Density Model for Common Bottlenose Dolphin (*Tursiops truncatus*) 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:

Roberts JJ, Yack TM, Halpin PN (2022) Density Model for Common Bottlenose Dolphin (*Tursiops truncatus*) for the U.S. Navy's AFTT Phase IV Study Area, Version 4, 2022-06-20, and Supplementary Report. Marine Geospatial Ecology Laboratory, Duke University, Durham, North Carolina.

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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.

*For questions or to offer feedback please contact Jason Roberts (jason.roberts@duke.edu) and Tina Yack (tina.yack@duke.edu)

1 Survey Data

Following Mannocci et al. (2017), whose model we were updating, we built this model from data collected in the east coast, Gulf of Mexico, and Caribbean and excluded surveys of Europe and the Mid-Atlantic Ridge. 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. 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	120	2,151	17.9
NEFSC	AMAPPS	2010-2019	83	105	902	8.6
NEFSC	NARWSS	2003-2016	380	56	500	8.9
NEFSC	Pre-AMAPPS	1999-2008	45	46	258	5.6
SEFSC	AMAPPS	2010-2020	112	1,237	12,354	10.0
SEFSC	GOMEX92-96	1992-1996	27	426	3,390	8.0
SEFSC	GulfCet I	1992-1994	50	74	1,025	13.9
SEFSC	GulfCet II	1996-1998	22	138	1,708	12.4
SEFSC	GulfSCAT 2007	2007-2007	18	273	1,898	7.0
SEFSC	MATS	2002-2005	27	574	7,831	13.6
U. La Rochelle	REMMOA	2008-2017	39	80	1,335	16.7
UNCW	MidA Bottlenose	2002-2002	15	343	1,831	5.3
UNCW	Navy Cape Hatteras	2011-2017	34	283	5,538	19.6
UNCW	Navy Jacksonville	2009-2017	92	421	3,514	8.3
UNCW	Navy Norfolk Canyon	2015-2017	14	67	1,593	23.8
UNCW	Navy Onslow Bay	2007-2011	49	143	2,553	17.9
UNCW	SEUS NARW EWS	2005-2008	106	1,786	12,518	7.0
VAMSC	MD DNR WEA	2013-2015	15	278	2,277	8.2
VAMSC	Navy VACAPES	2016-2017	18	129	1,252	9.7
VAMSC	VA CZM WEA	2012-2015	19	140	1,196	8.5
		Total	**1,175**	**6,719**	**65,624**	**9.8**
Shipboard Surveys						
MCR	SOTW Visual	2012-2019	9	29	272	9.4
NEFSC	AMAPPS	2011-2016	15	265	3,037	11.5
NEFSC	Pre-AMAPPS	1995-2007	17	172	2,283	13.3
NJDEP	NJEBS	2008-2009	14	156	2,369	15.2
SEFSC	AMAPPS	2011-2016	16	171	3,212	18.8
SEFSC	GOM Oceanic CetShip	1992-2001	49	206	3,220	15.6
SEFSC	GOM Shelf CetShip	1994-2001	10	256	2,835	11.1
SEFSC	Pre-AMAPPS	1992-2006	33	427	7,374	17.3
SEFSC	Pre-GoMMAPPS	2003-2009	19	62	2,083	33.6
SEFSC	SEFSC Caribbean	1995-2000	8	14	167	11.9
		Total	**190**	**1,758**	**26,852**	**15.3**
		Grand Total	**1,365**	**8,477**	**92,476**	**10.9**

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

Institution	Full Name
HDR	HDR, Inc.
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
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)
GOM Oceanic CetShip	Gulf of Mexico Oceanic CetShip Surveys	Mullin and Fulling (2004)
GOM Shelf CetShip	Gulf of Mexico Shelf CetShip Surveys	Fulling et al. (2003)
GOMEX92-96	GOMEX 1992-1996 Aerial Surveys	Blaylock and Hoggard (1994)
GulfCet I	GulfCet I Aerial Surveys	Davis and Fargion (1996)
