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

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This report documents the habitat-based density model for sei 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 sei 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
EC	663076.165	786
MAR	2424.421	54
All regions	665500.585	840

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

	Month	Effort	Sightings
4	April	105121.39	66
5	May	107303.24	246
6	June	118927.77	401
7	July	113904.31	82
8	August	110040.12	15
9	September	52584.62	2
10	October	57619.14	28
11	All Months	665500.59	840

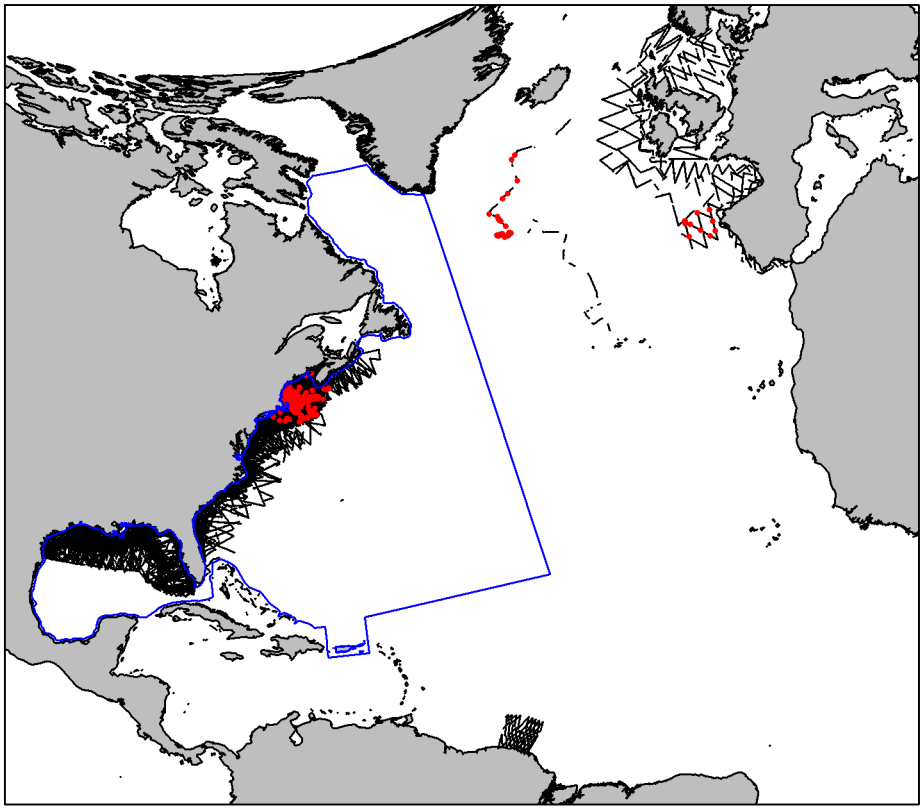


Figure 1: Map of segments (black lines) and sighting locations (red dots). An Albers equal area projection optimized for the AFTT area is used.

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

Sei whale (*Balaenoptera borealis*)

We note that the ambiguous sightings of Bryde's whale / sei whale in the east coast were used to model both species (for more details see Roberts et al. 2016).

Modeled season

Sei whales undertake seasonal migrations from low-latitude wintering areas to high-latitude summer feeding areas. Their migration patterns have not been completely elucidated and their winter distribution in the North Atlantic is vastly unknown (Prieto et al. 2012). Here, we present a habitat-based density model corresponding to the extended summer season, when sei whales are believed to feed at high latitudes. We defined the extended summer season from April to October. April was the month when individuals tagged in the Azores initiated their migrations to high-latitude feeding grounds (Olsen et al. 2009, Prieto et al. 2014). We designated October as the last month of summer following the findings that tagged individuals remained in the Labrador Sea feeding grounds until early fall (Prieto et al. 2014). We presumed that most individuals present in our study area during this extended summer season were feeding (some individuals were also migrating from/to breeding grounds).

Segments

We used segments from the east coast, Gulf of Mexico, Caribbean and mid-Atlantic ridge. No sei whale sightings were reported in the European Atlantic.

Special treatment in the Gulf of Mexico

Since sei whales were not sighted during the Gulf of Mexico surveys and the species is considered of accidental occurrence in the Gulf of Mexico (Jefferson and 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, production of epipelagic micronekton (EpiMnKPP), standard deviation of sea level anomaly (SLAStDev), sea surface temperature (SST)
- **Model summary**:

```
##
## Family: Tweedie(p=1.268)
## Link function: log
##
## Formula:
## abundance ~ s(Depth, k = 4, bs = "ts") + s(EpiMnkPP, k = 4, bs = "ts") +
##     s(SLAStDev, k = 4, bs = "ts") + s(SST, k = 4, bs = "ts") +
##     offset(log(area_km2))
## <environment: 0x1b06f11c>
##
## Parametric coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) -11.6380     0.6262  -18.58   <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)    2.821      3 76.381 < 2e-16 ***
## s(EpiMnkPP) 1.045      3  3.014 0.00142 **
## s(SLAStDev) 1.112      3 38.580 < 2e-16 ***
## s(SST)      2.749      3 60.494 < 2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## R-sq.(adj) =  0.0218   Deviance explained = 38.5%
## -REML = 4562.7  Scale est. = 27.751    n = 74989
```

