Density Model for Sei Whale (*Balaenoptera borealis*) for the U.S. Navy Atlantic Fleet Testing and Training (AFTT) Study Area: Supplementary Report

Model Version 4

Duke University Marine Geospatial Ecology Laboratory*

2022-06-20

Citation

When referencing our methodology or results generally, please cite Roberts et al. (2023), which documented the modeling cycle we completed in the 2022 for the U.S. Navy AFTT Phase IV Environmental Impact Statement, and Mannocci et al. (2017), which developed the original methodology and models upon which the 2022 models were based. The full citations appear in the References section at the end of this document.

To independently reference this specific model or Supplementary Report, please cite:

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Model Version History

Version	Date	Description
3	2016-10-01	First publicly-released version of this model, released in 2015 as part of the final delivery of the U.S. Navy Marine Species Density Database (NMSDD) for the Atlantic Fleet Testing and Training (AFTT) Phase III Environmental Impact Statement, and again as part of Mannocci et al. (2017).
4	2022-06-20	Updated the AFTT Phase III model with many additional surveys contributed since that time. Please see Roberts et al. (2022, 2023) for details. This update was released as part of the final delivery of the NMSDD for the AFTT Phase IV Environmental Impact Statement.

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1 Survey Data

Following Mannocci et al. (2017), whose model we were updating, we built this model from data collected in the east coast, Caribbean, and Mid-Atlantic Ridge regions and excluded surveys of Europe. Breaking with those authors, we also excluded data from the Gulf of Mexico, as sei whales do not inhabit it. We did include segments from two east-west basin-transiting surveys by R/V Song of the Whale. We excluded surveys that did not target sei whales or were otherwise problematic for modeling them. We restricted the model to survey transects with sea states of Beaufort 5 or less (for a few surveys we used Beaufort 4 or less) for both aerial and shipboard surveys. We also excluded transects with poor weather or visibility for surveys that reported those conditions. Table 1 summarizes the survey effort and sightings available after most exclusions were applied.

Table 1: Survey effort and observations considered for this model. Effort is tallied as the cumulative length of on-effort transects. Observations are the number of groups and individuals encountered while on effort. Off effort observations and those lacking an estimate of group size or distance to the group were excluded.

			Effort	Observations		
Institution	Program	Period	1000s km	Groups	Individuals	Mean Group Size
Aerial Surveys						
HDR	Navy Norfolk Canyon	2018-2019	11	3	4	1.3
NEAq	CNM	2017-2020	2	2	3	1.5
NEAq	MMS-WEA	2017-2020	32	21	54	2.6
NEAq	NLPSC	2011-2015	43	22	35	1.6
NEFSC	AMAPPS	2010-2019	89	17	28	1.6
NEFSC	NARWSS	2003-2020	471	1,245	3,204	2.6
NEFSC	Pre-AMAPPS	1999-2008	46	9	11	1.2
NJDEP	NJEBS	2008-2009	11	0	0	
NYS-DEC/TT	NYBWM	2017-2020	77	2	7	3.5
SEFSC	AMAPPS	2010-2020	114	0	0	
SEFSC	MATS	1995-2005	34	0	0	
SEFSC	SECAS	1992-1995	8	0	0	
U. La Rochelle	REMMOA	2008-2017	42	0	0	
UNCW	MidA Bottlenose	2002-2002	17	0	0	
UNCW	Navy Cape Hatteras	2011-2017	34	0	0	
UNCW	Navy Jacksonville	2009-2017	92	0	0	
UNCW	Navy Norfolk Canyon	2015-2017	14	0	0	
UNCW	Navy Onslow Bay	2007-2011	49	0	0	
UNCW	SEUS NARW EWS	2005-2008	114	0	0	
VAMSC	MD DNR WEA	2013-2015	16	0	0	
VAMSC	Navy VACAPES	2016-2017	19	0	0	
VAMSC	VA CZM WEA	2012-2015	21	0	0	
		Total	**1,358**	**1,321**	**3,346**	**2.5**
Shipboard Surveys						
IMR	MAR-ECO	2004-2004	2	24	69	2.9
MCR	SOTW Visual	2012-2019	9	6	10	1.7
NEFSC	AMAPPS	2011-2016	16	18	23	1.3
NEFSC	Pre-AMAPPS	1995-2007	18	10	13	1.3
NJDEP	NJEBS	2008-2009	14	0	0	
SEFSC	AMAPPS	2011-2016	17	0	0	
SEFSC	Pre-AMAPPS	1992-2006	33	3	5	1.7
SEFSC	SEFSC Caribbean	1995-2000	8	0	0	
		Total	**117**	**61**	**120**	**2.0**
		Grand Total	**1,475**	**1,382**	**3,466**	**2.5**

Table 2: Institutions that contributed surveys used in this model.

Institution	Full Name
HDR	HDR, Inc.
IMR	Norway Institute of Marine Research
MCR	Marine Conservation Research
NEAq	New England Aquarium
NEFSC	NOAA Northeast Fisheries Science Center
NJDEP	New Jersey Department of Environmental Protection
NYS-DEC/TT	New York State Department of Environmental Conservation and Tetra Tech, Inc.
SEFSC	NOAA Southeast Fisheries Science Center
U. La Rochelle	University of La Rochelle
UNCW	University of North Carolina Wilmington
VAMSC	Virginia Aquarium & Marine Science Center

Table 3: Descriptions and references for survey programs used in this model.

Program	Description	References
AMAPPS	Atlantic Marine Assessment Program for Protected Species	Palka et al. (2017), Palka et al. (2021)
CNM	Northeast Canyons Marine National Monument Aerial Surveys	Redfern et al. (2021)
MAR-ECO	Census of Marine Life Mid-Atlantic Ridge Ecology Program	Waring et al. (2008)
MATS	Mid-Atlantic Tursiops Surveys	
MD DNR WEA	Aerial Surveys of the Maryland Wind Energy Area	Barco et al. (2015)
MidA Bottlenose	Mid-Atlantic Onshore/Offshore Bottlenose Dolphin Surveys	Torres et al. (2005)
MMS-WEA	Marine Mammal Surveys of the MA and RI Wind Energy Areas	Quintana-Rizzo et al. (2021), O'Brien et al. (2022)
NARWSS	North Atlantic Right Whale Sighting Surveys	Cole et al. (2007)
Navy Cape Hatteras	Aerial Surveys of the Navy's Cape Hatteras Study Area	McLellan et al. (2018)
Navy Jacksonville	Aerial Surveys of the Navy's Jacksonville Study Area	Foley et al. (2019)
Navy Norfolk Canyon	Aerial Surveys of the Navy's Norfolk Canyon Study Area	Cotter (2019), McAlarney et al. (2018)
Navy Onslow Bay	Aerial Surveys of the Navy's Onslow Bay Study Area	Read et al. (2014)
Navy VACAPES	Aerial Survey Baseline Monitoring in the Continental Shelf Region of the VACAPES OPAREA	Mallette et al. (2017)
NJEBS	New Jersey Ecological Baseline Study	Geo-Marine, Inc. (2010), Whitt et al. (2015)
NLPSC	Northeast Large Pelagic Survey Collaborative Aerial Surveys	Leiter et al. (2017), Stone et al. (2017)
NYBWM	New York Bight Whale Monitoring Surveys	Zoidis et al. (2021)
Pre-AMAPPS	Pre-AMAPPS Marine Mammal Abundance Surveys	Mullin and Fulling (2003), Garrison et al. (2010), Palka (2006)
REMMOA	REcensement des Mammifères marins et autre Mégafaune pélagique par Observation Aérienne	Mannocci et al. (2013), Laran et al. (2019)
SECAS	Southeast Cetacean Aerial Surveys	Blaylock and Hoggard (1994)

Table 3: Descriptions and references for survey programs used in this model. *(continued)*

Program	Description	References
SEFSC Caribbean	SEFSC Surveys of the Caribbean Sea	Mullin (1995), Swartz and Burks (2000)
SEUS NARW EWS	Southeast U.S. Right Whale Early Warning System Surveys	
SOTW Visual	R/V Song of the Whale Visual Surveys	Ryan et al. (2013)
VA CZM WEA	Virginia CZM Wind Energy Area Surveys	Mallette et al. (2014), Mallette et al. (2015)

2 Density Model

Our objective was to update the model of Mannocci et al. (2017) with new data without substantially adjusting the model's overall structure or repeating the covariate selection exercise performed by those authors. Although the migration patterns of sei whales in the North Atlantic have not been completely elucidated, they appear to be highly migratory and exhibit a distinct seasonality. For this reason, Mannocci et al. split the year into two seasons—Winter (November-March) and Summer (April-October)—and fitted an independent model for each[1]. We followed this overall approach but adjusted the seasonal definitions to follow our East Coast (EC) regional sei whale model (version 10), which set Winter to October-February and Summer to March-September, based on the October-February period containing the all of the visual sightings reported south of Cape Hatteras by our collaborators, as well as the bulk of acoustic detections reported there (Davis et al. 2020; Kowarski et al. 2022). Please see the EC model report for a detailed discussion. We present the details for each updated seasonal model below. We present the summarized predictions in Section 3 and discuss them in Section 4.

[1]The publication, Mannocci et al. (2017), only included the supplementary report for their summer model. The report for their winter model is available on our website.

2.1 Winter (October-February)

Sei whales were rarely sighted in the AFTT study area during this season, but effort was restricted mostly to the U.S. continental shelf and a number of sightings were made beyond the shelf in very deep waters over the continental slope, both north and south of the Gulf Stream. Because of this, Mannocci et al. opted not to fit a traditional density surface model that related density to environmental covariates but instead defined a stratum extending from the southern extent of the AFTT study area to approximately 43.4 °N, the northernmost sighting reported during the season. Within this region, they fitted a density model with no covariates, yielding a uniform density surface, and assumed the species was absent elsewhere within the AFTT (i.e. the Gulf of Mexico and in waters north of 43.4 °N). We followed their approach.

This stratified approach necessarily assumed that density would be distributed uniformly throughout the stratum. This assumption, if true, would mean we would obtain similar density estimates under any sampling design within the stratum, and therefore it would not matter if there was some heterogeneity in sampling. However, we strongly caution that this assumption did not hold for the other, more-common species we successfully modeled with traditional density surface modeling, as evidenced by the non-uniform patterns in density predicted by those species' models. But without more data, we cannot elucidate those patterns confidently through the normal modeling process. Thus, for the much rarer species, such as sei whale documented here, we offer this simplified approach as a rough-and-ready substitute for a full density surface model. Figure 1 shows the segments and sightings used to make this estimate. Section 3 shows the result.

