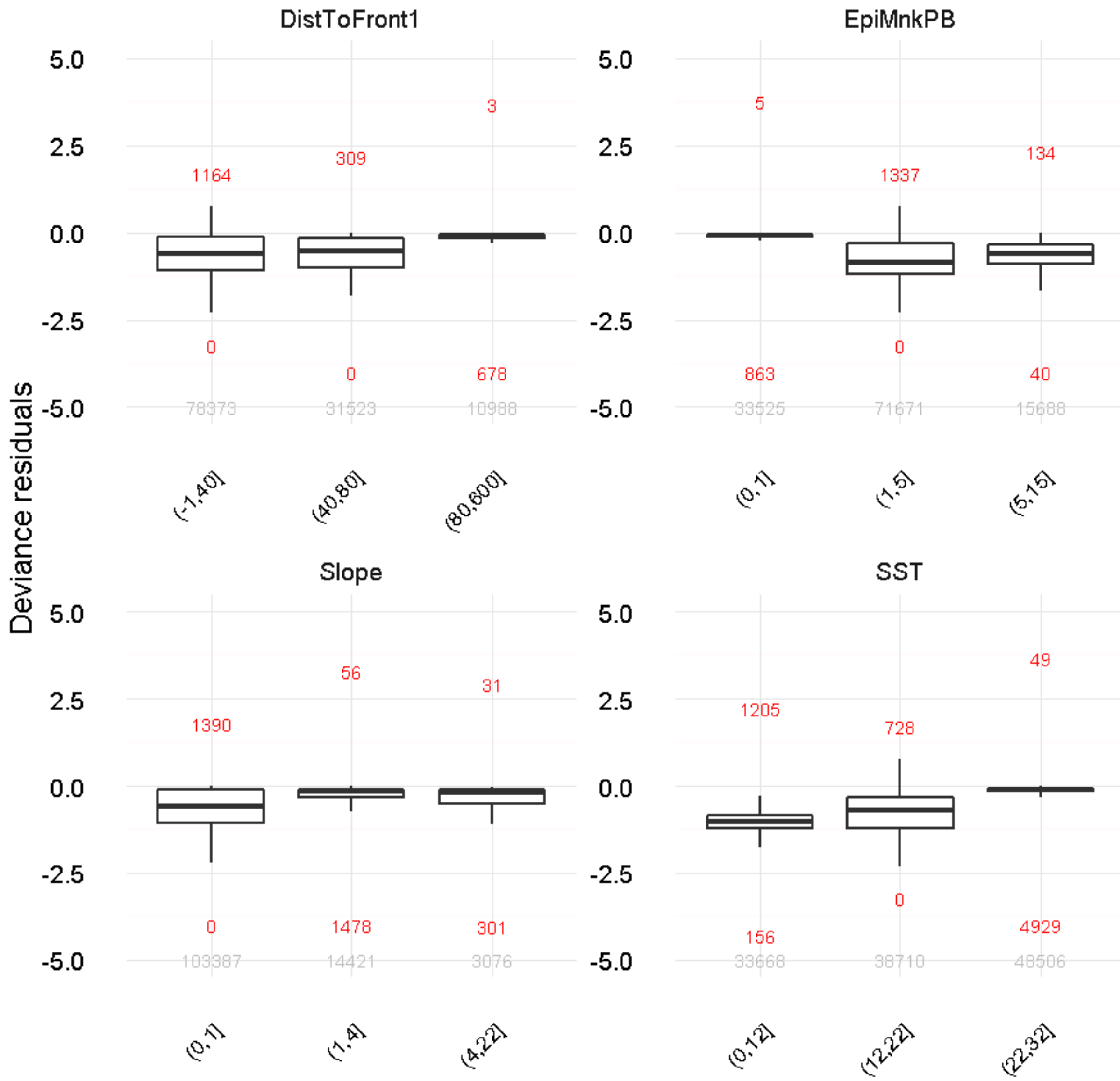


Figure 12: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers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