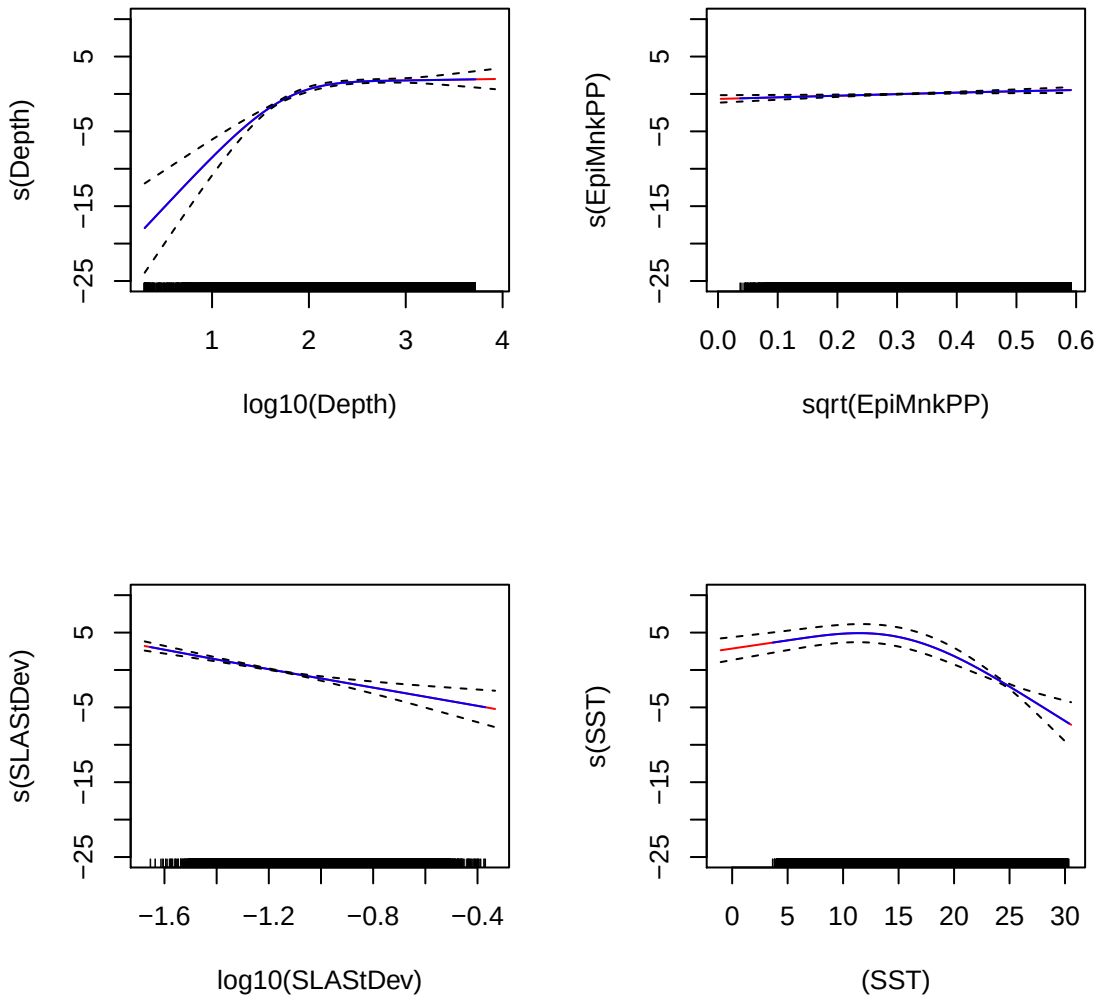


Figure 2: GAM term plots with the log-transformed abundance on the y axis. The solid blue line is the smooth function fitted to the data. The solid red line is the smooth function extrapolated to all covariate values in the prediction area. The dashed lines represent the approximate 95% confidence intervals.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

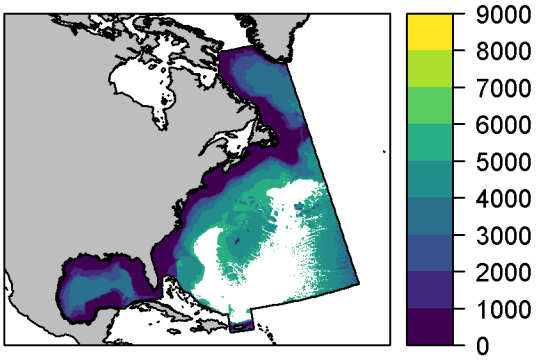
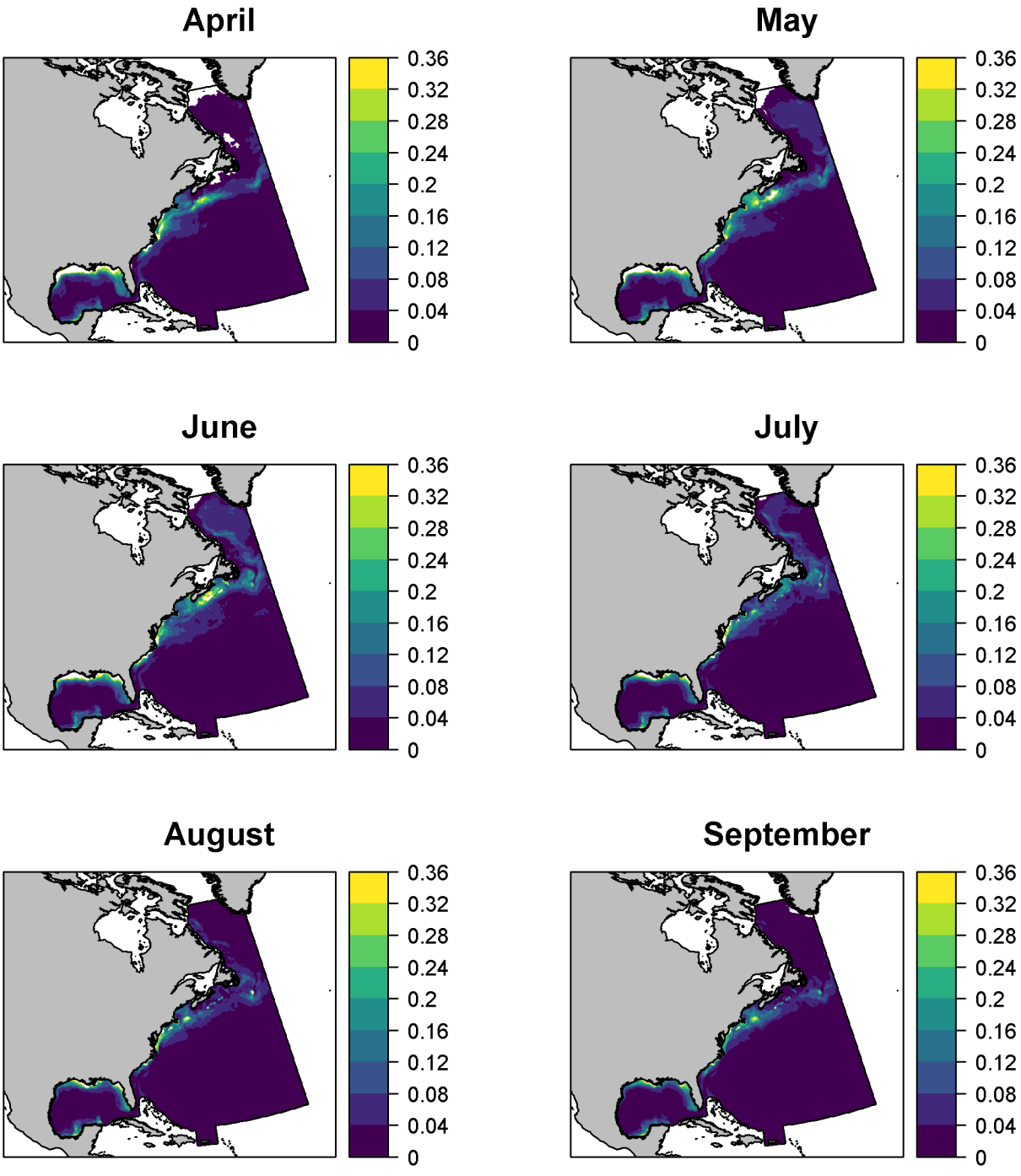


Figure 3: Environmental envelope for depth. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


April
May
June
July
August
September
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0

