Density Model for Short-Beaked Common Dolphin (*Delphinus delphis*) 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:

Roberts JJ, Yack TM, Halpin PN (2022) Density Model for Short-Beaked Common Dolphin (*Delphinus delphis*) for the U.S. Navy's AFTT Phase IV Study Area, Version 3, 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
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 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	47	8,736	185.9
NEFSC	AMAPPS	2010-2019	83	817	12,948	15.8
NEFSC	NARWSS	2003-2016	380	607	16,412	27.0
NEFSC	Pre-AMAPPS	1999-2008	45	237	5,985	25.3
SEFSC	AMAPPS	2010-2020	112	177	8,576	48.5
SEFSC	GOMEX92-96	1992-1996	27	0	0	
SEFSC	GulfCet I	1992-1994	50	0	0	
SEFSC	GulfCet II	1996-1998	22	0	0	
SEFSC	GulfSCAT 2007	2007-2007	18	0	0	
SEFSC	MATS	2002-2005	27	2	3,000	1,500.0
U. La Rochelle	REMMOA	2008-2017	39	0	0	
U. La Rochelle	SAMM	2011-2012	61	798	15,555	19.5
UNCW	MidA Bottlenose	2002-2002	15	5	64	12.8
UNCW	Navy Cape Hatteras	2011-2017	34	27	7,614	282.0
UNCW	Navy Jacksonville	2009-2017	92	0	0	
UNCW	Navy Norfolk Canyon	2015-2017	14	49	5,785	118.1
UNCW	Navy Onslow Bay	2007-2011	49	1	20	20.0
UNCW	SEUS NARW EWS	2005-2008	106	26	496	19.1
VAMSC	MD DNR WEA	2013-2015	15	22	169	7.7
VAMSC	Navy VACAPES	2016-2017	18	8	303	37.9
VAMSC	VA CZM WEA	2012-2015	19	22	333	15.1
		Total	**1,236**	**2,845**	**85,996**	**30.2**
Shipboard Surveys						
CODA	CODA	2007-2007	10	56	1,205	21.5
IMR	MAR-ECO	2004-2004	2	16	233	14.6
MCR	SOTW Visual	2004-2019	31	156	1,765	11.3
NEFSC	AMAPPS	2011-2016	15	334	14,096	42.2
NEFSC	Pre-AMAPPS	1995-2007	17	166	6,117	36.8
NJDEP	NJEBS	2008-2009	14	19	241	12.7
SCANS-II	SCANS-II	2005-2005	18	72	1,473	20.5
SEFSC	AMAPPS	2011-2016	16	2	63	31.5
SEFSC	GOM Oceanic CetShip	1992-2001	49	0	0	
SEFSC	GOM Shelf CetShip	1994-2001	10	0	0	
SEFSC	Pre-AMAPPS	1992-2006	33	40	5,064	126.6
SEFSC	Pre-GoMMAPPS	2003-2009	19	0	0	
SEFSC	SEFSC Caribbean	1995-2000	8	0	0	
		Total	**242**	**861**	**30,257**	**35.1**
		Grand Total	**1,477**	**3,706**	**116,253**	**31.4**

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 distance to SST fronts, the standard deviation of sea surface height anomaly, slope of the seafloor, and, initially, chlorophyll concentration. The resulting model predicted extreme densities in northern waters off Newfoundland, Labrador, and west Greenland. Total abundance was nearly double that of Mannocci et al. To avoid this unrealistic result, we switched to Mannocci's second-ranked model, which included primary productivity instead of chlorophyll concentration. The resulting relationships for the first three covariates (Figure 2) generally resembled those of Mannocci's model. The relationship for primary productivity was hump-shaped, indicating the highest boost to density at medium and high productivity values, with a sharp drop-off at the highest values, corresponding to inshore waters. Model predictions are shown in Section 3 and discussed in Section 4. 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

