Density Model for Pygmy Killer Whale (*Feresa attenuata*) for the U.S. Gulf of Mexico: Supplementary Report

Duke University Marine Geospatial Ecology Lab*

Model Version 1.3 - 2015-10-01

Citation

When referencing our methodology or results generally, please cite our open-access article:

Roberts JJ, Best BD, Mannocci L, Fujioka E, Halpin PN, Palka DL, Garrison LP, Mullin KD, Cole TVN, Khan CB, McLellan WM, Pabst DA, Lockhart GG (2016) Habitat-based cetacean density models for the U.S. Atlantic and Gulf of Mexico. Scientific Reports 6: 22615. doi: 10.1038/srep22615

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

Roberts JJ, Best BD, Mannocci L, Fujioka E, Halpin PN, Palka DL, Garrison LP, Mullin KD, Cole TVN, Khan CB, McLellan WM, Pabst DA, Lockhart GG (2015) Density Model for Pygmy Killer Whale (*Feresa attenuata*) for the U.S. Gulf of Mexico Version 1.3, 2015-10-01, and Supplementary Report. Marine Geospatial Ecology Lab, Duke University, Durham, North Carolina.

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Revision History

Version	Date	Description of changes
1	2015-01-22	Initial version.
1.1	2015-02-02	Updated the documentation. No changes to the model.
1.2	2015-05-14	Updated calculation of CVs. Switched density rasters to logarithmic breaks. No changes to the model.
1.3	2015-10-01	Updated the documentation. No changes to the model.

*For questions, or to offer feedback about this model or report, please contact Jason Roberts (jason.roberts@duke.edu)

Survey Data

Survey	Period	Length (1000 km)	Hours	Sightings
SEFSC GOMEX92-96 Aerial Surveys	1992-1996	27	152	0
SEFSC Gulf of Mexico Shipboard Surveys, 2003-2009	2003-2009	19	1156	8
SEFSC GulfCet I Aerial Surveys	1992-1994	50	257	4
SEFSC GulfCet II Aerial Surveys	1996-1998	22	124	3
SEFSC GulfSCAT 2007 Aerial Surveys	2007-2007	18	95	0
SEFSC Oceanic CetShip Surveys	1992-2001	49	3102	12
SEFSC Shelf CetShip Surveys	1994-2001	10	707	0
Total		195	5593	27

Table 2: Survey effort and sightings used in this model. Effort is tallied as the cumulative length of on-effort transects and hours the survey team was on effort. Sightings are the number of on-effort encounters of the modeled species for which a perpendicular sighting distance (PSD) was available. Off effort sightings and those without PSDs were omitted from the analysis.

Period	Length (1000 km)	Hours	Sightings
1992-2009	195	5592	27
1998-2009	62	2679	15
% Lost	68	52	44

Table 3: Survey effort and on-effort sightings having perpendicular sighting distances. % Lost shows the percentage of effort or sightings lost by restricting the analysis to surveys performed in 1998 and later, the era in which remotely-sensed chlorophyll and derived productivity estimates are available. See Figure 1 for more information.

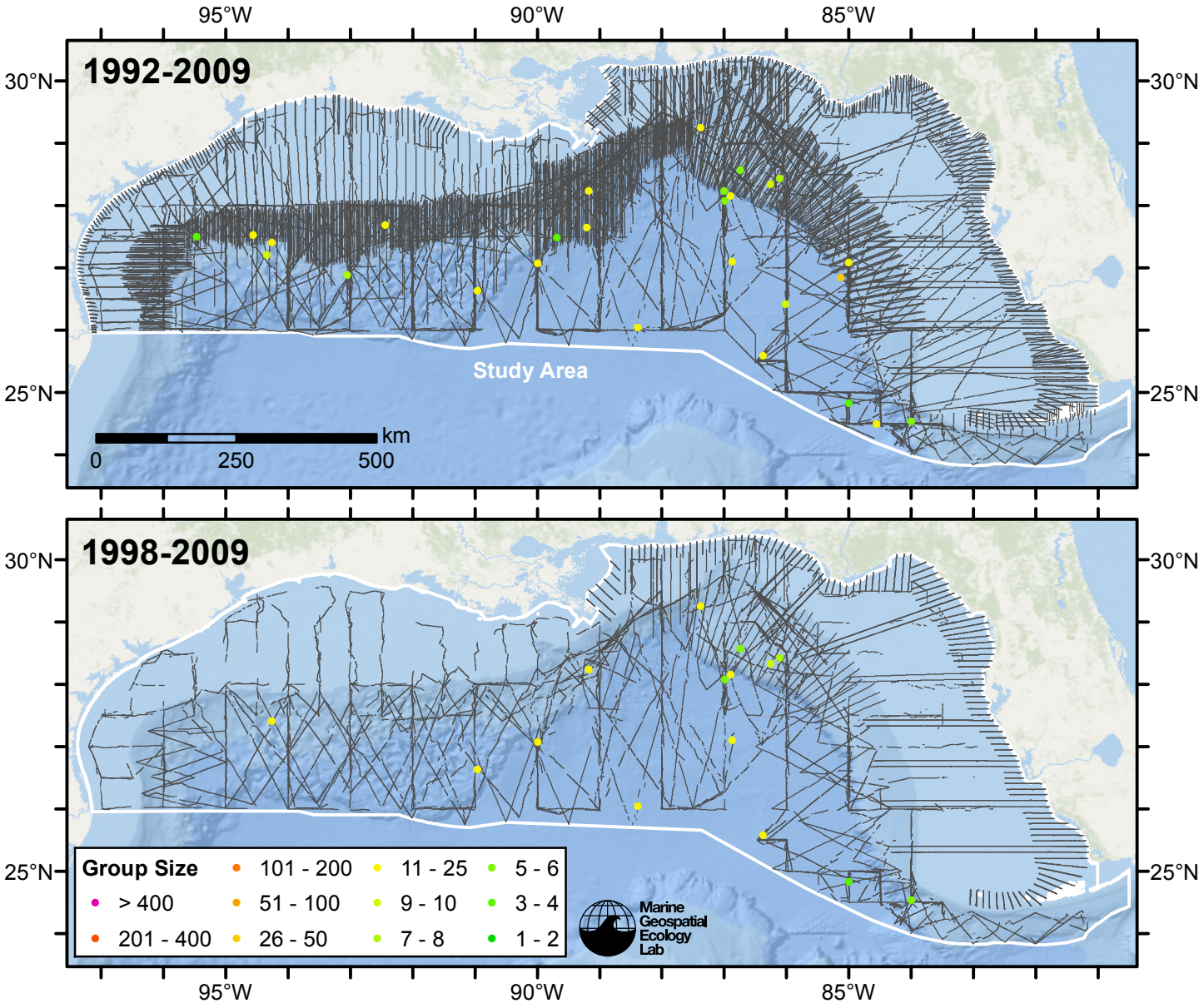


Figure 1: Pygmy killer whale sightings and survey tracklines. The top map shows all surveys. The bottom map shows surveys performed in 1998 or later. the era in which remotely-sensed chlorophyll and derived productivity estimates are available. Models fitted to contemporaneous (day-of-sighting) estimates of those predictors only utilize these surveys. These maps illustrate the survey data lost in order to utilize those predictors. Models fitted to climatogical estimates of those predictors do not suffer this data loss.

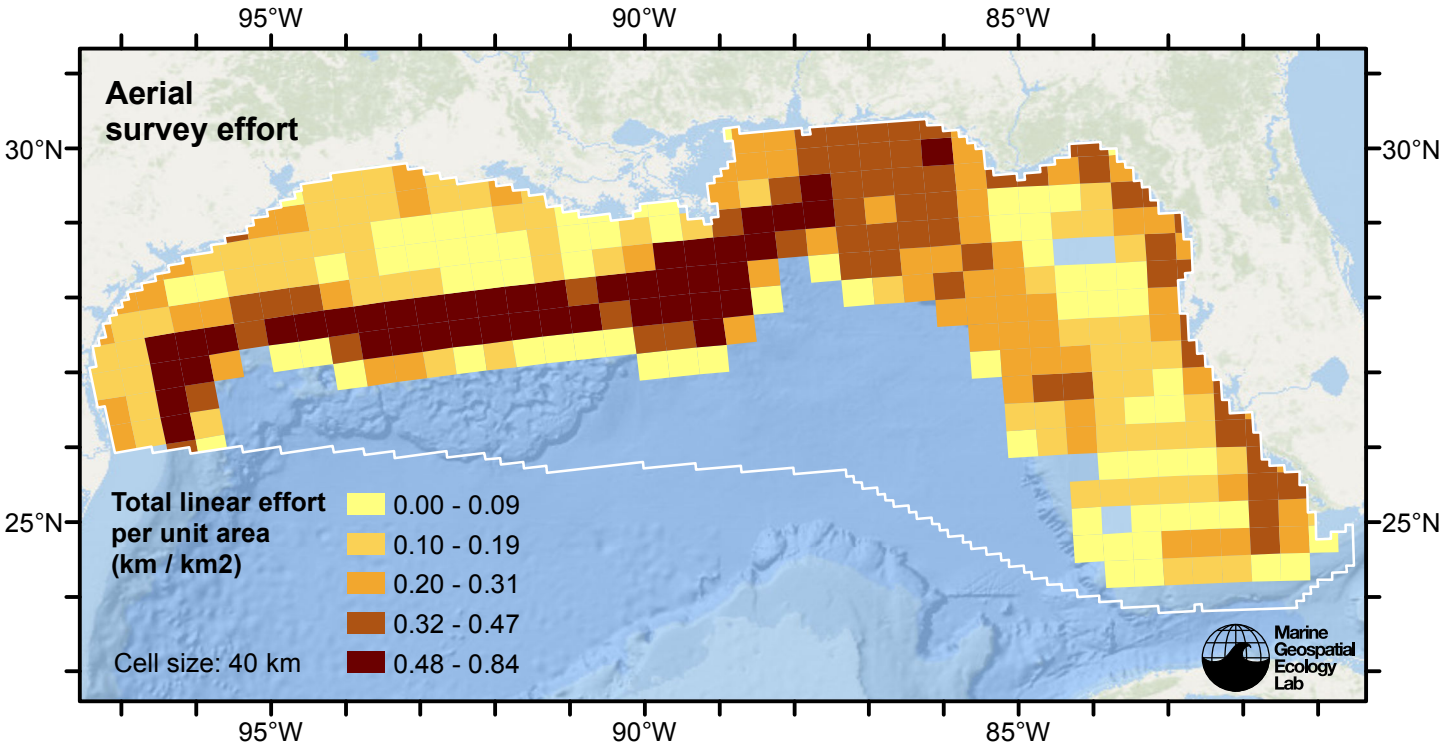


Figure 2: Aerial linear survey effort per unit area.

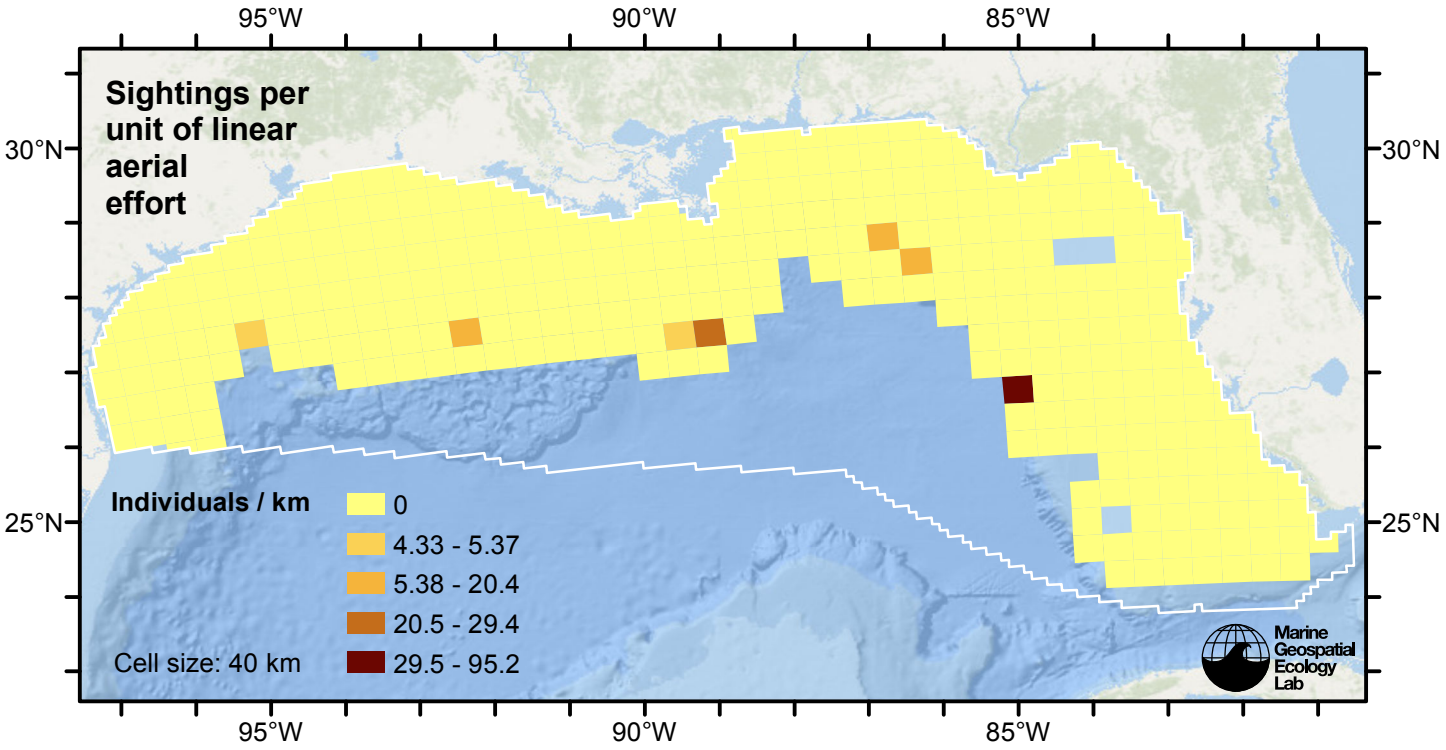


Figure 3: Pygmy killer whale sightings per unit aerial linear survey effort.

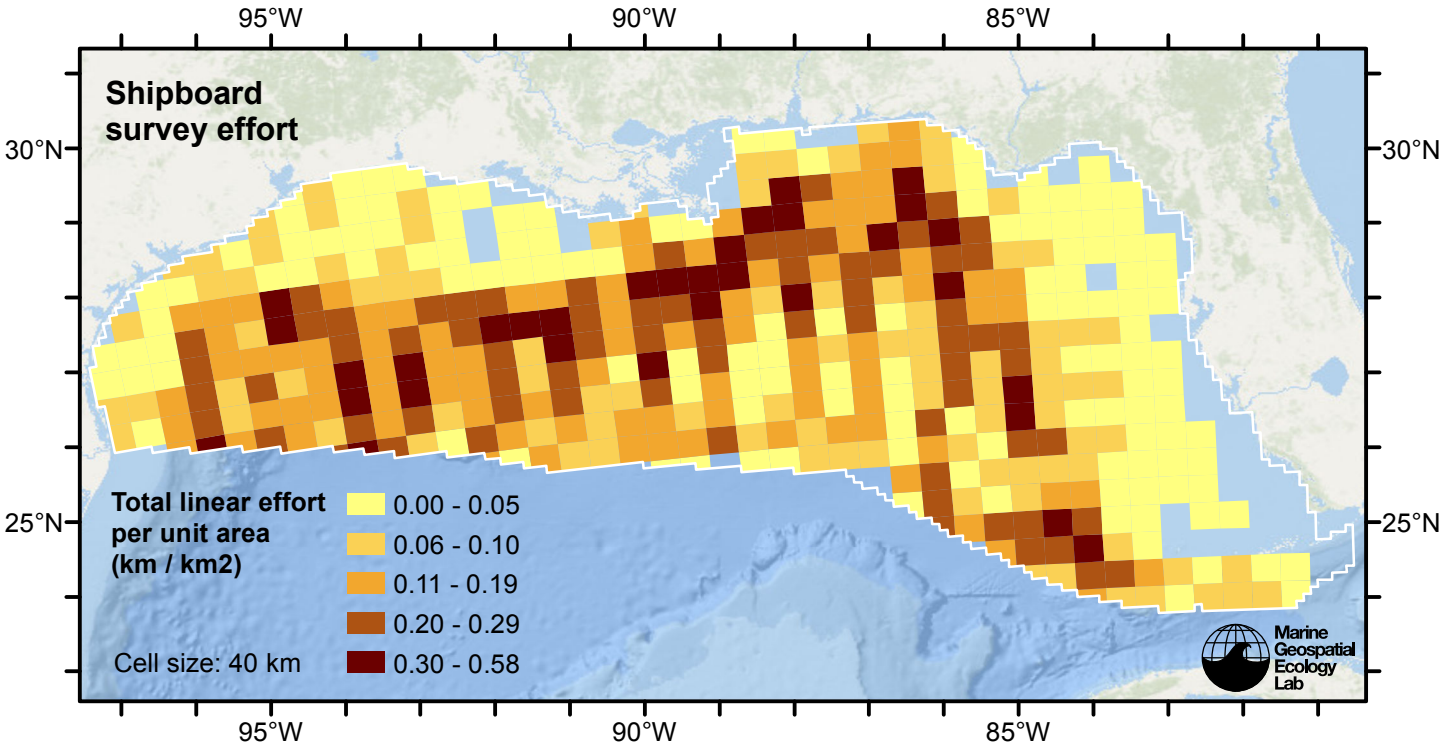


Figure 4: Shipboard linear survey effort per unit area.

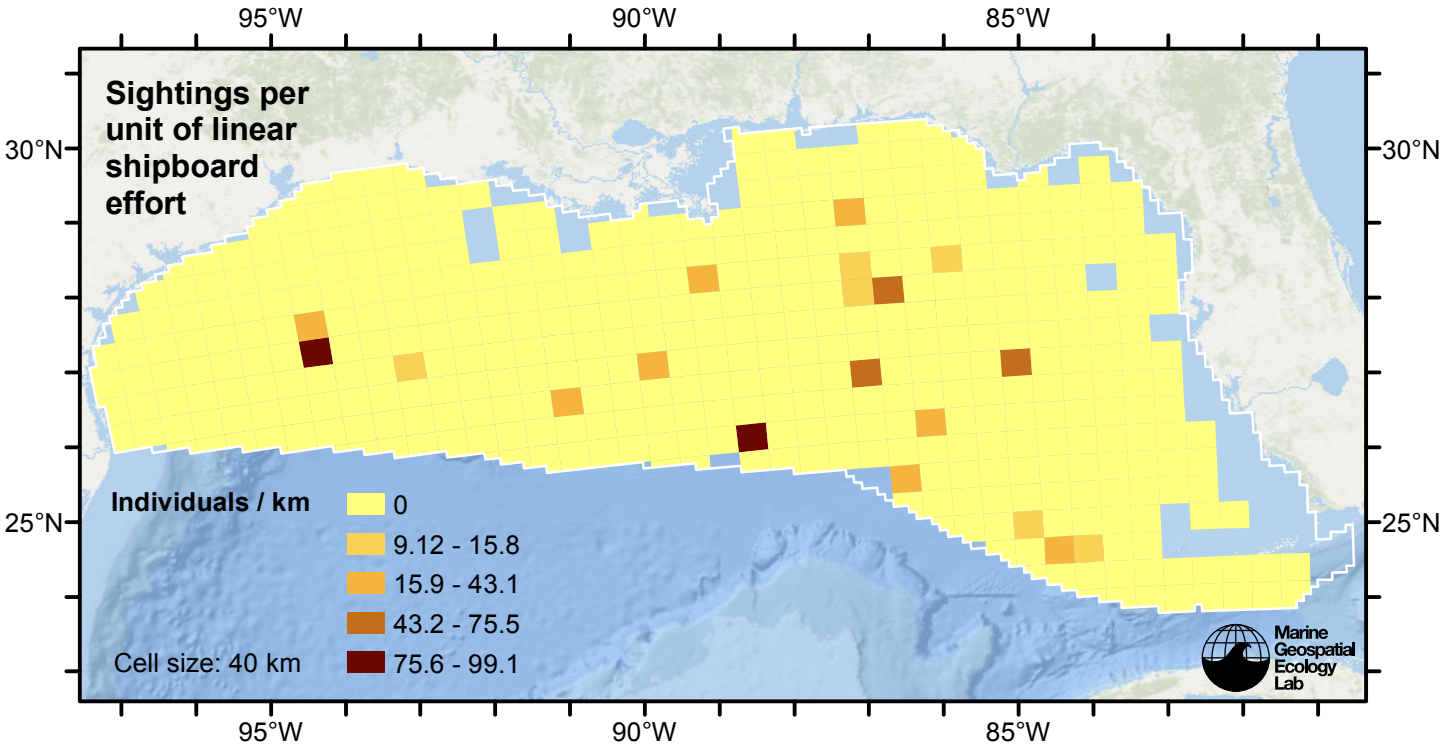


Figure 5: Pygmy killer whale sightings per unit shipboard linear survey effort.

