Density Model for Harbor Porpoise (*Phocoena phocoena*) for the U.S. Navy Atlantic Fleet Testing and Training (AFTT) Study Area: Supplementary Report

Model Version 3

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
2	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).
3	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 and Caribbean and excluded surveys of the Gulf of Mexico, Europe, and the Mid-Atlantic Ridge for the reasons mentioned by those authors. We did include segments south of 50 °N and west of 40 °W from a trans-Atlantic survey by R/V Song of the Whale. Harbor porpoises are small, cryptic odontocetes that are difficult to detect from long distances or in poor conditions. Accordingly, we excluded all surveys that did not target harbor porpoises as well as aerial surveys flown at altitudes higher than 750 ft., which species experts within our collaboration determined was the maximum altitude they were likely to be reliably detected without a belly observer or belly camera. Although detections at higher altitudes are possible, we lacked the counts needed to fit detection functions unless we pooled surveys flown at lower altitudes, which species experts determined would be inappropriate. Consistent with our regional models for the east coast, we restricted this model to survey transects collected in sea states of Beaufort 2 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						
NEFSC	AMAPPS	2010-2019	23	519	1,321	2.5
NEFSC	NARWSS	2003-2016	123	1,107	2,055	1.9
NEFSC	Pre-AMAPPS	1999-2008	21	357	952	2.7
NJDEP	NJEBS	2008-2009	6	5	8	1.6
SEFSC	AMAPPS	2010-2020	38	4	5	1.2
SEFSC	MATS	2002-2005	24	0	0	
U. La Rochelle	REMMOA	2008-2017	22	0	0	
VAMSC	MD DNR WEA	2013-2015	4	0	0	
		Total	**260**	**1,992**	**4,341**	**2.2**
Shipboard Surveys						
MCR	SOTW Visual	2005-2019	13	24	34	1.4
NEFSC	AMAPPS	2011-2016	3	14	25	1.8
NEFSC	Pre-AMAPPS	1995-2007	4	606	1,862	3.1
NJDEP	NJEBS	2008-2009	4	32	58	1.8
SEFSC	AMAPPS	2011-2016	5	0	0	
SEFSC	Pre-AMAPPS	1992-2006	9	0	0	
SEFSC	SEFSC Caribbean	1995-2000	2	0	0	
		Total	**40**	**676**	**1,979**	**2.9**
		Grand Total	**301**	**2,668**	**6,320**	**2.4**

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

Institution	Full Name
MCR	Marine Conservation Research
NEFSC	NOAA Northeast Fisheries Science Center
NJDEP	New Jersey Department of Environmental Protection
SEFSC	NOAA Southeast Fisheries Science Center
U. La Rochelle	University of La Rochelle
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)
MATS	Mid-Atlantic Tursiops Surveys	
MD DNR WEA	Aerial Surveys of the Maryland Wind Energy Area	Barco et al. (2015)
NARWSS	North Atlantic Right Whale Sighting Surveys	Cole et al. (2007)
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)
