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

Laura Mannocci, Jason J Roberts, David L Miller, Patrick N Halpin

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This report documents the habitat-based density model for Minke 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 Minke 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	2
EC	1044357.704	1030
EU	27526.342	76
MAR	2424.421	1
All regions	1098572.939	1109

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

Month	Effort	Sightings
January	71848.75	15
February	106927.44	16
March	105090.12	17
April	105570.01	90
May	107303.24	222
June	119895.45	279
July	140462.97	237
August	110040.12	162
September	53688.41	18
October	63529.31	28
November	60008.94	18
December	54208.17	7
All Months	1098572.94	1109

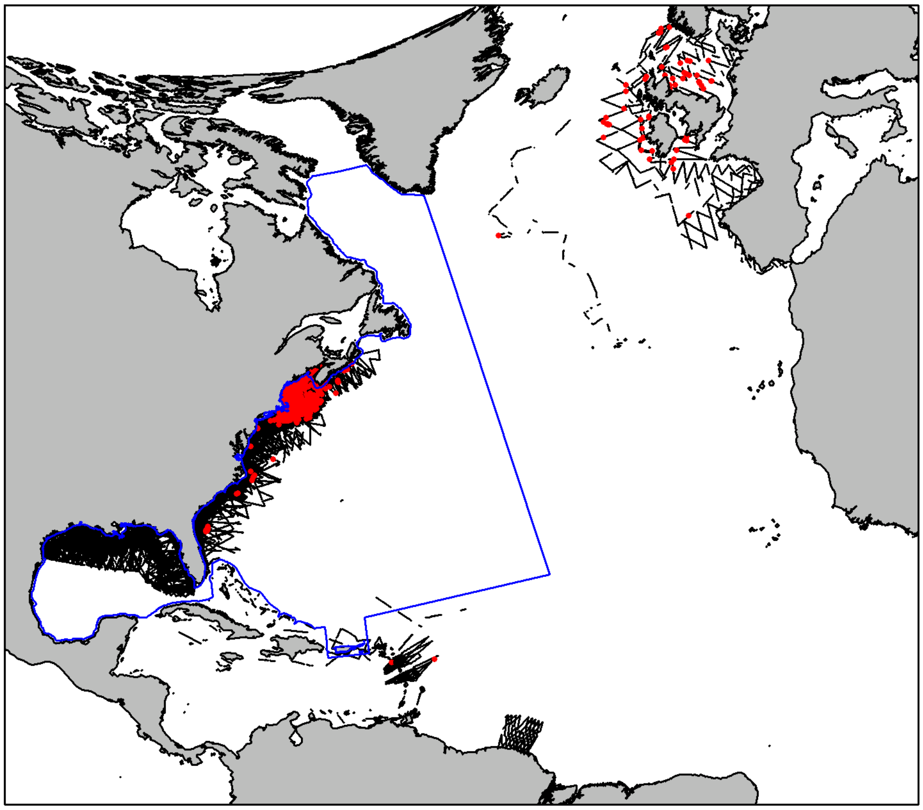


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

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

Common minke whale (*Balaenoptera acutorostrata*)

Modeled season

In the western North Atlantic, minke whales are known to undertake seasonal migrations between high-latitude summer feeding grounds and low-latitude winter breeding grounds (Risch et al. 2014). However, very few minke whale sightings were available from surveys in the winter season. Rather than attempting to fit separate habitat models in summer and winter, we fitted a year-round model incorporating survey data available in all months. We recognize that the sighting data included individuals involved in different activities (e.g., feeding, breeding and migrating) necessitating various habitat characteristics. Nevertheless, we note that minke whales were recorded by surveys in Gulf of Maine in winter, suggesting that part of the population may be feeding most of the year. For separate models of minke whale densities in summer and winter, we direct our readership to the results presented in Roberts et al. (2016) for the U.S. east coast.

Segments

In addition to segments from the western North Atlantic, we incorporated segments from the European Atlantic and the mid-Atlantic ridge to increase sighting numbers and the representativeness of offshore waters in our statistical sample.

Special treatment in the Gulf of Mexico

Since there were no minke whales sighted during the Gulf of Mexico surveys and the species is considered of accidental occurrence in the Gulf of Mexico (Jefferson & Schiro 1997), we assigned zero densities to the entire Gulf of Mexico rather than leaving the low densities predicted by the model.

3- Best model

- **Predictors**: depth, distance to sea surface temperature fronts (DistToFront), zooplankton biomass (PkPB)
- **Model summary**:

```
##
## Family: Tweedie(p=1.182)
## Link function: log
##
## Formula:
## abundance ~ s(Depth, k = 4, bs = "ts") + s(DistToFront1, k = 4,
##     bs = "ts") + s(PkPB, k = 4, bs = "ts") + offset(log(area_km2))
## <environment: 0x1e27dfd4>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -7.63472    0.08636  -88.41   <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)        2.984      3  75.295  < 2e-16 ***
## s(DistToFront1) 2.020      3   5.563 8.01e-05 ***
## s(PkPB)         2.950      3 156.937  < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.0128   Deviance explained = 23.6%
## -REML = 7154.5  Scale est. = 20.935    n = 127583
```

