Marine Mammal Science

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MARINE MAMMAL SCIENCE, 30(2): 810–818 (April 2014)

DOI: 10.1111/mms.12077

A new method to study inshore whale cue distribution from land-based observations

Patricia Arranz,[1] Sea Mammal Research Unit, University of St Andrews, East sands, St Andrews KY16 9LB, Scotland and Department of Animal Biology, La Laguna University, Astrofísico Francisco Sánchez, La Laguna 38206, Tenerife, Spain; **David L. Borchers**, Centre for Research into Environmental and Ecological Modeling, University of St Andrews, The Observatory Buchanan Gardens, St Andrews KY16 9LZ, Scotland; **Natacha Aguilar de Soto**, Sea Mammal Research Unit, University of St Andrews, East sands, St Andrews KY16 9LB, Scotland and Department of Animal Biology, La Laguna University, Astrofísico Francisco Sánchez, La Laguna 38206, Tenerife, Spain; **Mark P. Johnson**, Sea Mammal Research Unit, University of St Andrews, East sands, St Andrews KY16 9LB, Scotland; **Martin J. Cox**,[2] Pelagic Ecology Research Group, Scottish Oceans Institute, University of St Andrews, East sands, St Andrews KY16 9LB, Scotland.

The challenges involved in the visual detection of some cetacean species make it difficult to obtain information about their distribution and habitat preferences using traditional sampling methods (Barlow 1999). This is particularly the case for species such as beaked whales that spend a small amount of time at the surface and have inconspicuous surface behavior (Barlow 1999, Aguilar de Soto *et al*. 2011). Line-transect visual surveys provide low encounter rates for these species (Cañadas *et al*. 2005, Barlow *et al*. 2006). This impedes studies of their distribution which are required, among other things, to develop mitigation measures for potentially harmful impact of human activities (Simmonds and Lopez-Jurado 1991, Jepson *et al*. 2003).

The coastal waters around El Hierro (Canary Islands) hold year-round populations of two beaked whale species, Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) (Aguilar de Soto 2006), providing an ideal scenario to set up land-based point transect surveys to study the inshore behavior of these deep-diving species. However, coastal observations typically offer a skewed view of the actual distribution of animals because objects farther away are less likely to be detected than those closer

[1]Corresponding author (e-mail: parranz@st-andrews.ac.uk).
[2]Current address: Australian Antarctic Division, Channel Highway, Kingston, Tasmania 7050, Australia.

to shore. Distance sampling methods are able to deal with this by modeling detection probability as a function of distance from the observer. An important assumption of distance sampling is that animal density is uniform in the vicinity of the samplers (lines or points; see Buckland *et al.* 2001); this is achieved by placing the samplers randomly or systematically with a random start. When animal density varies with some environmental feature (such as seabed depth) and samplers are not located with a random start point the assumption of uniform animal distribution is violated. In this case animal density and detection probability are confounded and cannot be separated using traditional distance sampling methods (Buckland *et al.* 2004). However, by using observations of angles as well as distances to detected animals, it is possible to estimate both the detection function and the probability density function (pdf) of animal distribution (see Marques *et al.* 2010, Cox *et al.* 2011). These authors model the distribution of animals in relation to their distance from a linear feature (Marques *et al.* 2010 from roads and Cox *et al.* 2011 from the sea surface), but in many cases, the environmental features that may influence the distribution of animals are not linear. The present work extends these methods to allow the distribution of animals seen from an observation point on the coast to be modeled with respect to a nonlinear environmental feature (water depth). Depth is a key factor delimiting marine habitats and is especially relevant for understanding the distribution of deep-diving species such as beaked whales, which approach the seafloor to feed (Arranz *et al.* 2011).