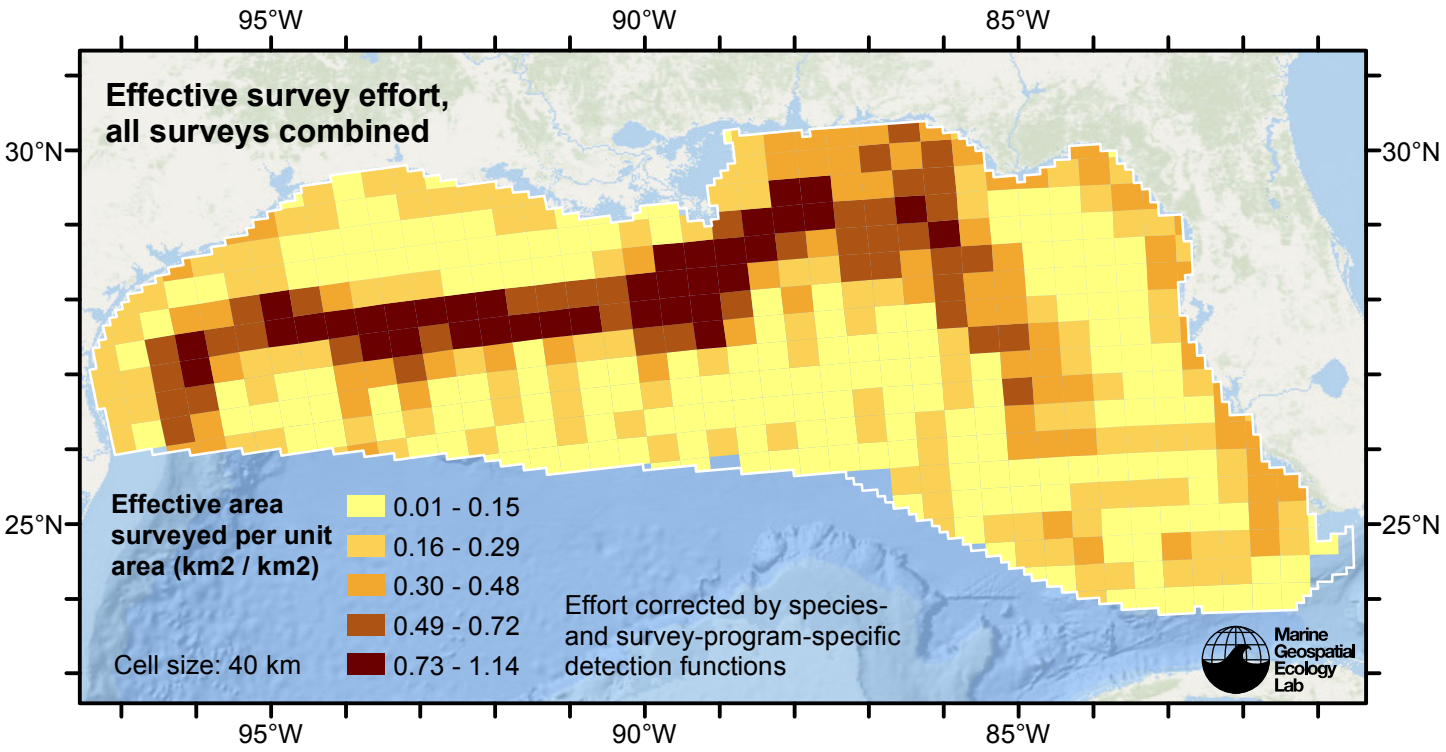


Figure 6: Effective survey effort per unit area, for all surveys combined. Here, effort is corrected by the species- and survey-program-specific detection functions used in fitting the density models.

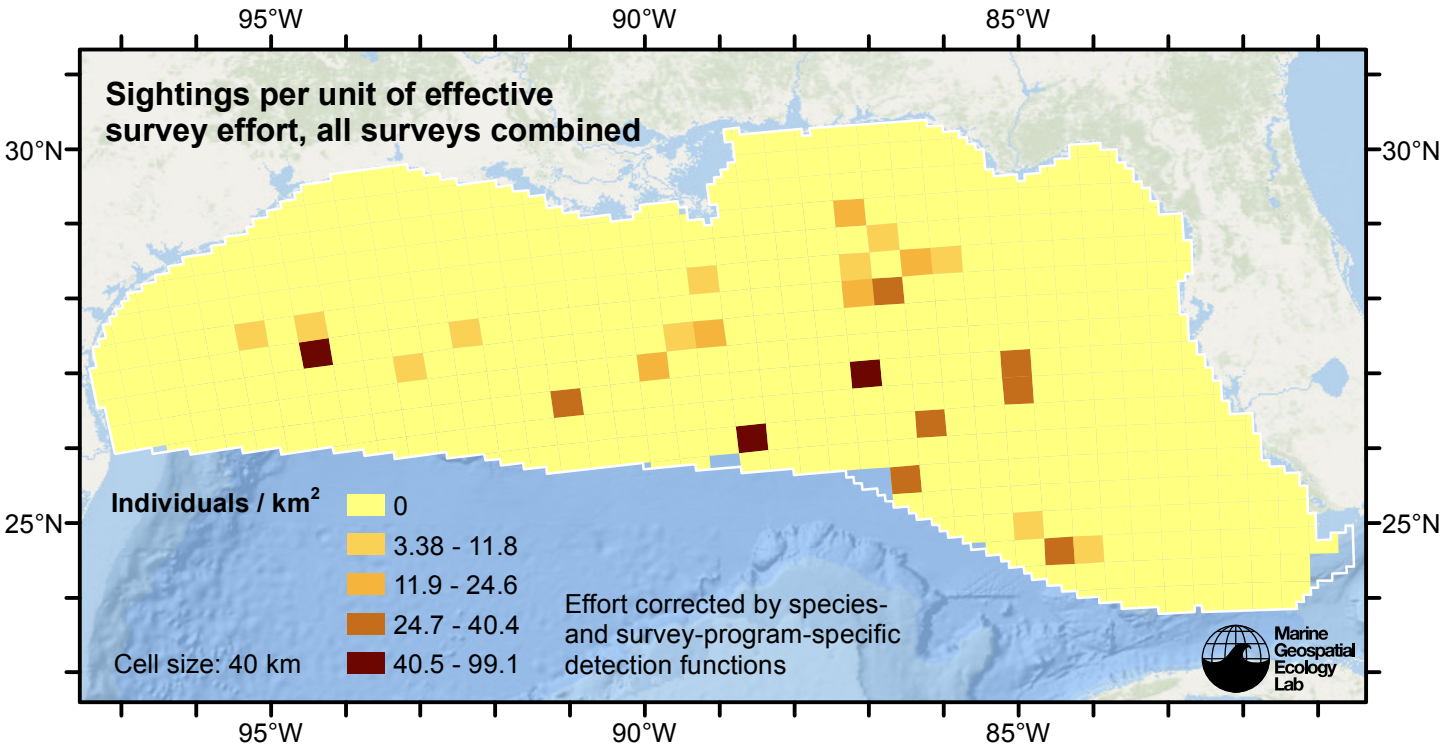


Figure 7: Pygmy killer whale sightings per unit of effective survey effort, for all surveys combined. Here, effort is corrected by the species- and survey-program-specific detection functions used in fitting the density models.

Reclassification of Ambiguous Sightings

Observers occasionally experience difficulty identifying species, due to poor sighting conditions or phenotypic similarities between the possible choices. For example, observers may not always be able to distinguish fin whales from sei whales (Tim Cole, pers. comm.). When this happens, observers will report an ambiguous identification, such as "fin or sei whale".

In our density models, we handled ambiguous identifications in three ways:

1. For sightings with very generic identifications such as "large whale", we discarded the sightings. These sightings represented a clear minority when compared to those with definitive species identifications, but they are uncounted animals and our density models may therefore underestimate density to some degree.
2. For sightings of certain taxa in which a large majority of identifications were ambiguous (e.g. "Globicephala spp.") rather than specific (e.g. "Globicephala melas" or "Globicephala macrorhynchus"), it was not tractable to model the individual species so we modeled the generic taxon instead.
3. For sightings that reported an ambiguous identification of two species (e.g. "fin or sei whale") that are known to exhibit different habitat preferences or typically occur in different group sizes, and for which we had sufficient number of definitive sightings of both species, we fitted a predictive model that classified the ambiguous sightings into one species or the other.

This section describes how we utilized the third category of ambiguous sightings in the density models presented in this report.

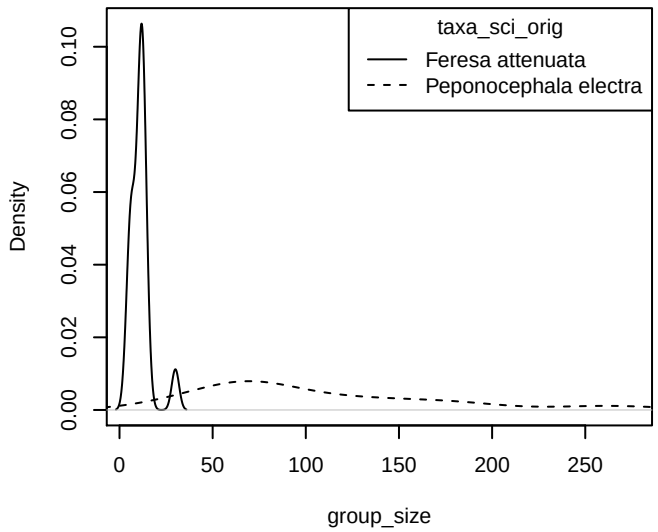
For the predictive model, we used the cforest classifier (Hothorn et al. 2006), an elaboration of the classic random forest classifier (Breiman, 2001). First, we trained a binary classifier using the sightings that reported definitive species identifications (e.g. "fin whale" and "sei whale"). The training data included all on-effort sightings, not just those in the focal study area. We used the species ID as the response variable and oceanographic variables or group size as predictor variables, depending on the species. We used receiver operating characteristic (ROC) curve analysis to select a threshold for classifying the probabilistic predictions of species identifications made by the model into a binary result of one species or another; for the threshold, we selected the value that maximized the Youden index (see Perkins and Schisterman, 2006).

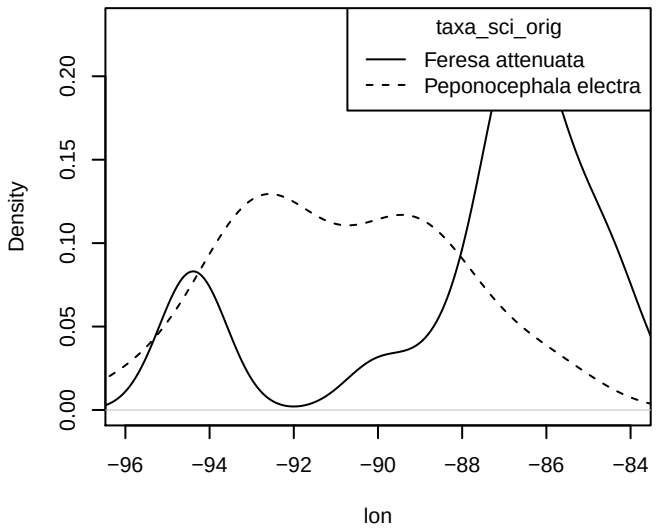
Then, for all sightings reporting the ambiguous identification, we reclassified the sighting as either one species or the other by processing the predictor values observed for that sighting through the fitted model. We then included the reclassified sightings in the detection functions and spatial models of density. The sightings reported elsewhere in this document incorporate both the definitive sightings and the reclassified sightings.

Reclassification of "Feresa attenuata/Peponocephala electra" in the Gulf of Mexico Region

Density Histograms

These plots show the per-species distribution of each predictor variable used in the reclassification model. When a variable exhibits a substantially different distribution for each species, it is a good candidate for classifying ambiguous sightings as one species or the other.





Statistical output

```
MODEL SUMMARY:
==============

     Random Forest using Conditional Inference Trees

Number of trees:  1000

Response:  factor(taxa_sci_orig)
Inputs:  group_size, lon
Number of observations:  43

Number of variables tried at each split: 5

Estimated predictor variable importance (conditional = FALSE):

           Importance
group_size    0.40973
lon           0.00633

MODEL PERFORMANCE SUMMARY:
==========================

Statistics calculated from the training data.

Area under the ROC curve (auc)           = 1.000
Mean cross-entropy (mxe)                 = 0.076
Precision-recall break-even point (prbe) = 1.000
Root-mean square error (rmse)            = 0.133

Cutoff selected by maximizing the Youden index = 0.695

Confusion matrix for that cutoff:

                              Actual Peponocephala electra  Actual Feresa attenuata  Total
Predicted Peponocephala electra                           25                        0     25
Predicted Feresa attenuata                                 0                       18     18
Total                                                     25                       18     43
```

```
Model performance statistics for that cutoff:

Accuracy (acc)                                = 1.000
Error rate (err)                              = 0.000
Rate of positive predictions (rpp)            = 0.581
Rate of negative predictions (rnp)            = 0.419

True positive rate (tpr, or sensitivity)      = 1.000
False positive rate (fpr, or fallout)         = 0.000
True negative rate (tnr, or specificity)      = 1.000
False negative rate (fnr, or miss)            = 0.000

Positive prediction value (ppv, or precision) = 1.000
Negative prediction value (npv)               = 1.000
Prediction-conditioned fallout (pcfall)       = 0.000
Prediction-conditioned miss (pcmiss)          = 0.000

Matthews correlation coefficient (mcc)        = 1.000
Odds ratio (odds)                             = Inf
SAR                                           = 0.711

Cohen's kappa (K)                             = 1.000
```

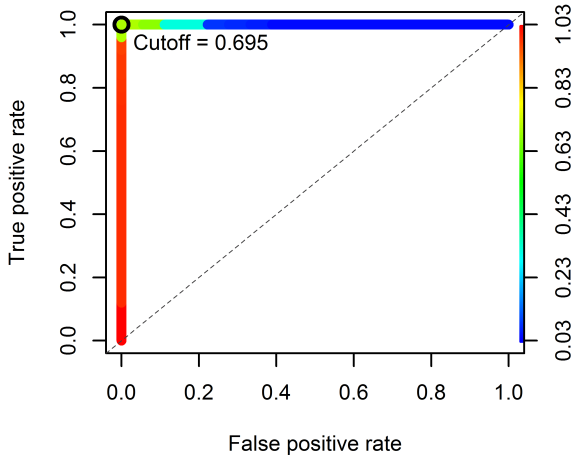


Figure 8: Receiver operating characteristic (ROC) curve illustrating the predictive performance of the model used to reclassify "Feresa attenuata/Peponocephala electra" sightings into one species or the other.

Reclassifications Performed

Survey	Definitive F. attenuata Sightings	Definitive P. electra Sightings	Ambiguous Sightings	Reclassed to F. attenuata	Reclassed to P. electra
SEFSC Gulf of Mexico Shipboard Surveys, 2003-2009	7	6	1	1	0
SEFSC GulfCet I Aerial Surveys	0	0	9	4	5
SEFSC GulfCet II Aerial Surveys	3	0	0	0	0

SEFSC Oceanic CetShip Surveys	8	18	4	4	0
SEFSC Shelf CetShip Surveys	0	1	0	0	0
Total	18	25	14	9	5

Table 4: Counts of definitive sightings, ambiguous sightings, and what the ambiguous sightings were reclassified to. Note that this analysis was performed on all on-effort sightings, not just those in the focal study area. These counts may therefore be larger than those presented in the Survey Data section of this report, which are restricted to the focal study area.

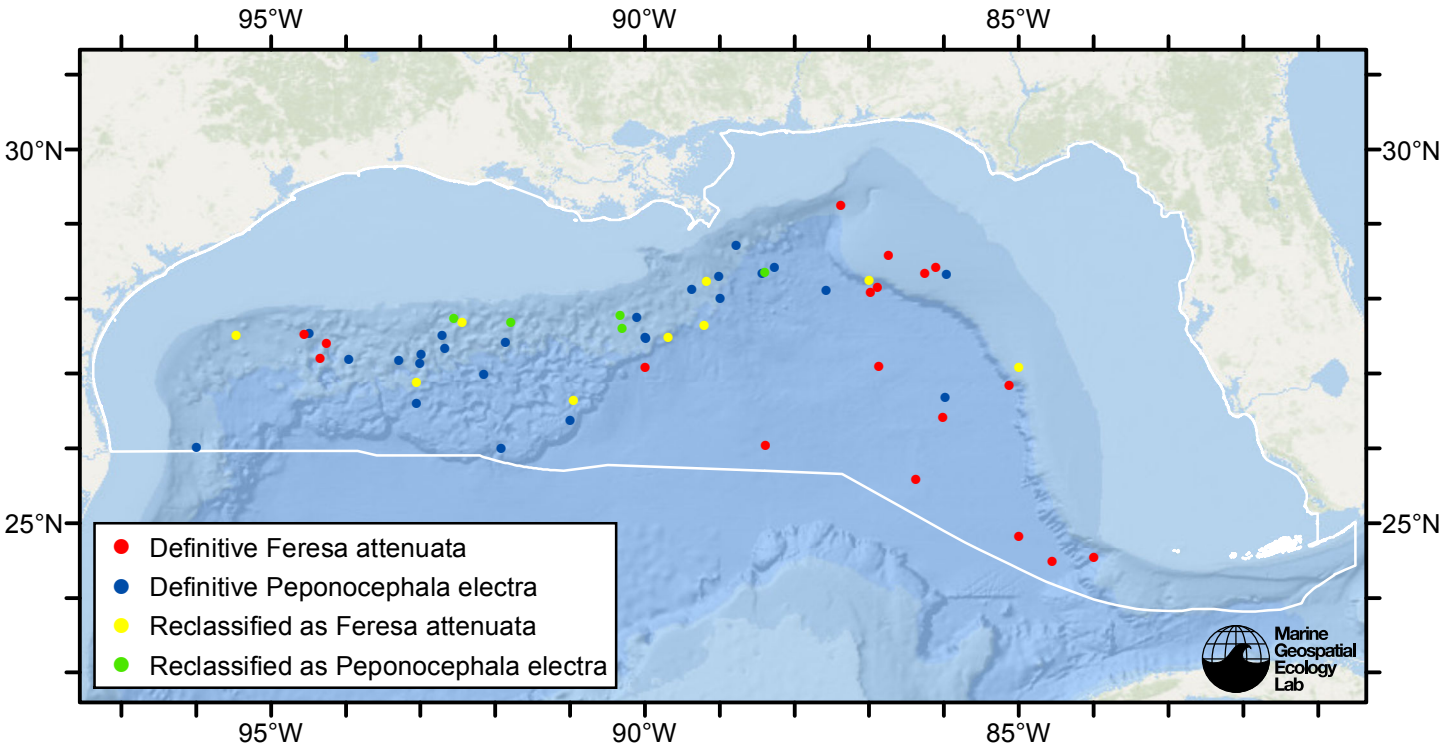


Figure 9: Definitive sightings used to train the model and ambiguous sightings reclassified by the model, by season.

Detection Functions

The detection hierarchy figures below show how sightings from multiple surveys were pooled to try to achieve Buckland et. al's (2001) recommendation that at least 60-80 sightings be used to fit a detection function. Leaf nodes, on the right, usually represent individual surveys, while the hierarchy to the left shows how they have been grouped according to how similar we believed the surveys were to each other in their detection performance.

At each node, the red or green number indicates the total number of sightings below that node in the hierarchy, and is colored green if 70 or more sightings were available, and red otherwise. If a grouping node has zero sightings–i.e. all of the surveys within it had zero sightings–it may be collapsed and shown as a leaf to save space.

Each histogram in the figure indicates a node where a detection function was fitted. The actual detection functions do not appear in this figure; they are presented in subsequent sections. The histogram shows the frequency of sightings by perpendicular sighting distance for all surveys contained by that node. Each survey (leaf node) recieves the detection function that is closest to it up the hierarchy. Thus, for common species, sufficient sightings may be available to fit detection functions deep in the hierarchy, with each function applying to only a few surveys, thereby allowing variability in detection performance between surveys to be addressed relatively finely. For rare species, so few sightings may be available that we have to pool many surveys together to try to meet Buckland's recommendation, and fit only a few coarse detection functions high in the hierarchy.

A blue Proxy Species tag indicates that so few sightings were available that, rather than ascend higher in the hierarchy to a point that we would pool grossly-incompatible surveys together, (e.g. shipboard surveys that used big-eye binoculars with those that used only naked eyes) we pooled sightings of similar species together instead. The list of species pooled is given in following sections.