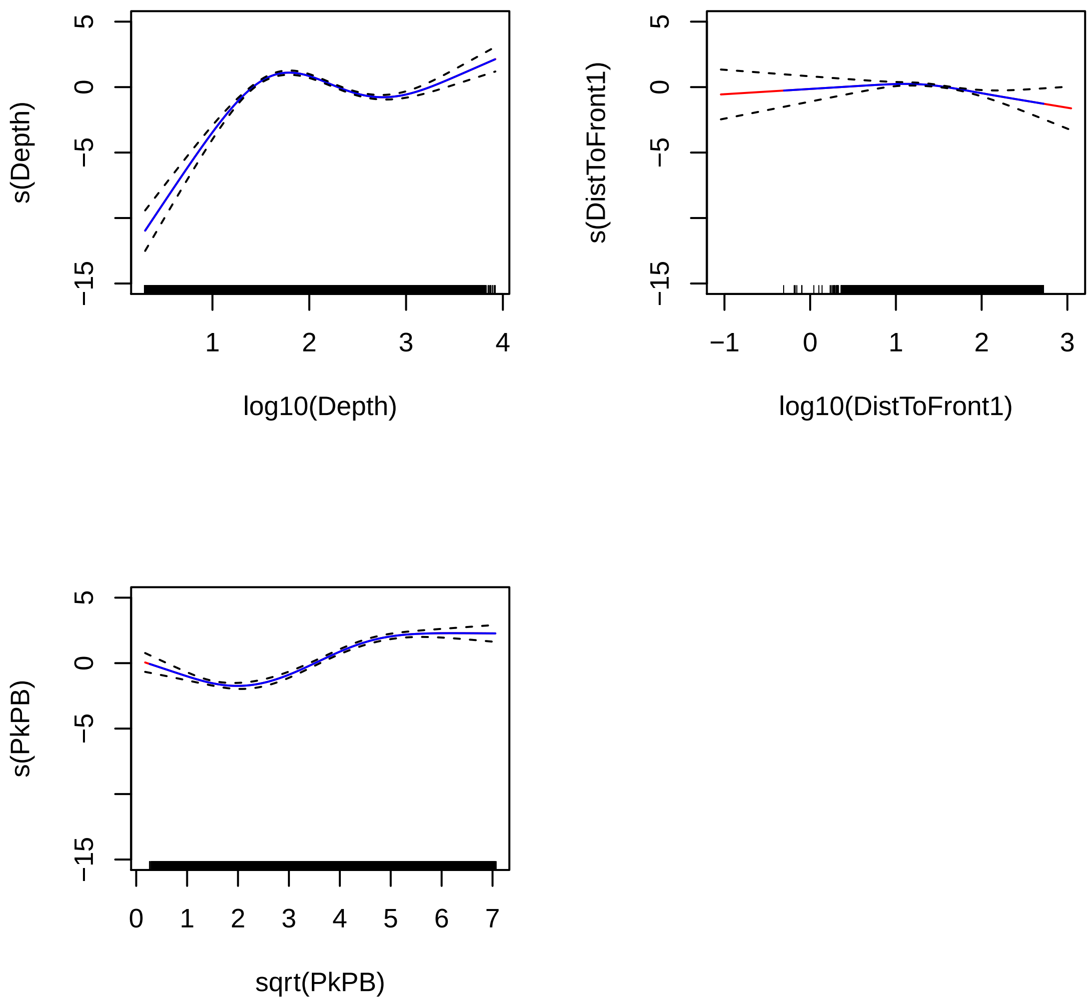


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals.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

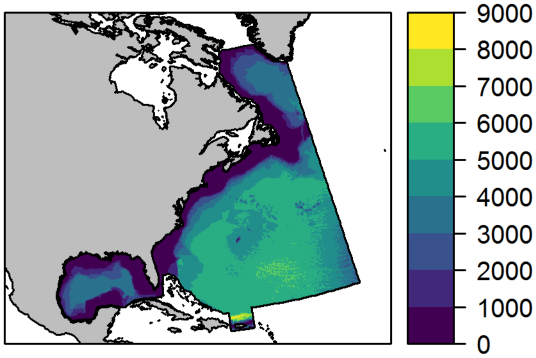
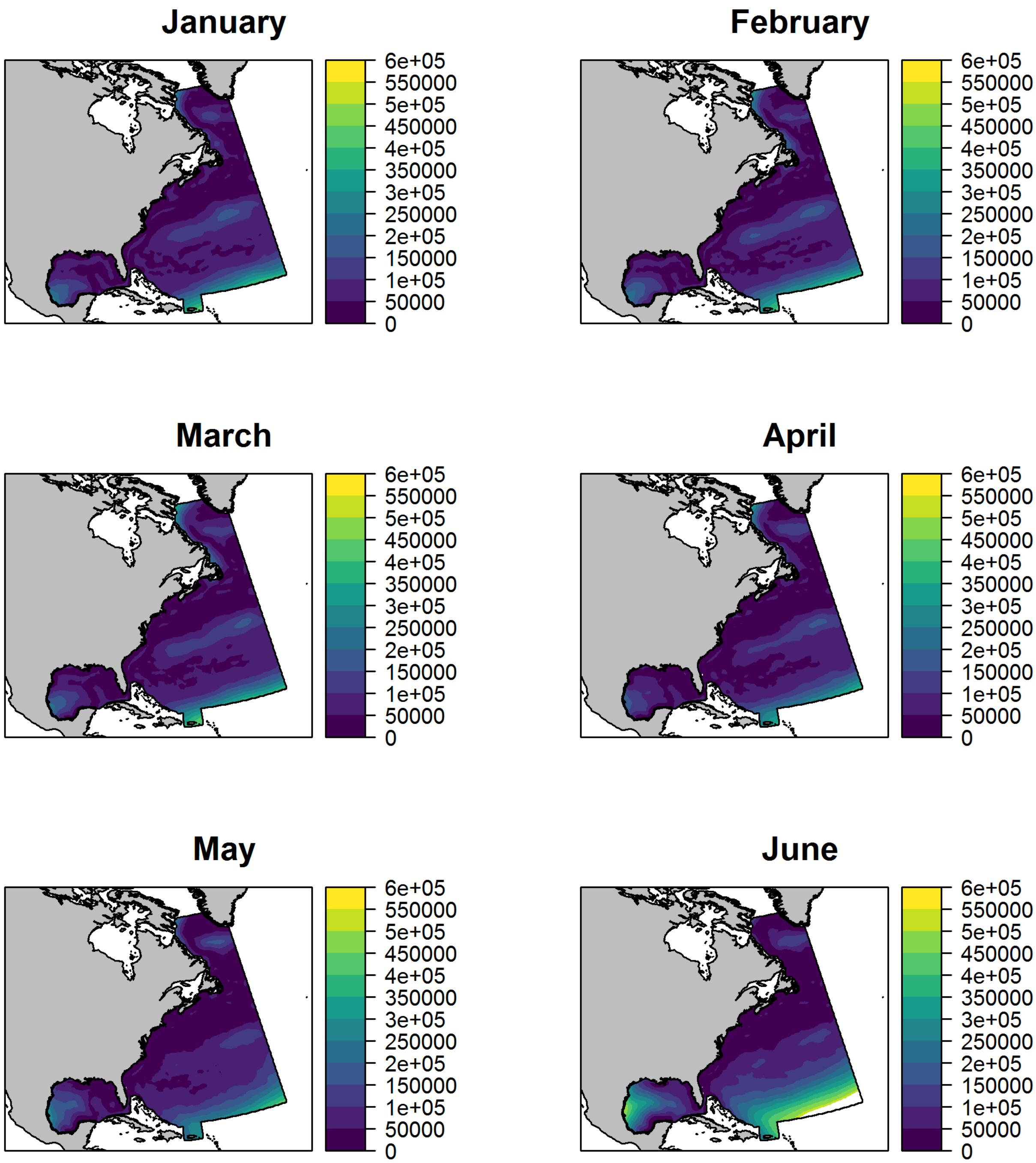


Figure 3: Environmental envelope for depth. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