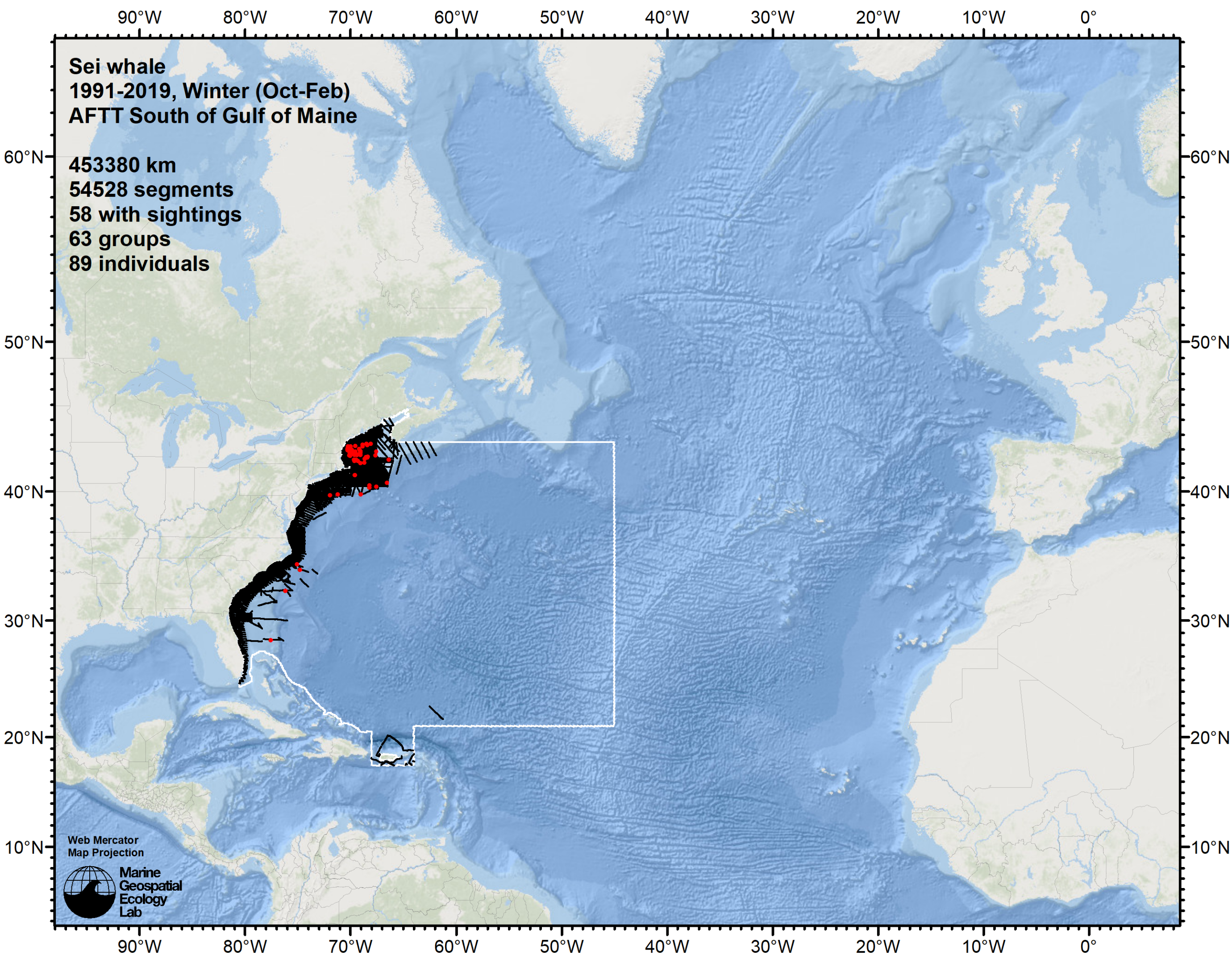


Figure 1: Survey segments and sightings used to estimate Sei whale density during the Winter season (October-February). Black lines and red points indicate the segments and sightings used to estimate density. White polygon indicates the region to which the density was applied.

2.2 Summer (March-September)

Following Mannocci et al., we fitted a 4-covariate model that included depth of the sea floor, micronekton productivity, the standard deviation of sea level anomaly, and sea surface temperature (SST). The resulting relationships (Figure 3) strongly resembled those of Mannocci et al.'s model except for that for the micronekton covariate, which was linear in Mannocci's model but hump-shaped in our model, and the depth covariate, which in our model turned slightly higher at the deepest depths compared to Mannocci's model. This resulted in lower predictions over the continental shelf waters of Canada north of Halifax, where micronekton productivity is high, and higher predictions in waters beyond the shelf (Figure 17). We discuss this in Section 4. Univariate extrapolation analyses (Section 2.2.3.1) displayed geographic patterns very similar to the environmental envelopes estimated by Mannocci et al. except for the depth covariate, for which the trans-Atlantic surveys by R/V Song of the Whale used in our model provided sampling at much deeper depths than the surveys available for Mannocci's model. In our model the necessity for univariate environmental extrapolation was driven by a lack of sampling in waters with very low sea surface temperatures (Figure 10), as occurs along the shelf of Newfoundland, Labrador, and Greenland in March-June. This geographic pattern was very similar to the environmental envelope estimated by Mannocci et al. However, we note that the outcome of no extrapolation being required for the micronekton productivity covariate likely depended upon the Winsorization applied to it, which followed what was done by Mannocci et al. Had the covariate not been Winsorized, it is possible that some extrapolation could have been required in areas of extremely high values (compare the plot in Figure 5 to the corresponding plots in Figure 6). Because of this, we recommend caution in shelf waters of Canada north of Halifax.

2.2.1 Final Model

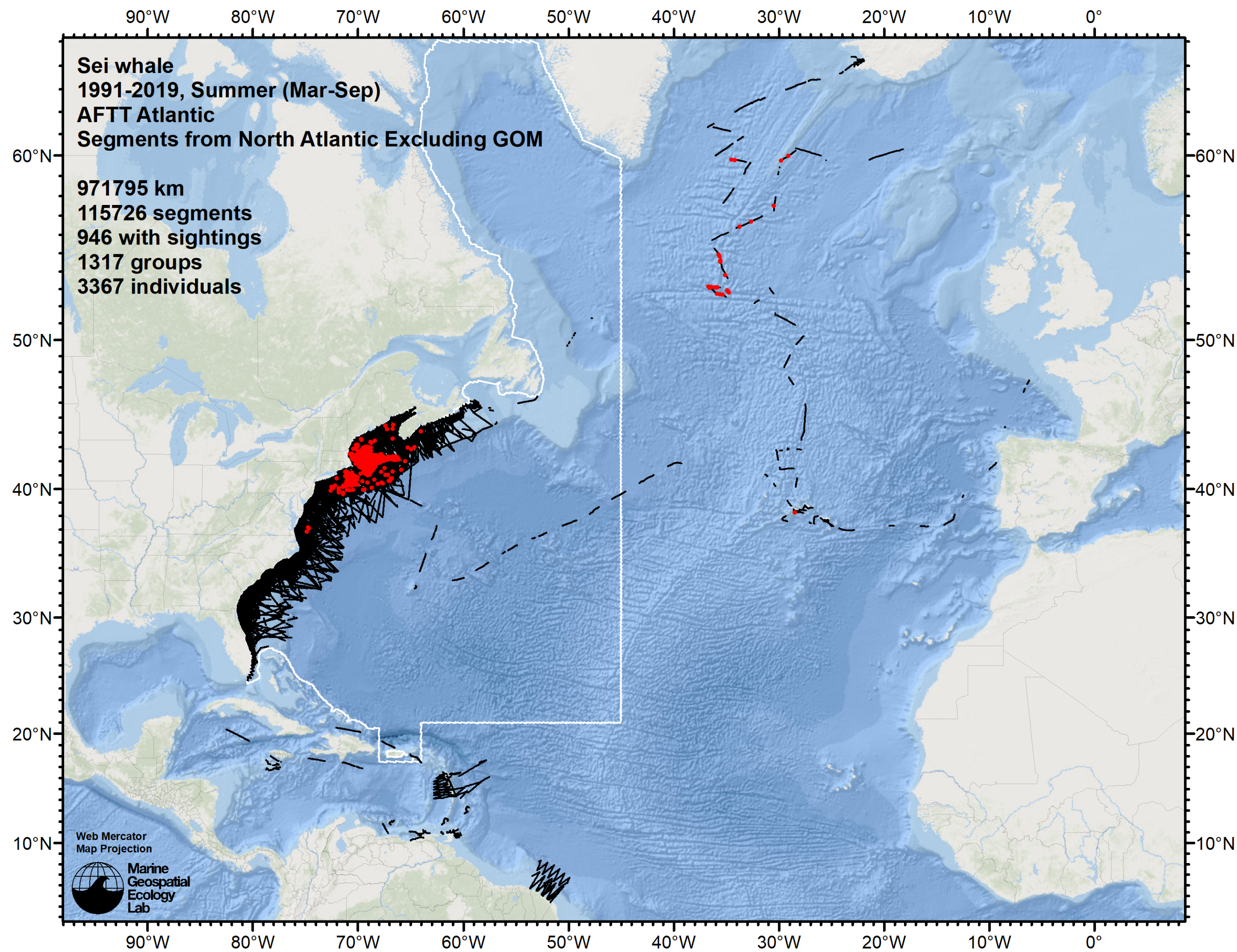
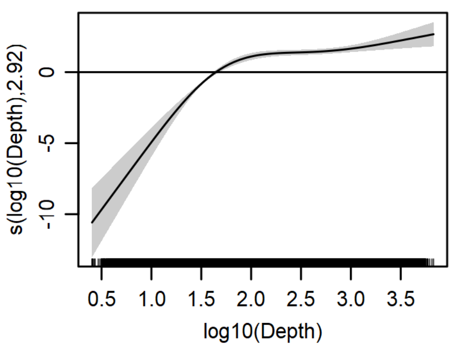


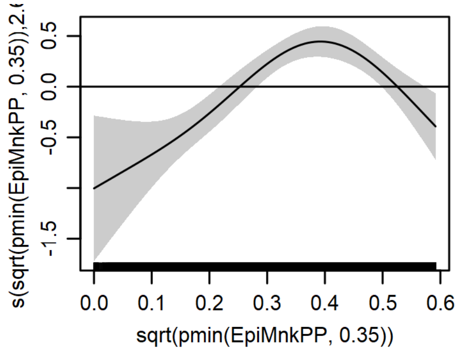
Figure 2: Survey segments (black lines) used to fit the model for the region AFTT Atlantic for Summer. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

Statistical output for this model:

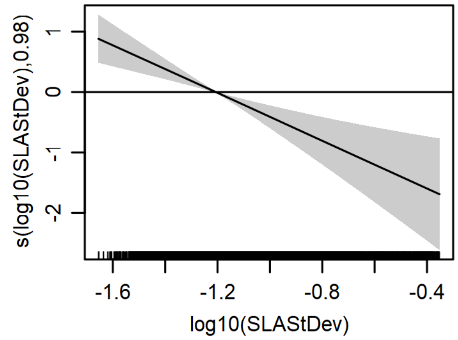
```
Family: Tweedie(p=1.267)
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(log10(Depth),
    bs = "ts", k = 4) + s(sqrt(pmin(EpiMnkPP, 0.35)), bs = "ts",
    k = 4) + s(log10(SLAStDev), bs = "ts", k = 4) + s(SST, bs = "ts",
    k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -23.2398     0.2783  -83.51   <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(log10(Depth))              2.9153      3 84.898  < 2e-16 ***
s(sqrt(pmin(EpiMnkPP, 0.35))) 2.6499      3 13.804  < 2e-16 ***
s(log10(SLAStDev))           0.9807      3  6.757 4.54e-06 ***
s(SST)                       2.8359      3 95.002  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0225   Deviance explained = 27.3%
-REML = 7150.5  Scale est. = 16.054    n = 115726

Method: REML   Optimizer: outer newton
full convergence after 13 iterations.
Gradient range [-0.001668215,0.001227747]
(score 7150.465 & scale 16.0543).
Hessian positive definite, eigenvalue range [0.4640814,4772.521].
Model rank =  13 / 13

Basis dimension (k) checking results. Low p-value (k-index<1) may
indicate that k is too low, especially if edf is close to k'.

                                k'   edf k-index p-value
s(log10(Depth))              3.000 2.915    0.85   0.015 *
s(sqrt(pmin(EpiMnkPP, 0.35))) 3.000 2.650    0.87   0.055 .
s(log10(SLAStDev))           3.000 0.981    0.85  <2e-16 ***
s(SST)                       3.000 2.836    0.83  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



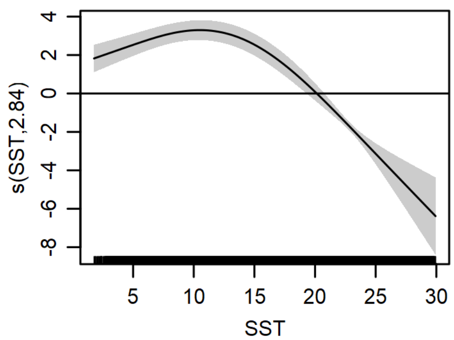
(a) Seafloor depth (m)



(b) Climatological epipelagic micronekton productivity (g m^{-2} d^{-1})



(c) Climatological standard deviation of sea surface height anomaly (m)



(d) Climatological sea surface temperature (°C)

Figure 3: Functional plots for the final model for the region AFTT Atlantic for Summer. Transforms and other treatments are indicated in axis labels. *log10* indicates the covariate was $\log_{10}$ transformed. *sqrt* indicates the covariate was square-root transformed. *pmax* and *pmin* indicate the covariate's minimum and maximum values, respectively, were Winsorized to the values shown. Winsorization was used to prevent runaway extrapolations during prediction when covariates exceeded sampled ranges, or for ecological reasons, depending on the covariate. */1000* indicates meters were transformed to kilometers for interpretation convenience.

Table 4: Covariates used in the final model for the region AFTT Atlantic for Summer.

Covariate	Description
Depth	Depth (m) of the seafloor, from SRTM30_PLUS (Becker et al. (2009))
EpiMnkPP	Climatological monthly mean micronekton production in the epipelagic zone (g m^{-2} d^{-1}) from SEAPODYM (Lehodey et al. (2008); Lehodey et al. (2015))
SLAStDev	Climatological standard deviation of sea surface height anomaly (m) derived from Aviso Ssalto/Duacs global gridded L4 reprocessed sea surface heights, produced and distributed by E.U. Copernicus Marine Service. doi: 10.48670/moi-00148
SST	Climatological monthly mean sea surface temperature (°C) from GHRSST Level 4 CMC0.2deg (Brasnett (2008); Canada Meteorological Center (2012))

2.2.2 Diagnostic Plots

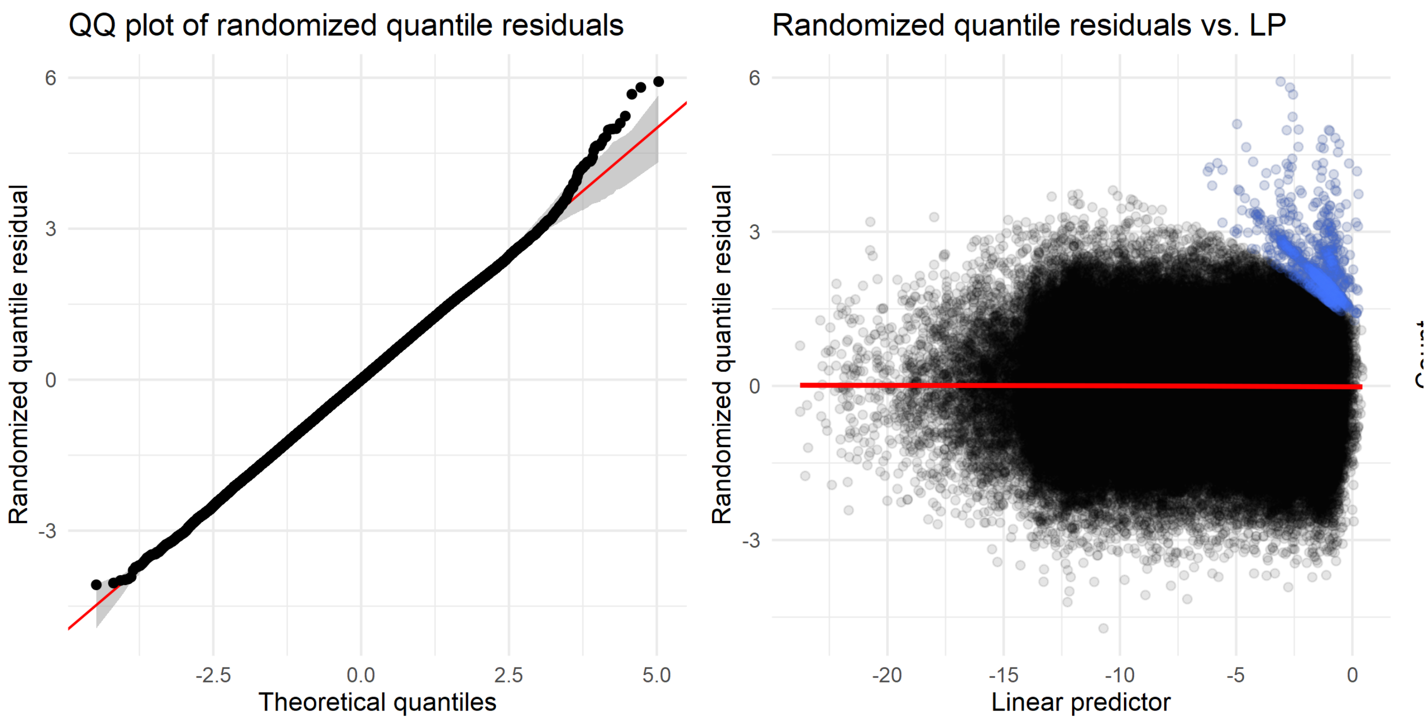


Figure 4: Residual plots for the final model for the region AFTT Atlantic for Summer.

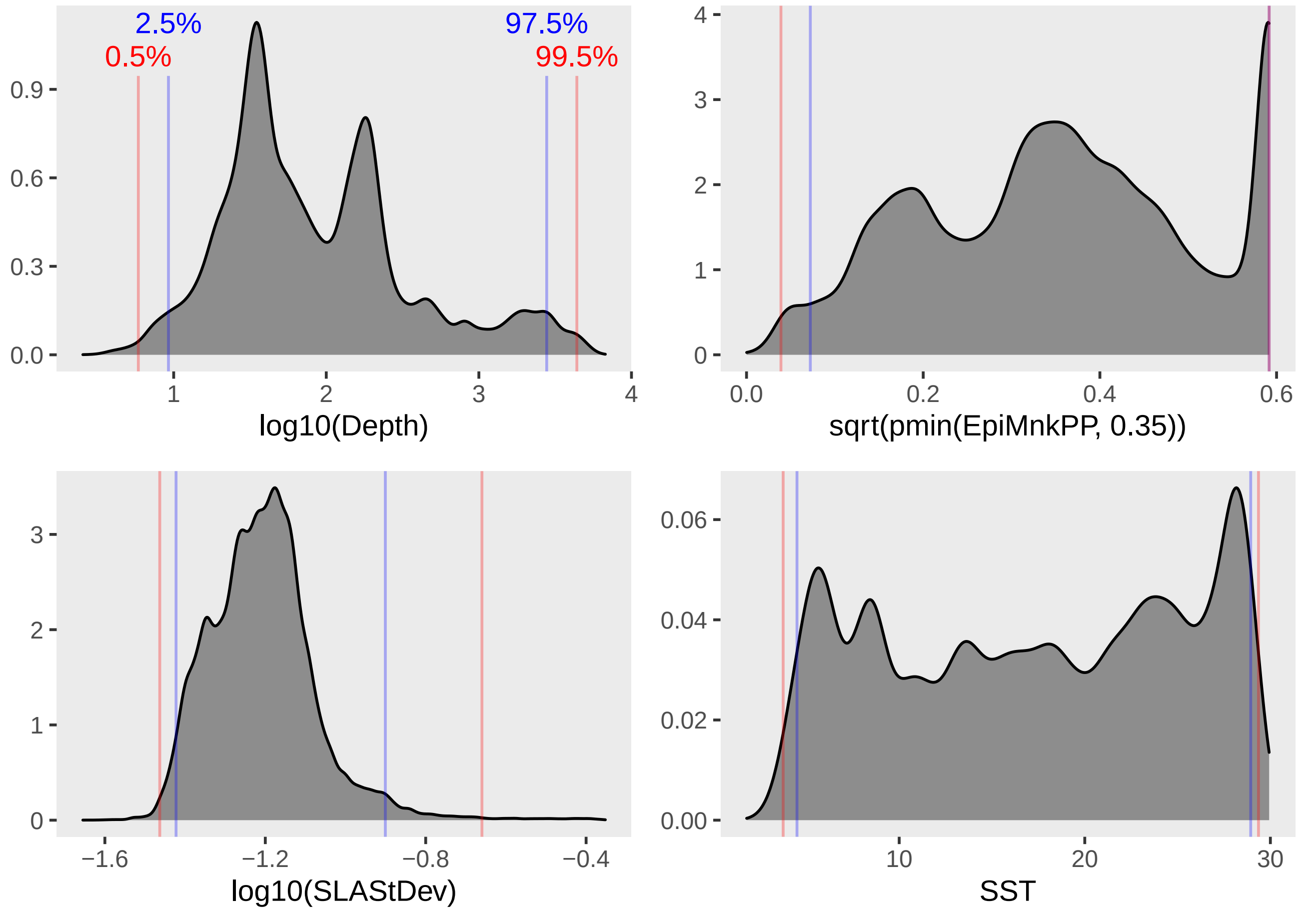


Figure 5: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 3), and additional covariates may have been considered in preceding selection steps. Red and blue lines enclose 99% and 95% of the distributions, respectively. Transforms and other treatments are indicated in axis labels. *log10* indicates the covariate was $\log_{10}$ transformed. *pmax* and *pmin* indicate the covariate's minimum and maximum values, respectively, were Winsorized to the values shown. Winsorization was used to prevent runaway extrapolations during prediction when covariates exceeded sampled ranges, or for ecological reasons, depending on the covariate. */1000* indicates meters were transformed to kilometers for interpretation convenience.

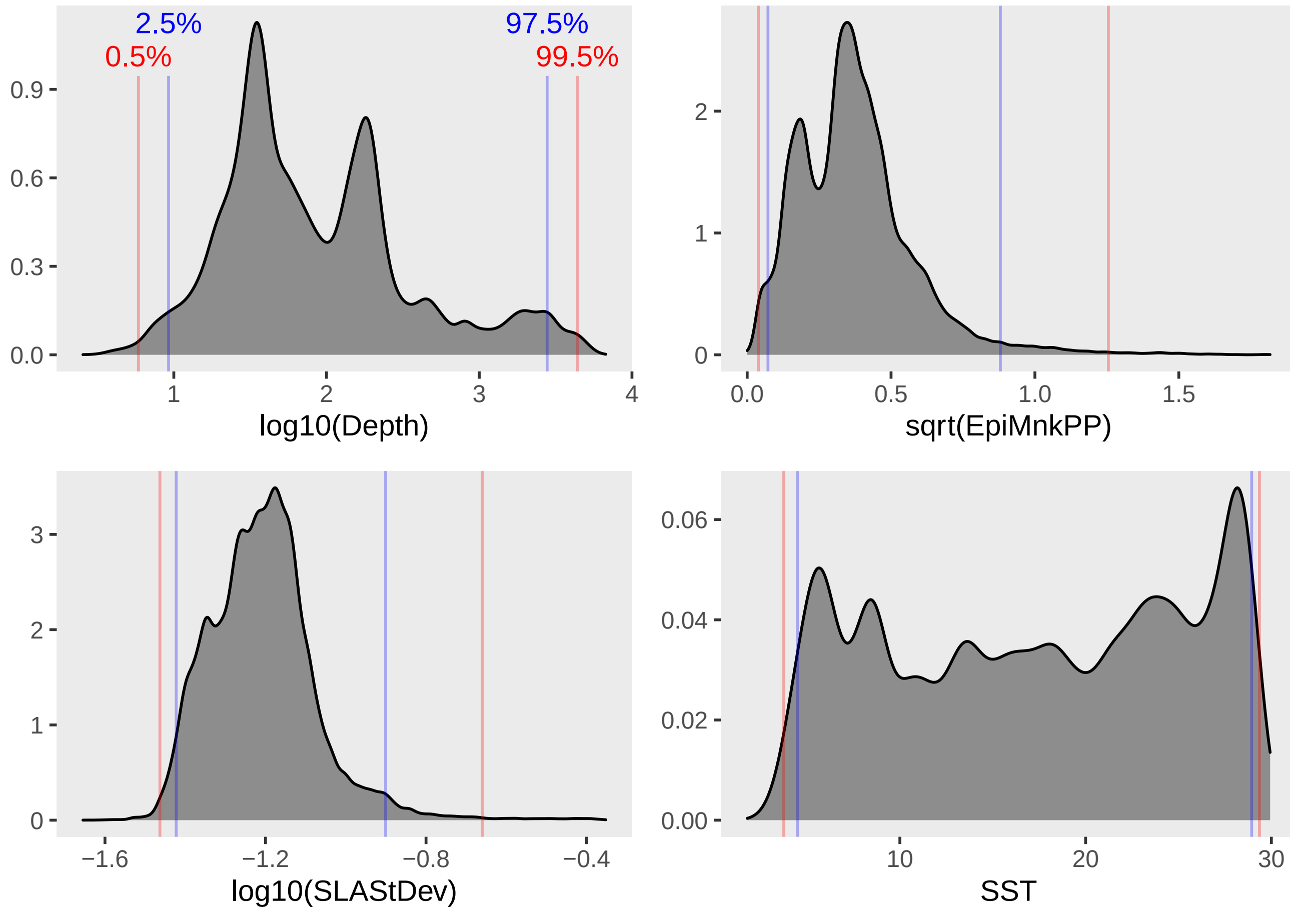


Figure 6: Density histograms shown in Figure 5 replotted without Winsorization, to show the full range of sampling represented by survey segments.

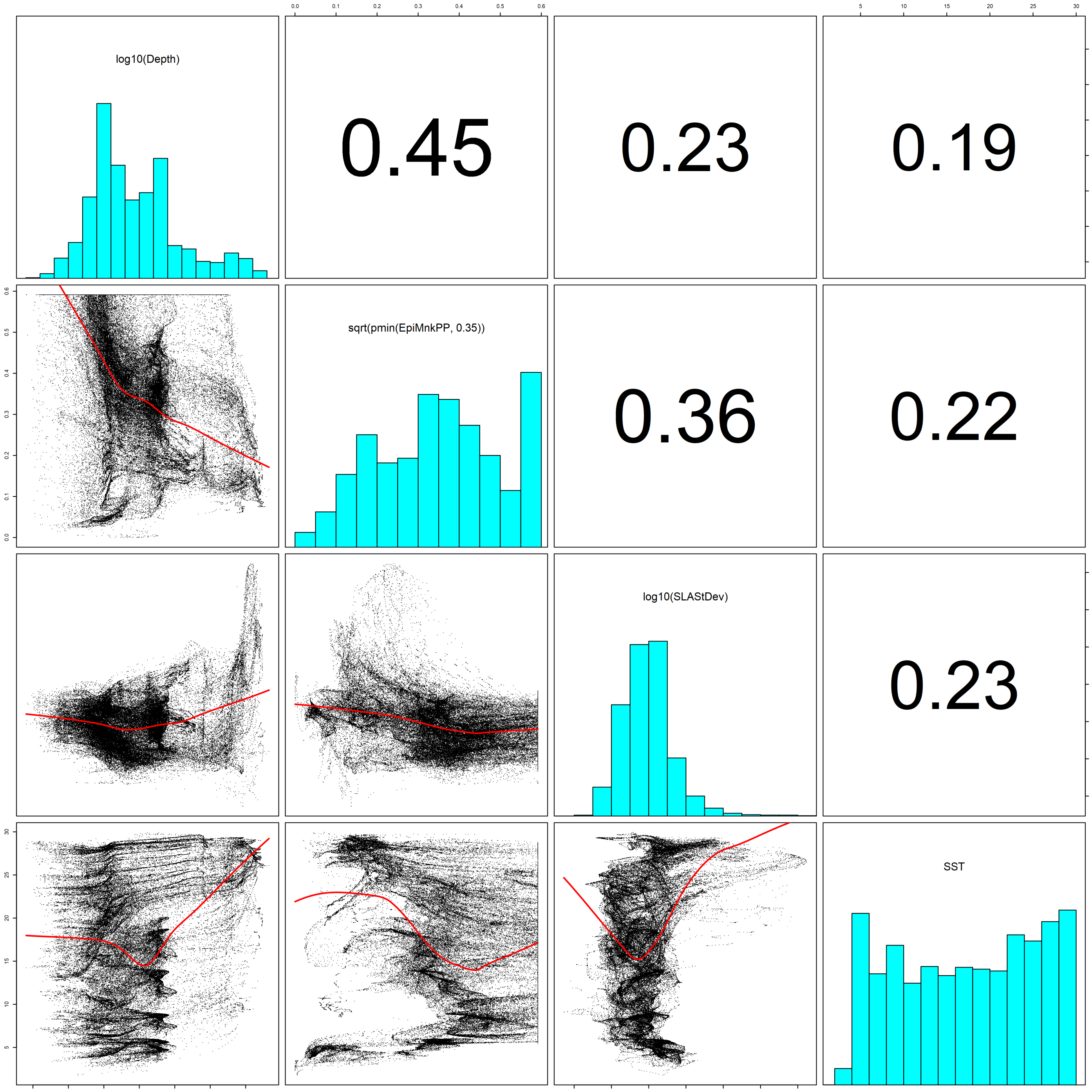


Figure 7: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 3), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized as shown in Figure 5. This plot is used to check simple correlations between covariates (via pairwise Pearson coefficients above the diagonal) and visually inspect for concurvity (via scatterplots and red lowess curves below the diagonal).