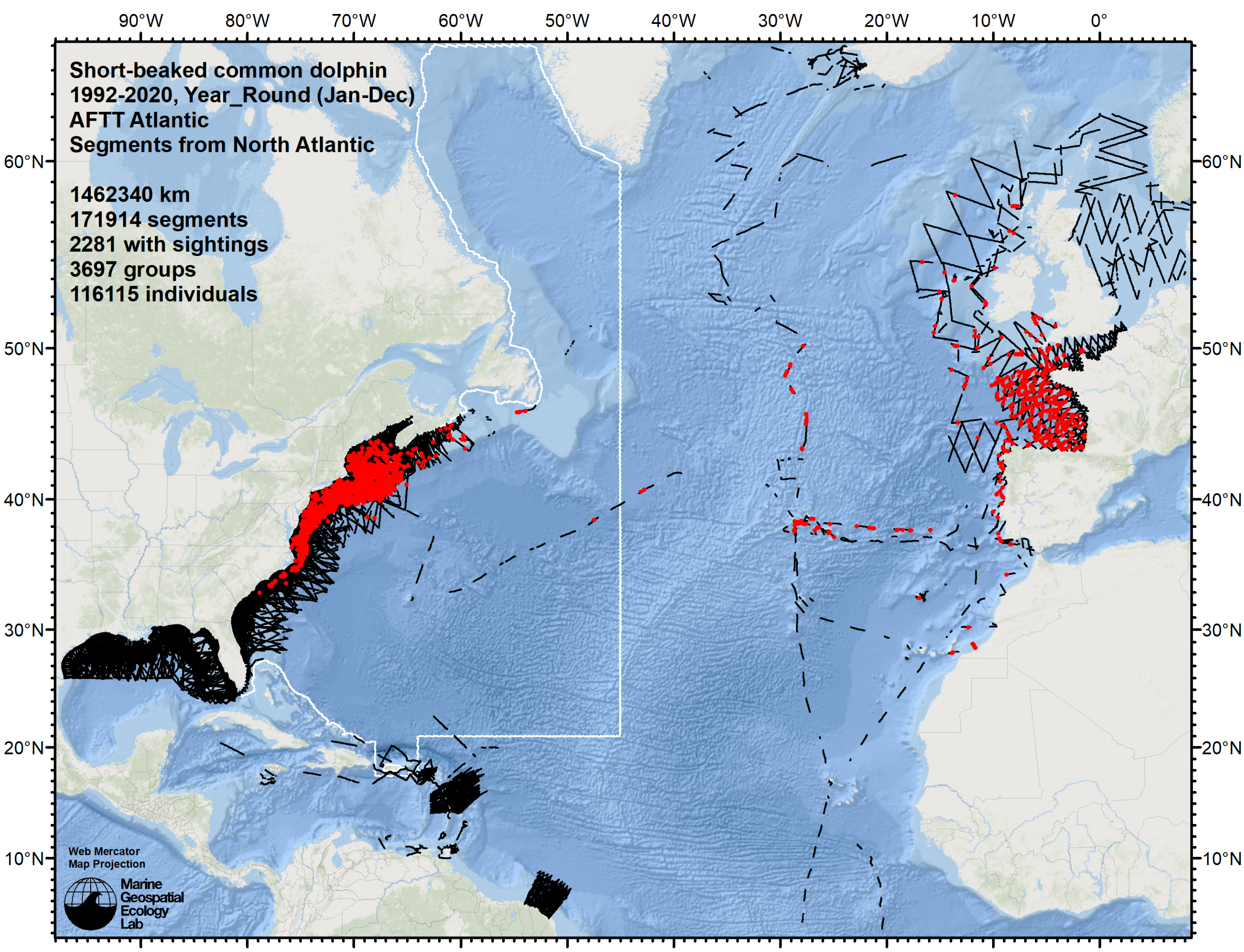
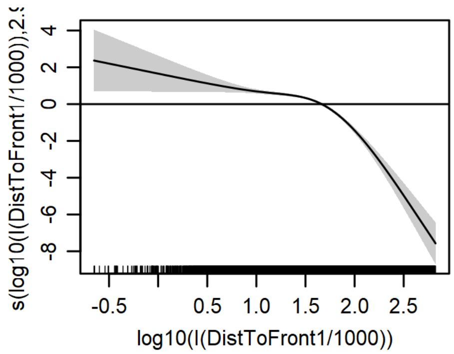


Figure 1: Survey segments (black lines) used to fit the model for the region AFTT Atlantic. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

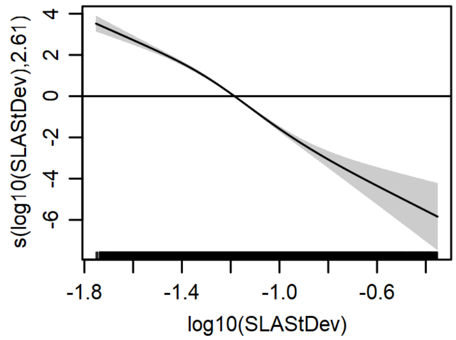
Statistical output for this model:

```
Family: Tweedie(p=1.545)
```

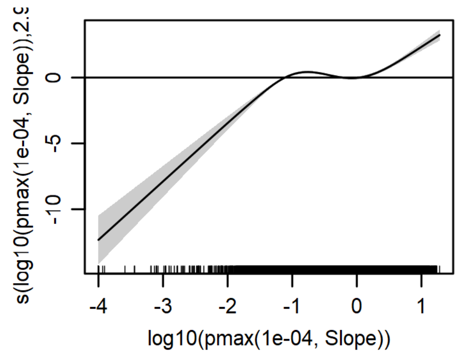
```
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(log10(pmax(1e-04,
    Slope)), bs = "ts", k = 4) + s(log10(pmax(300, VGPM)), bs = "ts",
    k = 4) + s(log10(I(DistToFront1/1000)), bs = "ts", k = 4) +
    s(log10(SLAStDev), bs = "ts", k = 4)

Parametric coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -17.56824    0.04084  -430.1   <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(pmax(1e-04, Slope)))   2.979      3 114.04  <2e-16 ***
s(log10(pmax(300, VGPM)))      2.958      3  70.77  <2e-16 ***
s(log10(I(DistToFront1/1000))) 2.929      3 114.66  <2e-16 ***
s(log10(SLAStDev))             2.613      3 329.15  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  -0.0316   Deviance explained = 29.4%
-REML =  22598  Scale est. = 114.96    n = 171812

Method: REML   Optimizer: outer newton
full convergence after 10 iterations.
Gradient range [-0.01216603,0.01106526]
(score 22597.69 & scale 114.9606).
Hessian positive definite, eigenvalue range [0.9932233,6265.554].
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(pmax(1e-04, Slope)))   3.00 2.98    0.57   0.185
s(log10(pmax(300, VGPM)))      3.00 2.96    0.56   0.090 .
s(log10(I(DistToFront1/1000))) 3.00 2.93    0.56   0.115
s(log10(SLAStDev))             3.00 2.61    0.56   0.075 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



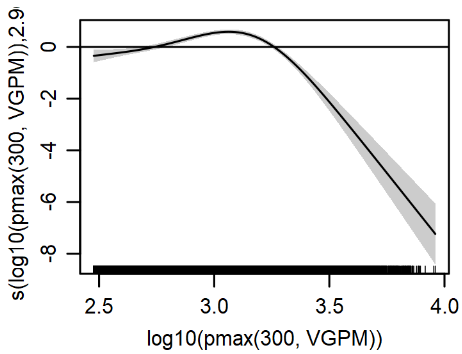
(a) Climatological distance to SST front (km)



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



(c) Seafloor slope (percent rise)



(d) Climatological net primary productivity (mg C m^{-2} day^{-1}) (VGPM)

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
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))
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
Slope	Slope (percent rise) of the seafloor, derived from SRTM30_PLUS (Becker et al. (2009))
VGPM	Climatological monthly mean net primary productivity (mg C m^{-2} day^{-1}) from the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski (1997))

2.2 Diagnostic Plots

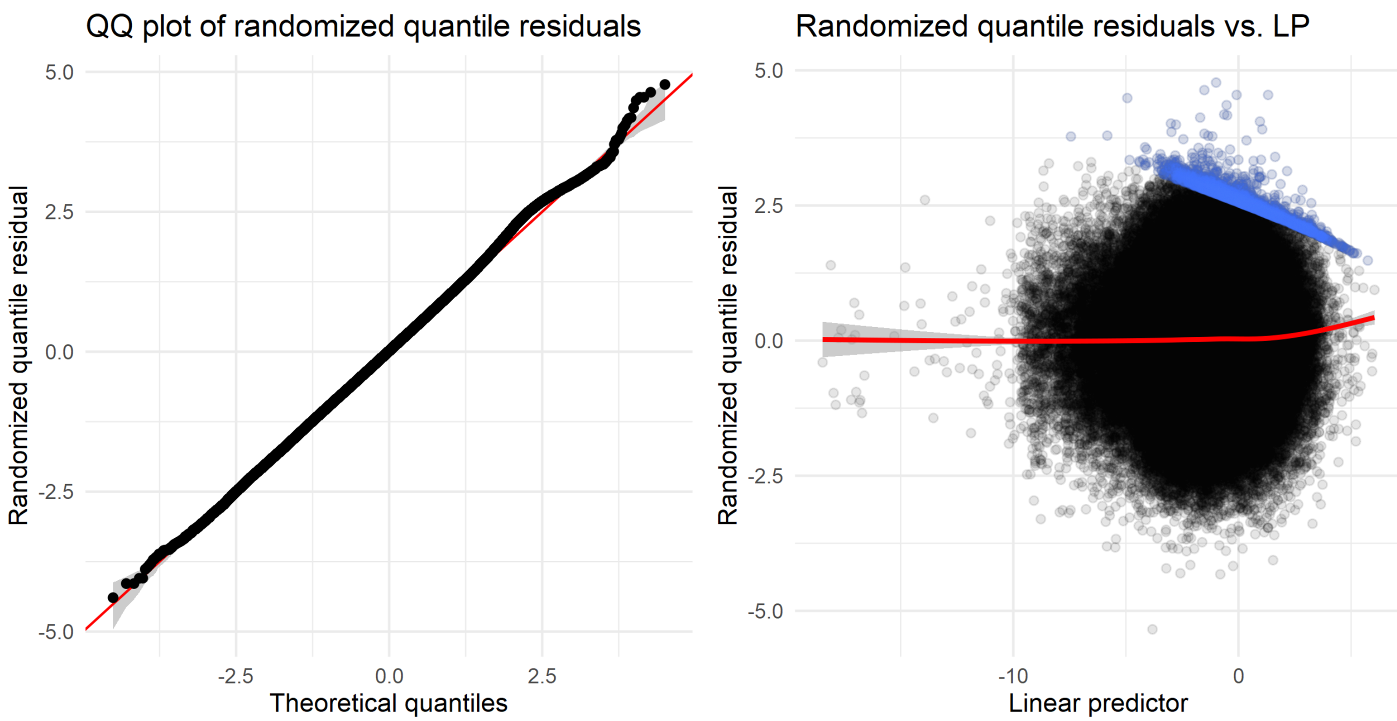


Figure 3: Residual plots for the final model for the region AFTT Atlantic.

