

Distribution and Abundance of Fin whales and other baleen whales in the European Atlantic

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ABSTRACT

The abundance of fin whales (*Balaenoptera physalus*) and other baleen whales was generated from data collected during shipboard sightings surveys as part of the Cetacean Offshore Distribution and Abundance in the European Atlantic project (CODA). The survey area covered offshore waters beyond the continental shelf of the UK, Ireland, France and Spain. The area was stratified into four blocks and was surveyed by five ships during July 2007. Double platform methods employing the trial-configuration method (BT-method) were used. Fin, sei (*B. borealis*) and minke whales (*B. acutorostrata*) were positively identified, with possible sightings of blue whales (*B. musculus*). Abundance was estimated for these species and for “large baleen whales” which included fin, sei, fin/sei and blue whales. Abundance for the larger species was estimated using the Mark-Recapture Line Transect design-based method and also model-based methods using density surface modelling. Sample size limitations dictated that conventional line transect sampling methods were used to estimate the abundance of minke whales. Estimates from the two methods were comparable but model-based methods improved the precision and were considered best estimates. The density of large baleen whale species was greatest in the southern end of the survey area and water depth, temperature and distance to the 2000m contour were important predictors of their distribution. The total abundance estimated for the entire survey area was 9,019 (CV=0.11) fin whales and 9,619 (CV= 0.11) large baleen whales. The uncertainty around these estimates due to duplicate classification and species identification were explored. The fin whale estimate is likely to be underestimated because it excludes unidentified large whales, of which a large proportion was likely to have been fin whales. Notwithstanding this, these large baleen whale abundance estimates are the first robust estimates (corrected for responsive movement and $g(0)$) for this area. The estimated abundance of minke whales was 6,765 (CV=0.99) and sightings were restricted to the northern blocks of the survey area. The minke whale estimate, although imprecise and likely underestimated, does provide a baseline figure for this area and, when considered with results from the SCANS-II continental shelf surveys of July 2005, gives a more comprehensive picture of this species in the European Atlantic. These abundance estimates are important contributions to the conservation and management of these species in the Northeast Atlantic.

FIN WHALE, MINKE WHALE, BALEEN WHALE, ABUNDANCE ESTIMATE, SHIPBOARD-SURVEYS, NORTHEAST ATLANTIC

INTRODUCTION

The abundance and distribution of cetaceans in offshore waters of the European Atlantic is poorly known. Some areas have been surveyed previously but the abundance estimates generated suffer from several sources of bias. The Cetacean Offshore Distribution and Abundance (CODA) project aimed to assess the abundance of cetaceans beyond the continental shelf of the UK, Ireland, France and Spain. Shipboard surveys were conducted in July 2007 and the abundance of eight species/species groups was estimated using a combination of design (Macleod *et al.*, 2008) and model based methods. One of the focal species was the fin whale (*Balaenoptera physalus*) and this paper reports the abundance estimated for this and other baleen whale species, including sei (*B. borealis*) and minke (*B. acutorostrata*) whales. The estimates for fin and sei whales are the first unbiased estimates (corrected for $g(0)$ and responsive movement) for this area. This information is needed for the conservation and management of species in these waters, which are faced with a number of potential threats from activities including fishing and whaling, oil and gas and military activities.

METHODS

Survey methods

The study area was divided into four strata (Figure 1) and was surveyed by five ships¹ during July 2007. Realised search effort is shown in Figure 2. Survey methods replicated those used during the SCANS-II project (SCANS-II 2008), which had previously been updated from the SCANS 1994 project (Hammond *et al.*, 2002) to incorporate new methods for data collection and analysis.

The shipboard survey was conducted using a ‘trial configuration’ or BT method (Laake & Borchers, 2004; Buckland & Turnock, 1992), with two teams of observers located on each survey vessel. The first team (referred to as observer 1) searched by naked eye close to the vessel (<500m). The second team (observer 2) searched with Bigeye or 7x50 binoculars, scanning a region sufficiently far ahead of the vessel that animals were unlikely to have reacted to the vessel’s presence before being detected. This scanned region was also sufficiently wide that animals outside it at greater distances from the transect would not be able to enter the region searched by observer 1. A third observer, the ‘Duplicate Identifier’, was informed of all detections as they were made and was responsible for classifying duplicates. A duplicate sighting occurred when a sighting made by the tracker was subsequently recorded by the observer 1 and were classified as either: D: definite (at least 90% likely), P: probable (more than 50% likely), and R: remote chance (less than 50% likely). All species were tracked until abeam of the vessel or for 2-3 re-sightings after they had been declared a duplicate. Sightings were classified with identification certainty levels: High, Medium, and Low.

Analysis methods

Estimates of abundance were calculated from the shipboard surveys for each survey block, corrected for animals missed on the transect line and for any responsive movement using design-based Mark Recapture Distance Sampling (MRDS). A common detection function was generated for a category ‘Large baleen whales’ (LB) which incorporated fin (FW), sei (SW), fin/sei (FS) and blue whales (BW). This was used to generate the abundance estimates for this category and for fin and sei whales separately. There were only two possible sightings of blue whales. The detection function was then used for the model-based Density Surface Modelling (DSM) analysis and abundance generated for LB and fin whales.

Many sightings of large whales, seen predominately as distant blows, could not be identified to species and were coded ‘Unidentified whale’ (“W?”). The use of this code varied between vessels and observers in block 2 were more cautious than other observers and tended to use W? instead of a possible FW identification. This category was excluded from the LB modelling because it was possible that there were some sperm whales in the group, which would be expected to have a different detection probability. Therefore, a separate abundance estimate was generated for the unidentified whales W?.

