Density Model for Humpback Whale (*Megaptera novaeangliae*) 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 Humpback Whale (*Megaptera novaeangliae*) 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 and Caribbean regions and excluded surveys of Europe and the Mid-Atlantic Ridge. Breaking with those authors, we excluded data from the Gulf of Mexico, as humpbacks do not inhabit it. 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 humpback whales or were otherwise problematic for modeling them. We restricted the model to survey transects with sea states of Beaufort 5 or less (for a few surveys we used Beaufort 4 or less) for both aerial and shipboard surveys. We also excluded transects with poor weather or visibility for surveys that reported those conditions. Table 1 summarizes the survey effort and sightings available after most exclusions were applied.

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						
FWRI	SEUS NARW EWS	2003-2020	668	56	56	1.0
HDR	Navy Norfolk Canyon	2018-2019	11	9	22	2.4
NEAq	CNM	2017-2020	2	2	2	1.0
NEAq	MMS-WEA	2017-2020	32	37	78	2.1
NEAq	NLPSC	2011-2015	43	59	124	2.1
NEAq	SEUS NARW EWS	2003-2010	227	8	8	1.0
NEFSC	AMAPPS	2010-2019	89	148	195	1.3
NEFSC	NARWSS	2003-2020	471	3,241	6,582	2.0
NEFSC	Pre-AMAPPS	1999-2008	46	113	153	1.4
NJDEP	NJEBS	2008-2009	11	3	5	1.7
NYS-DEC/TT	NYBWM	2017-2020	77	57	159	2.8
SEFSC	AMAPPS	2010-2020	114	15	20	1.3
SEFSC	MATS	1995-2005	34	4	4	1.0
SEFSC	SECAS	1992-1995	8	0	0	
U. La Rochelle	REMMOA	2008-2017	42	7	9	1.3
UNCW	Navy Cape Hatteras	2011-2017	34	6	9	1.5
UNCW	Navy Jacksonville	2009-2017	92	2	2	1.0
UNCW	Navy Norfolk Canyon	2015-2017	14	3	4	1.3
UNCW	Navy Onslow Bay	2007-2011	49	1	2	2.0
VAMSC	MD DNR WEA	2013-2015	16	2	2	1.0
VAMSC	Navy VACAPES	2016-2017	19	7	8	1.1
VAMSC	VA CZM WEA	2012-2015	21	12	20	1.7
WLT/SSA/CMARI	SEUS NARW EWS	2003-2020	652	45	50	1.1
		Total	**2,775**	**3,837**	**7,514**	**2.0**
Shipboard Surveys						
MCR	SOTW Visual	2012-2019	9	20	33	1.6
NEFSC	AMAPPS	2011-2016	16	124	178	1.4
NEFSC	Pre-AMAPPS	1995-2007	18	202	331	1.6
NJDEP	NJEBS	2008-2009	14	7	9	1.3
SEFSC	AMAPPS	2011-2016	17	1	1	1.0
SEFSC	Pre-AMAPPS	1992-2006	33	0	0	
SEFSC	SEFSC Caribbean	1995-2000	8	31	50	1.6
		Total	**115**	**385**	**602**	**1.6**
		Grand Total	**2,889**	**4,222**	**8,116**	**1.9**

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

Institution	Full Name
FWRI	FWC Fish and Wildlife Research Institute
HDR	HDR, Inc.
MCR	Marine Conservation Research
NEAq	New England Aquarium
NEFSC	NOAA Northeast Fisheries Science Center
NJDEP	New Jersey Department of Environmental Protection
NYS-DEC/TT	New York State Department of Environmental Conservation and Tetra Tech, Inc.
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
WLT/SSA/CMARI	Wildlife Trust, Sea to Shore Alliance, and Clearwater Marine Aquarium Research Institute

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)
CNM	Northeast Canyons Marine National Monument Aerial Surveys	Redfern et al. (2021)
MATS	Mid-Atlantic Tursiops Surveys	
MD DNR WEA	Aerial Surveys of the Maryland Wind Energy Area	Barco et al. (2015)
MMS-WEA	Marine Mammal Surveys of the MA and RI Wind Energy Areas	Quintana-Rizzo et al. (2021), O'Brien et al. (2022)
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)
NLPSC	Northeast Large Pelagic Survey Collaborative Aerial Surveys	Leiter et al. (2017), Stone et al. (2017)
NYBWM	New York Bight Whale Monitoring Surveys	Zoidis et al. (2021)
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)
SECAS	Southeast Cetacean Aerial Surveys	Blaylock and Hoggard (1994)
SEFSC Caribbean	SEFSC Surveys of the Caribbean Sea	Mullin (1995), Swartz and Burks (2000)

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

Program	Description	References
SEUS NARW EWS	Southeast U.S. Right Whale Early Warning System Surveys	Gowan and Ortega-Ortiz (2014)
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 adjusting the model's overall structure or repeating the covariate selection exercise performed by those authors. Humpback whales are highly migratory and exhibit a distinct seasonality in the western North Atlantic. For this reason, Mannocci et al. split the year into two seasons—Winter (December-March) and Summer (April-November)—and fitted an independent model for each. We followed this decision; for further details about it, please see the supplementary report for humpback whales in that publication[1], and also that for our updated east coast model (version 11). We present the details for each updated seasonal model below. We present the summarized predictions in Section 3 and discuss them in Section 4.

2.1 Winter (December-March)

Following Mannocci et al., we fitted a single-covariate model relating density to sea surface temperature (SST). The resulting relationship (Figure 2) resembled the general "U" shape obtained by Mannocci et al., but was much less flat. A positive influence on density was indicated above about 22 °C and below about 15 °C, with a negative influence in between. This result reflected the splitting of the population between the warm calving grounds in the Caribbean islands, where a large fraction of the population migrates to in winter, and the cold feeding grounds along the North American coast, where a fraction remains to overwinter, although photographic evidence suggests not all of the whales here are from the Gulf of Maine stock that feeds in the region in summer (Barco 2002; Brown et al. 2022). Please see the east coast humpback whale report (version 11) for additional discussion. Extrapolation analysis (Section 2.1.3) showed that the necessity for environmental extrapolation was driven by a lack of sampling in waters with very low sea surface temperatures (Figure 6), as occurs along the shelf of Newfoundland, Labrador, and Greenland. This geographic pattern was very similar to the environmental envelope estimated by Mannocci et al.

[1] The publication, Mannocci et al. (2017), only included the supplementary report for their summer model. The report for their winter model is available on our website.

2.1.1 Final Model

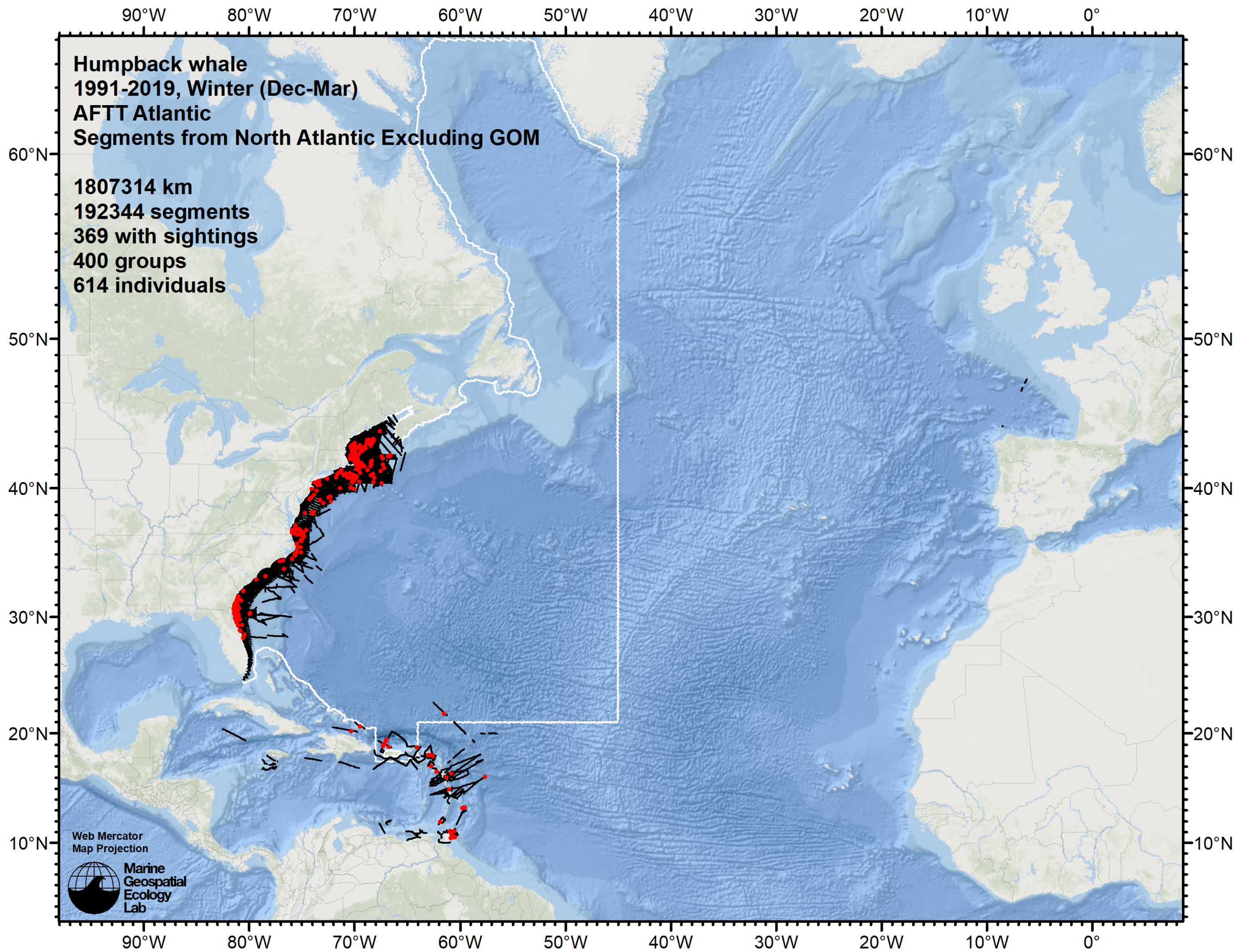


Figure 1: Survey segments (black lines) used to fit the model for the region AFTT Atlantic for Winter. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

Statistical output for this model:

```
Family: Tweedie(p=1.115)
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(SST, bs = "ts",
    k = 4)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -23.1938     0.0879  -263.9   <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(SST) 2.985      3 179  <2e-16 ***
```

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.00708   Deviance explained = 16.7%
-REML = 2990.2  Scale est. = 5.5906    n = 192343

Method: REML   Optimizer: outer newton
full convergence after 11 iterations.
Gradient range [-0.00140242,0.0007144137]
(score 2990.227 & scale 5.590598).
Hessian positive definite, eigenvalue range [1.456598,4013.797].
Model rank =  4 / 4

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(SST) 3.00 2.98    0.81   0.025 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

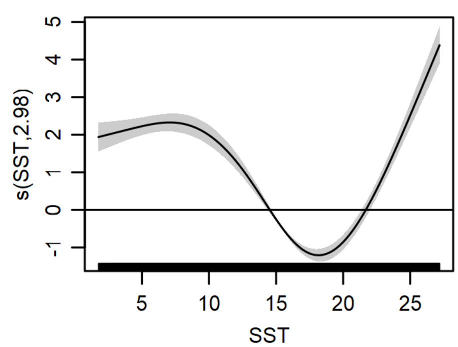


Figure 2: Functional plots for the final model for the region AFTT Atlantic for Winter. Transforms and other treatments are indicated in axis labels. *log10* indicates the covariate was $\log_{10}$ transformed. *sqrt* indicates the covariate was square-root transformed. */1000* indicates meters were transformed to kilometers for interpretation convenience.

