Density Model for Bryde's Whale (*Balaenoptera edeni*) for the U.S. Navy Atlantic Fleet Testing and Training (AFTT) Study Area: Supplementary Report

Model Version 2

Duke University Marine Geospatial Ecology Laboratory*

2022-06-20

Citation

When referencing our methodology or results generally, please cite Roberts et al. (2023), which documented the modeling cycle we completed in the 2022 for the U.S. Navy AFTT Phase IV Environmental Impact Statement, and Mannocci et al. (2017), which developed the original methodology and models upon which the 2022 models were based. The full citations appear in the References section at the end of this document.

To independently reference this specific model or Supplementary Report, please cite:

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Model Version History

Version	Date	Description
1	2015-01-23	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.
2	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

The goal of this project was to build, for the U.S. Navy's AFTT Phase IV Environmental Impact Statement (EIS), an update to the model we developed for the AFTT Phase III EIS. The Phase III model was developed using the methodology of Mannocci et al. (2017) by L. Mannocci but not included in the 2017 publication. Following the approach taken by that model, we built this update from data collected in the east coast, Gulf of Mexico, and Caribbean regions. That model also included the MAR-ECO survey of the Mid-Atlantic Ridge, which reported a sighting north of the Azores, and excluded surveys of Europe, which did not report any sightings. We also included the MAR-ECO survey, but only segments south of 50 °N, based on the Bryde's whale's tropical, subtropical, and warm-temperate distribution. We also included segments south of 50 °N from trans-Atlantic surveys by R/V Song of the Whale, which were not available for the Phase III model.

Since the Phase III model was developed in 2015, the Bryde's-like whale that inhabits the Gulf of Mexico was determined to be a separate species, Rice's whale (*Balaenoptera ricei*) (Rosel et al. 2021). Under the assumption that the overall ecology of Rice's whale is similar to that of Bryde's whale (the limited distribution of Rice's whale notwithstanding), and in keeping with the prior model, we included the Rice's whale sightings in the Gulf of Mexico as a proxy for Bryde's whale. Breaking with the prior model, we excluded four ambiguous "sei or Bryde's whale" sightings reported by NOAA SEFSC in the 1990s along the U.S. east coast. In the prior modeling cycle, we included these in both the sei whale and Bryde's whale models, out of an abundance of caution. Subsequently, Rosel et al. (2021) reviewed multiple lines of evidence, including our prior model, and concluded that "Overall, the evidence to date indicates Bryde's whales are extremely rare in U.S. waters of the western North Atlantic." They pointed out that passive acoustic monitoring had not recorded whale call types associated with any type of Bryde's whale along the east coast, but sei whales had been regularly recorded. Lacking any more recent possible evidence of Bryde's whales in the east coast study area, and given the expert opinions of Rosel et al., our conclusion is that the ambiguous sightings from the 1990s were sei whales, and in this modeling cycle we only included them in the sei whale model.

For all surveys, we restricted the updated 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 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	11	0	0	
NEAq	CNM	2017-2020	2	0	0	
NEAq	MMS-WEA	2017-2020	37	0	0	
NEAq	NLPSC	2011-2015	43	0	0	
NEFSC	AMAPPS	2010-2019	89	0	0	
NEFSC	NARWSS	2003-2020	484	0	0	
NEFSC	Pre-AMAPPS	1999-2008	46	0	0	
NJDEP	NJEBS	2008-2009	11	0	0	
NYS-DEC/TT	NYBWM	2017-2020	77	0	0	
SEFSC	AMAPPS	2010-2020	114	0	0	
SEFSC	GOMEX92-96	1992-1996	27	0	0	
SEFSC	GulfCet I	1992-1994	50	1	1	1.0
SEFSC	GulfCet II	1996-1998	22	1	2	2.0
SEFSC	GulfSCAT 2007	2007-2007	18	2	2	1.0
SEFSC	MATS	1995-2005	34	0	0	
SEFSC	SECAS	1992-1995	8	0	0	
U. La Rochelle	REMMOA	2008-2017	42	0	0	
UNCW	MidA Bottlenose	2002-2002	17	0	0	
UNCW	Navy Cape Hatteras	2011-2017	34	0	0	
UNCW	Navy Jacksonville	2009-2017	92	0	0	
UNCW	Navy Norfolk Canyon	2015-2017	14	0	0	
UNCW	Navy Onslow Bay	2007-2011	49	0	0	
UNCW	SEUS NARW EWS	2005-2008	114	0	0	