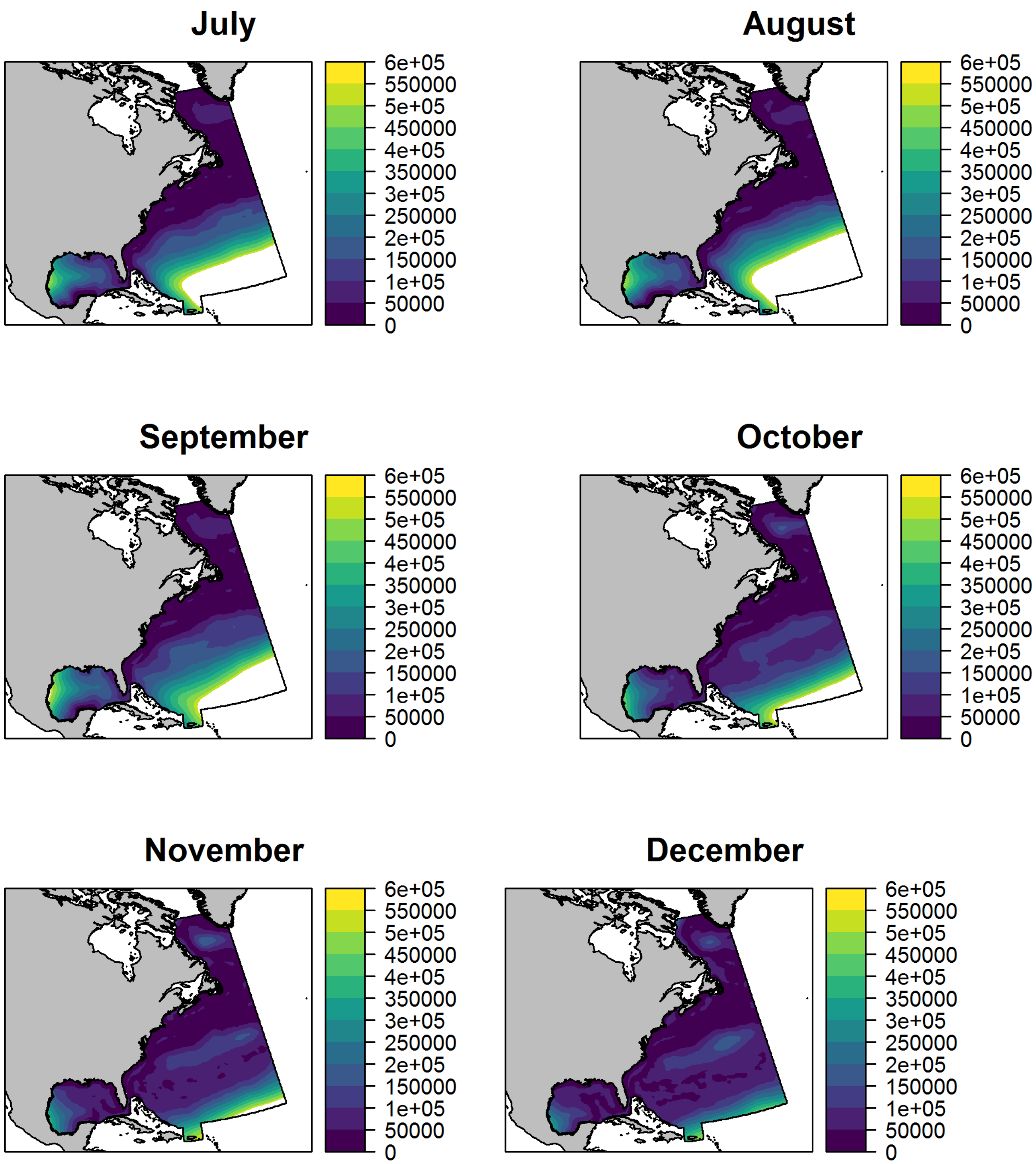
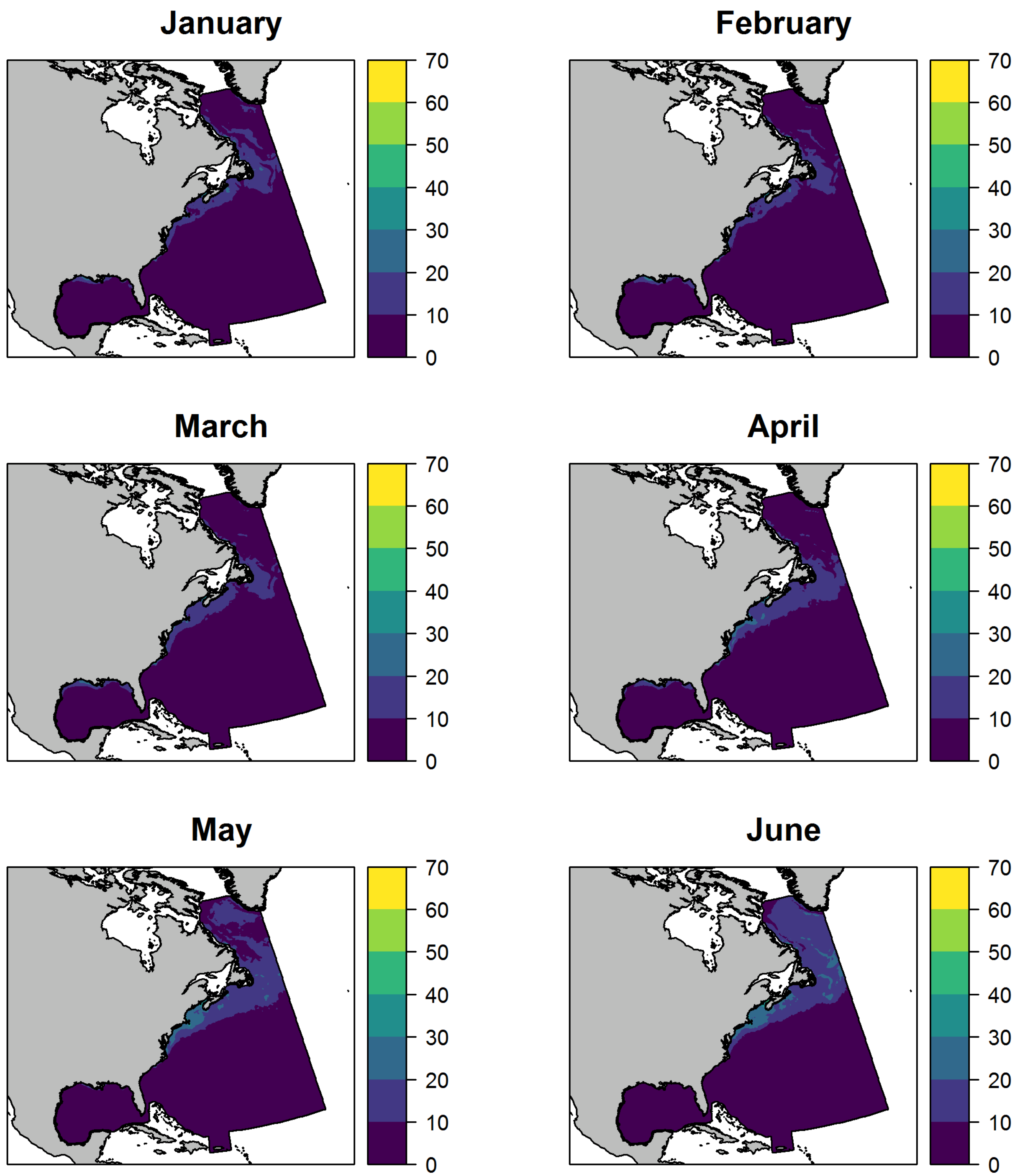


Figure 4: Monthly environmental envelopes for distance to sea surface temperature fronts. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