Table 4: Covariates used in the final model for the region AFTT Atlantic for Winter.

Covariate	Description
SST	Climatological monthly mean sea surface temperature (°C) from GHRSST Level 4 CMC0.2deg (Brasnett (2008); Canada Meteorological Center (2012))

2.1.2 Diagnostic Plots

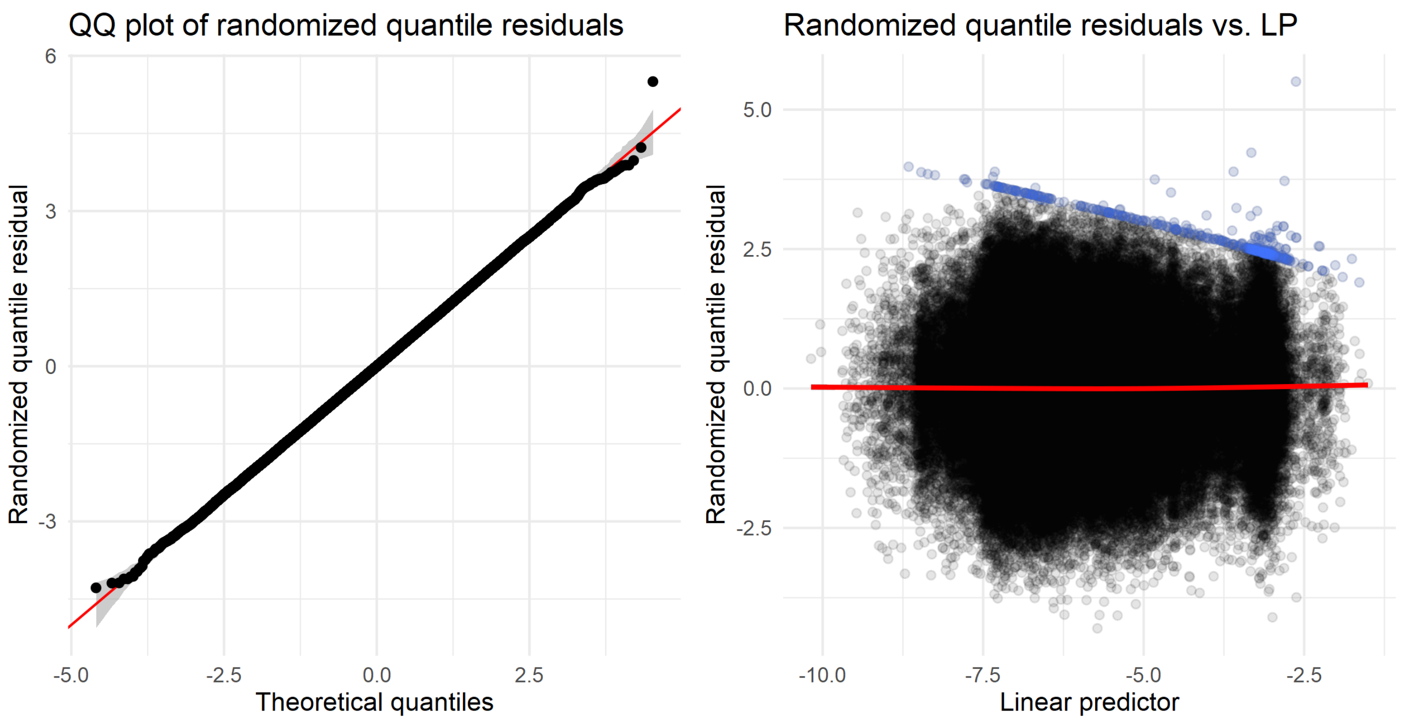


Figure 3: Residual plots for the final model for the region AFTT Atlantic for Winter.

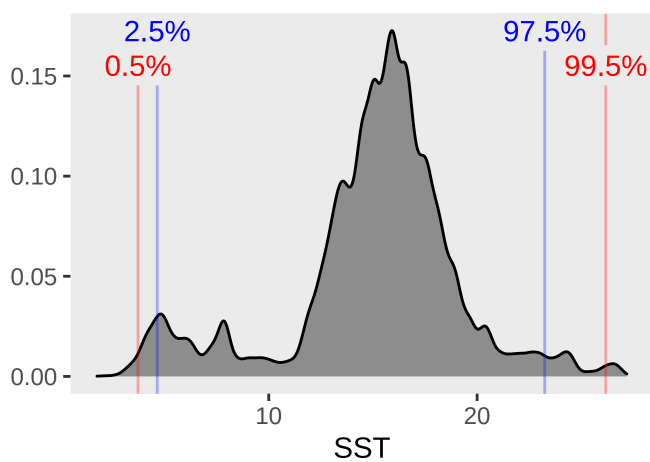


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red 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. */1000* indicates meters were transformed to kilometers for interpretation convenience.

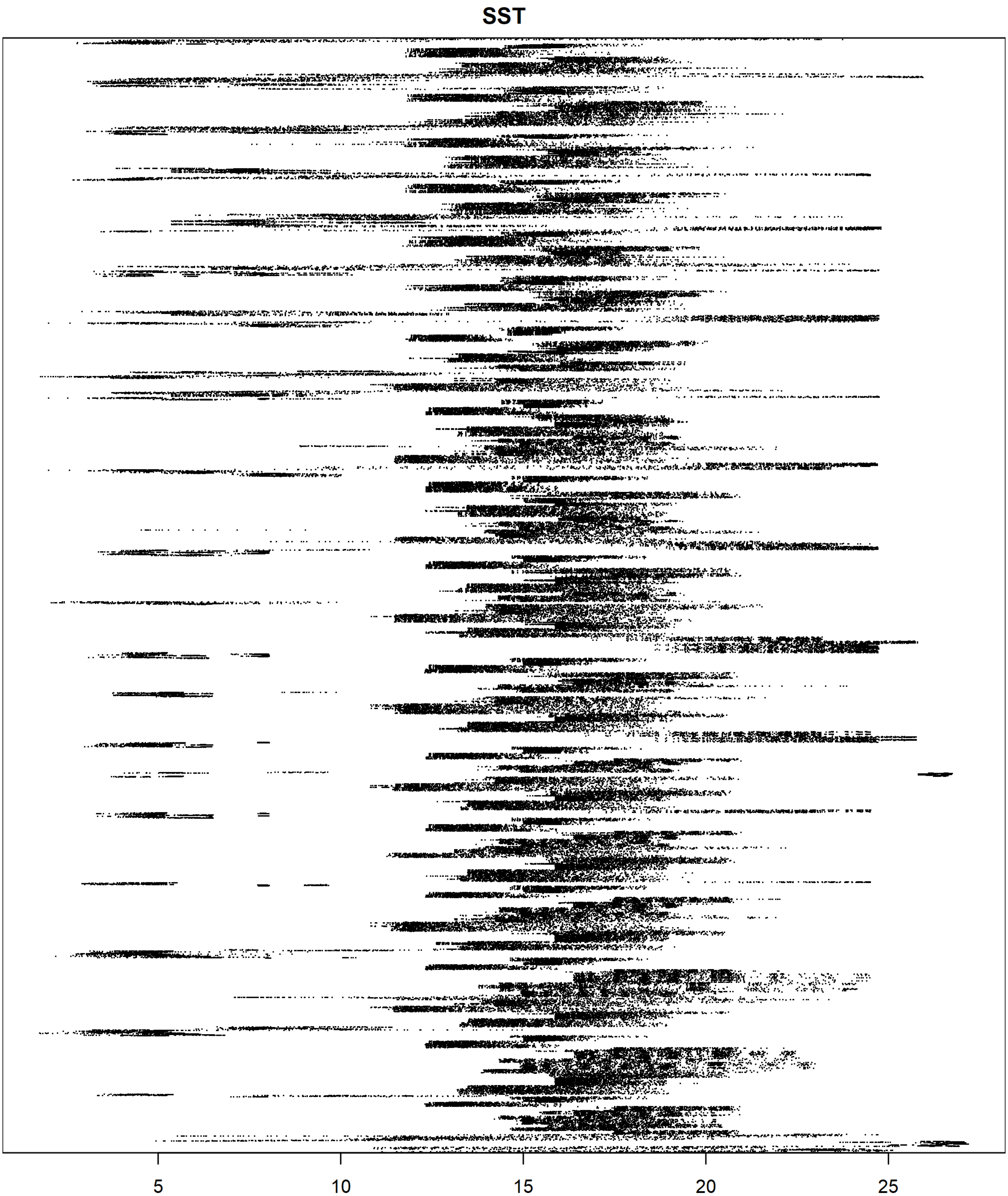
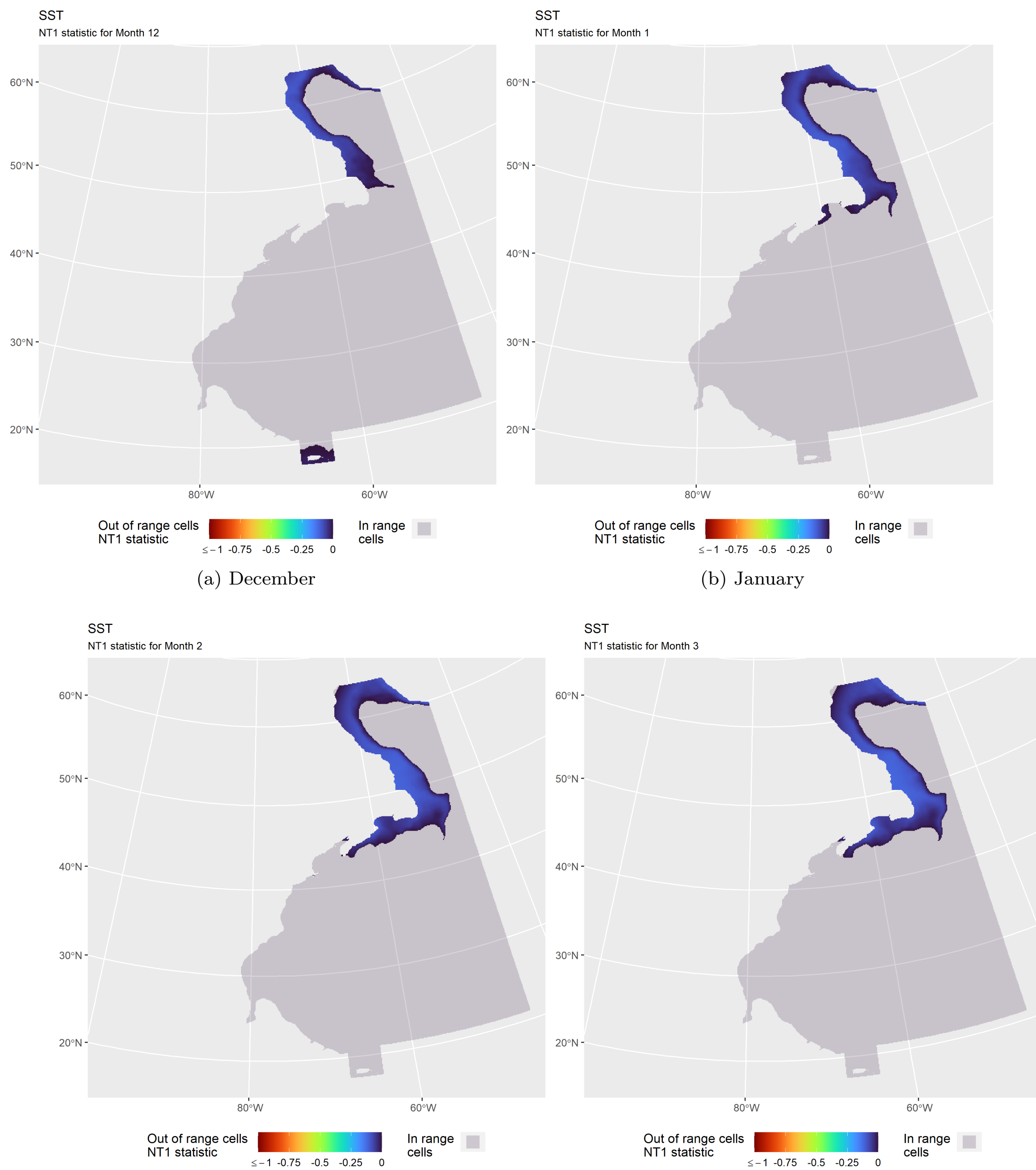