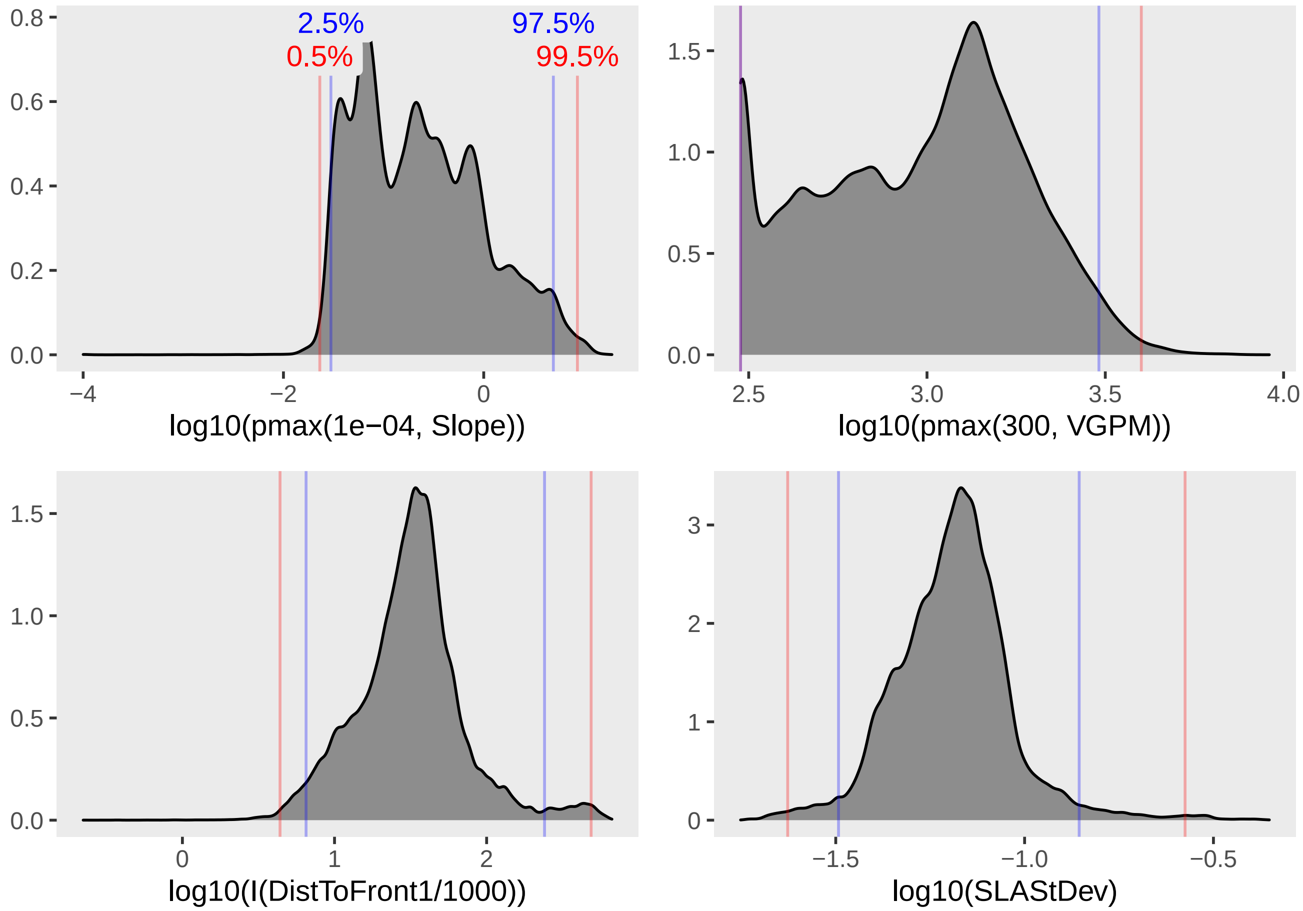


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red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

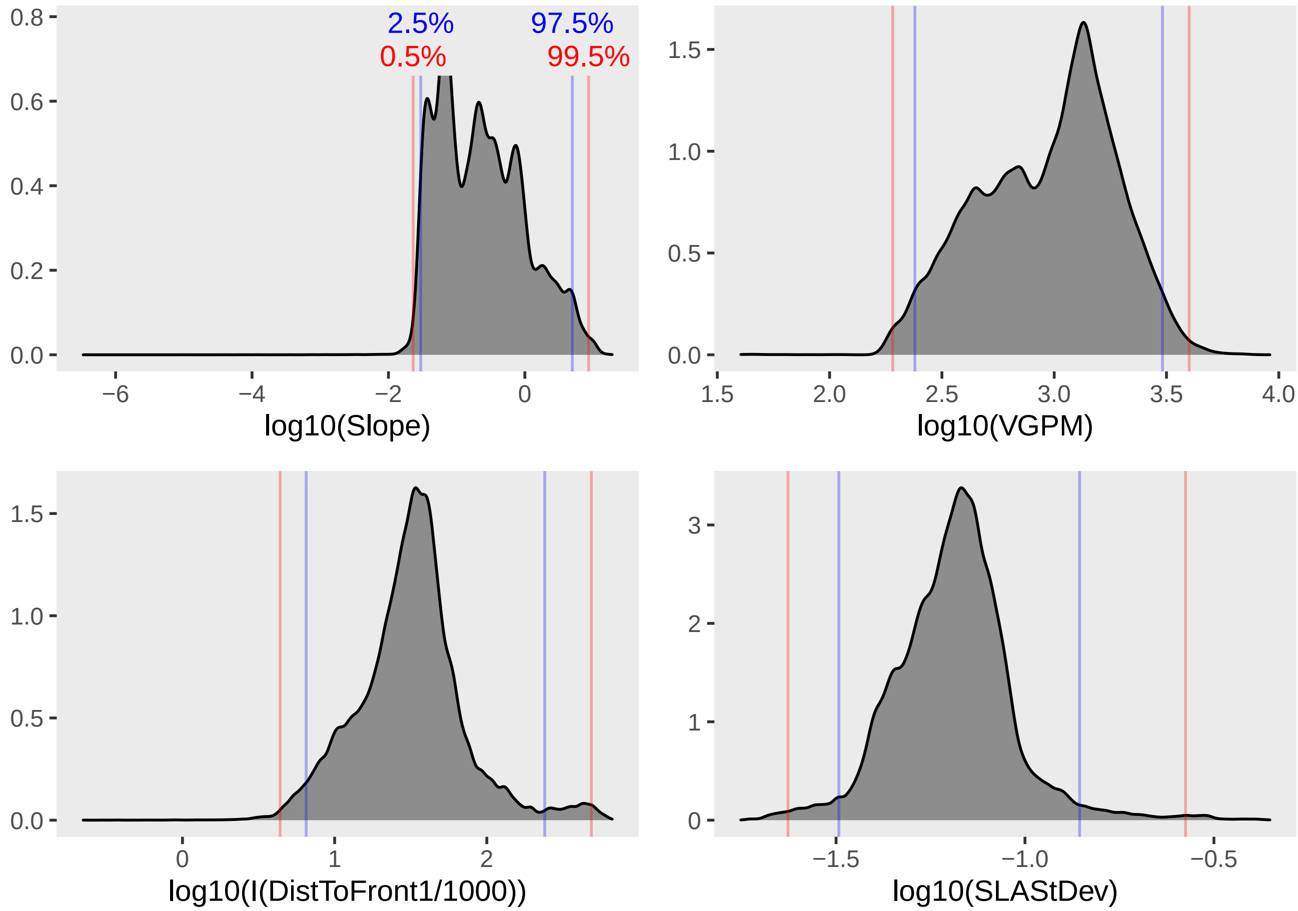


Figure 5: Density histograms shown in Figure 4 replotted without Winsorization, to show the full range of sampling represented by survey segments.