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

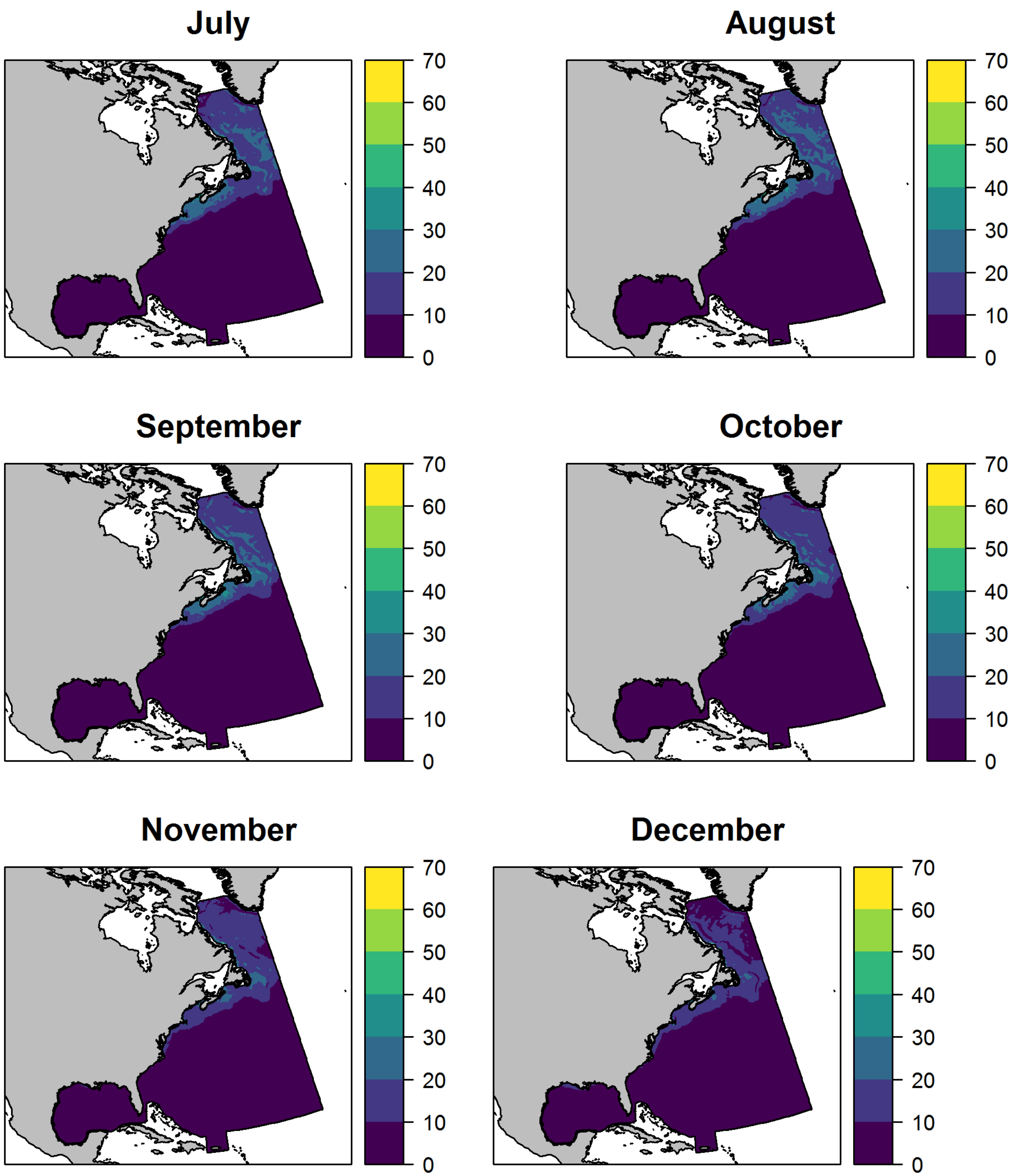


Figure 5: Monthly environmental envelopes for zooplankton biomass. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