Figure 5: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed as shown in Figure 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.

2.1.3 Extrapolation Diagnostics



(a) December

(b) January

(c) February

(d) March

Figure 6: NT1 statistic (Mesgaran et al. (2014)) for the SST covariate in the model for the region AFTT Atlantic for Winter. 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.

2.2 Summer (April-November)

Following Mannocci et al., we fitted a 4-covariate model that included chlorophyll concentration, depth of the sea floor, distance to SST fronts, and the standard deviation of sea level anomaly. All covariates were retained during smoothness selection but moderately different relationships were fitted to all covariates except for chlorophyll concentration (Figure 8), for which the fit was essentially the same as Mannocci et al.'s model. The covariate that yielded the largest difference in the predictions was depth. In Mannocci's model the depth relationship was hump-shaped like ours, but turned strongly positive for depths deeper than 3.3 on the $\log_{10}$ scale (about 2000 m), while in ours it remained slightly negative. This drove predictions in Mannocci's model to much higher levels beyond the continental shelf than occurred with our model (Figure

21). We discuss this result further in Section 4. The distance to fronts covariate was shaped similarly in the two models, but was substantially higher in Mannocci's model at very low values, essentially corresponding to grid cells that occurred directly on persistent SST fronts. This did not make a substantial difference in the predictions, as such locations are relatively rare. Finally, the standard deviation of sea level anomaly covariate was hump-shaped in Mannocci's model but linear in our model. This led to strong deviations between the models in regions of high sea level anomalies, such as the Gulf Stream, where in Mannocci's model the relationship pulled density strongly down, while in our model it boosted density slightly up. This allowed density in our model to remain slightly above negligible values just north of the Gulf Stream, while in Mannocci's, the relationship forced density down in such highly dynamic areas.

Univariate extrapolation analyses (Section 2.2.3.1) displayed geographic patterns very similar to the environmental envelopes estimated by Mannocci et al. except for the depth covariate, for which the trans-Atlantic survey by R/V Song of the Whale used in our model provided sampling at much deeper depths than the surveys available for Mannocci's model. In our model the necessity for univariate environmental extrapolation was driven mainly by a lack of sampling in waters with with very low chlorophyll concentration (Figure 14) or few SST fronts, (Figure 15) as occurs in the southeast of the AFTT study area. We found this outcome no cause for concern, as humpbacks are almost never found in such warm, southerly waters during the summer feeding season. Small patches of univariate extrapolation of the sea level anomaly covariate occurred in waters around Labrador, driven by very low values of the covariate. We advise caution with predictions in this area, as discussed in Section 4.

2.2.1 Final Model

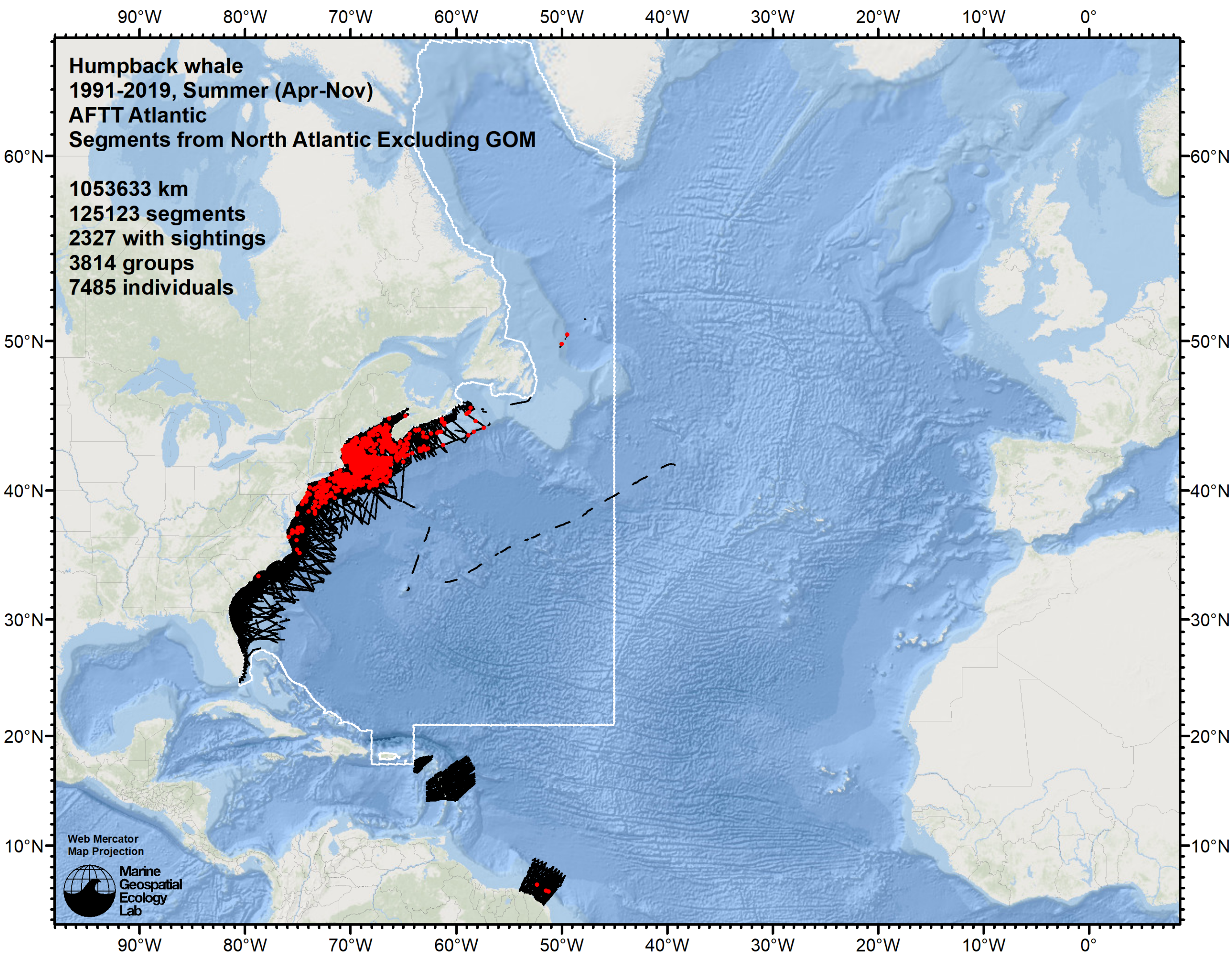
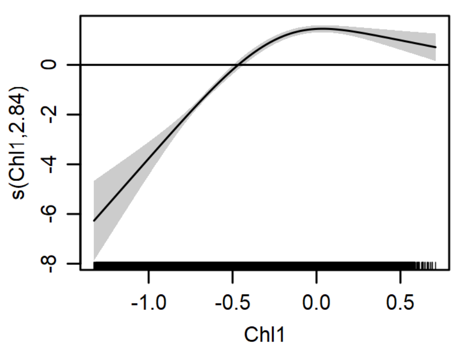


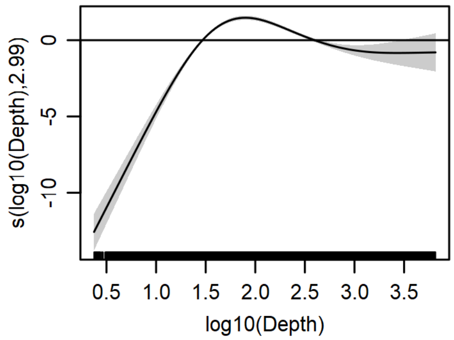
Figure 7: Survey segments (black lines) used to fit the model for the region AFTT Atlantic for Summer. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

Statistical output for this model:

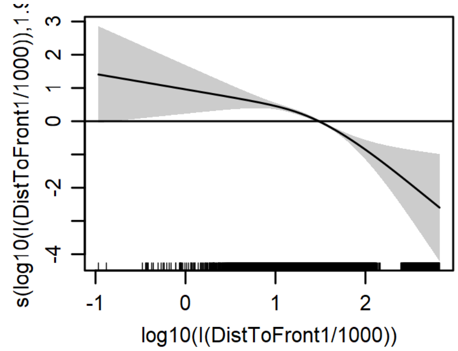
```
Family: Tweedie(p=1.282)
Link function: log

Formula:
IndividualsCorrected ~ offset(log(SegmentArea)) + s(log10(Depth),
    bs = "ts", k = 4) + s(Chl1, 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) -21.24956    0.07884  -269.5   <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))                2.9868      3 200.795  < 2e-16 ***
s(Chl1)                        2.8450      3 174.530  < 2e-16 ***
s(log10(I(DistToFront1/1000))) 1.9150      3  32.905  < 2e-16 ***
s(log10(SLAStDev))             0.9581      3   4.442 0.000151 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0227   Deviance explained =   20%
-REML =  15749  Scale est. = 11.069    n = 125123

Method: REML   Optimizer: outer newton
full convergence after 11 iterations.
Gradient range [-0.0002893464,0.0002834348]
(score 15749.25 & scale 11.06878).
Hessian positive definite, eigenvalue range [0.2792042,11415.33].
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))                3.000 2.987    0.75   0.005 **
s(Chl1)                        3.000 2.845    0.77   0.020 *
s(log10(I(DistToFront1/1000))) 3.000 1.915    0.79   0.180
s(log10(SLAStDev))             3.000 0.958    0.80   0.365
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```



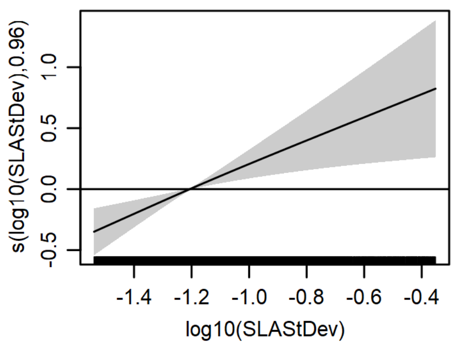
(a) Climatological chlorophyll a concentration ($\log_{10}$ mg m^{-3})



(b) Seafloor depth (m)



(c) Climatological distance to SST front (km)



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

Figure 8: Functional plots for the final model for the region AFTT Atlantic for Summer. 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. */1000* indicates meters were transformed to kilometers for interpretation convenience.

Table 5: Covariates used in the final model for the region AFTT Atlantic for Summer.

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))
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

2.2.2 Diagnostic Plots

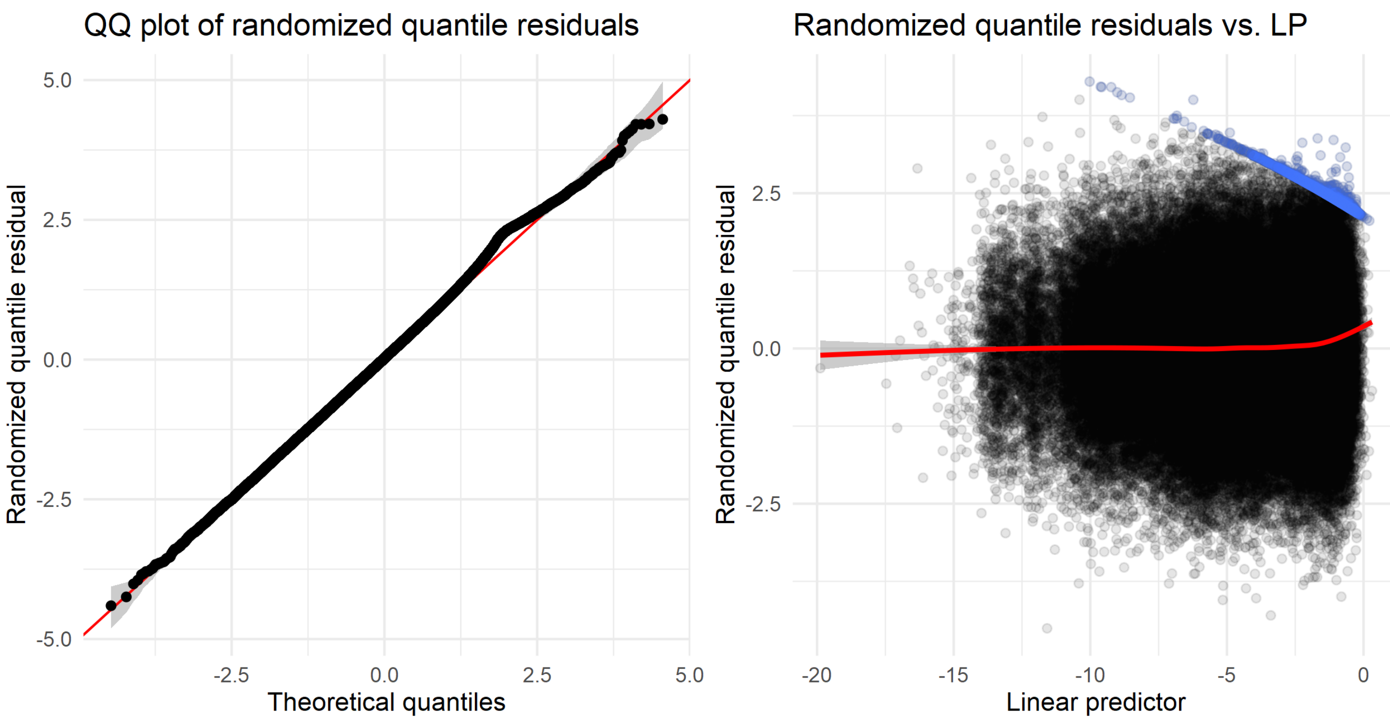


