Density Model for White-Beaked Dolphin (*Lagenorhynchus albirostris*) 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	2015-01-23	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.
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

The goal of this project was to build, for the U.S. Navy's AFTT Phase IV Environmental Impact Statement (EIS), an update to the model we developed for the AFTT Phase III EIS. The Phase III model was developed using the methodology of Mannocci et al. (2017) by L. Mannocci but not included in the 2017 publication. Following the approach taken by that model, we built this update from data collected in the east coast, Mid-Atlantic Ridge, and Europe regions. We also added trans-Atlantic and eastern Atlantic surveys by R/V Song of the Whale that were not available for the Phase III analysis. We excluded surveys that did not target small cetaceans or were otherwise problematic for modeling them. We restricted the model to aerial survey transects with sea states of Beaufort 4 or less (for a few surveys we used Beaufort 3 or less) and shipboard transects with Beaufort 5 or less (for a few we used Beaufort 4 or less). We also excluded transects with poor weather or visibility for surveys that reported those conditions. Table 1 summarizes the survey effort and sightings available for the model after most exclusions were applied. Figure 1 shows the data actually used to fit the model.

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	10	0	0	
NEFSC	AMAPPS	2010-2019	83	3	29	9.7
NEFSC	NARWSS	2003-2016	380	6	43	7.2
NEFSC	Pre-AMAPPS	1999-2008	45	4	11	2.8
SEFSC	AMAPPS	2010-2020	112	0	0	
SEFSC	MATS	2002-2005	27	0	0	
UNCW	MidA Bottlenose	2002-2002	15	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	106	0	0	
VAMSC	MD DNR WEA	2013-2015	15	0	0	
VAMSC	Navy VACAPES	2016-2017	18	0	0	
VAMSC	VA CZM WEA	2012-2015	19	0	0	
		Total	**1,020**	**13**	**83**	**6.4**
Shipboard Surveys						
CODA	CODA	2007-2007	10	0	0	
IMR	MAR-ECO	2004-2004	2	1	9	9.0
MCR	SOTW Visual	2004-2019	31	64	302	4.7
NEFSC	AMAPPS	2011-2016	15	0	0	
NEFSC	Pre-AMAPPS	1995-2007	17	1	7	7.0
NJDEP	NJEBS	2008-2009	14	0	0	
SCANS-II	SCANS-II	2005-2005	18	28	97	3.5
SEFSC	AMAPPS	2011-2016	16	0	0	
SEFSC	Pre-AMAPPS	1992-2006	33	0	0	
SEFSC	SEFSC Caribbean	1995-2000	8	0	0	
		Total	**164**	**94**	**415**	**4.4**
		Grand Total	**1,183**	**107**	**498**	**4.7**

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

Institution	Full Name
CODA	Partners of the CODA project (see Hammond et al. 2009)
HDR	HDR, Inc.

Table 2: Institutions that contributed surveys used in this model. *(continued)*

Institution	Full Name
IMR	Norway Institute of Marine Research
MCR	Marine Conservation Research
NEFSC	NOAA Northeast Fisheries Science Center
NJDEP	New Jersey Department of Environmental Protection
SCANS-II	Partners of the SCANS-II project (see Hammond et al. 2013)
SEFSC	NOAA Southeast Fisheries Science Center
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)
CODA	Cetacean Offshore Distribution and Abundance in the European Atlantic	Hammond et al. (2009)
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)
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)
Pre-AMAPPS	Pre-AMAPPS Marine Mammal Abundance Surveys	Mullin and Fulling (2003), Garrison et al. (2010), Palka (2006)
SCANS-II	Small Cetaceans in the European Atlantic and North Sea	Hammond et al. (2013)
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 Phase III model with new data without repeating the covariate selection exercise performed by those authors. We therefore fitted a year-round, 2-covariate model that included micronekton productivity and zooplankton biomass. (We $\log_{10}$-transformed the zooplankton covariate instead of square-root-transforming it.) The resulting relationships (Figure 2) generally resembled those of Mannocci's model. Model predictions are shown in Section 3 and discussed in Section 4. Extrapolation analysis (Section 2.3) displayed geographic patterns very similar to the environmental envelopes estimated by Mannocci et al., with negligible extrapolation required. However, we note that this outcome likely depended upon the Winsorization applied to both covariates, which followed what was done for the Phase III model. Had the covariates not been Winsorized, it is possible that some extrapolation could have been required in areas of extremely high values of either covariate. Diagnostic plots indicate this likely would have occurred for micronekton productivity but not for zooplankton biomass, as the Winsorization applied to the former was much stronger than for the latter (compare plots in Figure 4 to the corresponding plots in Figure 5).