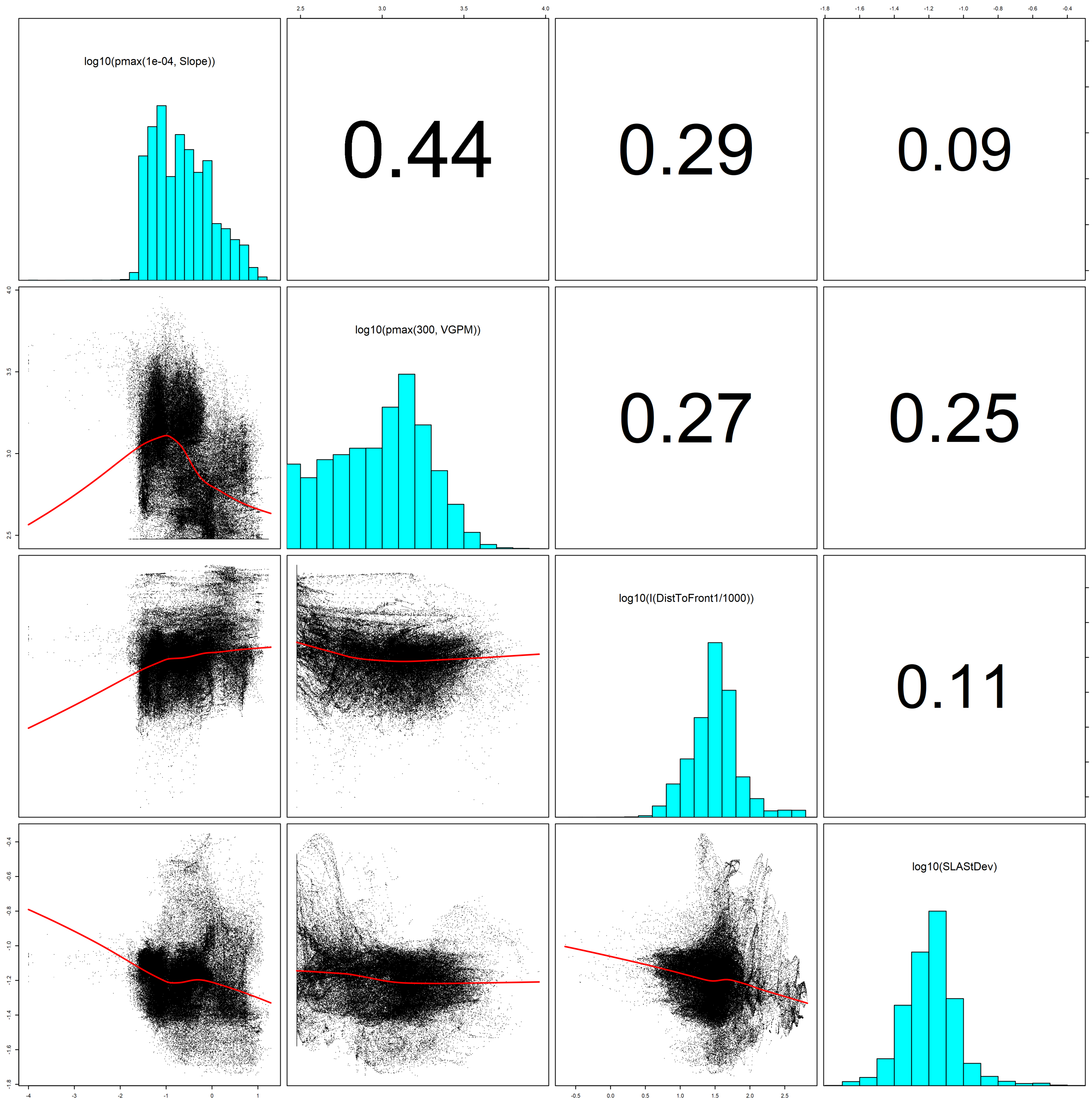


Figure 6: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and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

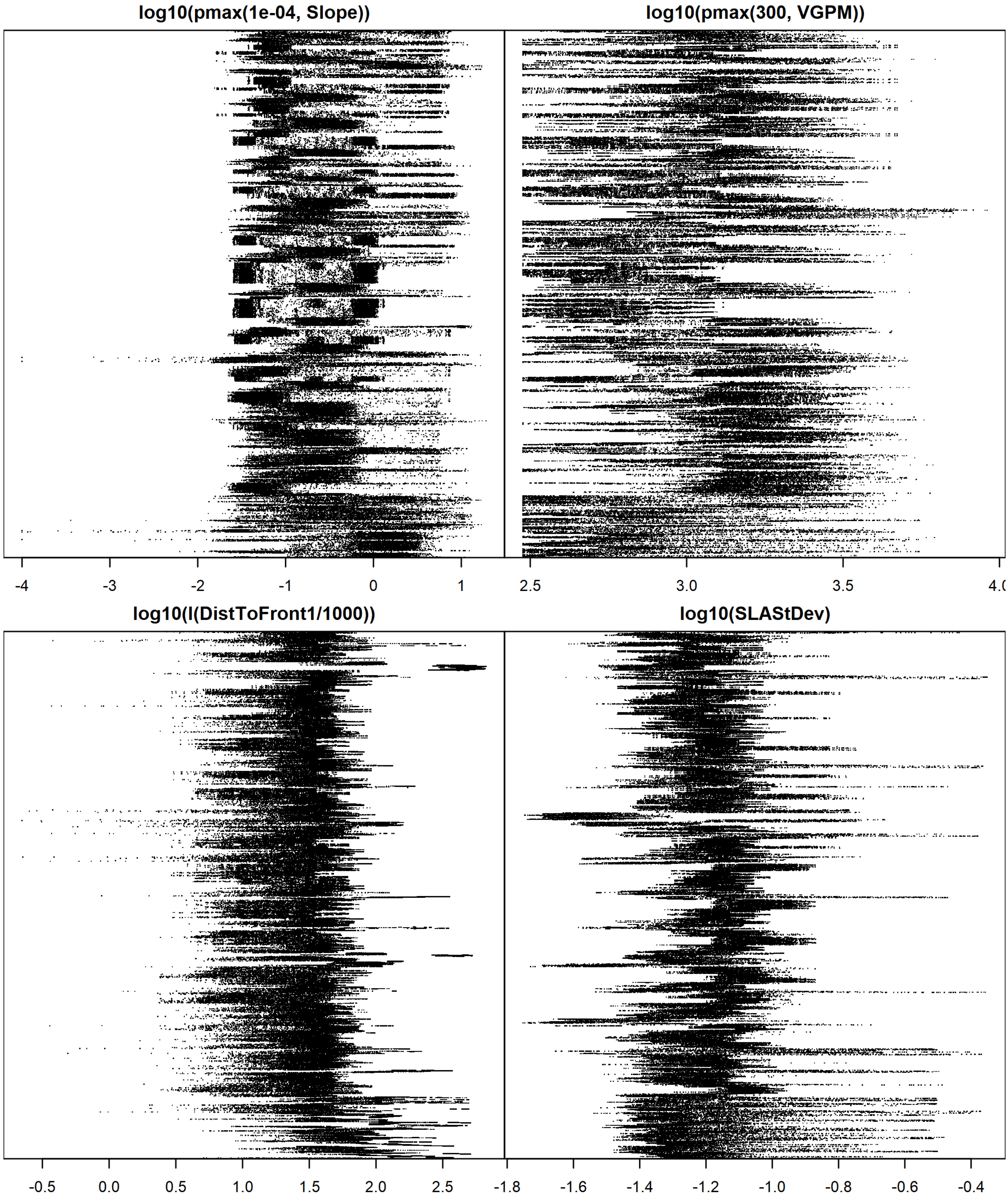


Figure 7: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed and Winsorized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

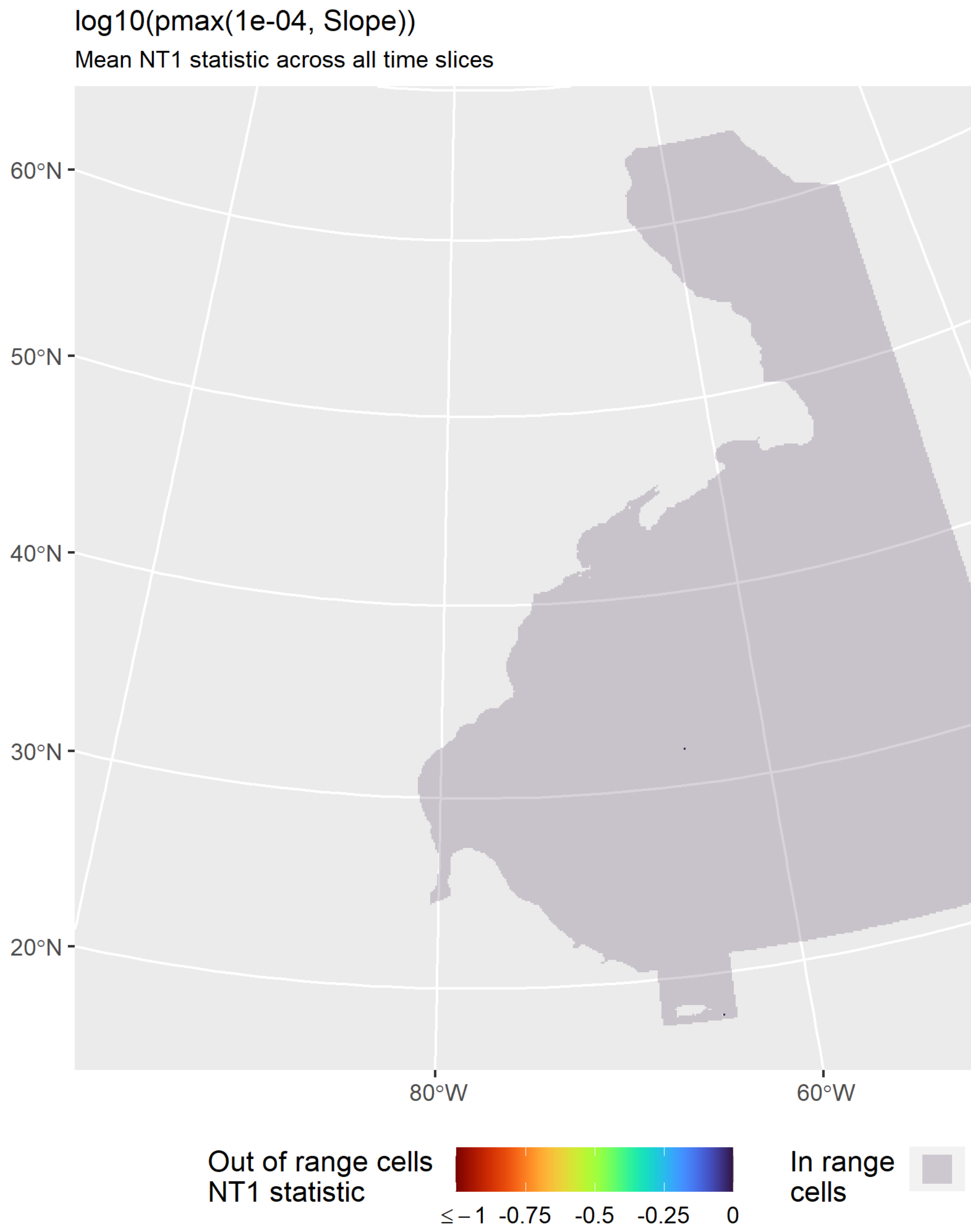
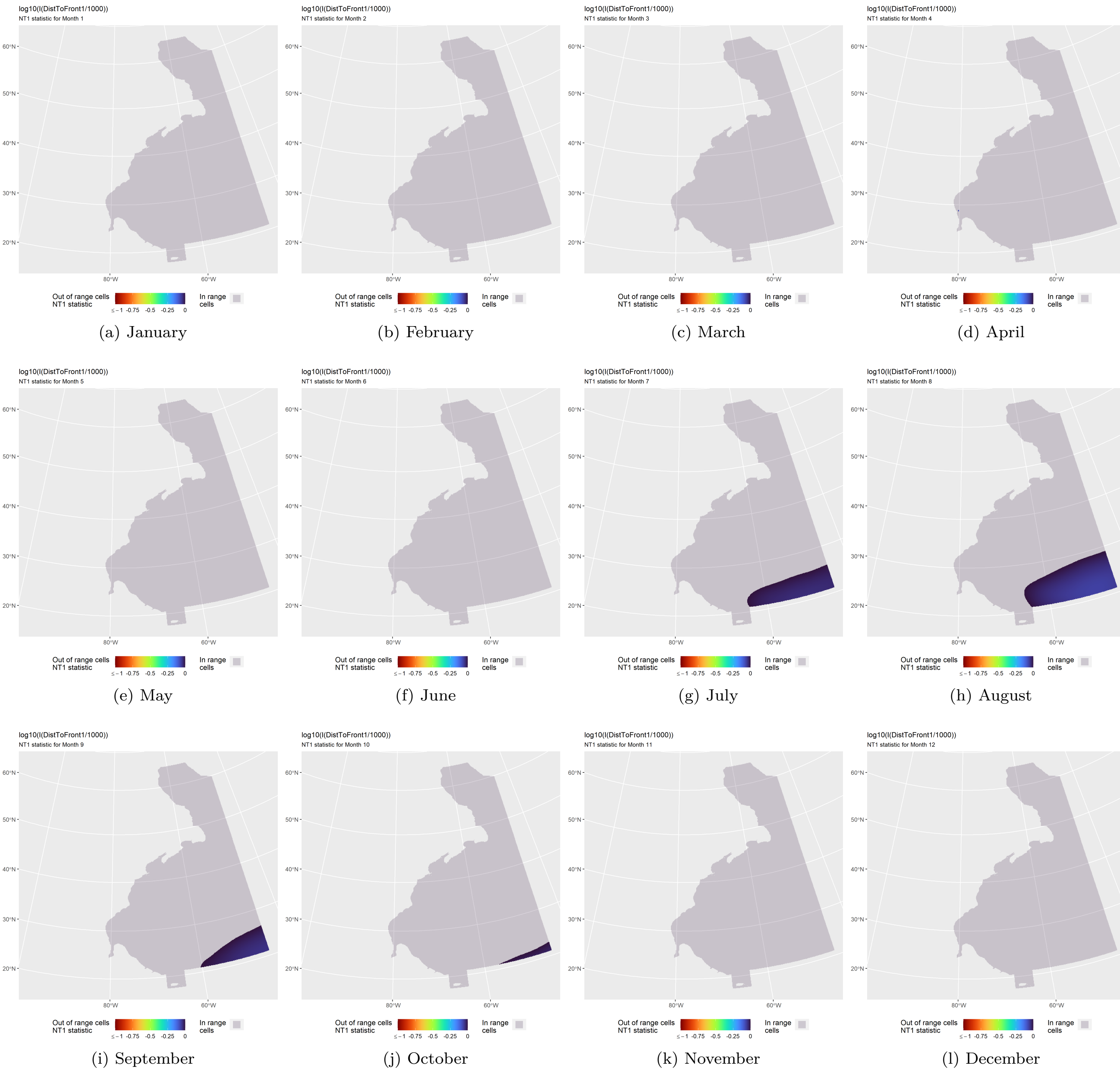


Figure 8: NT1 statistic (Mesgaran et al. (2014)) for static covariates used in the model for the region AFTT Atlantic. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there. Areas within the sampled range appear in gray, indicating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