Shipboard Surveys

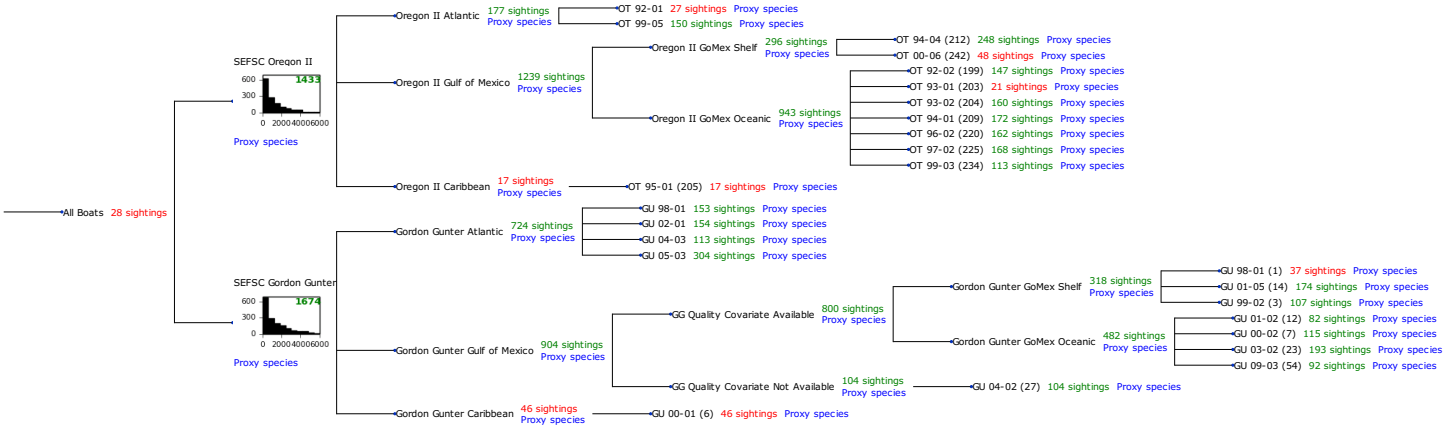


Figure 10: Detection hierarchy for shipboard surveys

SEFSC Oregon II

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Delphinus capensis	Long-beaked common dolphin	0
Delphinus delphis	Short-beaked common dolphin	2
Delphinus delphis/Lagenorhynchus acutus	Short-beaked common or Atlantic white-sided dolphin	0
Delphinus delphis/Stenella	Short-beaked common dolphin or Stenella spp.	0
Delphinus delphis/Stenella coeruleoalba	Short-beaked common or striped dolphin	0
Feresa attenuata	Pygmy killer whale	11
Grampus griseus	Risso's dolphin	156
Grampus griseus/Tursiops truncatus	Risso's or Bottlenose dolphin	0
Lagenodelphis hosei	Fraser's dolphin	3
Lagenorhynchus acutus	Atlantic white-sided dolphin	0
Lagenorhynchus albirostris	White-beaked dolphin	0
Lagenorhynchus albirostris/Lagenorhynchus acutus	White-beaked or white-sided dolphin	0
Peponocephala electra	Melon-headed whale	13
Stenella	Unidentified Stenella	17
Stenella attenuata	Pantropical spotted dolphin	347
Stenella attenuata/frontalis	Pantropical or Atlantic spotted dolphin	0
Stenella clymene	Clymene dolphin	44

Stenella coeruleoalba	Striped dolphin	48
Stenella frontalis	Atlantic spotted dolphin	242
Stenella frontalis/Tursiops truncatus	Atlantic spotted or Bottlenose dolphin	0
Stenella longirostris	Spinner dolphin	38
Steno bredanensis	Rough-toothed dolphin	22
Steno bredanensis/Tursiops truncatus	Bottlenose or rough-toothed dolphin	0
Tursiops truncatus	Bottlenose dolphin	490
Total		1433

Table 5: Proxy species used to fit detection functions for SEFSC Oregon II. The number of sightings, n, is before truncation.

The sightings were right truncated at 5000m.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 6: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr			beaufort, size	Yes	0.00	867
hr			quality, size	Yes	3.65	790
hr			size	Yes	40.44	738
hr			beaufort, quality	Yes	54.00	598
hr			quality	Yes	78.89	556
hr			beaufort	Yes	96.10	523
hr	poly	4		Yes	101.63	515
hr	poly	2		Yes	109.37	538
hr				Yes	125.96	475
hn	cos	3		Yes	346.75	1367
hn	cos	2		Yes	350.33	1525
hn			beaufort, quality, size	Yes	392.90	1971
hn			quality, size	Yes	413.78	1967
hn			beaufort, size	Yes	445.02	1998
hn			beaufort, quality	Yes	454.89	1948
hn			quality	Yes	464.32	1951
hn			size	Yes	465.68	1991

hn			beaufort	Yes	524.83	1961
hn				Yes	533.10	1963
hn	herm	4		No		
hr			beaufort, quality, size	No		

Table 7: Candidate detection functions for SEFSC Oregon II. The first one listed was selected for the density model.

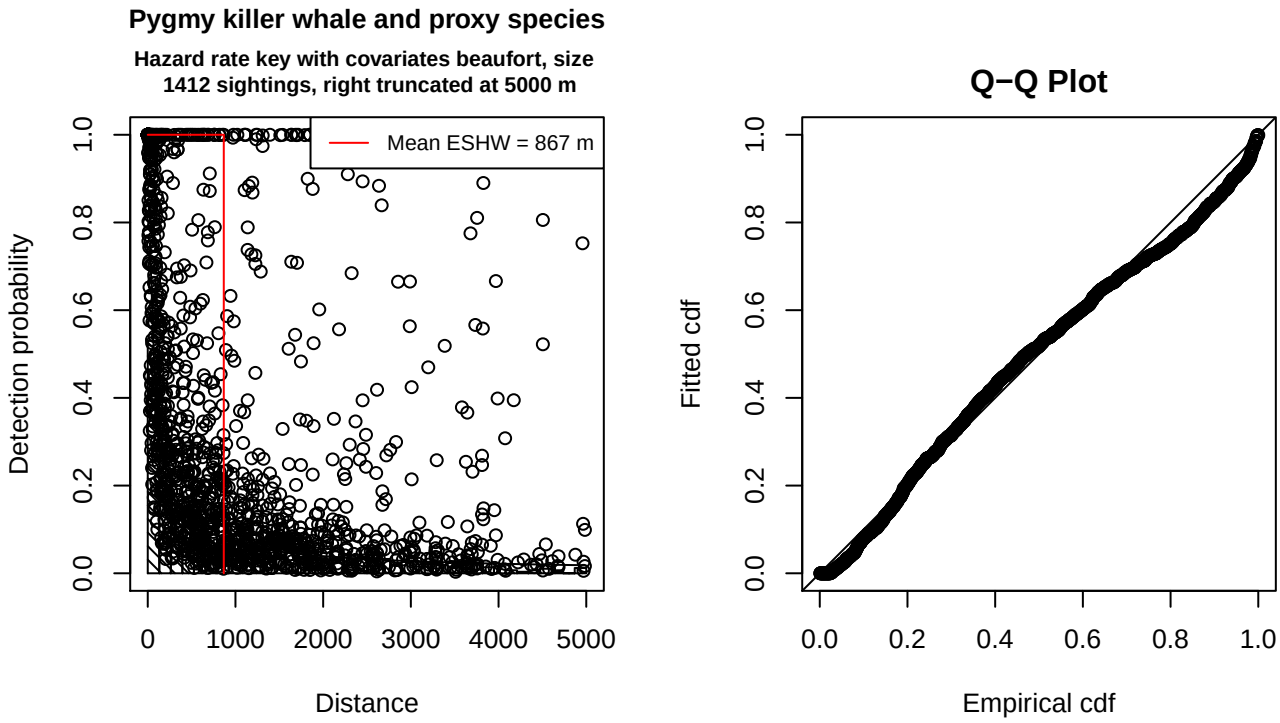


Figure 11: Detection function for SEFSC Oregon II that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  1412
Distance range         :  0  -  5000
AIC                    :  22270.99

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
             estimate         se
(Intercept)  5.1928930 0.21118617
beaufort    -0.5654155 0.06792705
size         2.3308851 0.22444978

Shape parameters:
            estimate         se
```

```
(Intercept)        0 0.03443879

                         Estimate           SE        CV
Average p            6.393312e-02 6.600196e-03 0.1032359
N in covered region 2.208558e+04 2.357900e+03 0.1067620
```

Additional diagnostic plots:

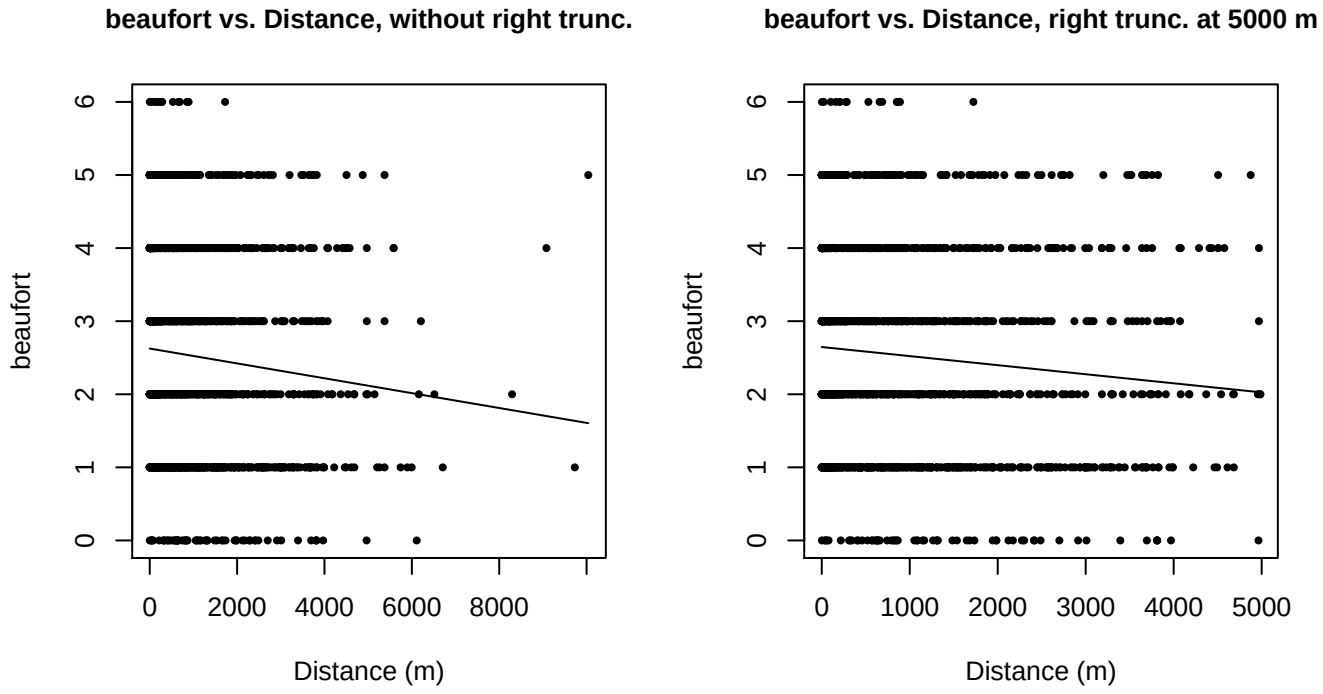


Figure 12: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

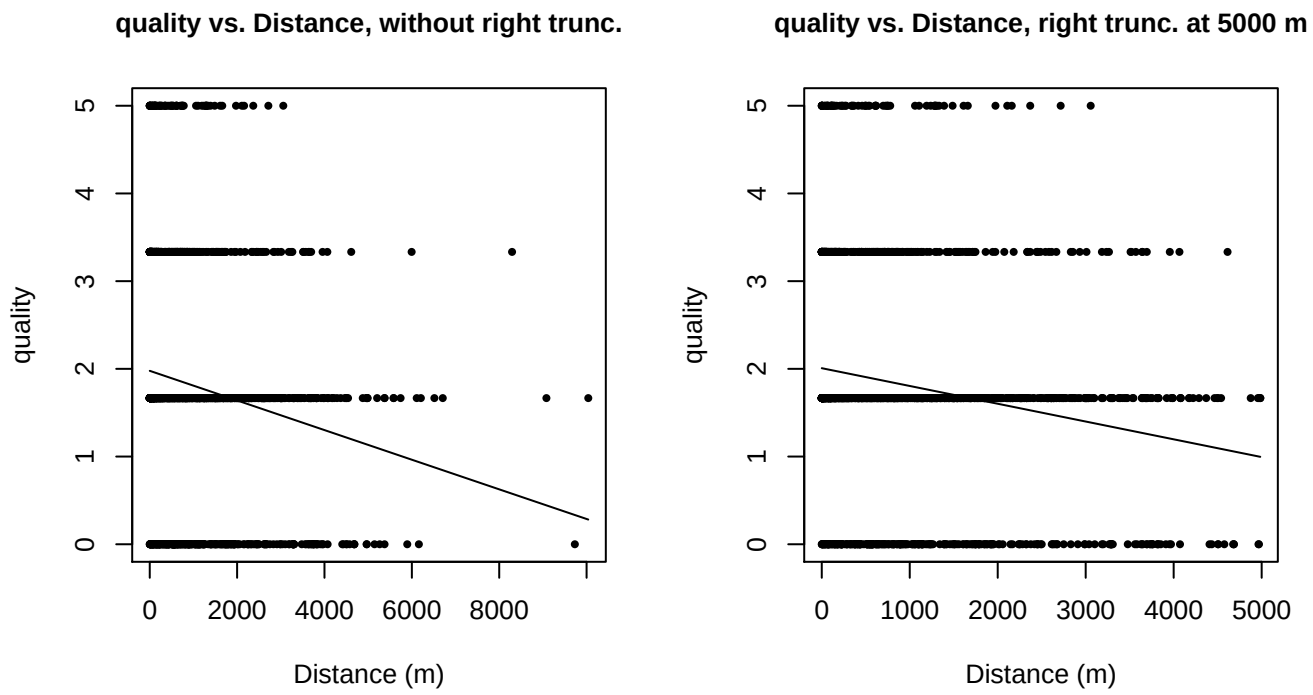


Figure 13: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

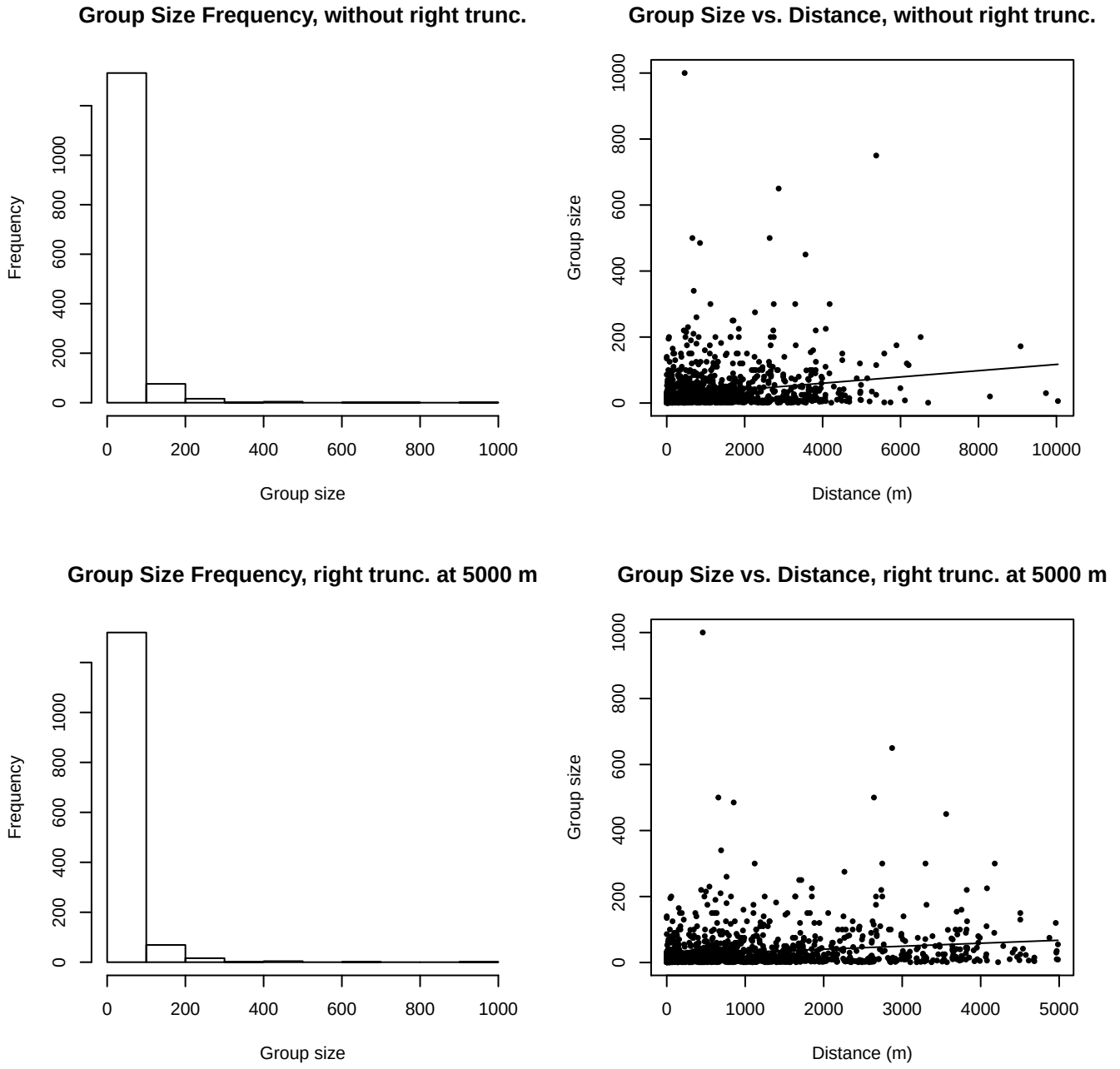


Figure 14: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

SEFSC Gordon Gunter

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Delphinus capensis	Long-beaked common dolphin	9
Delphinus delphis	Short-beaked common dolphin	35

Delphinus delphis/Lagenorhynchus acutus	Short-beaked common or Atlantic white-sided dolphin	0
Delphinus delphis/Stenella	Short-beaked common dolphin or Stenella spp.	0
Delphinus delphis/Stenella coeruleoalba	Short-beaked common or striped dolphin	0
Feresa attenuata	Pygmy killer whale	14
Grampus griseus	Risso's dolphin	129
Grampus griseus/Tursiops truncatus	Risso's or Bottlenose dolphin	0
Lagenodelphis hosei	Fraser's dolphin	1
Lagenorhynchus acutus	Atlantic white-sided dolphin	0
Lagenorhynchus albirostris	White-beaked dolphin	0
Lagenorhynchus albirostris/Lagenorhynchus acutus	White-beaked or white-sided dolphin	0
Peponocephala electra	Melon-headed whale	15
Stenella	Unidentified Stenella	30
Stenella attenuata	Pantropical spotted dolphin	303
Stenella attenuata/frontalis	Pantropical or Atlantic spotted dolphin	0
Stenella clymene	Clymene dolphin	29
Stenella coeruleoalba	Striped dolphin	78
Stenella frontalis	Atlantic spotted dolphin	376
Stenella frontalis/Tursiops truncatus	Atlantic spotted or Bottlenose dolphin	1
Stenella longirostris	Spinner dolphin	24
Steno bredanensis	Rough-toothed dolphin	24
Steno bredanensis/Tursiops truncatus	Bottlenose or rough-toothed dolphin	0
Tursiops truncatus	Bottlenose dolphin	606
Total		1674

Table 8: Proxy species used to fit detection functions for SEFSC Gordon Gunter. The number of sightings, n, is before truncation.

The sightings were right truncated at 6000m.

Covariate	Description
beaufort	Beaufort sea state.
size	Estimated size (number of individuals) of the sighted group.

Table 9: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr			beaufort	Yes	0.00	844
hr			size	Yes	56.75	836
hr	poly	4		Yes	112.47	671
hr	poly	2		Yes	124.37	706

hn			beaufort, size	Yes	366.29	2367
hn	cos	2		Yes	378.69	1850
hn	cos	3		Yes	380.80	1668
hn			beaufort	Yes	455.35	2337
hn			size	Yes	502.99	2400
hn				Yes	574.63	2360
hn	herm	4		No		
hr				No		
hr			beaufort, size	No		

Table 10: Candidate detection functions for SEFSC Gordon Gunter. The first one listed was selected for the density model.

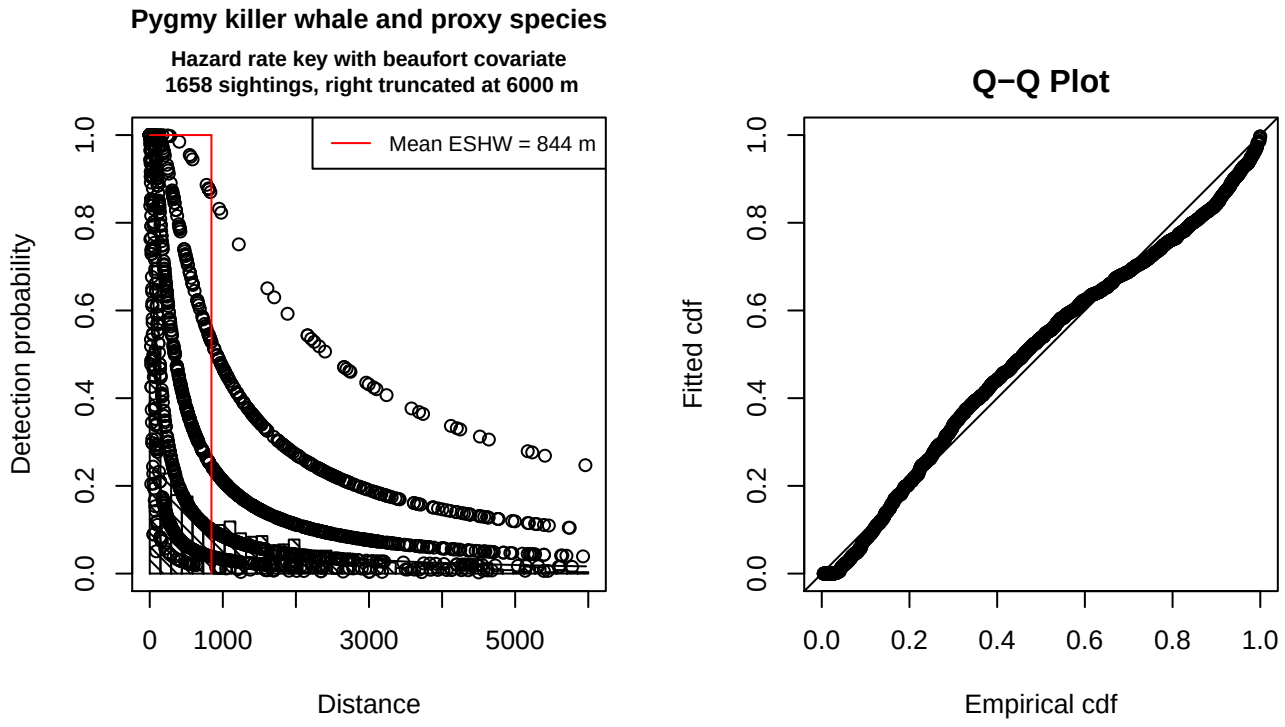


Figure 15: Detection function for SEFSC Gordon Gunter that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  1658
Distance range         :  0  -  6000
AIC                    :  26811.56

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
```

```
              estimate        se
(Intercept)  7.4342445 0.1890137
beaufort    -0.9817427 0.0716962

Shape parameters:
            estimate         se
(Intercept)        0 0.03314981

                         Estimate           SE        CV
Average p            6.406313e-02 6.666152e-03 0.1040560
N in covered region 2.588072e+04 2.767951e+03 0.1069503
```