Figure 9: Residual plots for the final model for the region AFTT Atlantic for Summer.

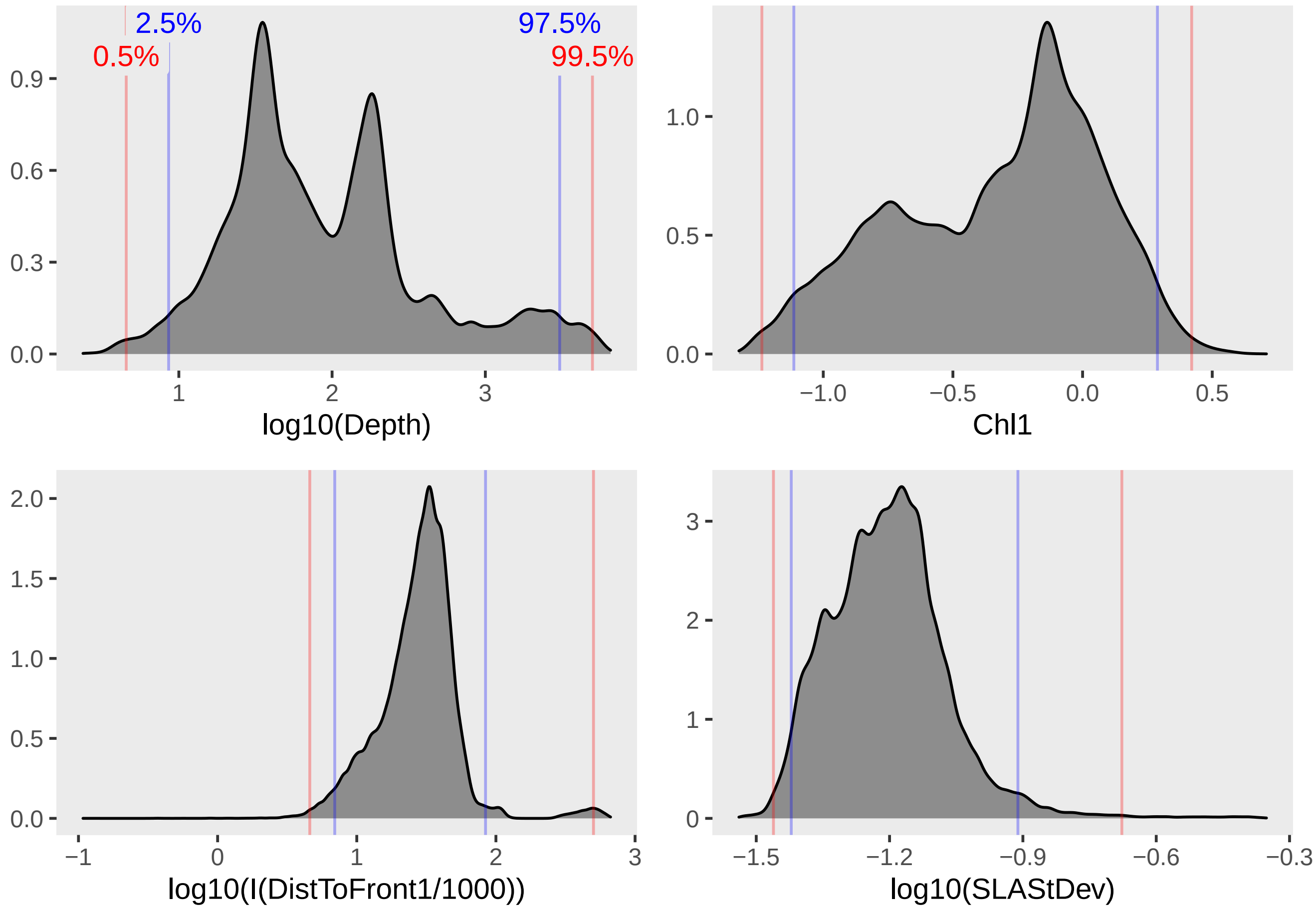


Figure 10: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 8), and additional covariates may have been considered in preceding selection steps. Red 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. */1000* indicates meters were transformed to kilometers for interpretation convenience.

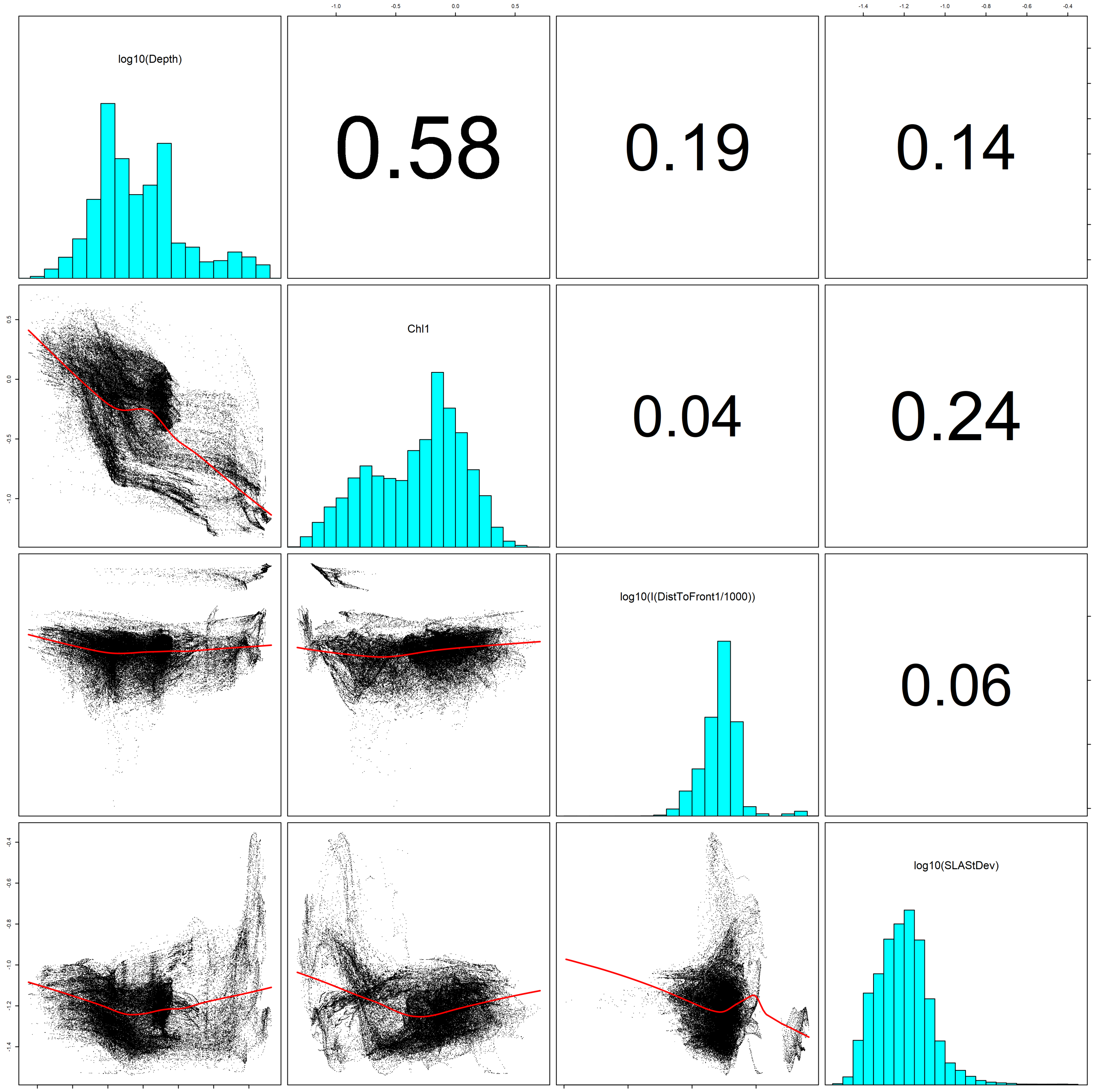


Figure 11: Scatterplot matrix of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 8), and additional covariates may have been considered in preceding selection steps. Covariates are transformed as shown in Figure 10. 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).

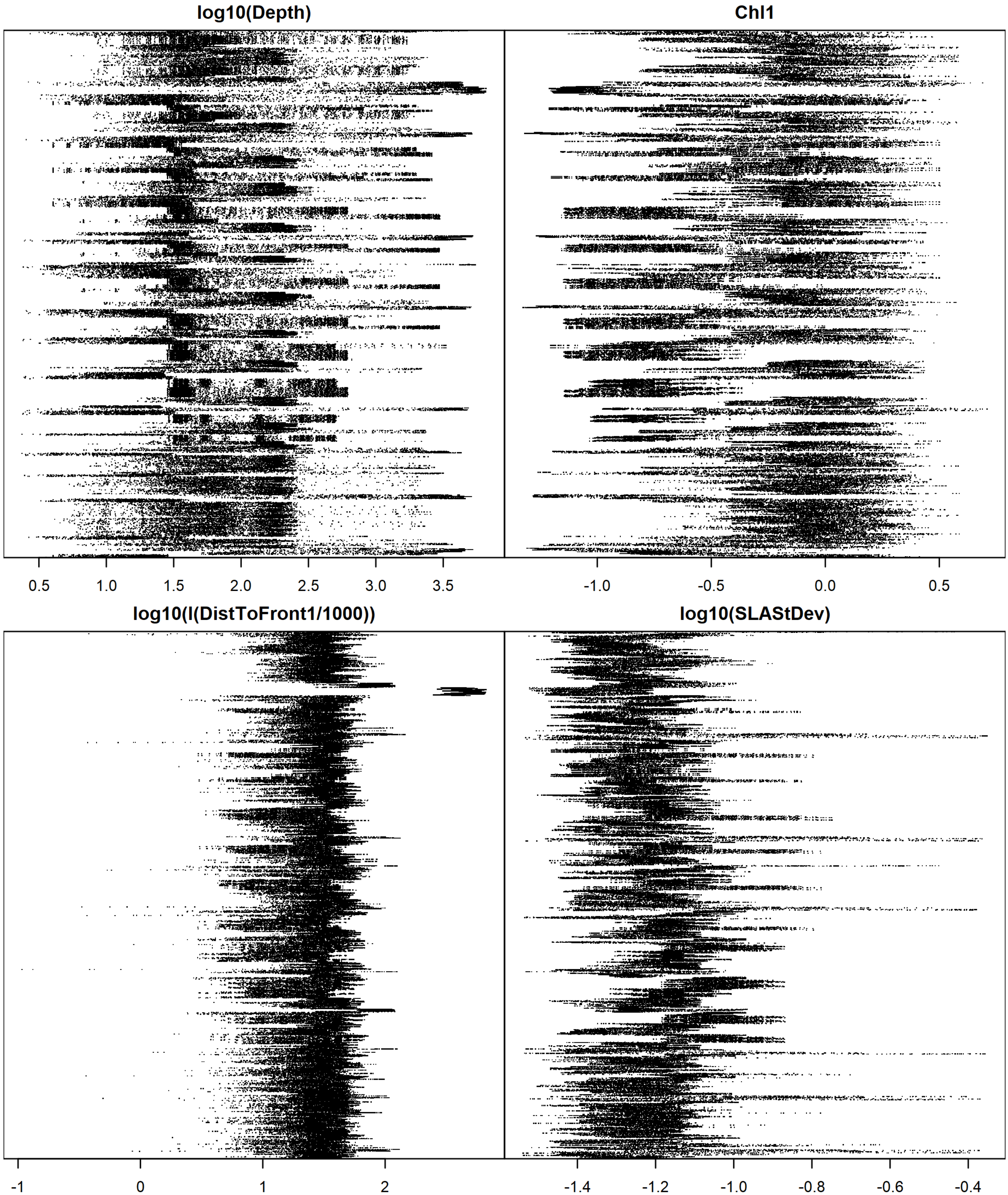


Figure 12: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 8), and additional covariates may have been considered in preceding selection steps. Covariates are transformed as shown in Figure 10. This plot is used to check for suspicious patterns and outliers in the data. Points are ordered vertically by segment ID, sequentially in time.

2.2.3 Extrapolation Diagnostics

2.2.3.1 Univariate Extrapolation

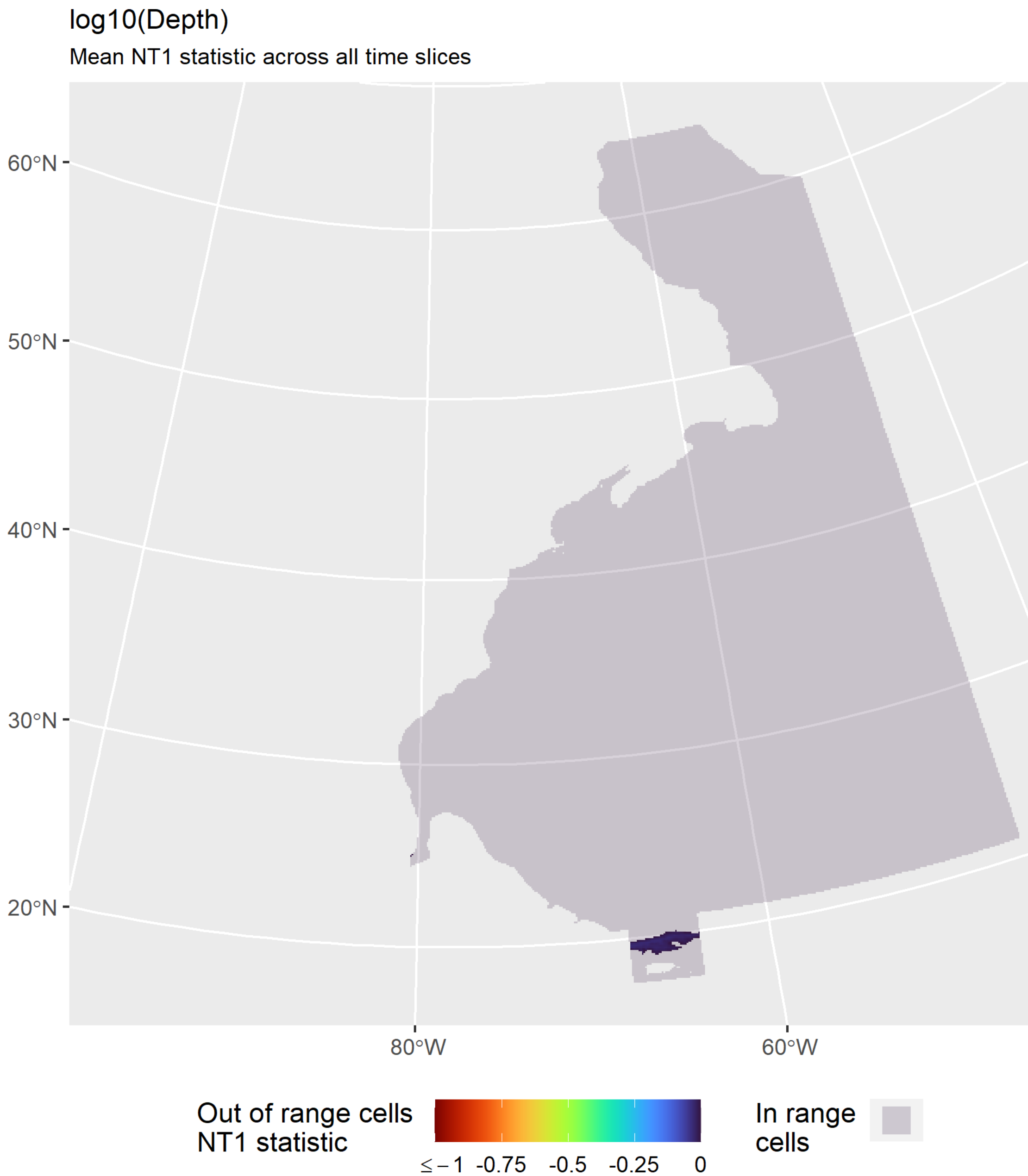
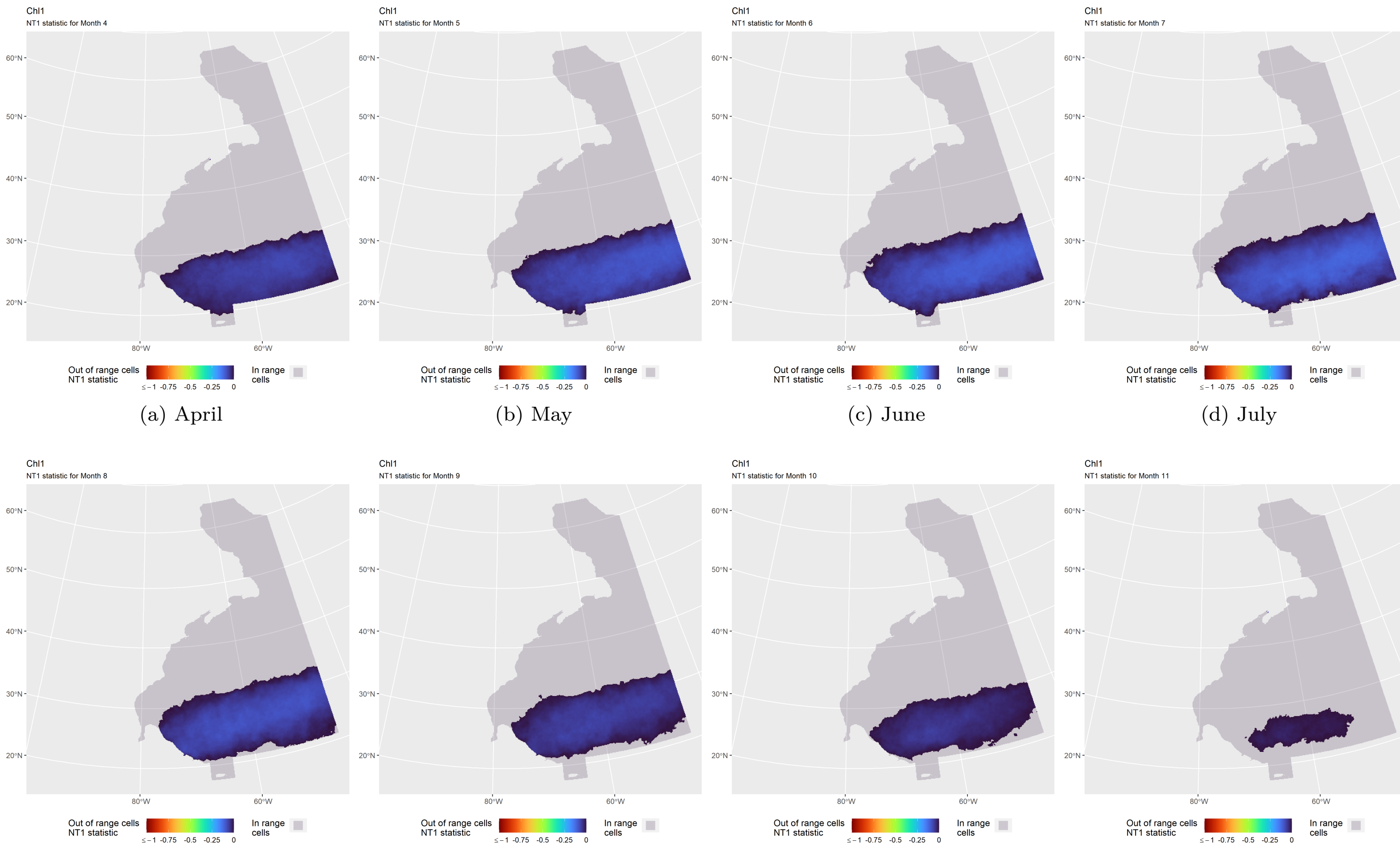


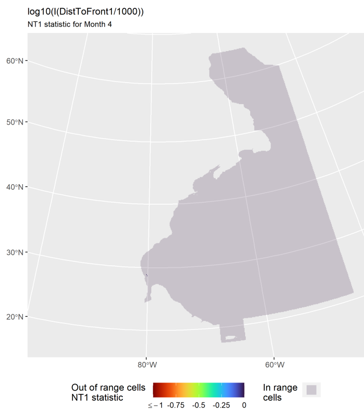
Figure 13: NT1 statistic (Mesgaran et al. (2014)) for static covariates used in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there. Areas within the sampled range appear in gray, indicating it did not occur.



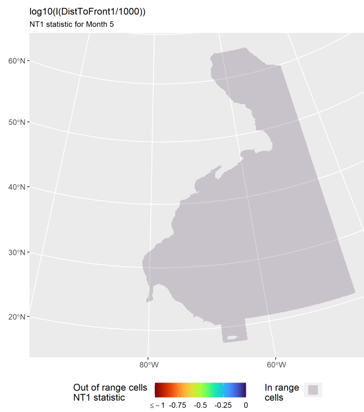
(a) April (b) May (c) June (d) July

(e) August (f) September (g) October (h) November

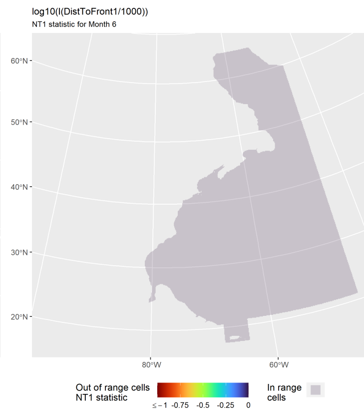
Figure 14: NT1 statistic (Mesgaran et al. (2014)) for the Chl1 covariate in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range appear in gray, indicating it did not occur.



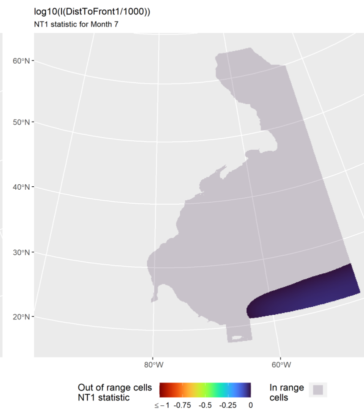
(a) April



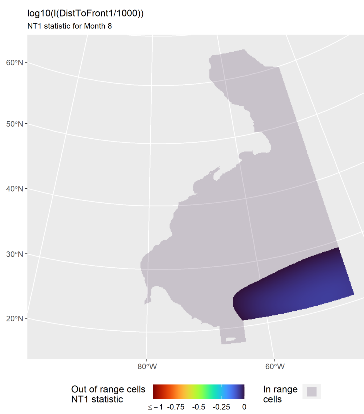
(b) May



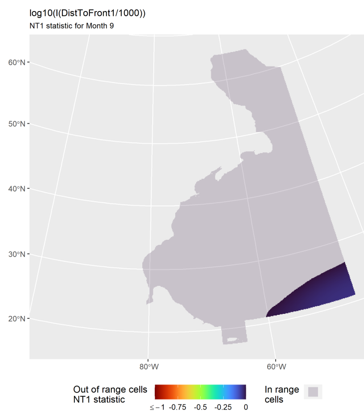
(c) June