REMMOA	REcensement des Mammifères marins et autre Mégafaune pélagique par Observation Aérienne	Mannocci et al. (2013), Laran et al. (2019)
SEFSC Caribbean	SEFSC Surveys of the Caribbean Sea	Mullin (1995), Swartz and Burks (2000)
SOTW Visual	R/V Song of the Whale Visual Surveys	Ryan et al. (2013)

2 Density Model

Our objective was to update the model of Mannocci et al. (2017) with new data without repeating the covariate selection exercise performed by those authors. We therefore fitted a year-round, 4-covariate model that included depth, micronekton productivity, zooplankton biomass, and the standard deviation of sea surface height anomaly. The resulting relationships (Figure 2) generally resembled those of Mannocci et al.'s model (but see discussion in Section 4). Model predictions are shown in Section 3. Univariate extrapolation analyses (Section 2.3.1) displayed geographic patterns very similar to the environmental envelopes estimated by Mannocci et al. Little environmental extrapolation was necessary, and was driven mainly by a lack of sampling in waters with a very low or very high standard deviation of sea level anomaly, as were found sporadically in the Labrador Sea and shelf (very low values) and in the Gulf Stream (very high values) (Figure 11).

2.1 Final Model

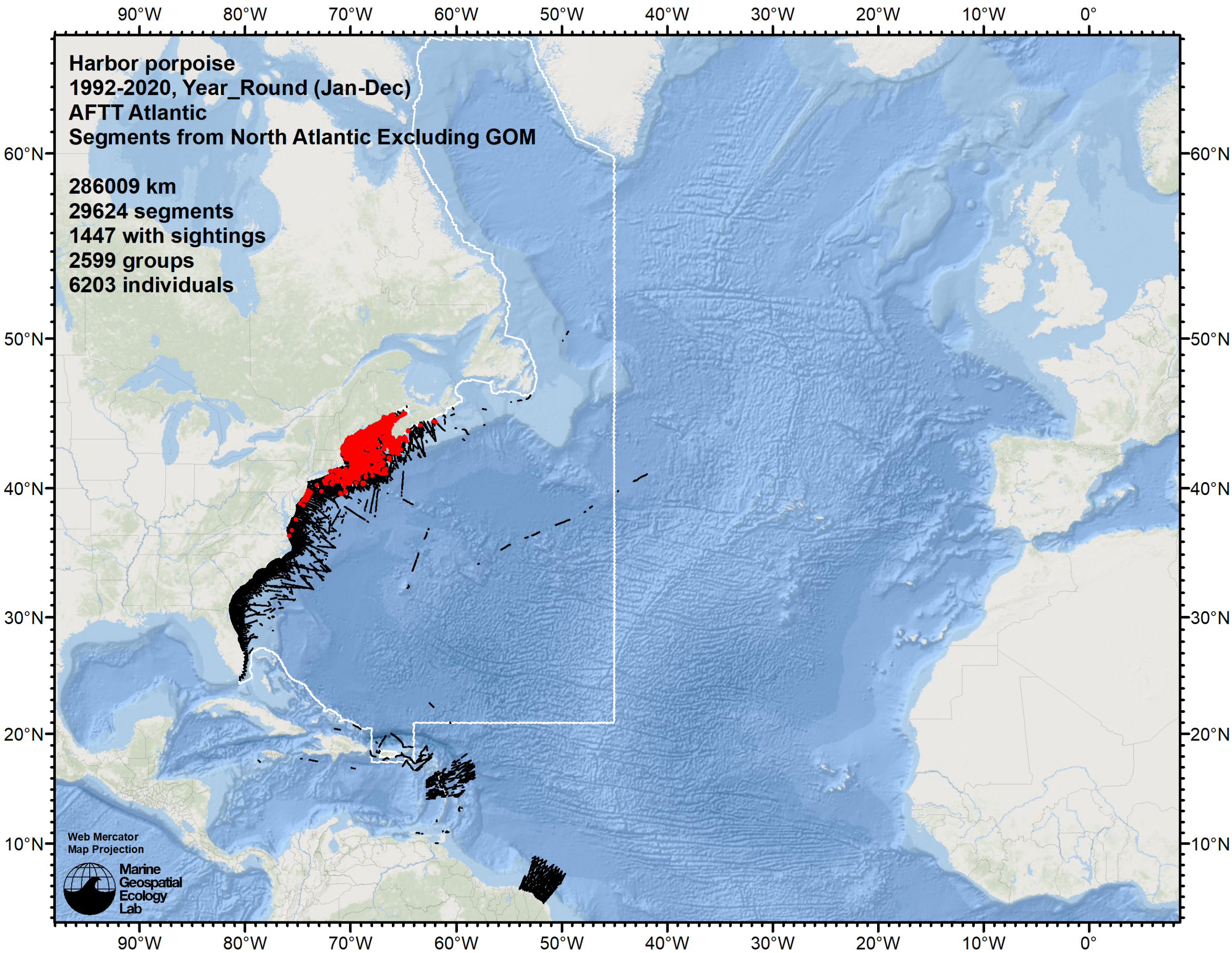
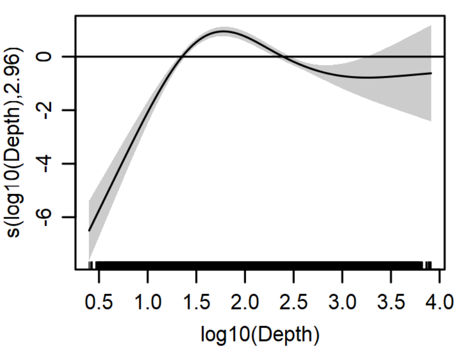


Figure 1: Survey segments (black lines) used to fit the model for the region AFTT Atlantic. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

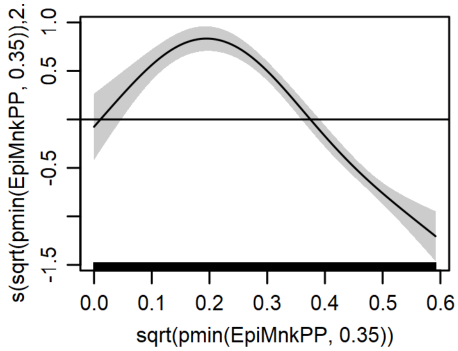
Statistical output for this model:

```
Family: Tweedie(p=1.387)
Link function: log

Formula:
```

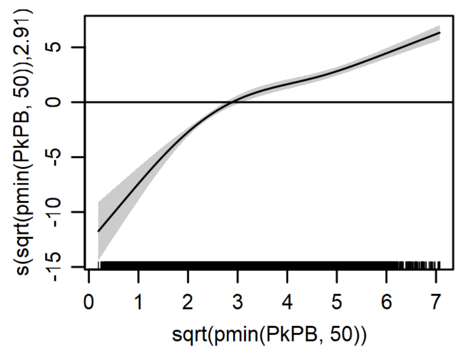
```
IndividualsCorrected ~ offset(log(SegmentArea)) + s(log10(Depth),
    bs = "ts", k = 4) + s(sqrt(pmin(EpiMnkPP, 0.35)), bs = "ts",
    k = 4) + s(sqrt(pmin(PkPB, 50)), bs = "ts", k = 4) + s(log10(SLAStDev),
    bs = "ts", k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -19.008      0.188  -101.1   <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))               2.960      3  62.65  <2e-16 ***
s(sqrt(pmin(EpiMnkPP, 0.35))) 2.897      3  70.76  <2e-16 ***
s(sqrt(pmin(PkPB, 50)))       2.910      3 227.29  <2e-16 ***
s(log10(SLAStDev))            1.088      3  14.70  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0581   Deviance explained = 32.8%
-REML =   9476  Scale est. = 14.922    n = 29624

Method: REML   Optimizer: outer newton
full convergence after 12 iterations.
Gradient range [-1.707415e-05,2.062844e-05]
(score 9475.994 & scale 14.92173).
Hessian positive definite, eigenvalue range [0.1465804,4556.89].
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))               3.00 2.96    0.76  <2e-16 ***
s(sqrt(pmin(EpiMnkPP, 0.35))) 3.00 2.90    0.80   0.055 .
