Density Model for Striped Dolphin (*Stenella coeruleoalba*) 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 Striped Dolphin (*Stenella coeruleoalba*) 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 all of the regions used by their analysis: the east coast, Gulf of Mexico, Caribbean, Europe, and the Mid-Atlantic Ridge. We also added trans-Atlantic and eastern Atlantic surveys by R/V Song of the Whale, which spanned the Equator to Iceland. 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	14	990	70.7
NEFSC	AMAPPS	2010-2019	83	13	461	35.5
NEFSC	NARWSS	2003-2016	380	0	0	
NEFSC	Pre-AMAPPS	1999-2008	45	1	130	130.0
SEFSC	AMAPPS	2010-2020	112	1	110	110.0
SEFSC	GOMEX92-96	1992-1996	27	0	0	
SEFSC	GulfCet I	1992-1994	50	8	370	46.2
SEFSC	GulfCet II	1996-1998	22	7	467	66.7
SEFSC	GulfSCAT 2007	2007-2007	18	0	0	
SEFSC	MATS	2002-2005	27	0	0	
U. La Rochelle	REMMOA	2008-2017	39	0	0	
U. La Rochelle	SAMM	2011-2012	61	12	181	15.1
UNCW	MidA Bottlenose	2002-2002	15	0	0	
UNCW	Navy Cape Hatteras	2011-2017	34	7	1,021	145.9
UNCW	Navy Jacksonville	2009-2017	92	0	0	
UNCW	Navy Norfolk Canyon	2015-2017	14	12	1,614	134.5
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	**1,236**	**75**	**5,344**	**71.3**
Shipboard Surveys						
CODA	CODA	2007-2007	10	22	455	20.7
IMR	MAR-ECO	2004-2004	2	8	86	10.8
MCR	SOTW Visual	2004-2019	31	16	506	31.6
NEFSC	AMAPPS	2011-2016	15	174	6,881	39.5
NEFSC	Pre-AMAPPS	1995-2007	17	125	6,786	54.3
NJDEP	NJEBS	2008-2009	14	0	0	
SCANS-II	SCANS-II	2005-2005	18	3	69	23.0
SEFSC	AMAPPS	2011-2016	16	11	1,554	141.3
SEFSC	GOM Oceanic CetShip	1992-2001	49	49	2,305	47.0
SEFSC	GOM Shelf CetShip	1994-2001	10	6	371	61.8
SEFSC	Pre-AMAPPS	1992-2006	33	74	7,018	94.8
SEFSC	Pre-GoMMAPPS	2003-2009	19	19	836	44.0
SEFSC	SEFSC Caribbean	1995-2000	8	1	140	140.0
		Total	**242**	**508**	**27,007**	**53.2**
		Grand Total	**1,477**	**583**	**32,351**	**55.5**

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.
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
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)
CODA	Cetacean Offshore Distribution and Abundance in the European Atlantic	Hammond et al. (2009)
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	
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)
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)

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

Program	Description	References
SAMM	Suivi Aérien de la Mégafaune Marine	Pettex et al. (2014)
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 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 chlorophyll concentration, depth, distance to SST fronts, and micronekton productivity. 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 low chlorophyll concentration (Figure 9) or with very few SST fronts (Figure 10), as occurs in the southeast part of the AFTT.

2.1 Final Model

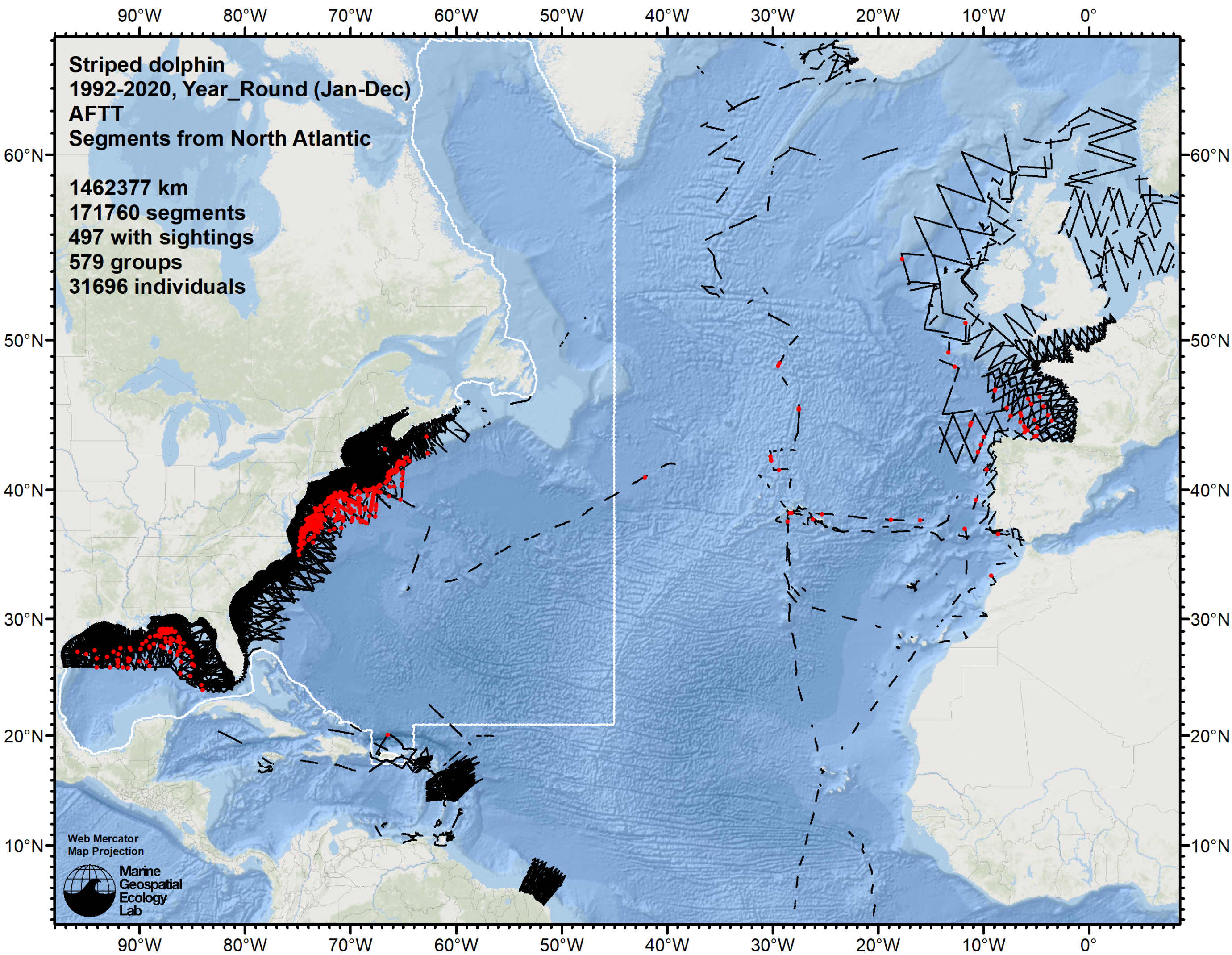
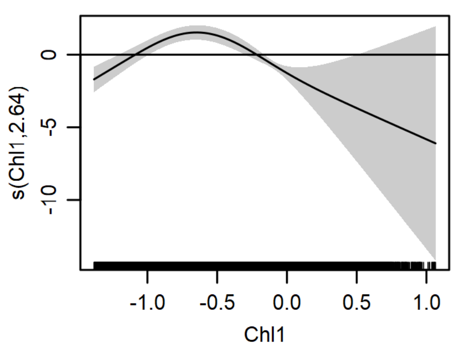


Figure 1: Survey segments (black lines) used to fit the model. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

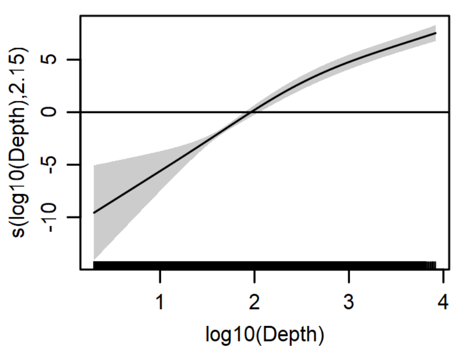
Statistical output for this model:

```
Family: Tweedie(p=1.336)
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(log10(Depth),
```

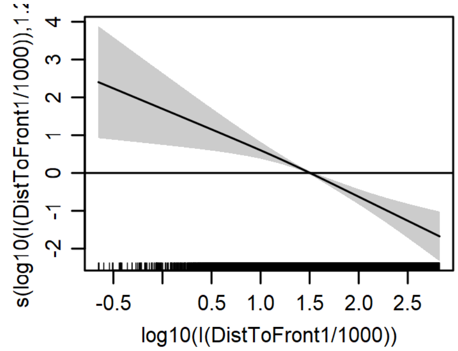
```
    bs = "ts", k = 4) + s(log10(I(DistToFront1/1000)), bs = "ts",
    k = 4) + s(Chl1, bs = "ts", k = 4) + s(sqrt(pmin(EpiMnkPP,
    0.35)), bs = "ts", k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -22.8505     0.3681  -62.07   <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))                2.152      3 198.64  <2e-16 ***
s(log10(I(DistToFront1/1000))) 1.209      3  12.91  <2e-16 ***
s(Chl1)                        2.640      3  32.88  <2e-16 ***
s(sqrt(pmin(EpiMnkPP, 0.35)))  1.592      3  30.46  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0124   Deviance explained = 44.2%
-REML = 5162.2  Scale est. = 105.25    n = 171658

Method: REML   Optimizer: outer newton
full convergence after 14 iterations.