MRDS methods require an adequate sample size of duplicate sightings for fitting the detection function. For the minke whale, there were too few sightings so sightings data from observers 1 and 2 were combined and one of the duplicate pair removed to create a dataset of unique sightings. This dataset was then analysed using conventional distance sampling (CDS) (Buckland *et al.*, 2001) methods. For all analyses, only data collected during Beaufort sea state ≤ 4 were used. Analyses were carried out in DISTANCE 6 Beta 4 (Thomas *et al.*, 2006).

Fitting the Detection Function

The MRDS methodology used was developed by Borchers *et al.* (1998) and Borchers *et al.* (2006). In BT survey mode, the role of observer 2 is to generate detections of animals before they have responded to the vessel. Estimation of the detection function for observer 1 is then conditioned on these detections, which serve as a set of binary trials in which success corresponds to a detection by

¹ The survey was planned with one ship per stratum but due to engine failure, two ships covered stratum 2.

observer 1. The probability that an animal is detected by observer 1 at a given perpendicular distance x and covariates z , $p_1(x, z)$ is modelled as a logistic function:

$$p_1(x, z) = \frac{e^{(\theta_{10} + \theta_{11}x + \sum_{r=1}^R \theta_{(r+1)} z_r)}}{1 + e^{(\theta_{10} + \theta_{11}x + \sum_{r=1}^R \theta_{(r+1)} z_r)}}$$

where $\theta_i = (\theta_{i0}, \dots, \theta_{iQ_i})'$ represents the Q_i parameters of the detection function of observer i ($i=1,2$).

Several explanatory variables were explored in conjunction with perpendicular distance to fit the detection function models. These were: group size, vessel, primary platform height, Beaufort sea state, swell, glare, visibility, cue, sightability, precipitation and cloud cover.

One or two detection functions were fitted to the sightings data depending on the type of model used: point or full independence. The choice of model is dependent on whether there is evidence of responsive movement in the sightings data; if so, the full independence model is preferable.

MRDS Abundance estimates

Using a Horvitz-Thompson-like estimator, group abundance is given by

$$\hat{N}_1 = \sum_{j=1}^{n_1} \frac{1}{p_{1.}(z_j | \hat{\theta})} \quad (1)$$

where n_1 is the number of detections made by observer 1 (some of which may have been seen by observer 2) and $p_{1.}(z)$ represents the integration over the range of x .

For species that occur in groups, an estimate of individual abundance is obtained by replacing the numerator in equation (1) with the group size, s_{j1} , where s_{j1} is the size of the j th detected group.

$$\hat{N}_{1_{indiv}} = \sum_{j=1}^{n_1} \frac{s_{j1}}{p_{1.}(z_j | \hat{\theta})}$$

Estimates of mean group size were obtained as

$$E[s_1]_1 = \frac{\hat{N}_{1_{indiv}}}{\hat{N}_1}$$

Density and abundance estimates were generated by survey block and for the entire area. The estimated variance was based on the empirical variance in estimated density between samples (Innes *et al.* 2002).

Density Surface Modelling

CDS and MRDS provide estimates of abundance for predetermined survey blocks but do not provide any information on density at a finer spatial resolution. In the DSM approach, animal density is modelled in a Generalised Additive Model (GAM) framework using physical and environmental covariates to generate abundance estimates.

For the DSM analysis, the effort data need to be divided into segments. Each transect was divided into segments of approximately equal lengths. This gave a total of 1,359 segments totalling 9,494km of effort. Each baleen whale sighting was assigned to the corresponding segment. Values of the physical and environmental covariates were assigned to the mid point of each segment.

A grid for prediction of abundance throughout the survey area was generated. A resolution of 0.25 degrees was chosen, corresponding to the coarsest resolution in the available environmental covariates, yielding a total of 2,046 grid cells. Each grid cell was characterized by the centre values of physical and environmental data used as potential predictive covariates in the DSM.

The estimation process was carried out as follows:

- 1) a detection function was estimated from the line transect data and any covariates that could affect detection probability (obtained from the MRDS analysis);
- 2) the number of groups in each segment of effort was estimated through the Horvitz-Thompson estimator (Borchers *et al.*, 2002).
- 3) the abundance of groups was modelled using a Generalized Additive Model (GAM) with a logarithmic link function. Due to over-dispersion in the data, a quasi-Poisson error distribution was used, with variance proportional to the mean, and using the searched area of each segment as an offset. The general structure of the model was:

$$\hat{N}_i = \exp \left[\ln(a_i) + \theta_0 + \sum_k f_k(z_{ik}) \right] \quad (2)$$

where the offset a_i is the search area for the i^{th} segment (calculated as the length of the segment multiplied by twice the truncation distance), θ_0 is the intercept, f_k are smoothed functions of the explanatory covariates, and z_{ik} is the value of the k^{th} explanatory covariate in the i^{th} segment. The covariates used in the models included depth, sea surface temperature, chlorophyll-a, distance to the 200m and 2000m contour, aspect, slope, sea-surface height anomaly, latitude and longitude.

- 4) abundance of animals was estimated in each grid cell as the product of model predictions from step 3 and a mean group size.

The selection of the best model was based on three criteria: (a) the GCV (General Cross Validation score); (b) the percentage of deviance explained; and (c) whether each explanatory variable was statistically significant.