2.1 Final Model

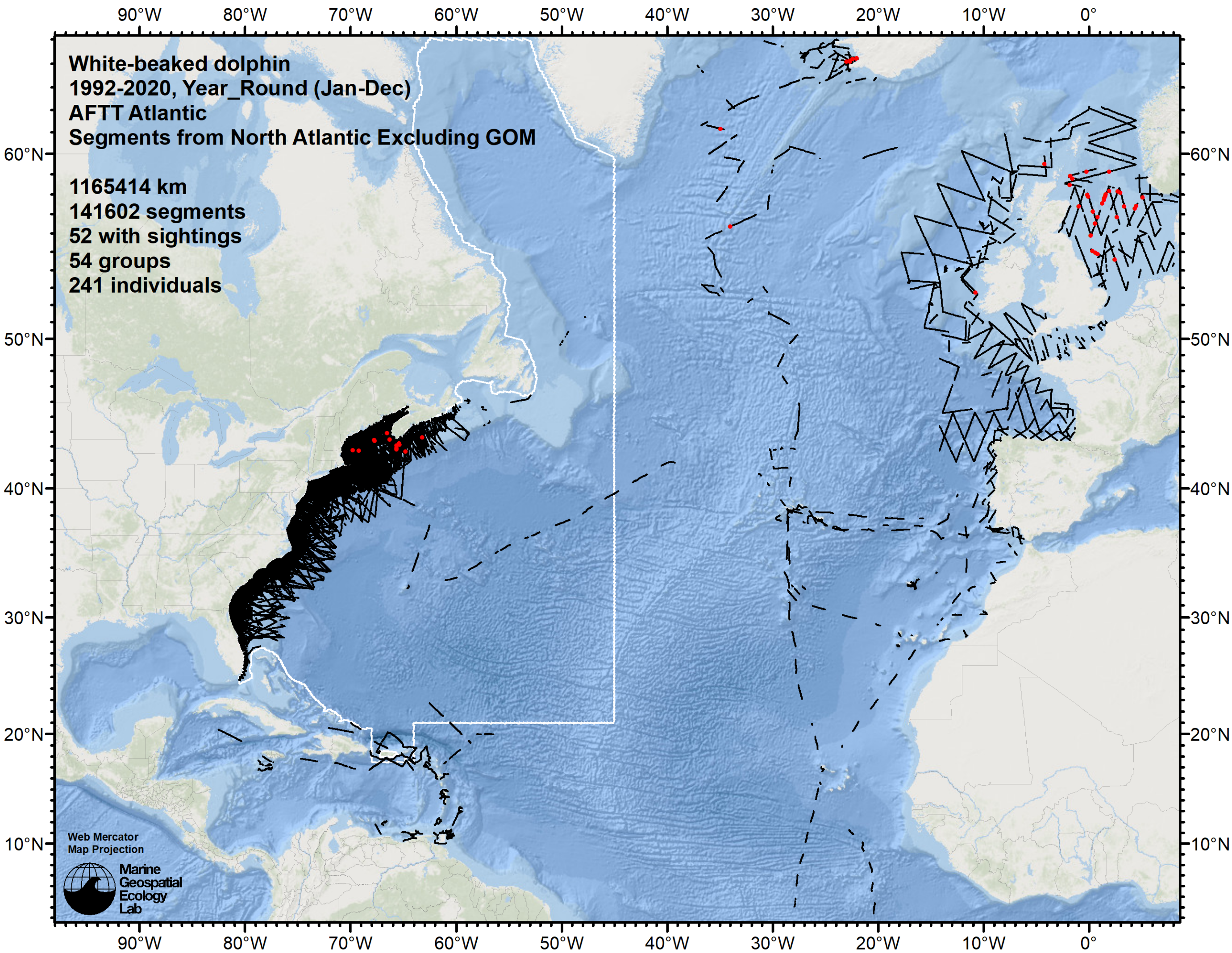
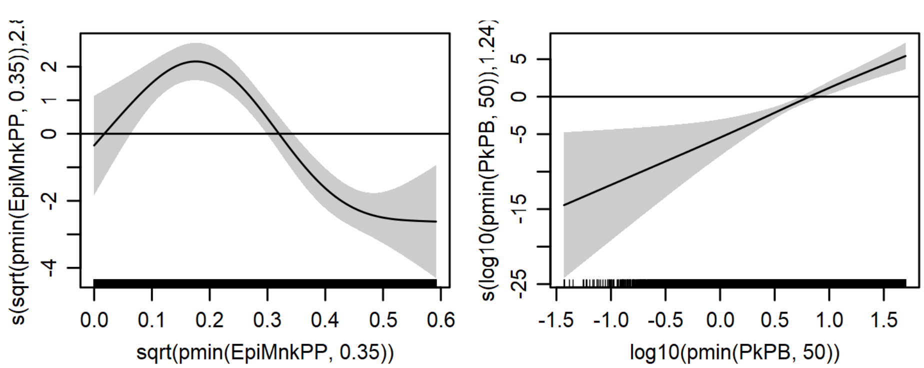


Figure 1: Survey segments (black lines) used to fit the model for the region AFTT Atlantic. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

Statistical output for this model:

```
Family: Tweedie(p=1.229)
```

```
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(sqrt(pmin(EpiMnkPP,
    0.35)), bs = "ts", k = 4) + s(log10(pmin(PkPB, 50)), bs = "ts",
    k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -24.325      0.625  -38.92   <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(sqrt(pmin(EpiMnkPP, 0.35))) 2.821      3 20.07  <2e-16 ***
s(log10(pmin(PkPB, 50)))      1.240      3 12.75  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.00284   Deviance explained = 31.5%
-REML = 576.98  Scale est. = 41.082    n = 141598

Method: REML   Optimizer: outer newton
full convergence after 13 iterations.
Gradient range [-2.644466e-07,1.06812e-07]
(score 576.9772 & scale 41.08159).
Hessian positive definite, eigenvalue range [0.4250057,446.2159].
Model rank =  7 / 7

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(sqrt(pmin(EpiMnkPP, 0.35))) 3.00 2.82    0.84  <2e-16 ***
s(log10(pmin(PkPB, 50)))      3.00 1.24    0.79  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



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

(b) Climatological zooplankton biomass (g C m^{-2})

Figure 2: Functional plots for the final model for the region AFTT Atlantic. 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.