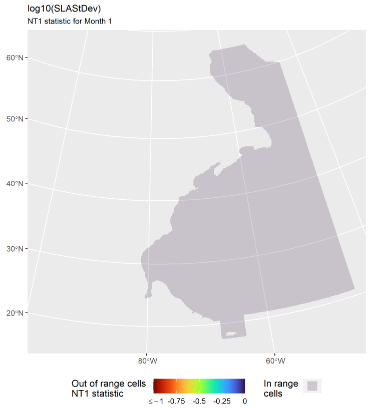


(a) January (b) February (c) March (d) April

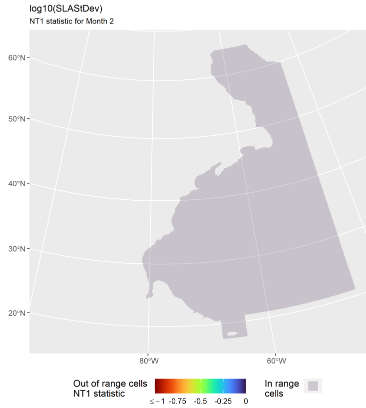
(e) May (f) June (g) July (h) August

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

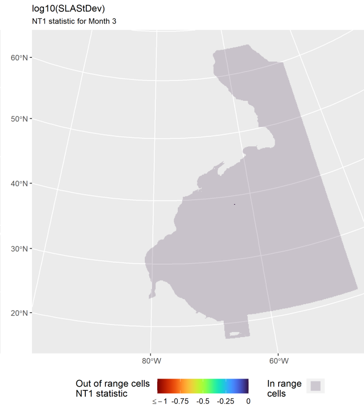
Figure 9: NT1 statistic (Mesgaran et al. (2014)) for the DistToFront1 covariate in the model for the region AFTT Atlantic. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range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



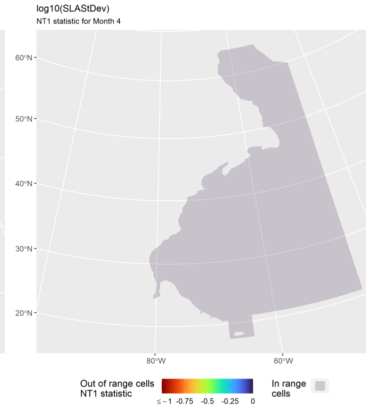