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. *(continued)*

			Effort	Observations		
Institution	Program	Period	1000s km	Groups	Individuals	Mean Group Size
VAMSC	MD DNR WEA	2013-2015	16	0	0	
VAMSC	Navy VACAPES	2016-2017	19	0	0	
VAMSC	VA CZM WEA	2012-2015	21	0	0	
		Total	**1,493**	**4**	**5**	**1.2**
Shipboard Surveys						
IMR	MAR-ECO	2004-2004	1	1	1	1.0
MCR	SOTW Visual	2005-2019	23	7	8	1.1
NEFSC	AMAPPS	2011-2016	16	0	0	
NEFSC	Pre-AMAPPS	1995-2007	18	0	0	
NJDEP	NJEBS	2008-2009	14	0	0	
SEFSC	AMAPPS	2011-2016	17	5	15	3.0
SEFSC	GOM Oceanic CetShip	1992-2001	49	11	22	2.0
SEFSC	GOM Shelf CetShip	1994-2001	10	1	1	1.0
SEFSC	Pre-AMAPPS	1992-2006	33	1	2	2.0
SEFSC	Pre-GoMMAPPS	2003-2009	19	5	7	1.4
SEFSC	SEFSC Caribbean	1995-2000	8	4	6	1.5
		Total	**208**	**35**	**62**	**1.8**
		Grand Total	**1,701**	**39**	**67**	**1.7**

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

Institution	Full Name
HDR	HDR, Inc.
IMR	Norway Institute of Marine Research
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

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)
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)

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

Program	Description	References
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)
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)
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)
SECAS	Southeast Cetacean Aerial Surveys	Blaylock and Hoggard (1994)
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 Phase III model with new data without repeating the covariate selection exercise performed during its development. We therefore fitted a year-round model that included sea surface temperature as the only covariate, as done for the prior model. The resulting relationship (Figure 2) strongly resembled that of the prior model. Model predictions are shown in Section 3. Because Bryde's whale is considered absent in the Gulf of Mexico and extremely rare in U.S. waters of the western North Atlantic (Rosel et al. 2021), we set density to zero in the Gulf of Mexico and East Coast regions (see Roberts et al. (2023) for additional discussion). Univariate extrapolation analyses displayed geographic patterns very similar to the environmental envelope estimated for the prior model (Figure 6). The necessity for environmental extrapolation was driven mainly by a lack of sampling in waters with very low sea surface temperatures, as occurred of northern Newfoundland, Labrador, and west Greenland in non-summer months.

