Appendix IV

Abundance of sperm whales (*Physeter macrocephalus*) estimated from acoustic data for Blocks 2, 3 and 4 (French and Spanish sectors)

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INTRODUCTION

Sperm whales produce loud (up to 236 dB *re*: 1 μ Pa (rms) Møhl *et al.* 2003), audible, broadband regular clicks for most of the time they are engaged in deep dives. Deep dives can last for over an hour, and surface rest intervals (5-10 minutes) are typically short compared to dive times. The characteristics of sperm whale clicks makes them easy to detect and localise acoustically using relatively simple hydrophones towed behind platforms of opportunity or survey vessels (e.g. Gillespie & Leaper 1996; Leaper *et al.* 2000).

Acoustic estimates of sperm whale density have been made in the past using a variety of different methods and from a number of different platforms. Gillespie (1997) used a towed array and Cartwheels sampling to estimate densities of sperm whales in the Southern Ocean Sanctuary. Leaper *et al.* (2000) used a towed array and Conventional Distance Sampling methods to estimate densities of vocalising sperm whales in the Southern Ocean, and Hastie *et al.* (2003) used similar methods from a platform of opportunity to estimate sperm whale densities in the Faroe-Shetland Channel. Barlow & Taylor (2005) used a combination of acoustic methods to locate groups of sperm whales along with visual estimates of group size in the Eastern Tropical Pacific. In all of these studies, the time of arrival differences of the signal at two hydrophones was used to calculate bearings to individual clicks and locations were obtained by crossing bearings to multiple clicks as the survey vessels progressed along the trackline.

Prior to 2005 and the SCANS-II surveys, no systematic broad scale acoustic surveys had been conducted in European Shelf waters (0-200m), and no broad scale acoustic surveys had been conducted in the deep waters (>200m) to the west of the European Continental Shelf. The CODA (Cetacean Offshore Distribution and Abundance) surveys in 2007 presented a unique opportunity for collecting broadband (0-250kHz) and broad scale acoustic data in areas that that had never before been surveyed using this method. Below we present estimates of sperm whale density and abundance in the CODA area from acoustic data.

METHODS

Data collection and analysis was split into 5 distinct and separate stages; (1) At sea data collection, (2) Click detection, (3) Click train identification, (4) Tracking and (5) Density estimation using program DISTANCE.

All acoustic data analysis was conducted without access to the visual data in order to maintain acoustic / visual platform independence.

(1) At-sea data collection

The design of the acoustic data collection system used at sea during the CODA surveys was based on the system used during the SCANS-II surveys and incorporated many common components from that survey. The towed array consisted of the 200m SCANS-II array; three broadband hydrophone elements and pre-amplifiers (2-200kHz) and depth sensor; spliced onto a second 200m section of cable containing two additional two broadband hydrophone elements (2-200kHz). Hydrophone elements were thus towed at 200, 203, 400, 400.25 and 403 m behind the vessel. The design of this array gave an optimal hydrophone spacing for tracking both large and small odontocetes and its length was designed to minimise vessel noise.

Data from the array was streamed to two desktop computers via a custom built amplifier box (Seiche

Measurement Systems, UK), this also supplied power to the hydrophone pre-amplifiers and routed audio signals and depth sensor information to external connectors. Signals from elements at 400 and 400.25 m were routed to a National Instruments PCI 6250 data acquisition board in a desktop computer running a high frequency version of IFAW's RainbowClick software (Gillespie and Leaper 1996). The high frequency version of RainbowClick had enhanced digital filters and a high frequency click identification algorithm developed for harbour porpoises as part of the SCANS-II surveys. Acoustic data from elements at 200, 203, 400 and 403 m were routed to an external RME FireFace800 soundcard connected via a Firewire cable to a second desktop running IFAW's Logger2000 software. Data from these 4 channels were continuously recorded to large hard drives at a sample rate of 192 kHz using Logger2000's tape deck facility. This generated a new 650Mb 4-channel wav file approximately every 7 minutes. PC clocks were synchronised using an external GPS and the ship's position, speed and heading were logged every 10 seconds by Logger2000.

The arrays were deployed by hand and towed by each of the five vessels used during the CODA surveys:

M/V *Mars Chaser* (UK sector, Block 1)

A634 *Rari* (Block 2, French sector, Leg One)

F735 *Germinal* (Block 2, French sector, Leg Two)

B/O *Cornide de Saavedra* (Block 3, Spanish sector, Leg Two)

M/V *Investigador* (Block 4, Spanish sector, Leg One)

Acoustic data were duplicated onto two 2-terabyte drives every evening.