Covariate	Description
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))
PkPB	Climatological monthly mean zooplankton biomass expressed in carbon (g C m^{-2}) from SEAPODYM (Lehodey et al. (2008); Lehodey et al. (2015))

2.2 Diagnostic Plots

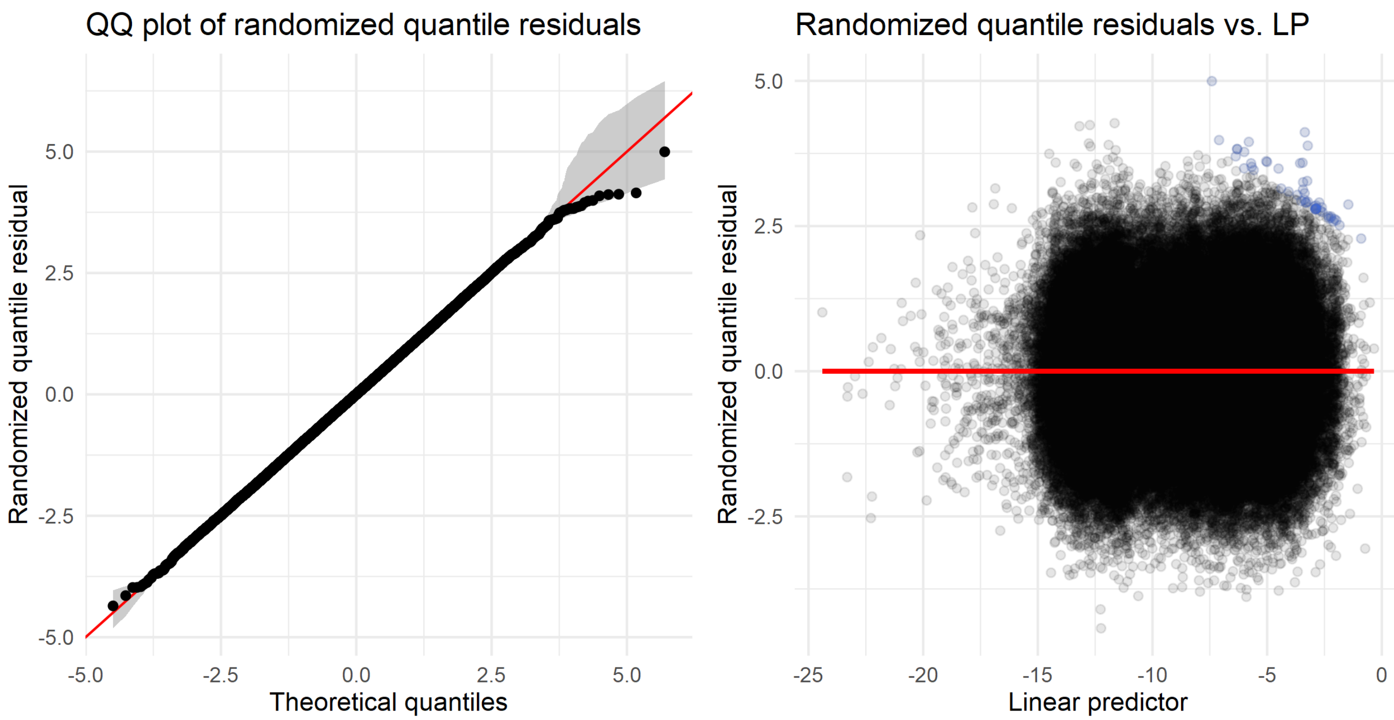


Figure 3: Residual plots for the final model for the region AFTT Atlantic.

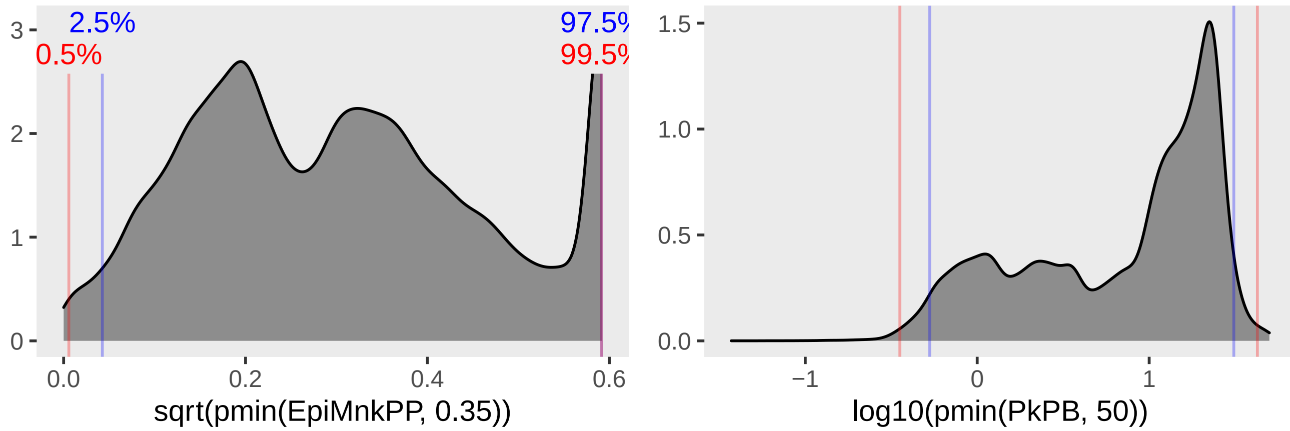


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red 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.

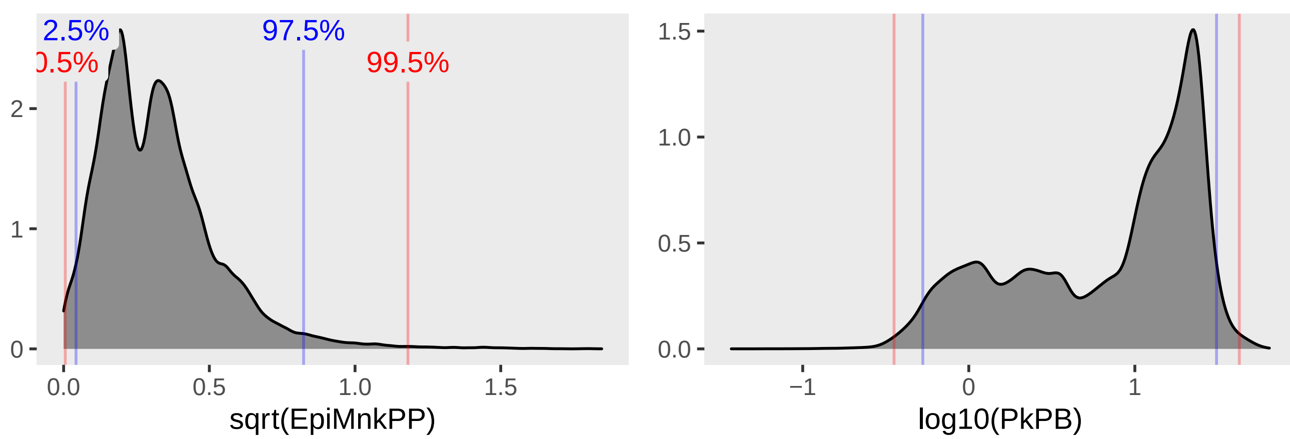


Figure 5: Density histograms shown in Figure 4 replotted without Winsorization, to show the full range of sampling represented by survey segments.