GulfCet II	GulfCet II Aerial Surveys	Davis et al. (2000)
GulfSCAT 2007	GulfSCAT 2007 Aerial Surveys	
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)
Pre-GoMMAPPS	Pre-GoMMAPPS Marine Mammal Abundance Surveys	Mullin (2007)
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)
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)

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

Program	Description	References
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 repeating the covariate selection exercise performed by those authors. We therefore fitted a year-round, 4-covariate model that included depth, distance to SST fronts, micronekton productivity, and zooplankton biomass. The resulting relationships (Figure 2) strongly resembled those of Mannocci et al.'s model. 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. The necessity for environmental extrapolation was driven mainly by a lack of sampling in waters with very few SST fronts, as occurs in the southeast in summer (Figure 9).

2.1 Final Model

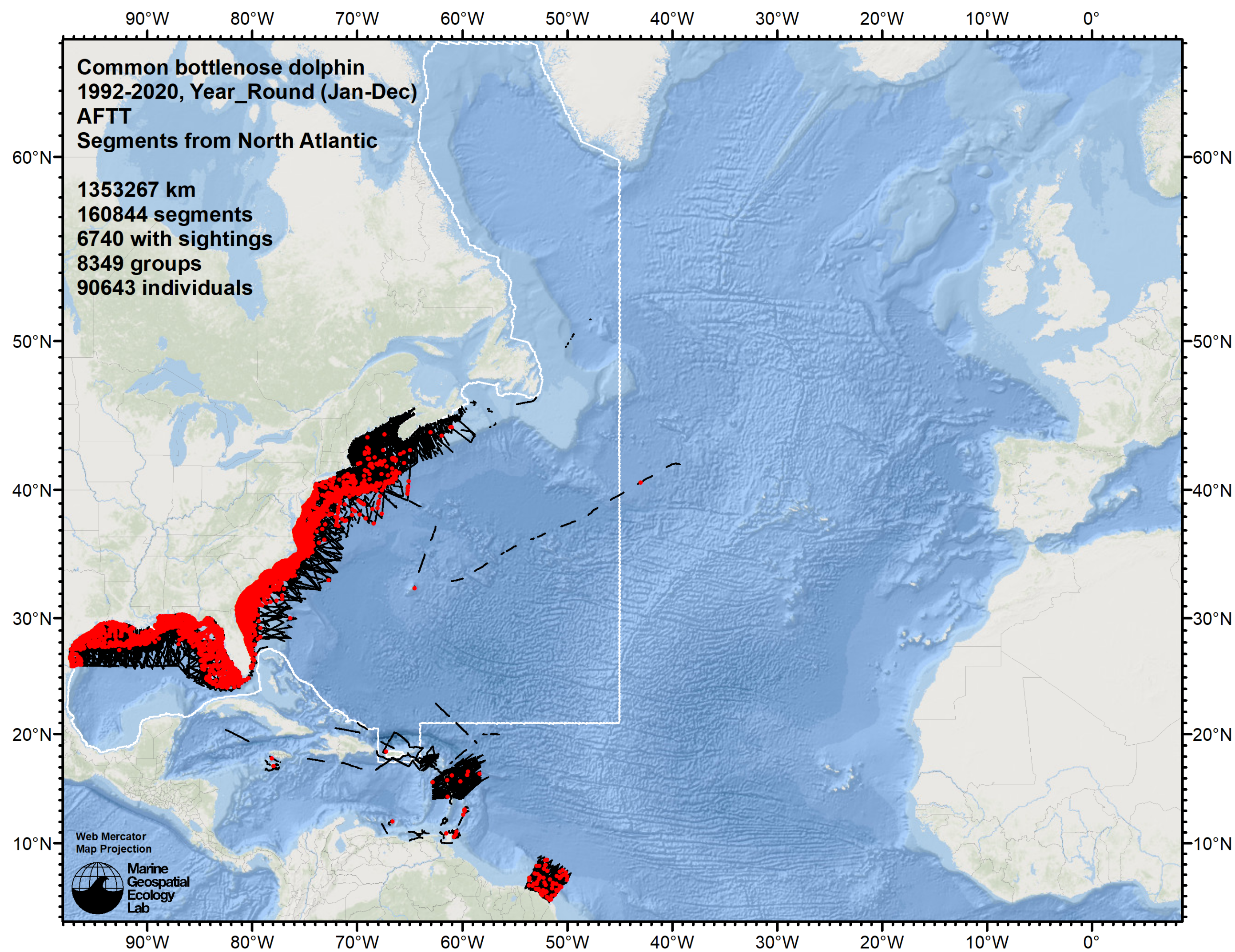
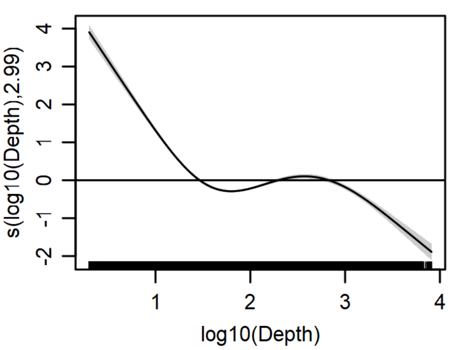


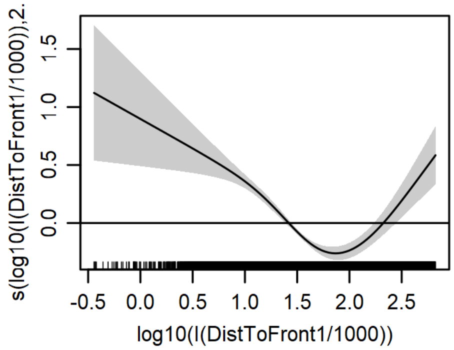
Figure 1: Survey segments (black lines) used to fit the model. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

Statistical output for this model:

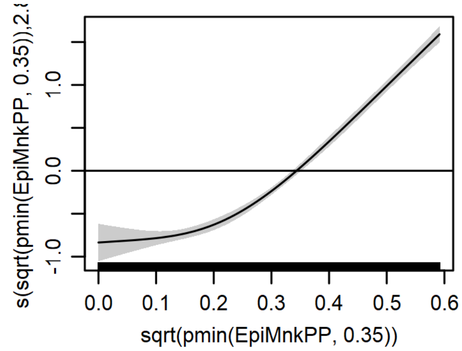
```
Family: Tweedie(p=1.485)
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(log10(Depth),
    bs = "ts", k = 4) + s(log10(I(DistToFront1/1000)), bs = "ts",
    k = 4) + s(sqrt(pmin(EpiMnkPP, 0.35)), bs = "ts", k = 4) +
    s(sqrt(pmin(PkPB, 50)), bs = "ts", k = 4)

Parametric coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -16.75669    0.01996  -839.5   <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))                2.995      3 649.23  <2e-16 ***
s(log10(I(DistToFront1/1000))) 2.898      3  53.62  <2e-16 ***
s(sqrt(pmin(EpiMnkPP, 0.35)))  2.828      3 420.38  <2e-16 ***
s(sqrt(pmin(PkPB, 50)))        2.867      3 503.78  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  -0.111   Deviance explained = 19.2%
-REML =  54323  Scale est. = 40.186    n = 160746

Method: REML   Optimizer: outer newton
full convergence after 10 iterations.
Gradient range [-0.005062837,0.004958681]
(score 54322.52 & scale 40.18631).
Hessian positive definite, eigenvalue range [1.239238,16846.14].
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 2.99    0.61    0.12
s(log10(I(DistToFront1/1000))) 3.00 2.90    0.63    0.69
s(sqrt(pmin(EpiMnkPP, 0.35)))  3.00 2.83    0.62    0.21
s(sqrt(pmin(PkPB, 50)))        3.00 2.87    0.61    0.07 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



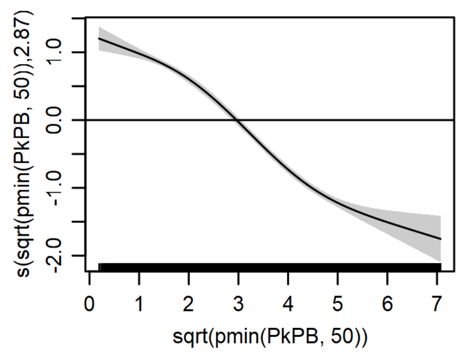
(a) Seafloor depth (m)



(b) Climatological distance to SST front (km)



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



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

Figure 2: Functional plots for the final model. 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.