Visual surveys for beaked whales were performed seasonally from 2004 to 2010 from the southwest coast of the island of El Hierro. Observations were made from a coastal cliff, 119 m above sea level (27.675ºN, 18.025ºW; Fig. 1), with a field of view spanning 134º (160º–294º true) and 39 km long, taken from the coastline up to the horizon as seen from the observation station, covering coastal, slope, and abyssal waters. Observations were made by a team of three or four observers working in 30 min shifts with one rest/data-entry position every 1.5 h. The area was scanned continuously by two or three observers with the aid of binoculars (Fujinon 15 × 80 and 7 × 50) equipped with compass and ocular reticules to estimate the bearing and distance to detected beaked whale groups. Sighting locations were converted to geographic coordinates following the method of Lerczak and Hobbs (1998). A sighting was defined as the detection of a group of beaked whales (*i.e.*, one or more beaked whales swimming in close spatial and temporal association at the surface). To avoid errors in tracking beaked whale groups, which may remain underwater from 10 to 120 min between successive surfacings (Tyack *et al.* 2006), no attempt was made to associate sightings with groups. Sampling effort spanned 1,164 h over 175 d covering different seasons in the seven years of study. A total of 1,789 beaked whale sightings were gathered from the land-based platform, including sightings of Blainville's and Cuvier's beaked whales and unidentified ziphiids. The distribution of sightings was not analyzed at species level to eliminate potential errors in distinguishing beaked whale species at long ranges in variable light conditions. Beaked whale species were easily distinguishable from other cetaceans present in the area, *i.e.*, bottlenose dolphins (*Tursiops truncatus*). Blainville's and Cuvier's beaked whales were the only species confirmed photographically from a research boat in 864 of the sightings, 367 of them pertaining to *M. densirostris* and 497 to *Z. cavirostris*. The land station guided the boat, *via* radio, to the position of the sightings using custom made software. This software plots in real time the location of the sighting, derived from the magnetic angle and the reticle in the binoculars, and the position of the boat, received by radio every few seconds. Sightings occurred at seabed depths of 190–2,260 m.

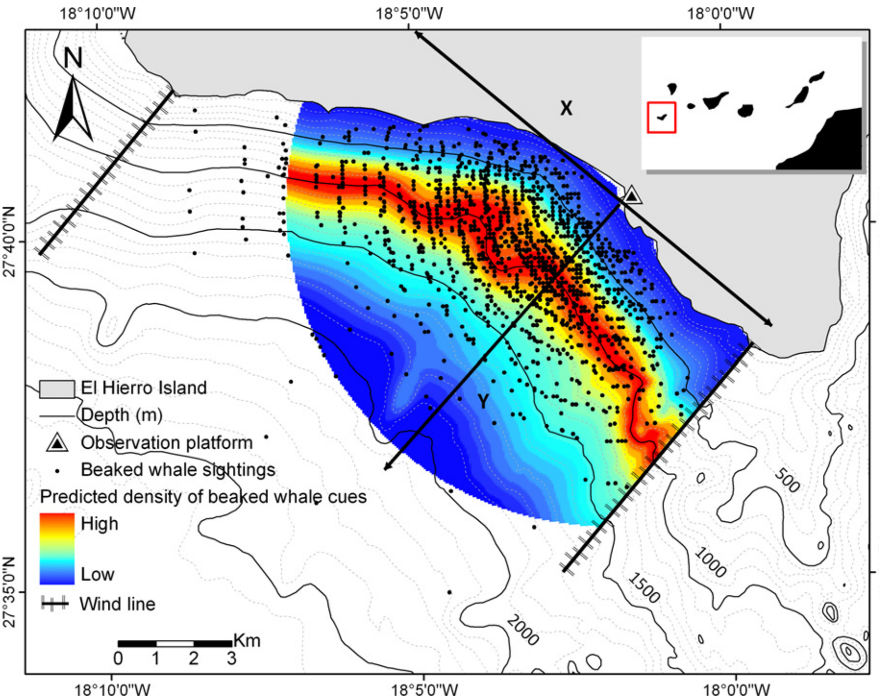

Figure 1. Beaked whale sightings (black dots) off the southwest coast of El Hierro (Canary Islands) collected from 2004 to 2010 from a coastal observation platform (triangle). A system of Cartesian coordinates (x, y) oriented as shown by the black arrows was used to define the location of sightings in the horizontal plane. The sea state was generally ≤ 3 in the survey area, enclosed within the wind lines (dashed lines) generated by prevailing winds from the northeast. Predicted density of beaked whale cues in relation to the bathymetry in the study area is shown in colors: the highest density of beaked whale cues is expected around the 1,000 m seabed depth.