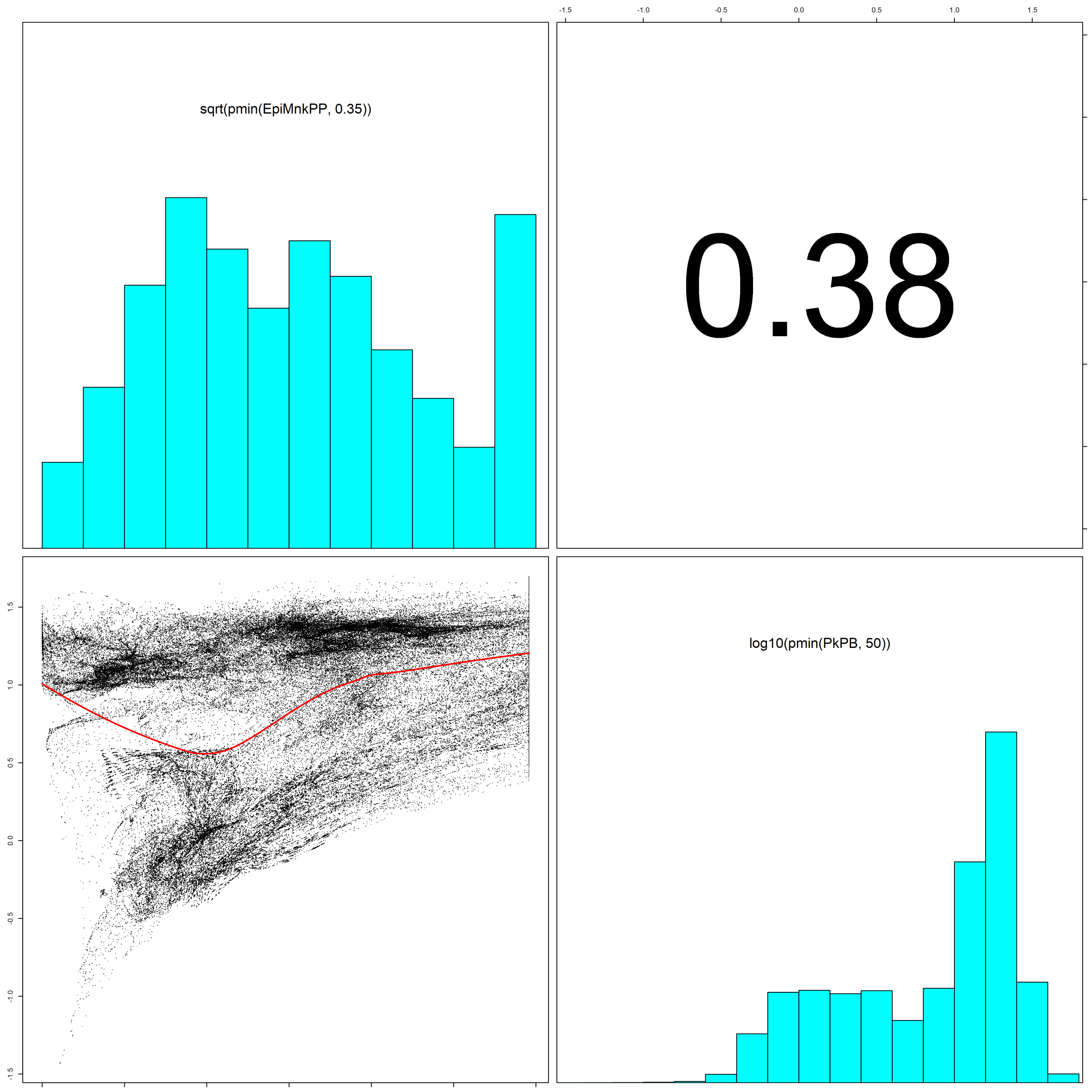


Figure 6: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized as shown in Figure 4. 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).