(a) January



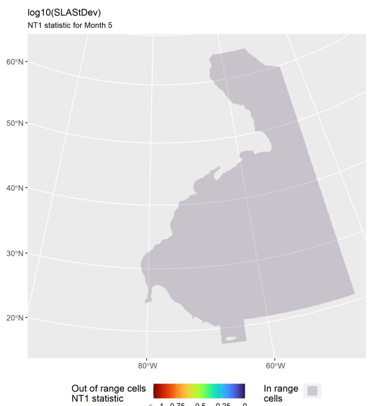
(b) February



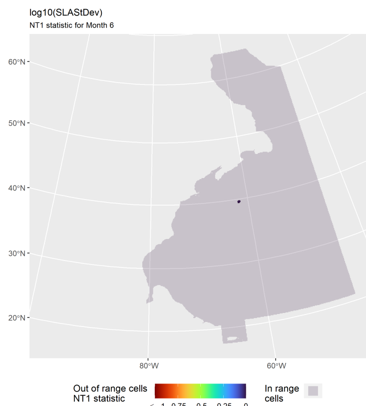
(c) March



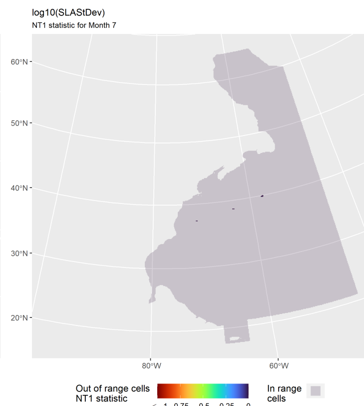
(d) April



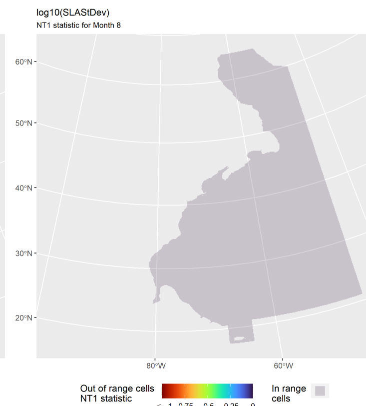
(e) May



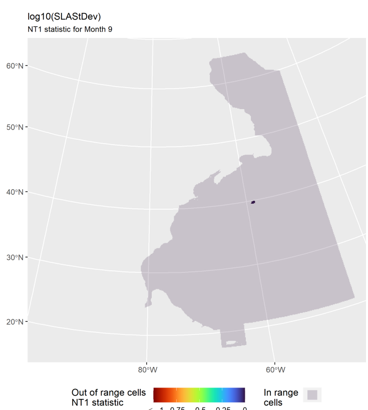
(f) June



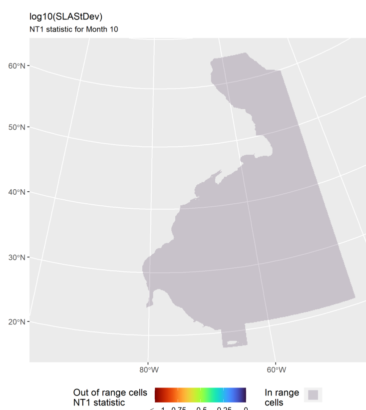
(g) July



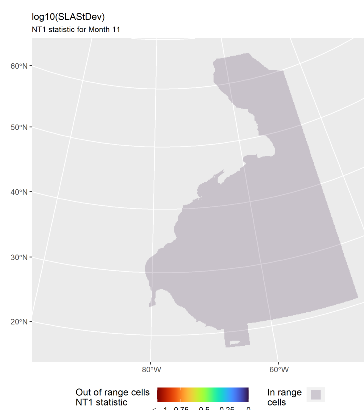
(h) August



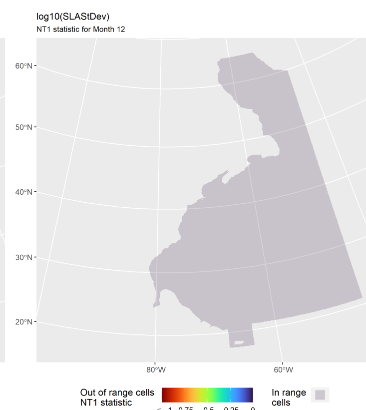
(i) September



(j) October



(k) November



(l) December

Figure 10: NT1 statistic (Mesgaran et al. (2014)) for the 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.