Additional diagnostic plots:

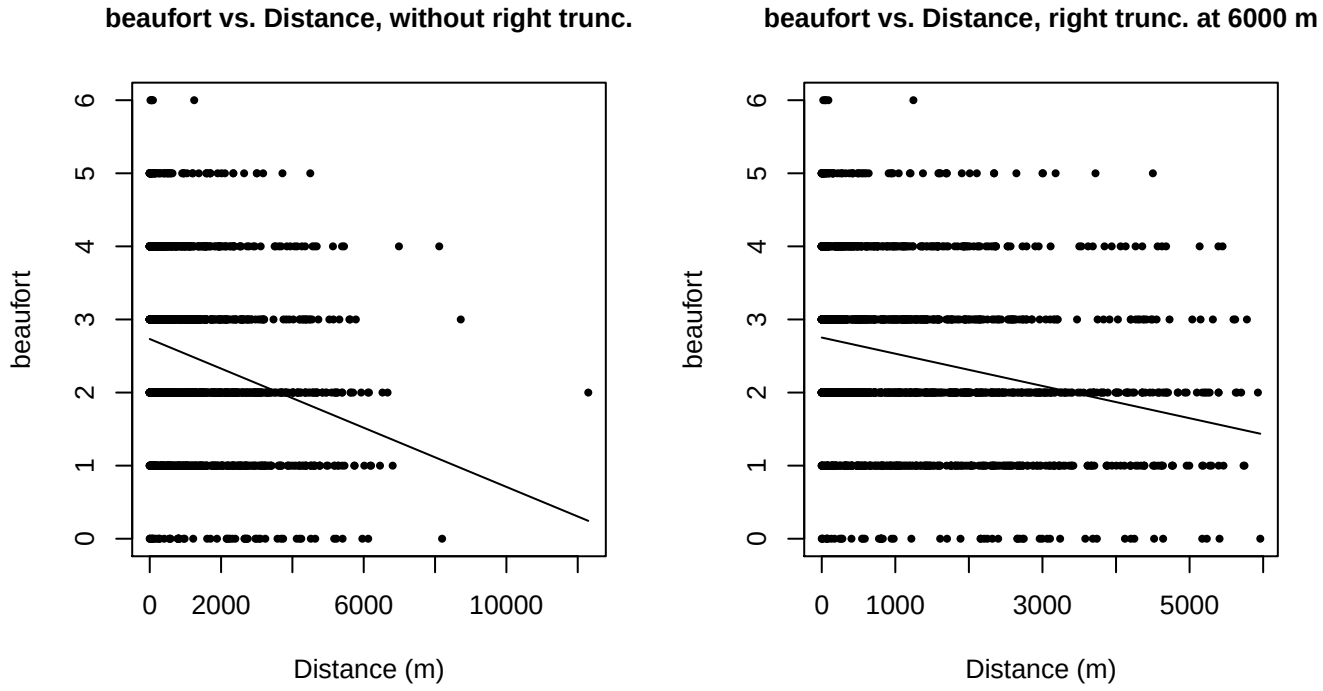


Figure 16: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

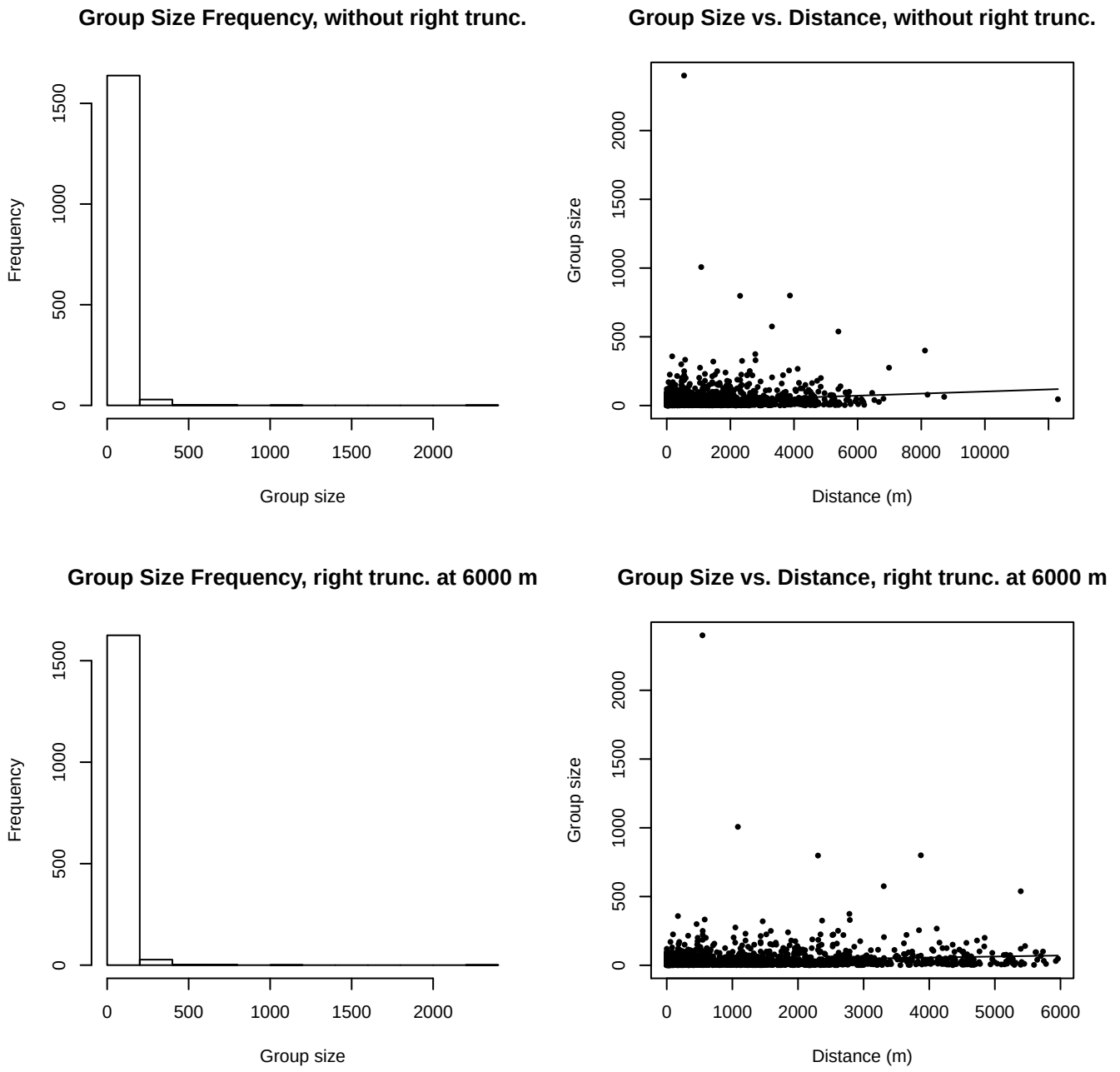


Figure 17: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

Aerial Surveys

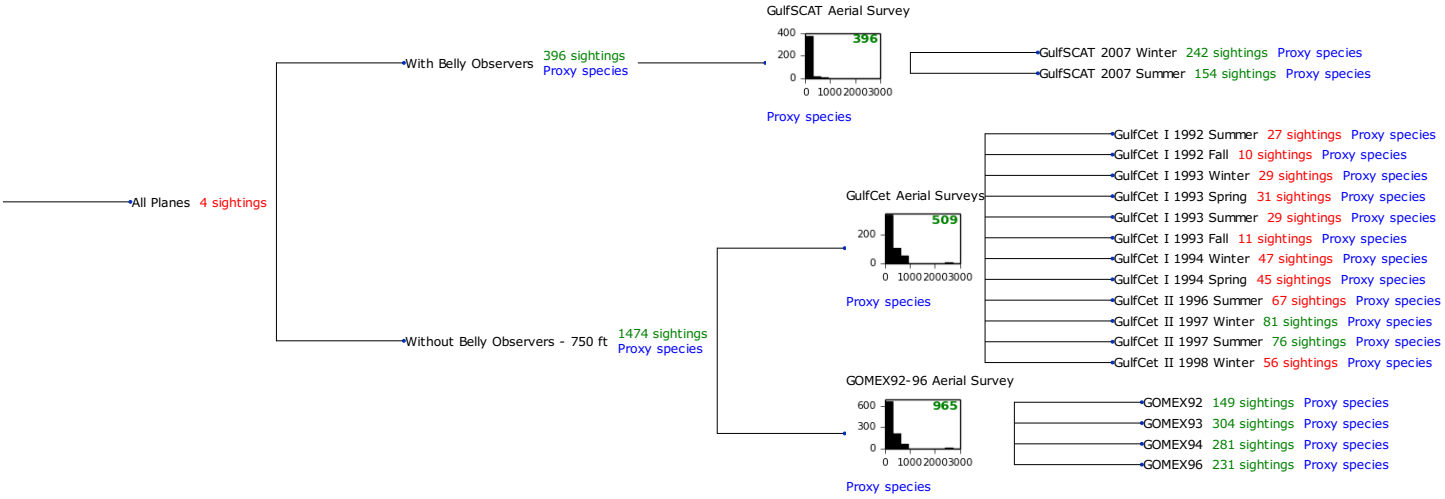


Figure 18: Detection hierarchy for aerial surveys

GulfSCAT Aerial Survey

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Delphinus capensis	Long-beaked common dolphin	0
Delphinus delphis	Short-beaked common dolphin	0
Delphinus delphis/Lagenorhynchus acutus	Short-beaked common or Atlantic white-sided dolphin	0
Delphinus delphis/Stenella	Short-beaked common dolphin or Stenella spp.	0
Delphinus delphis/Stenella coeruleoalba	Short-beaked common or striped dolphin	0
Feresa attenuata	Pygmy killer whale	0
Grampus griseus	Risso's dolphin	0
Grampus griseus/Tursiops truncatus	Risso's or Bottlenose dolphin	0
Lagenodelphis hosei	Fraser's dolphin	0
Lagenorhynchus acutus	Atlantic white-sided dolphin	0
Lagenorhynchus albirostris	White-beaked dolphin	0
Lagenorhynchus albirostris/Lagenorhynchus acutus	White-beaked or white-sided dolphin	0
Peponocephala electra	Melon-headed whale	0
Stenella	Unidentified Stenella	0
Stenella attenuata	Pantropical spotted dolphin	0
Stenella attenuata/frontalis	Pantropical or Atlantic spotted dolphin	0
Stenella clymene	Clymene dolphin	0
Stenella coeruleoalba	Striped dolphin	0
Stenella frontalis	Atlantic spotted dolphin	15
Stenella frontalis/Tursiops truncatus	Atlantic spotted or Bottlenose dolphin	0

Stenella longirostris	Spinner dolphin	0
Steno bredanensis	Rough-toothed dolphin	0
Steno bredanensis/Tursiops truncatus	Bottlenose or rough-toothed dolphin	0
Tursiops truncatus	Bottlenose dolphin	381
Total		396

Table 11: Proxy species used to fit detection functions for GulfSCAT Aerial Survey. The number of sightings, n, is before truncation.

The sightings were right truncated at 400m.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 12: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hn	herm	4		Yes	0.00	218
hn	cos	2		Yes	0.09	221
hn				Yes	0.90	199
hn			size	Yes	2.21	199
hn	cos	3		Yes	2.37	209
hr	poly	2		Yes	2.39	218
hr	poly	4		Yes	2.47	223
hr				Yes	4.46	230
hr			size	Yes	5.04	232
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		
hr			quality	No		
hn			beaufort, quality	No		
hr			beaufort, quality	No		
hn			beaufort, size	No		
hr			beaufort, size	No		
hn			quality, size	No		
hr			quality, size	No		
hn			beaufort, quality, size	No		
hr			beaufort, quality, size	No		

Table 13: Candidate detection functions for GulfSCAT Aerial Survey. The first one listed was selected for the density model.

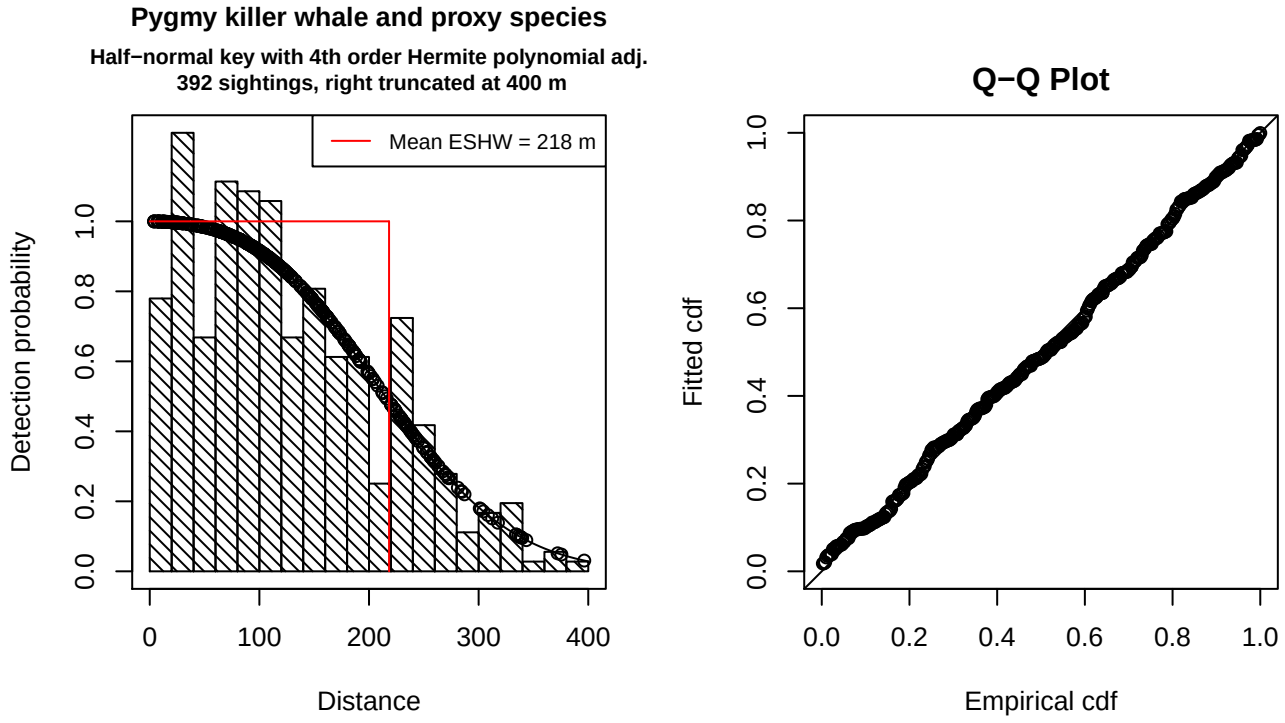


Figure 19: Detection function for GulfSCAT Aerial Survey that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  392
Distance range         :  0  -  400
AIC                    :  4505.917

Detection function:
 Half-normal key function with Hermite polynomial adjustment term of order 4

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 4.855663 0.07416756

Adjustment term parameter(s):
                 estimate         se
herm, order 4 -0.04125524 0.01270718


Monotonicity constraints were enforced.
                       Estimate          SE         CV
Average p             0.5457496  0.04201245 0.07698119
N in covered region 718.2781801 60.45882379 0.08417188
```