Variance was estimated using a parametric moving-block bootstrap and the number of bootstrap resamples generated was 499. The moving-blocks were essentially defined as follows: a block consisted of a number of adjacent segments along a transect; having specified the first block along a transect; the next block was generated by moving along one so that the first segment was dropped and then another segment added and so on to generate more blocks. The resampling unit corresponded to blocks of residuals; the residuals were obtained from the fitted model. For each resample, blocks were selected at random (and with replacement) until enough blocks had been chosen so that the total number of segments in the resample equalled the total number of segments in the original data. A new value was then obtained for each segment in the original data from the fitted value for that segment plus the new residual. This method preserved both the spatial coverage of the original data and any correlation observed in the residuals along the transect line by adjusting the number of the segments that made up a block.

RESULTS

Mark Recapture Distance Sampling

Detection Function

The detection function was modelled using the LB whale dataset that comprised 223 observer 2 sightings, 204 observer 1 sightings and 92 duplicate sightings. A full independence model was fitted because there was some evidence of responsive movement of fin whales to the survey vessels (Figure 3). A truncation distance of 4000m was applied. The final model included Sightability (factor with 4 levels) and primary (observer 1) platform height in addition to perpendicular distance (Figure 4). The chosen detection function model used D and P duplicates only. The average detection probability for observer 1 under this model was 0.6 (CV 0.10) and p(0) was 0.54 (CV = 0.10).

A full independence model was also fitted to the W? data because of some evidence of responsive movement. The data were truncated at 6000m removing two outlying observations. The final sample size was 159 observations; 97 observer 1, 86 observer 2 and 24 duplicate sightings. The final model included perpendicular distance and cloud cover (as a continuous variable) (Figure 5).

Finally, we pooled the category “W?” with the LB whale category to obtain an estimate for all large whales (under the assumption that the majority of W? sightings were large baleen whales) in the survey area. A separate detection function was fitted to this category. A full independence model and a truncation distance of 6000m were used. The final model of the detection function included perpendicular distance, cloud cover and primary (observer 1) platform height (Figure 6).

Abundance estimates

The total abundance of LB whales in the survey area was 8,237 (CV=0.20). The abundance of fin and sei whales in the survey area was 7,625 (0.21) and 366 (0.33), respectively (Table 1). Abundance of unidentified whales, W?, was estimated to be 6,601 (0.40) whales (Table 1). Pooling LB and W? observations generated an abundance of 14,550 (0.26).

Exploring Uncertainty in data classification

Duplicate Classification

An analysis of the effect of duplicate classification was undertaken on the LB whale dataset, in which abundance was estimated for: all duplicates (D, P and R), D and P, and D only. Table 2 shows that including R duplicates had little effect but removing P duplicates had a greater effect.

Large whale identification certainty

Estimates of abundance were generated using the detection function for LB whales to look at the effects of identification certainty on the abundance estimates. Table 3 shows that removing low certainty sightings had little effect but that removing medium and assumed high certainty sightings had a large effect.

Conventional line transect estimate for minke whale

Using a conventional line transect analysis, 22 observations were used to fit the detection function to the minke whale dataset. The data were truncated at 1400m and pooled over strata. A hazard rate function fitted to perpendicular distance data was selected as the best model (Figure 7). Total abundance of minke whales in the survey area was estimated to be 6,765 (CV = 0.99) (Table 4).

Density Surface Modelling

Large baleen and fin whales

The models showed five variables to be important in predicting fin whale density; sea surface temperature, average depth, longitude, contour index and distance to the 2000m contour (Table 5). The

total estimate of abundance of LB baleen whales was 9,619 (0.11; 95% CI 7,760 – 11,924) (Table 6) and the surface map of smoothed predicted abundance of animals is shown in Figure 8. The total estimate of abundance of fin whales was 9,019 (0.11; 95% CI 7,265 – 11,197) (Table 6). The surface map of smoothed predicted abundance of animals is shown in Figure 9.

DISCUSSION

Large baleen whales were encountered throughout the survey area, although they were few in the northern part (block 1) of the area. Occurrence of fin whales in this area during July may be highly variable, having been recorded in this region during previous surveys (Pollock et al., 2000; Macleod et al., 2006) and not in others (Joyce et al., 1990). Large baleen whale densities were highest in the southern part of the CODA survey area. There were two areas in particular which had the highest predicted densities; the southern end of block 2 and in the northeastern part of block 3 off the Galician coast. Sei whale sightings were confined to block 3. The GAM predicted higher densities of fin whales in areas of sea surface temperature between 16-19°C and in depths between 1000-3500m. Peak density was predicted within 50m of the 2000m contour. The relationship with longitude was more difficult to interpret. The predictors for large baleen whales were similar.

The abundance estimates for the LB and fin whales generated by the design- and model-based methods were comparable. The precision of the estimates was improved by using the DSM approach and for this reason, considered the better of the two: best estimates of abundance were therefore 9,019 (CV 0.11) fin whales and 9,619 (CV 0.11) large baleen whales.

Several abundance estimates for fin whales in the Northeast Atlantic have been generated from the North Atlantic Sightings Surveys (NASS) of 1987, 1989, 1995 and 2001. Estimates from these surveys are likely underestimates because they did not cover the whole of the fin whales range nor were they corrected for availability and perception biases. Abundance estimates for fin whales corrected for $g(0)$ from the recent TNASS surveys of 2007 are available for areas north of CODA. The CODA area lies within the British Isles-Spain-Portugal (SPB) management area as defined by the IWC and the abundance of fin whales within this area was estimated to be 17,355 (CV 0.27) from the 1989 NASS data (Buckland *et al.*, 1992). The CODA estimate of 9,019 (0.11) fin whales is the most recent and precise estimate approximating the SPB area, although there was little survey effort west of 14°W. If we were to assume that all unidentified large whales were also fin whales, then the best abundance estimate for this species in the CODA area is 13,966 (0.27).