Covariate	Description
Depth	Depth (m) of the seafloor, from SRTM30_PLUS (Becker et al. (2009))
DistToFront1	Climatological monthly mean distance (km) to the closest sea surface temperature front detected in daily GHRSST Level 4 CMC0.2deg images (Brasnett (2008); Canada Meteorological Center (2012)) with MGET's implementation of the Canny edge detector (Roberts et al. (2010); Canny (1986))
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

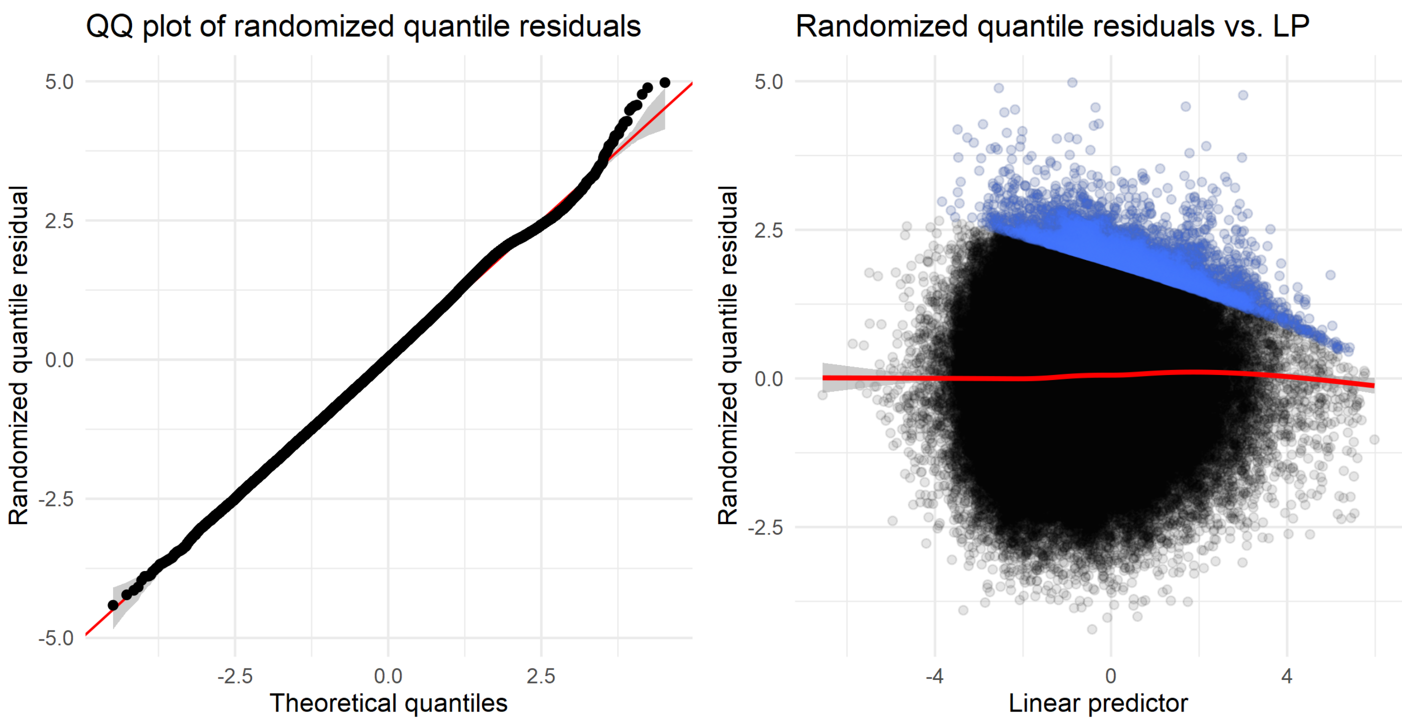