(2) Click Detection

Only data from the hydrophone pair at 400 and 403 m have been analysed to search for sperm whales since data from the hydrophones closer to the vessel had considerably higher levels of noise.

Recordings were searched for clicks using the click detector in the PAMGUARD software (Gillespie *et al.* 2008). This is basically the same algorithm as runs in the RainbowClick software, but is more suited to bulk offline file analysis. The algorithm, which is described in Gillespie and Leaper (1996) searches for candidate clicks using a relatively simple threshold detector to select candidate clicks which have significant energy in the frequency band of interest. Bearings to candidate clicks are then calculated by measuring the time of arrival difference of the signal arriving on two hydrophones. Candidate clicks are then written to file in a format compatible with the RainbowClick software for further analysis. The software generated one click file for each 7 minute wav file.

(3) Click Train Identification and tracking

Sperm whales are easily identified by the regularity and consistency of their clicks. Where bearing information are available (as in this study) a sperm whale is recognised as a sequence of regularly spaced clicks on a bearing which changes slowly with time as the survey vessel moves past the animal. Although click detection is a fully automatic process, we have so far been unable to develop an algorithm which can reliably group clicks together and assign them to individuals, so this stage of the analysis required considerable operator input. Each click file, generated in step (2) above was opened with the RainbowClick Graphical user Interface (GUI) and viewed by an experienced operator (RJS). Sperm whales appear in the RainbowClick bearing-time display as lines of dots, spaced at regular intervals on a steadily varying bearing (Figure 1). The operator would identify groups of clicks (or click trains) both by eye and by listening to the clicks played back over headphones and then use the mouse to group clicks believed to be from an individual whale, or a group of whales too close to be separated, into an 'event'.

The operator scanned through all files three times. As well as selecting sperm whale events, click trains from other odontocete species were also selected and noise from vessels and other sources were also noted. A limitation of the RainbowClick display is that only data from a single 7 minute file can be viewed at a time. To aid tracking of whales across multiple files, additional software was developed in Matlab which would permit viewing of click bearing / time data across multiple files.

Even when groups of whales are encountered, the bearing resolution of the system (approximately 1 degree) is generally adequate to separate individual whales within the group. A display of inter click interval verses time is used to ensure that only a single whale is included in each event. On rare occasions, when whales are too close together) it is impossible to separate all individuals, in which case clicks from two or more whales would be grouped into the same event and a best estimate of the number of individuals present in the event made by detailed examination of shorter sections of data in which a temporary spatial separation (due to movement of the animals) would occur.

Event information was written to a relational database (MS Access format).

Three survey days where sperm whales were detected were randomly selected from data collected in the Spanish Sector. Click files were then independently processed by a second independent operator working in Spain (JAV). This operator worked under the same conditions as RJS and had no access to the visual data; and was tasked with identifying and tracking sperm whale click trains between files. These data will be used to cross-validate the work carried out by RJS by comparing detection rates, detection functions and density estimates.

(4) Tracking

A tracking algorithm, implemented in Matlab, was used to calculate the most probable position of each whale and calculate a perpendicular distance from the track line to the whale. The algorithm takes data from the click train analysis outlined above and combines them with navigational data from the ship's GPS. The ship's course and heading, and bearings to individual clicks within an event are plotted, showing where bearings cross (Figure 2). The algorithm estimates a location for the vocalising animal using target motion analysis by minimising the difference between observed and expected bearings using a Chi-squared test, and assuming a stationary animal and moving survey platform. Two possible positions are calculated on either side of the trackline and the position with smallest Chi-squared value is assumed to be the location of the vocalising animal. The products of this algorithm are a whale location, from which the perpendicular distance to the animal from the trackline and the time at which the animal passed abeam can be calculated.

(5) Density estimation using program DISTANCE

Exploratory data analysis indicated that vessel was an important factor affecting our ability to detect and track sperm whales, to include this variation in our acoustic estimates of sperm whale abundance and density we used Multiple Covariates Distance Sampling (MCDS) (Marques & Buckland, 2003; Buckland *et. al.*, 2004). MCDS was carried out in the programme Distance V5 Release 2 (Thomas *et al.*, 2006) using only those events that could be tracked and which were detected during visual survey effort. Vessel was included in all models as a Covariate Factor and model output was stratified by Block. Global density was estimated as the mean of stratum estimates weighted by stratum area. For all models we assumed that g(0) was equal to 1, i.e. that we could detect all whales on the track line, and used Akaike's Information Criterion (AIC) to select between fitted models (Burnham & Anderson, 2002). Size bias regression was used to determine cluster size where the regression was significant at an alpha level of 0.15, where it was not significant the mean of observations was used. Cluster size was not used a covariate. Initial modelling was undertaken to determine a truncation distance that provided the most reliable fit to the data.