s(sqrt(pmin(PkPB, 50)))       3.00 2.91    0.77  <2e-16 ***
s(log10(SLAStDev))            3.00 1.09    0.81   0.340
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



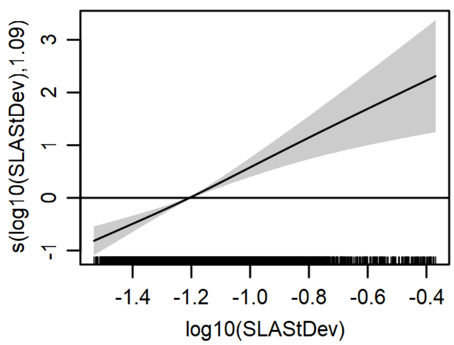
(a) Seafloor depth (m)



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



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



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

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
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))
PkPB	Climatological monthly mean zooplankton biomass expressed in carbon (g C m^{-2}) 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

2.2 Diagnostic Plots

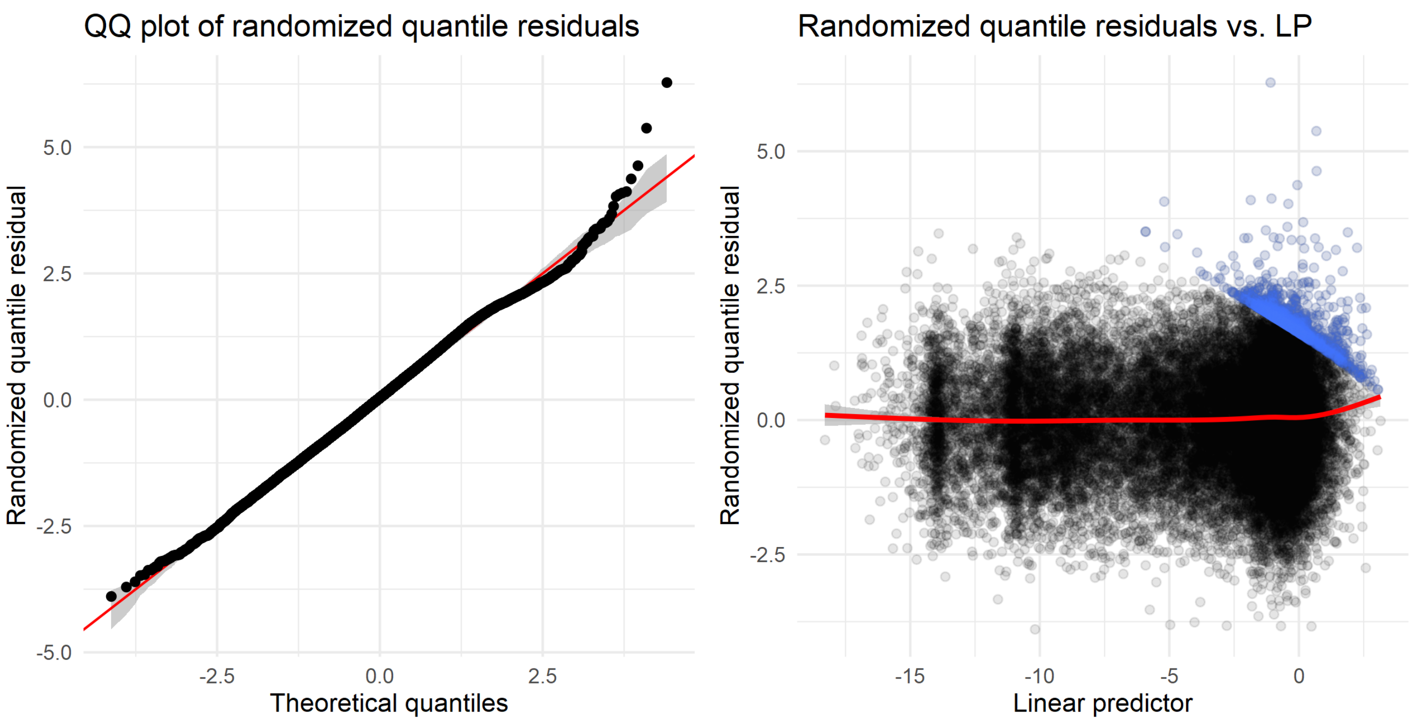


Figure 3: Residual plots for the final model for the region AFTT Atlantic.

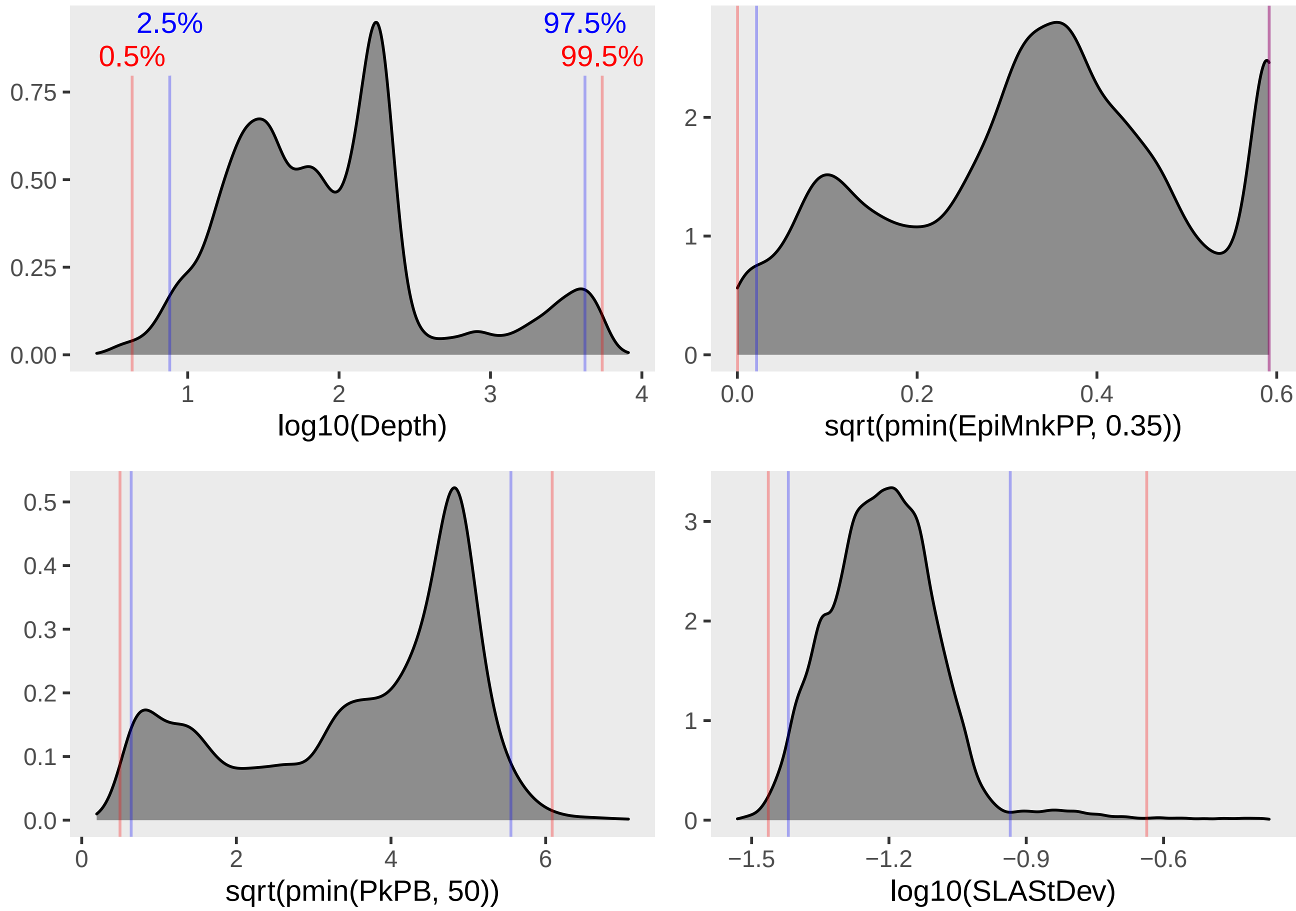


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red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

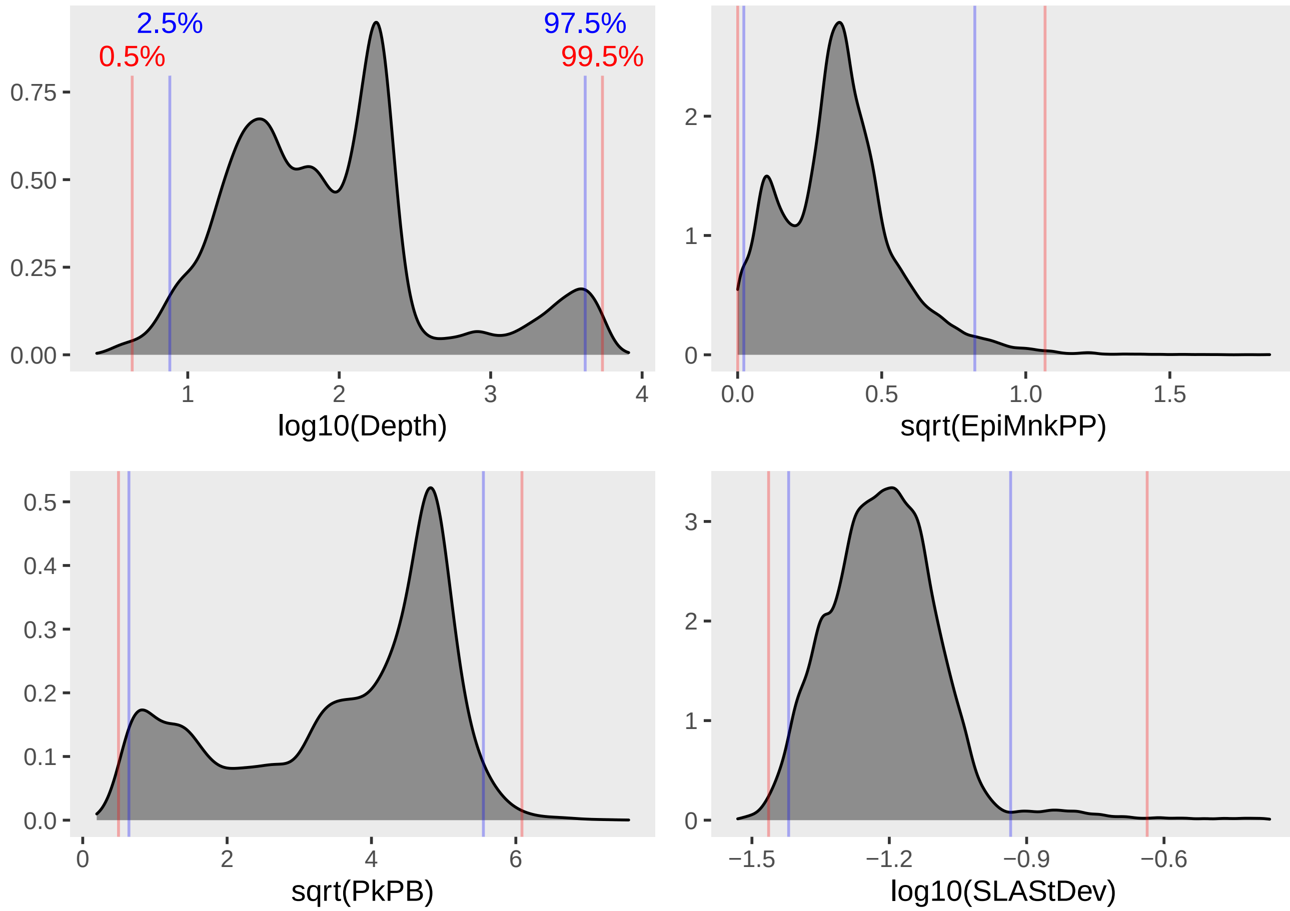


Figure 5: Density histograms shown in Figure 4 replotted without Winsorization, to show the full range of sampling represented by survey segments.