Gradient range [-0.002488932,0.002439777]
(score 5162.217 & scale 105.2538).
Hessian positive definite, eigenvalue range [0.5738831,1636.118].
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 2.15    0.74  <2e-16 ***
s(log10(I(DistToFront1/1000))) 3.00 1.21    0.87   0.035 *
s(Chl1)                        3.00 2.64    0.83   0.025 *
s(sqrt(pmin(EpiMnkPP, 0.35)))  3.00 1.59    0.86   0.030 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



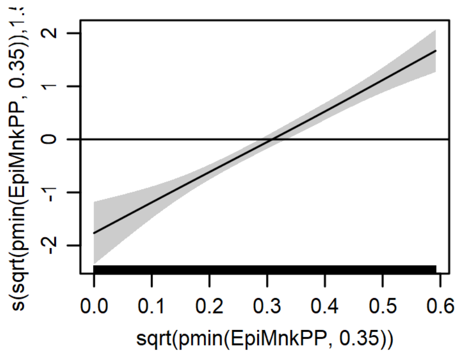
(a) Climatological chlorophyll a concentration ($\log_{10}$ mg m^{-3})



(b) Seafloor depth (m)



(c) Climatological distance to SST front (km)



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

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 (Chl1 was already provided in $\log_{10}$ scale by the covariate developer). *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
Chl1	Climatological mean monthly merged SeaWiFS/Aqua/MERIS/VIIRS chlorophyll-a concentration ($\log_{10}$ mg m^{-3}) from GSM (Maritorena et al. (2010)), smoothed with 3D Gaussian smoother to reduce daily data loss to $< 10\%$
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))

2.2 Diagnostic Plots

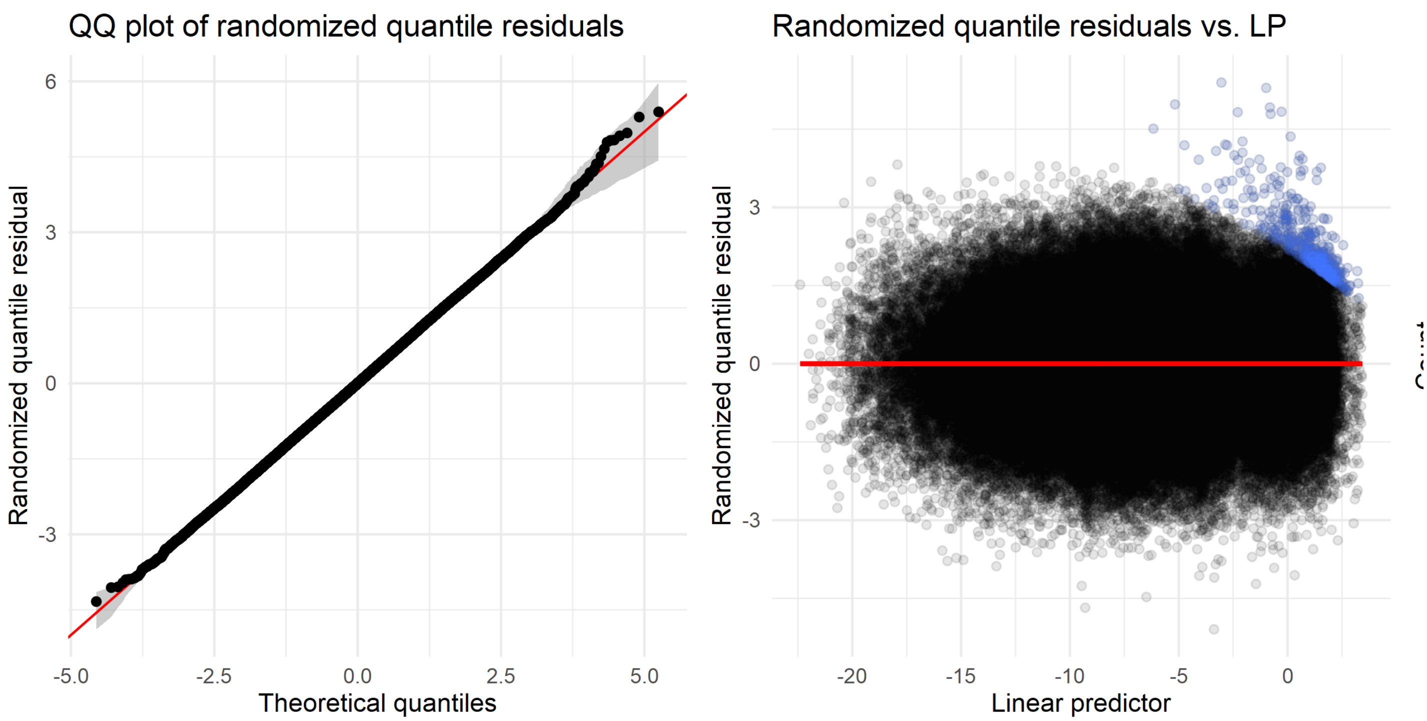


Figure 3: Residual plots for the final model.