Minke whales occur both on and off the continental shelf. Because the CODA area adjoins the SCANS-II area, the estimate from the 2007 CODA project 6,765 (CV=0.99) can be added to the 2005 SCANS-II estimate of 18,614 (CV=0.30) to give a total estimate of 25,379, with CV=0.34 calculated by the Delta method and ignoring any additional variance. The CODA estimate is likely biased low because it does not account for missed animals on the transect line. In addition, it may be biased low because it does not account for previously observed responsive avoidance movement, which can generate negative bias (Palka & Hammond 2001; Hammond et al. 2002). The CODA estimate is also imprecise, but nevertheless helps provides a baseline for this region.

Minke whale abundance in the northeastern Atlantic has been estimated as 63,730 (CV=0.19) in 1988-89; 112,125 (CV=0.10) in 1995, and 80,487 (CV=0.15) in 1996-2001 (Schweder et al. 1997; Skaug et al. 2004). A preliminary estimate for 2002-2007 of 78,572 (CV=0.16) has also been presented (Bothun 2008). The area covered by these surveys includes part of the North Sea but does not include waters to the west and south of Britain and Ireland.

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References

- Borchers DL, Buckland ST, Zucchini W. 2002. Estimating animal abundance. Closed populations. Springer, London
- Buckland, S.T.; K.L. Cattanaach and S. Lens. 1992. Fin whale abundance in the eastern North Atlantic, estimated from Spanish NASS-89 data". Rep. Int. Whal. Commn 42: 457-460.
- Borchers, D.L., Buckland, S.T., Goedhart, P.W., Clarke, E.D. and Hedley S.L. 1998. Horvitz-Thompson estimators for double-platform line transect surveys. *Biometrics* 54:1221-1237
- Borchers, D.L., Laake, J.L., Southwell, C. and Paxton, C.G.M. 2006. Accommodating unmodelled heterogeneity in double-observer distance sampling surveys. *Biometrics* 62: 372-378.
- Buckland, S.T. and Turnock, B.J. (1992) A robust line transect method. *Biometrics* 48: 901-909
- Bøthun, G., Skaug, H.J. & Øien, N. 2008. Towards an estimate of minke whale abundance in the northeast Atlantic based on survey data collected over the period 2002-2007. Paper SC/60/PF14 presented to the IWC Scientific Committee. 10pp.
- Buckland, S.T, Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers D.L. and Thomas, L. 2001. Introduction to distance sampling. Oxford University Press, Oxford.
- CODA 2009. Cetacean Offshore Distribution and Abundance in the European Atlantic (CODA). Report available from SMRU, Gatty Marine Laboratory, University of St Andrews, St Andrews, Fife KY16 8LB, UK.
- Hammond, P.S., Berggren, P., Benke, H., Borchers, D.L., Collet, A., Heide-Jørgensen, M.P., Heimlich, S., Hiby, A.R., Leopold, M.F. & Øien, N. 2002. Abundance of harbour porpoises and other cetaceans in the North Sea and adjacent waters. *Journal of Applied Ecology* 39: 361-376.
- Innes, S., Heide-Jørgensen, M.P., Laake, J.L., Laidre, K.L., Cleator, H.J., Richard, P. and Stewart, R.E.A. 2002. Surveys of belugas and narwhals in the Canadian High Arctic in 1996. NAMMCO Scientific Publications 4: 169-190
- Joyce, G.G., Desportes G, Bloch D. 1990. The Faroese NASS-89 Sightings cruise. Paper SC/42/011 presented to the Scientific Committee of the International Whaling Commission 10 pp.
- Macleod, K., Burt, M, L., Cañadas, A, Rogan, E., Santos, B., Uriarte, A., Van Canneyt, O, Vazques A and Hammond PS. 2008. Preliminary abundance estimates of cetaceans in offshore European Atlantic waters. Paper SC/60/02 prepared for the 2008 Scientific Committee of the International Whaling Commission. Pollock et al., 2000.
- Palka, D.L. & Hammond, P.S. 2001. Accounting for responsive movement in line transect estimates of abundance. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 777-787.
- SCANS-II 2008. 2008. Small Cetaceans in the European Atlantic and North Sea (SCANS-II). Final report to the European Commission LIFE Nature programme on project LIFE04NAT/GB/000245.
- Schweder, T., Skaug, H.J, Dimakos, X. K., Langas, M. and Øien, N. 1997. Abundance of northeastern Atlantic minke whales, estimates for 1989 and 1995. Rep. Int. Whal. Commn. 47:453-483
- Skaug, H.J., Øien, N., Schweder, T. & Bøthun, G. 2004. Abundance of minke whales (*Balaenoptera acutorostrata*) in the Northeastern Atlantic; *Can. J. Fish. Aquat. Sci.* 61: 870-86.
- Thomas, L., Laake, J.L., Rexstad, E., Strindberg, S., Marques, F.F.C., Buckland, S.T., Borchers, D.L., Anderson, D.R., Burnham, K.P., Burt, M.L., Hedley, S.L., Pollard, J.H., Bishop, J.R.B. and Marques, T.A. 2006. Distance 6.0. Release 4. Research Unit for Wildlife Population Assessment, University of St. Andrews, UK. <http://www.ruwpa.st-and.ac.uk/distance/>

APPENDIX

Species code	Common name
BW	Blue whale
FW	Fin whale
FS	Fin or Sei whale
SW	Sei whale
MW	Minke whale
LB	Large baleen whale
W?	Unidentified whale

Physical and environmental covariates used in the density surface modelling.