A Cartesian coordinate system was defined with x being the distance from the observation point in the NW-SE direction (roughly parallel to the coast) and y being perpendicular to x in the offshore direction, NE–SW (Fig. 1). The depth $z(x, y)$ at each sighting location is the explanatory variable for the animal density model, while the radial distance r between the sightings and the observation platform is the explanatory variable for the detection probability model. We assumed that animals' depths are independent draws from some probability density function pdf $\pi_z(z; \phi)$, where ϕ is a vector of unknown parameters, and we assume that animals are distributed uniformly with respect to distance along the x-axis, independently of their depth. That is, the joint pdf of animals' depth and distance along the x-axis is $\pi_z(z, x; \phi) = \pi_z(z; \phi)\pi_x(x) = \pi_z(z; \phi)(2w_x)^{-1}$ (where $w_x = 39$ km is the maximum distance from the observer in the x direction that was considered in the analysis). Marques *et al*. (2010) and Cox *et al*. (2011) provide methods for estimating animal density when there is nonuniform cue density in the y direction and the pdf in $\frac{\delta z}{\delta y}$ the x direction is uniform. To adapt these methods to the current problem, we transform variables from (x, y) to (x, z) by expressing depth as a function of Cartesian position $z(x, y)$ and using as a standard change of variables from y to z as follows:

$$\pi_{x,\,y}(x, y) = \frac{\pi_z[z(x, y); \varphi]}{2w_x}\left|\frac{\delta z}{\delta y}\right| \tag{1}$$

We model detection probability as $r = (\sqrt{x^2 + y^2})$ a function of radial distance alone, so that the probability that a cue (*i.e.*, one or more beaked whales at the surface available to be seen) at (x, y) was detected was simply $g(r; \theta)$, where and θ is a vector of unknown parameters. In practice, detections beyond a radial distance of $w_r = 9$ km were truncated for more robust estimation of the detection function and hence we defined $g(r) = 0$ for $r > w_r$. The truncation distance was chosen to coincide with a mid-point in the banding pattern of the sighting distances, resulting from rounding the reticle number.

Based on the detection function model $g(r; \theta)$ and the cue density model $\pi_z(z; \phi)$, we obtained the following likelihood for θ and ϕ, given detections n at $(X, Y) = (x_1, y_1), (x_2, y_2),\ldots,(x_n, y_n)$:

$$L(\varphi, \theta; X, Y) = \prod_{i=1}^{n} \frac{g\left[(\sqrt{x_i^2 + y_i^2}); \theta\right] \dfrac{\pi_z[z(x_i, y_i); \varphi]}{2w_x}\left|\dfrac{\delta z_i}{\delta y_i}\right|}{P} \tag{2}$$

Where P is the expected probability of detecting a cue in a rectangle extending a distance w_x in the x direction either side of the observer and at a distance w_y offshore:

$$P = \int\int g\left[(\sqrt{x^2 + y^2}); \theta\right] \frac{\pi_z[z(x, y); \varphi]}{2w_x}\left|\frac{\delta z}{\delta y}\right| \tag{3}$$

To evaluate the likelihood, we calculated $z(x, y)$ and $\frac{\delta z}{\delta y}$ numerically using inverse distance weighted interpolation, with an output cell size of 50 × 50 m, between depths at a grid of points across the area. Depth values were obtained from a digital bathymetric map of the Canary Islands, with vertical resolution of 50 m (IEO-IHM 2001). Given the steep bathymetry in the study area and the relatively large distances covered by each binocular reticle, this depth resolution was sufficient.

Model parameters were estimated assuming the pdf $\pi_z(z; \phi)$ to be normal, scaled, log-normal, uniform, or a normal mixture (made up of up to four component normal pdfs). A half-normal shape was used for the detection function $g(r; \theta)$. Parameters were estimated using R software (R Core Development Team 2012) and the optimum model selected using Akaike's Information Criterion (AIC, Akaike 1973). Model goodness-of-fit was evaluated using a χ^2 statistic. Model parameter variance was estimated using the percentile method with a nonparametric bootstrap and day as the sampling unit. The R code developed for this analysis, along with data examples, are available as part of the R package nupoint (see Cox *et al.* 2013). The nupoint package also contains simulation functions permitting examination of the effect of varying seabed depth resolution on maximum likelihood estimates. The distribution of beaked whale cue density in relation to seabed depth for the study area was plotted using the Spatial Analyst toolbox in ArcMap 9.2 (Environmental Systems Resource Institute, Redlands, CA).