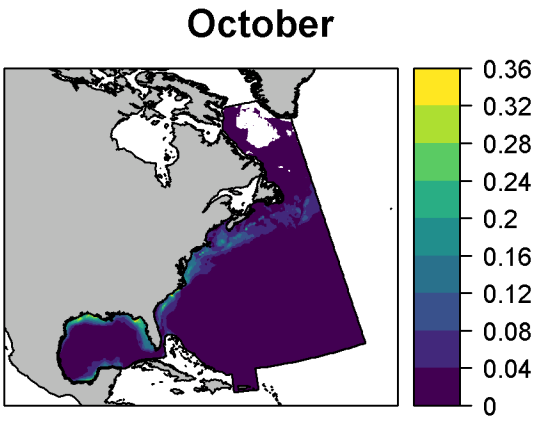
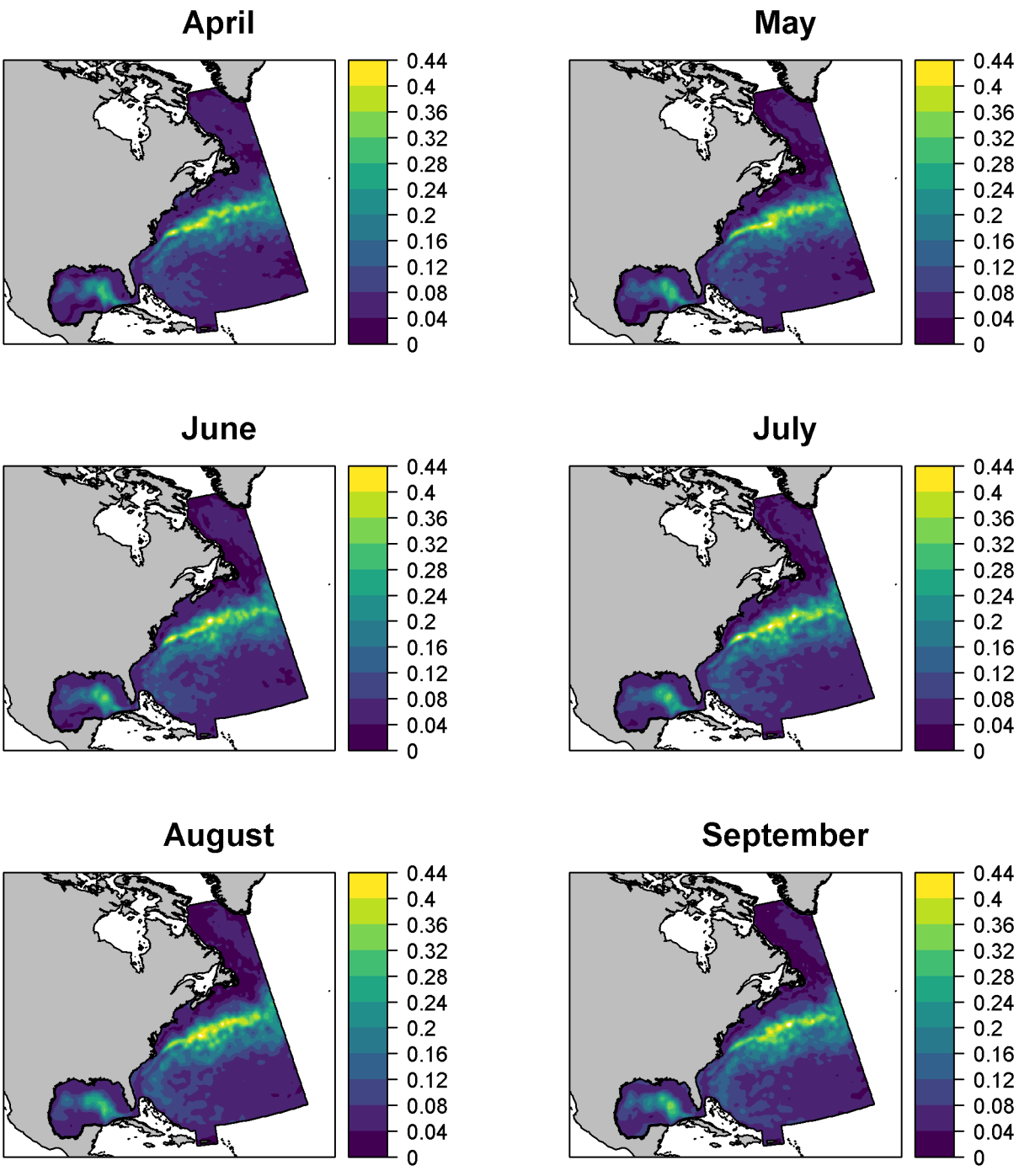


Figure 4: Monthly environmental envelopes for production of epipelagic micronekton. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


April
May
June
July
August
September
0.44
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0

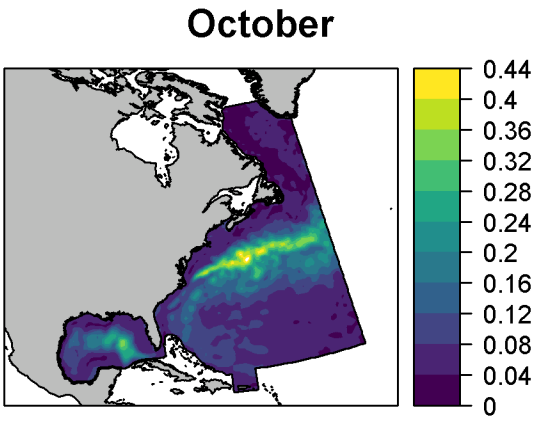
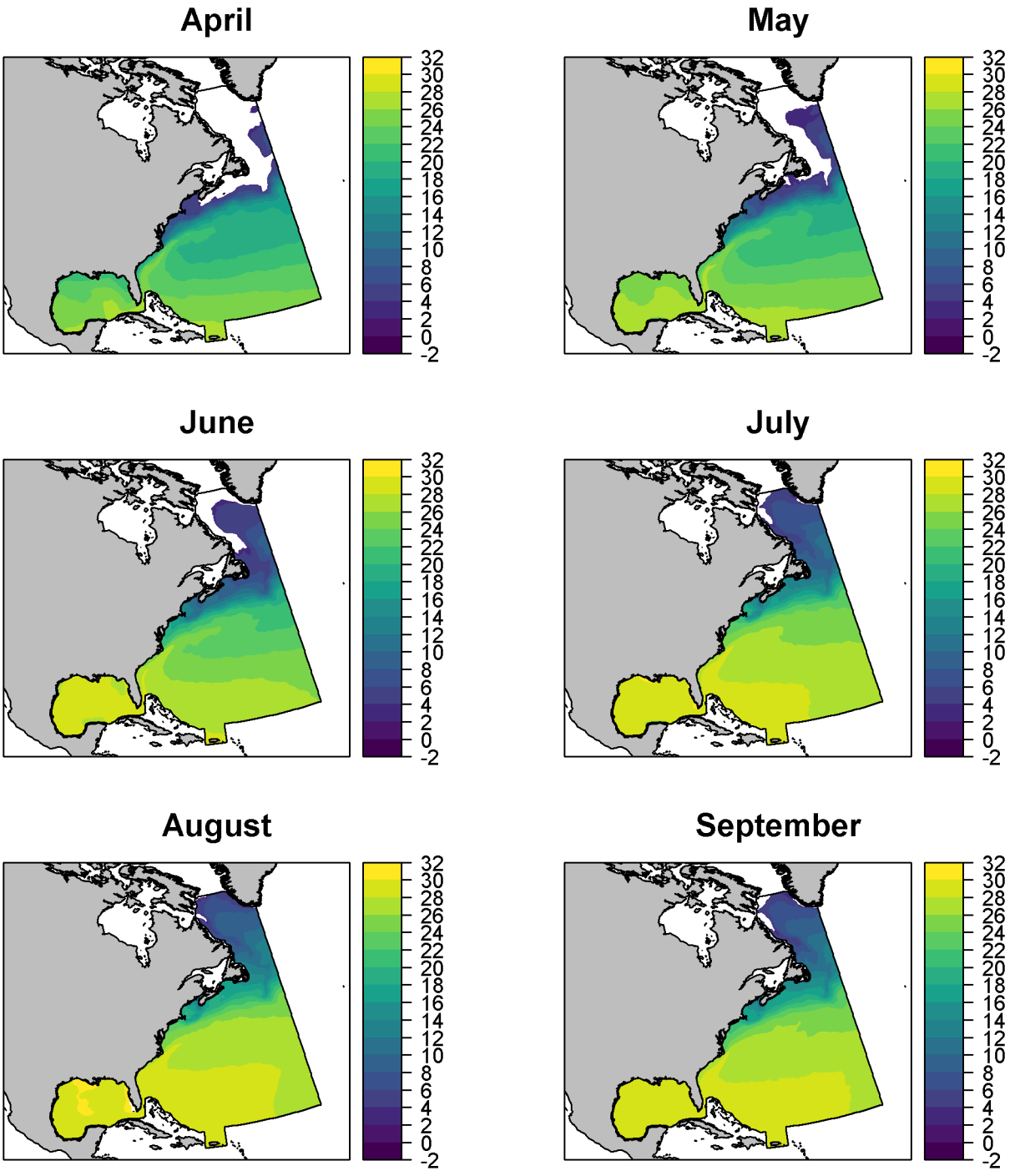