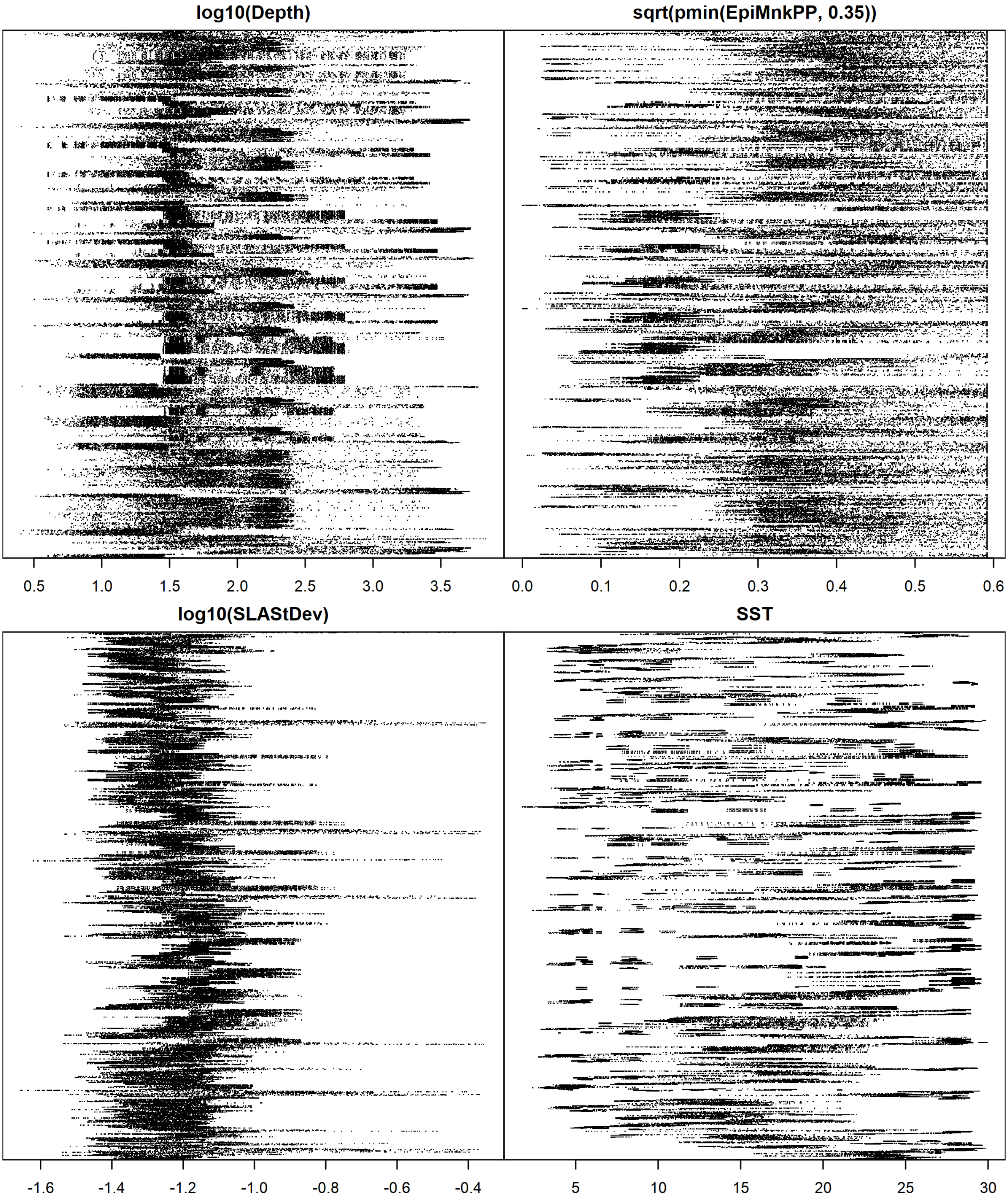


Figure 8: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 3), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized as shown in Figure 5. This plot is used to check for suspicious patterns and outliers in the data. Points are ordered vertically by segment ID, sequentially in time.

2.2.3 Extrapolation Diagnostics

2.2.3.1 Univariate Extrapolation

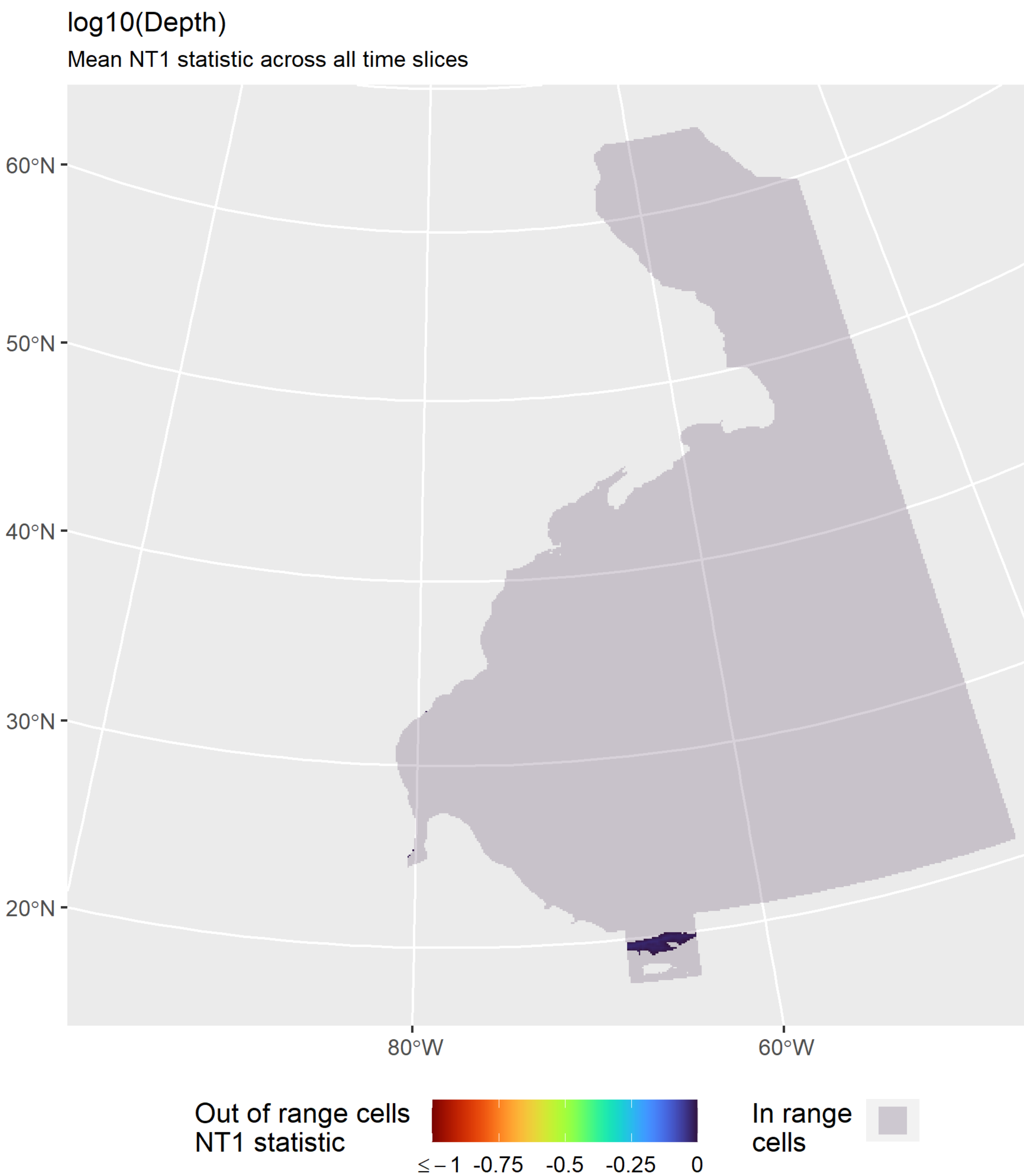
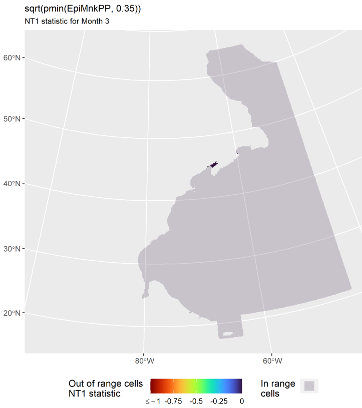
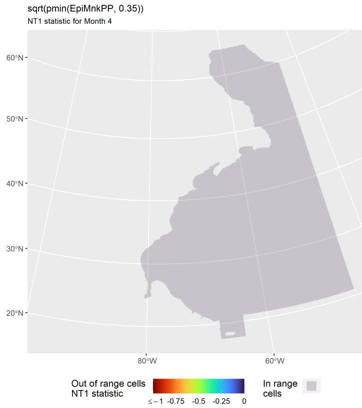


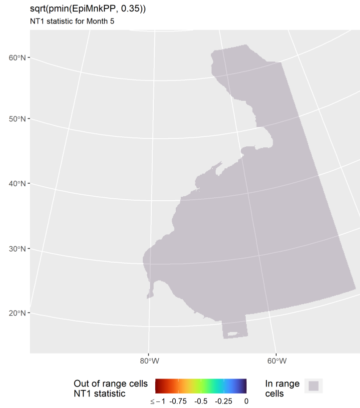
Figure 9: NT1 statistic (Mesgaran et al. (2014)) for static covariates used in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there. Areas within the sampled range appear in gray, indicating it did not occur.



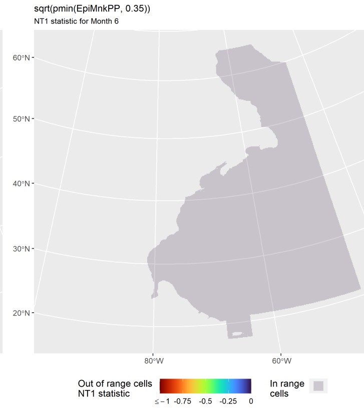
(a) March



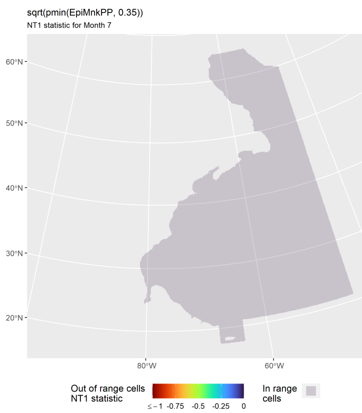
(b) April



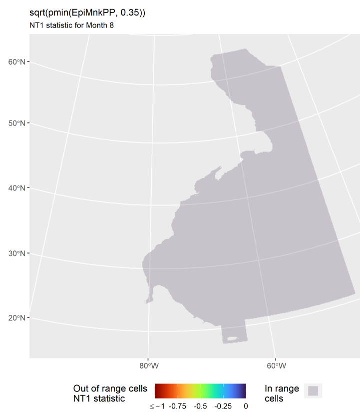
(c) May



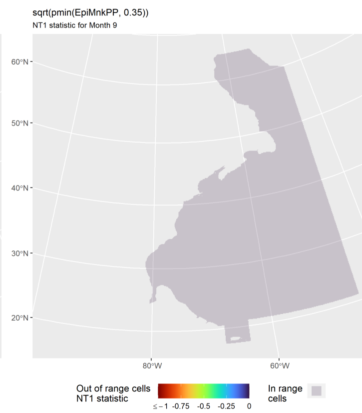
(d) June



(e) July

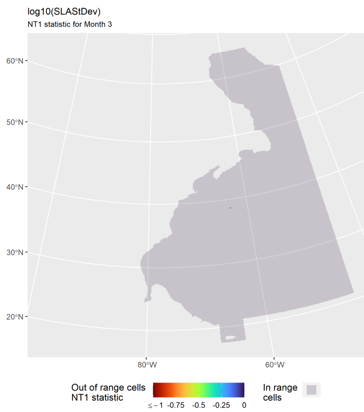


(f) August

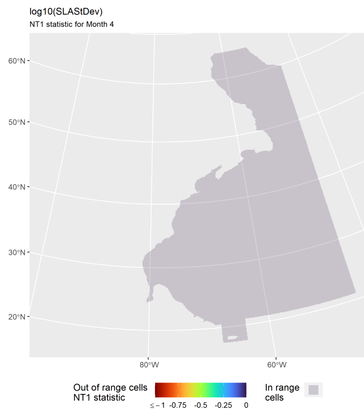


(g) September

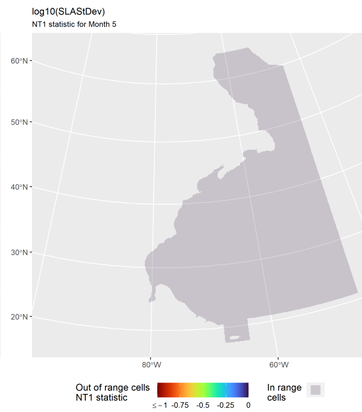
Figure 10: NT1 statistic (Mesgaran et al. (2014)) for the EpiMnkPP covariate in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range appear in gray, indicating it did not occur.



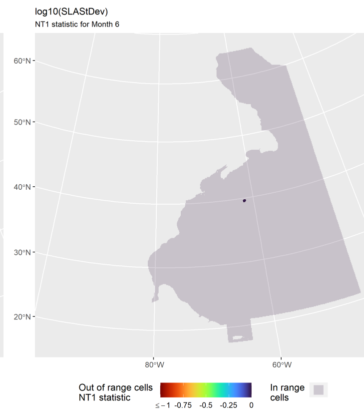
(a) March



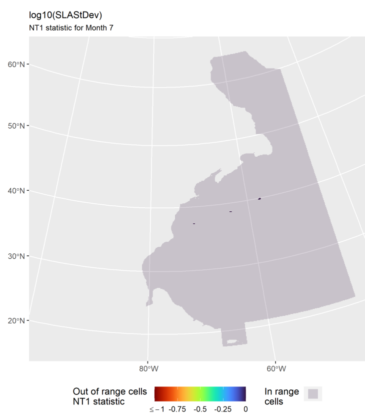
(b) April



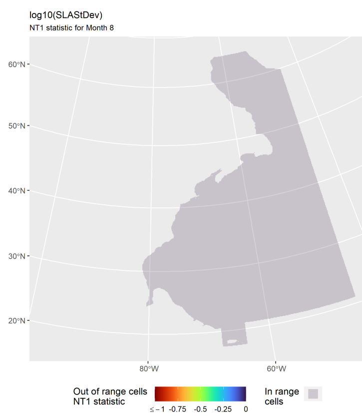
(c) May



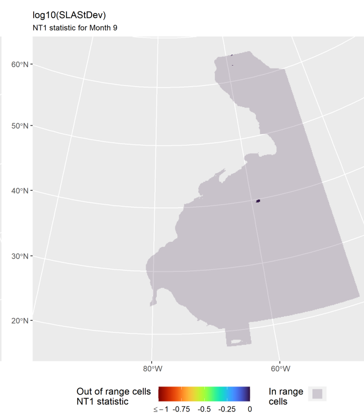
(d) June



(e) July

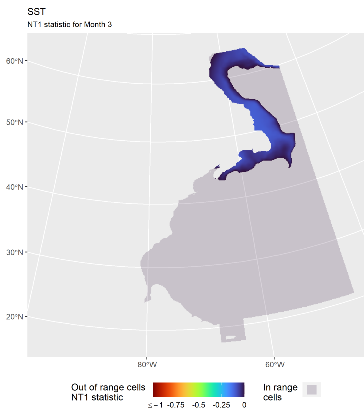


(f) August

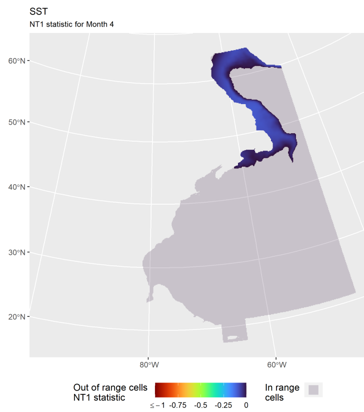


(g) September

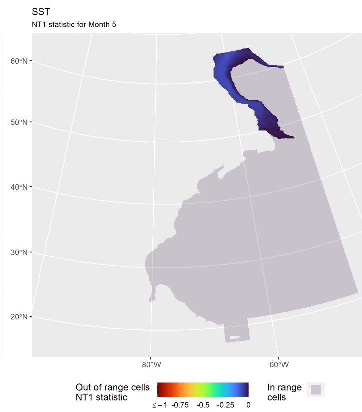
Figure 11: NT1 statistic (Mesgaran et al. (2014)) for the SLAStDev covariate in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range appear in gray, indicating it did not occur.



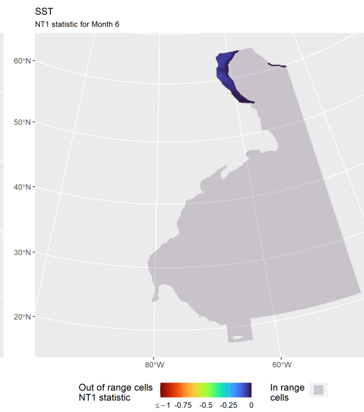
(a) March



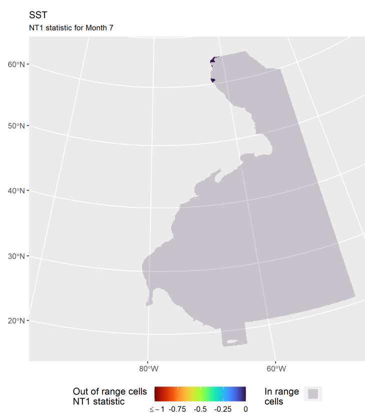
(b) April



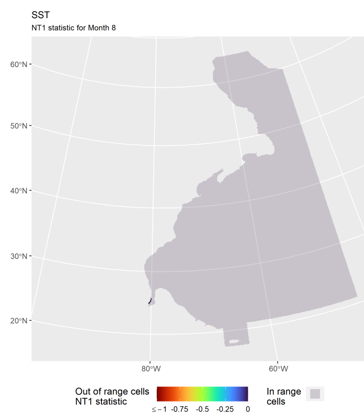
(c) May



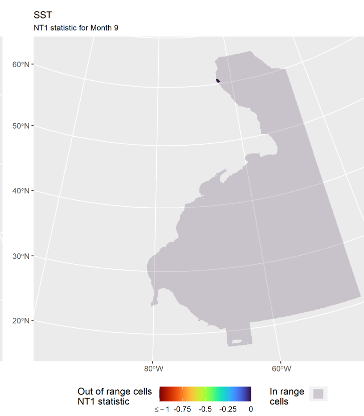
(d) June



(e) July



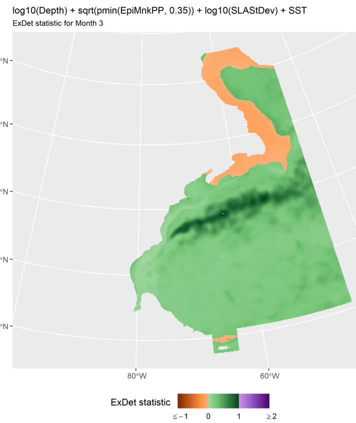
(f) August



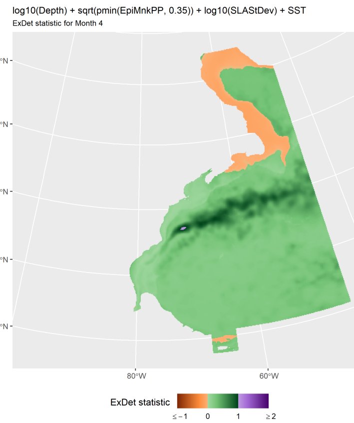
(g) September

Figure 12: NT1 statistic (Mesgaran et al. (2014)) for the SST covariate in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range appear in gray, indicating it did not occur.

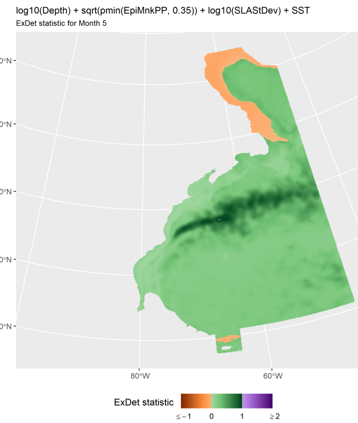
2.2.3.2 Multivariate Extrapolation



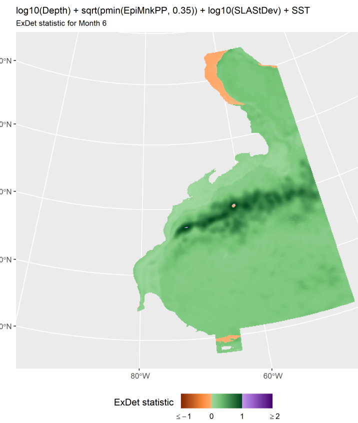
(a) March



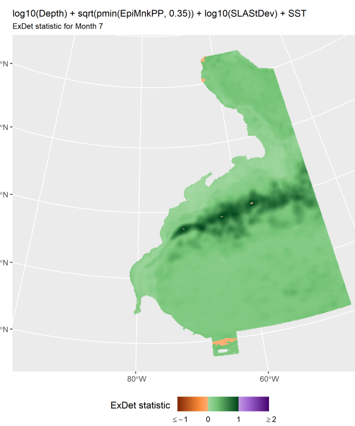
(b) April



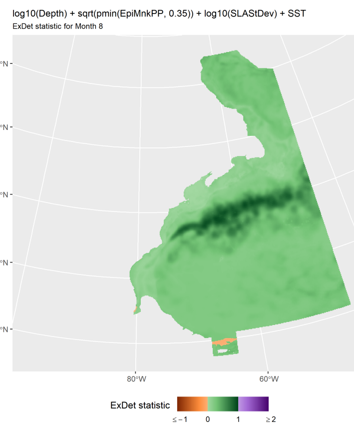
(c) May



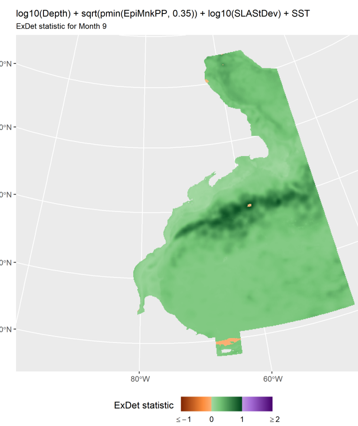
(d) June



(e) July



(f) August



(g) September

Figure 13: ExDet statistic (Mesgaran et al. (2014)) for all of the covariates used in the model for the region AFTT Atlantic for Summer. Areas in orange (ExDet < 0) required univariate extrapolation of one or more covariates (see previous section). Areas in purple (ExDet > 1), did not require univariate extrapolation but did require multivariate extrapolation, by virtue of having novel combinations of covariates not represented in the survey data, according to the NT2 statistic (Mesgaran et al. (2014)). Areas in green ($0 \geq$ ExDet ≤ 1) did not require either type of extrapolation.

3 Predictions

3.1 Summarized Predictions

3.1.1 Winter (December-March)

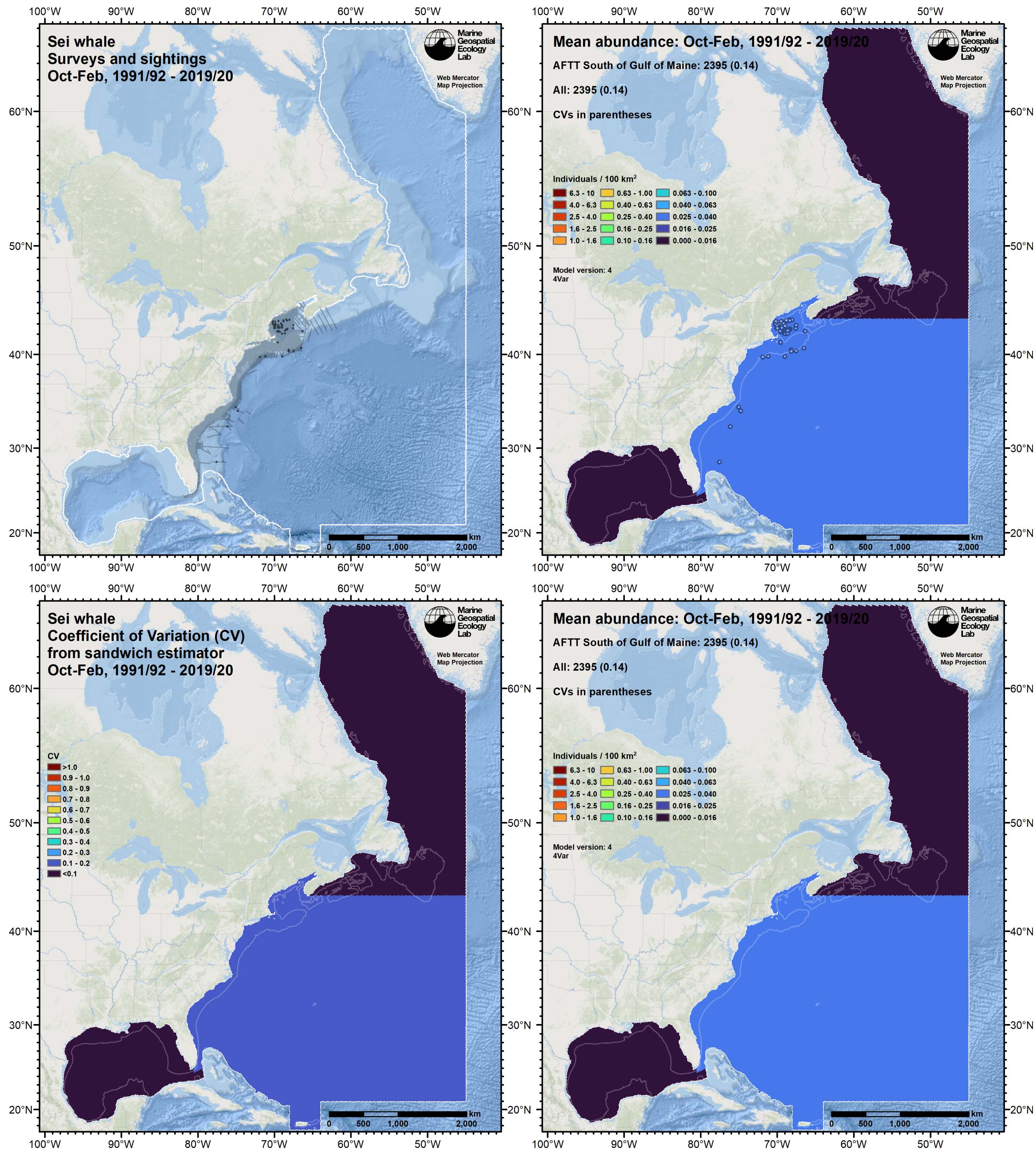


Figure 14: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for Winter the given era. Variance was estimated with the analytic approach given by Miller et al. (2022), Appendix S1, and accounts both for uncertainty in model parameter estimates and for temporal variability in dynamic covariates. These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

3.1.2 Summer (April-November)

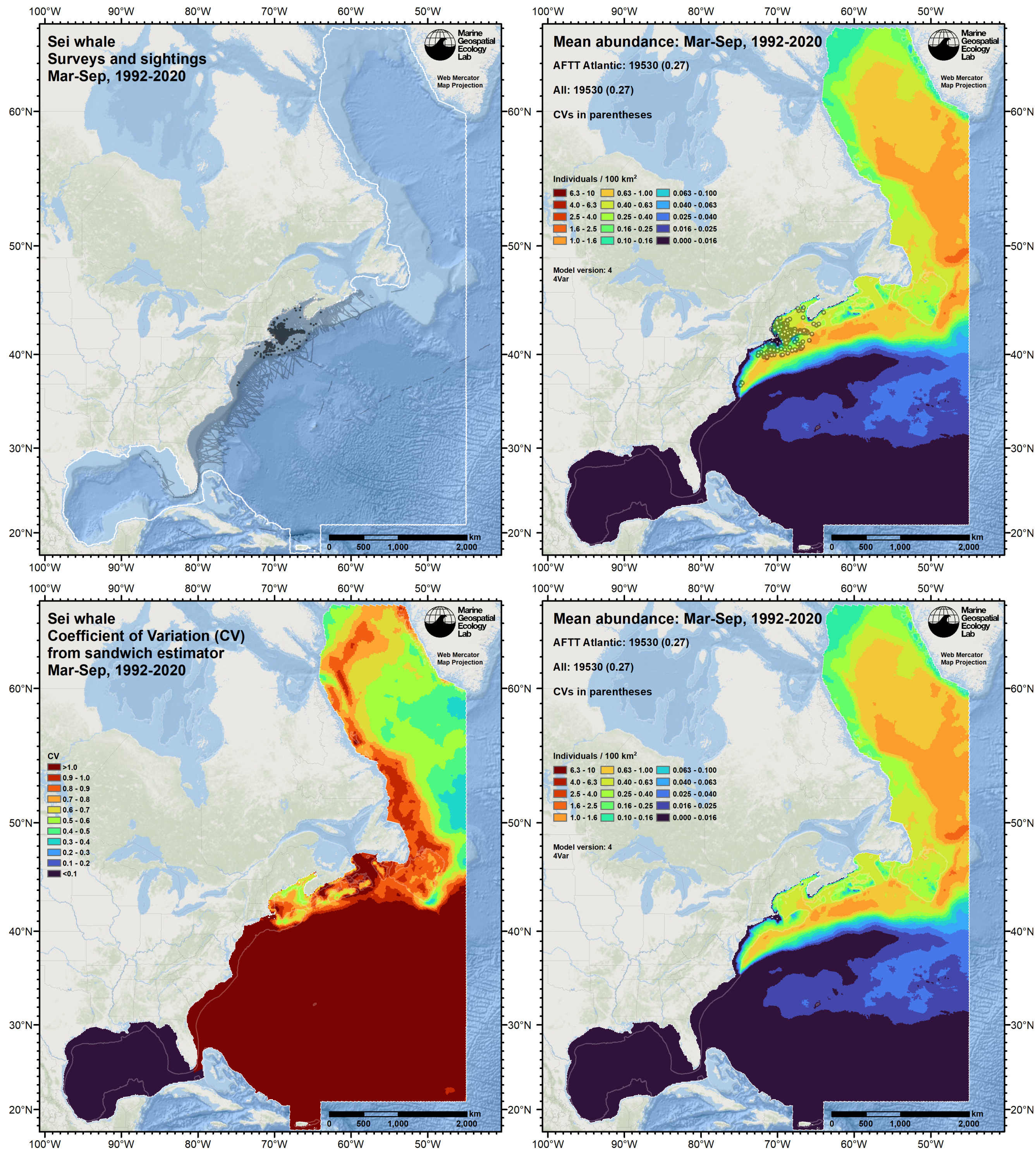


Figure 15: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for Summer the given era. Variance was estimated with the analytic approach given by Miller et al. (2022), Appendix S1, and accounts both for uncertainty in model parameter estimates and for temporal variability in dynamic covariates. These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

3.2 Comparison to Previous Density Model

3.2.1 Winter (December-March)

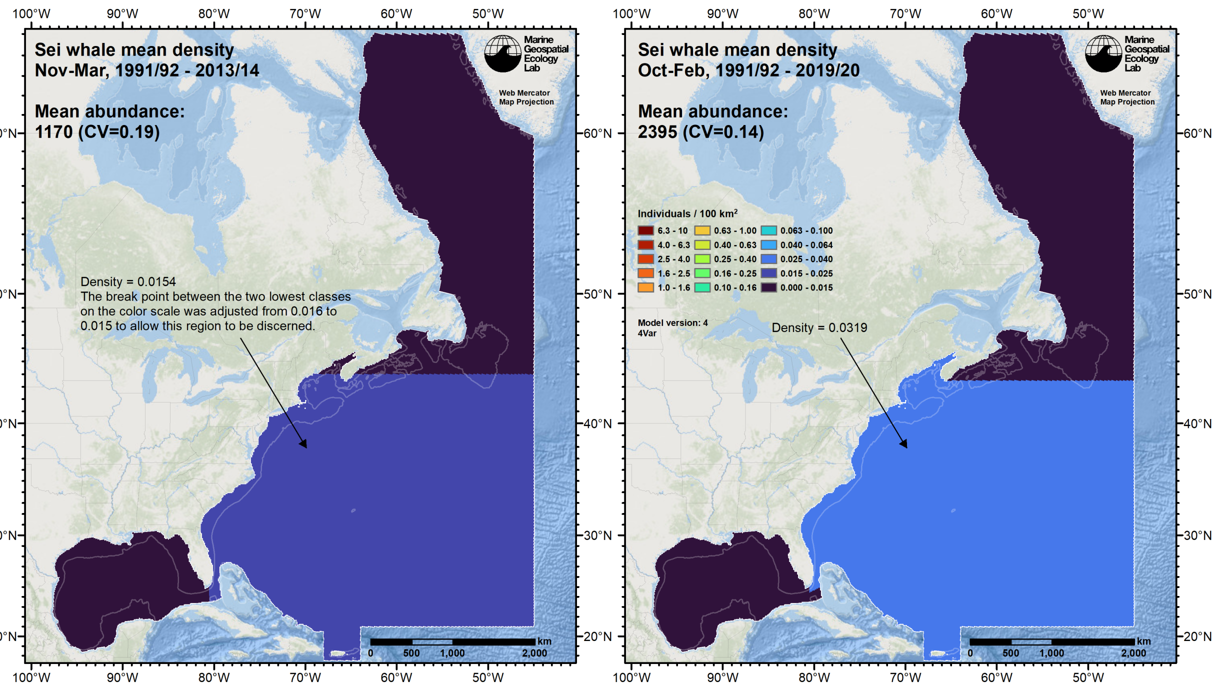