2.1 Final Model

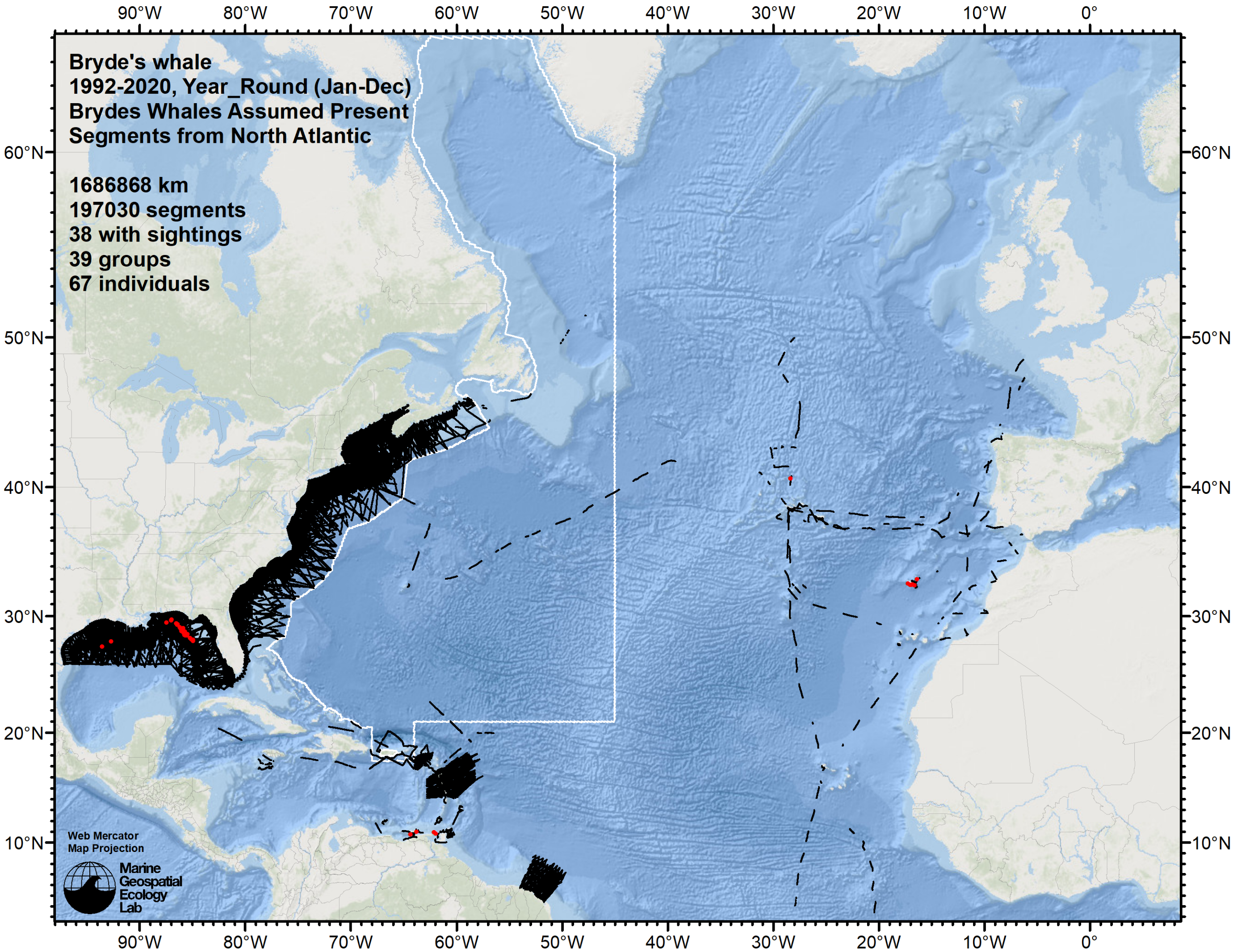


Figure 1: Survey segments (black lines) used to fit the model for the region Brydes Whales Assumed Present. Red points indicate segments with observations. This map uses a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

Statistical output for this model:

```
Family: Tweedie(p=1.272)
Link function: log
```

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

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -27.382      1.459  -18.76   <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) 2.051      3 4.772 0.000564 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.000513   Deviance explained = 21.1%
-REML = 417.33  Scale est. = 33.261    n = 196932

Method: REML   Optimizer: outer newton
full convergence after 12 iterations.
Gradient range [-1.608598e-06,1.047483e-06]
(score 417.3302 & scale 33.26104).
Hessian positive definite, eigenvalue range [0.5034328,427.0678].
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 2.05    0.11  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

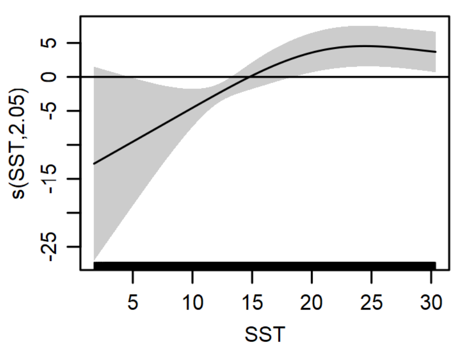


Figure 2: Functional plots for the final model for the region Brydes Whales Assumed Present. Transforms and other treatments are indicated in axis labels. *log10* indicates the covariate was $\log_{10}$ transformed. *sqrt* indicates the covariate was square-root transformed. */1000* indicates meters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

Table 4: Covariates used in the final model for the region Brydes Whales Assumed Present.