We maximized the likelihood equation (3) to estimate θ and ϕ (Table 1). On the basis of AIC, the three-component normal mixture model was selected for depth preference, with an AIC weight of 0.78, and a χ^2 goodness-of-fit P-value = 0.11 (Fig. 2). The predicted distribution of beaked whale cues in space is shown in Figure 1. The

Table 1. Model parameter estimates describing the probability density function (pdf), $\pi_z(z;\ \phi)$ of beaked whale sightings with respect to seabed depth, and half-normal detection function, $g(r;\ \theta)$; Parameter estimates for each of the candidate distributions are provided. $\hat{\varphi}$ is a vector of parameter estimates for the beaked whale cue depth distribution model and $\hat{\theta}$ is the half-normal detection function parameter estimate. [ ] denote vectors. Density models are parameterized in terms of their means ($\hat{\mu}$) and standard deviations ($\hat{\sigma}$), and in the case of normal mixture models, the means and standard deviations of each component of the mixture together with mixture weights ($\hat{\alpha}$). Whale cue distribution models are given in order of lowest to highest AIC.

Distribution	Parameter estimates for beaked whale sightings with depth $\hat{\varphi}$	Detection function parameter $\hat{\theta}$	AIC	ΔAIC	AIC weight
Mixture: 3 normal	$\hat{\mu} = [688, 1,000, 1,529]$; $\hat{\sigma} = [435, 186, 219]$, $\hat{\alpha} = [0.33, 0.44, 0.23]$	3,350	34,935	0	0.78
Mixture: 4 normal	$\hat{\mu} = [540, 960, 1,400, 3,037]$; $\hat{\sigma} = [272, 162, 293, 304]$, $\hat{\alpha} = [0.17, 0.33, 0.34, 0.16]$	3,339	34,937	1.3	0.22
Mixture: 2 normal	$\hat{\mu} = [1,815, 1,029]$; $\hat{\sigma} = [5,132, 264]$, $\hat{\alpha} = [0.80, 0.20]$	3,399	34,953	17.8	0
Normal	$\hat{\mu} = 105; \hat{\sigma} = 408$	3,350	34,984	48.9	0
Scaled beta	$\hat{\mu} = 2.8; \hat{\sigma} = 2.3$	3,305	35,055	120.2	0
Log-normal	$\hat{\mu} = 8.0; \hat{\sigma} = 0.9$	3,118	35,137	202.6	0
Uniform	–	3,542	35,551	615.7	0

estimated probability of detection drops from 1 at distance zero to 0.5 at a range of 4 km (Fig. 3, lower panel). Figure 3 (upper panel) shows the estimated depth preference model $\pi_z(z;\ \phi)$, from which it is apparent that the model predicts the highest density of beaked whale cues around the 1,000 m isobath and most (90%) of the groups surfacing in waters with seabed depths between 325 and 1,660 m depth. This broadly aligns with the range of the seabed depths (400–1,400 m) recorded from tagged *M. densirostris* whales on their foraging dives in the same area off El Hierro (Arranz *et al.* 2011). Here, this species feeds both on mesopelagic and deep benthopelagic prey, often close to the steep seafloor of the island (Arranz *et al.* 2011). No data are available regarding the foraging behavior of *Z. cavirostris* in the Canaries, but this species might also feed close to the seabed as well as in open waters (Woodside *et al.* 2006, Santos *et al.* 2007). The slope favors the overlap of mesopelagic and deep benthopelagic species at depth (Mauchline and Gordon 1991, Reid *et al.* 1991, Gordon *et al.* 1995, Herring 2002) that is probably used by these beaked whales to access a range of trophic resources in a small area. The distribution of the sightings of *Z. cavirostris* and *M. densirostris* suggest that the habitat selection of both species is probably driven by an increased prey availability on the slope of the island. However, because the number of sightings at a given depth is not necessarily proportional to the number of groups present, additional information on surfacing rates, and how they vary with depth, is required to draw inferences about animal distribution. This