Figure 5: Monthly environmental envelopes for standard deviation of sea level anomaly. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.


April
May
June
July
August
September
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2

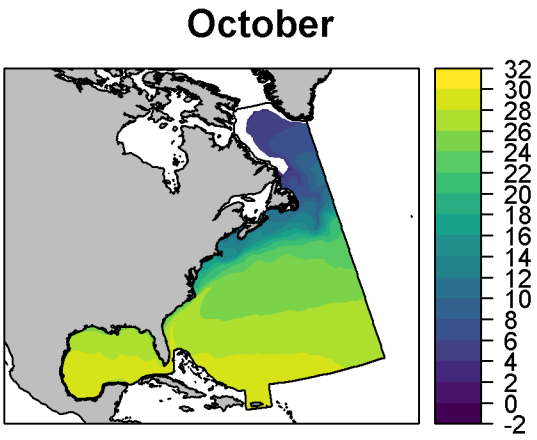


Figure 6: Monthly environmental envelopes for sea surface temperature. White cells within the AFTT polygon indicate areas where covariate values fell beyond the range of covariate values sampled by the surveys.

5- Predicted densities

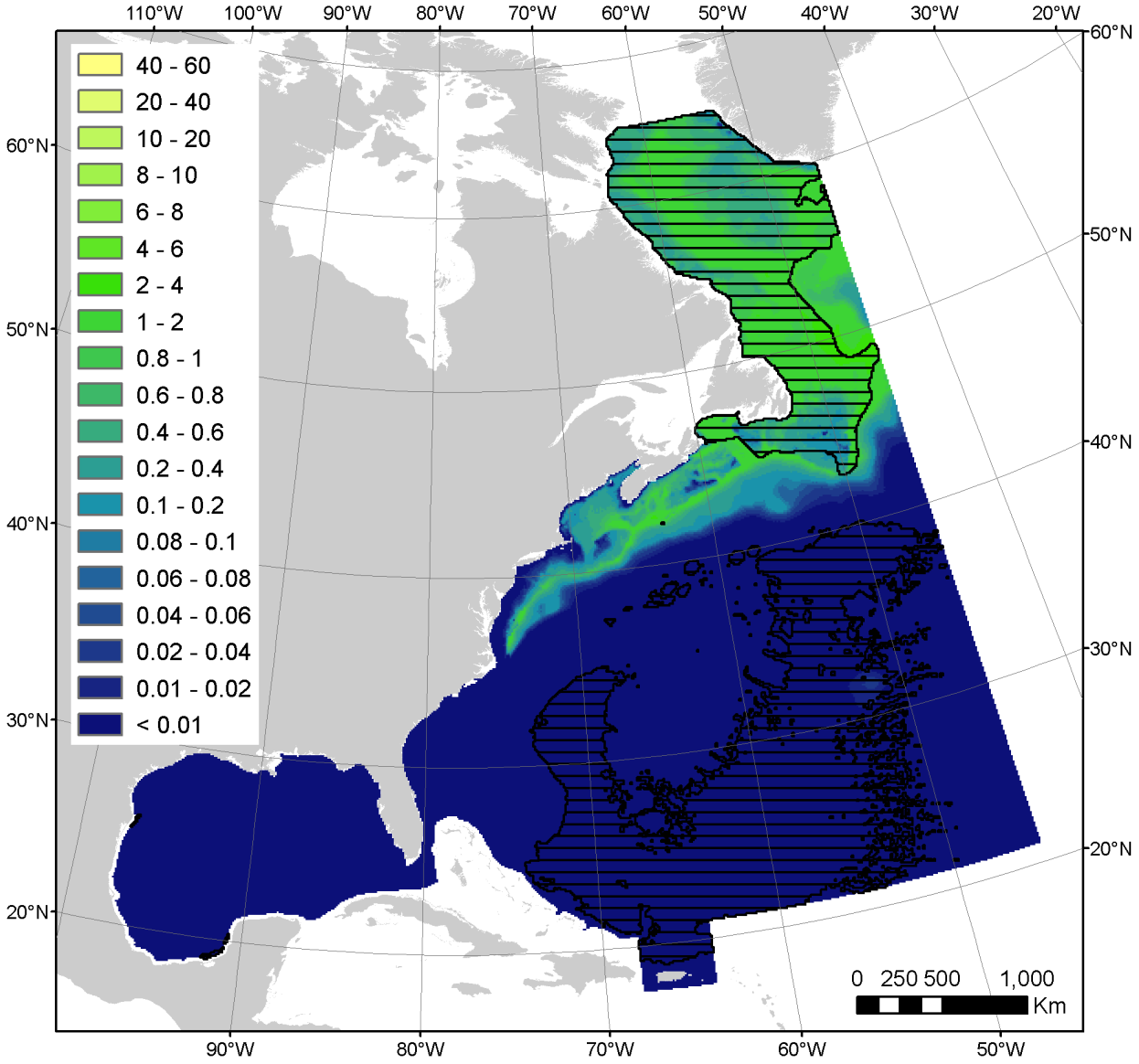


Figure 7: Mean predicted densities (individuals 100 km-2) in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and predicted densities should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