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

2.2 Diagnostic Plots

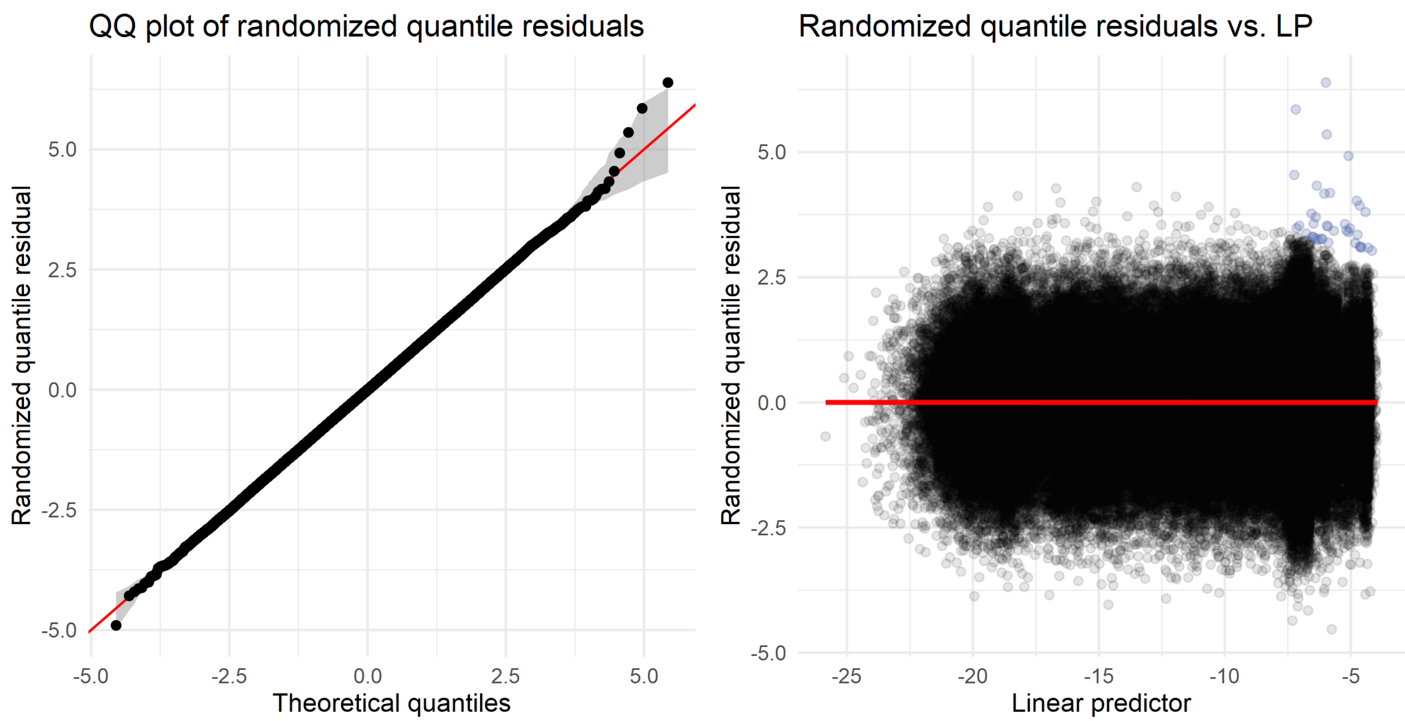


Figure 3: Residual plots for the final model for the region Brydes Whales Assumed Present.

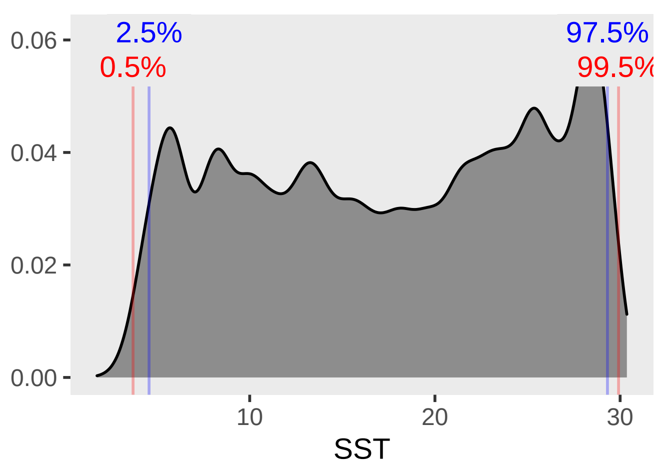


Figure 4: Density histograms showing the distributions of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Red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