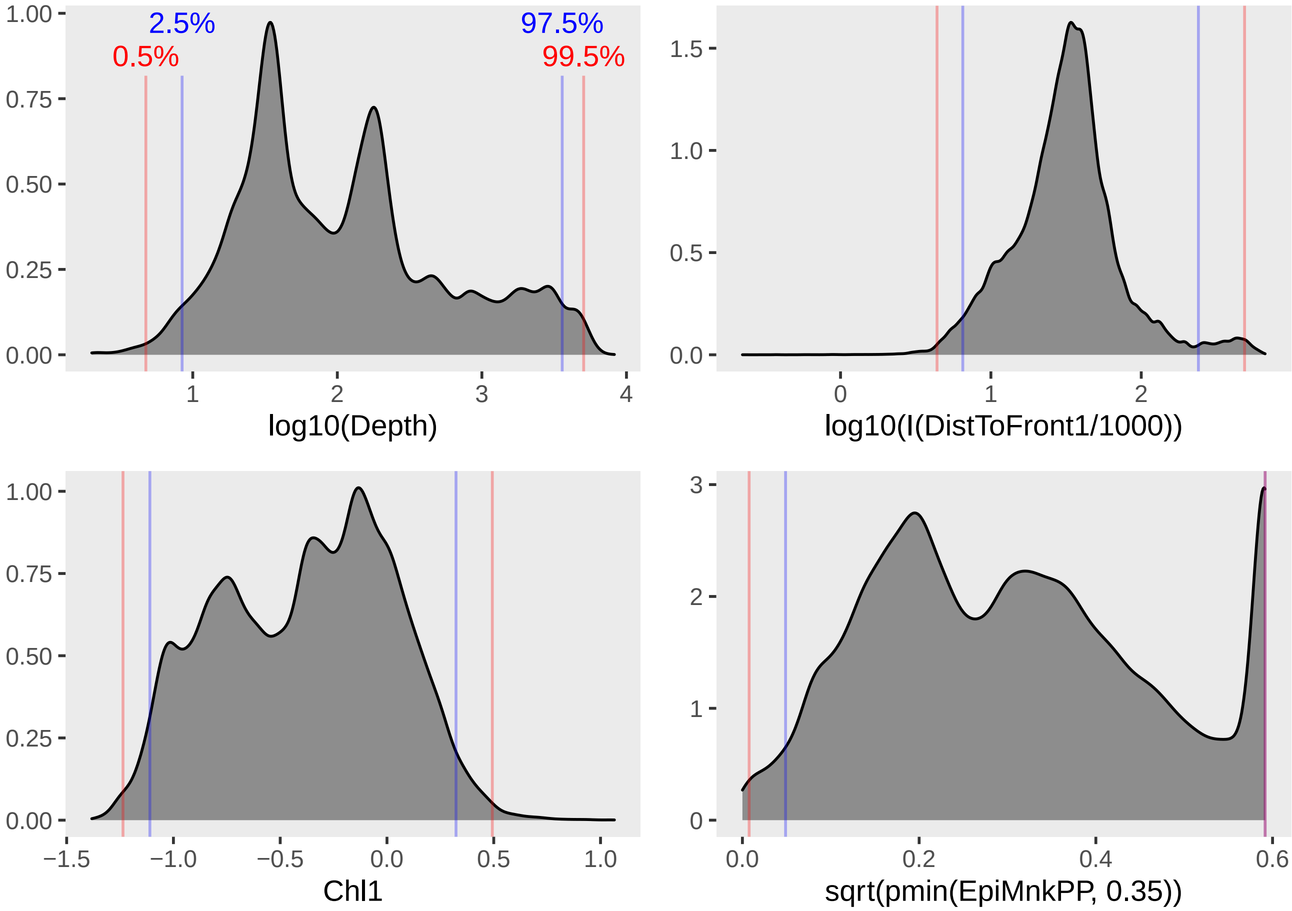


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red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

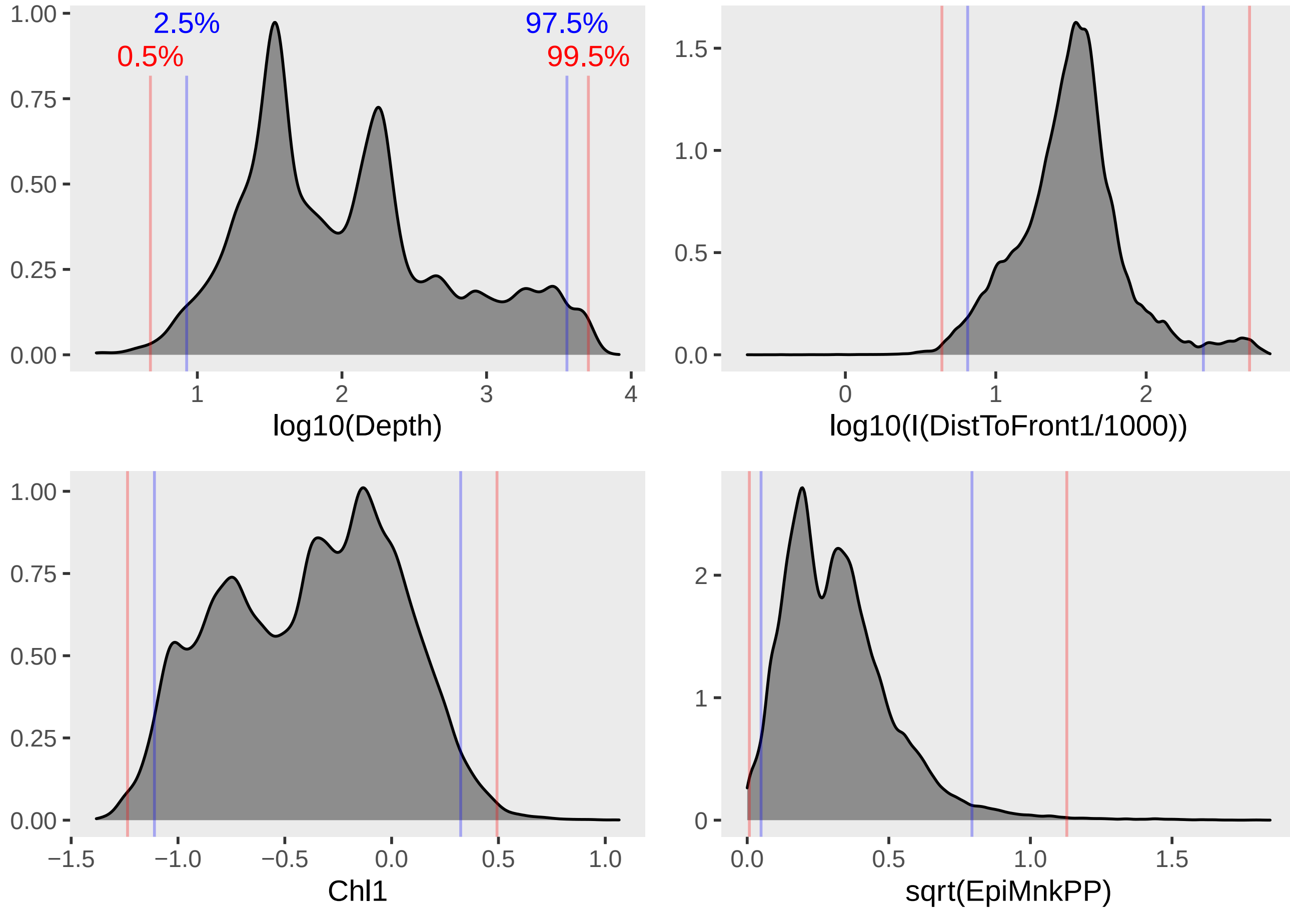


Figure 5: Density histograms shown in Figure 4 replotted without Winsorization, to show the full range of sampling represented by survey segments.