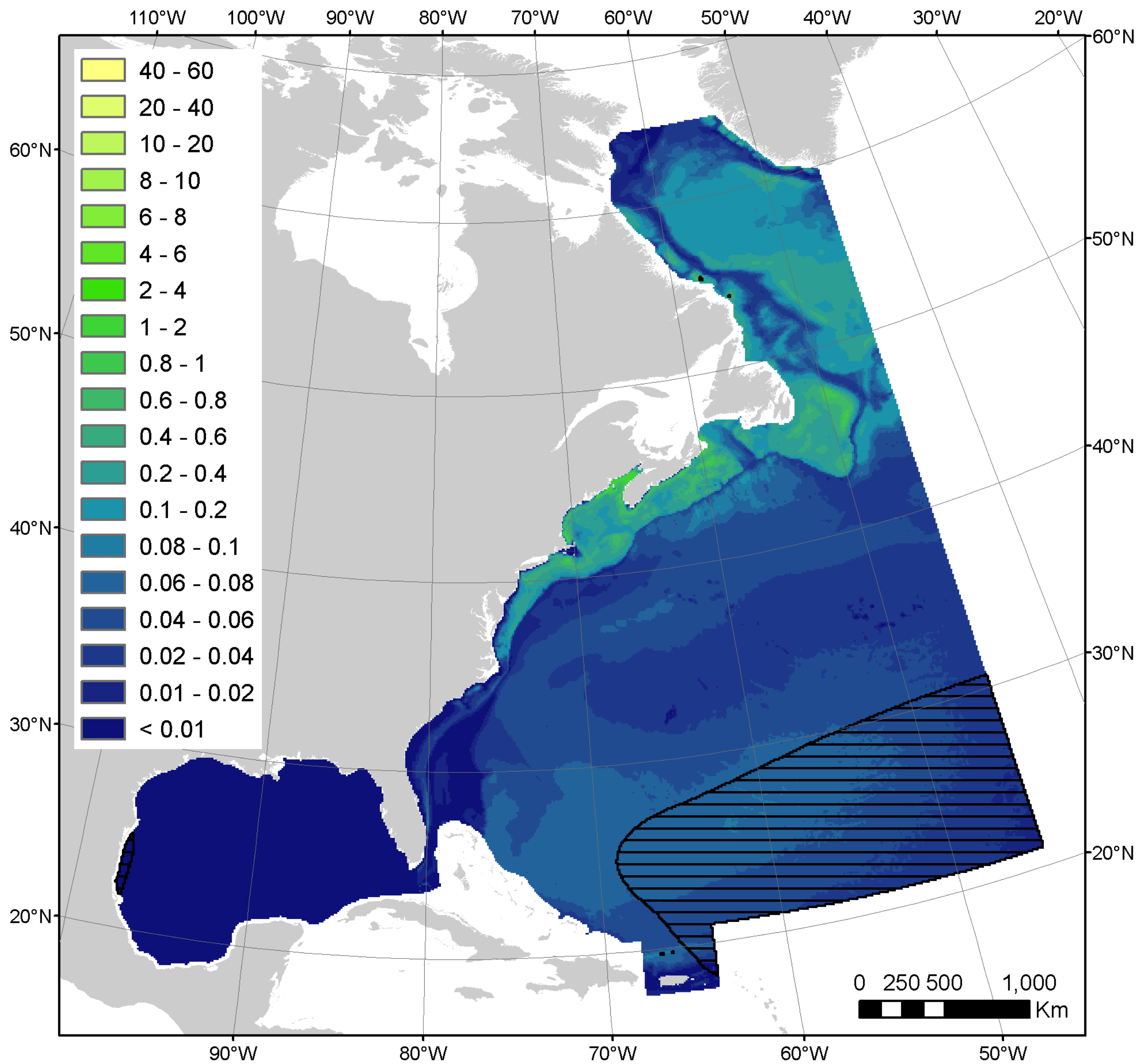


Figure 6: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

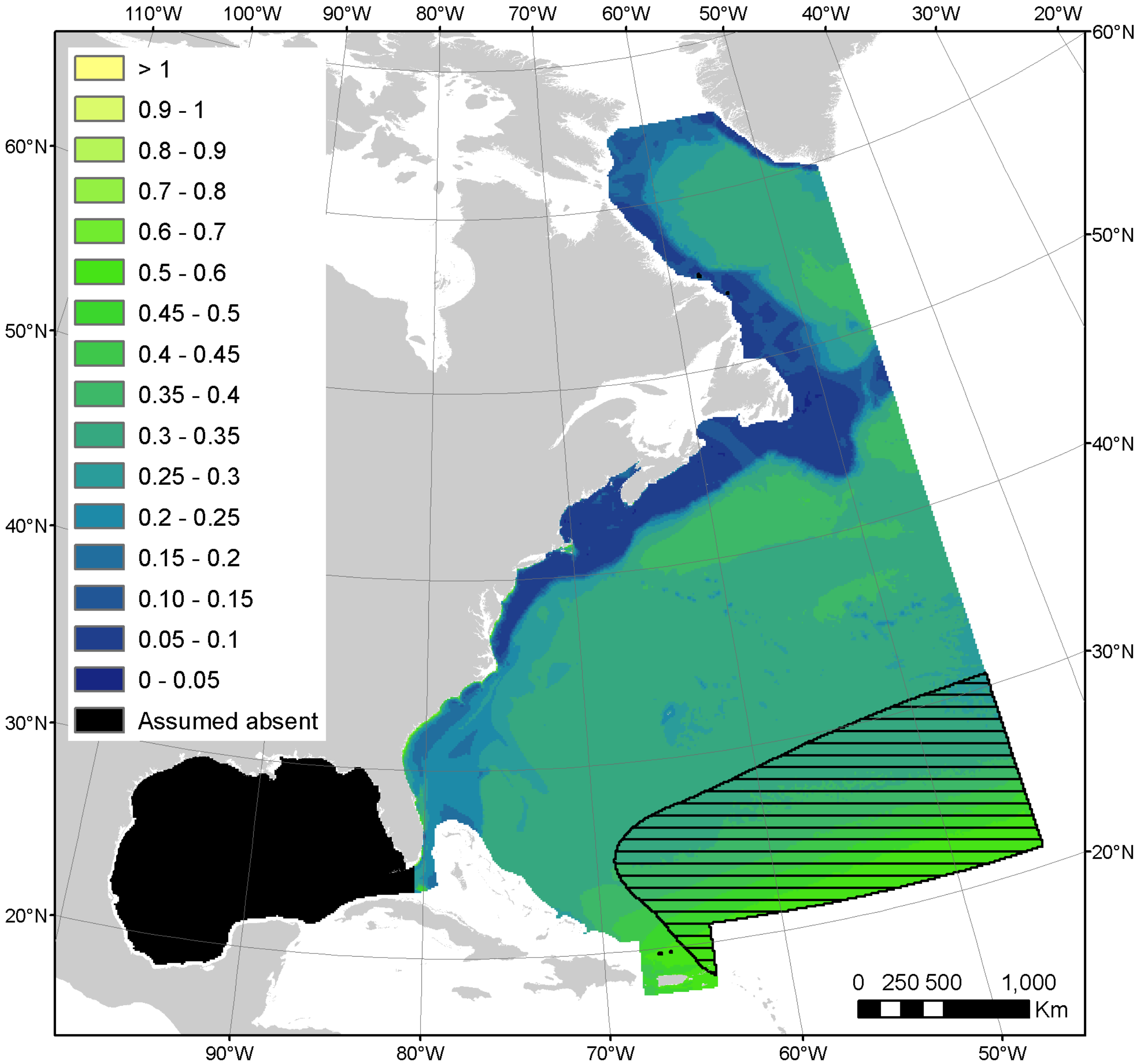


Figure 7: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

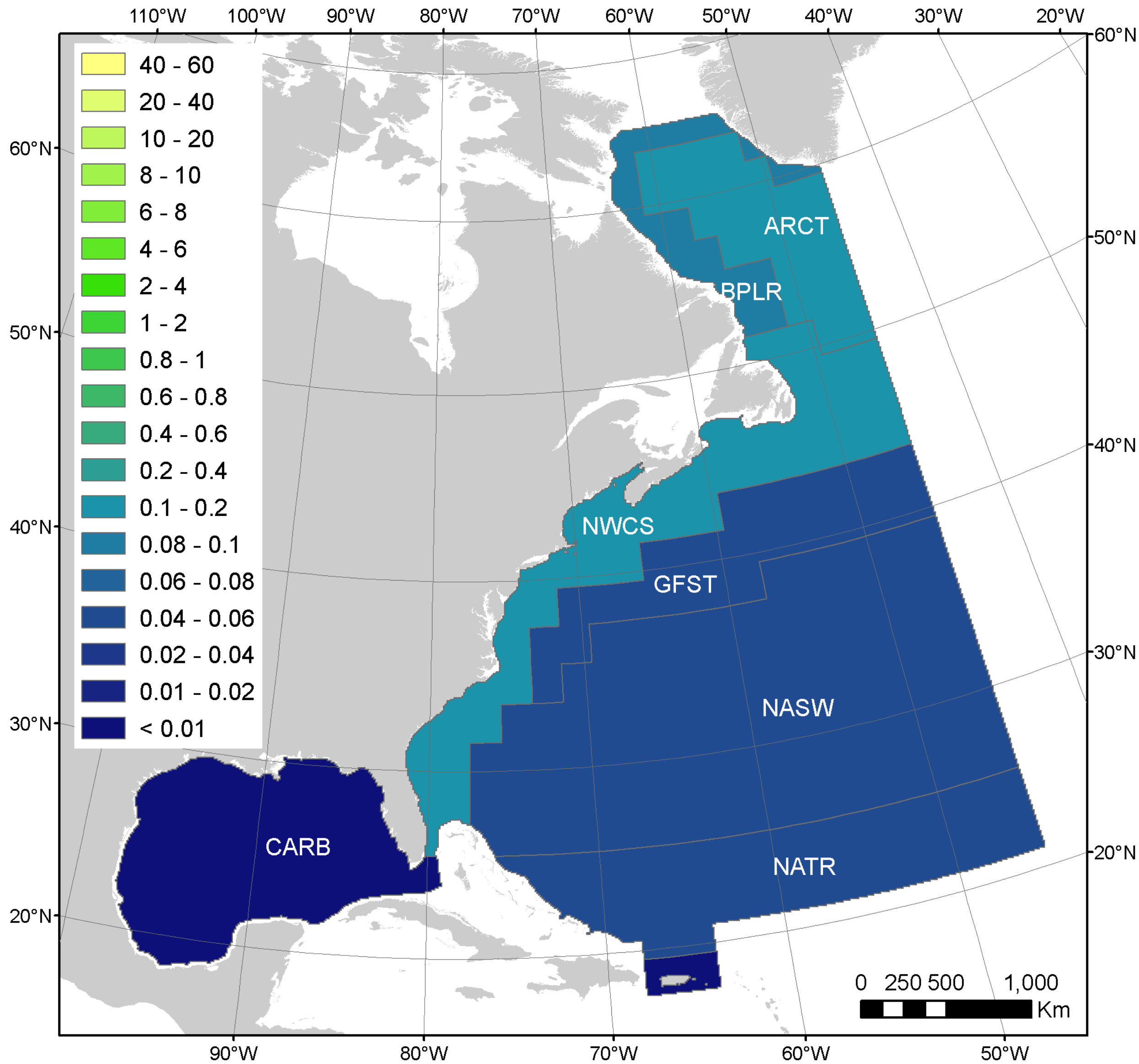


Figure 8: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic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

8- Alternate models

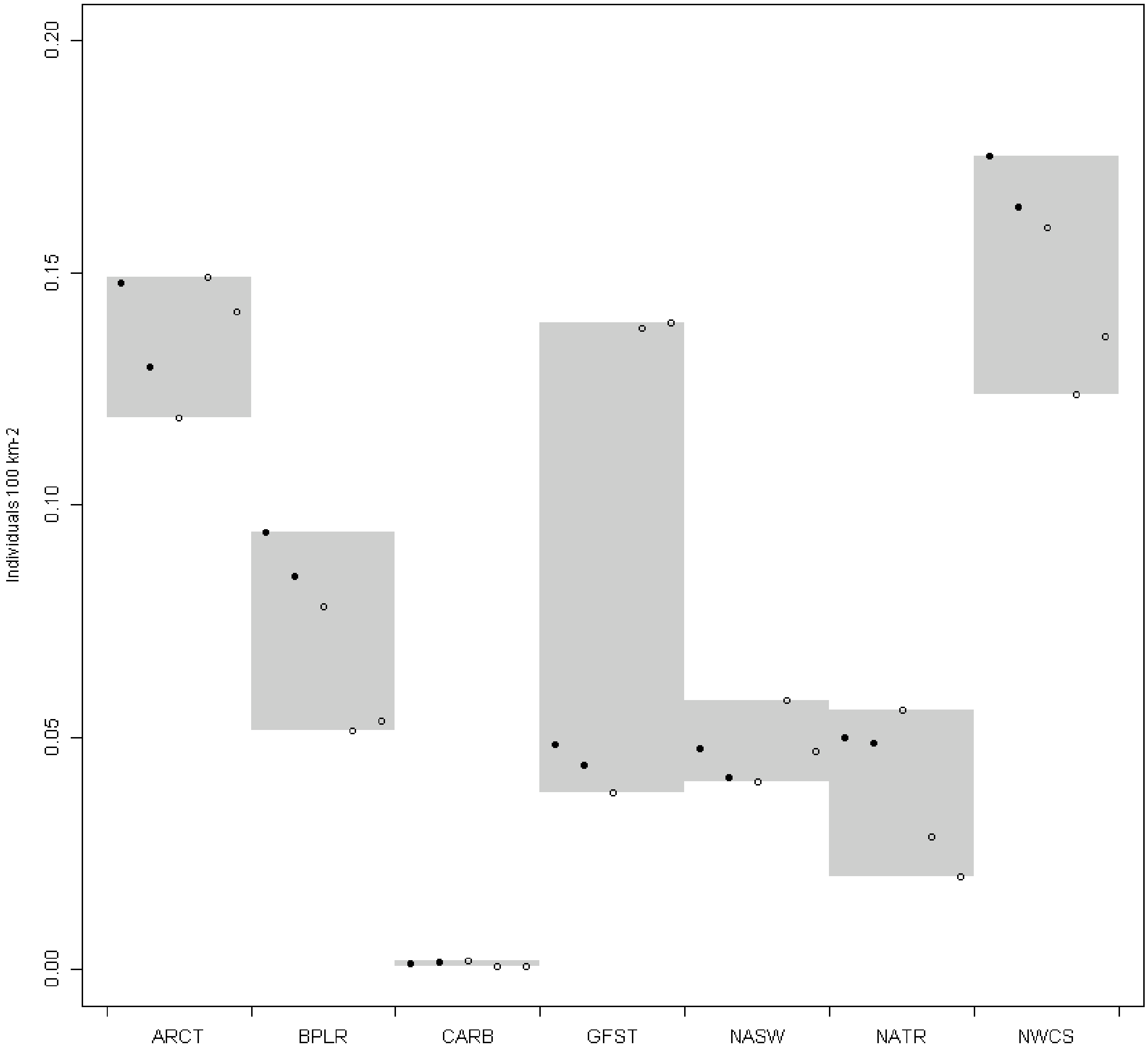