Name	Description	Source
depth_av	Average depth in the grid cell	2-Minute Gridded Global Relief Data (ETOPO2v2). National Geophysical Data Center (NGDC). NOAA Satellite and Information Service.
depth_sd	Standard deviation of the depth data points within the grid cell	Derived from ETOPO2 bathymetric data
depth_cv	Coefficient of variation of the depth data points within the grid cell	Derived from ETOPO2 bathymetric data
dist200_deg	Distance to the 200 m depth contour, in decimal degrees	Calculated with the Spatial Analyst extension of ArcGis 9.2, using GEBCO bathymetric data.
dist2000_deg	Distance to the 2000 m depth contour, in decimal degrees	Calculated with the Spatial Analyst extension of ArcGis 9.2, using GEBCO bathymetric data.
Slope_per	Slope of the sea floor as a percentage, calculated as follows: $\frac{\text{depth}_{\text{max}} - \text{depth}_{\text{min}}}{\text{distance in km}(\text{depth}_{\text{max}} - \text{depth}_{\text{min}})} \times 100$	Derived from ETOPO2 bathymetric data
slope_deg	Slope of the sea floor in degrees, calculated as follows: $\text{degrees} \left(\tan \left(\frac{\text{slope}_{\text{per}}}{100} \right) \right)$	Derived from ETOPO2 bathymetric data
ci	Contour index of the sea floor, calculated as follows: $\frac{\text{depth}_{\text{max}} - \text{depth}_{\text{min}}}{\text{depth}_{\text{max}}} \times 100$	Derived from ETOPO2 bathymetric data
ssh	Average Sea Surface Height Anomaly for the month of July 2007, calculated as the difference between measured SSH and the expected mean SSH.	Altimetry Sensors on multiple spacecrafts (JASON-1, TOPEX/POSEIDON, ENVISAT, GFO, ERS 1/2, GEOSAT). Resolution: 0.25 degrees. NOAA CoastWatch Program
sst	Average Sea Surface Temperature for the month of July 2007 for Blocks 1 and 2, for the first fortnight of July 2007 for Block 4 and for the second fortnight of July 2007 for Block 4.	Sensor: Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua, Advanced Very High Resolution Radiometer (AVHRR) on POES, Imager on GOES, Advanced Microwave Scanning Radiometer (AMSR-E) on Aqua. Resolution: 0.1 degrees. NOAA CoastWatch Program

sst_sd	Standard deviation of Sea Surface Temperature for the month of July 2007 for Blocks 1 and 2, for the first fortnight of July 2007 for Block 4 and for the second fortnight of July 2007 for Block 4.	Derived from NOAA CoastWatch Program sea surface temperature data.
chl_a	Average Chlorophyll-a concentration for the month of July 2007 for Blocks 1 and 2, for the first fortnight of July 2007 for Block 4 and for the second fortnight of July 2007 for Block 4.	Sensor: Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Resolution: 0.1 degrees. NOAA CoastWatch Program
chl_a_sd	Standard deviation of Chlorophyll-a concentration for the month of July 2007 for Blocks 1 and 2, for the first fortnight of July 2007 for Block 4 and for the second fortnight of July 2007 for Block 4.	Derived from NOAA CoastWatch Program Chlorophyll-a concentration data.
aspect	Orientation of the sea floor as a factor with 8 levels(N, NE, E, SE, S, SW, W, NW)	Calculated with the Spatial Analyst extension of ArcGis 9.2, using ETOPO2 bathymetric data.
aspectxyz	Orientation of the sea floor as a continuous variable (0 to 359)	Calculated with the Spatial Analyst extension of ArcGis 9.2, using ETOPO2 bathymetric data.
lat	Latitude in decimal degrees	
lon	Longitude in decimal degrees	