6- Coefficients of variation

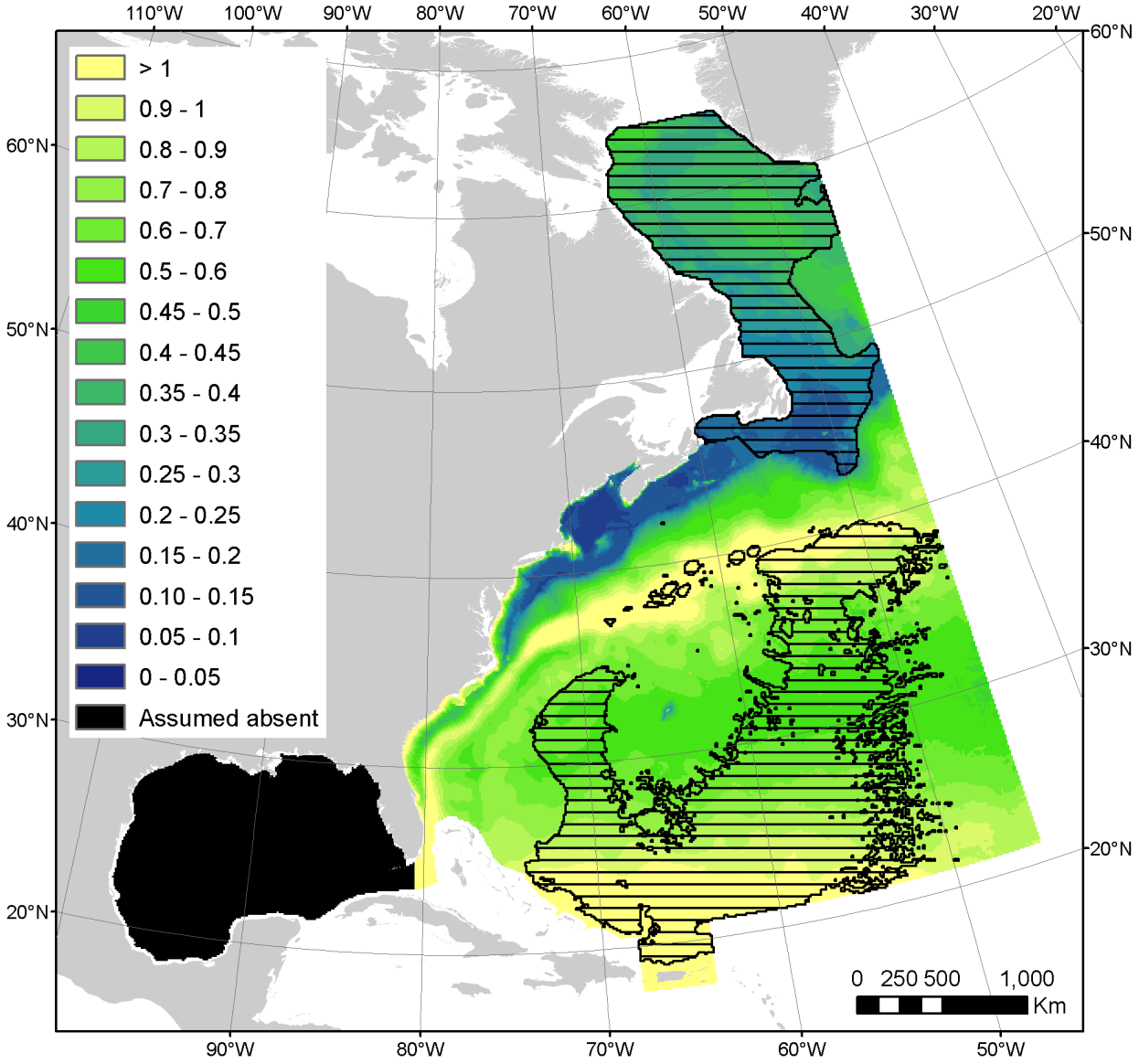


Figure 8: Mean predicted coefficients of variation derived from GAM parameters in the AFTT area. Areas where we extrapolated beyond sampled predictor ranges and coefficients of variation should not be trusted are indicated with black crosshatches. An Albers equal area projection is used.