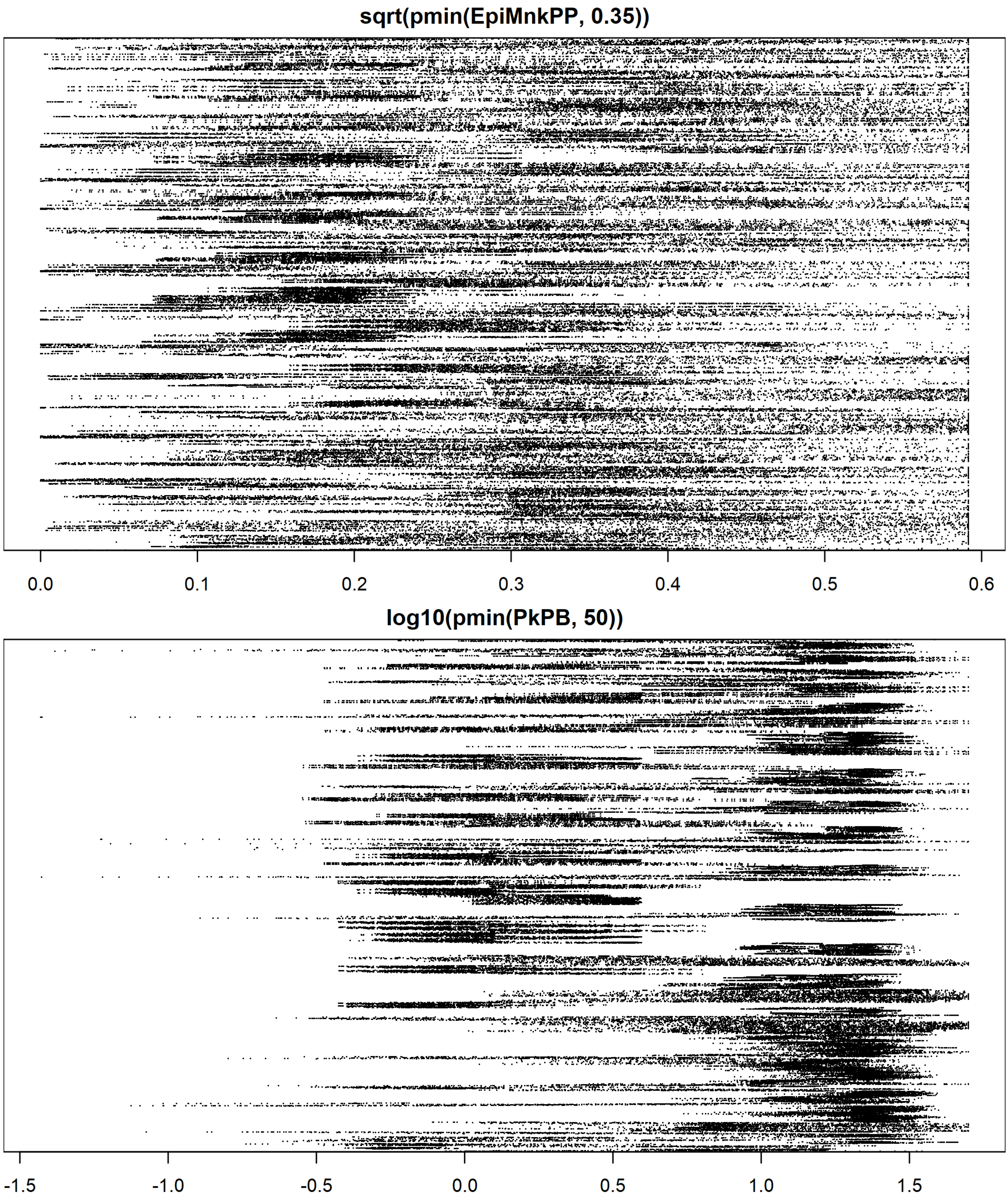
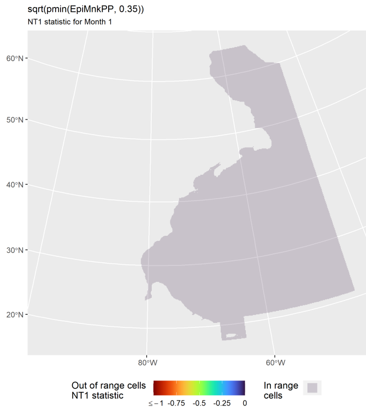


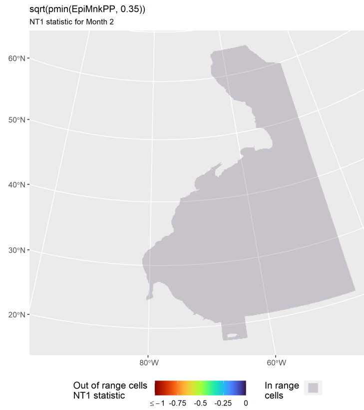
Figure 7: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized as shown in Figure 4. This plot is used to check for suspicious patterns and outliers in the data. Points are ordered vertically by segment ID, sequentially in time.

2.3 Extrapolation Diagnostics

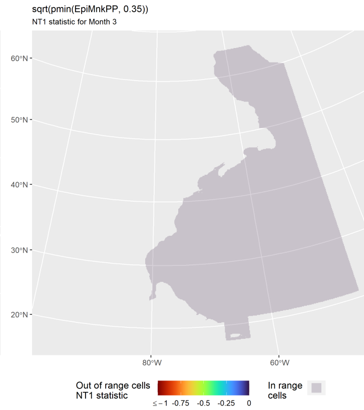
2.3.1 Univariate Extrapolation



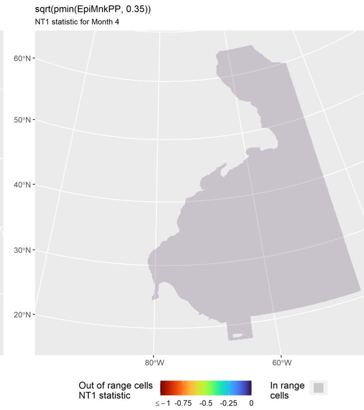
(a) January



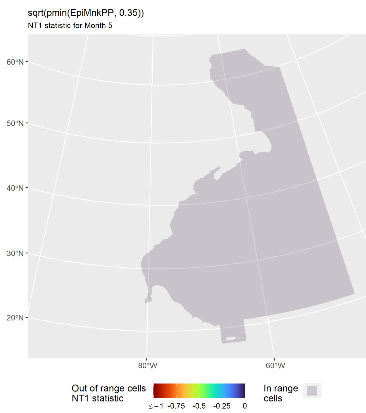
(b) February



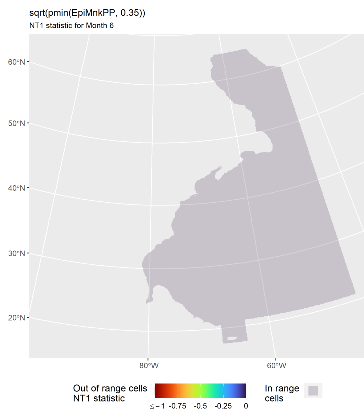
(c) March



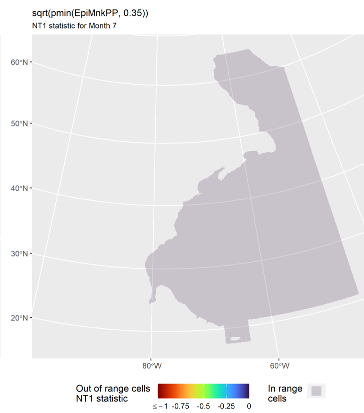
(d) April



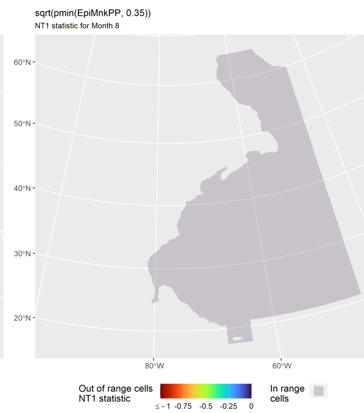
(e) May



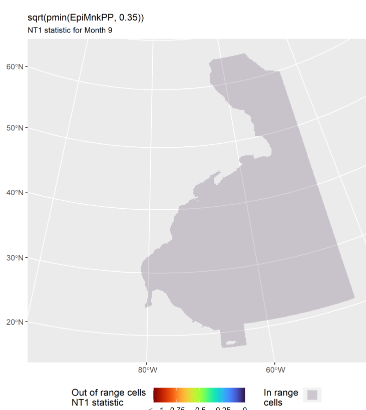