Figure 9: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to models 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	PkPB	DistToFront1	ns	119466.9	0.0
Depth	PkPB	DistToFront1	EpiMnkPP	119467.0	0.1
Depth	PkPB	ns	EpiMnkPP	119471.8	4.9
Depth	PkPP	SST	EpiMnkPB	119490.0	23.1
Depth	PkPP	SST	EpiMnkPP	119495.4	28.5

9- Residual diagnostics

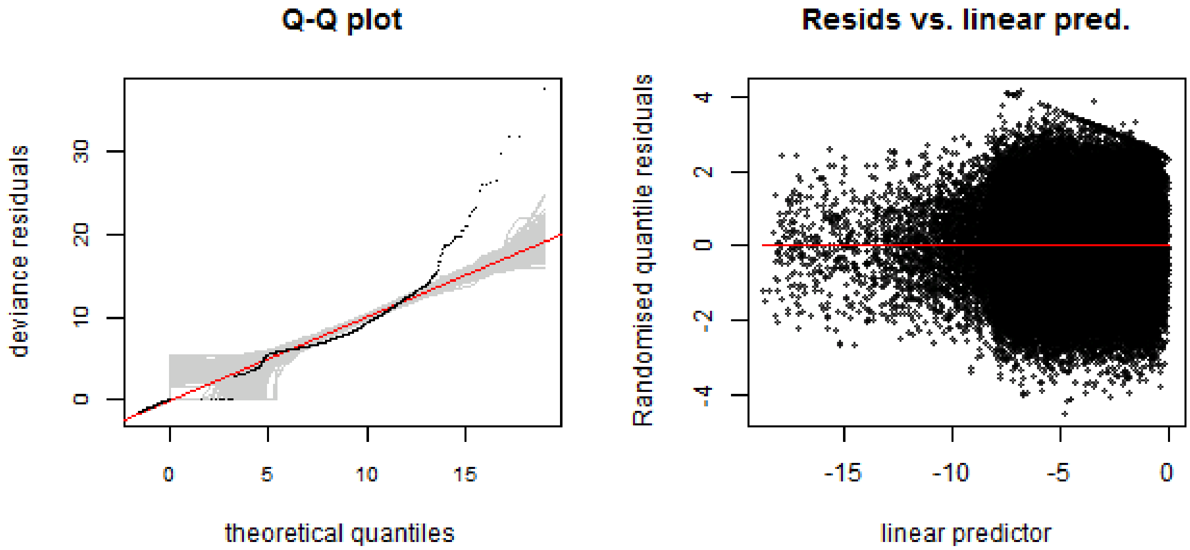


Figure 10: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates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