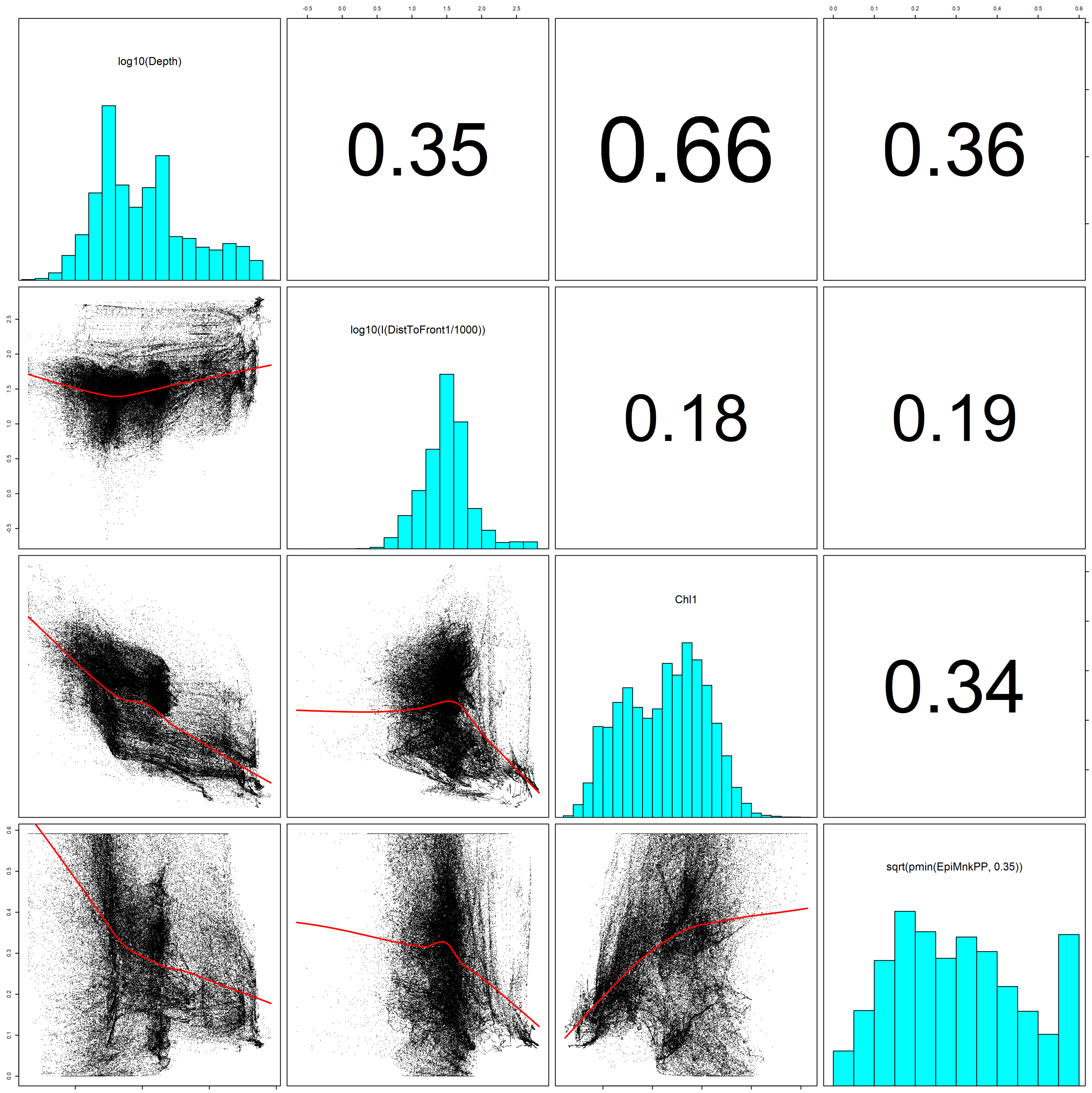


Figure 6: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and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

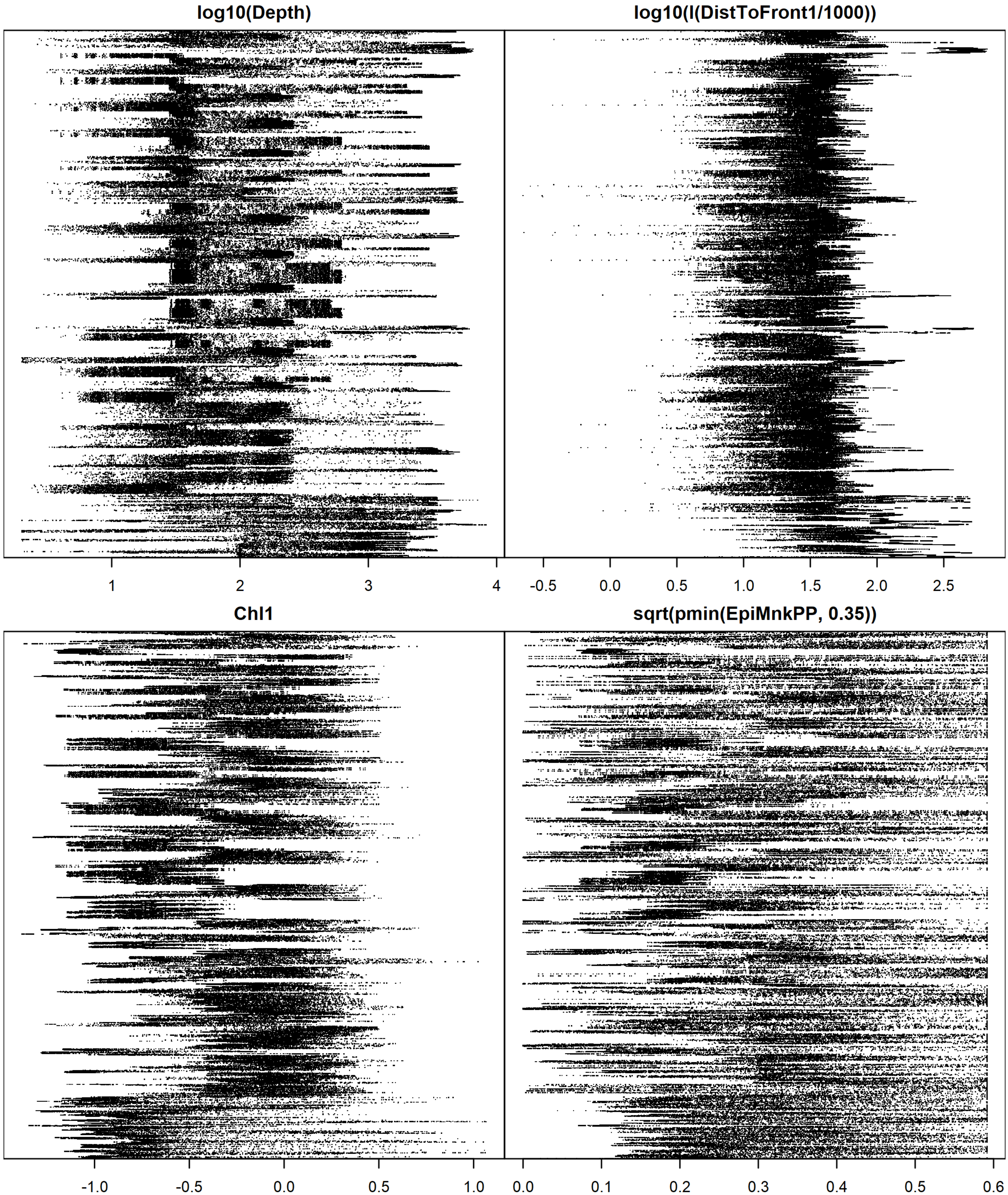


Figure 7: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized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