(f) June



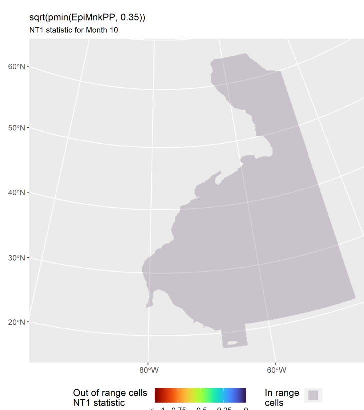
(g) July



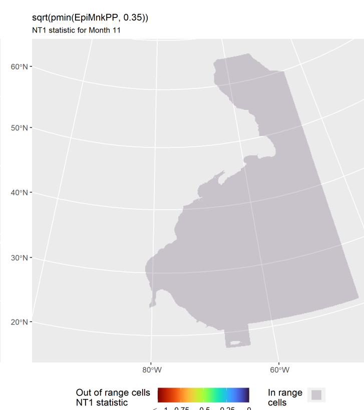
(h) August



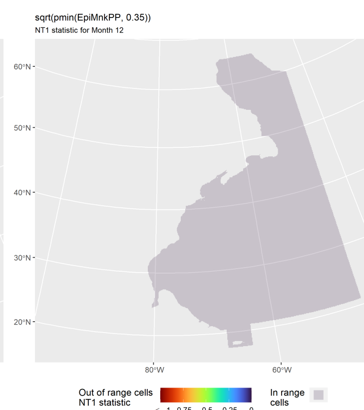
(i) September



(j) October



(k) November



(l) December

Figure 8: NT1 statistic (Mesgaran et al. (2014)) for the EpiMnkPP covariate in the model for the region AFTT Atlantic. 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.

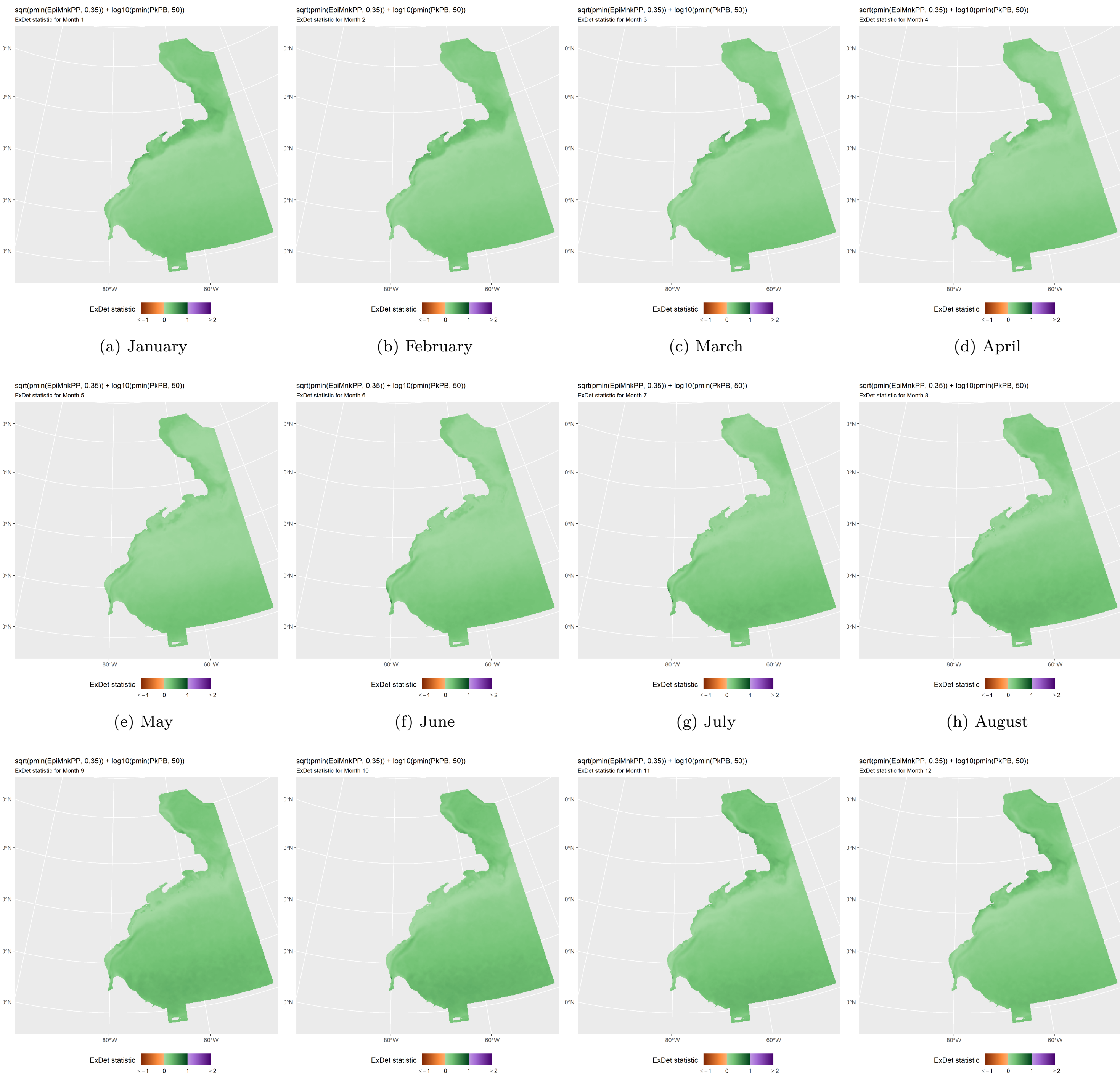
(a) January (b) February (c) March (d) April

(e) May (f) June (g) July (h) August

(i) September (j) October (k) November (l) December

Figure 9: NT1 statistic (Mesgaran et al. (2014)) for the PkPB covariate in the model for the region AFTT Atlantic. 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.