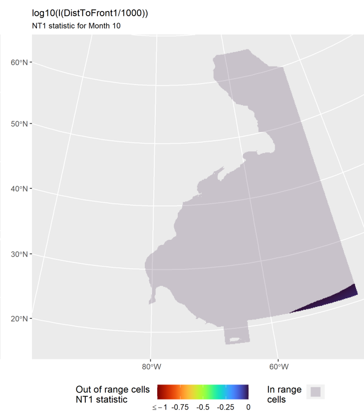
(d) July



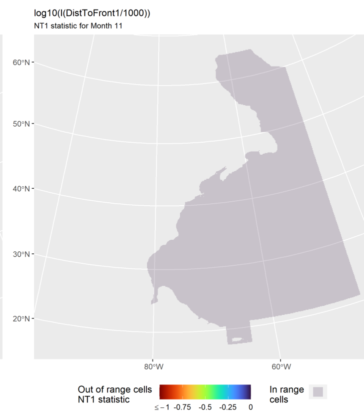
(e) August



(f) September

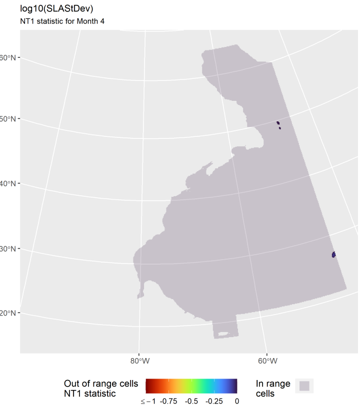


(g) October

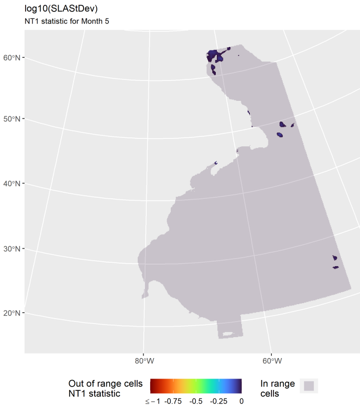


(h) November

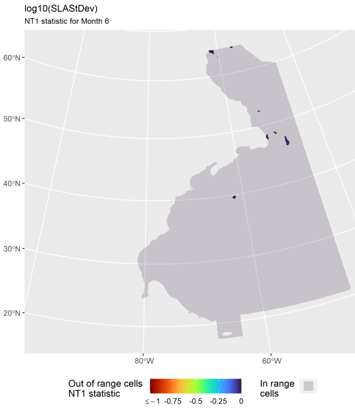
Figure 15: NT1 statistic (Mesgaran et al. (2014)) for the DistToFront1 covariate in the model for the region AFTT Atlantic for Summer. Areas outside the sampled range of a covariate appear in color, indicating univariate extrapolation of that covariate occurred there during the month. Areas within the sampled range appear in gray, indicating it did not occur.



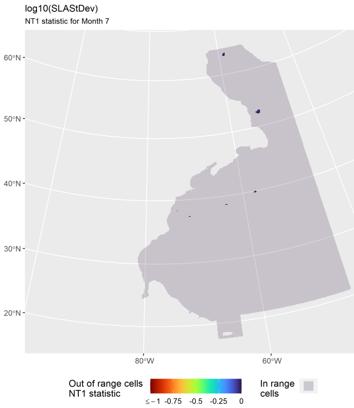
(a) April



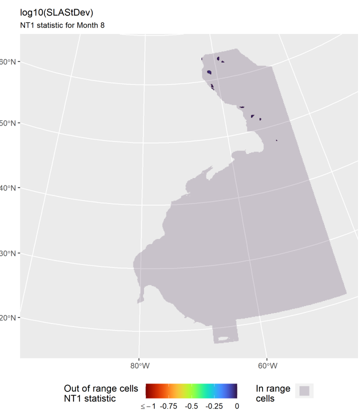
(b) May



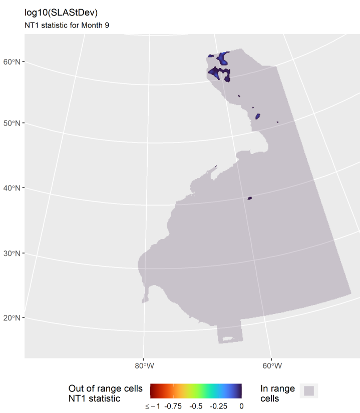
(c) June



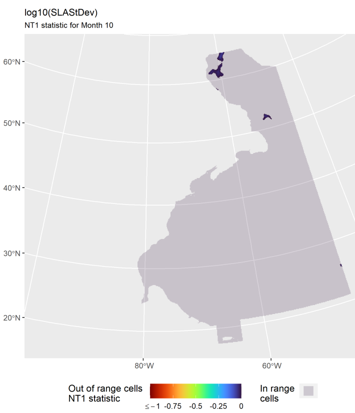
(d) July



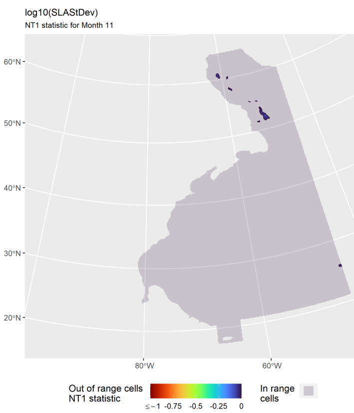
(e) August



(f) September



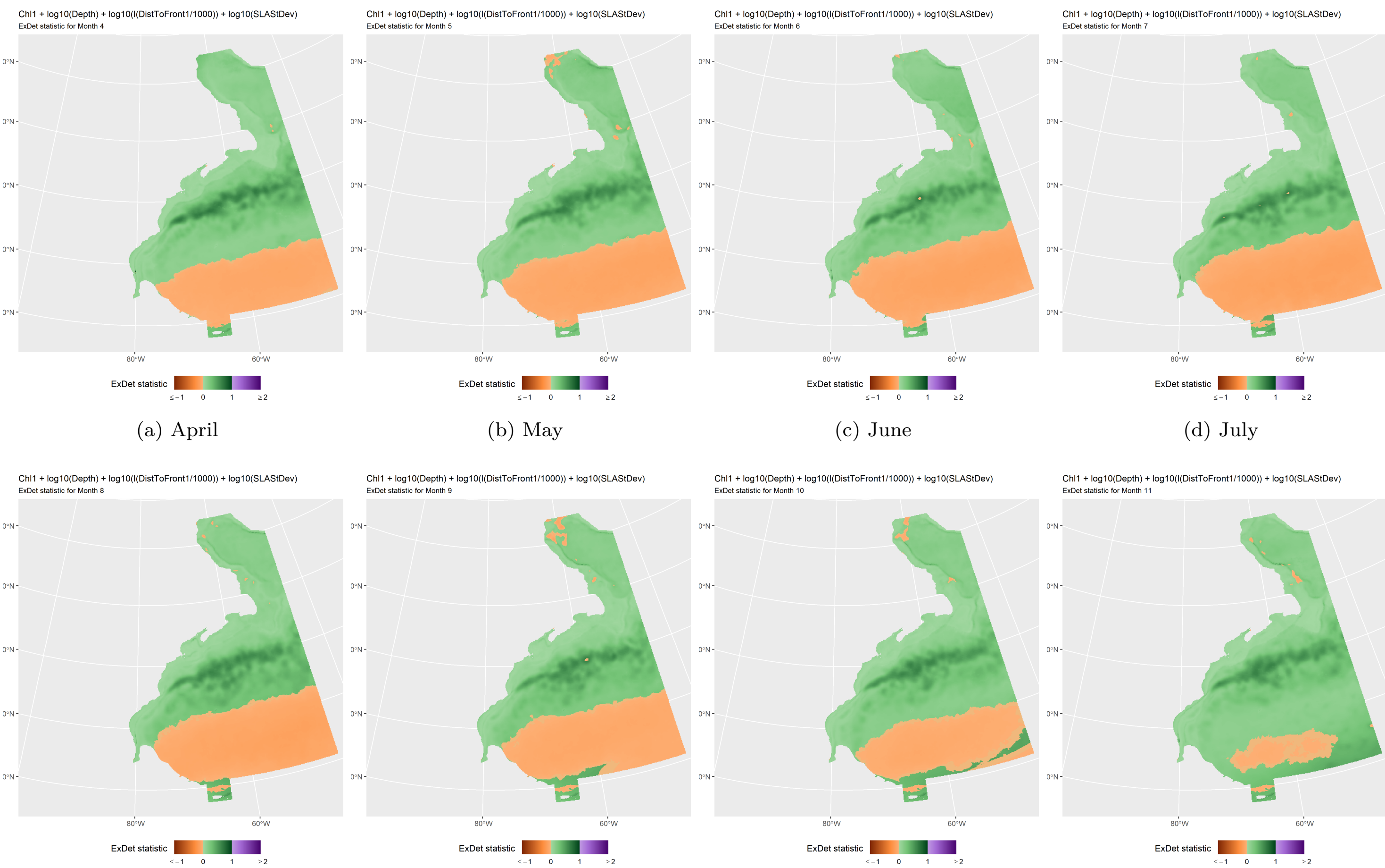
(g) October



(h) November

Figure 16: NT1 statistic (Mesgaran et al. (2014)) for the SLAStDev covariate in the model for the region AFTT Atlantic for Summer. 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.

2.2.3.2 Multivariate Extrapolation



(a) April (b) May (c) June (d) July

(e) August (f) September (g) October (h) November

Figure 17: ExDet statistic (Mesgaran et al. (2014)) for all of the covariates used in the model for the region AFTT Atlantic for Summer. 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

3.1.1 Winter (December-March)

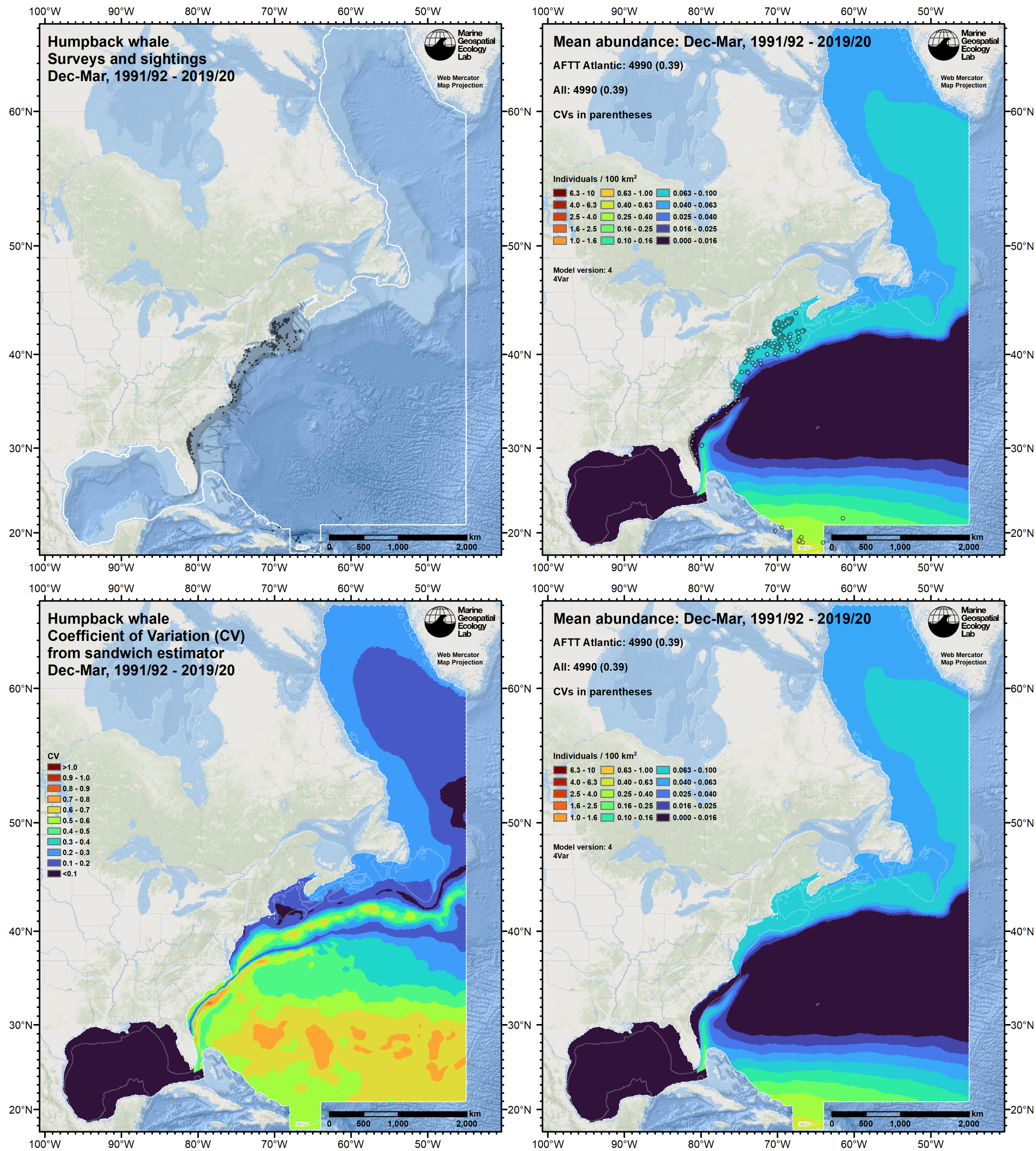


Figure 18: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for Winter the given era. Variance was estimated with the analytic approach given 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.

3.1.2 Summer (April-November)

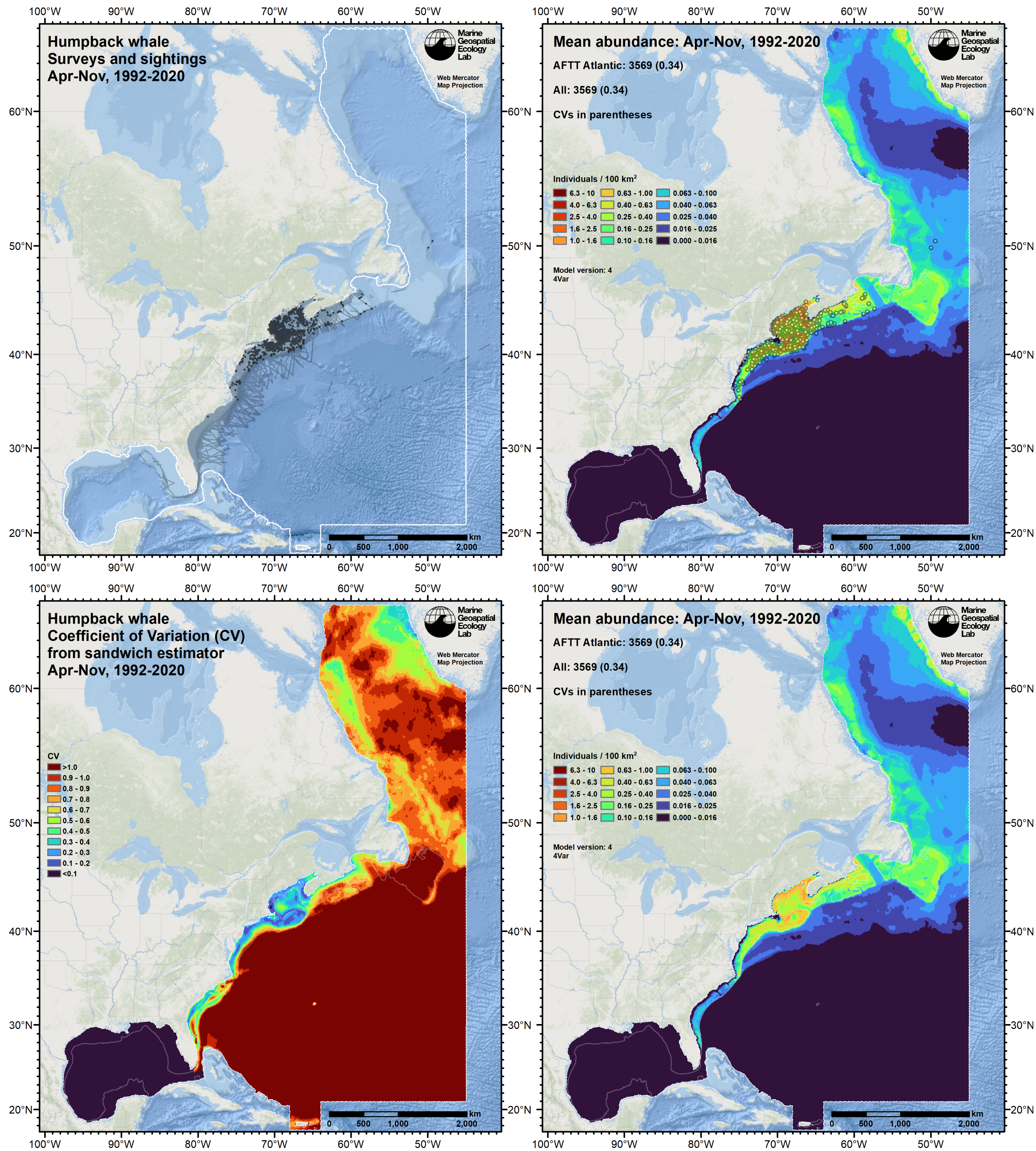


Figure 19: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for Summer the given era. Variance was estimated with the analytic approach given 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