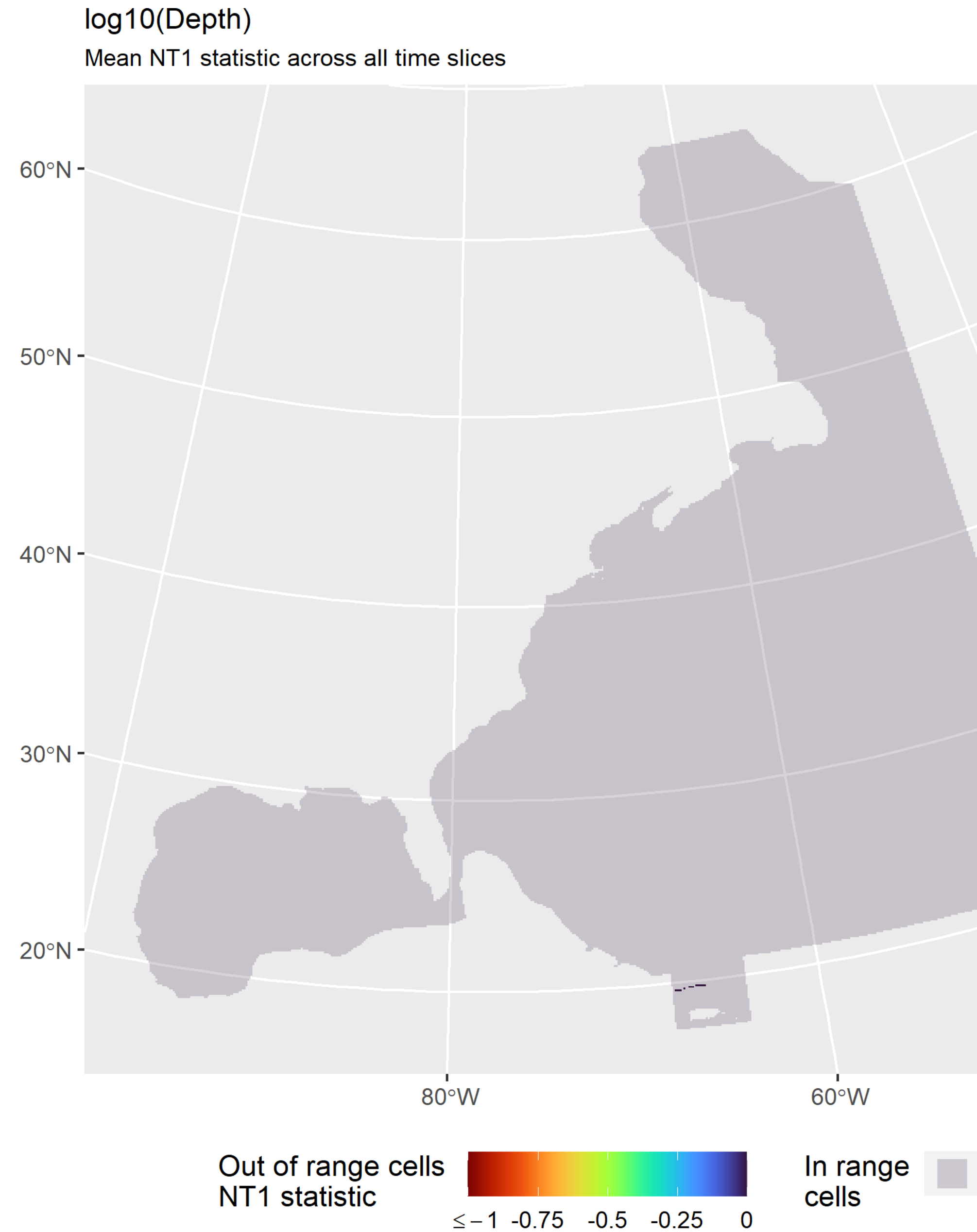
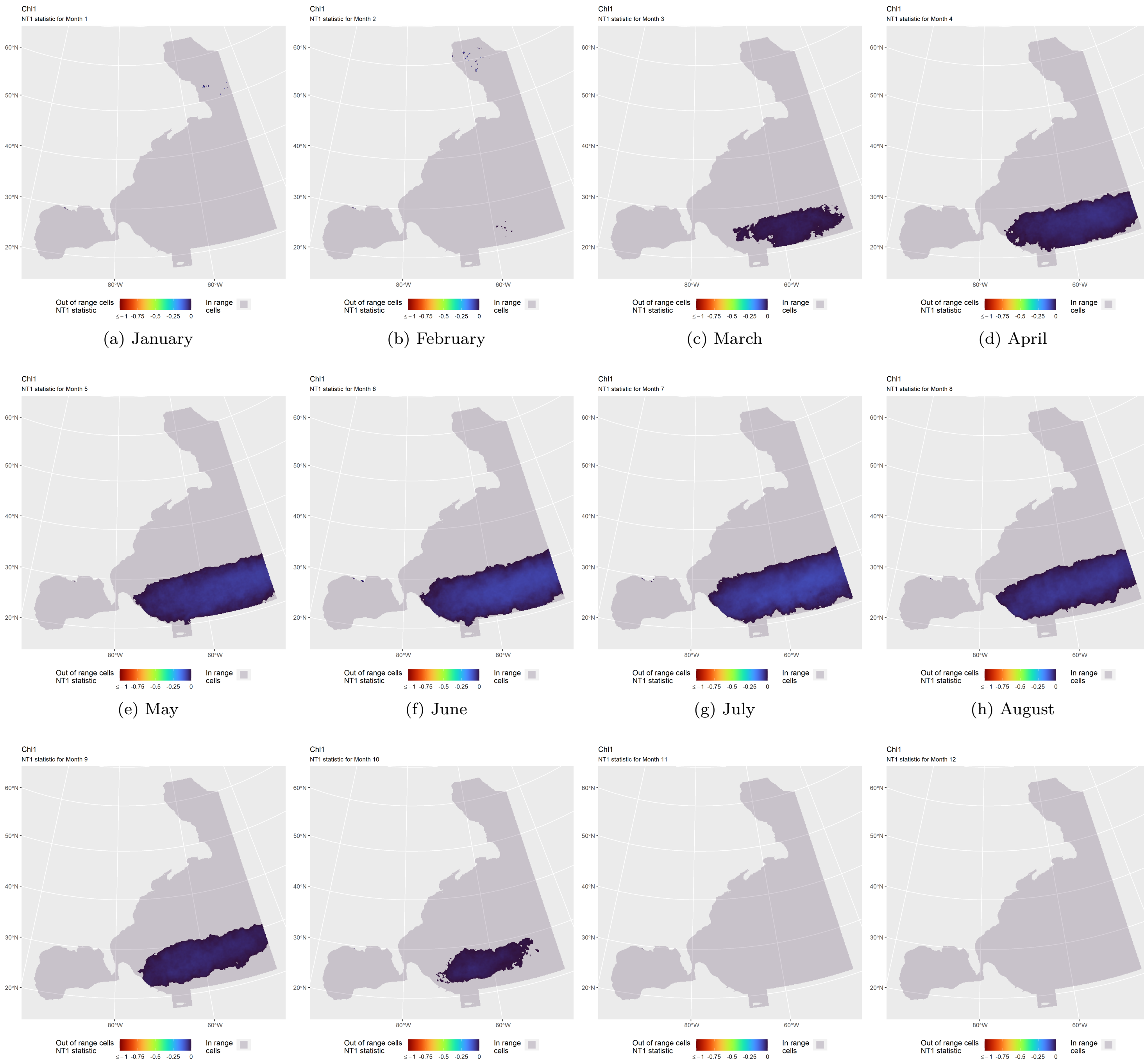


Figure 8: NT1 statistic (Mesgaran et al. (2014)) for static covariates used in the model. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there. Areas within the sampled range appear in gray, indicating it did not occur.