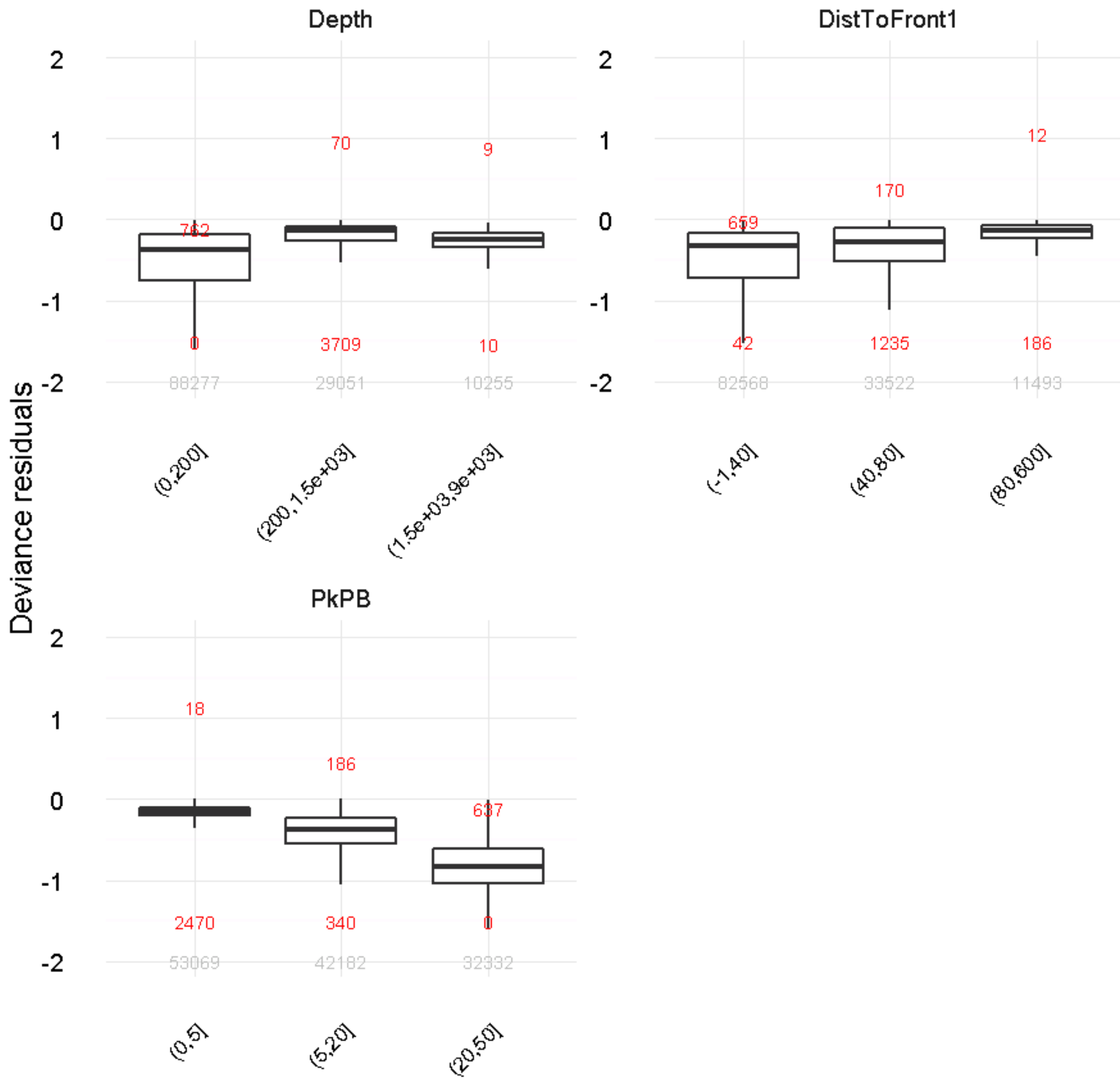


Figure 11: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers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