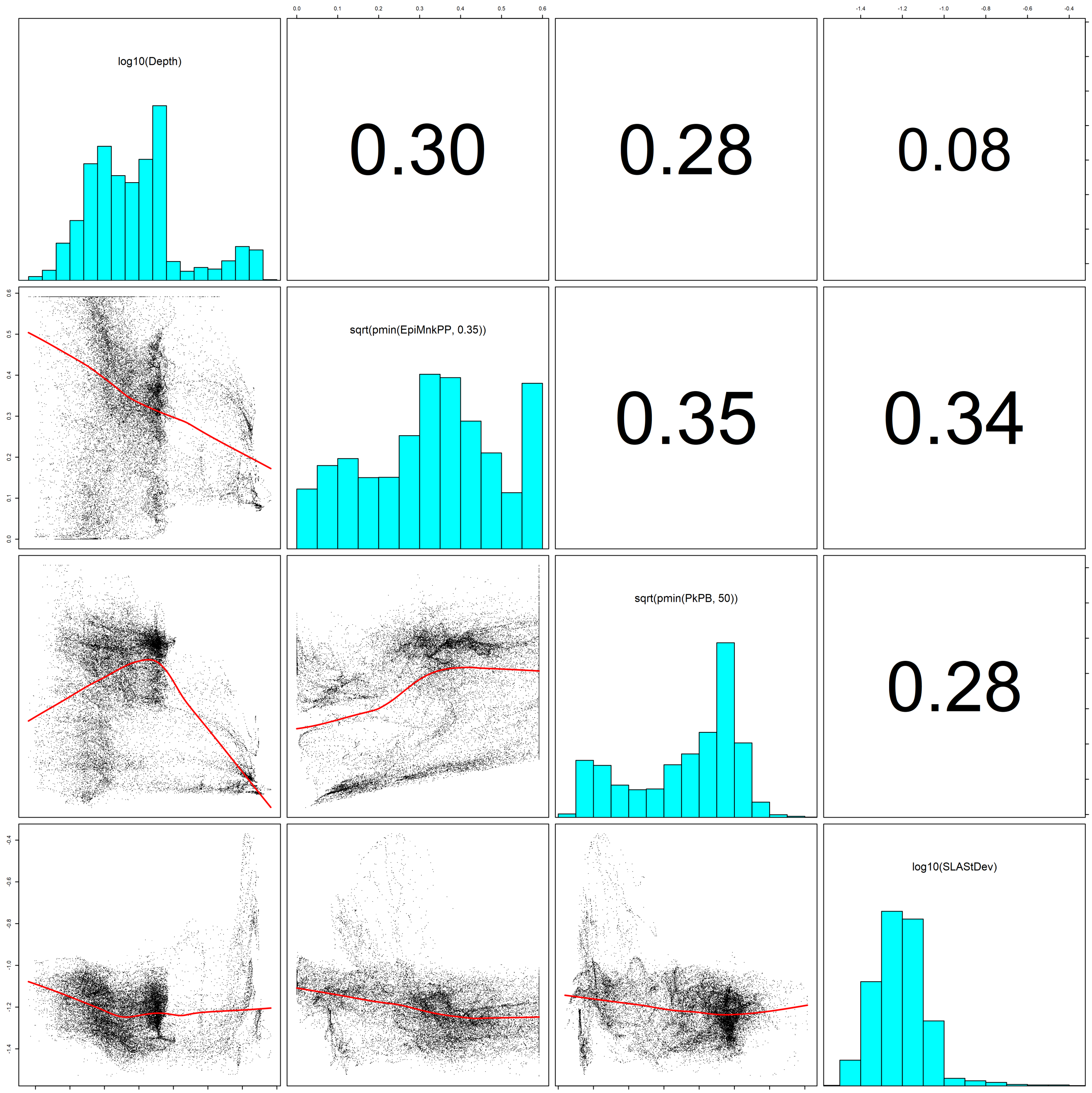


Figure 6: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and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

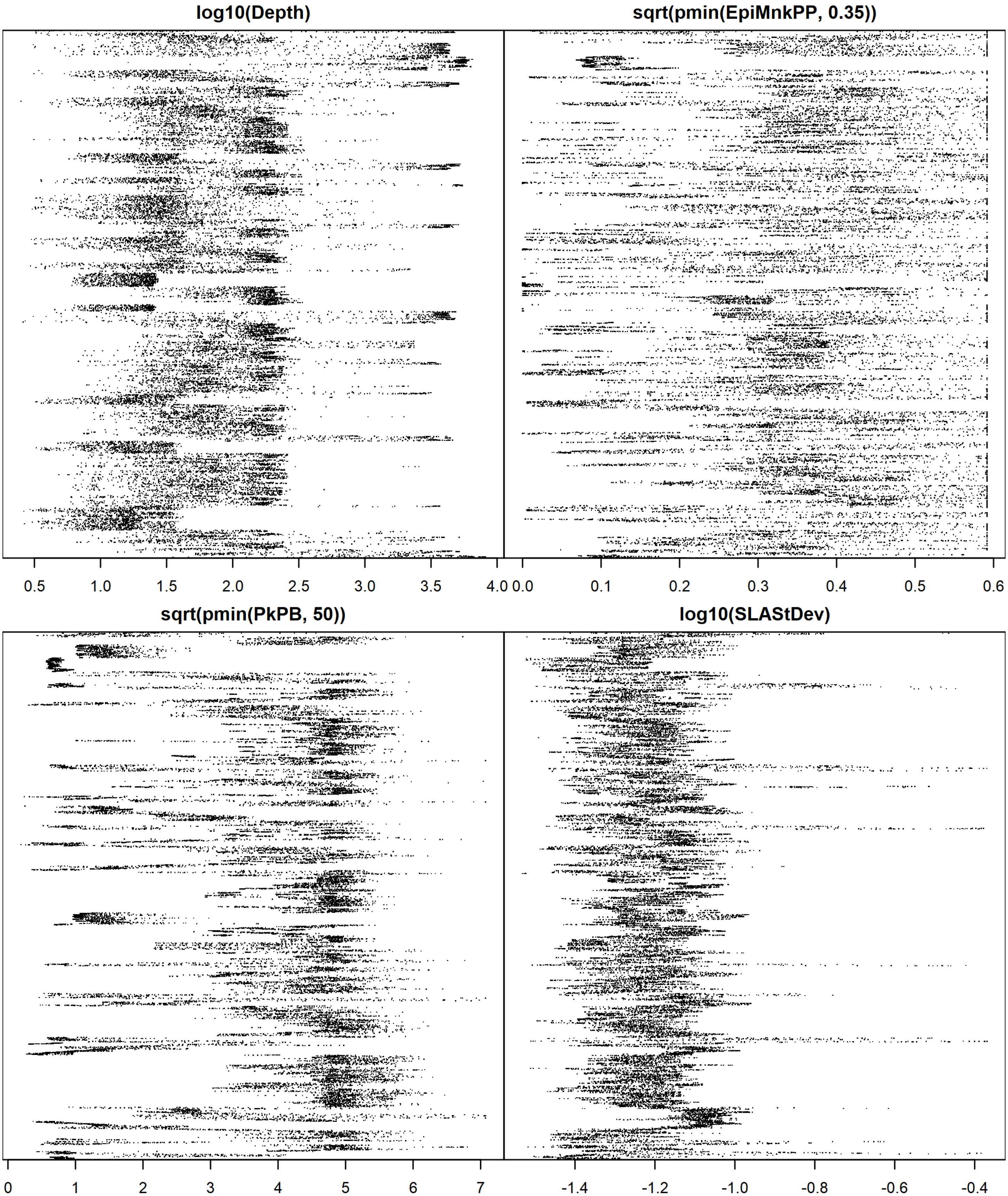


Figure 7: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized 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

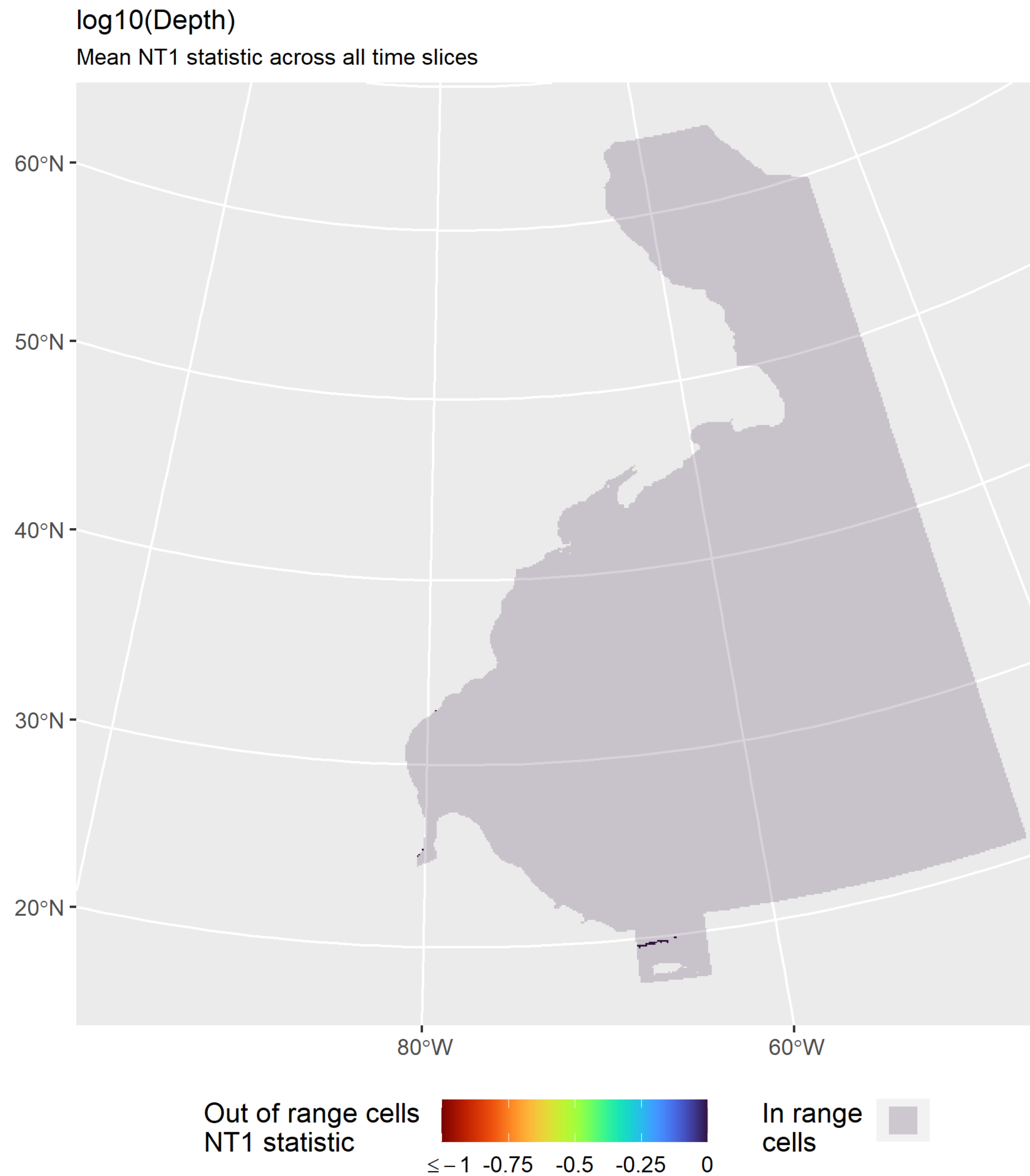


Figure 8: NT1 statistic (Mesgaran et al. (2014)) for static covariates used in the model for the region AFTT Atlantic. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there. Areas within the sampled range appear in gray, indicating 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 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 10: 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.