```
Monotonicity constraints were enforced.
```

Additional diagnostic plots:

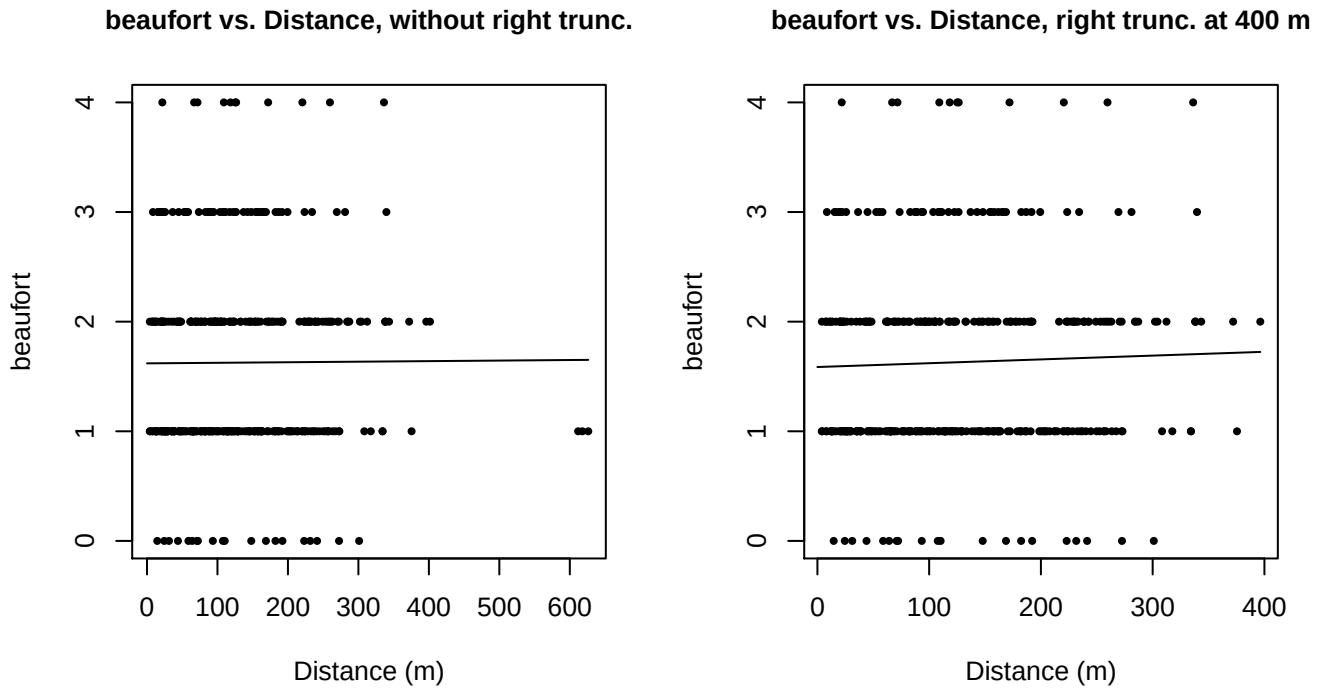


Figure 20: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

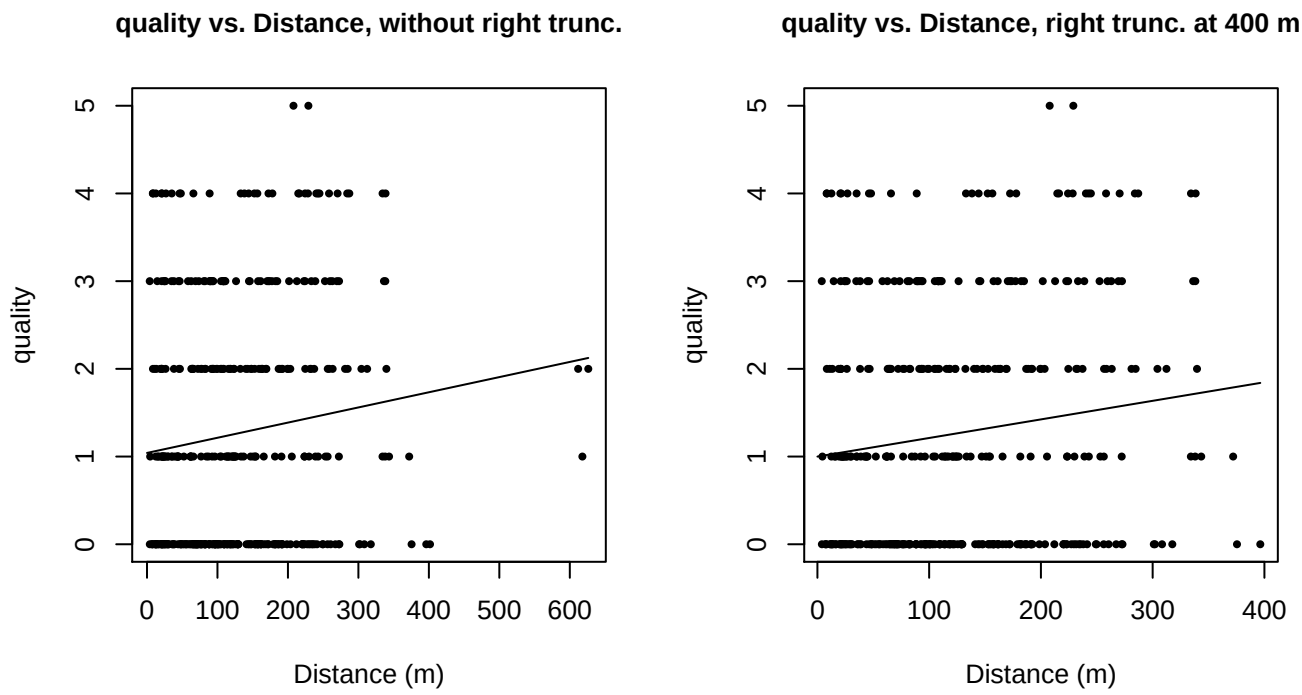


Figure 21: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

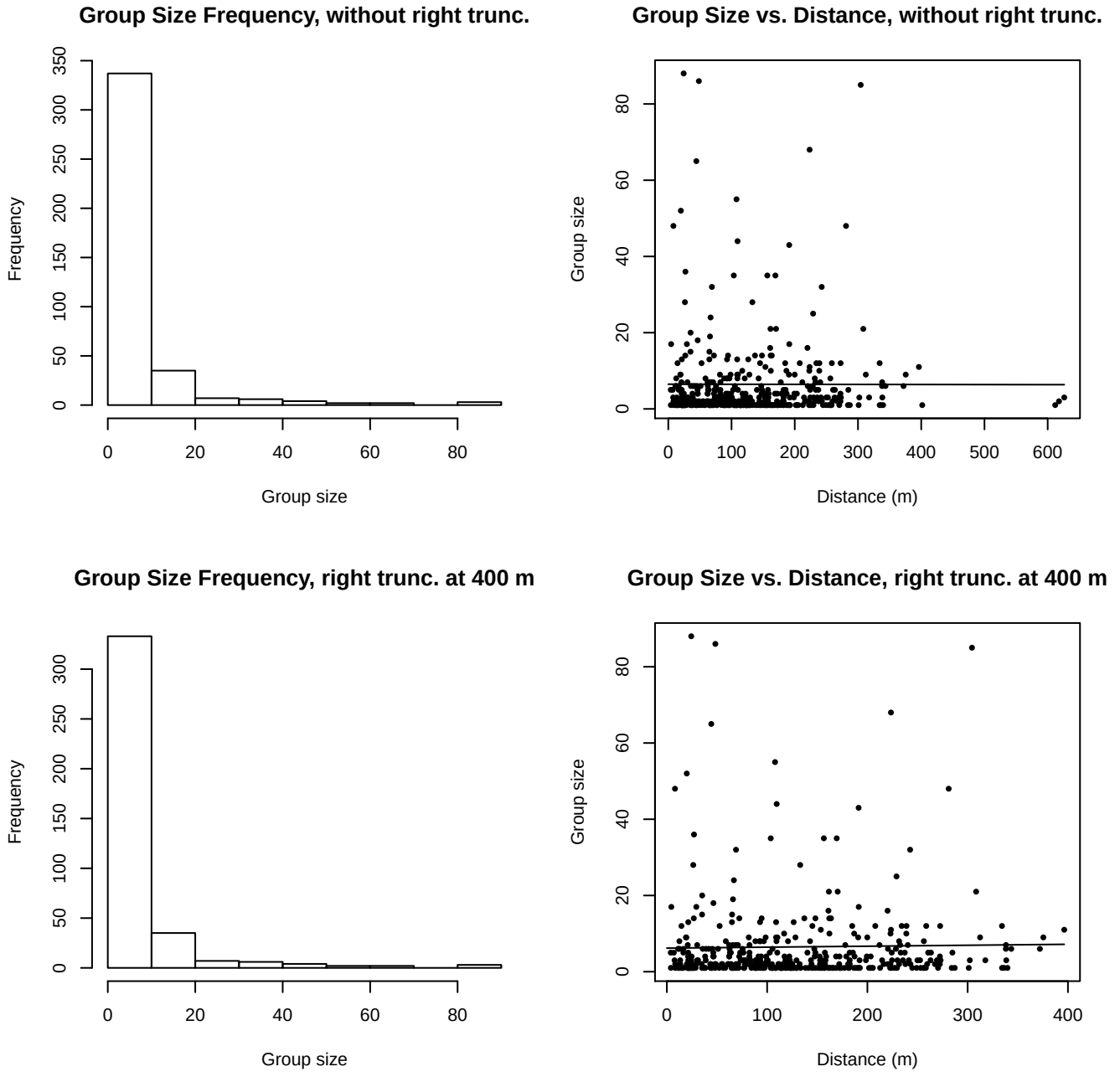


Figure 22: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

GulfCet Aerial Surveys

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Delphinus capensis	Long-beaked common dolphin	0
Delphinus delphis	Short-beaked common dolphin	0

Delphinus delphis/Lagenorhynchus acutus	Short-beaked common or Atlantic white-sided dolphin	0
Delphinus delphis/Stenella	Short-beaked common dolphin or Stenella spp.	0
Delphinus delphis/Stenella coeruleoalba	Short-beaked common or striped dolphin	0
Feresa attenuata	Pygmy killer whale	7
Grampus griseus	Risso's dolphin	71
Grampus griseus/Tursiops truncatus	Risso's or Bottlenose dolphin	0
Lagenodelphis hosei	Fraser's dolphin	2
Lagenorhynchus acutus	Atlantic white-sided dolphin	0
Lagenorhynchus albirostris	White-beaked dolphin	0
Lagenorhynchus albirostris/Lagenorhynchus acutus	White-beaked or white-sided dolphin	0
Peponocephala electra	Melon-headed whale	4
Stenella	Unidentified Stenella	10
Stenella attenuata	Pantropical spotted dolphin	94
Stenella attenuata/frontalis	Pantropical or Atlantic spotted dolphin	0
Stenella clymene	Clymene dolphin	12
Stenella coeruleoalba	Striped dolphin	16
Stenella frontalis	Atlantic spotted dolphin	36
Stenella frontalis/Tursiops truncatus	Atlantic spotted or Bottlenose dolphin	0
Stenella longirostris	Spinner dolphin	11
Steno bredanensis	Rough-toothed dolphin	9
Steno bredanensis/Tursiops truncatus	Bottlenose or rough-toothed dolphin	0
Tursiops truncatus	Bottlenose dolphin	237
Total		509

Table 14: Proxy species used to fit detection functions for GulfCet Aerial Surveys. The number of sightings, n, is before truncation.

The sightings were right truncated at 1296m. The vertical sighting angles were heaped at 10 degree increments, so the candidate detection functions were fitted using linear bins scaled accordingly.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 15: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr				Yes	0.00	393

hr	poly	2		Yes	2.00	393
hr	poly	4		Yes	2.00	393
hn	cos	2		Yes	3.05	366
hn	cos	3		Yes	9.66	340
hn			size	Yes	29.80	440
hn				Yes	34.48	438
hn	herm	4		Yes	36.24	438
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		
hr			quality	No		
hr			size	No		
hn			beaufort, quality	No		
hr			beaufort, quality	No		
hn			beaufort, size	No		
hr			beaufort, size	No		
hn			quality, size	No		
hr			quality, size	No		
hn			beaufort, quality, size	No		
hr			beaufort, quality, size	No		

Table 16: Candidate detection functions for GulfCet Aerial Surveys. The first one listed was selected for the density model.

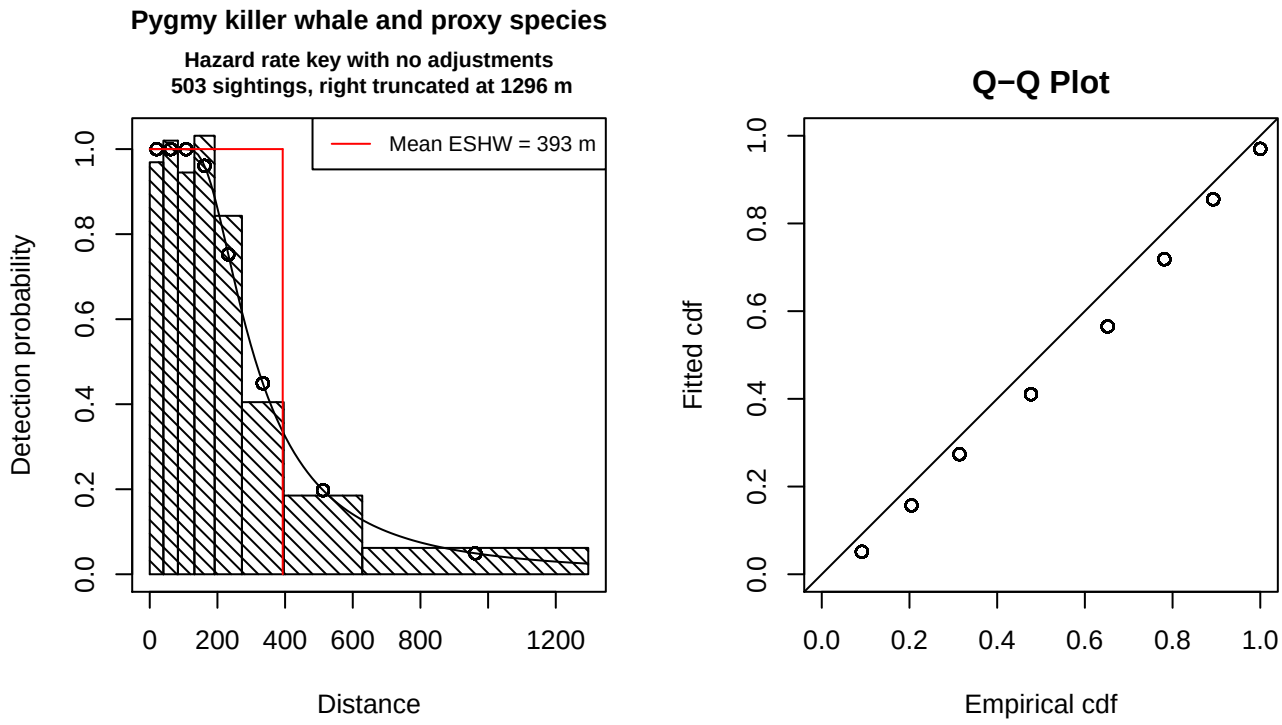


Figure 23: Detection function for GulfCet Aerial Surveys that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  503
Distance range         :  0  -  1296
AIC                    :  2078.71

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
            estimate         se
(Intercept) 5.590311 0.08294157

Shape parameters:
             estimate         se
(Intercept) 0.8474162 0.08116411

                         Estimate           SE         CV
Average p                0.3032173   0.01648324 0.05436115
N in covered region 1658.8765467 109.28948122 0.06588162
```

Additional diagnostic plots:

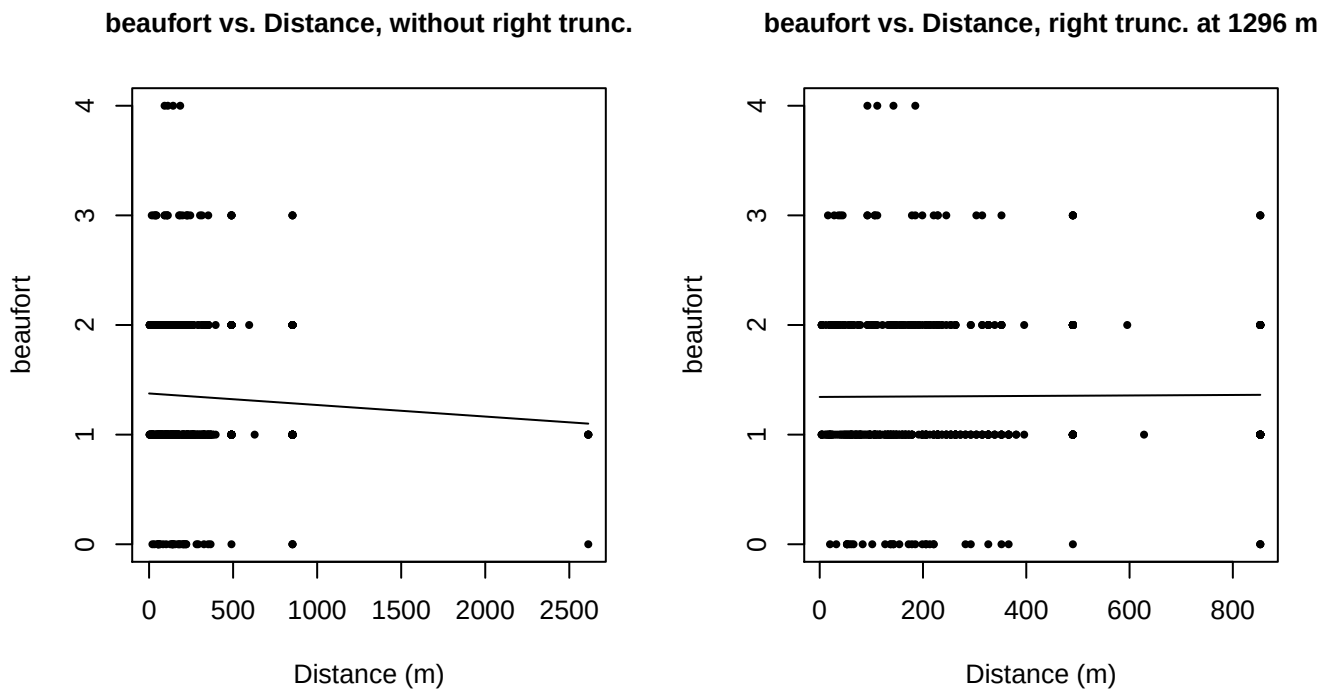


Figure 24: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

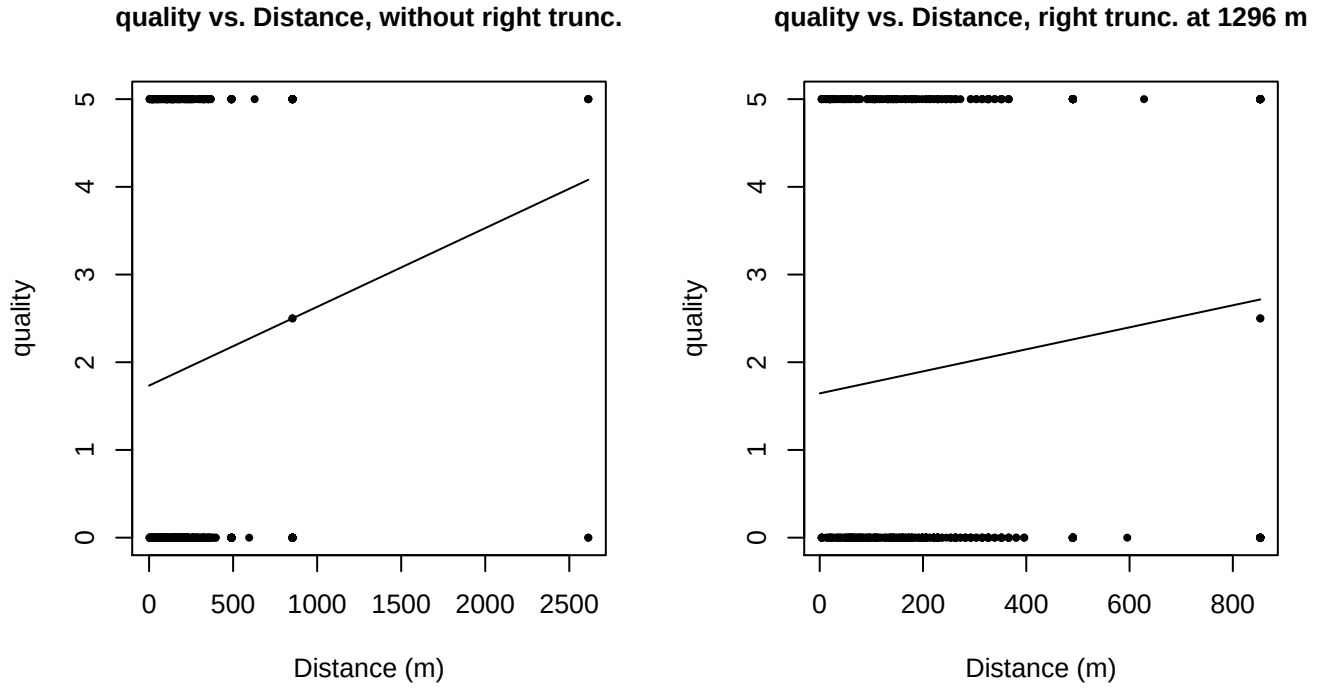


Figure 25: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

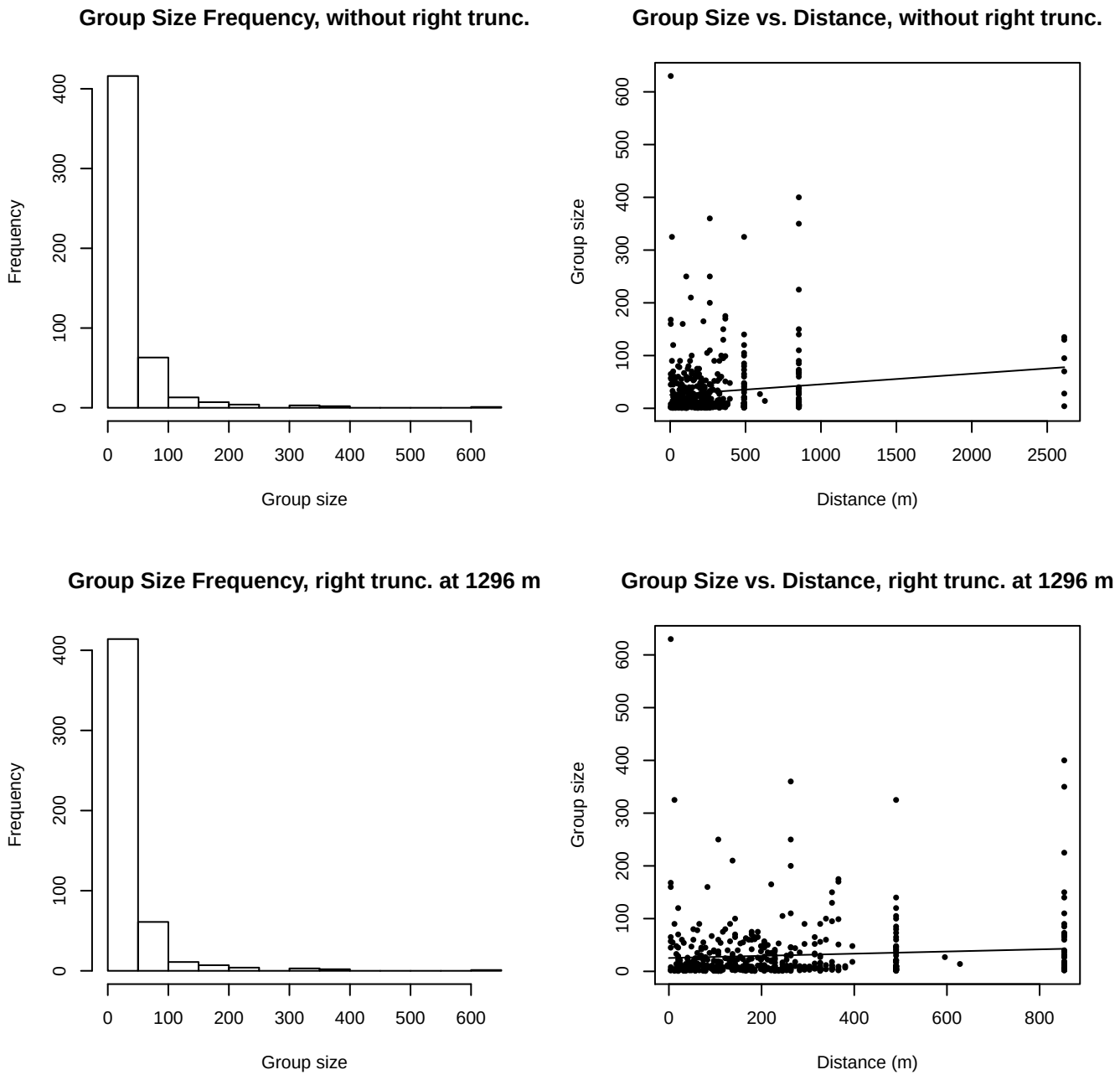


Figure 26: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

GOMEX92-96 Aerial Survey

Because this taxon was sighted too infrequently to fit a detection function to its sightings alone, we fit a detection function to the pooled sightings of several other species that we believed would exhibit similar detectability. These "proxy species" are listed below.