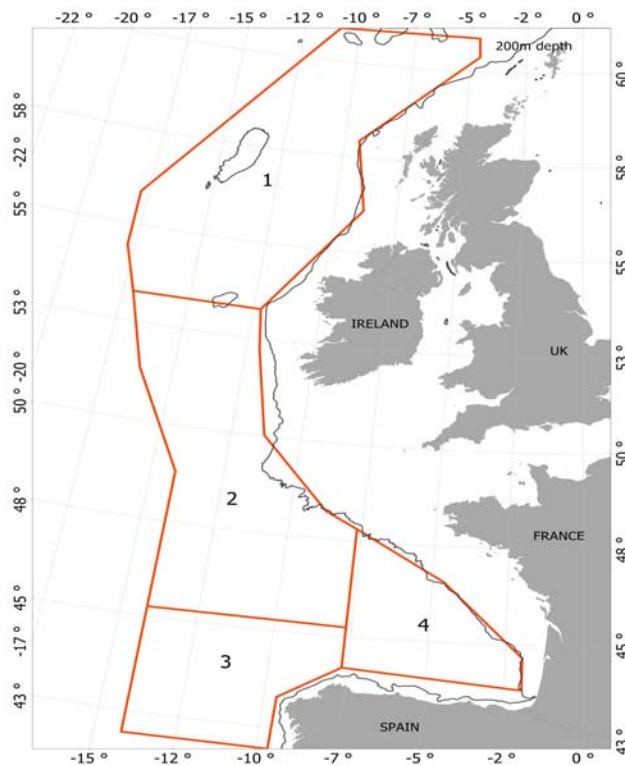


Figure 1: CODA survey area and survey blocks

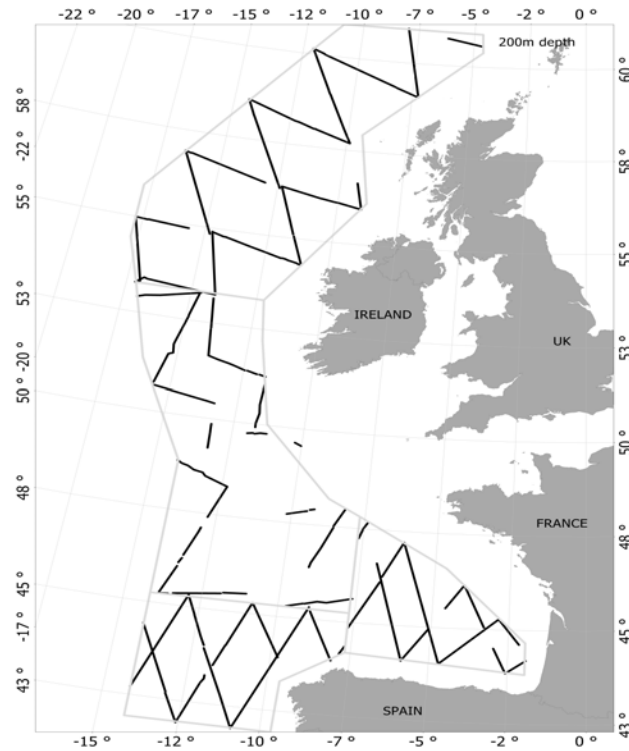


Figure 2: Realised survey effort during the CODA surveys, July 2005.

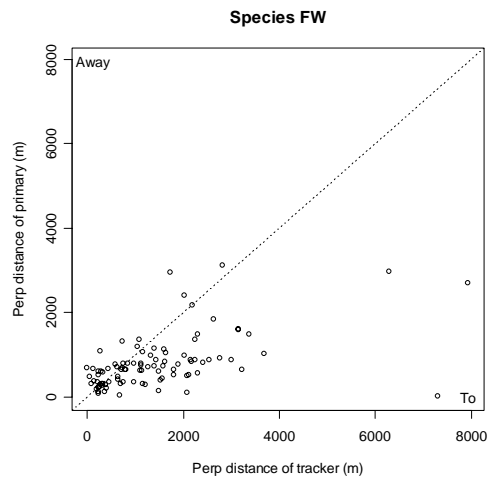


Figure 3: Plot of perpendicular distances of duplicates at the time they were seen by the tracker (x-axis) and then by the primary (y-axis) for fin whales. The dotted line corresponds to no movement in relation to the trackline. Points above the line correspond to animals moving away from the trackline, while those below correspond to movement towards the trackline.

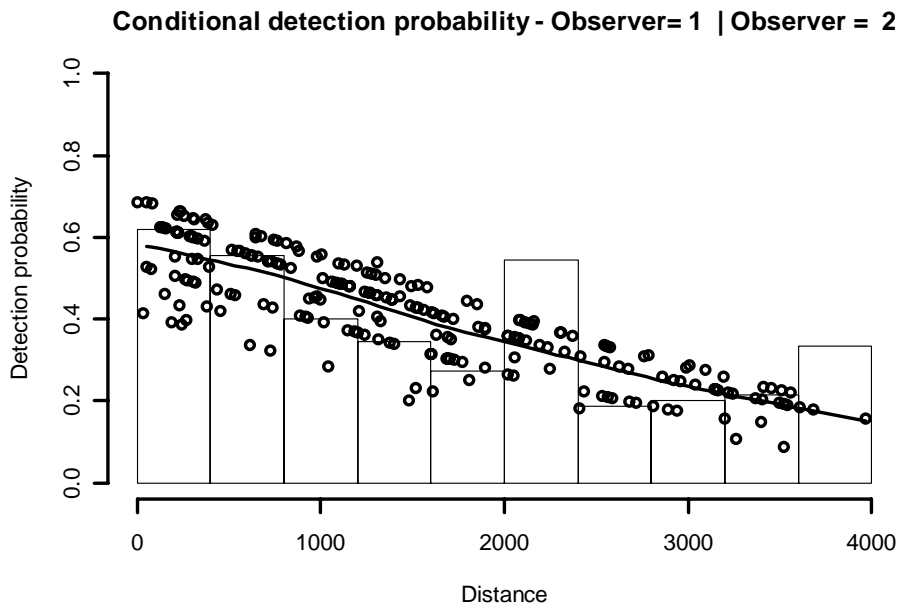


Figure 4: Conditional detection probability plot, for the LB dataset

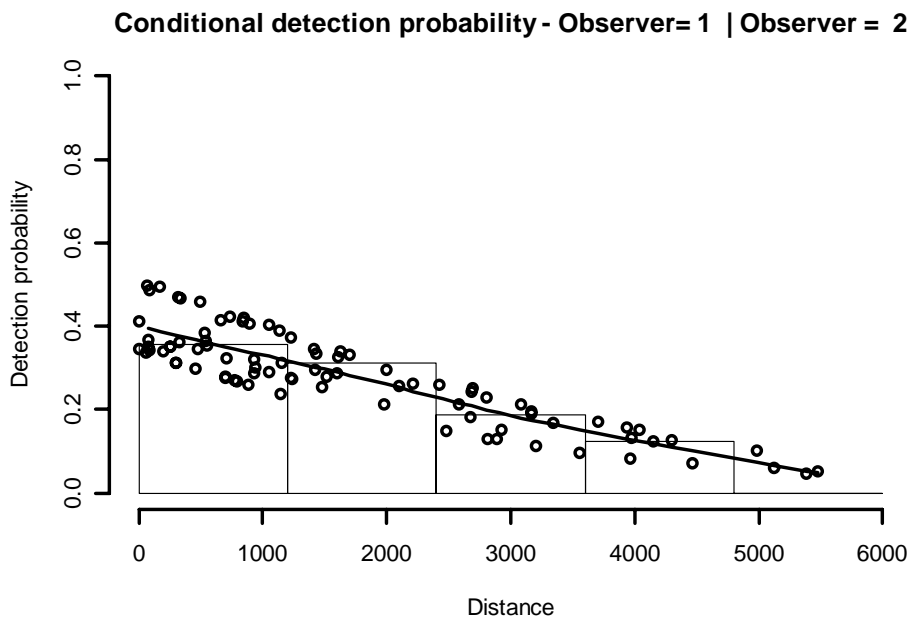


Figure 5: Conditional probability plot for unidentified large whales, W?.