Figure 3: Residual plots for the final model.

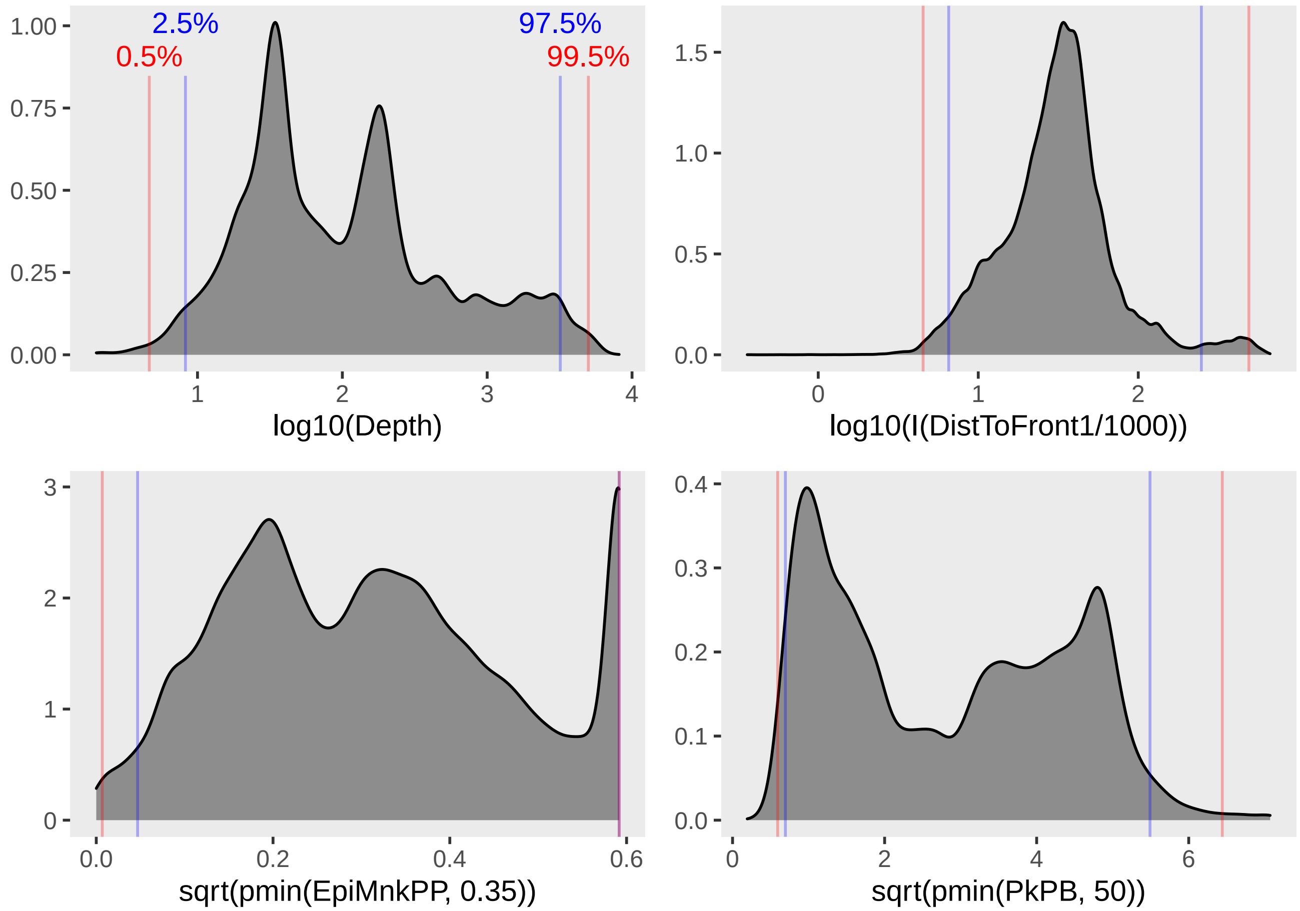


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red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

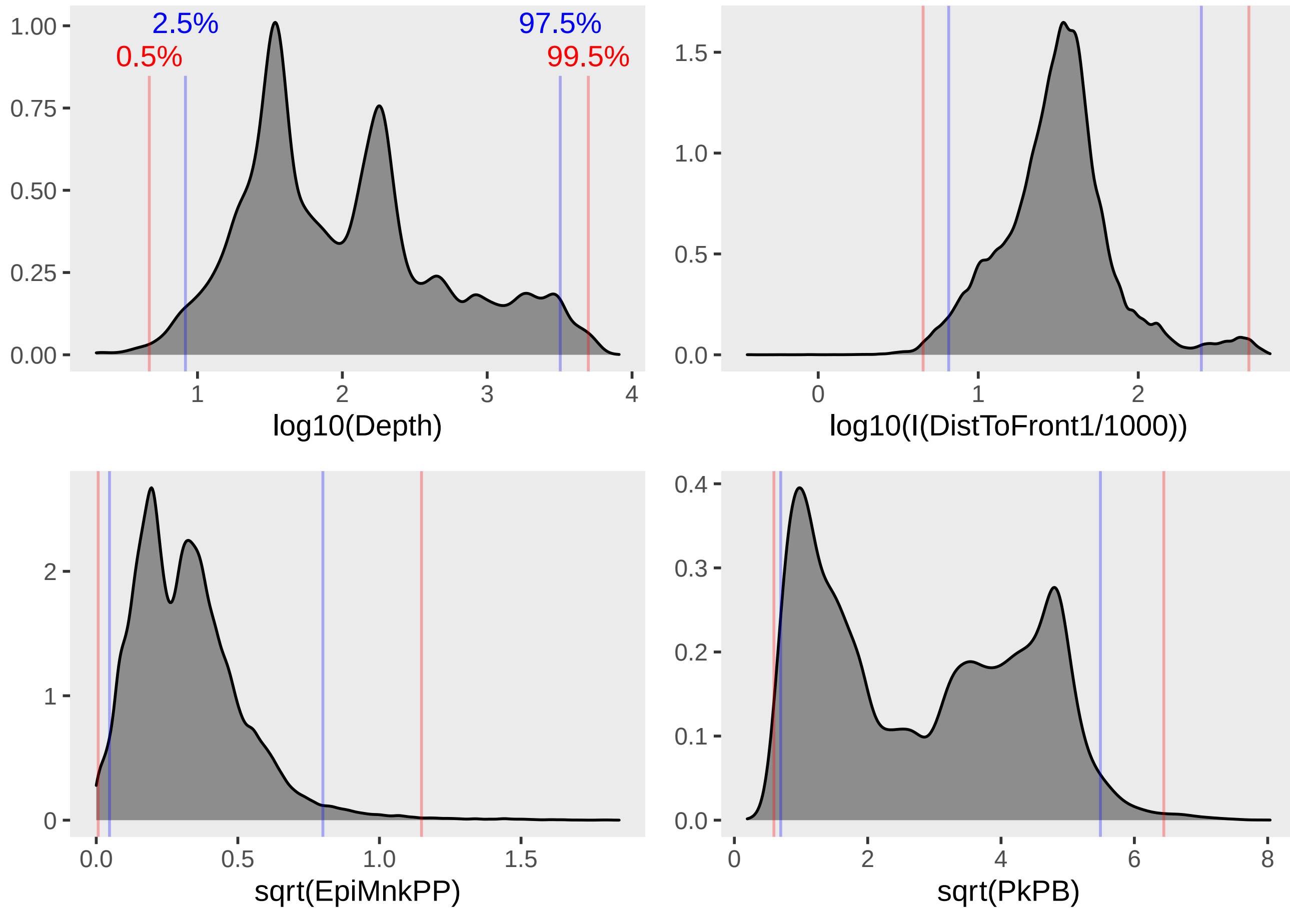


Figure 5: Density histograms shown in Figure 4 replotted without Winsorization, to show the full range of sampling represented by survey segments.

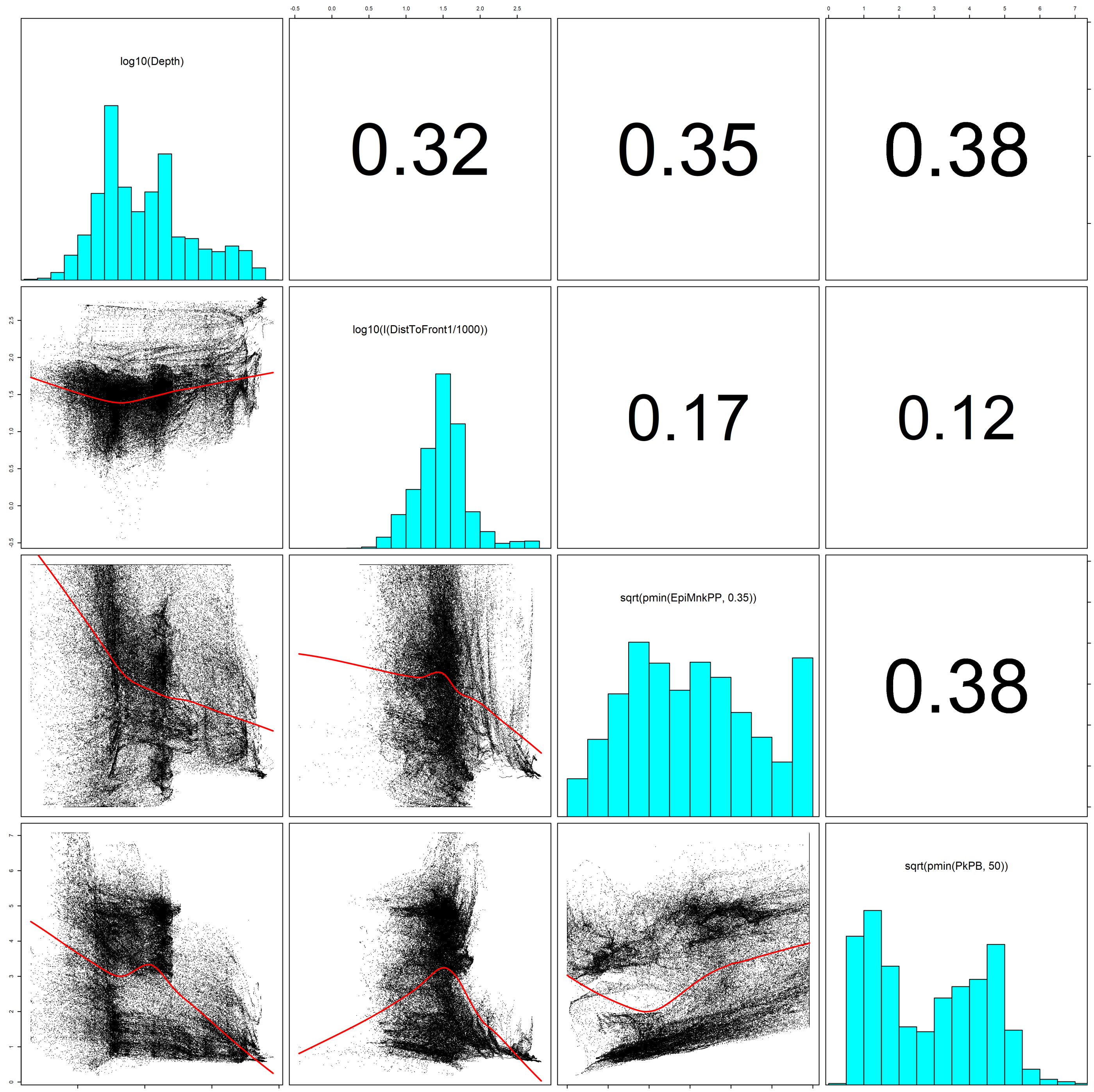


Figure 6: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and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