Figure 16: Comparison of the mean density predictions from the previous model (left) to those from this model (right) for the Winter season (December-March). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

3.2.2 Summer (April-November)

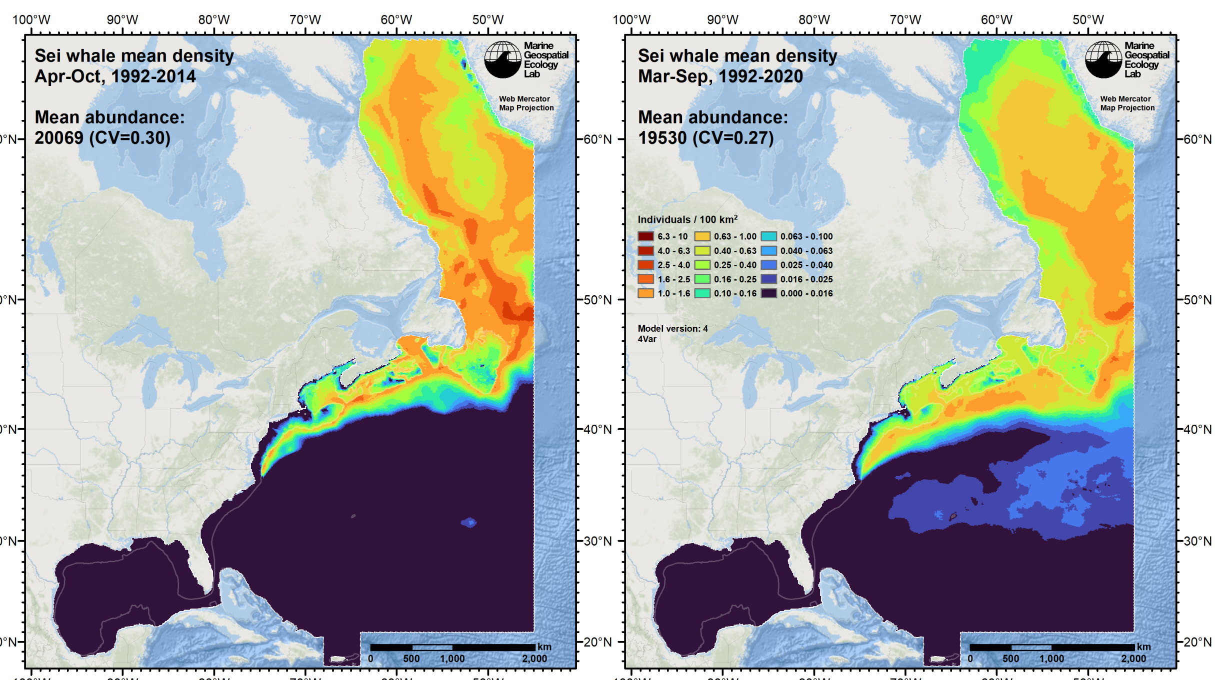


Figure 17: Comparison of the mean density predictions from the previous model (left) to those from this model (right) for the Summer season (April-November). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

4 Discussion

Following Mannocci et al. (2017), we summarized this model into two mean seasonal density surfaces (Figures 14, 15). Although our figures show predictions for the entire AFTT study area, we recommend that the regional East Coast (EC) model be used for the waters it covers, and that the AFTT model be used only for waters outside that region. Sei whales are absent in the Gulf of Mexico, so no regional model was fitted there. See Roberts et al. (2023) for more discussion of the models.

The predictions generally accorded with what has been reported in the literature and generally resembled the predictions of Mannocci et al. (2017), but with some important differences and caveats in both seasons. In winter, little data exist to evaluate the prediction of sei whales across the AFTT study area south of Nova Scotia and the absence of sei whales north of there. We followed Mannocci et al. in choosing southern Nova Scotia as the delimiter between the zone of presence and absence and defined the winter season as starting in October based on presence of sei whales south Cape Hatteras starting that month. Davis et al. (2020) and data subsequently aggregated in the PACM archive (PACM 2023) showed detections during these months at recorders deployed beyond the continental shelf in U.S. waters, but these were on the continental slope relatively close to the shelf. No data were available far offshore. In the north, acoustic detections were reported in the vicinity of the Gully canyon from November-February; this argues for expanding the zone of presence slightly further north. Also, acoustic detections were reported in October 2007 at the Davis Strait although not the prior year, the only other year monitored. We advise caution in northern waters during October. Also, given that the number of visual sightings on surveys beyond the shelf break were high relative to the quantity of effort there, particularly south of Cape Hatteras, we advise strong caution in these offshore waters during winter, and recommend additional surveying of any area where activities that are potentially harmful to sei whales might take place.

Our winter model estimated more than twice the density and abundance of Mannocci et al.'s model (Figure 16), although estimated winter abundance in the AFTT was only about a 1/10th of estimated summer abundance. We attribute this change mainly to the additional sightings available for the new model.

In summer, the new model estimated a mean abundance only 3% lower than the old model, a difference that was not statistically significant. The big difference between the models was that the new model predicted higher density off-shelf than on-shelf in the northern Newfoundland and Labrador regions, while the old model predicted comparable density on and off the shelf there (Figure 17). Although data to evaluate these predictions were sparse, the new model's predictions were better supported by available acoustic, telemetry, and opportunistic visual data. Delarue et al. (2022) deployed 25 acoustic recorders throughout the Scotian, Newfoundland, and southern Labrador shelves to monitor the seasonal presence of baleen whales. The performance of their automated detection procedure did not reach the threshold they required to report full seasonal results for sei whales, but they did report that for sei whales "the prime detection area was off the southern Labrador Shelf and in the Orphan Basin where detections occurred almost exclusively from May to November" and that "detections occurred more frequently at the deep stations off the continental shelf than on the shelf". Prieto et al. (2014) tracked 7 sei whales departing the Azores for the Labrador Sea in 2008 and 2009. Once they arrived at the Labrador Sea, they remained in off-shelf waters. Finally, the OBIS-SEAMAP archive (Halpin et al. 2009) reported another tagged sei whale entering the Labrador Sea in spring 2005, plus a few opportunistic sightings scattered around the edge of the Labrador Sea, with only one reported up on the shelf (https://seamap.env.duke.edu/species/180526). Aerial