2.3.2 Multivariate Extrapolation



(a) January (b) February (c) March (d) April

(e) May (f) June (g) July (h) August

(i) September (j) October (k) November (l) December

Figure 10: ExDet statistic (Mesgaran et al. (2014)) for all of the covariates used in the model for the region AFTT Atlantic. 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

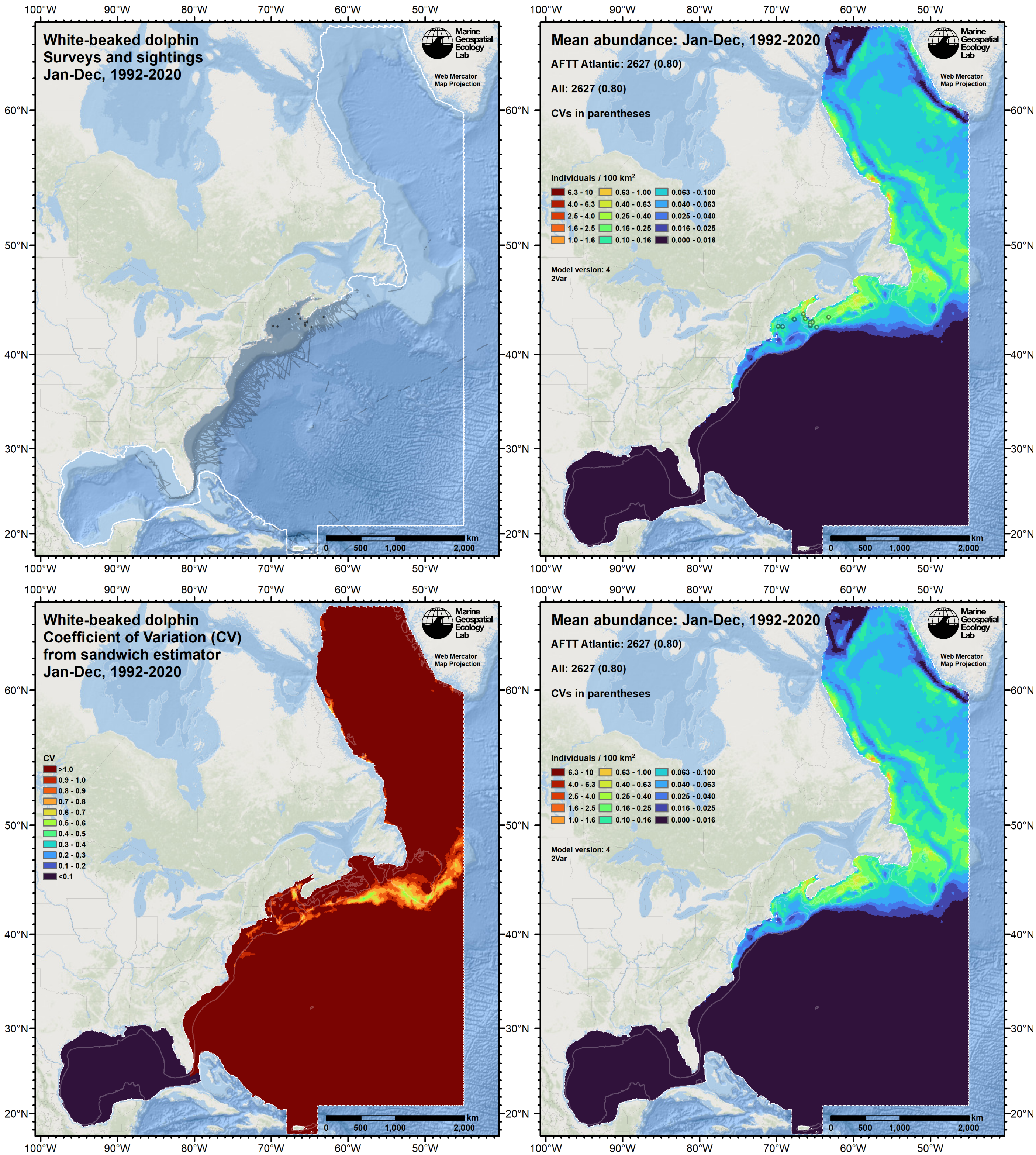


Figure 11: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for the given era. Variance was estimated with the analytic approach given by 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

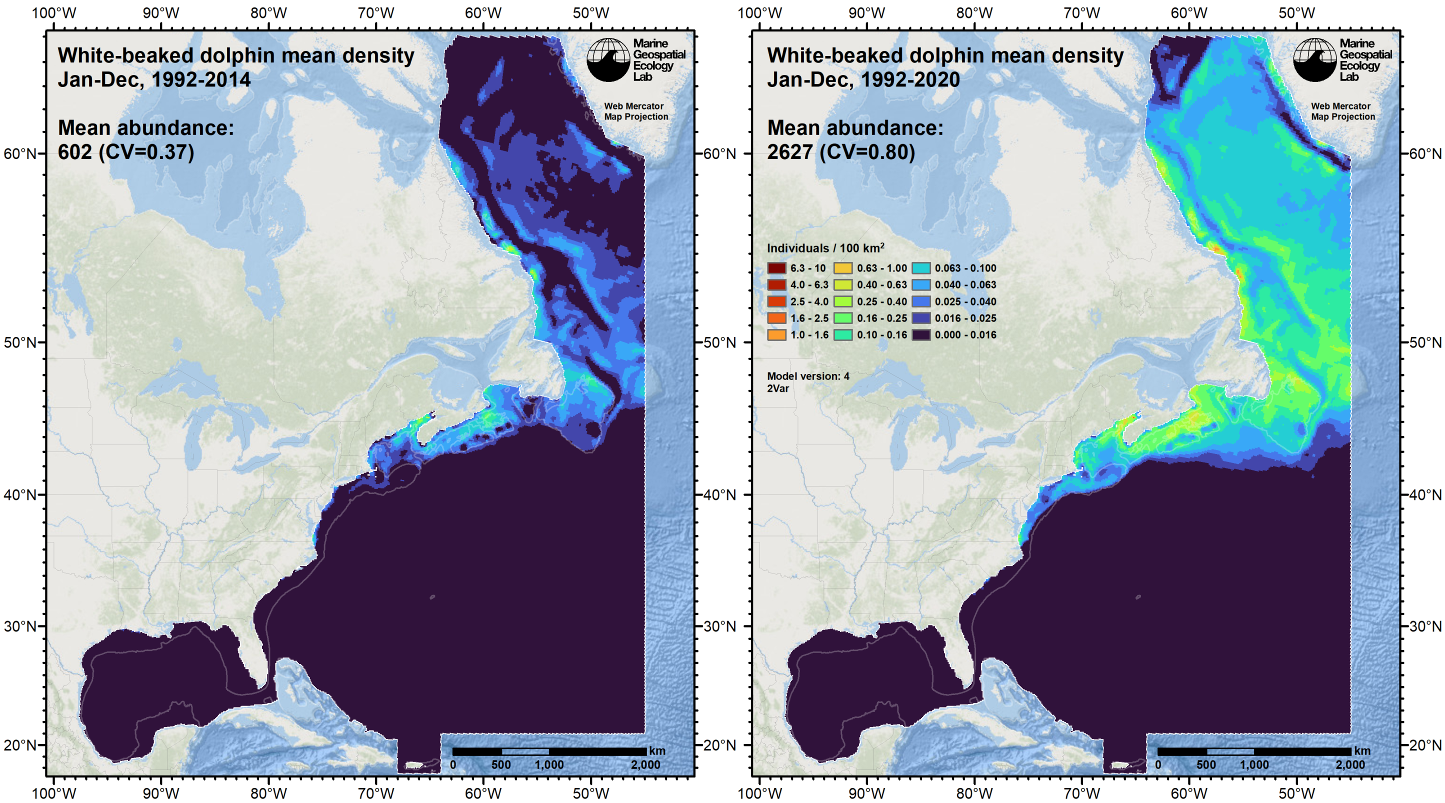


Figure 12: Comparison of the mean density predictions from the previous model (left) released by Mannocci et al. (2017) to those from this model (right). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

4 Discussion

Following what was done for the Phase III model, we summarized this updated model into a single year-round mean density surface (Figure 11). 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. White-beaked dolphins do not inhabit the Gulf of Mexico, so predictions in the AFTT model were set to zero there, and no regional model was fitted. See Roberts et al. (2023) for more discussion of the models.

The new AFTT model's predictions generally accorded with what has been reported in the literature and largely resembled the predictions of the Phase III model but with a markedly higher density (Figure 12). Abundance in the new model was more than quadruple that of the Phase III model. The large change likely resulted from the introduction of the R/V Song of the Whale surveys by MCR, which alone contributed 64 sightings—more than all other programs combined—collected on only 31,000 km effort. Most of these sightings were reported in coastal Iceland.