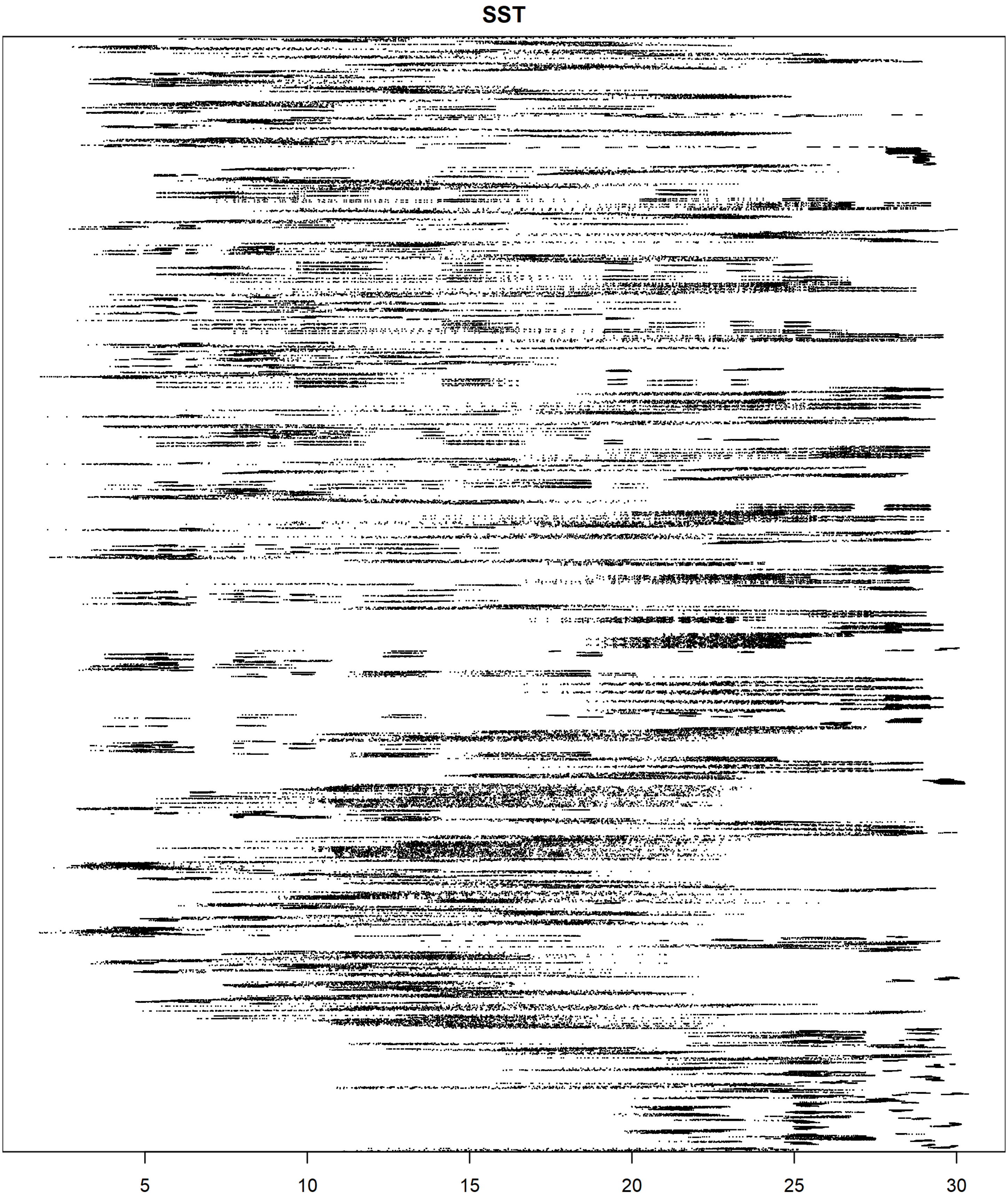