surveys of the shelves of Newfoundland and Labrador in 2015 reported four sei whales sighted in deeper waters near the outer margins of southern Newfoundland (Lawson and Gosselin 2018). A similar survey in 2007 reported a single sighting in the same overall vicinity but the precise location was not described or shown (Lawson and Gosselin 2009). One sei whale was reported in an aerial survey of west Greenland in 2015, near the offshore end of a transect during which a sperm whale was also sighted (Hansen et al. 2019). None of the surveys of Canada or Greenland were available for use in our model; future updates would benefit from their inclusion. In any case, all of these results, when taken together, support the new model's prediction of higher density in the Labrador Sea than in the surrounding shelves of Newfoundland, Labrador, and west Greenland.

5 References

Barco SG, Burt L, DePerte A, Digiovanni R Jr. (2015) Marine Mammal and Sea Turtle Sightings in the Vicinity of the Maryland Wind Energy Area July 2013-June 2015, VAQF Scientific Report #2015-06. Virginia Aquarium & Marine Science Center Foundation, Virginia Beach, VA

Becker JJ, Sandwell DT, Smith WHF, Braud J, Binder B, Depner J, Fabre D, Factor J, Ingalls S, Kim S-H, Ladner R, Marks K, Nelson S, Pharaoh A, Trimmer R, Von Rosenberg J, Wallace G, Weatherall P (2009) Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. Marine Geodesy 32:355–371. doi: 10.1080/01490410903297766

Blaylock RA, Hoggard W (1994) Preliminary Estimates of Bottlenose Dolphin Abundance in Southern U.S. Atlantic and Gulf of Mexico Continental Shelf Waters: NOAA Technical Memorandum NMFS-SEFSC-356. NOAA National Marine

Fisheries Service, Southeast Fisheries Science Center, Miami, FL

Brasnett B (2008) The impact of satellite retrievals in a global sea-surface-temperature analysis. Quarterly Journal of the Royal Meteorological Society 134:1745–1760. doi: 10.1002/qj.319

Canada Meteorological Center (2012) GHRSST Level 4 CMC0.2deg Global Foundation Sea Surface Temperature Analysis Version 2.0. PODAAC, CA, USA. doi: 10.5067/GHCMC-4FM02

Cole T, Gerrior P, Merrick RL (2007) Methodologies of the NOAA National Marine Fisheries Service Aerial Survey Program for Right Whales (Eubalaena glacialis) in the Northeast U.S., 1998-2006. U.S. Department of Commerce, Woods Hole, MA

Cotter MP (2019) Aerial Surveys for Protected Marine Species in the Norfolk Canyon Region: 2018–2019 Final Report. HDR, Inc., Virginia Beach, VA

Davis GE, Baumgartner MF, Corkeron PJ, Bell J, Berchok C, Bonnell JM, Bort Thornton J, Brault S, Buchanan GA, Cholewiak DM, Clark CW, Delarue J, Hatch LT, Klinck H, Kraus SD, Martin B, Mellinger DK, Moors-Murphy H, Nieukirk S, Nowacek DP, Parks SE, Parry D, Pegg N, Read AJ, Rice AN, Risch D, Scott A, Soldevilla MS, Stafford KM, Stanistreet JE, Summers E, Todd S, Van Parijs SM (2020) Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data. Glob Change Biol gcb.15191. doi: 10.1111/gcb.15191

Delarue JJ-Y, Moors-Murphy H, Kowarski KA, Davis GE, Urazghildiiev IR, Martin SB (2022) Acoustic occurrence of baleen whales, particularly blue, fin, and humpback whales, off eastern Canada, 2015-2017. Endang Species Res 47:265–289. doi: 10.3354/esr01176

Foley HJ, Paxton CGM, McAlarney RJ, Pabst DA, Read AJ (2019) Occurrence, Distribution, and Density of Protected Species in the Jacksonville, Florida, Atlantic Fleet Training and Testing (AFTT) Study Area. Duke University Marine Lab, Beaufort, NC

Garrison LP, Martinez A, Maze-Foley K (2010) Habitat and abundance of cetaceans in Atlantic Ocean continental slope waters off the eastern USA. Journal of Cetacean Research and Management 11:267–277.

Geo-Marine, Inc. (2010) New Jersey Department of Environmental Protection Baseline Studies Final Report Volume III: Marine Mammal and Sea Turtle Studies. Geo-Marine, Inc., Plano, TX

Halpin P, Read A, Fujioka E, Best B, Donnelly B, Hazen L, Kot C, Urian K, LaBrecque E, Dimatteo A, Cleary J, Good C, Crowder L, Hyrenbach KD (2009) OBIS-SEAMAP: The World Data Center for Marine Mammal, Sea Bird, and Sea Turtle Distributions. Oceanography 22:104–115. doi: 10.5670/oceanog.2009.42

Hansen RG, Boye TK, Larsen RS, Nielsen NH, Tervo O, Nielsen RD, Rasmussen MH, Sinding MHS, Heide-Jørgensen MP (2019) Abundance of whales in West and East Greenland in summer 2015. NAMMCO Scientific Publications. doi: 10.7557/3.4689

Kowarski KA, Martin SB, Maxner EE, Lawrence CB, Delarue JJ-Y, Miksis-Olds JL (2022) Cetacean acoustic occurrence on the US Atlantic Outer Continental Shelf from 2017 to 2020. Marine Mammal Science mms.12962. doi: 10.1111/mms.12962