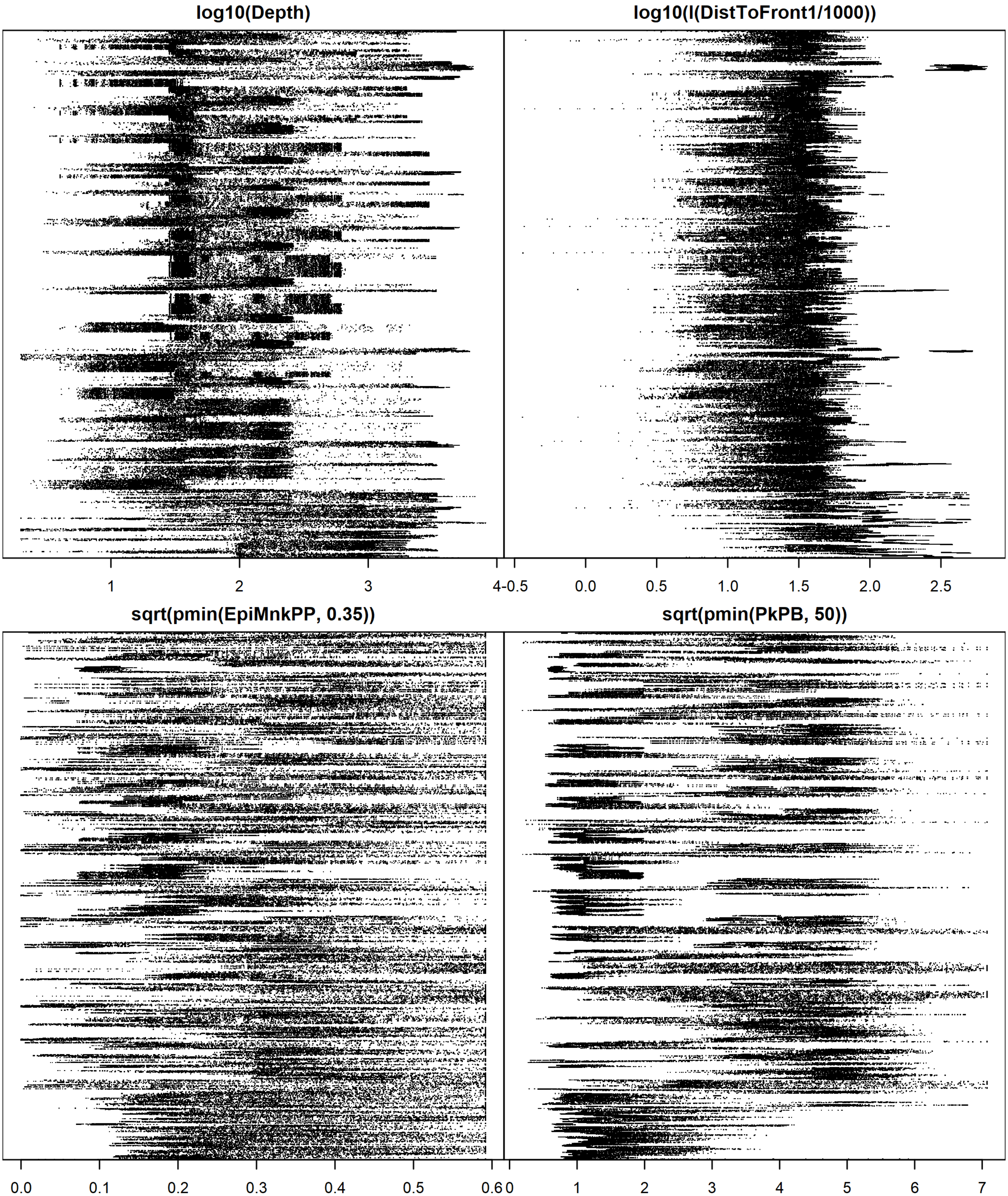


Figure 7: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized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

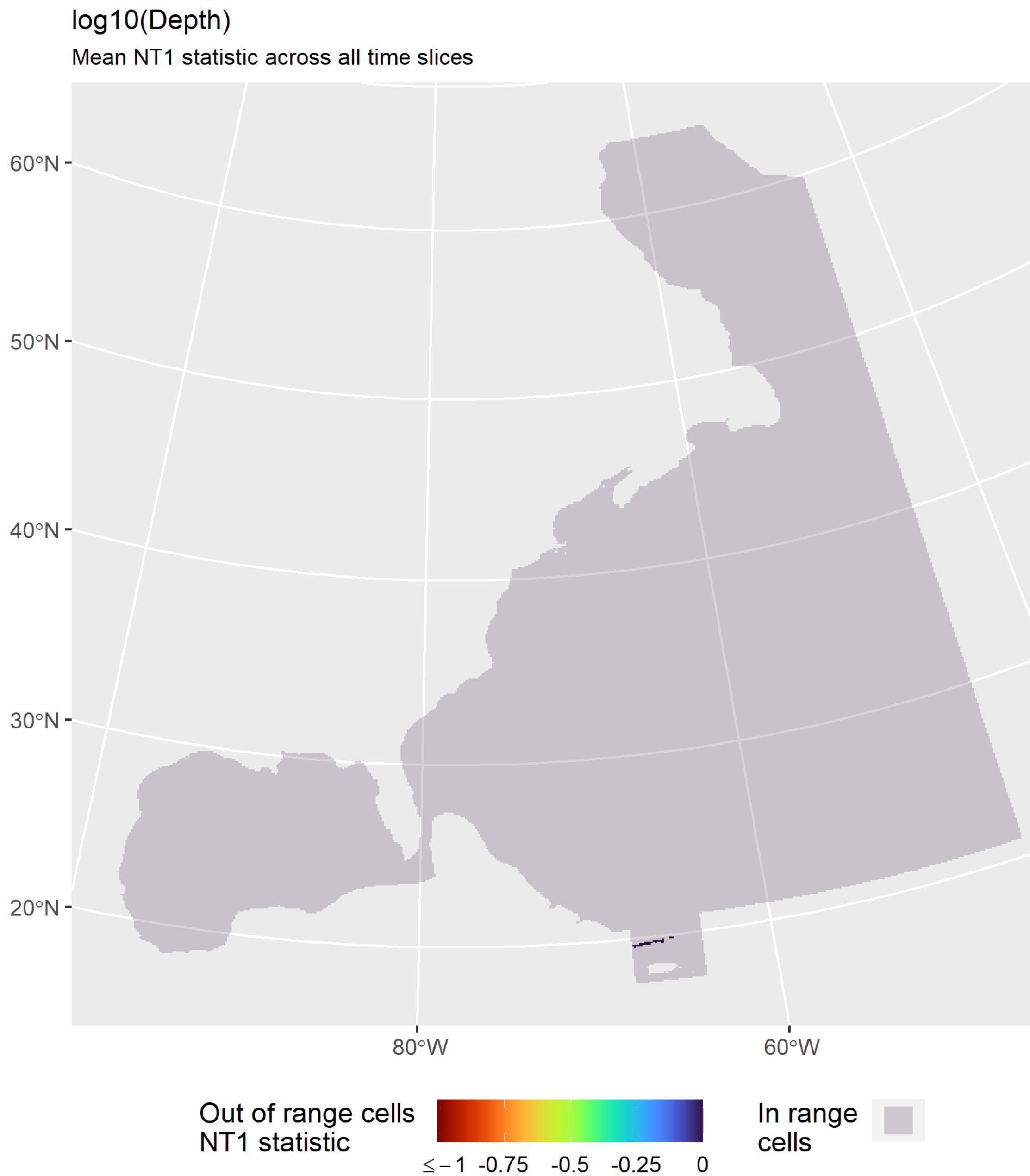


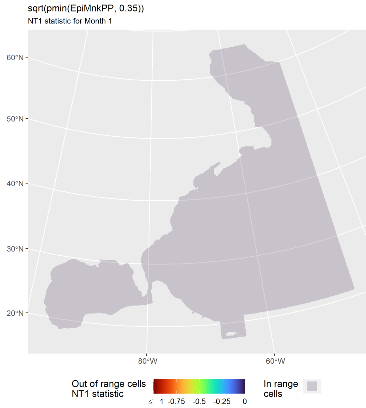
Figure 8: NT1 statistic (Mesgaran et al. (2014)) for static covariates used in the model. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there. Areas within the sampled range appear in gray, indicating it did not occur.