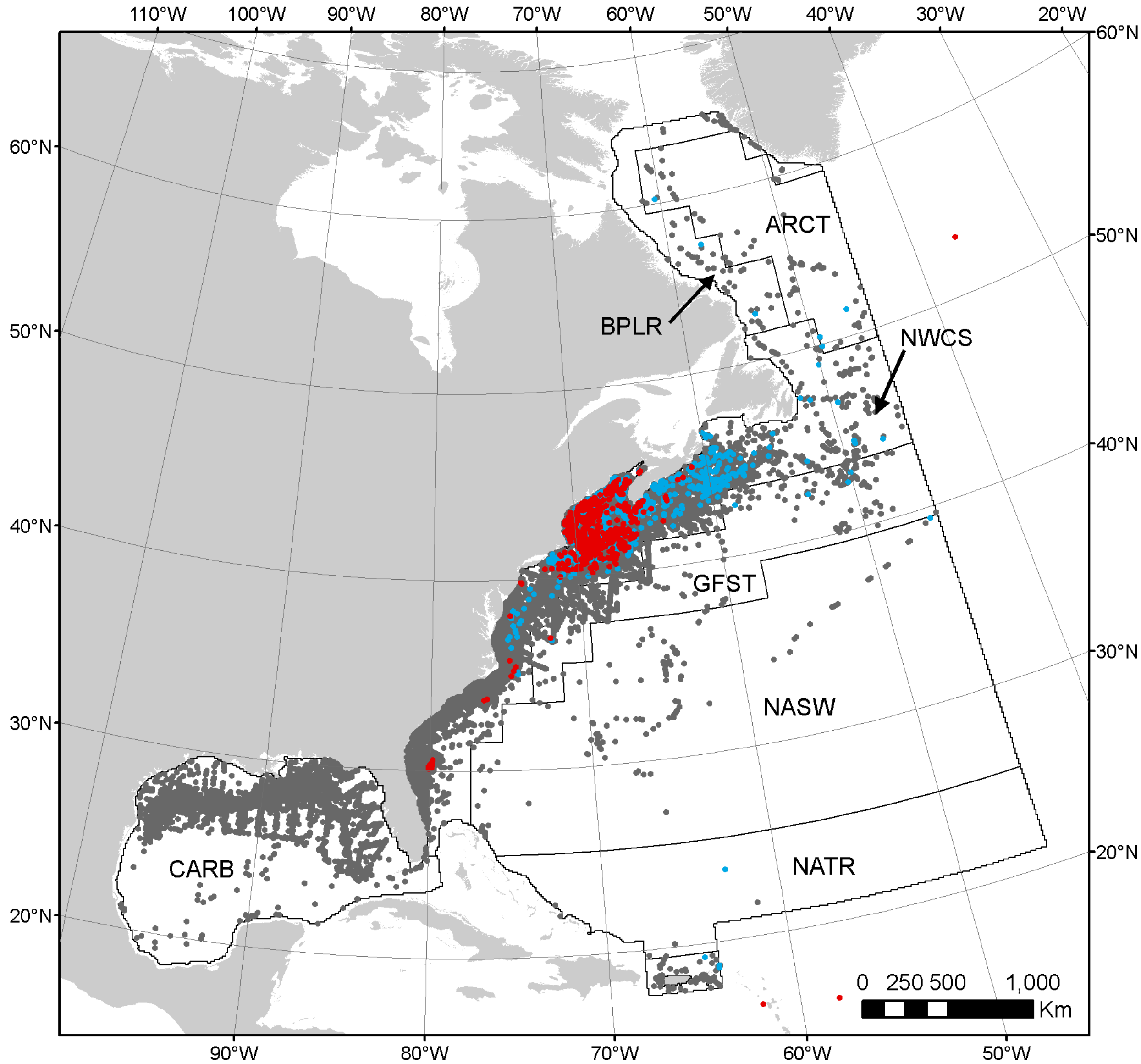


Figure 12: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other 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 relatively large sample size of 1109 sightings was available 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 or first model included zooplankton biomass, depth and distance to fronts (listed in decreasing order of importance according to F-scores) and had an explained deviance of 23.6%. The second model retained the same three predictors plus micronekton production and had a delta AIC < 2. The first and second models were statistically supported sensu Burnham and Anderson (2002) (Table 3). Predicted densities from the first and second models were overall similar in all provinces (the largest difference was found in the ARCT province where the first model predicted 0.15 indiv. 100km-2 and the second model, 0.13 indiv. 100km-2) (Figure 10). Predicted densities from the top five models differed roughly by a factor 2 in the BPLR and NATR provinces and a factor 3 in the GFST province and were quite similar in the other provinces.

In the western North Atlantic, minke whales occur as far north as Baffin Bay during the summer feeding season (Perrin & Brownell 2009). During the winter breeding season, they are thought to migrate to lower latitudes but their wintering grounds are poorly known as few sighting records exist for that season. Various studies have suggested that minke whales overwinter in offshore North Atlantic waters (Mitchell 1991; Risch et al. 2014; Víkingsson & Heide-Jørgensen 2015).

Our predictions seemed generally in line with these documented distribution patterns, although they primarily reflected summer months when most sightings data were available. 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

Predicted densities were on average higher in the ARCT province than in the BPLR province. No survey data were available to support the medium predicted densities in offshore waters of the ARCT province but a few sightings were reported in OBIS-SEAMAP (although observation effort was very sparse) and one sighting was recorded during the MAR-ECO cruise along the mid-Atlantic ridge (Waring et al. 2008) (Figure 12). In the BPLR province, predicted densities were higher nearshore.

In West Greenland minke whales are still hunted for aboriginal subsistence and surveys have been conducted to monitor their abundance. Minke whales were sighted on 42 occasions during an aerial survey in September 2005 (Heide-Jørgensen et al. 2007), and on 12 occasions during a shipboard survey at the same period (Heide-Jørgensen et al. 2008). Sightings were distributed along the coast of West Greenland with no apparent concentrations (Heide-Jørgensen et al. 2008). Individuals may initiate their southbound migration in September as suggested by tagging studies of individuals from Icelandic feeding grounds (Víkingsson & Heide-Jørgensen 2014).

During the Canadian TNASS survey in summer 2007, minke whales were sighted on 4 occasions in the BPLR province (sighting locations are not publically available) (Lawson & Gosselin 2009). A few sightings were also reported in OBIS-SEAMAP for this province (Figure 12).

Although they remain largely speculative, we believe predicted densities in these provinces are not implausible given the results documented above.

North West Atlantic shelves (NWCS) province

Predicted densities were highest on the continental shelf north of Cape Hatteras where most sightings were reported (Figure 12). This is consistent with the description of the continental shelf as primary feeding habitat for minke whales (Perrin and Brownell 2009).

During the TNASS survey in summer 2007, minke whales were sighted on 21 occasions east of Newfoundland, 28 occasions south of Newfoundland and 86 occasions on the Scotian shelf (Lawson and Gosselin 2009) (sightings not contributed to OBIS-SEAMAP and therefore not shown on Figure 12).

Minke whales are regularly reported In summer in waters < 200m near the Gully canyon on the Scotian shelf edge (Hooker et al. 1999). Recent results from Bartha et al. (2011) suggested minke whale's fidelity to the shelf off Nova Scotia.

Multiple winter sightings of individuals presumably migrating were reported by surveys near the continental shelf break from North Carolina to Florida (Figure 12). The model predicted overall low densities in these waters.

North Atlantic tropical gyral (NATR), North Atlantic subtropical gyral (NASW) and Gulf Stream (GFST) provinces

Intermediate densities were predicted in offshore waters of the NATR, NASW and GFST provinces.

Mitchell (1991) reported winter sightings of minke whale accompanied by calves in offshore waters of the western north Atlantic (sightings mostly from the 1960s and 1970s). Sightings were concentrated in offshore waters between 16-33°N and 54-80°W (corresponding to the eastern parts of the NASW and NATR provinces) and near the Bahamas and the West Indies. In OBIS-SEAMAP, a winter sighting was reported for the NATR province (Figure 12).

Risch et al. (2014) analyzed acoustic recordings of minke whales from different sites across the North Atlantic. Detections were abundant off the shelf off the southeastern U.S. and in the Caribbean during winter, suggesting a broad breeding and calving area south of 30°N. The authors postulated that minke whales occupy waters further offshore during their southward fall migration than during their northward spring migration during which they may follow the Gulf Stream.

Hydrophone array data from the Integrated Undersea Sound Surveillance System revealed higher detections of individual singers in lower latitudes during winter and suggested a clockwise movement of minke whales through the Caribbean region from winter to spring months (Clark & Gagnon 2004). Similarly, passive acoustic detections along the mid-Atlantic ridge peaked at lower latitudes in winter months (Nieukirk et al. 2004).

Interestingly, the intermediate densities predicted by our model corresponded to the broad region identified by both Mitchell (1991) and Risch et al. (2014) as a winter breeding and calving area. We warn, however, that extrapolation further from fronts occurred in large parts of the NATR and NASW provinces and therefore predictions should be considered with extreme caution.

Caribbean (CARB) province

Predicted densities north of Puerto Rico appeared compatible with 3 winter sightings reported in OBIS-SEAMAP (Figure 12) and 3 winter sightings reported by Mignucci-Giannoni (1998). We note that Mellinger et al. (2000) recorded acoustic detections of minke whales 150-250km northeast of Puerto Rico, roughly corresponding to an area where our model predicted intermediate densities.

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. Predictions were in line with the occurrence of humpback whales at high latitudes where they are known to feed in summer but predicted densities in northernmost waters remain speculative. 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 minke 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. Predictions in the North Atlantic gyre seemed compatible with a suspected wintering ground but predicted densities remain speculative. If additional survey data become available in this region, it may be possible to fit a separate winter model.

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