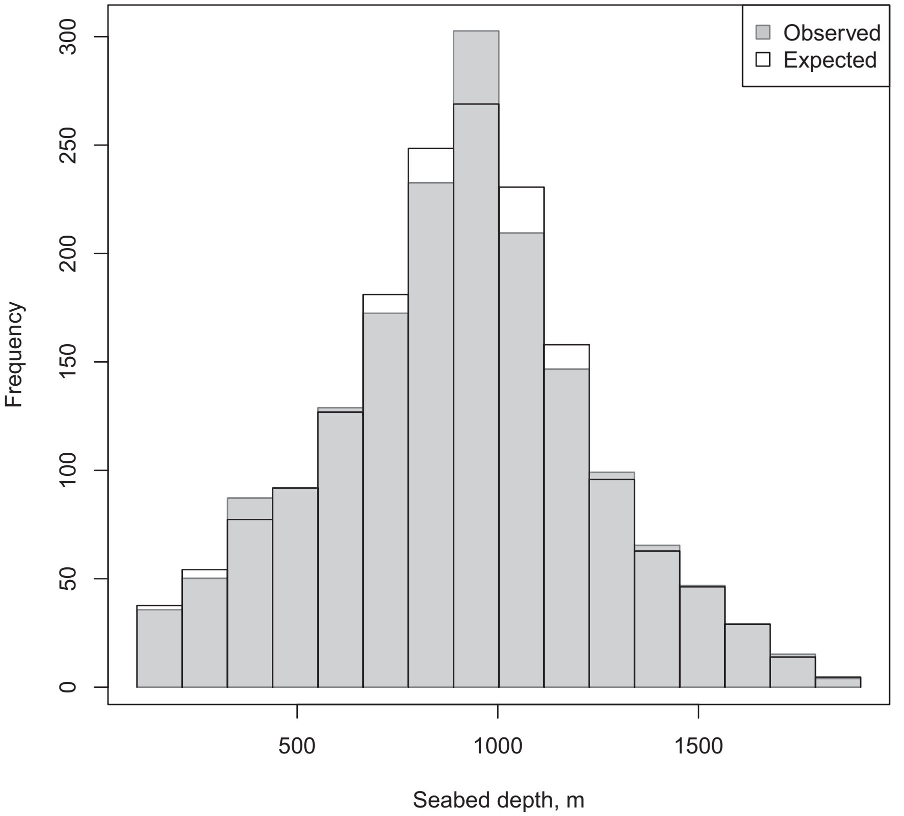

Figure 2. Predicted and observed detection frequencies for the three-normal mixture for beaked whale cue sightings and the half-normal detection function model. Observed sighting frequency is given by the gray histogram, expected frequency by the unfilled histogram. χ^2 goodness-of-fit P-value = 0.11. See Table 1 for parameter estimates.

information was not available for this study due to the limited positioning accuracy of tagged whales, but the method could be readily extended to incorporate this information when it is available, *e.g.*, from tags equipped with GPS.

Because of the steep underwater topography of the study area (Gee *et al.* 2001), a visual land-based survey can cover a range of beaked whale habitats allowing inferences about the distribution of these species with respect to depth to be drawn using the methods described above. However, because the observation point was not chosen using a randomized design, inferences cannot be drawn about distributions at locations other than the area within the view of the observers. With a suitably randomized design for observer location conclusions about other areas could be drawn, but in all cases drawing inference about distribution beyond the maximum observable distance from shore will be assumption-based rather than data-based. In conclusion, the method is useful to investigate the distribution and habitat selection of animals in relation to environmental variables using observations from land. In this particular study, we lacked information relating to changes in detectability with angle (*e.g.*, glare) leading to any such changes being confounded with changes in