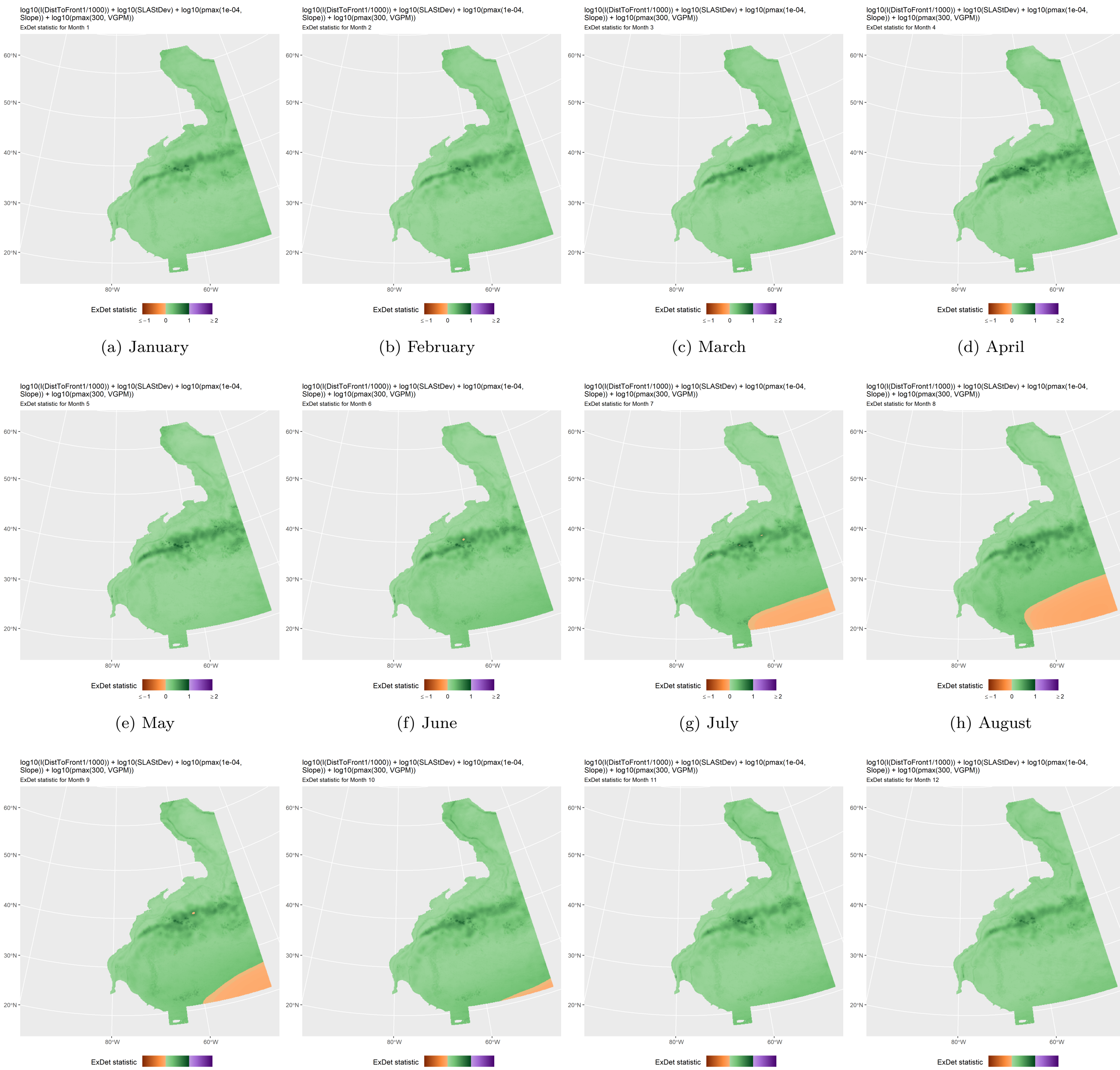
(a) January (b) February (c) March (d) April

(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 VGPM 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 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

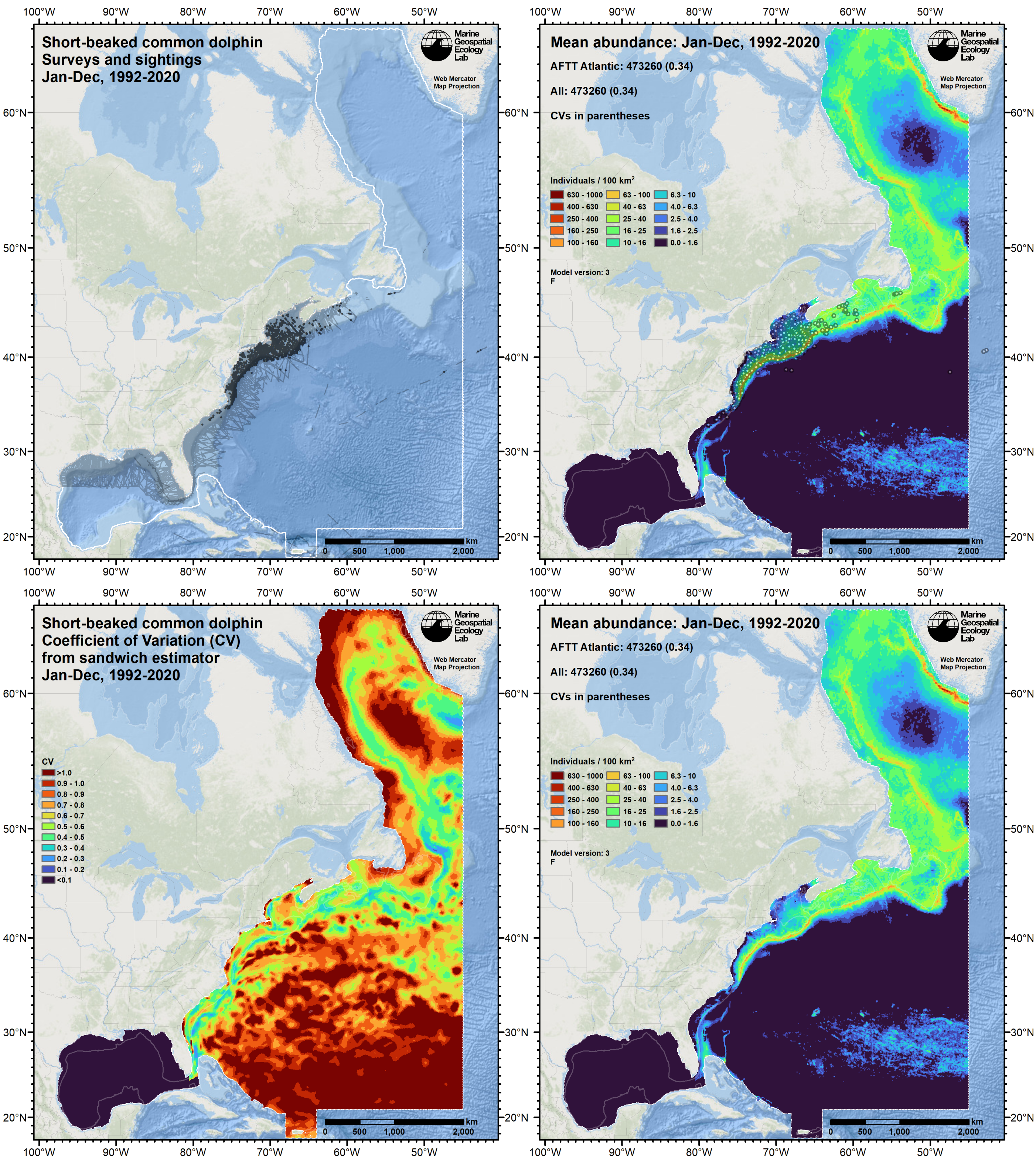


Figure 13: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for the given era. Variance was estimated with the analytic approach given by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

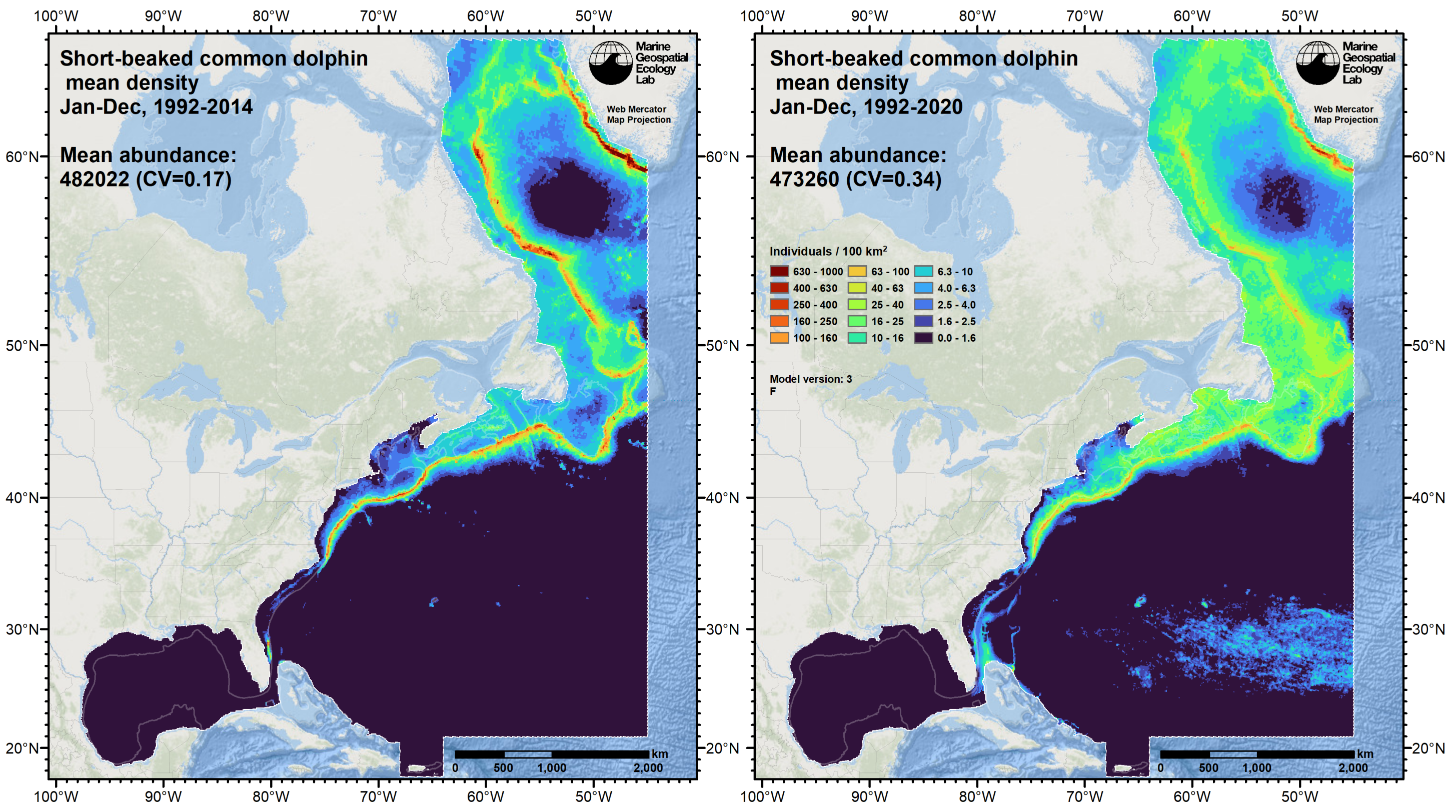


Figure 14: Comparison of the mean density predictions from the previous model (left) released by Mannocci et al. (2017) to those from this model (right). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

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. Short-beaked common dolphins are considered absent in the Gulf of Mexico (Jefferson et al. 2009), so predictions in the AFTT model were set to zero, and no regional model was fitted there. We note that although the OBIS-SEAMAP archive (Halpin et al. 2009) showed several sightings in the Gulf of Mexico (https://seamap.env.duke.edu/species/180438), these were from the 1970s and 1980s, and a comprehensive review of extant sightings across the the eastern coasts of North, Central, and South America, including the Gulf of Mexico, concluded these were misidentifications, or should otherwise be rejected (Jefferson et al. 2009).

The model's predictions generally accorded with what has been reported in the literature and largely resembled the predictions of Mannocci et al. (2017) and estimated a similar abundance (Figure 14). A notable difference is that Mannocci et al.'s model concentrated density very strongly at the continental shelf break, while our model predicted a more diffuse density spread across the shelf. Another difference is that Mannocci et al.'s model predicted very little density south of Cape Hatteras, North Carolina, while our model predicted some strands of low to medium density extending over the Blake Plateau to the