7- Predicted densities per province

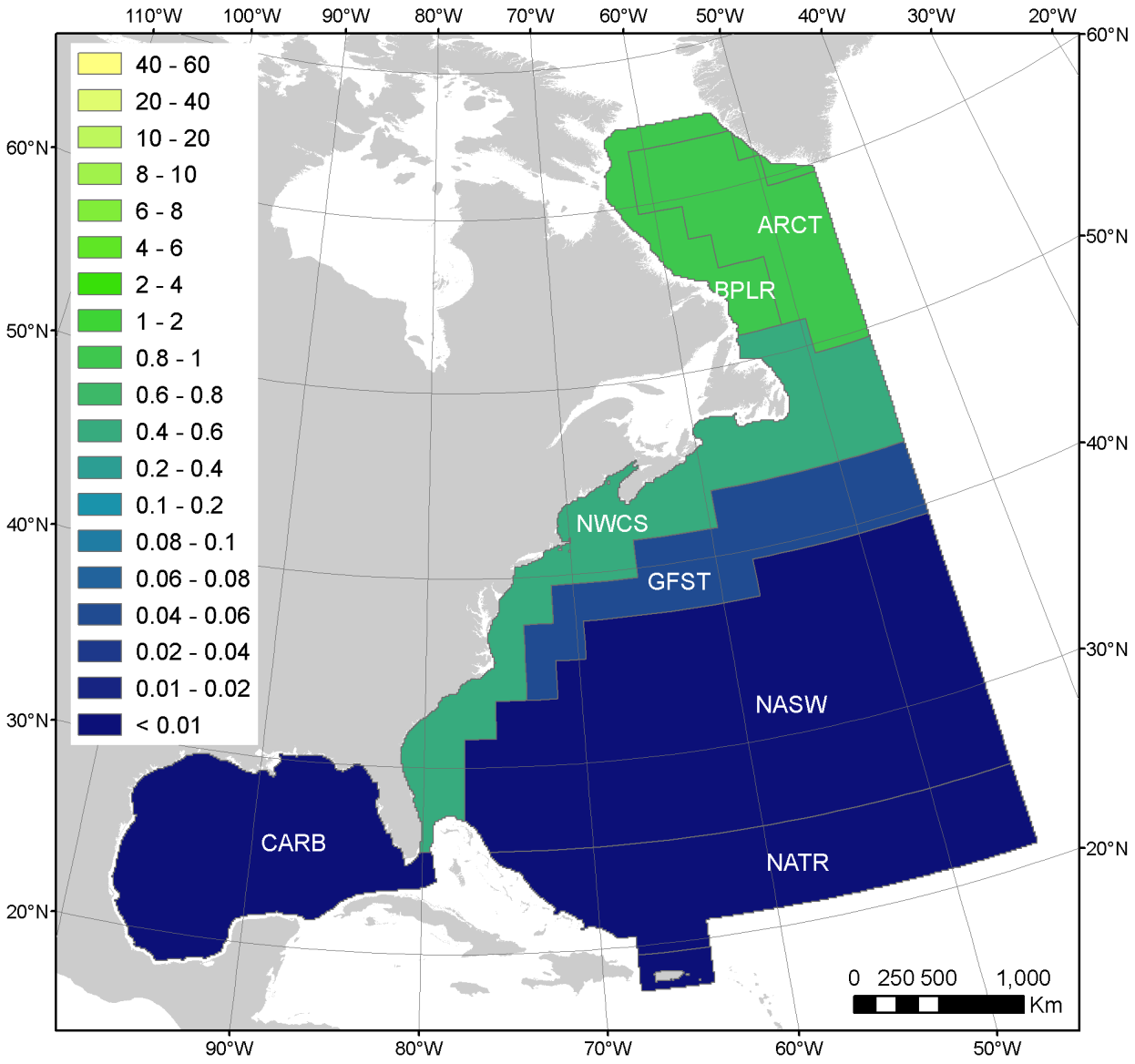


Figure 9: Predicted densities (individuals 100 km-2) averaged per Longhurst's biogeographical province. Note that the color scheme is the same as in Figure 7. Provinces: ARCT: Atlantic Arctic Province; BPLR: Boreal Polar Province; CARB: Caribbean Province; GFST: Gulf Stream Province; NATR: North Atlantic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

8- Alternate models

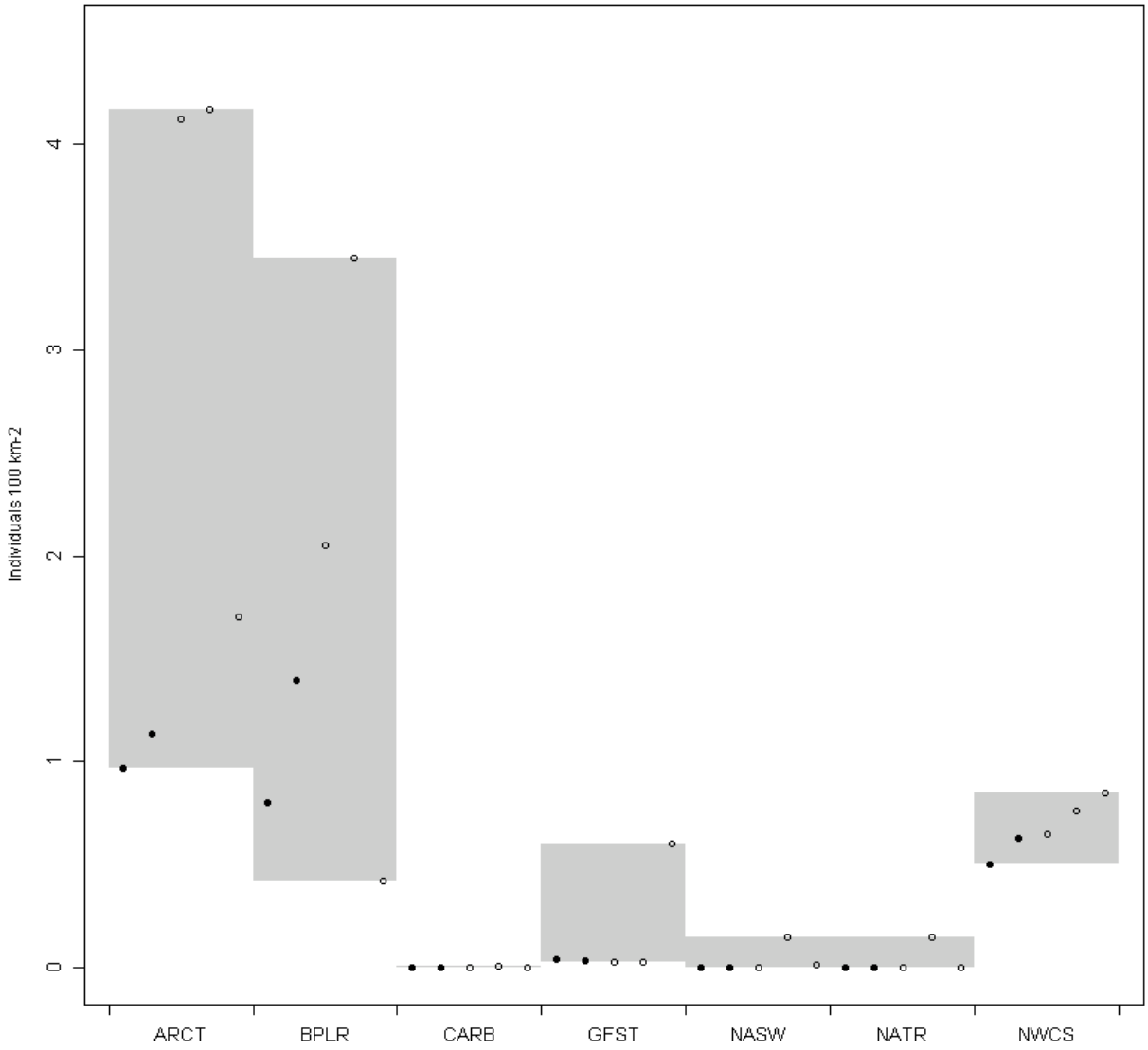


Figure 10: Sensitivity of densities predicted by the five top models per Longhurst's biogeographical province. Points represent predicted densities (individuals 100 km-2) for the five top models listed in Table 3, with the first to fifth models ordered from left to right. Filled points correspond to 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
Depth	EpiMnkPP	SLAStDev	SST	77127.3	0.0
Depth	DistToFront1	SLAStDev	SST	77129.1	1.8
Depth	DistToFront1	SLAStDev	PkPB	77139.9	12.6
Depth	DistToFront1	EKE	EpiMnkPP	77152.7	25.4
Depth	DistToFront1	EpiMnkPB	SST	77156.0	28.7