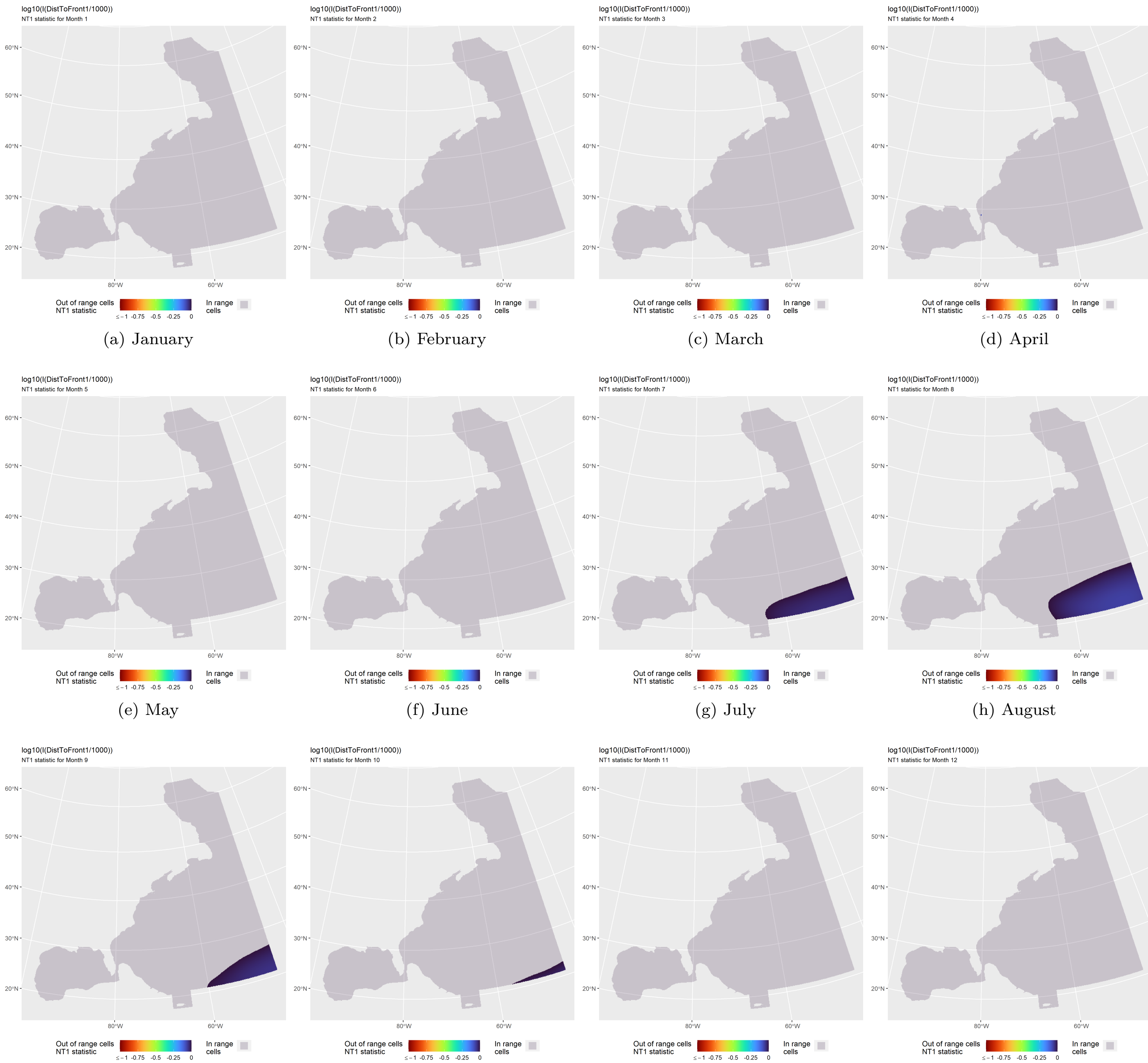


(a) January (b) February (c) March (d) April

(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 Chl1 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.

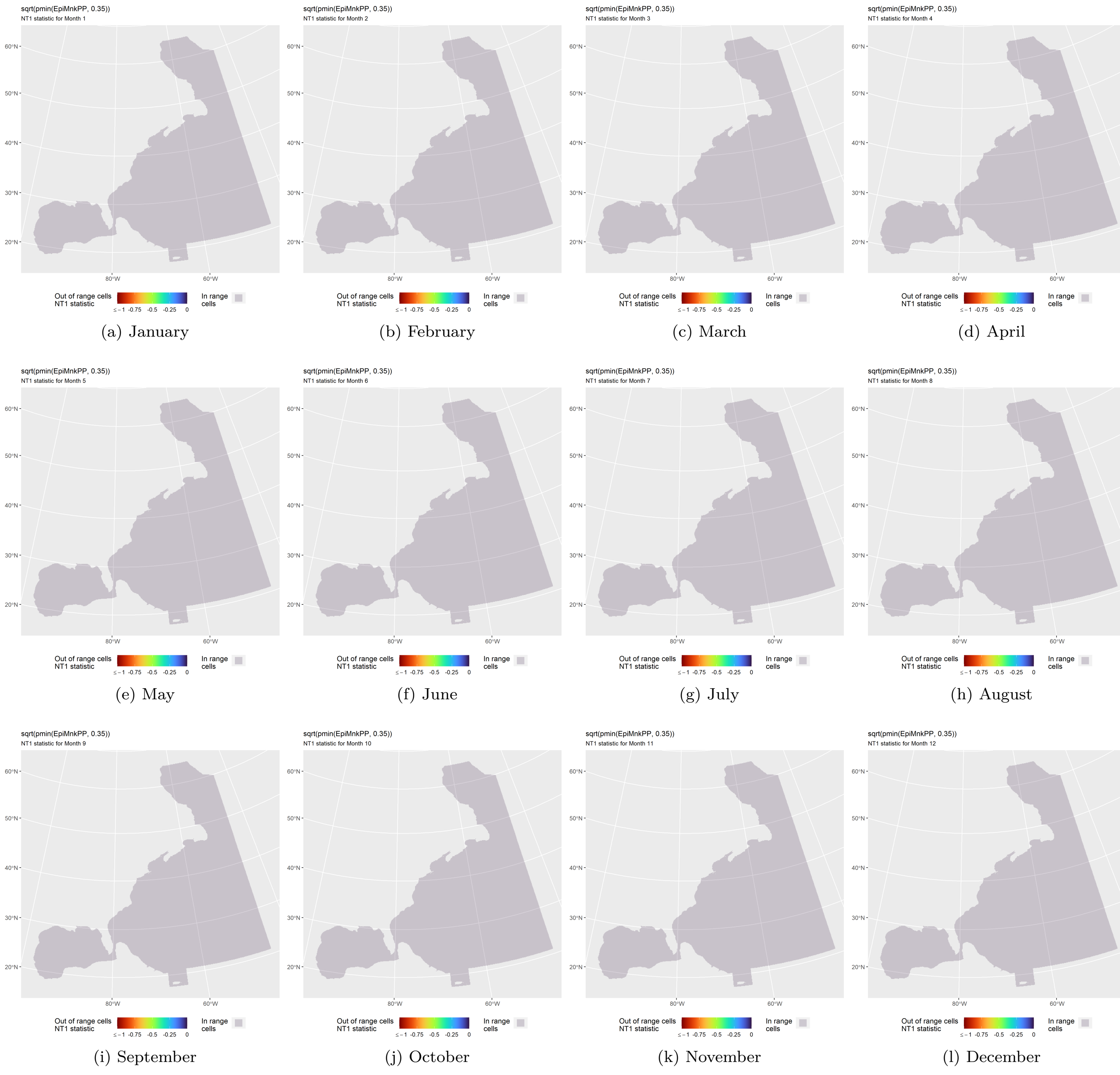


(a) January (b) February (c) March (d) April

(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 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.



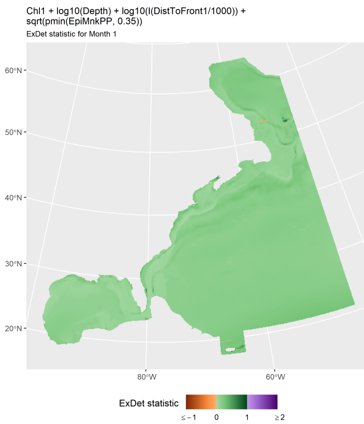
(a) January (b) February (c) March (d) April

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

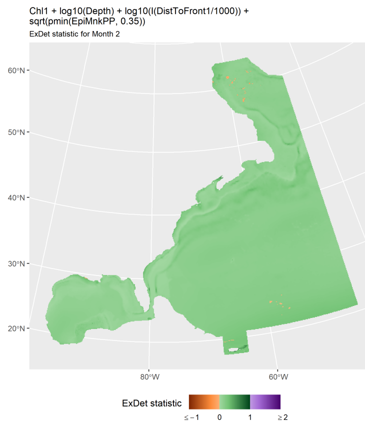
(i) September (j) October (k) November (l) December

Figure 11: 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.