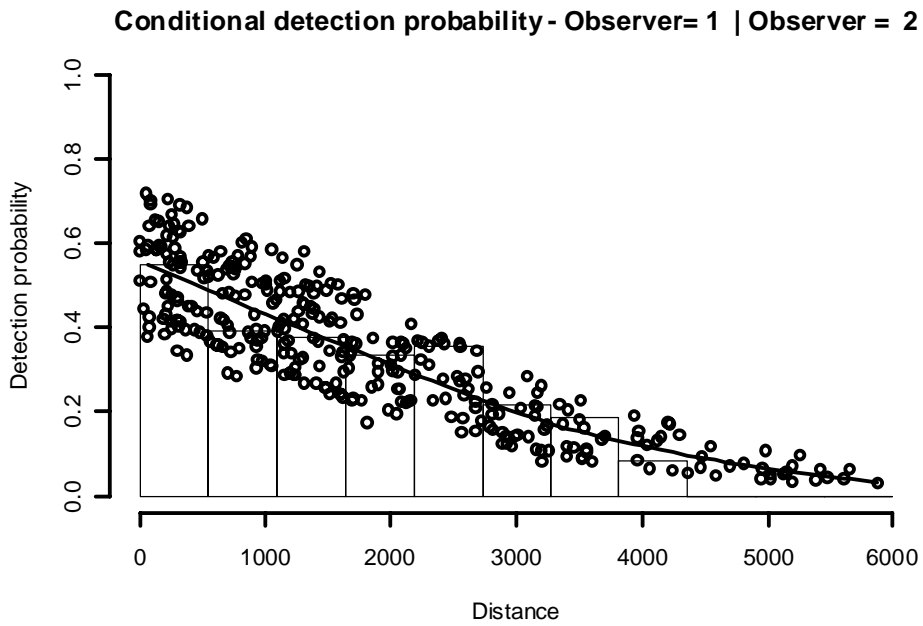


Figure 6: Conditional probability plot for all large whales; LB and W?.

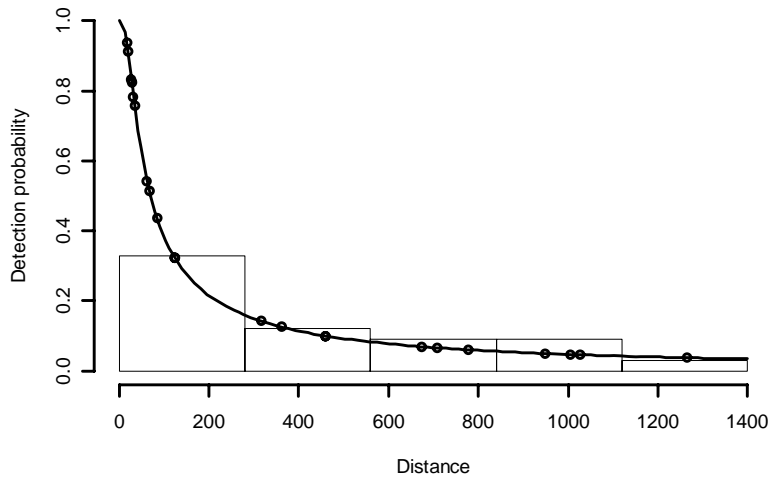


Figure 7: Distribution of perpendicular distances and fitted detection function for the minke whale.

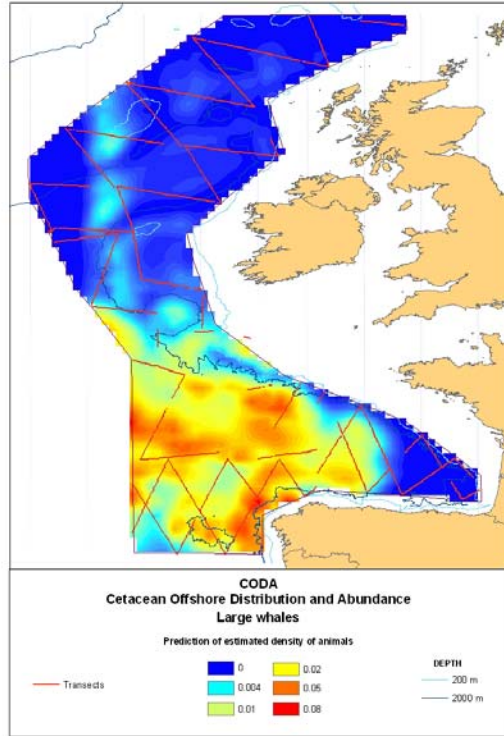


Figure 8: Surface map of smoothed predicted abundance of animals of large baleen whales.