Despite this increase, we strongly caution that our model almost certainly underestimates density in Newfoundland, Labrador, west Greenland, and the Labrador Sea. Lawson and Gosselin (2018) surveyed Newfoundland and Labrador by aircraft in 2015 and reported 403 sightings of 6,893 individuals in those regions alone. Their total abundance estimate for those regions, fully corrected for perception and availability biases, was 530,538—more than two orders of magnitude higher than our estimate for the entire AFTT study area.

The fundamental problem with our model is that it relied on data collected off North America by U.S. organizations, which surveyed no farther north than the Laurentian Channel at the entrance to the Gulf of St. Lawrence. The region southwest of the Laurentian Channel that the U.S.-based surveys were restricted to appears to be the extreme southwestern edge of the species' habitat. Extrapolating our model built from surveys conducted in this marginal habitat, even when complemented with data from Iceland which appears to be much better habitat, appeared to insufficiently reproduce the high abundance found north of the Laurentian Channel. The striking difference in density northeast and southwest of the Laurentian Channel may be seen simply by examining the map of sightings in Lawson and Gosselin (2018) Figure 4A.

However, there is reason to believe that Lawson et al.'s result from the 2015 surveys may itself be anomalous. Their prior survey from 2007, conducted over a similar study area with similar effort, only reported 68 sightings of 537 individuals (Lawson and Gosselin 2009), yielding a corrected abundance estimate of 15,625 (Lawson and Gosselin 2011).

Until this extreme variability is understood, which will likely require repeated follow-on surveys in Canada, we recommend extreme caution north of 46 °N. Future updates to this model would benefit from the introduction of the surveys from Canada, as well surveys of west Greenland which in 2015 reported 50 sightings of white-beaked dolphins and estimated an abundance there of 15,261 (Hansen et al. 2019). (None of the surveys of Canada or Greenland were available for the current analysis.)

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