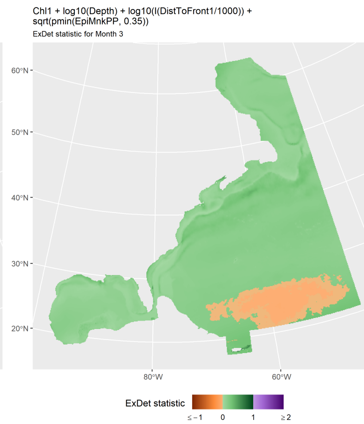
2.3.2 Multivariate Extrapolation



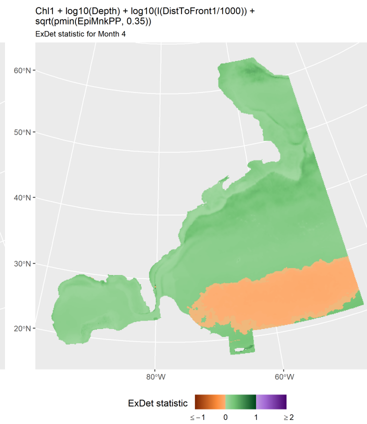
(a) January



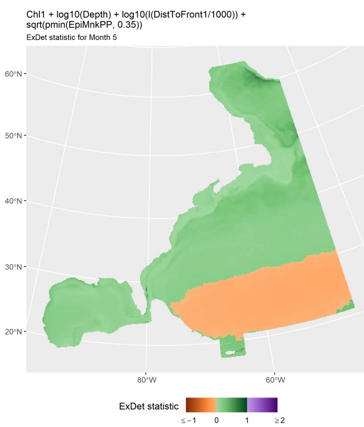
(b) February



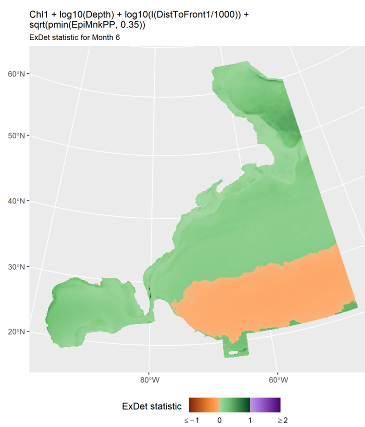
(c) March



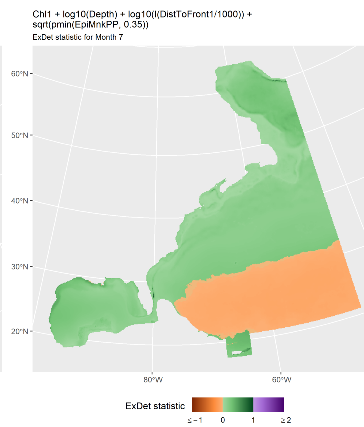
(d) April



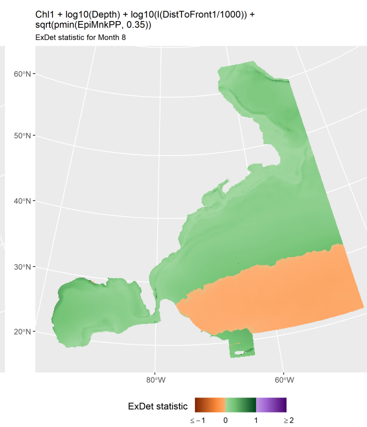
(e) May



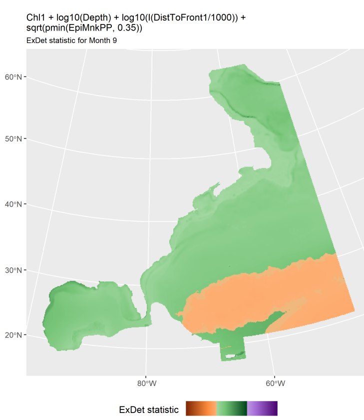
(f) June



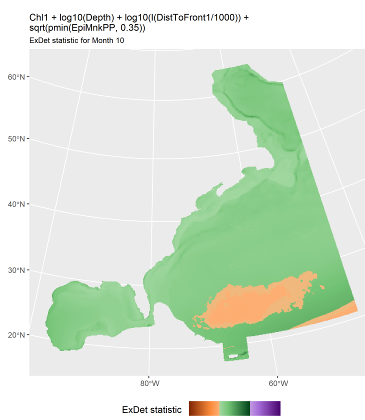
(g) July



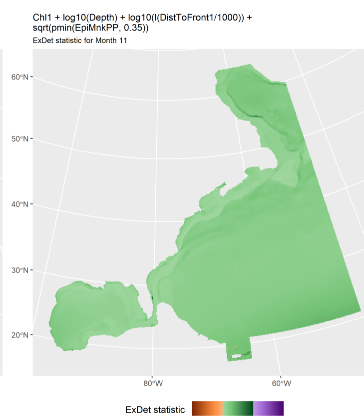
(h) August



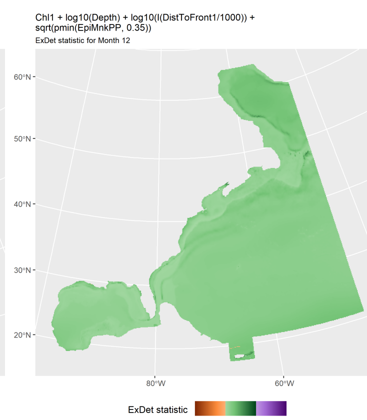
(i) September



(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

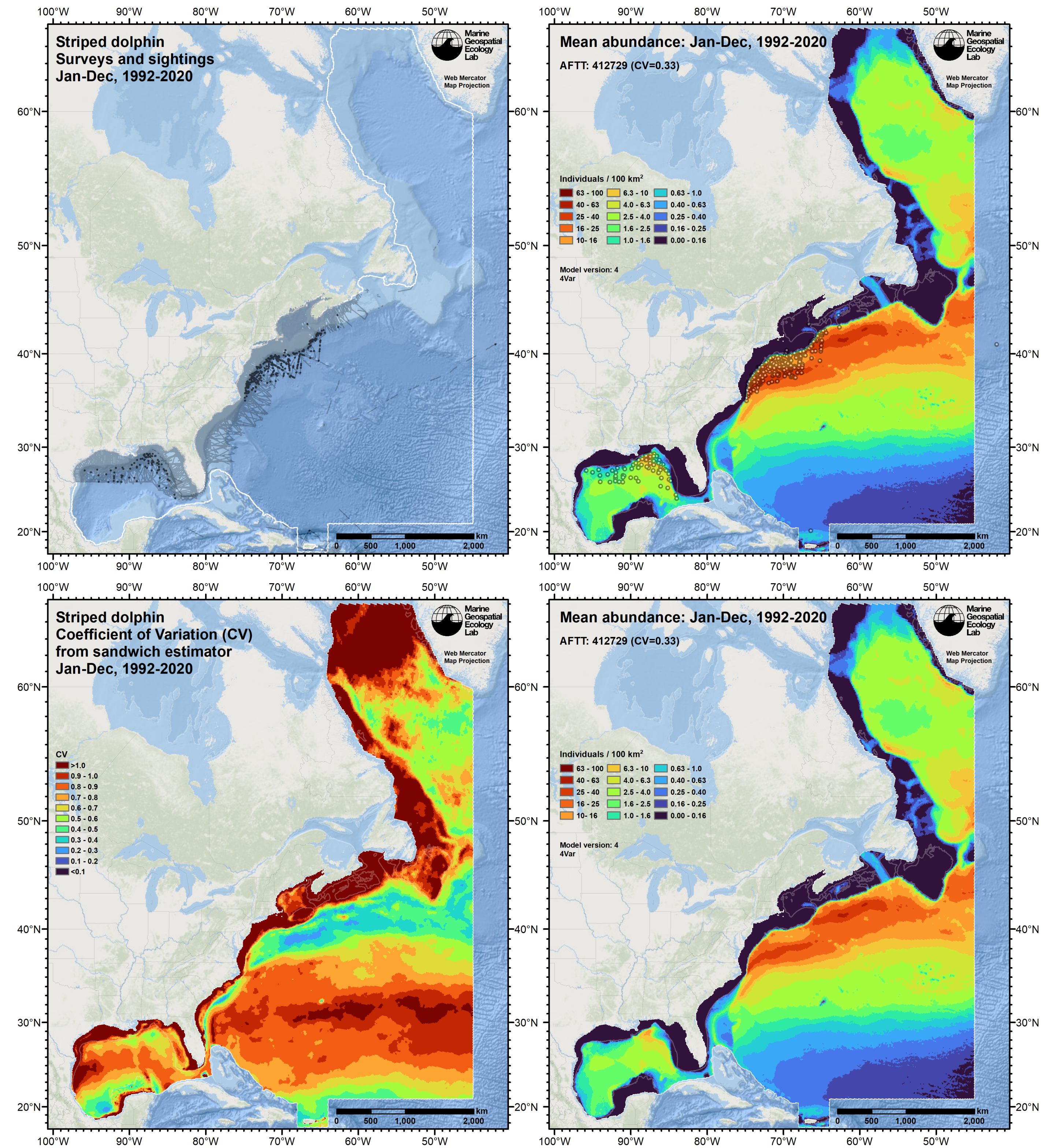


Figure 13: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for the given era. Variance was estimated with the analytic approach given by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

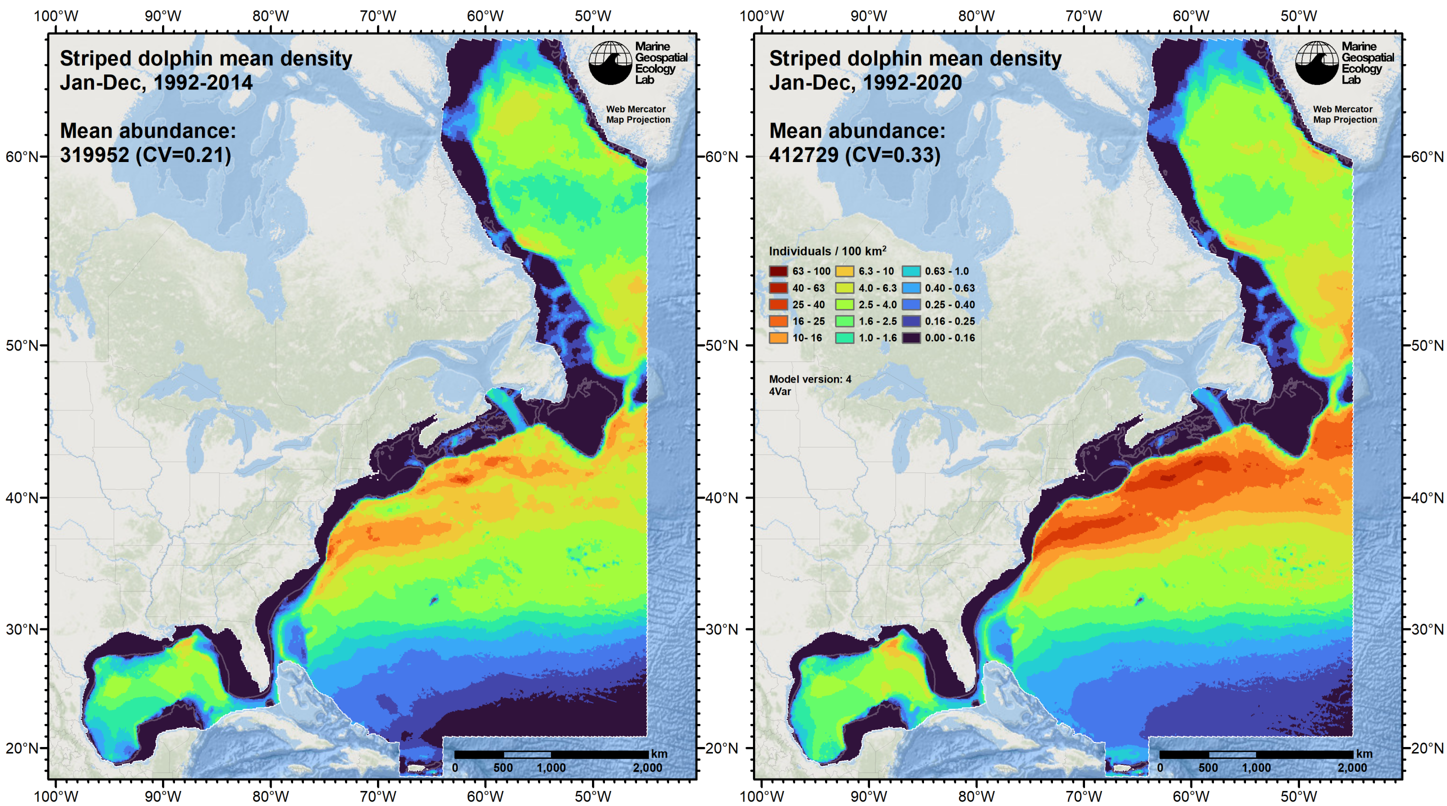


Figure 14: Comparison of the mean density predictions from the previous model (left) released by Mannocci et al. (2017) to those from this model (right). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

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 model's predictions generally accorded with what has been reported in the literature and largely resembled the predictions of Mannocci et al. (2017) (Figure 14). We caution that, like Mannocci et al.'s model, our model predicted moderate to high density in off-shelf waters east of Newfoundland up through the Labrador Sea. We consider this prediction to be an overestimate. Aerial surveys in 2007 and 2015 of northern Newfoundland and southern Labrador (Lawson and Gosselin 2009, 2018) and of western Greenland (Hansen and Heide-Jørgensen 2013; Hansen et al. 2019) did not report any sightings. These surveys of Canada and Greenland were not available for use in this model; future updates would benefit from their inclusion.