Bahamas, and a large patch of low density in the Sargasso Sea. The species has been occasionally sighted in winter as far south as the North Carolina-South Carolina border in recent decades (see sightings in OBIS-SEAMAP) and historically was distributed as far south as Florida but has been considered absent there since the 1960s. We therefore consider it likely that the density predictions in the vicinity of Georgia, Florida, and the Bahamas are an overestimate. Similarly, the predictions in the Sargasso Sea appear implausible. We are unaware of any sightings to support a prediction of density there, but caution that OBIS-SEAMAP showed numerous sightings east of the Mid-Atlantic Ridge in distant offshore waters. Future updates to this model would benefit from surveys of distant offshore waters west of the Mid-Atlantic Ridge (as far as we know, none currently exist).

Like Mannocci et al.'s model, our model predicted high density along the shelves of northern Newfoundland, Labrador, and west Greenland. Like those authors, we consider this prediction to be an overestimate. Aerial surveys of Canada in 2007 and 2015 reported several sightings in northern Newfoundland and southern Labrador (Lawson and Gosselin 2009, 2018) but they appear to be too few to support a density as high there as along the U.S. east coast and Nova Scotia. Aerial surveys of west Greenland completed in 2007 and 2015 did not report any sightings (Hansen and Heide-Jørgensen 2013; Hansen et al. 2019). These surveys of Canada and Greenland were not available for use in this model; future updates would benefit from their inclusion.

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. However, given that the relationship for this covariate estimated that density decreased strongly as distance to fronts decreased, we are not concerned by this extrapolation. The questionable predictions of density in the Sargasso Sea occurred in winter, not in summer when the distance to fronts extrapolation was necessary.

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