RESULTS

Data from the vessel operating in the British sector suffered from high levels of noise and it has not been possible to extract clicks trains from those data. In the Spanish and French sectors (Blocks 2, 3 and 4) a total of 237 sperm whale events were identified, of which only four events contained clicks from more than one whale (Table 1). The total number of whales was 247 (mean number of whales per event = 1.042). Three events, one from the Spanish sector and two from the French, did not contain enough clicks for the whale to be tracked. We believe that this is because the whales in these events were close to the limits of detection so it is likely that these individuals would have been discarded from the DISTANCE analysis in any case.

The maximum range over which sperm whales were detected was 11,857m and the mean range of detection was 2,926 (SD 2,012) m, (Table 2). Mean and maximum detection ranges to sperm whales varied between vessels (Figure 3, Table 2). We believe that this variation is due to differences in radiated and system noise associated with each vessel, and for this reason vessel was used a Covariate Factor in MCDS.

Combined acoustic and visual effort in Blocks 2, 3 & 4 was 6,238.3 km in an area totalling 620,273 km^2 (Figure 4). Total effort in Block 2 (336,556 km^2) was 2295.3 km, and coverage was split 32% (731.8 km) to 68% (1,563.5 km) between the vessels *Rari* and *Germinal* respectively. Total effort in Blocks 3 and 4 (160,537 km^2) was 2,179.0 km and 1,764.0km, respectively. Sperm whale detections were widely distributed through out Blocks 2, 3 and 4 (Figure 5).

For fitting the detection functions, the perpendicular distance data were right truncated at 7,700m, and twenty five of the most distant events were not included in MCDS modelling (Table 3). The fitted detection functions are shown in Figure 6 for each vessel and in Figure 7 for the pooled data.

Sperm whale abundance for Blocks 2, 3 & 4 was 2,239 (95% CI: 1,707 – 2,936) animals, and density was estimated at 0.0036 (CV = 0.14) animals/km^2. Estimates of sperm whale abundance and density for each block are given in Table 3.

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Table 1. Summary of sperm whale detections. Values shown represent the number of Events detected and total number of Individuals detected in parentheses. Perpendicular distances could only be calculated to tracked Events; Events that could not be tracked were not included in MCDS sampling.

Block	**Detections Tracked (Whales)**	**Detections Not Tracked (Whales)**	**Total Detections (Whales)**	**Mean group size (SD)**
Block 2	80 (86)	2 (2)	82 (88)	1.073 (0.562)
Block 3	77 (78)	1 (1)	78 (79)	1.013 (0.113)
Block 4	77 (80)	-	77 (80)	1.039 **(**0.342)
Overall	234 (244)	3 (3)	237 (247)	1.026 **(**0.254)

Table 2. Summary of detection ranges (m) to tracked sperm whale groups from the different ships used to survey Blocks 2, 3 and 4.

	Detection range (m)			
Vessel	**Mean (SD)**	**Minimum**	**Maximum**	**n**
Block 2 – A634 *Rari*	2925.3 (2242.8)	368	7996	23
Block 2 – F735 *Germinal*	3662.3 (1853.4)	485	11857	57
Block 3 – *B/O Cornide de Saavedra*	2259.5 (1596.9)	378	7533	77
Block 4 – *M/V Investigador*	3049.1 (2237.5)	237	9509	77
Overall	2926.5 (2012.4)	237	11857	234

Table 3. Acoustic estimates of sperm whale abundance and density (animals/km^2). Figures in parentheses are CVs. Figures in square brackets are 95% confidence intervals.