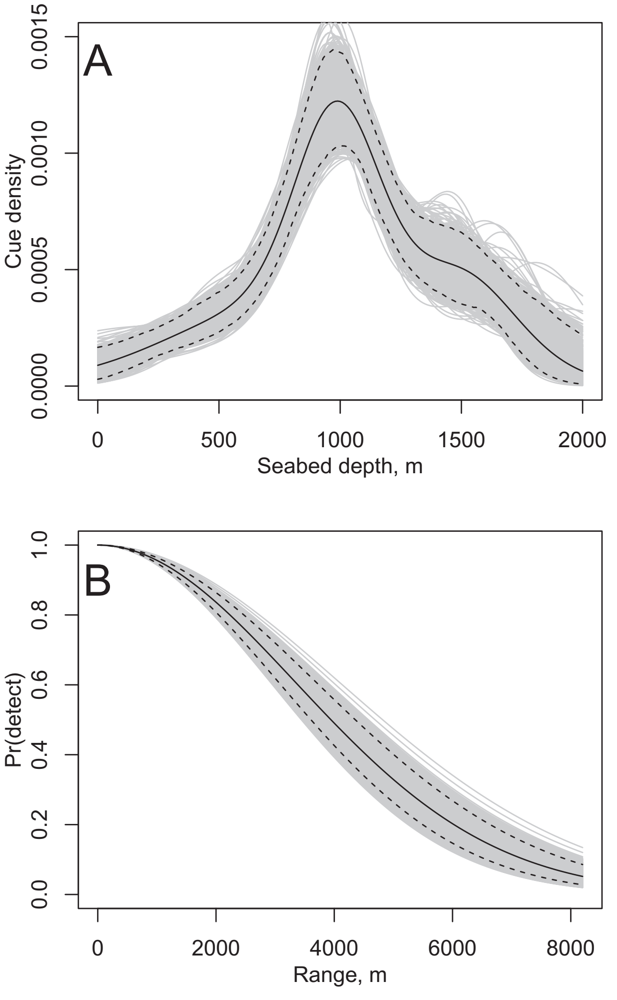

Figure 3. Fitted depth probability density function and detection function, with non-parametric bootstrap results. Each realization is shown as a gray line, the mean is shown as a solid black line and 95% confidence intervals, determined using the percentile method, as dashed black lines. (A) Three-component normal mixture pdf of beaked whale sightings. (B) Half-normal detection function for beaked whale sightings.

density. It may be possible to check for changes in the model goodness-of-fit by dividing the observed area into arbitrary sector angles. The package nupoint (Cox *et al*. 2013) includes a more flexible hazard rate detection function and future development work will allow multiple covariates, such as glare and sea state, in the detection function.

With suitable further development we hope to implement density estimates using smoothing approaches that allow multiple environmental features to be considered. Combined with a model of cue rates for the species, and how they vary with depth, the results of this study would enable us to make inferences about the distribution of the coastal populations of beaked whales. In turn these results could be used to identify critical habitats within which to mitigate human activities.

Acknowledgments

Thanks to M. Bayona, C. Aparicio, M. Guerra, I. Domínguez, P. Díaz, A. Hernández, A. Schiavi, C. Reyes, A. Fais, J. Marrero, A. Escánez, M. Moral, and many others for their help in the collection of the data, as well as to the people of La Restinga for their support. Data collection between 2004–2010 was funded by the Office of Naval Research and the National Ocean Partnership Program (US) and by a consortium consisting of the Canary Islands Government and the Spanish Ministries of Environment, Science and Defense. Since 2010 data collection was funded by the Spanish Ministry of Science through the National Research Project CETOBAPH (CGL2009-13112). Additional funds came from the Island Council of El Hierro and the Canarian Agency of Research, Innovation and Information Society through the European Environmental Funding Program. PA was funded by the National Research Project CETOBAPH and NAS by a Marie Curie fellowship from the 7th European Frame Program. MJ was supported by the National Ocean Partnership Program and by the Marine Alliance for Science and Technology, Scotland. The authors have declared that no competing interests exist.

Literature Cited

Aguilar de Soto, N. 2006. Comportamiento acústico y de buceo del calderón de aleta corta (*Globicephala macrorhynchus*) y del zifio de Blainville (*Mesoplodon densirostris*) en las Islas Canarias. Ph.D. thesis, University of La Laguna, Tenerife, Spain. 252 pp.

Aguilar de Soto, N., P. T. Madsen, P. L. Tyack, *et al*. 2011. No shallow talk: Cryptic strategy in the vocal communication of Blainville 's beaked whales. Marine Mammal Science 28: E75–E92.

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267–281 *in* P. N. Petrov and F. Csaki, eds. Second International Symposium on Information Theory. Akademiai Kiado, Budapest, Hungary.

Arranz, P., N. Aguilar Soto, P. T. Madsen, A. Brito, F. Bordes and M. P. Johnson. 2011. Following a foraging fish-finder: Diel habitat use of Blainville's beaked whales revealed by echolocation. PLOS ONE 6:e28353.

Barlow, J. 1999. Trackline detection probability for long-diving whales. Pages 209–221 *in* G. W. Garner, ed. Marine mammal survey and assessment methods. Balkema Press, Leiden, The Netherlands.