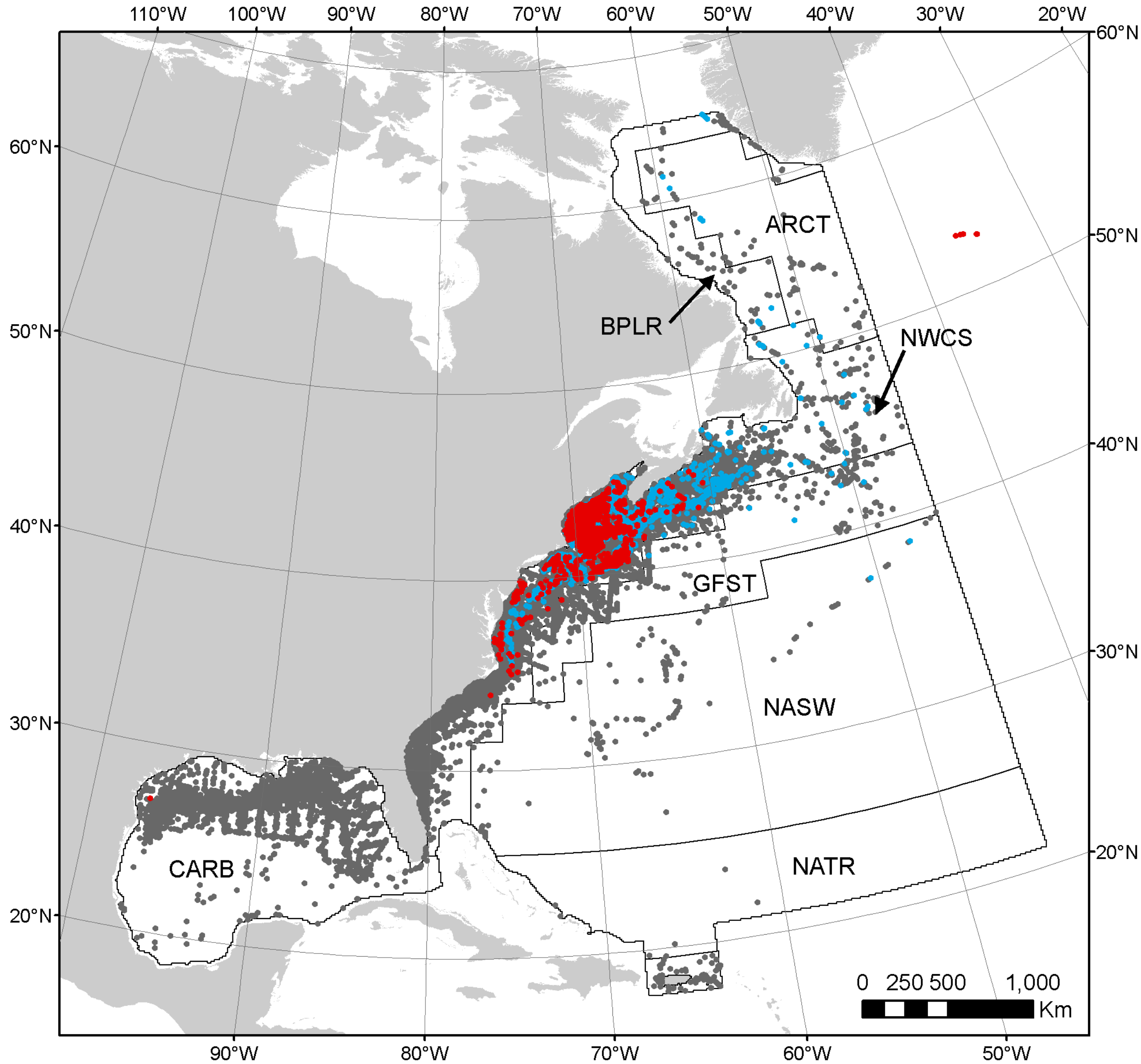


Figure 13: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other 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

We used a total of 1785 sightings to fit the habitat-based density model (the vast majority of the sightings came from surveys in the U.S. east coast). The lowest AIC model included micronekton biomass, slope, sea surface temperature and distance to fronts (listed in decreasing order of importance according to F-scores) and had an explained deviance of 22.9%. It was the only statistically supported model sensu Burnham and Anderson (2002) (Table 3). All top five models included distance to fronts as a predictor and the top three models also included slope. Predicted densities from all top five models were very low in the CARB, NASW and NATR provinces (Figure 10). They were fairly similar in the NWCS province while they differed by a factor 2 in the GFST province and a factor 4 in the ARCT and BPLR province. When examining these results, it is important to keep 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).

Overall, model predictions appeared concordant with the described distribution of fin whales in temperate and sub-polar waters of the North Atlantic mostly north of 30°N and their affinity for the continental slope (Aguilar 2009; Edwards et al. 2015). Fin whales are generally more abundant at high latitudes in warmer months and at low latitudes (greater than 20°N) in colder months (Edwards et al. 2015). Unlike humpback and blue whales, fin whales do not undertake long-range migrations (Edwards et al. 2015, Aguilar 2009) and there is evidence that some individuals remain at mid latitudes year-round (Hain et al. 1992). It has been suggested that fin whales disperse in offshore waters in winter, possibly to breed (Hain et al. 1992; Aguilar 2009), but no definite wintering grounds have been identified.

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

In these Northern provinces, fin whales were predicted both on the continental shelf and in offshore waters beyond the continental slope. We warn that extrapolation to colder waters occurred throughout the BPLR province and therefore predictions should be considered with extreme caution.

In West Greenland fin whales are hunted for aboriginal subsistence and surveys have been conducted to monitor their abundance. Fin whales were sighted on 78 occasions during an aerial survey in September 2005 (Heide-Jørgensen et al. 2008), and on 45 occasions during a shipboard survey at the same period (Heide-Jørgensen et al. 2007). Sightings were distributed near the 200m isobath along the coast of West Greenland, with largest concentrations observed in offshore waters off Central West Greenland (Heide-Jørgensen et al. 2008).