9- Residual diagnostics

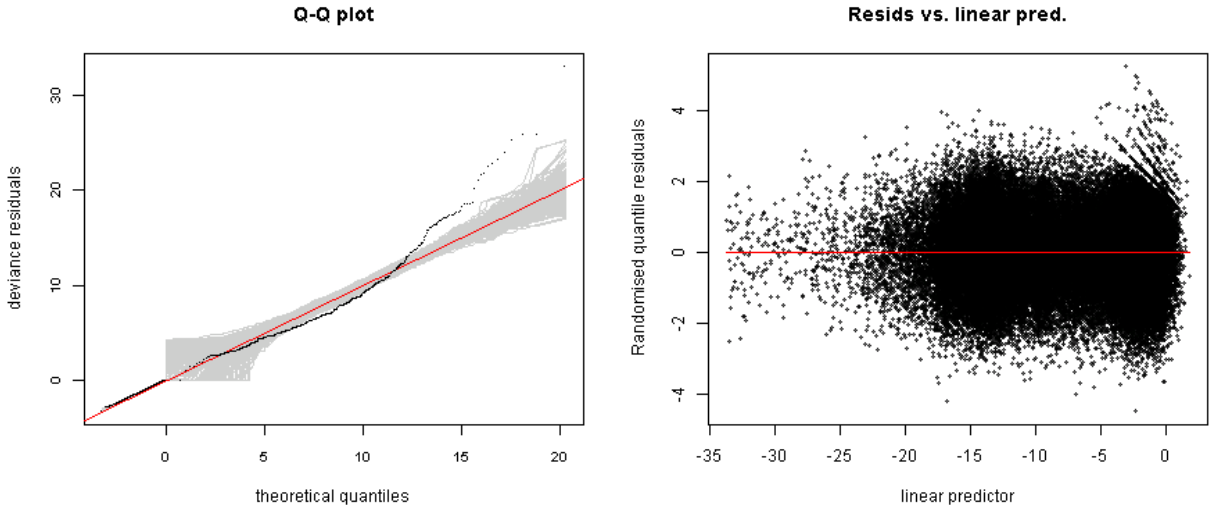


Figure 11: Diagnostic plots of residuals. Left: Quantile-quantile (Q-Q) plot of deviance residuals generated using the qq.gam function with 100 simulations (Augustin et al. 2012). Grey lines are possible simulated Q-Q plots under the assumption that the model is correct. The red reference line indicates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

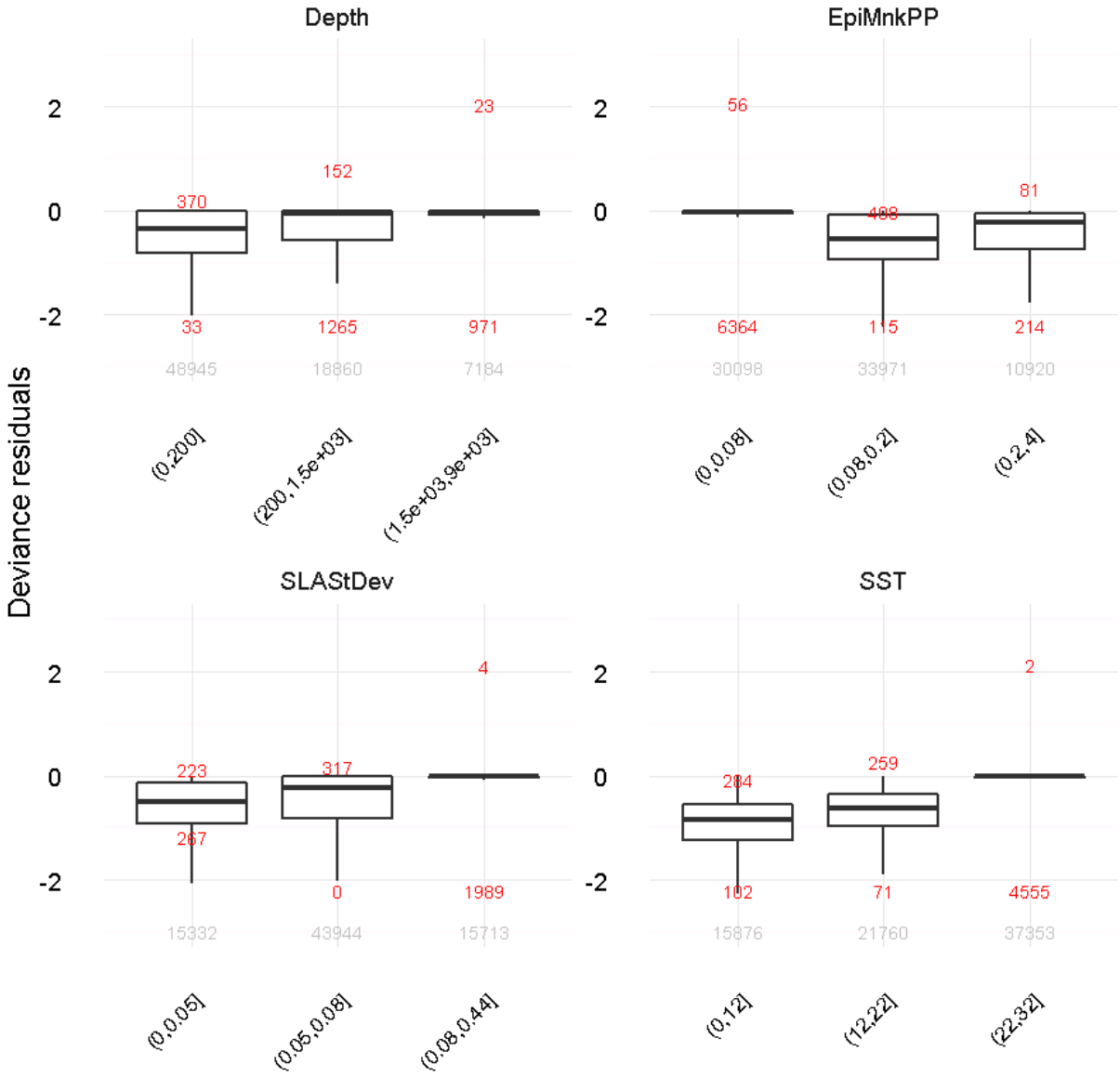


Figure 12: Boxplots of deviance residuals, binned for each predictor. The horizontal line represents the median, and the bottom and top of the box represent the first and third quartiles respectively. Whiskers extend 1.5 times the inter-quartile range following McGill et al. (1978). Total counts of outliers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