(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 11: NT1 statistic (Mesgaran et al. (2014)) for the SLAStDev 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

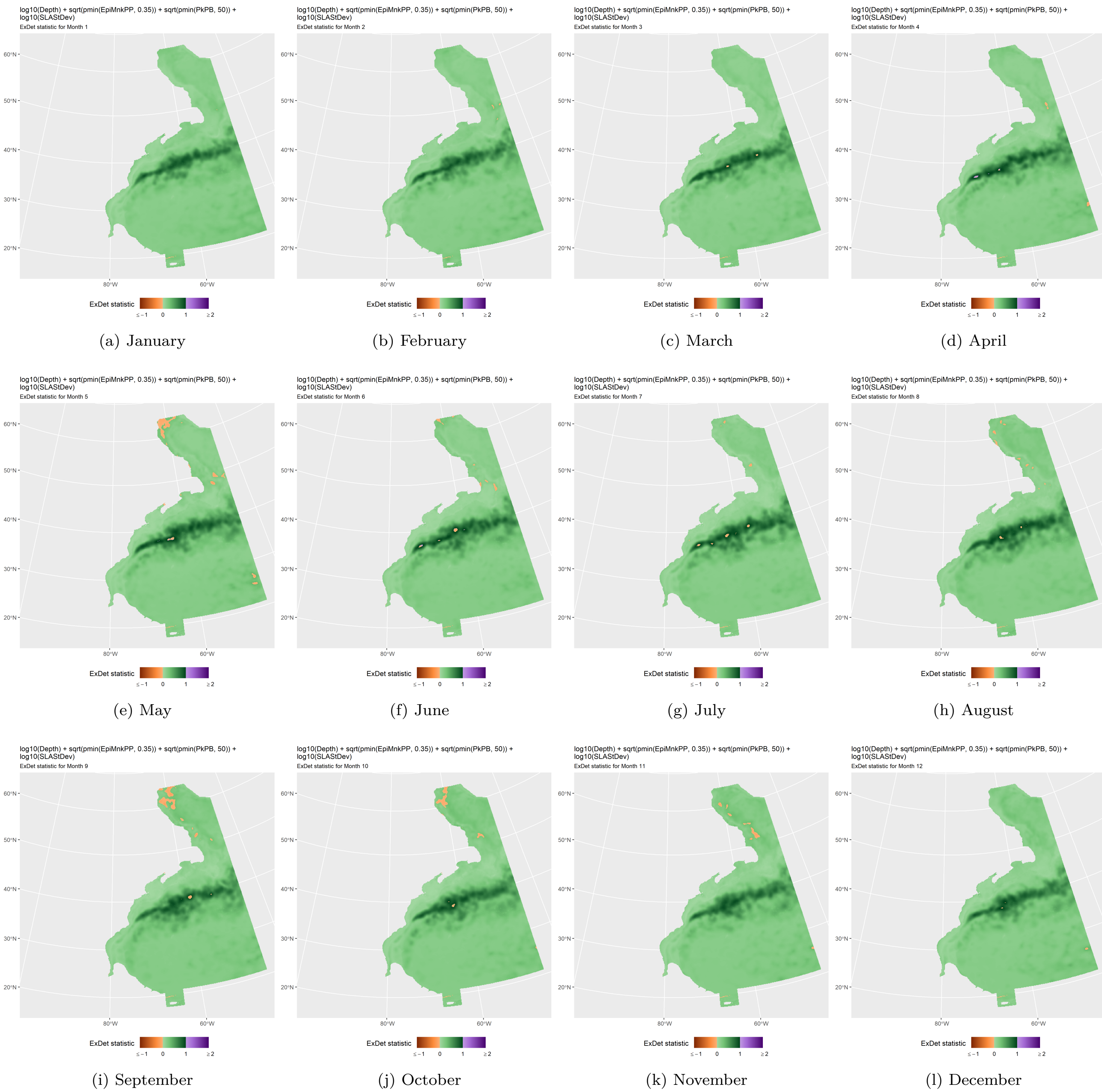


Figure 12: ExDet statistic (Mesgaran et al. (2014)) for all of the covariates used in the model for the region AFTT Atlantic. Areas in orange (ExDet < 0) required univariate extrapolation of one or more covariates (see previous section). Areas in purple (ExDet > 1), did not require univariate extrapolation 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

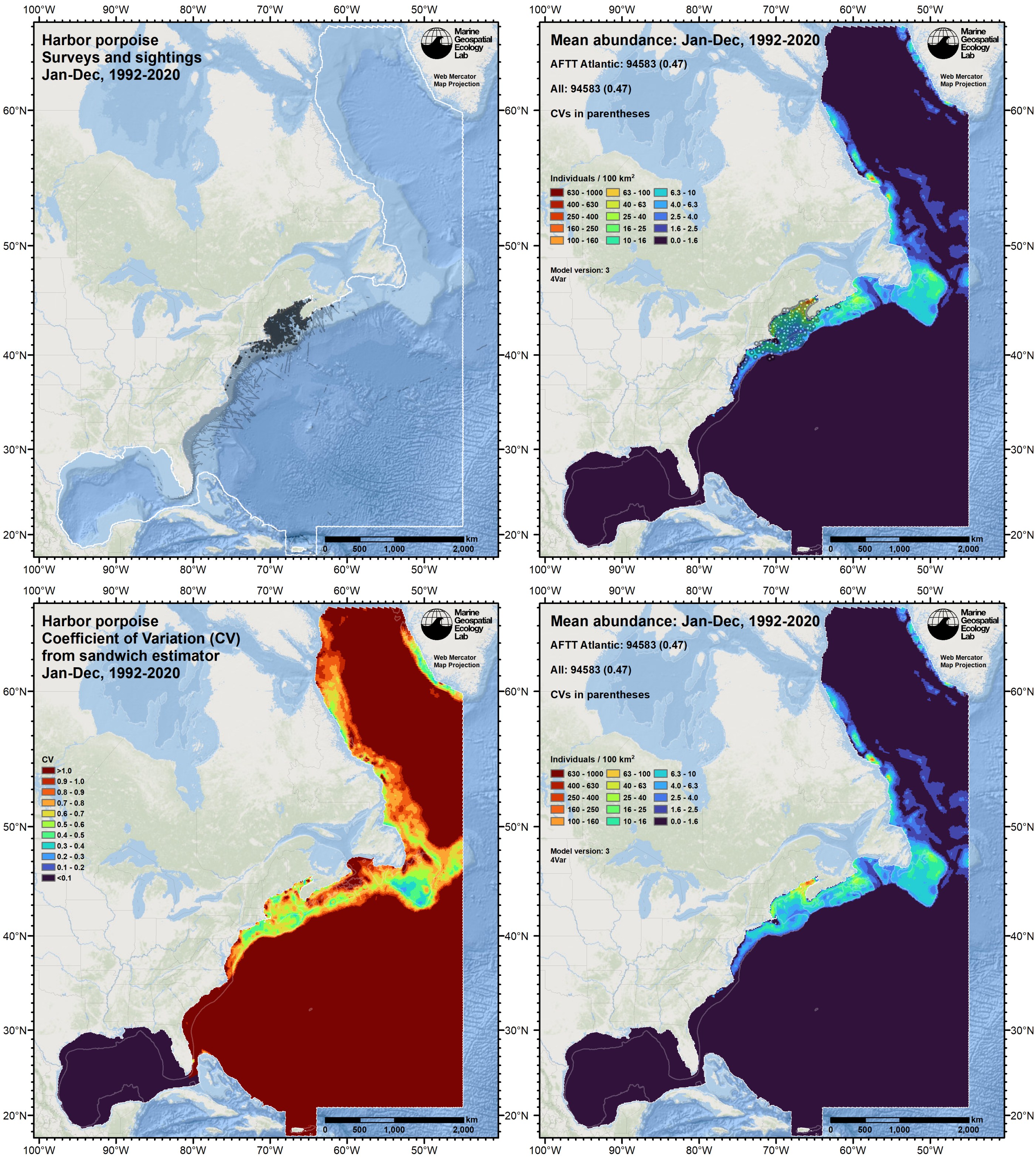


Figure 13: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for the given era. Variance was estimated with the analytic approach given by 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

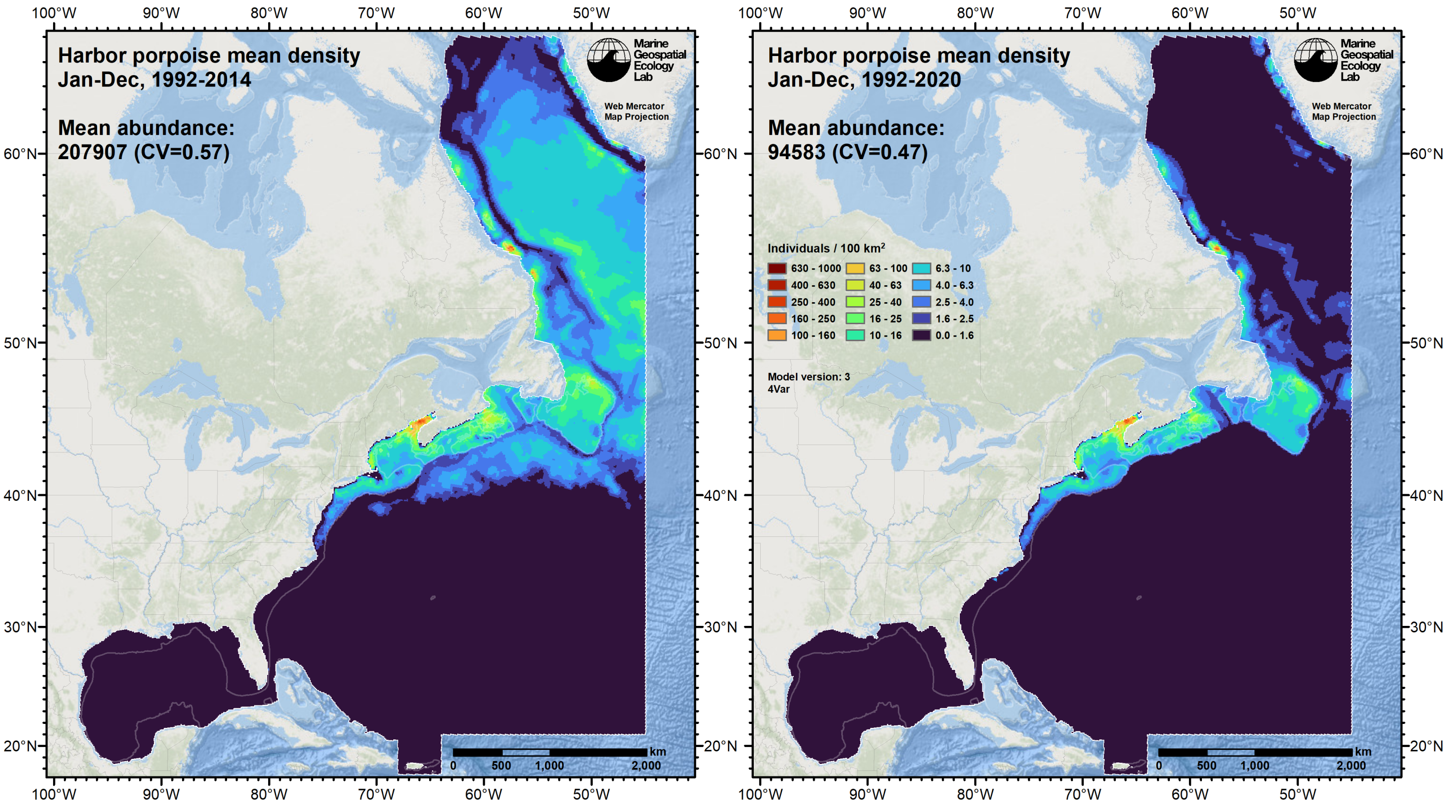


Figure 14: Comparison of the mean density predictions from the previous model (left) released by Mannocci et al. (2017) to those from this model (right). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

4 Discussion

Following Mannocci et al. (2017), we summarized this model into a single year-round mean density surface (Figure 13). 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. The EC model provides predictions as 12 monthly means, rather than a single year-round mean. Harbor porpoises 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 strongly resembled the predictions of Mannocci et al. (2017) for the continental shelf but estimated much lower density beyond the shelf, leading to to a total abundance estimate that was about 55% lower (Figure 14). The predictions of harbor porpoise presence along the shelf