An aerial survey conducted in West Greenland in August-September 2007 recorded 24 fin whale sightings, mostly located near the western edge of the surveyed area (Heide-Jørgensen et al. 2010). The authors noted that the survey covered a small portion of fin whale's presumed distribution throughout Baffin Bay and suggested that the West Greenland population could be increasing, as suspected for populations in the eastern North Atlantic (Víkingsson et al. 2009). Satellite tracking data from two individuals tagged in West Greenland indicated a potential large range of fin whales in West Greenland (Heide-Jørgensen et al. 2003). Heide-Jørgensen et al. (2003) also noted numerous sightings of fin whales in offshore waters of Baffin Bay (although these sightings were from the 1980s). Finally, Figure 13 shows several offshore sightings in Baffin Bay (Figure 13).

Together, these results suggest that fin whale's distribution extends far into the offshore waters of Baffin Bay, supporting the intermediate densities predicted by our model. However, no data are currently available to support the relatively high predicted densities in offshore waters between 50 and 56°N.

During the TNASS survey in summer 2007, fin whales were sighted once in the BPLR province (Lawson and Gosselin 2009). A few sightings were also reported in OBIS-SEAMAP on the continental shelf in the southern part of this province (but observation effort was very sparse) (Figure 13). Predicted densities on the Canadian continental shelf remain largely speculative as they are currently supported by relatively few available sightings.

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

Predicted densities were highest on the continental shelf and slope north of Cape Hatteras where fin whales were sighted year-round.

High fin whale densities were predicted on the continental slope between 40 and 46°N, corresponding to the eastern part of the NWCS province/western part of the Gulf Stream province. Predicted densities on the continental slope between 40 and 42°N were supported by extensive survey effort which revealed large numbers of fin whales. Predictions on the continental slope north of 42°N were supported by comparatively little survey effort. We believe these predictions are plausible as they are supported by some sightings from OBIS-SEAMAP (Figure 13).

During the TNASS survey in summer 2007, fin whales were sighted on 17 occasions east of Newfoundland, 55 occasions south of Newfoundland and 44 occasions on the Scotian shelf (Lawson and Gosselin 2009) (sightings not contributed to OBIS-SEAMAP and therefore not shown on Figure 13). Fin whales have also been reported near the Gully canyon, on the Scotian shelf edge (Hooker et al 1999). In OBIS-SEAMAP, large numbers of sightings were reported on the Scotian shelf, while sightings were sparser on the continental shelf and slope south and east of Newfoundland (but observation effort was also much sparser). Predicted densities on the continental shelf and slope in the northern part of the NWCS province did not seem incompatible with these sightings. However, they should be considered with extreme caution as they were derived from extrapolation to colder waters.

The southernmost sightings were reported near 36°N. The model predicted low fin whale densities in coastal waters as far south as 33°N. We believe these predictions are potentially realistic as one sighting was reported in OBIS-SEAMAP at 34°N (Figure 13) and a fin whale was photographed off Sapelo Island, Georgia in March 2012 (Florida Fish and Wildlife Conservation Commission, unpublished).

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

Hydrophone array data from the Integrated Undersea Sound Surveillance System in the western North Atlantic indicated that fin whales calls peaked in winter and were more common at high latitudes (off eastern Canada and the northeastern U.S.) than low latitudes (North of the Antillean Arc) (Clark and Gagnon 2004). These findings seemed to support the relatively low densities predicted in the NATR and NASW provinces. Similarly, passive acoustic detections along the mid-Atlantic ridge peaked in winter months north of 32°N (Nieukirk et al. 2004, 2012), supporting the hypothesis that fin whales disperse in mid-latitudes offshore waters during the wintertime.

Despite very sparse observation effort, we note two sightings reported in OBIS-SEAMAP in the northern part of the NASW province (Figure 13).

We warn that extrapolation further from fronts occurred in large parts of the NATR and NASW provinces and therefore predicted densities should be considered with extreme caution.

Caribbean (CARB) province

Very low densities were predicted in the Gulf of Mexico and near Puerto Rico. Fin whales have been reported near Puerto Rico in winter on only 3 occasions (Mignucci-Giannoni 1998) and are considered of accidental occurrence in the Gulf of Mexico (Jefferson and Schiro 1997).

Overall confidence: level 2

Large amounts of survey data were available in the Gulf of Maine feeding ground and predictions in northern waters were largely derived from these data. The model successfully predicted the occurrence of fin whales at high latitudes where they are known to feed in summer but predicted densities remain speculative as they were derived from extrapolation to colder waters. The incorporation of line transect survey data from Canada and Greenland would be critical to increase the reliability of predicted densities at high latitudes where fin whales are known to feed in summer. 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.

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