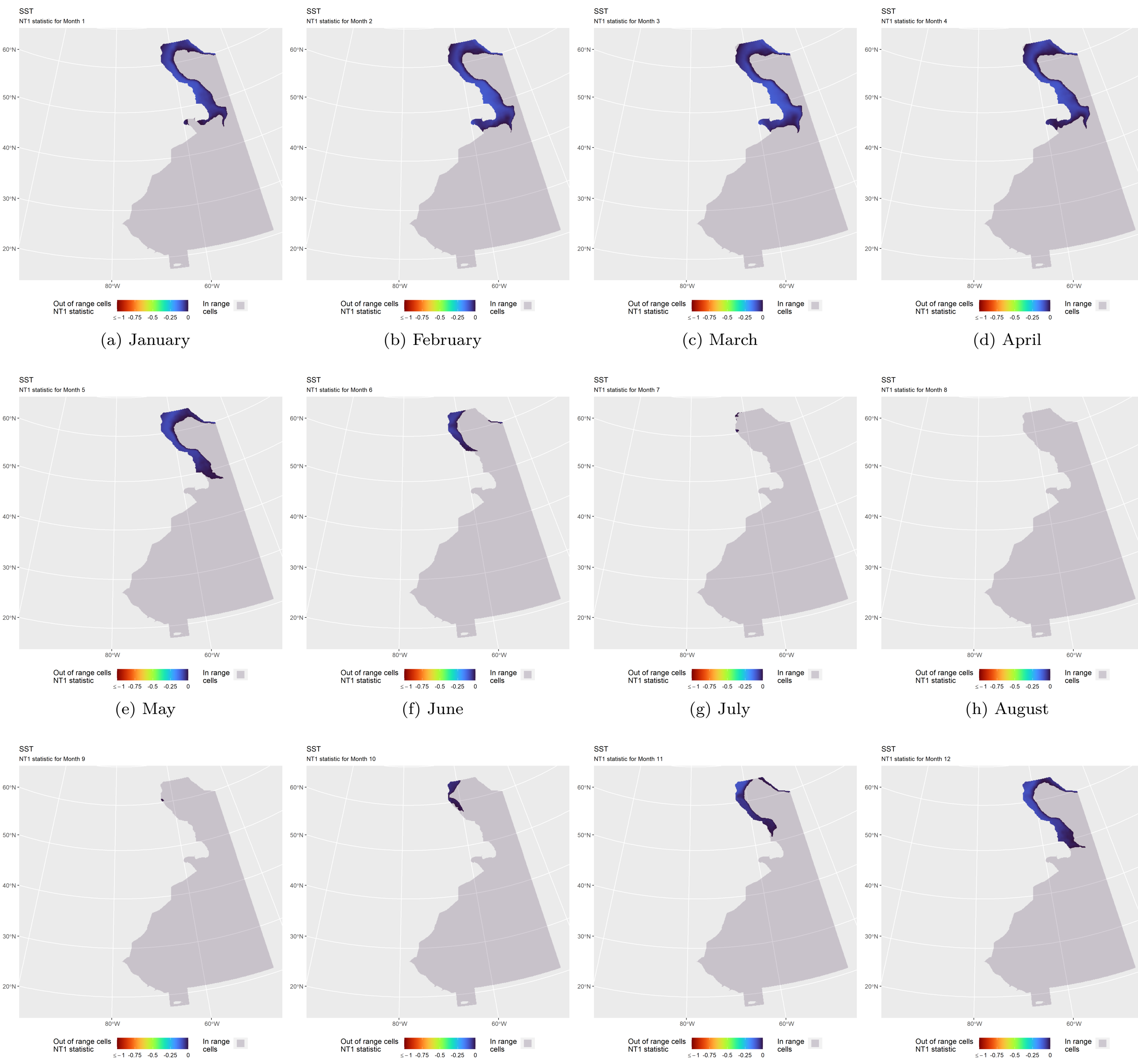