Laran S, Bassols N, Dorémus G, Authier M, Ridoux V, Van Canneyt O (2019) Distribution et abondance de la mégafaune marine aux Petites Antilles et en Guyane: REMMOA-II Petites Antilles & Guyane - 2017: Rapport final. Observatoire Pelagis, Université de La Rochelle, La Rochelle, France

Lawson JW, Gosselin J-F (2009) Distribution and preliminary abundance estimates for cetaceans seen during Canada's Marine Megafauna Survey-A component of the 2007 TNASS. Department of Fisheries and Oceans, St. John's, NL, Canada

Lawson JW, Gosselin J-F (2018) Estimates of cetacean abundance from the 2016 NAISS aerial surveys of eastern Canadian waters, with a comparison to estimates from the 2007 TNASS. NAMMCO SC/25/AE/09. In: Proceedings of the NAMMCO 25th Scientific Committee (SC). North Atlantic Marine Mammal Commission, Bergen-Tromsø, Norway,

Lehodey P, Senina I, Murtugudde R (2008) A spatial ecosystem and populations dynamics model (SEAPODYM)–Modeling of tuna and tuna-like populations. Progress in Oceanography 78:304–318. doi: 10.1016/j.pocean.2008.06.004

Lehodey P, Conchon A, Senina I, Domokos R, Calmettes B, Jouanno J, Hernandez O, Kloser R (2015) Optimization of a micronekton model with acoustic data. ICES Journal of Marine Science 72:1399–1412. doi: 10.1093/icesjms/fsu233

Leiter S, Stone K, Thompson J, Accardo C, Wikgren B, Zani M, Cole T, Kenney R, Mayo C, Kraus S (2017) North Atlantic right whale Eubalaena glacialis occurrence in offshore wind energy areas near Massachusetts and Rhode Island, USA. Endang Species Res 34:45–59. doi: 10.3354/esr00827

Mallette SD, Lockhart GG, McAlarney RJ, Cummings EW, McLellan WA, Pabst DA, Barco SG (2014) Documenting Whale Migration off Virginia's Coast for Use in Marine Spatial Planning: Aerial and Vessel Surveys in the Proximity of the Virginia Wind Energy Area (VA WEA), VAQF Scientific Report 2014-08. Virginia Aquarium & Marine Science Center Foundation, Virginia Beach, VA

Mallette SD, Lockhart GG, McAlarney RJ, Cummings EW, McLellan WA, Pabst DA, Barco SG (2015) Documenting Whale Migration off Virginia's Coast for Use in Marine Spatial Planning: Aerial Surveys in the Proximity of the Virginia Wind Energy Area (VA WEA) Survey/Reporting Period: May 2014 - December 2014, VAQF Scientific Report 2015-02. Virginia Aquarium & Marine Science Center Foundation, Virginia Beach, VA

Mallette SD, McAlarney RJ, Lockhart GG, Cummings EW, Pabst DA, McLellan WA, Barco SG (2017) Aerial Survey Baseline Monitoring in the Continental Shelf Region of the VACAPES OPAREA: 2016 Annual Progress Report. Virginia Aquarium & Marine Science Center Foundation, Virginia Beach, VA

Mannocci L, Monestiez P, Bolaños-Jiménez J, Dorémus G, Jeremie S, Laran S, Rinaldi R, Van Canneyt O, Ridoux V (2013) Megavertebrate communities from two contrasting ecosystems in the western tropical Atlantic. Journal of Marine Systems 111–112:208–222. doi: 10.1016/j.jmarsys.2012.11.002

Mannocci L, Roberts JJ, Miller DL, Halpin PN (2017) Extrapolating cetacean densities to quantitatively assess human impacts on populations in the high seas. Conservation Biology 31:601–614. doi: 10.1111/cobi.12856

McAlarney R, Cummings E, McLellan W, Pabst A (2018) Aerial Surveys for Protected Marine Species in the Norfolk Canyon Region: 2017 Annual Progress Report. University of North Carolina Wilmington, Wilmington, NC

McLellan WA, McAlarney RJ, Cummings EW, Read AJ, Paxton CGM, Bell JT, Pabst DA (2018) Distribution and abundance of beaked whales (Family Ziphiidae) Off Cape Hatteras, North Carolina, U.S.A. Marine Mammal Science. doi: 10.1111/mms.12500

Mesgaran MB, Cousens RD, Webber BL (2014) Here be dragons: A tool for quantifying novelty due to covariate range and correlation change when projecting species distribution models. Diversity Distrib 20:1147–1159. doi: 10.1111/ddi.12209

Miller DL, Becker EA, Forney KA, Roberts JJ, Cañadas A, Schick RS (2022) Estimating uncertainty in density surface models. PeerJ 10:e13950. doi: 10.7717/peerj.13950

Mullin KD (1995) Cruise Report: Oregon II Cruise 215 (95-01): 26 January - 11 March 1995. NOAA National Marine Fisheries Service, Southeast Fisheries Science Center, Pascagoula, MS

Mullin KD, Fulling GL (2003) Abundance of cetaceans in the southern U.S. North Atlantic Ocean during summer 1998. Fishery Bulletin 101:603–613.

O'Brien O, Pendleton DE, Ganley LC, McKenna KR, Kenney RD, Quintana-Rizzo E, Mayo CA, Kraus SD, Redfern JV (2022) Repatriation of a historical North Atlantic right whale habitat during an era of rapid climate change. Sci Rep 12:12407. doi: 10.1038/s41598-022-16200-8