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

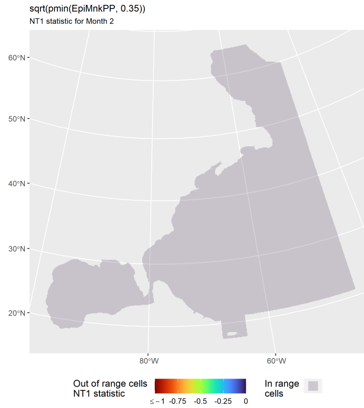
(e) May (f) June (g) July (h) August

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

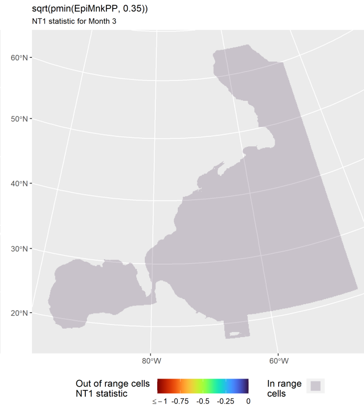
Figure 9: NT1 statistic (Mesgaran et al. (2014)) for the DistToFront1 covariate in the model. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range appear in gray, indicating it did not occur.



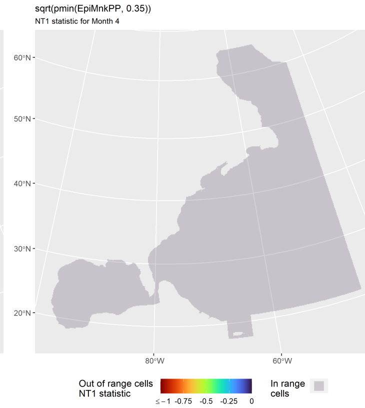
(a) January



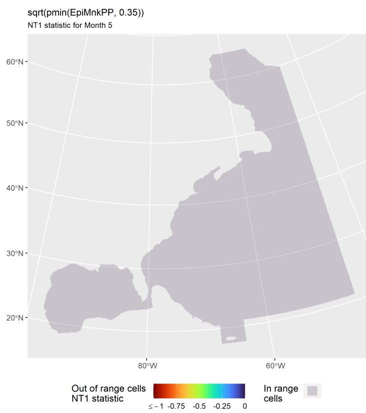
(b) February



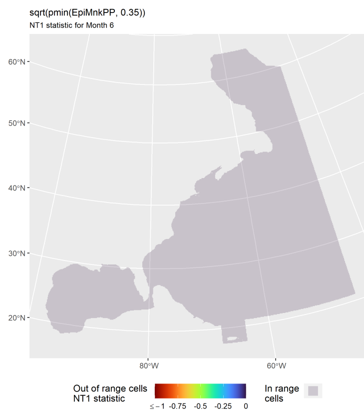
(c) March



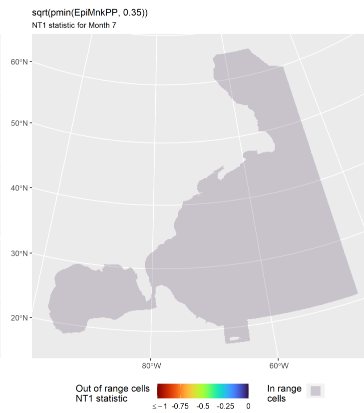
(d) April



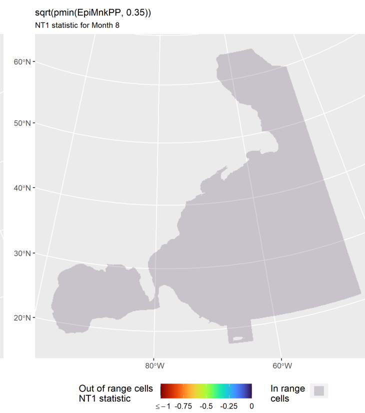
(e) May



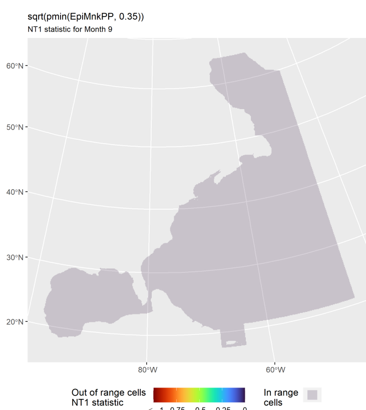
(f) June



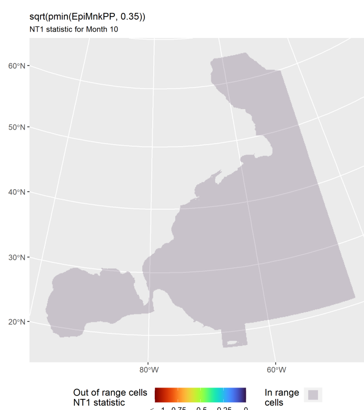
(g) July



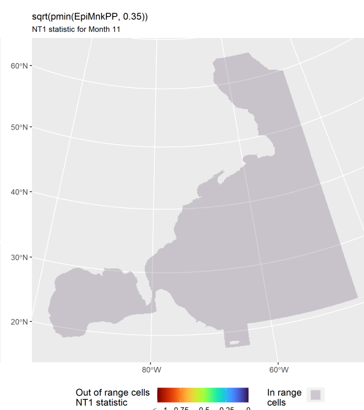
(h) August



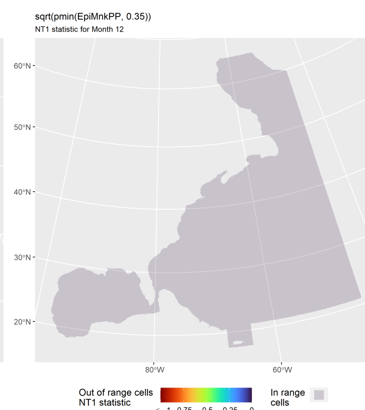
(i) September



(j) October



(k) November



(l) December

Figure 10: NT1 statistic (Mesgaran et al. (2014)) for the EpiMnkPP covariate in the model. 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.