Figure 5: Dotplot of the covariates considered during the final model selection step. The final model may have included only a subset of the covariates shown here (see Figure 2), and additional covariates may have been considered in preceding selection steps. Covariates are transformed as shown in Figure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

2.3 Extrapolation Diagnostics



(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 6: NT1 statistic (Mesgaran et al. (2014)) for the SST covariate in the model for the region Brydes Whales Assumed Present. 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.

3 Predictions

3.1 Summarized Predictions

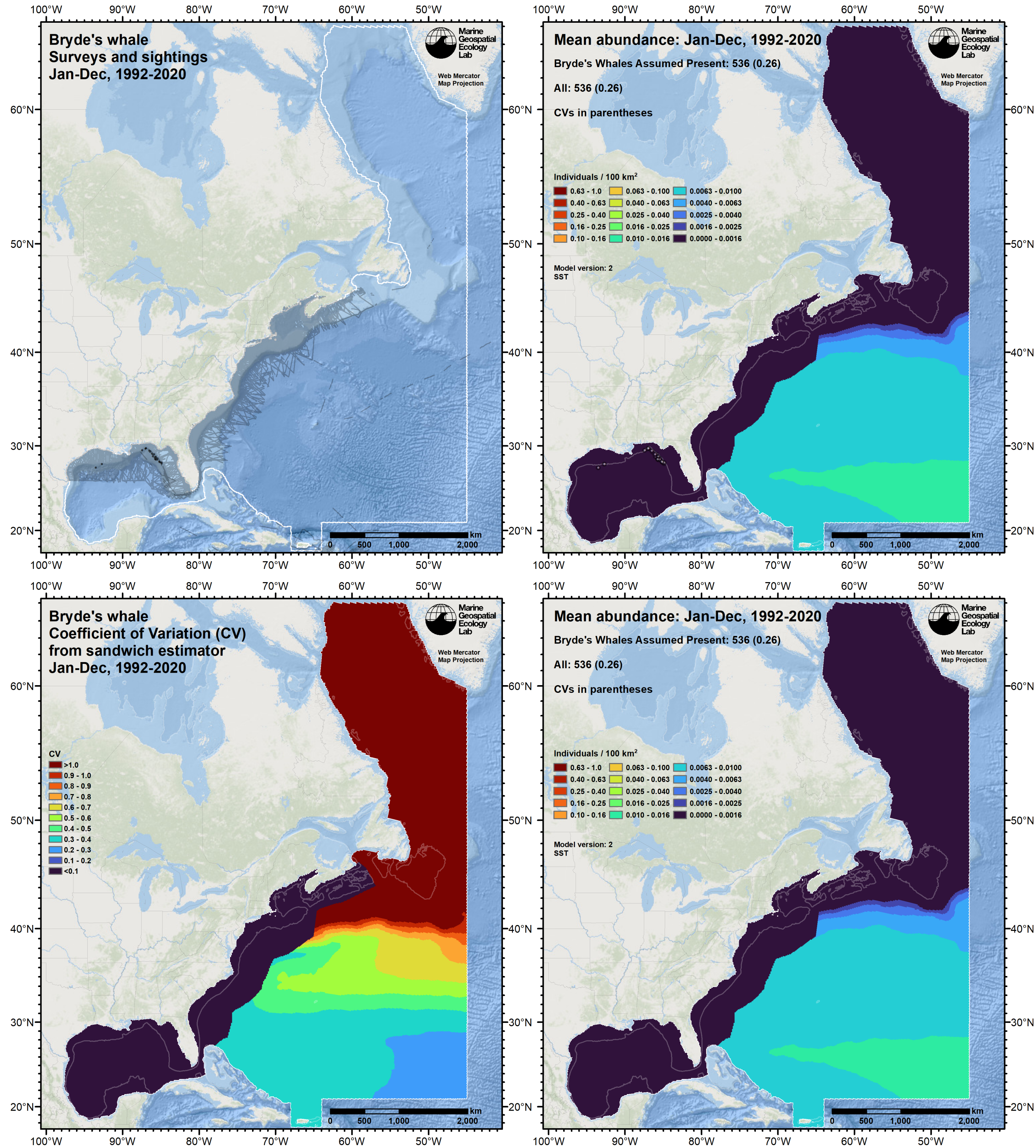


Figure 7: Survey effort and observations (top left), predicted density with observations (top right), predicted density without observations (bottom right), and coefficient of variation of predicted density (bottom left), for the given era. Variance was estimated with the analytic approach given by Miller 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