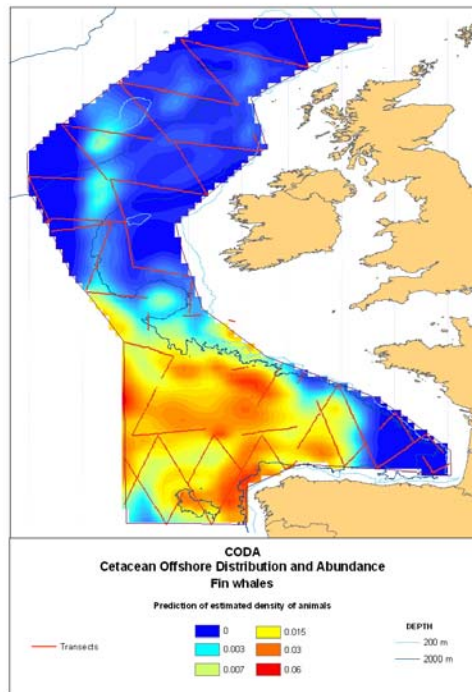


Figure 9: Surface map of smoothed predicted abundance of animals of fin whales.

Table 1: Estimates of animal abundance and animal density (animals/km²) using the MRDS approach. Figures in parentheses are percentage CVs. Figures in square brackets are 95% confidence intervals.

Species	Block	Animal abundance	Animal density (animals/km ²)
Large Baleen Whales (FW, SW, FS, BW)	1	250 (0.44)	0.0007 (0.44)
	2	3,853 (0.33)	0.011 (0.33)
	3	3,529 (0.22)	0.022 (0.22)
	4	605 (0.72)	0.005 (0.72)
	Total	8,237 (0.20) [5476 – 12,390]	0.008 (0.20)
Fin Whale	1	248 (0.45)	0.001 (0.45)
	2	3,668 (0.34)	0.011 (0.34)
	3	3,113 (0.22)	0.019 (0.22)
	4	595 (0.72)	0.005 (0.72)
	Total	7,625 (0.21) [5,028 – 11,563]	0.008 (0.21)
Sei Whale	1	0	0
	2	0	0
	3	366 (0.33)	0.002 (0.33)
	4	0	0
	Total	366 (0.33) [176 – 762]	0.0004 (0.33)
Unidentified whale	1	352 (0.43)	0.001 (0.43)
	2	5,997 (0.43)	0.018 (0.43)
	3	226 (0.32)	0.001 (0.32)
	4	26 (0.71)	0.0002 (0.71)
	Total	6,601 (0.40) [3,003 – 14,512]	0.007 (0.40)
Large Baleen + Unidentified whale	1	573.5 (0.27)	0.002 (0.27)
	2	9647.8 (0.37)	0.029 (0.37)
	3	3635.5 (0.19)	0.022 (0.19)
	4	693 (0.70)	0.006 (0.70)
	Total	14,550 (0.26) [8,560-24,729]	0.015 (0.26)
Fin Whale + Unidentified whale	1	574 (0.27)	0.002 (0.27)
	2	9493(0.37)	0.028 (0.37)
	3	3207 (0.19)	0.020 (0.19)
	4	693 (0.70)	0.006 (0.70)
	Total	13,966 (0.27) [8,088-24,119]	0.014 (0.27)

Table 2: Effect of duplicate classification on the abundance of large baleen whales.

Duplicate Classification	D (CV)	N (CV)
Definite only	0.009 (0.21)	9,164 (0.21)
Definite + probable	0.008 (0.20)	8,237 (0.20)
Definite + probable + remote	0.008 (0.20)	8,107 (0.20)

Table 3: The effects if identification certainty on large baleen whale abundance; H = high, AH = assumed high, M = medium and L= low. Figures in bold show the categories in the results elsewhere.

Certainty category	Abundance (CV)
H	3,355 (0.42)
H, AH	5,578 (0.40)
H, AH, M	8,160 (0.21)
H, AH, M, L	8,237 (0.20)

Table 4: Conventional line transect abundance estimates. Figures in parentheses are CVs. Figures in square brackets are 95% confidence intervals.

Species	Block	Animal abundance	Animal density (animals/km ²)
MW	1	5,547 (1.03)	0.016 (1.03)
	2	1,218 (1.04)	0.004 (1.04)
	3	0	0
	4	0	0
	Total		6,765 (0.99) [1,239 – 36,925]

Table 5: Density surface models fitted to CODA data. The term $s(cov, df)$ represents a smooth function of the explanatory variable cov with df estimated degrees of freedom. The expression $k=n$ means that the function has been limited to fitting a smooth up to a maximum of n df. If k is not specified, then the maximum df allowed was 10 and 30 for a 1D and 2D smooth, respectively. %Deviance is the percentage of deviance explained by the model.

Species	Chosen Model	% Deviance
Large baleen whales	$s(sst, 6.82) + s(depth_av, 2.9) + s(longitude, 8.98) + s(dist2000km, 5.78, k=7) + s(ci, 7.98)$	47
Fin whale	$s(sst, 7.01) + s(depth_av, 8.56) + s(longitude, 8.92) + s(dist2000km, 5.72, k=7)$	40

Table 6: Model based abundance estimates by stratum and overall with 95% confidence intervals derived from bootstrapping

Species	Stratum	Abundance of animals (CV)	95% Confidence Interval
LB	1	206 (0.12)	163-259
	2	5,171 (0.12)	4,072- 6,566
	3	3,487 (0.11)	2,789-4,358
	4	756 (0.12)	592- 965
	Total	9,619 (0.11)	7,760 – 11,924
FW	1	204 (0.11)	163-255
	2	4,854 (0.12)	3,855-6,112
	3	3,206 (0.11)	2,573-3,996
	4	755 (0.13)	585-974
	Total	9,019 (0.11)	7,265 – 11,197