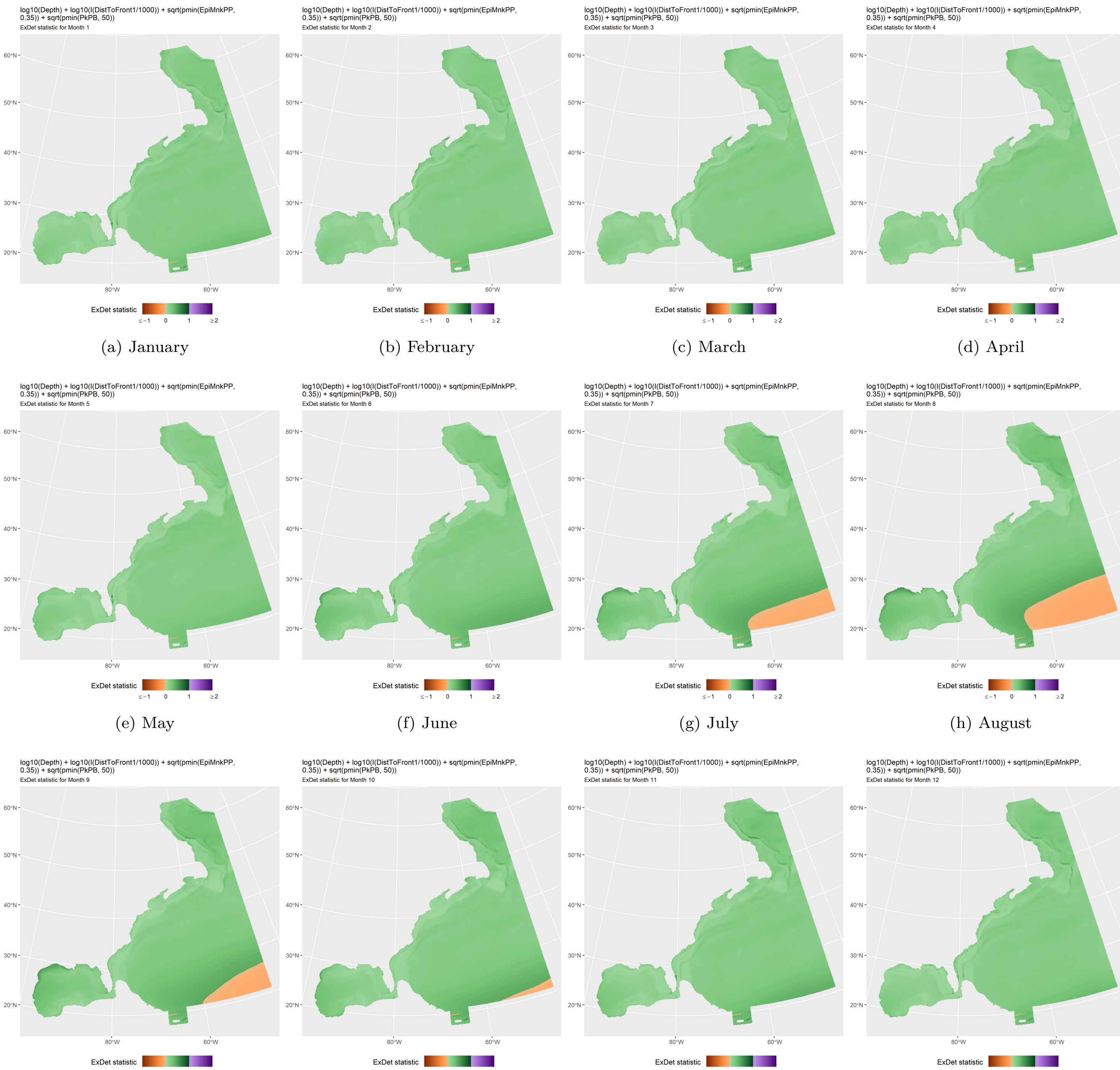
(a) January (b) February (c) March (d) April

(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 PkPB covariate in the model. 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 12: ExDet statistic (Mesgaran et al. (2014)) for all of the covariates used in the model. 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

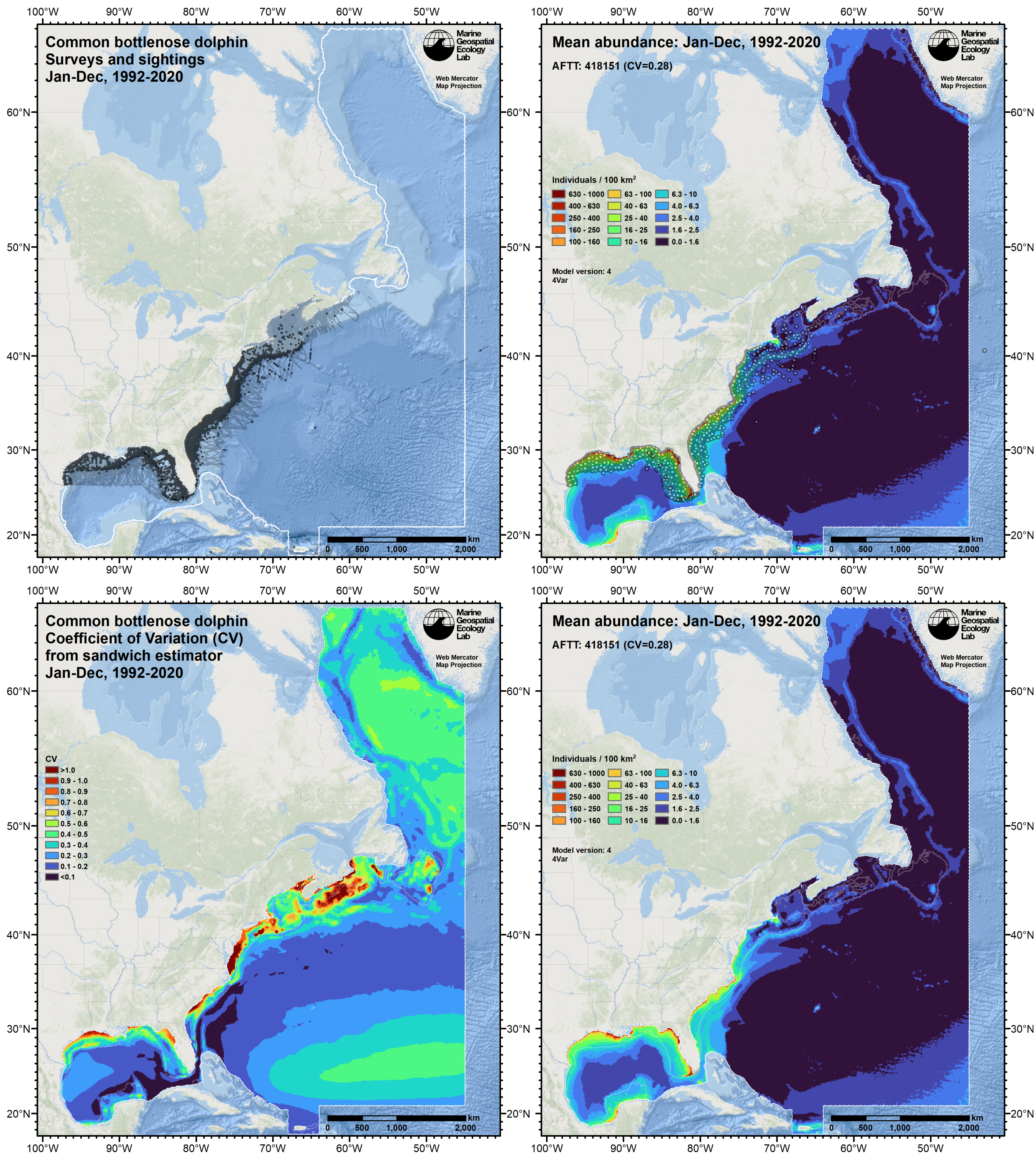


Figure 13: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for the given era. Variance was estimated with the analytic approach given by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

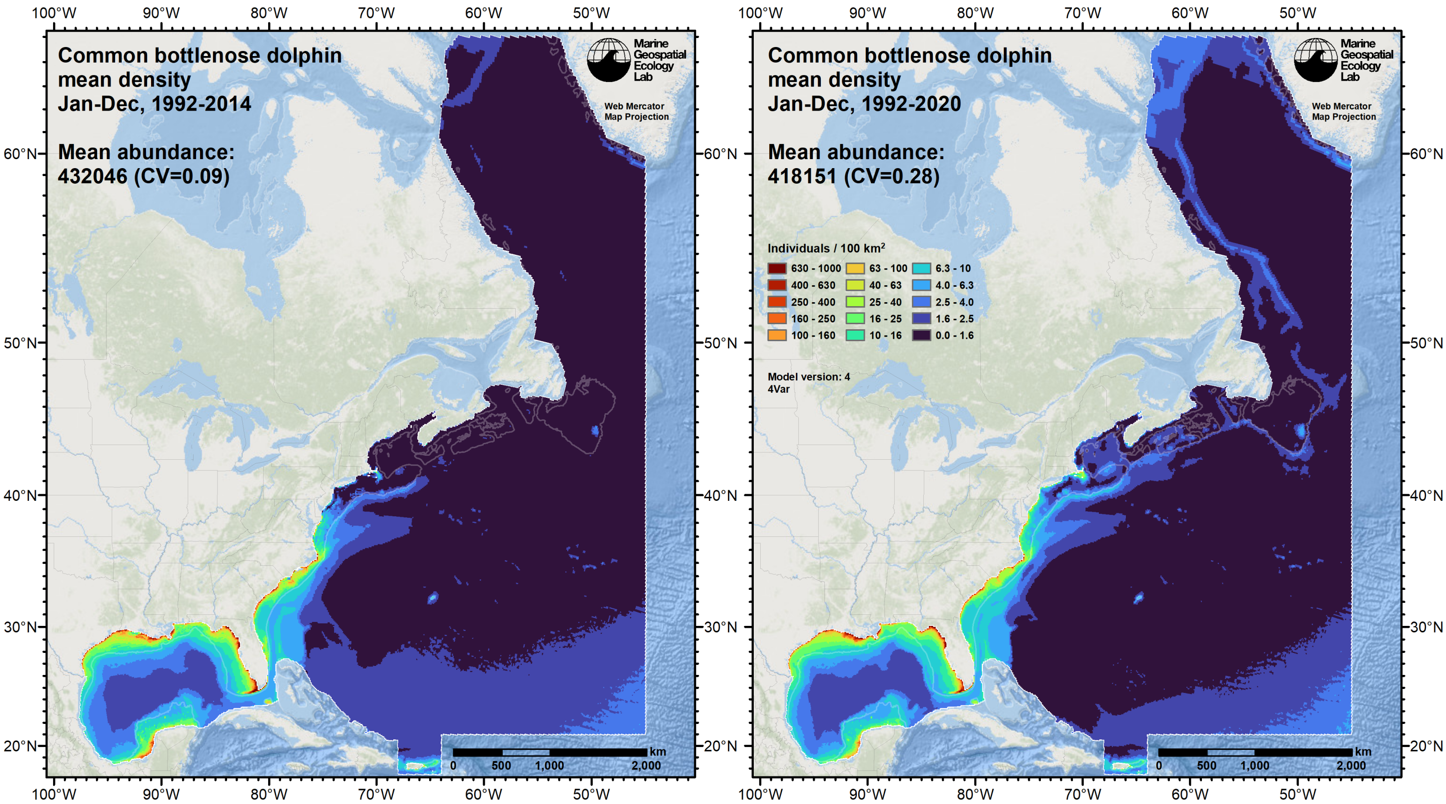


Figure 14: Comparison of the mean density predictions from the previous model (left) released by Mannocci et al. (2017) to those from this model (right). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

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) and Gulf of Mexico (GOM) models be used for the waters they cover, and that the AFTT model be used only for waters outside those regions. See Roberts et al. (2023) for more discussion of the models. The EC and GOM models provide predictions as 12 monthly means, rather than a single year-round mean.

The predictions generally accorded with what has been reported in the literature and strongly resembled the predictions of Mannocci et al. (2017) (Figure 14). Please see Mannocci et al. (2017) for a detailed discussion of the predictions as compared to the literature. The new model estimated about 3% lower abundance than the prior model, but the abundance estimates of the two models were not significantly different statistically. The new model estimated slightly lower density in various areas south of 35 °N and slightly higher density north of it. This apparent northern shift is consistent other recent reports (Chavez-Rosales et al. 2022; Thorne et al. 2022). That said, sightings of bottlenose dolphins are very rare north of southern Newfoundland, and predictions of nonzero density should be viewed skeptically. Systematic surveys of the shelf of eastern Newfoundland and Labrador did not report any sightings (Lawson and Gosselin 2009, 2018), nor did surveys of west Greenland (Hansen and Heide-Jørgensen 2013; Hansen et al. 2019). These surveys were not available for use in this model; future updates would benefit from their inclusion. At the time of this writing, the OBIS-SEAMAP archive (Halpin et al. 2009) did report one sighting along the Labrador shelf at 57.5 °N (https://seamap.env.duke.edu/species/180426).

Multivariate extrapolation analysis (Figure 12) showed that environmental extrapolation was necessary in the southeast corner of the study area in summer, driven by low SST front activity there during these months. We therefore advise caution in this area. Future updates would benefit from the inclusion of surveys of this area (as far as we know, no such surveys exist beyond those we already incorporated).

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