Reported By Observer	Common Name	n
Delphinus capensis	Long-beaked common dolphin	0
Delphinus delphis	Short-beaked common dolphin	0

Delphinus delphis/Lagenorhynchus acutus	Short-beaked common or Atlantic white-sided dolphin	0
Delphinus delphis/Stenella	Short-beaked common dolphin or Stenella spp.	0
Delphinus delphis/Stenella coeruleoalba	Short-beaked common or striped dolphin	0
Feresa attenuata	Pygmy killer whale	0
Grampus griseus	Risso's dolphin	4
Grampus griseus/Tursiops truncatus	Risso's or Bottlenose dolphin	0
Lagenodelphis hosei	Fraser's dolphin	0
Lagenorhynchus acutus	Atlantic white-sided dolphin	0
Lagenorhynchus albirostris	White-beaked dolphin	0
Lagenorhynchus albirostris/Lagenorhynchus acutus	White-beaked or white-sided dolphin	0
Peponocephala electra	Melon-headed whale	0
Stenella	Unidentified Stenella	1
Stenella attenuata	Pantropical spotted dolphin	0
Stenella attenuata/frontalis	Pantropical or Atlantic spotted dolphin	0
Stenella clymene	Clymene dolphin	0
Stenella coeruleoalba	Striped dolphin	0
Stenella frontalis	Atlantic spotted dolphin	24
Stenella frontalis/Tursiops truncatus	Atlantic spotted or Bottlenose dolphin	0
Stenella longirostris	Spinner dolphin	0
Steno bredanensis	Rough-toothed dolphin	0
Steno bredanensis/Tursiops truncatus	Bottlenose or rough-toothed dolphin	0
Tursiops truncatus	Bottlenose dolphin	936
Total		965

Table 17: Proxy species used to fit detection functions for GOMEX92-96 Aerial Survey. The number of sightings, n, is before truncation.

The sightings were right truncated at 1296m. Due to a reduced frequency of sightings close to the trackline that plausibly resulted from the behavior of the observers and/or the configuration of the survey platform, the sightings were left truncted as well. Sightings closer than 83 m to the trackline were omitted from the analysis, and it was assumed that the the area closer to the trackline than this was not surveyed. This distance was estimated by inspecting histograms of perpendicular sighting distances. The vertical sighting angles were heaped at 10 degree increments, so the candidate detection functions were fitted using linear bins scaled accordingly.

Covariate	Description
beaufort	Beaufort sea state.
quality	Survey-specific index of the quality of observation conditions, utilizing relevant factors other than Beaufort sea state (see methods).
size	Estimated size (number of individuals) of the sighted group.

Table 18: Covariates tested in candidate "multi-covariate distance sampling" (MCDS) detection functions.

Key	Adjustment	Order	Covariates	Succeeded	Δ AIC	Mean ESHW (m)
hr			size	Yes	0.00	281
hr	poly	4		Yes	4.73	273
hn	cos	3		Yes	4.85	220
hr				Yes	4.90	278
hr	poly	2		Yes	5.13	269
hn	cos	2		Yes	12.07	259
hn			size	Yes	39.53	304
hn				Yes	41.94	304
hn	herm	4		Yes	43.71	304
hn			beaufort	No		
hr			beaufort	No		
hn			quality	No		
hr			quality	No		
hn			beaufort, quality	No		
hr			beaufort, quality	No		
hn			beaufort, size	No		
hr			beaufort, size	No		
hn			quality, size	No		
hr			quality, size	No		
hn			beaufort, quality, size	No		
hr			beaufort, quality, size	No		

Table 19: Candidate detection functions for GOMEX92-96 Aerial Survey. The first one listed was selected for the density model.

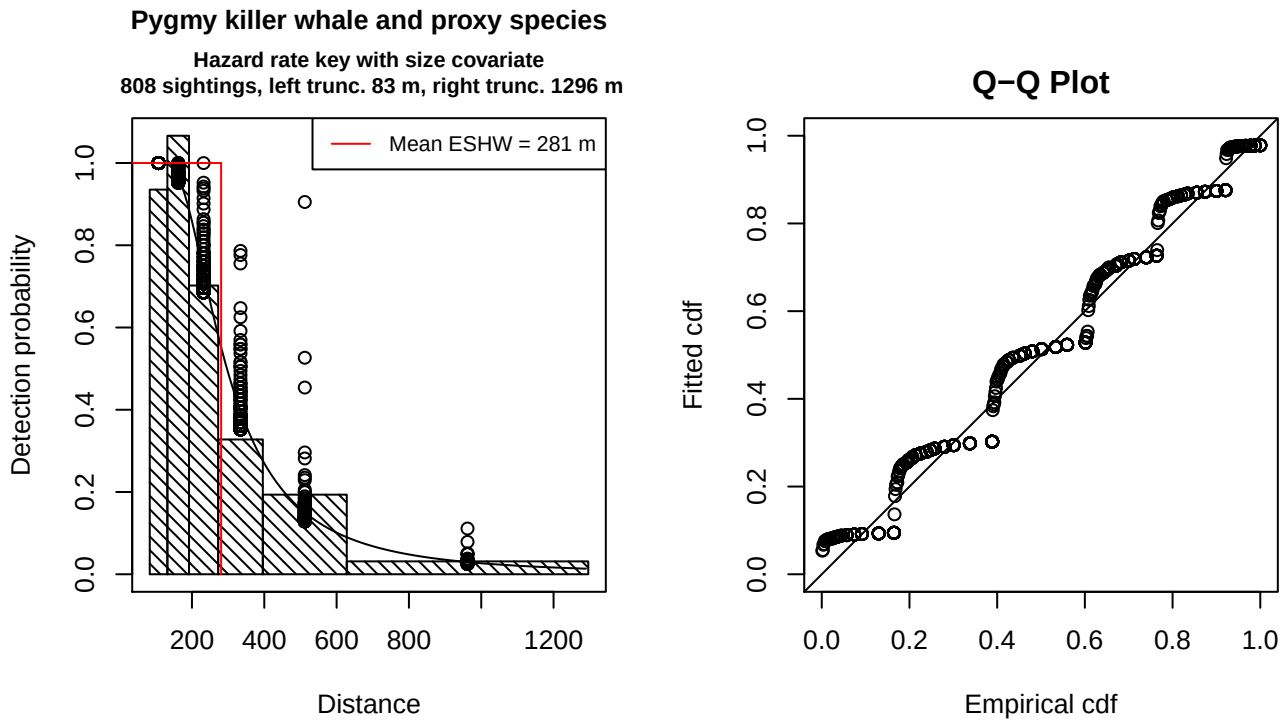


Figure 27: Detection function for GOMEX92-96 Aerial Survey that was selected for the density model

Statistical output for this detection function:

```
Summary for ds object
Number of observations :  808
Distance range         :  83.2036  -  1296
AIC                    :  2832.217

Detection function:
 Hazard-rate key function

Detection function parameters
Scale Coefficients:
             estimate         se
(Intercept) 5.49007390 0.06761203
size        0.09577309 0.04016336

Shape parameters:
            estimate         se
(Intercept) 0.9893445 0.05859387

                         Estimate           SE         CV
Average p                0.2138621   0.01146898 0.05362795
N in covered region 3778.1360570 234.49525749 0.06206639
```

Additional diagnostic plots:

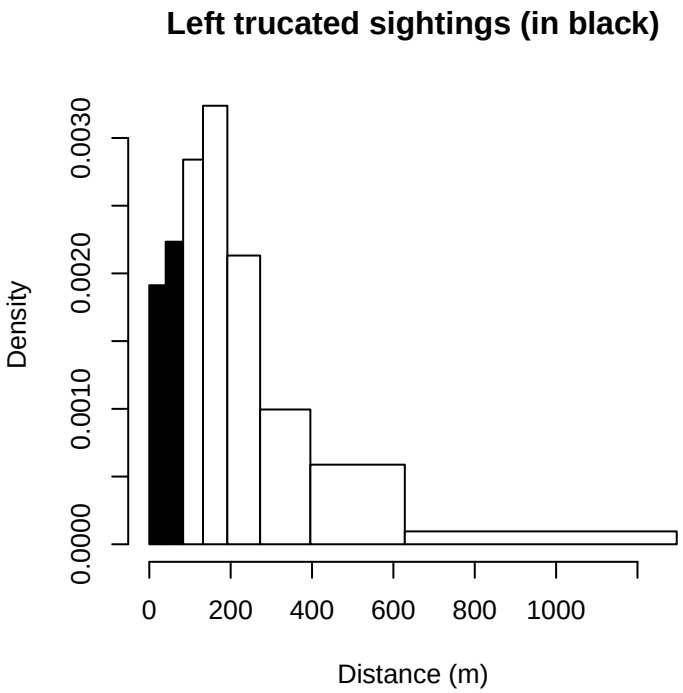


Figure 28: Density of sightings by perpendicular distance for GOMEX92-96 Aerial Survey. Black bars on the left show sightings that were left truncated.

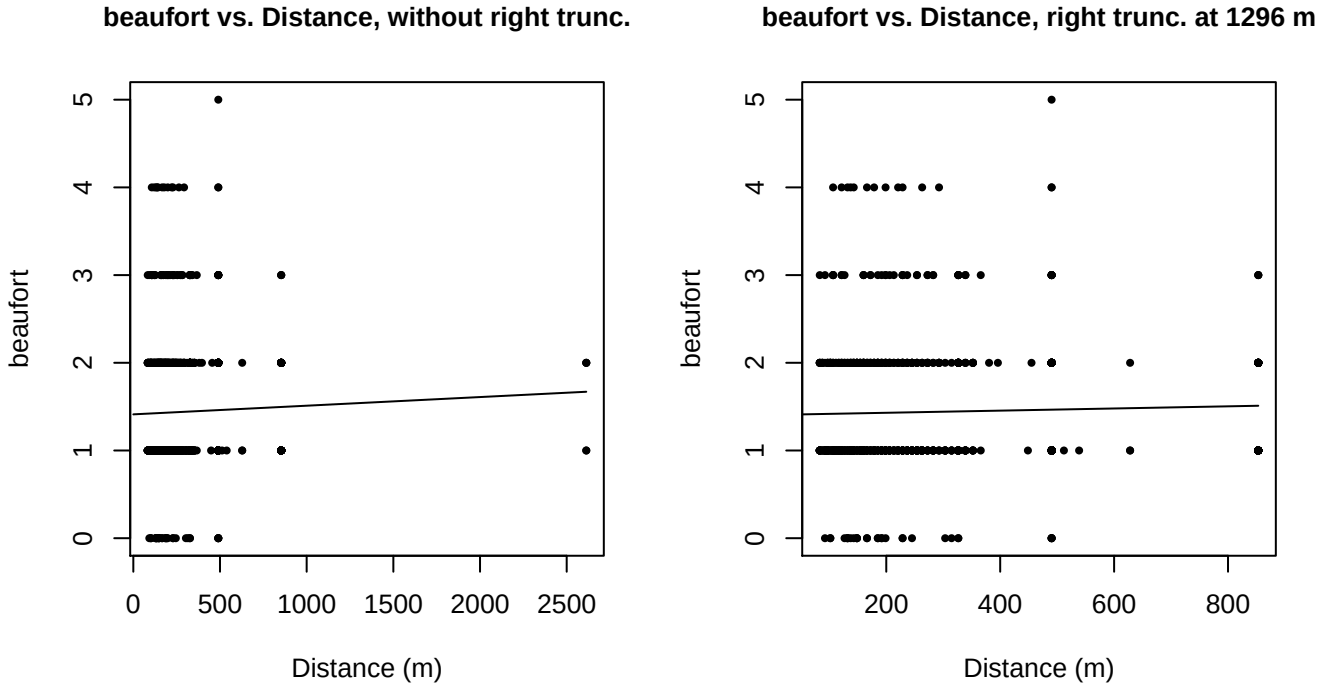


Figure 29: Scatterplots showing the relationship between Beaufort sea state and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). The line is a simple linear regression.

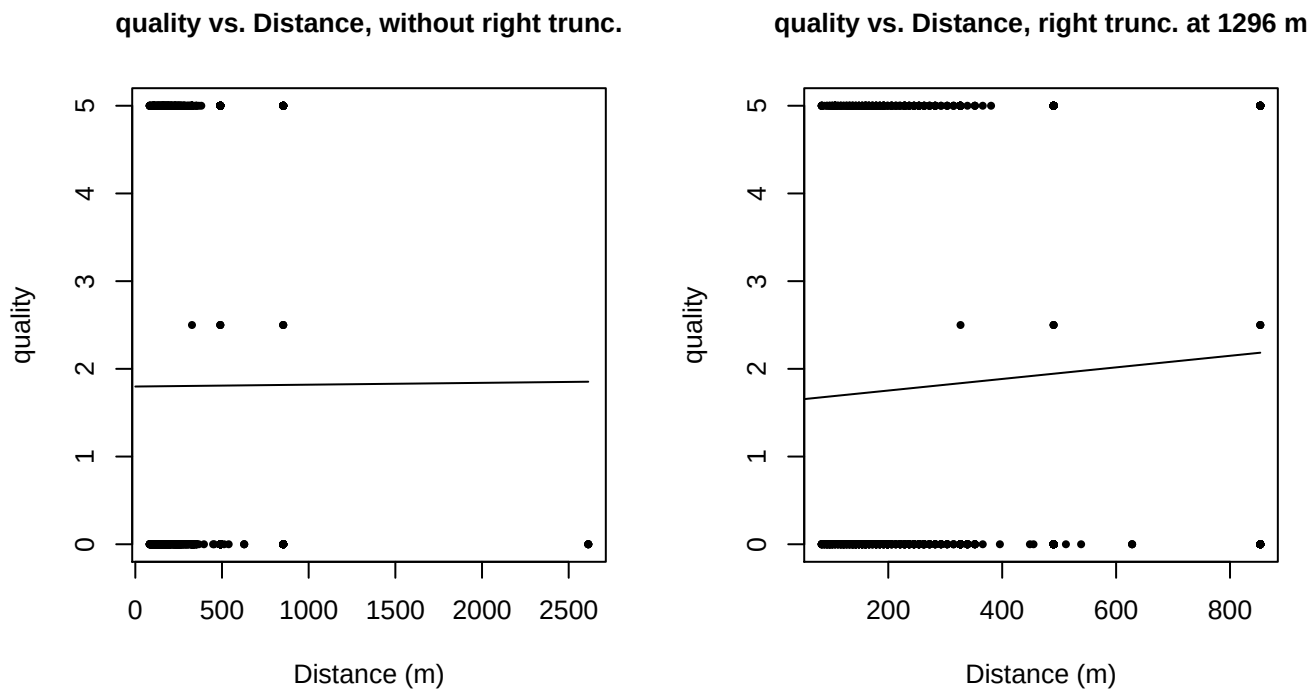


Figure 30: Scatterplots showing the relationship between the survey-specific index of the quality of observation conditions and perpendicular sighting distance, for all sightings (left) and only those not right truncated (right). Low values of the quality index correspond to better observation conditions. The line is a simple linear regression.

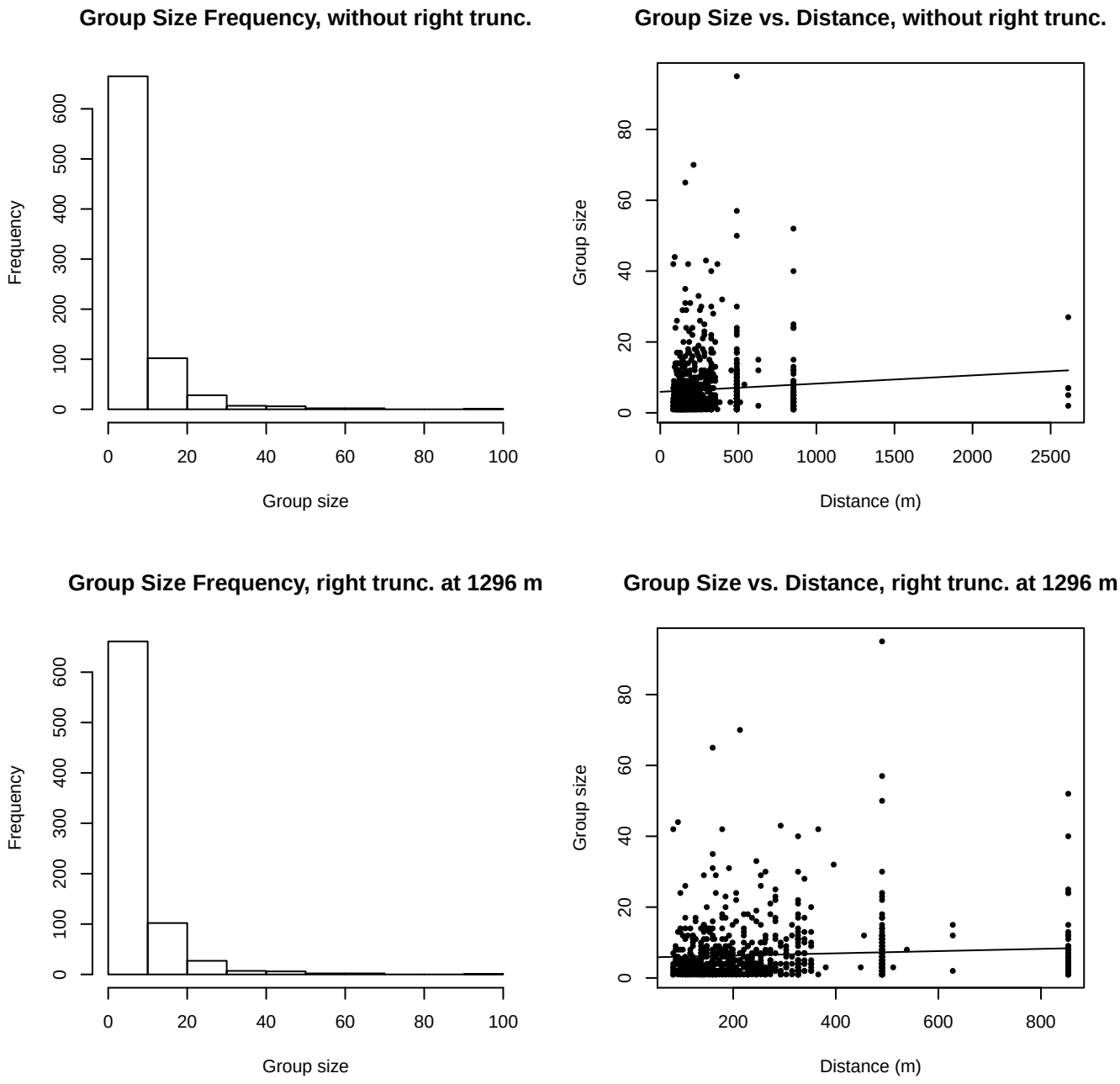


Figure 31: Histograms showing group size frequency and scatterplots showing the relationship between group size and perpendicular sighting distance, for all sightings (top row) and only those not right truncated (bottom row). In the scatterplot, the line is a simple linear regression.

g(0) Estimates

Platform	Surveys	Group Size	*g(0)*	Biases Addressed	Source
Shipboard	All	1-20	0.856	Perception	Barlow and Forney (2007)
		>20	0.970	Perception	Barlow and Forney (2007)
Aerial	All	1-5	0.43	Both	Palka (2006)
		>5	0.960	Both	Carretta et al. (2000)

Table 20: Estimates of *g(0)* used in this density model.