PACM (2023) Passive acoustic cetacean map, v1.1.4, accessed 2023-05-27. NOAA Northeast Fisheries Science Center, Woods Hole, MA

Palka D, Aichinger Dias L, Broughton E, Chavez-Rosales S, Cholewiak D, Davis G, DeAngelis A, Garrison L, Haas H, Hatch J, Hyde K, Jech M, Josephson E, Mueller-Brennan L, Orphanides C, Pegg N, Sasso C, Sigourney D, Soldevilla M, Walsh H (2021) Atlantic Marine Assessment Program for Protected Species: FY15 – FY19 (OCS Study BOEM 2021-051). U.S. Deptartment of the Interior, Bureau of Ocean Energy Management, Washington, DC

Palka DL (2006) Summer abundance estimates of cetaceans in US North Atlantic navy operating areas (NEFSC Reference Document 06-03). U.S. Department of Commerce, Northeast Fisheries Science Center, Woods Hole, MA

Palka DL, Chavez-Rosales S, Josephson E, Cholewiak D, Haas HL, Garrison L, Jones M, Sigourney D, Waring G, Jech M, Broughton E, Soldevilla M, Davis G, DeAngelis A, Sasso CR, Winton MV, Smolowitz RJ, Fay G, LaBrecque E, Leiness JB, Dettloff K, Warden M, Murray K, Orphanides C (2017) Atlantic Marine Assessment Program for Protected Species: 2010-2014 (OCS Study BOEM 2017-071). U.S. Deptartment of the Interior, Bureau of Ocean Energy Management, Washington, DC

Prieto R, Silva MA, Waring GT, Gonalves JMA (2014) Sei whale movements and behaviour in the North Atlantic inferred from satellite telemetry. Endang Species Res 26:103–113. doi: 10.3354/esr00630

Quintana-Rizzo E, Leiter S, Cole T, Hagbloom M, Knowlton A, Nagelkirk P, O'Brien O, Khan C, Henry A, Duley P, Crowe L, Mayo C, Kraus S (2021) Residency, demographics, and movement patterns of North Atlantic right whales Eubalaena glacialis in an offshore wind energy development area in southern New England, USA. Endang Species Res 45:251–268. doi: 10.3354/esr01137

Read AJ, Barco S, Bell J, Borchers DL, Burt ML, Cummings EW, Dunn J, Fougeres EM, Hazen L, Hodge LEW, Laura A-M, McAlarney RJ, Peter N, Pabst DA, Paxton CGM, Schneider SZ, Urian KW, Waples DM, McLellan WA (2014) Occurrence, distribution and abundance of cetaceans in Onslow Bay, North Carolina, USA. Journal of Cetacean Research and Management 14:23–35.

Redfern JV, Kryc KA, Weiss L, Hodge BC, O'Brien O, Kraus SD, Quintana-Rizzo E, Auster PJ (2021) Opening a Marine Monument to Commercial Fishing Compromises Species Protections. Front Mar Sci 8:645314. doi: 10.3389/fmars.2021.645314

Roberts JJ, Yack TM, Halpin PN (2023) Marine mammal density models for the U.S. Navy Atlantic Fleet Training and Testing (AFTT) study area for the Phase IV Navy Marine Species Density Database (NMSDD), Document Version 1.3. Duke University Marine Geospatial Ecology Lab, Durham, NC

Ryan C, Boisseau O, Cucknell A, Romagosa M, Moscrop A, McLanaghan R (2013) Final report for trans-Atlantic research passages between the UK and USA via the Azores and Iceland, conducted from R/V Song of the Whale 26 March to 28 September 2012. Marine Conservation Research International, Essex, UK

Stone KM, Leiter SM, Kenney RD, Wikgren BC, Thompson JL, Taylor JKD, Kraus SD (2017) Distribution and abundance of cetaceans in a wind energy development area offshore of Massachusetts and Rhode Island. J Coast Conserv 21:527–543. doi: 10.1007/s11852-017-0526-4

Swartz SL, Burks C (2000) Cruise Results: Windwards Humpback (Megaptera novaeangliae) Survey: NOAA Ship Gordon Gunter Cruise GU-00-01: 9 February to 3 April 2000 (NOAA Technical Memorandum NMFS-SEFSC-438). NOAA National Marine Fisheries Service, Southeast Fisheries Science Center, Miami, FL

Torres LG, Mclellan WA, Meagher E, Pabst DA (2005) Seasonal distribution and relative abundance of bottlenose dolphins, Tursiops truncatus, along the US mid-Atlantic coast. Journal of Cetacean Research and Management 7:153.

Waring GT, Nøttestad L, Olsen E, Skov H, Vikingsson G (2008) Distribution and density estimates of cetaceans along the mid-Atlantic Ridge during summer 2004. Journal of Cetacean Research and Management 10:137–146.

Whitt AD, Powell JA, Richardson AG, Bosyk JR (2015) Abundance and distribution of marine mammals in nearshore waters off New Jersey, USA. Journal of Cetacean Research and Management 15:45–59.

Zoidis AM, Lomac-MacNair KS, Ireland DS, Rickard ME, McKown KA, Schlesinger MD (2021) Distribution and density of six large whale species in the New York Bight from monthly aerial surveys 2017 to 2020. Continental Shelf Research 230:104572. doi: 10.1016/j.csr.2021.104572