3.2.1 Winter (December-March)

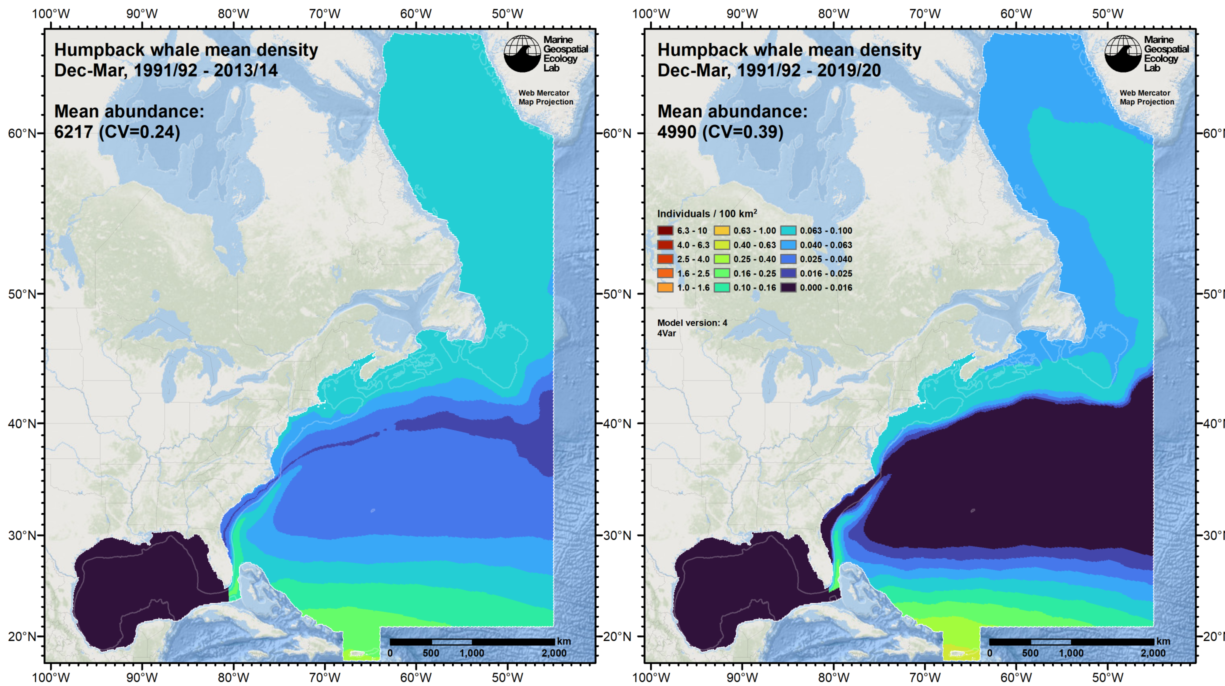


Figure 20: Comparison of the mean density predictions from the previous model (left) to those from this model (right) for the Winter season (December-March). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

3.2.2 Summer (April-November)

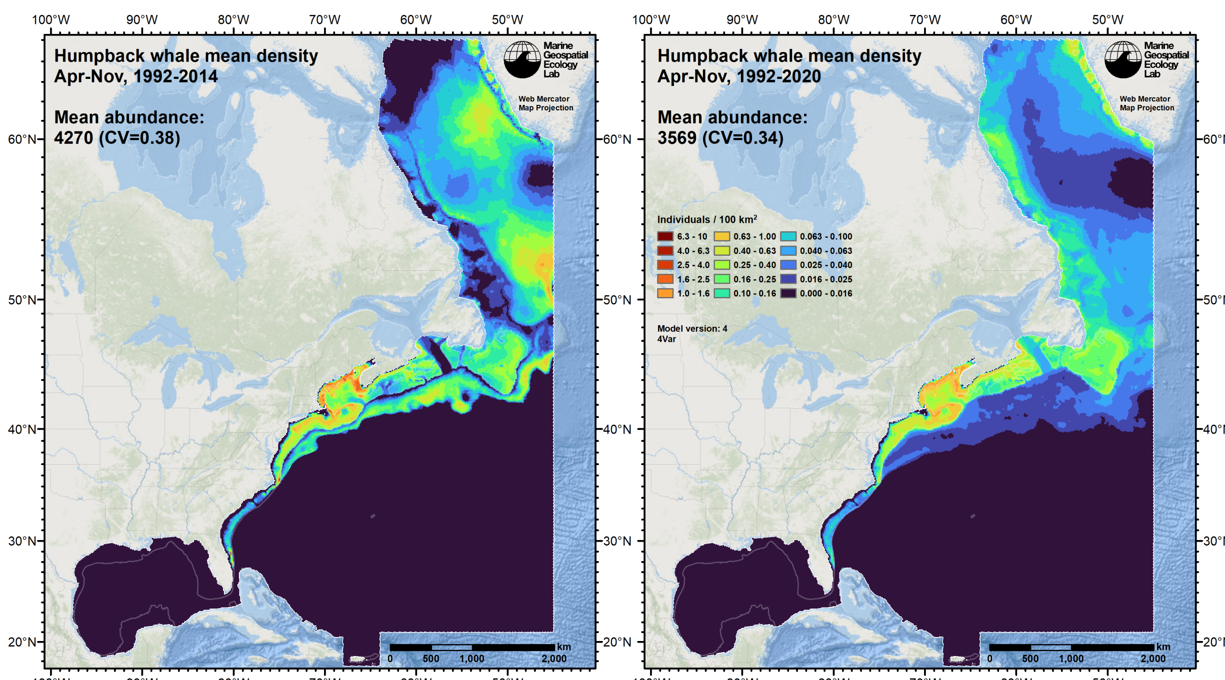


Figure 21: Comparison of the mean density predictions from the previous model (left) to those from this model (right) for the Summer season (April-November). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

4 Discussion

Following Mannocci et al. (2017), we summarized this model into two mean seasonal density surfaces (Figures 18, 19). 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. Humpback whales 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 generally resembled the predictions of Mannocci et al. (2017), but with some important differences in both seasons (Figures 20, 21). In winter, our model estimated negligible density beyond the continental shelf roughly between latitudes 30-40 °N while Mannocci's estimated low density across the region. While our model's predictions are consistent with what is known about the humpback's winter distribution, which is split between calving grounds around Caribbean islands and feeding grounds along the North American shelf, we caution that very little surveying has been done in distant offshore waters of the AFTT study area, particularly in winter. We also note that migrating humpbacks cross through this zone (Kennedy et al. 2014). Both models predicted non-negligible density across the most northern waters. This prediction was supported on the continental shelf by passive acoustic monitoring in Labrador and the Davis Strait (Davis et al. 2020; Delarue et al. 2022). The predictions of non-negligible density in off-shelf waters of the Labrador Sea is not consistent with the species' ecology, but no winter surveying has been done there so no data exist to refute this prediction or better calibrate the model