For shipboard surveys, we were unable to find a species-specific g(0) estimate for pygmy killer whales in the literature. Barlow (2006) estimated g(0)=0.77 (CV=0.14) for groups of 1-20 individuals of 11 species of small delphinids pooled together, including pygmy killer whales, produced from several years of dual-team surveys that used bigeye binoculars and similar protocols to the surveys in our study. This analysis was based on Barlow's (1995) analysis of cetaceans observed by shipboard surveys in California waters. Barlow and Forney (2007) reported an updated estimate of g(0)=0.856, incorporating additional surveys from the California Current ecosystem (CCE) and yielding a lower CV (0.056). Although Barlow and Forney did not apply the updated estimate to pygmy killer whales (they reported no observations in the CCE), we favored the updated estimate because it was more recent, incorporated more data, and had a lower CV.

Barlow and Forney's estimate accounted for perception bias but not availability bias. For long diving cetaceans such as sperm whales, Kogia spp., and beaked whales, the authors used Barlow's (1999) model of g(0) that incorporated dive behavior to address availability bias. McSweeney et al. (2009) reported that "pygmy killer whales are relatively easy to detect from visual surveys and show no obvious avoidance of vessels or evidence of extended dive durations", thus we do not expect availability bias to significant.

For aerial surveys, we were also unable to find a species-specific g(0) estimate for pygmy killer whales in the literature. For small groups, defined here as 1-5 individuals, we used Palka's (2006) estimate of g(0) for groups of 1-5 small cetaceans, estimated from two years of aerial surveys using the Hiby (1999) circle-back method. This estimate accounted for both availability and perception bias, but pooled sightings of several species together to provide a generic estimate for all delphinids, due to sample-size limitations. For large groups, defined here as greater than 5 individuals, Palka (2006) assumed that g(0) was 1. When we discussed this with NOAA SWFSC reviewers, they agreed that it was safe to assume that the availability bias component of g(0) was 1 but insisted that perception bias should be slightly less than 1, because it was possible to miss large groups. We agreed to take a conservative approach and obtained our g(0) for large groups from Carretta et al. (2000), who estimated g(0) for both small and large groups of delphinids. We used Carretta et al.'s g(0) estimate for groups of 1-25 individuals (0.960), rather than their larger one for more than 25 individuals (0.994), to account for the fact that we were using Palka's definition of large groups as those with more than 5 individuals.

Density Model

The pygmy killer whale is an oceanic species distributed worldwide in tropical and subtropical waters (Waring et al. 2013). The surveys from the Gulf of Mexico contributed by NOAA for this analysis reported only 18 definitive sightings of pygmy killer whales for the 1992-2009 study period. Pygmy killer whales can be difficult for observers to distinguish from melon-headed whales (Mullin et al. 1994). The surveys in our database reported 14 ambiguous "melon-headed or pygmy killer whale" sightings. The definitive melon-headed whale and pygmy killer whale sightings showed distinct differences in distributions of group size and latitude, with melon-headed whales occurring in larger groups mainly on the western side of the Gulf of Mexico, and pygmy killer whales occurring in smaller groups mainly on the eastern side. To avoid underestimating density by omitting these 14 ambiguous sightings, we built a classification model that classified 5 as melon-headed whales and 9 as pygmy killer whales (see Reclassification of Ambiguous Sightings section above).

After reclassification, the aggregate 27 sightings (Fig. 32) displayed a more cosmopolitan distribution, with sightings across the eastern, central, and western Gulf of Mexico, compared to the 18 definitive sightings (Fig. 9, red points), which occurred mainly in the eastern and central Gulf, with the exception of three in the western Gulf. All 27 sightings occurred off the

continental shelf, both along the continental slope and over the deep waters of the central Gulf. We split the study area at the shelf break, defined here as the 100m isobath, and assumed the species was absent from the shelf. With 27 sightings, we were right at the threshold we used to determine whether to fit a spatial model from environmental predictors or a stratified model that estimated mean abundance over the occupied area. Given the bias of increasing effort approaching the shelf break (Fig. 6) with no corresponding increase in sightings, it appeared that pygmy killer whales were not distributed uniformly with depth. To test this, we fitted a simple model with the logarithm of depth as the only covariate. Then, to test whether other covariates offered any additional explanatory power, we added each one of them in turn.

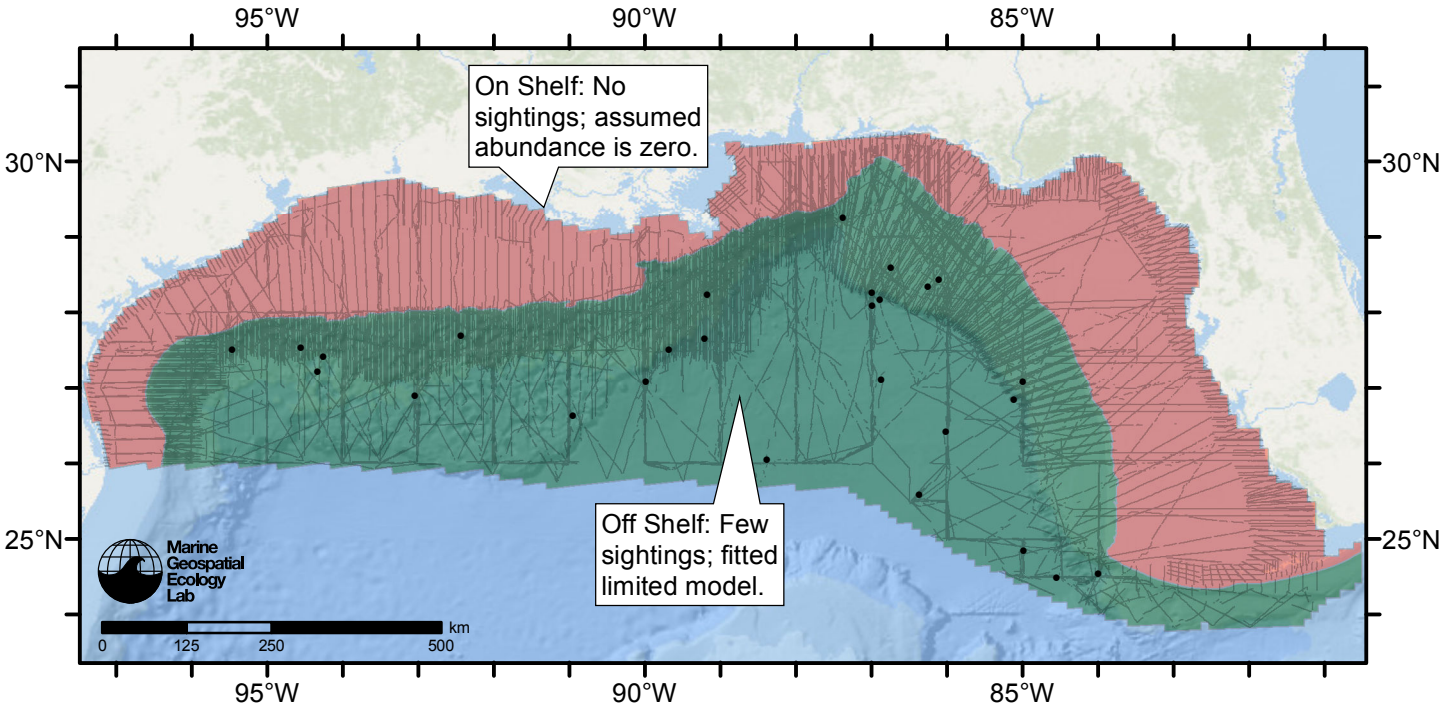


Figure 32: Pygmy killer whale density model schematic. All on-effort sightings are shown, including those that were truncated when detection functions were fitted.

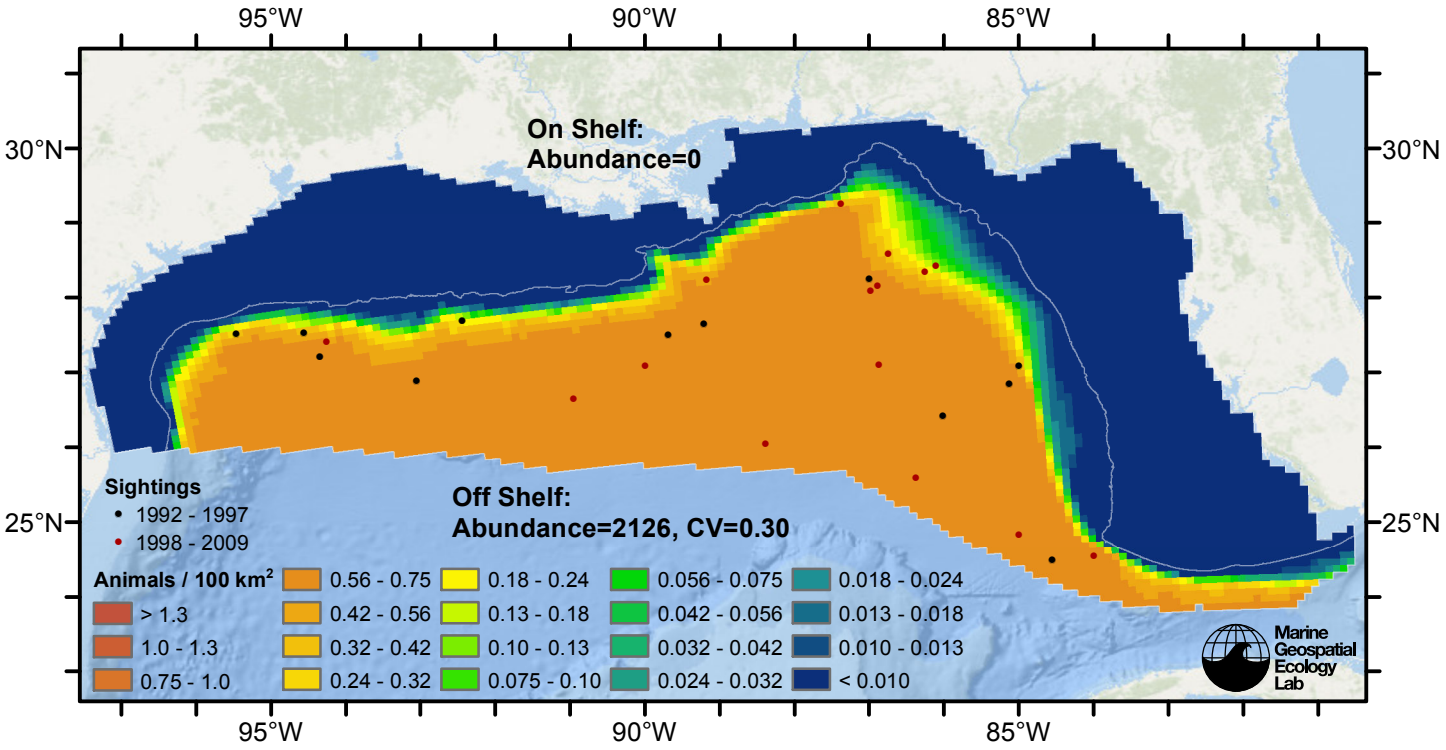


Figure 33: Pygmy killer whale density predicted by the climatological model that explained the most deviance. Pixels are 10x10 km. The legend gives the estimated individuals per pixel; breaks are logarithmic. Abundance for each region was computed by summing the density cells occuring in that region.

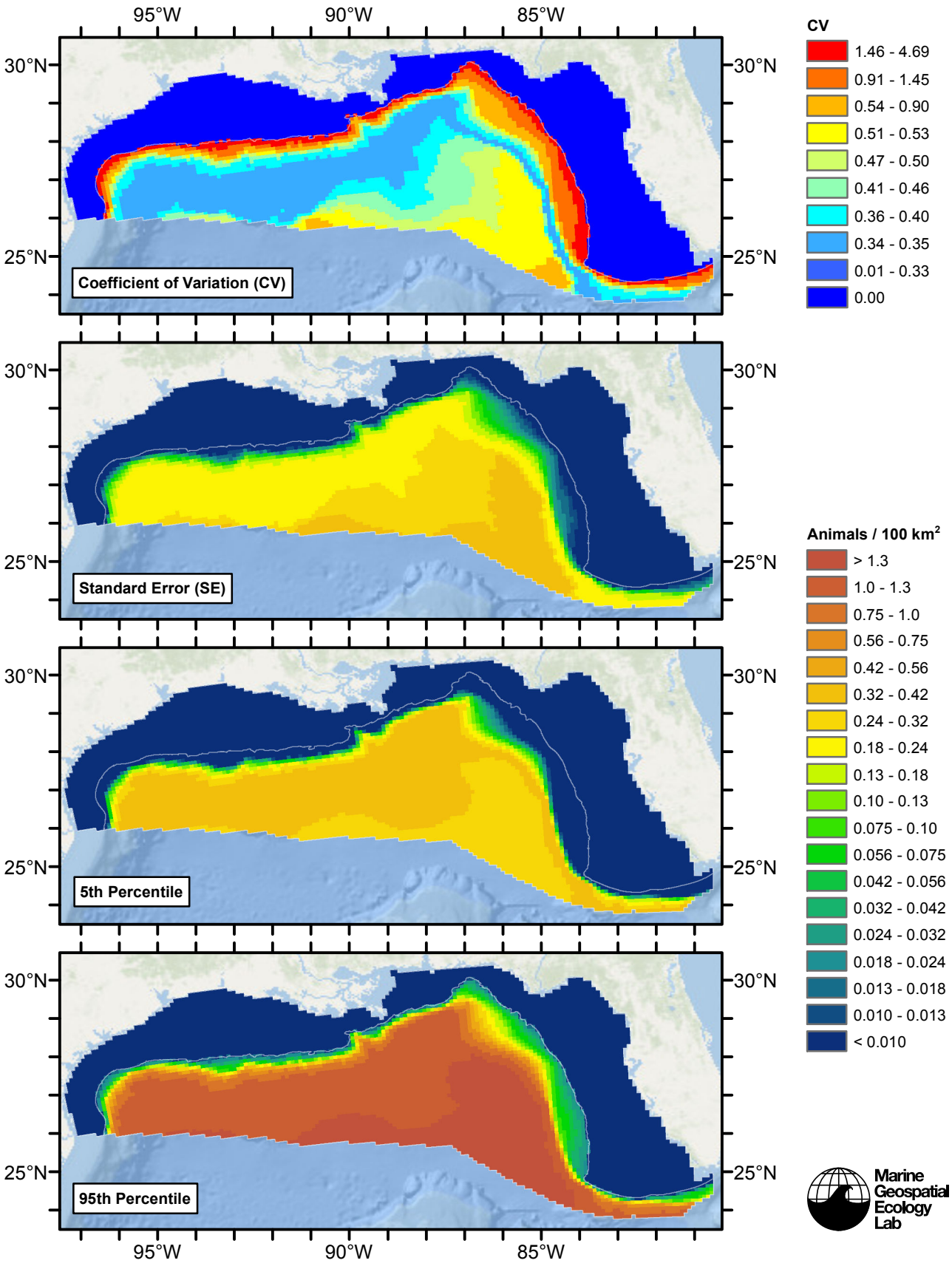


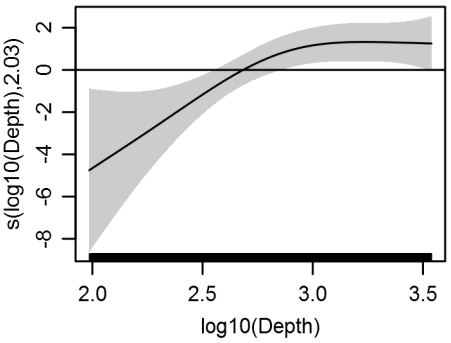
Figure 34: Estimated uncertainty for the climatological model that explained the most deviance. These estimates only incorporate the statistical uncertainty estimated for the spatial model (by the R mgcv package). They do not incorporate uncertainty in the detection functions, g(0) estimates, predictor variables, and so on.

Off Shelf

Statistical output

```
Rscript.exe: This is mgcv 1.8-2. For overview type 'help("mgcv-package")'.


Family: Tweedie(p=1.449)
Link function: log

Formula:
abundance ~ offset(log(area_km2)) + s(log10(Depth), bs = "ts",
    k = 5)

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -6.2988     0.4107  -15.34   <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)) 2.025      4 2.483 0.00413 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  -0.000134   Deviance explained = 13.3%
-REML = 354.48  Scale est. = 421.22    n = 14455

All predictors were significant. This is the final model.
Creating term plots.
Diagnostic output from gam.check():

Method: REML   Optimizer: outer newton
full convergence after 11 iterations.
Gradient range [-2.031311e-05,7.394517e-06]
(score 354.4828 & scale 421.2231).
Hessian positive definite, eigenvalue range [0.2474481,95.30512].
Model rank =  5 / 5

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)) 4.000 2.025   0.669    0.01

Predictors retained during the model selection procedure: Depth

Predictors dropped during the model selection procedure:
```

Model term plots



Diagnostic plots

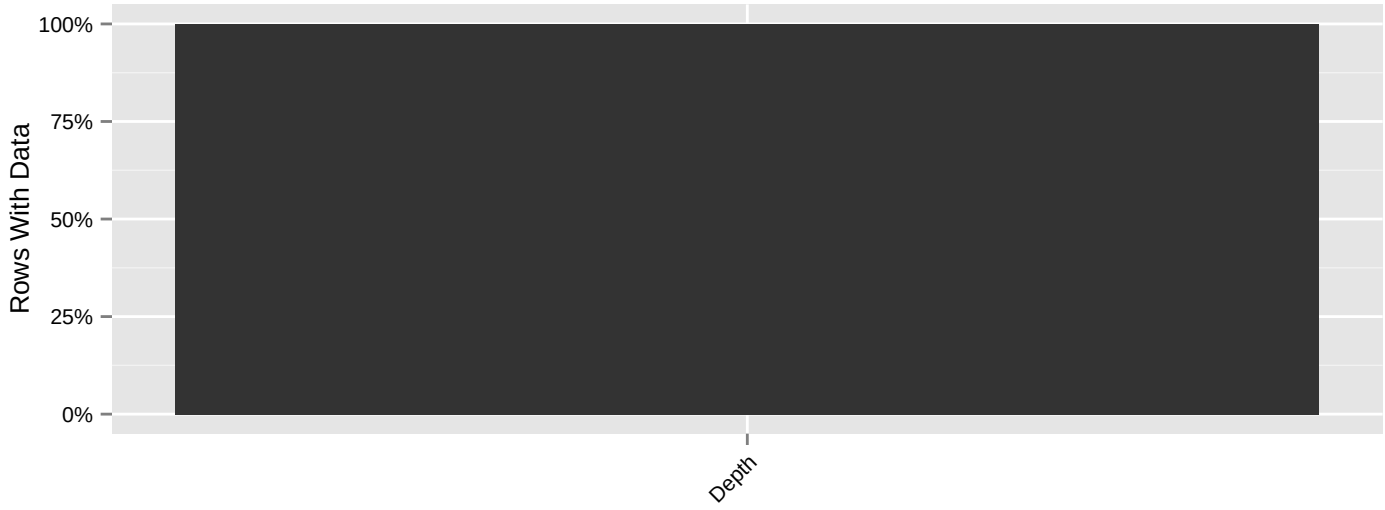


Figure 35: Segments with predictor values for the Pygmy killer whale Climatological model, Off Shelf. This plot is used to assess how many segments would be lost by including a given predictor in a model.