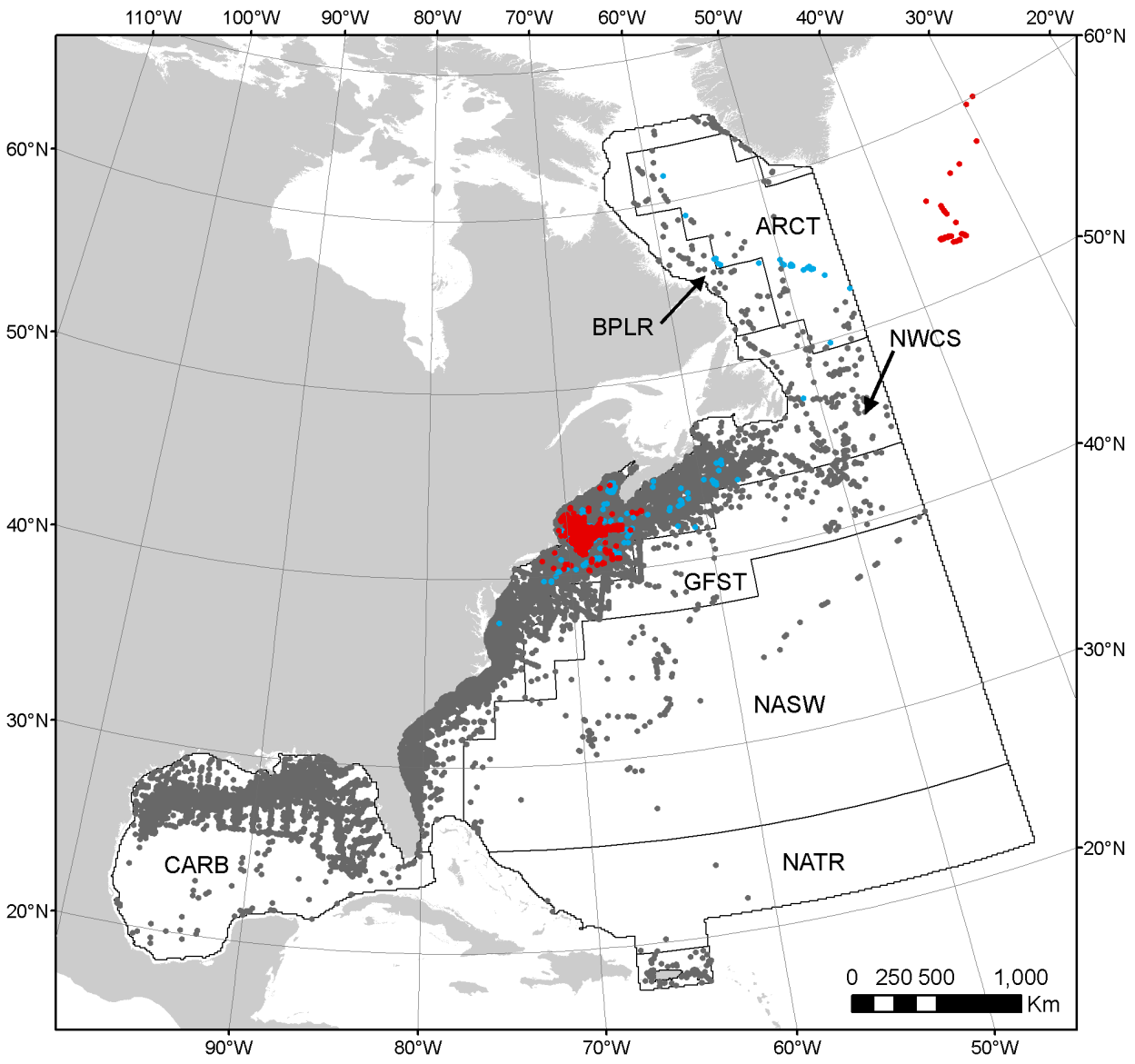


Figure 13: Red points are sightings of the taxon from line transect surveys used in this study. Blue points are sightings of the taxon reported by other datasets not used in our study for 1992-2016 (e.g., because they were not compatible with our methodology). Underlain grey points are sightings of other 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 840 sightings were available to fit the habitat-based density model. The first or lowest AIC model included depth, sea surface temperature, standard error of sea level anomaly and micronekton production (listed in decreasing order of importance according to F-scores) and had an explained deviance of 38.5%. The second model included the same predictors with distance to fronts instead of 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 BPLR province where the first model predicted 0.8 indiv. 100km-2 and the second model, 1.4 indiv. 100km-2) (Figure 10). Predicted densities from all top five models were very low in the CARB, NASW and NATR provinces, while they differed dramatically in the BPLR, ARCT and GFST provinces. When examining these results, it is important to keep in mind that the third, fourth and fifth models had a large delta AIC and therefore little statistical support. The first model had the lowest AIC and explained slightly more deviance than the second model, suggesting it was more suitable for modeling sei whale densities.

There are still important gaps in our understanding of the distribution and migration of sei whales in the North Atlantic (Prieto et al. 2012, Horwood 2009). Overall, model predictions seemed to agree with the described distribution of sei whales in temperate to subpolar waters, primarily in deep waters on the continental slope and beyond (Prieto et al. 2012).

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 the highest in the ARCT and BPLR provinces. Model uncertainty was also relatively high in these provinces (the second model predicted slightly higher densities than the first model).

Sei whales were sighted during aerial and shipboard surveys in September 2005 in West Greenland (Heide-Jørgensen et al. 2007, 2008), mostly in large groups concentrated in offshore waters. According to Heide-Jørgensen et al. (2007), sei whale abundance is overall low in West Greenland and seems to increase during periods of warm water influx. Sei whale was the most common cetacean species seen during the MAR-ECO cruise along the mid-Atlantic ridge (Waring et al. 2008) (Figure 13). All sightings were made north of the Charlie-Gibbs Fracture Zone which was suggested as a foraging hotspot.

High predicted densities in the Labrador Sea seemed consistent with a presumed summer feeding ground revealed by satellite telemetry tracks of sei whales tagged in the Azores (Olsen et al. 2009, Prieto et al. 2014). Locations of the individual tagged by Olsen et al. (2009), contributed to OBIS-SEAMAP, are shown on Figure 13.

Sei whales tagged by Prieto et al. (2014) from May to June in the Azores travelled across the North Atlantic to reach the Labrador Sea where they exhibited foraging behavior. Individuals arrived in the Labrador Sea as early as mid-May, and some animals stayed until at least mid-September. The tracking data suggested a possible offshore migratory corridor between the Azores and the Labrador Sea.

We warn that extrapolation beyond predictor ranges occurred in most of the ARCT and BPLR provinces. Therefore, predictions are largely speculative and should be considered with great caution. Nevertheless, predictions appeared compatible with the suggested importance of the Labrador Sea as a summer feeding area.

North West Atlantic shelves (NWCS) province

Highest densities were predicted on the outer continental shelf and slope north of Cape Hatteras, North Carolina (Figure 13).

During the Canadian TNASS survey in summer 2007, sei whales were sighted once south of Newfoundland and twice on the Scotian shelf (Lawson and Gosselin 2009) (sightings not contributed to OBIS-SEAMAP and therefore not shown on Figure 13). Sightings available from OBIS-SEAMAP were mostly concentrated on

the continental shelf and slope between 40 and 47°N (Figure 13). Sei whales have been occasionally reported near the Gully canyon off the Scotian shelf in summer (Hooker et al. 1999).

The southernmost sightings reported by surveys used in this study were located around 41°N. The model predicted intermediate densities on the outer continental shelf and slope all the way to 36°N. As these predictions were supported by only one sighting reported around 37°N (Figure 13), we believe they are largely speculative.

Gulf Stream (GFST) province

Low predicted densities in the GFST province seemed consistent with the absence of sightings reported in OBIS-SEAMAP (Figure 13). We warn that extrapolation beyond predictions ranges occurred in parts of the GFST province and therefore predictions should be considered with due caution.

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

Very low densities were predicted in these provinces, consistent with the affinity of sei whales for cold temperate and subpolar waters (Prieto et al. 2012). We caution that extrapolation to deeper waters occurred in large parts of the NASW and NATR provinces, leading to speculative predictions.

Records of sei whales in the Gulf of Mexico are restricted to 4 strandings in eastern Louisiana (Jefferson & Schiro 1997). In Puerto Rico, sei whales have been reported on only 2 occasions in the winter (Mignucci-Giannoni 1998).

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 appeared in line with suggested summer feeding grounds in the Labrador Sea but predicted densities, derived from extrapolation beyond predictor ranges, remain largely speculative and should be interpreted with great caution. The incorporation of line transect survey data from Canada and Greenland would be critical to increase the reliability of predicted densities at high latitudes. 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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