there. Mean abundance estimated by our updated model was 20% lower than that of Mannocci's model, largely due to the difference at latitudes 30-40 °N, but the total abundance difference was not statistically significant. If potentially harmful activities are planned for those latitudes during these months, we advise caution and that a broad-scale survey program be initiated to better characterize cetacean density there.

In summer, the biggest difference between the models concerned predictions beyond the continental shelf, from Cape Hatteras through the Labrador Sea, where Mannocci's model predicted densities similar to or higher than those predicted on the shelf, while our model predicted much lower densities. The models differed substantially on the shelf of northern Newfoundland through Labrador and the Davis Strait. These differences were driven by different relationships fitted to the depth covariate in the two models (see Section 2.2). The predictions of our updated model were supported by sightings reported by aerial surveys of the Newfoundland and Labrador shelf in 2007 and 2015 (Lawson and Gosselin 2009, 2011, 2018). Surveys of the west Greenland shelf were made in the same years and also reported humpbacks (Heide-Jørgensen et al. 2010; Hansen et al. 2019). None of these surveys were available for use in our model; future updates would benefit from their inclusion. Predictions in these northern shelf areas were also supported by passive acoustic monitoring (Davis et al. 2020; Delarue et al. 2022) and opportunistic sightings reported in the OBIS-SEAMAP archive (Halpin et al. 2009) (https://seamap.env.duke.edu/species/180530). In general, the new model's prediction of higher density on the shelf than in the Labrador Sea better accords with the known ecology of the species than the old model's prediction of the opposite pattern. The new model did predict about 16% lower mean abundance but the difference from the old model was not statistically significant.

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