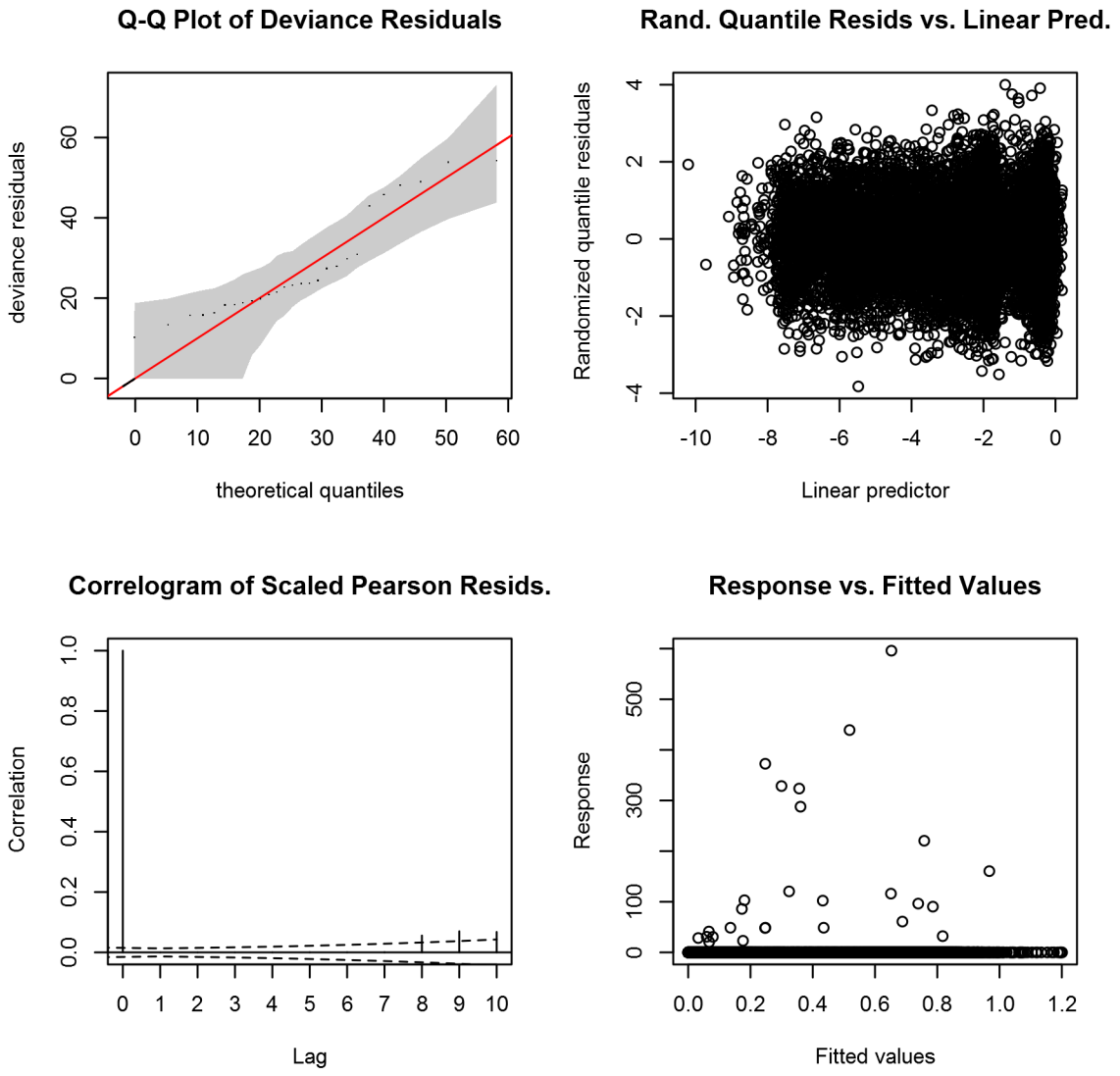


Figure 36: Statistical diagnostic plots for the Pygmy killer whale Climatological model, Off Shelf.

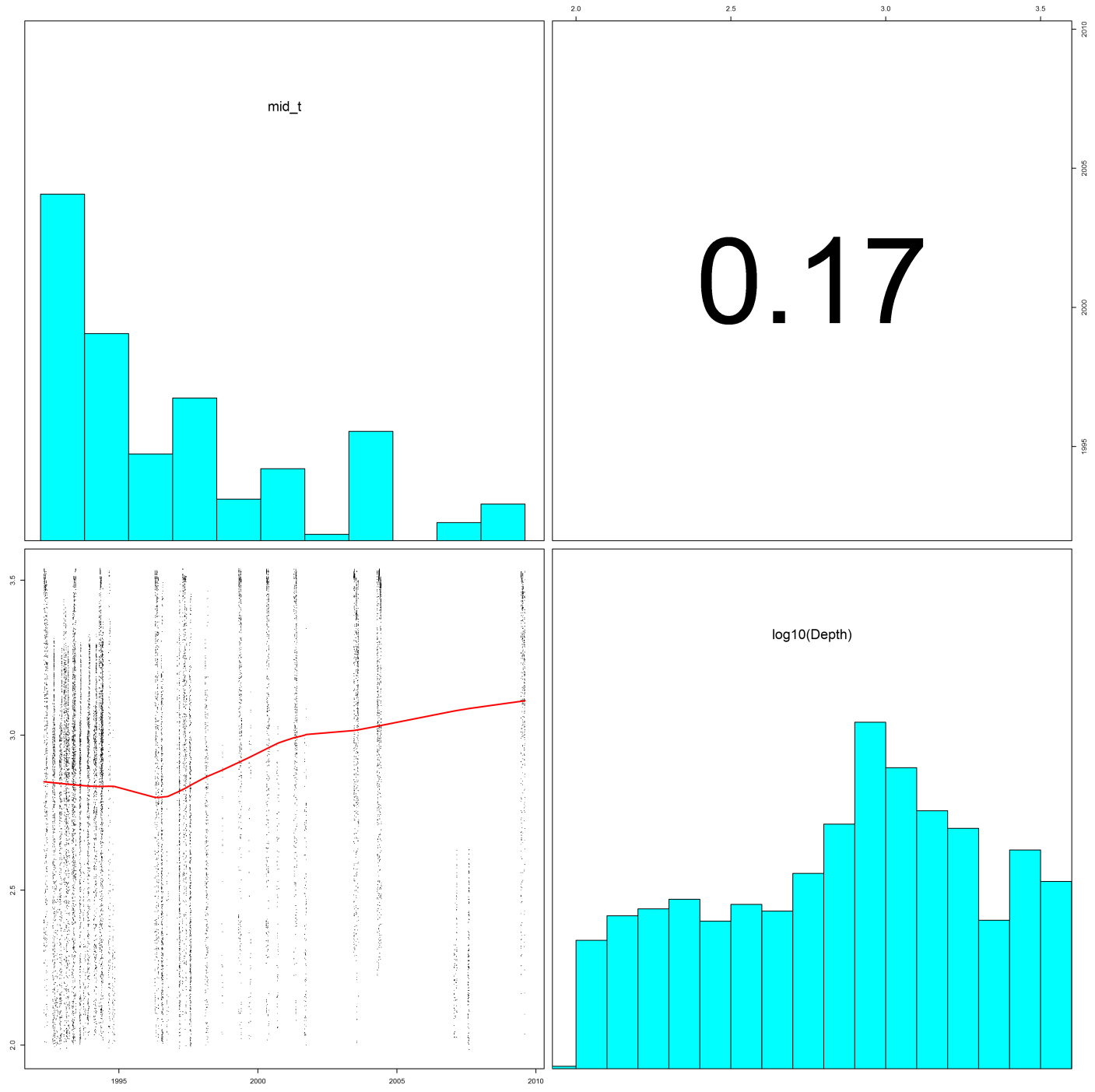


Figure 37: Scatterplot matrix for the Pygmy killer whale Climatological model, Off Shelf. This plot is used to inspect the distribution of predictors (via histograms along the diagonal), simple correlation between predictors (via pairwise Pearson coefficients above the diagonal), and linearity of predictor correlations (via scatterplots below the diagonal). This plot is best viewed at high magnification.

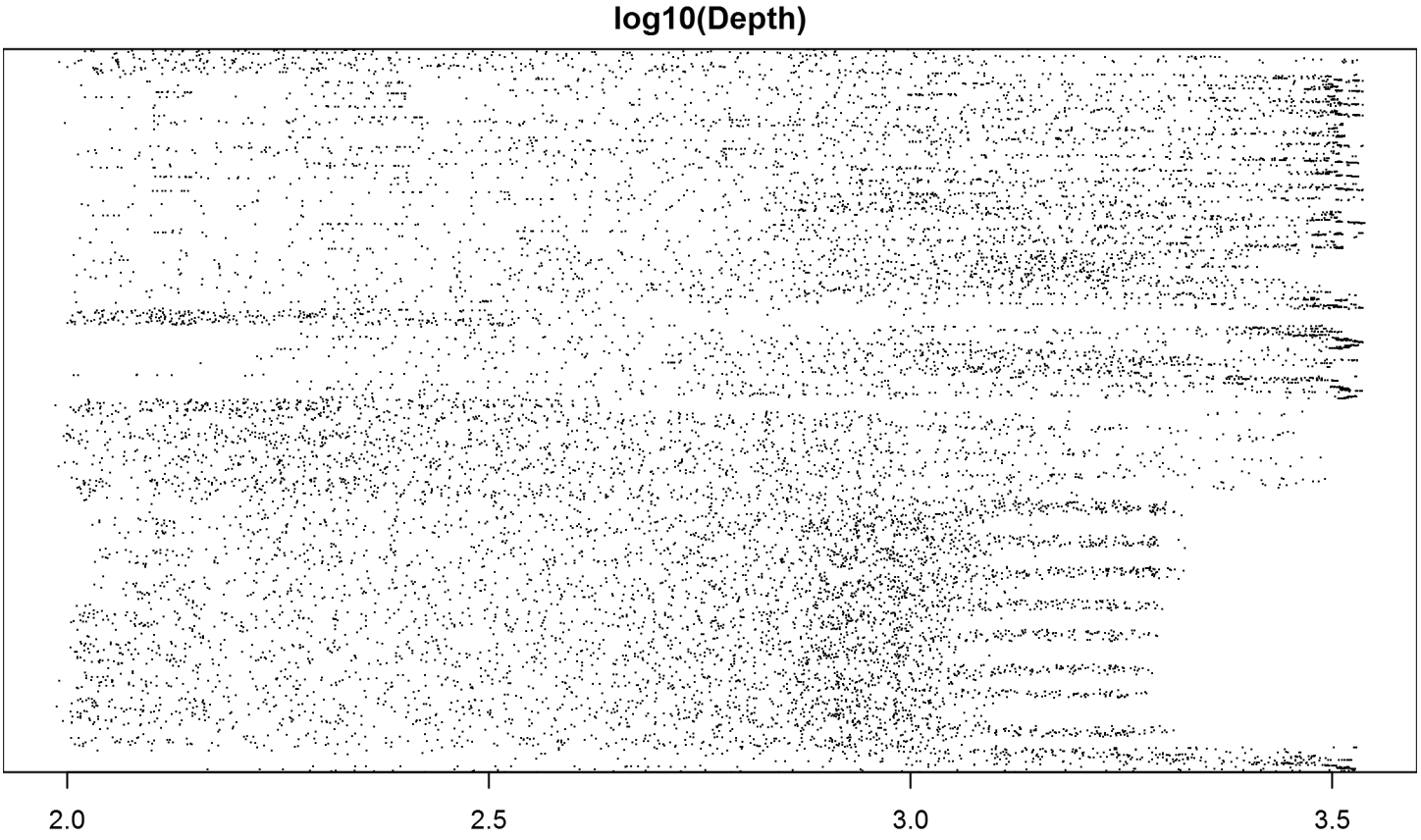


Figure 38: Dotplot for the Pygmy killer whale Climatological model, Off Shelf. This plot is used to check for suspicious patterns and outliers in the data. Points are ordered vertically by transect ID, sequentially in time.

On Shelf

Density assumed to be 0 in this region.

Model Comparison

Abundance Estimates

The table below shows the estimated mean abundance (number of animals) within the study area. The Assumed g(0)=1 column specifies whether the abundance estimate assumed that detection was certain along the survey trackline. Studies that assumed this did not correct for availability or perception bias, and therefore underestimated abundance. The In our models column specifies whether the survey data from the study was also used in our models. If not, the study provides a completely independent estimate of abundance.

Dates	Model or study	Estimated abundance	CV	Assumed g(0)=1	In our models
1992-2009	Climatological model	2126	0.30	No	
2009	Oceanic waters, Jun-Aug (Waring et al. 2013)	152	1.02	Yes	Yes
2003-2004	Oceanic waters, Jun-Aug (Mullin 2007)	323	0.60	Yes	Yes
1996-2001	Oceanic waters, Apr-Jun (Mullin and Fulling 2004)	408	0.60	Yes	Yes
1991-1994	Oceanic waters, Apr-Jun (Hansen et al. 1995)	518	0.81	Yes	Yes

Table 21: Estimated mean abundance within the study area. For comparison, independent abundance estimates from NOAA technical reports and/or the scientific literature are shown. Please see the Discussion section below for our evaluation of our models compared to the other estimates. Note that our abundance estimates are averaged over the whole year, while the other studies may have estimated abundance for specific months or seasons. Our coefficients of variation (CVs) underestimate the true uncertainty in our estimates, as they only incorporated the uncertainty of the GAM stage of our models. Other sources of uncertainty include the detection functions and g(0) estimates. It was not possible to incorporate these into our CVs without undertaking a computationally-prohibitive bootstrap; we hope to attempt that in a future version of our models.

Density Map

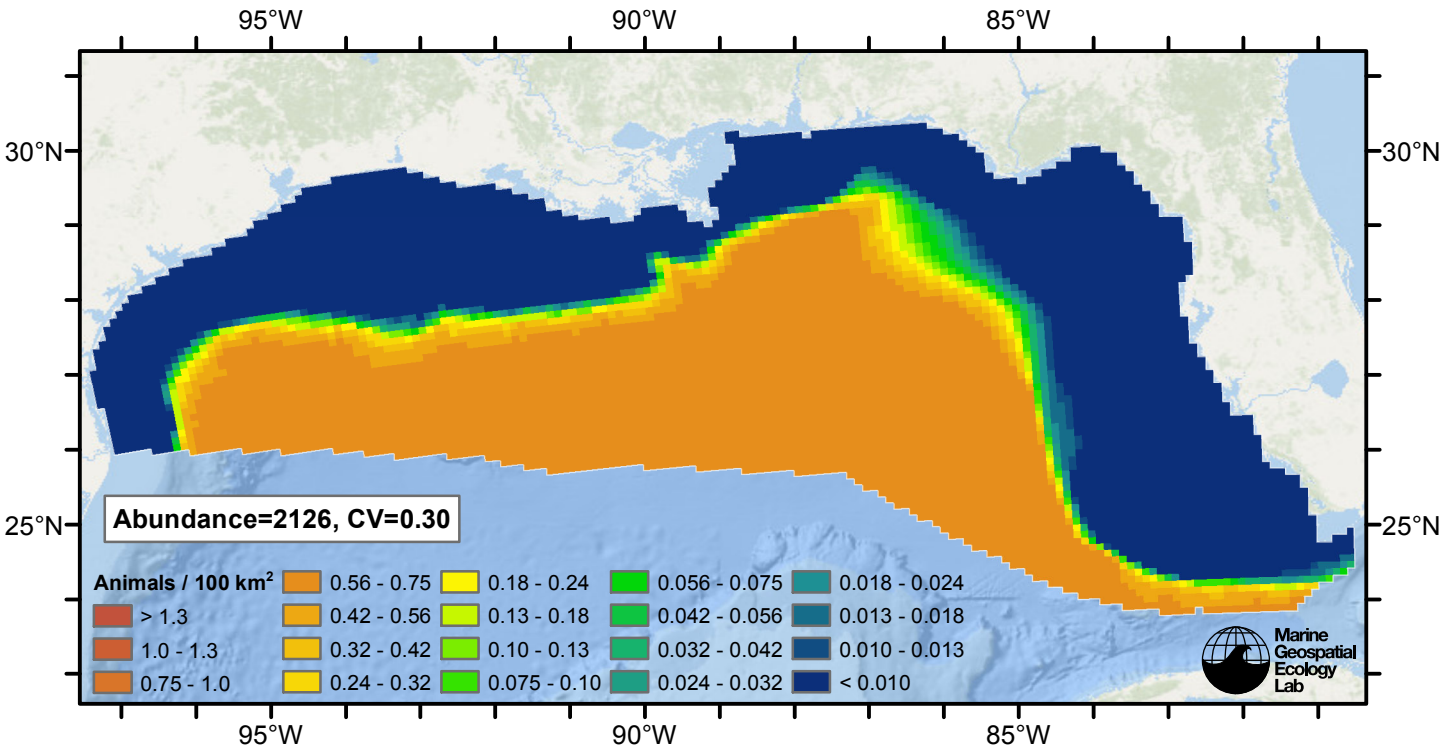


Figure 39: Pygmy killer whale density and abundance predicted by the climatological predictor model. Regions inside the study area (white line) where the background map is visible are areas we did not model (see text).

Discussion

In our model with the logarithm of depth as the only covariate, our automated model selection procedure retained depth as a statistically significant covariate. The model predicted that pygmy killer whale density increased steadily until about 1000 m depth and then plateaued, yielding a density surface that shows zero density on the shelf, a steady progression moving away from the shelf break until the 1000 m isobath, and constant density for waters deeper than 1000 m (Fig. 33). Although this model was based on a limited number of sightings and must be interpreted cautiously, the resulting pattern is very simple and, we would argue, a conservative and appropriate treatment of the limited data.

When we tested the remaining predictors, adding each in turn to a model that included depth, they were all discarded as not significant. This was not surprising given the limited number of sightings and their apparent random distribution (except with depth).

Our estimate of pygmy killer whale abundance, 2126, is roughly 4-14x larger than NOAA's series of estimates, which ranged from 518 for 1991-1994 to 152 in 2009. We believe this large difference may be traced to several factors that combine in a multiplicative way to cause our estimate to be much larger than NOAAs. First, NOAA's estimates were only based on the definitive sightings; our database contained 18. Our procedure for classifying the ambiguous "melon-headed or pygmy killer whale" sightings introduced 9 additional sightings that NOAA would not have considered. All else being equal, this would yield a 50% increase in estimated abundance.

The second factor relates to differences in detection functions. NOAA's detection functions typically had a larger effective strip half width than ours. For example, for the most recent NOAA analysis for which detailed documentation was publicly available (Mullin 2007), from 2003-2004, NOAA's shipboard detection function for Small Whales/Large Dolphins had an effective strip half width (ESHW) of 2392m. Our shipboard detection functions had mean ESHWs of 867m and 844m. Abundance scales inversely with ESHW, so it is not surprising that our estimate would be 3x larger when our ESHWs were 3x smaller.

Finally, a third factor concerns the g(0) parameter: NOAA's estimates assumed that g(0)=1 while we did not. All but 1 of the shipboard sightings in our analysis were of groups of 1-20 individuals. To correct for perception bias, we applied g(0)=0.856

to these sightings. Abundance scales inversely with g(0), so if g(0)=0.856 is assumed instead of g(0)=1, abundance increases 17%.

Chaining these three factors together and holding all else equal, our abundance estimate would be at least 5x larger than NOAA's. Thus the difference between the estimates is not entirely surprising after all.

In any case, at the time of this writing, NOAA's most recent abundance estimate of 152 is what NOAA used to estimate stock-level parameters important to management, including the Minimum Population Estimate (Nmin) and the Potential Biological Removal (PBR). Because these estimates are very low relative to the abundance we estimated, it is likely that if our results are used to estimate population-level impacts from potentially harmful human activities (i.e. "takes", as defined by the Marine Mammal Protection Act), the estimated impacts will be very high relative NOAA's estimated stock size (i.e. the estimated takes will greatly exceed PBR).

There is no easy solution to this problem. One possibility is that NOAA could recalculate stock-level parameters such as Nmin and PBR using our results. But this would violate NOAA's guideline that data older than 8 years not be used to estimate stock-level parameters (Moore et al. 2011). Alternatively, impacts could be estimated using NOAA's abundance estimate of 152, computing density by dividing this number by the total area of the off-shelf portion of the U.S. Exclusive Economic Zone in the Gulf of Mexico. But this would fail to account for the non-uniform distribution of pygmy killer whales predicted by our study (although the result might not be that bad, as our model predicted essentially uniform distribution for seafloor depths greater than 1000 m). Finally, in a hybrid approach, a new density surface could be obtained by apportioning NOAA's abundance estimate of 152 proportionally according to the density surface predicted by our models. To do that, divide our density surface by our total estimated abundance (2126), then multiply every cell by 152. To check that the result computed correctly, sum up all of the cells; the result should equal 152. This new density surface would reflect the distribution pattern predicted by our study but use the total abundance estimate from NOAA.

Interested parties should consult with NOAA about the best way to proceed with this problem.

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