Barlow, J., M. Ferguson, W. F. Perrin, *et al*. 2006. Abundance and density of beaked and bottlenose whales (Family Ziphiidae). Journal of Cetacean Research and Management 7:263–270.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers and L. Thomas. 2001. Introduction to distance sampling. Oxford University Press, Oxford, U.K.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers and L. Thomas. 2004. Advanced distance sampling. Oxford University Press, Oxford, U.K.

Cañadas, A., R. Sagarminaga, R. De Stephanis, E. Urquiola and P. Hammond. 2005. Habitat preference modelling as a conservation tool: Proposals for marine protected areas for cetaceans in southern Spanish waters. Aquatic Conservation: Marine and Freshwater Ecosystems 15:495–521.

Cox, M. J., D. L. Borchers, D. A. Demer, G. R. Cutter and A. Brierley. 2011. Estimating the density of Antarctic krill (*Euphausia superba*) from multi-beam echo-sounder observations using distance sampling methods. Journal of the Royal Statistical Society: Series C (Applied Statistics) 60:301–316.

Cox, M. J., D. L. Borchers, N. Kelly. 2013. Nupoint: An R package for density estimation from point transects in the presence of nonuniform animal density. Methods in Ecology and Evolution 4:589–594.

Gee, M. J. R., D. G. Masson, A. B. Watts and N. C. Mitchel. 2001. Offshore continuation of volcanic rift zones, El Hierro, Canary Islands. Journal of Volcanology and Geothermal Research 105:107–119.

Gordon, J. D. M., N. R. Merrett and R. L. Haedrich. 1995. Environmental and biological aspects of slope-dwelling fishes of the North Atlantic. Pages 1–26 *in* A. G. Hopper, ed. Deep-water fisheries of the North Atlantic oceanic slope. Kluwer, Dordrecht, The Netherlands.

Herring, P. 2002. The biology of the deep ocean. Oxford University Press, Oxford, U.K.

IEO-IHM. 2001. Zona Económica Exclusiva. Mapa Batimétrico. Ministerio de Ciencia y Tecnología–Instituto Español de Oceanografía, Madrid, Spain.

Jepson, P. D., M. Arbelo, R. Deaville, *et al*. 2003. Gas-bubble lesions in stranded cetaceans. Was sonar responsible for a spate of whale deaths after an Atlantic military exercise? Nature 425:575–576.

Lerczak, J. A., and R. C. Hobbs. 1998. Calculating sighting distances from angular readings during shipboard, aerial, and shore-based marine mammal surveys. Marine Mammal Science 14:590–599.

Marques, T. A., S. Buckland, D. L. Borchers, D. Tosh and R. McDonald. 2010. Point transect sampling along linear features. Biometrics 66:1247–1255.

Mauchline, J., and J. D. M. Gordon. 1991. Oceanic pelagic prey of benthopelagic fish in the benthic boundary layer of a marginal oceanic region. Marine Ecology Progress Series 74:109–115.

R Core Development Team 2012. R version 2.15. Foundation for Statistical Computing, Vienna, Austria.

Reid, S. B., J. Hirota, R. E. Young and L. E. Hallacher. 1991. Mesopelagic-boundary community in Hawaii: Micronekton at the interface between neritic and oceanic ecosystems. Marine Biology 109:427–440.

Santos, M. B., V. Martín, M. Arbelo, A. Fernández and G. J. Pierce. 2007. Insights into the diet of beaked whales from the atypical mass stranding in Canary Islands in September 2002. Journal of Marine Biological Association UK 87:243–251.

Simmonds, M. P., and L. F. López-Jurado. 1991. Whales and the military. Nature 351:448.

Tyack, P. L., M. P. Johnson, N. Aguilar Soto, A. Sturlese and P. T. Madsen. 2006. Extreme diving of beaked whales. The Journal of Experimental Biology 209:4238–4253.

Woodside, J. M., L. David, A. Frantzis and S. K. Hooker. 2006. Gouge marks on deep-sea mud volcanoes in the eastern Mediterranean: Caused by Cuvier's beaked whales? Deep Sea Research Part I: Oceanographic Research Papers 53:1762–1771.

Received: 15 January 2013
Accepted: 4 August 2013