of Newfoundland and Labrador were supported by sightings reported by aerial surveys in 2007 and 2015 (Lawson and Gosselin 2009, 2011, 2018). The predictions of presence along the shelf of west Greenland were supported by sightings reported by aerial surveys there in 2007 (Hansen and Heide-Jørgensen 2013). None of these surveys were available for use in our model; future updates would benefit from their inclusion. Please see the harbor porpoise report from Mannocci et al. (2017) for additional discussion of the literature.

The differing predictions beyond the continental shelf are a concern. The difference was driven by the relationship fitted to the depth covariate. In Mannocci et al. (2017), depth showed a positive effect on density in waters deeper than about 1000 m (about 3.0 in $\log_{10}$ scale), but in our model remained negative throughout this range. Our model benefited from additional off-shelf shipboard surveys, mainly from NOAA AMAPPS and MCR (Table 1). Nearly all of the sightings reported by these surveys were made on transects that occurred over the shelf or at the shelf break. This additional absence data beyond the shelf drove down the depth relationship there, yielding lower predicted densities. Despite this additional data—which, in principle, reduces uncertainty about porpoise density beyond the shelf—we advise caution in northern off-shelf waters such as the Labrador Sea, as none of the surveys occurred there and model predictions represent a geographical extrapolation. At the time of this writing, the OBIS-SEAMAP archive (Halpin et al. 2009) reported several sightings in off-shelf waters there.

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