The new model estimated about 29% higher abundance than the prior model. In this region, striped dolphins occur mainly beyond the continental shelf, which was surveyed mainly by ship. The new model used a stronger perception bias correction for shipboard sightings of groups of 1-20 animals than Mannocci et al.'s model. This could explain part of the difference but all of it. Striped dolphins occur in large groups (Table 1), and for groups of more than 20 animals, the same weak correction ($g_{0P} = 0.97$) was applied in both models. Our best guess is that the additional data introduced in the new model influenced density higher. The area of greatest change was north of the Gulf Stream between Cape Hatteras and the Flemish Cap. This area was surveyed mainly by NEFSC. The old model only utilized the Pre-AMAPPS surveys, which reported 125 sightings during 17,000 km effort. The new model incorporated the AMAPPS surveys, which reported 174 sightings on 15,000 km effort. Although the two survey programs did not cover exactly the same area, they did roughly coincide, and the markedly higher sighting rate during AMAPPS likely influenced density to be higher in the new model.

Extrapolation analysis (Figure 12) showed that univariate environmental extrapolation was necessary in the southern half of the Atlantic waters of the study area (e.g. the Sargasso Sea) except in late fall and winter, driven by a lack of surveying in waters with low chlorophyll concentration or low SST front activity. We therefore advise caution in these areas. Future updates would benefit from the inclusion of survey data from these areas (no such data were available for our use in this analysis).

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