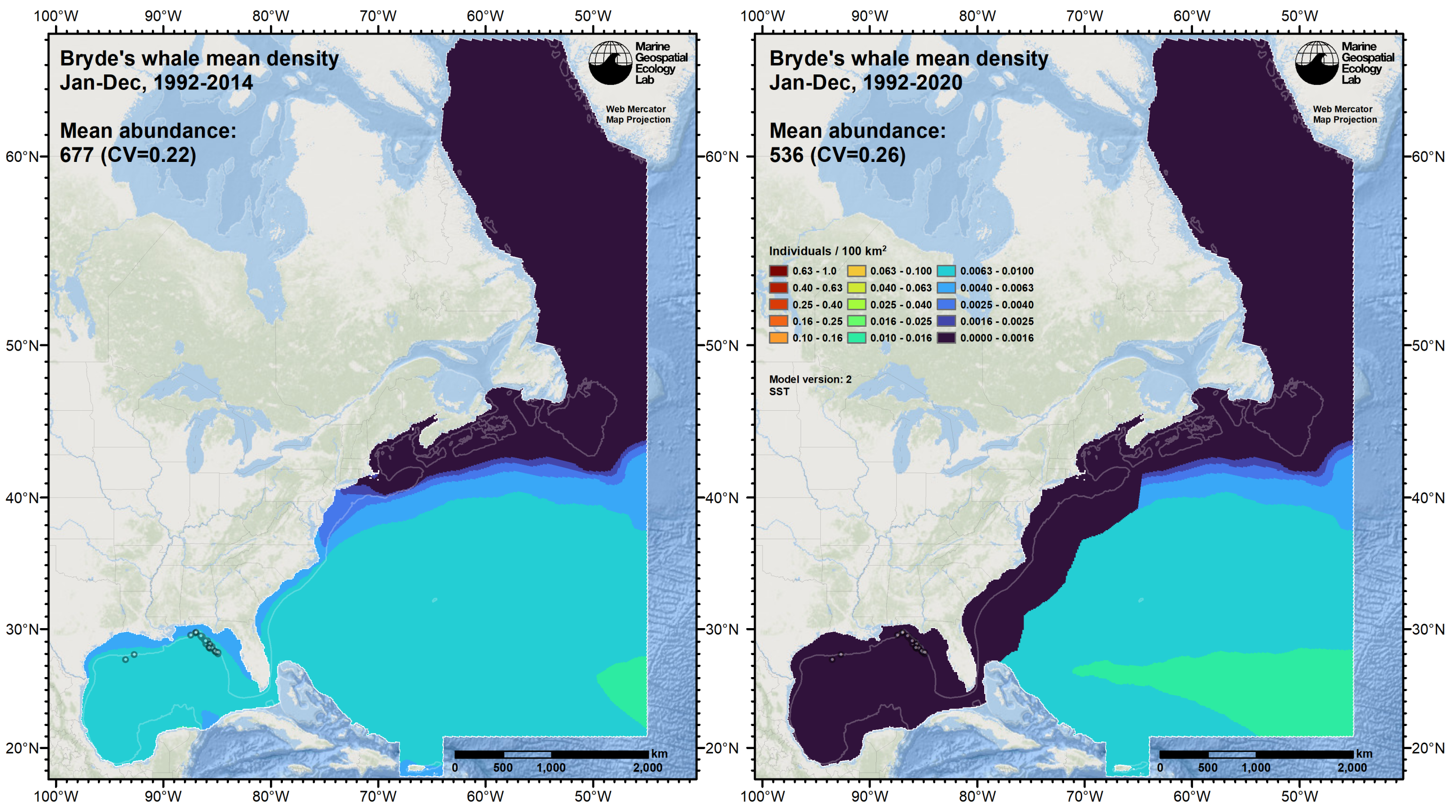


Figure 8: Comparison of the mean density predictions from the previous model (left) to those from this model (right). These maps use a Web Mercator projection but the analysis was conducted in an Albers Equal Area coordinate system appropriate for density modeling.

4 Discussion

Following what was done for the prior model, we summarized this updated model into a single year-round mean density surface (Figure 7). The predictions strongly resembled the prior model's predictions (Figure 8), except that we explicitly set density in the Gulf of Mexico and East Coast study areas to zero (see Section 2 and Roberts et al. (2023)). Mean abundance predicted by the new model was very similar to that of the old model, once the differences in the Gulf of Mexico and East Coast were taken into account.

Extrapolation analysis (Figure 6) showed that environmental extrapolation was necessary off northern Newfoundland, Labrador, and west Greenland in non-summer months, driven by the low sea surface temperatures there during those months. However, the Bryde's whale, a tropical, subtropical, and warm-temperate species, is considered absent in these areas, so we do not find this extrapolation as cause for concern.

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