	Samples	**Animal abundance**	**Density (animals/km^2)**
Block 2	69	1,111 [753 – 1,638]	0.0033 (0.20)
Block 3	72	557 [347 – 893]	0.0046 (0.24)
Block 4	71	570 [343 – 949]	0.0036 (0.26)
Overall	212	2,239 [1,707 – 2,936]	0.0036 (0.14)

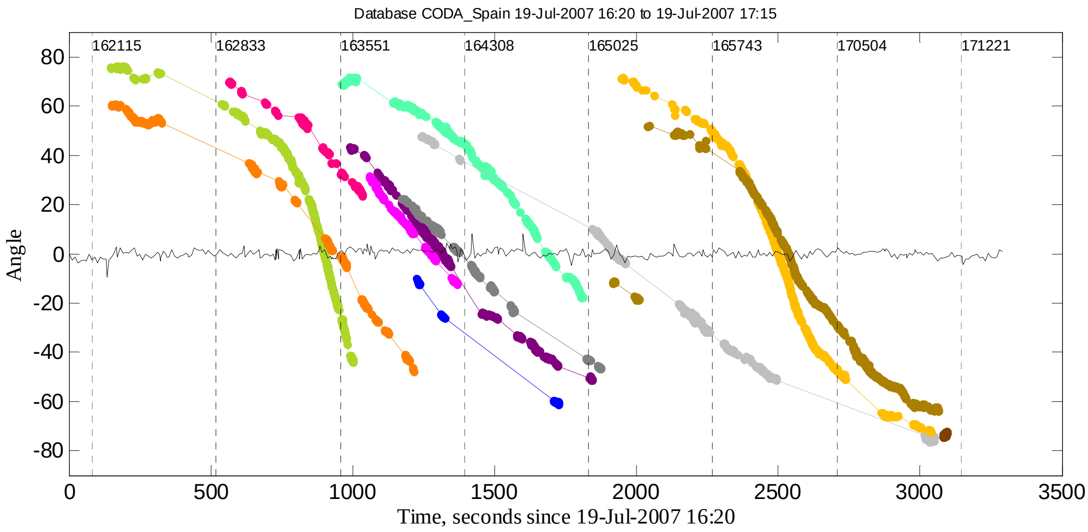

Figure 1. Bearing time display for clicks from multiple sperm whales

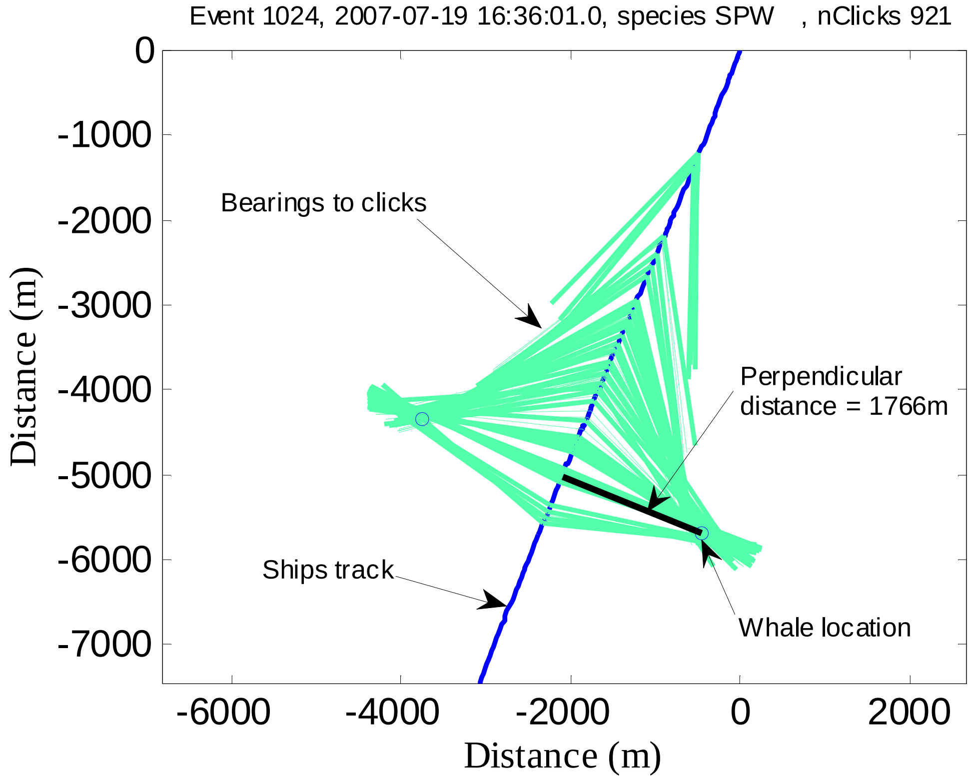

Figure 2. Target motion analysis in which the crossing point of bearings to individual clicks is used to estimate the whale's location and the perpendicular distance from the trackline.

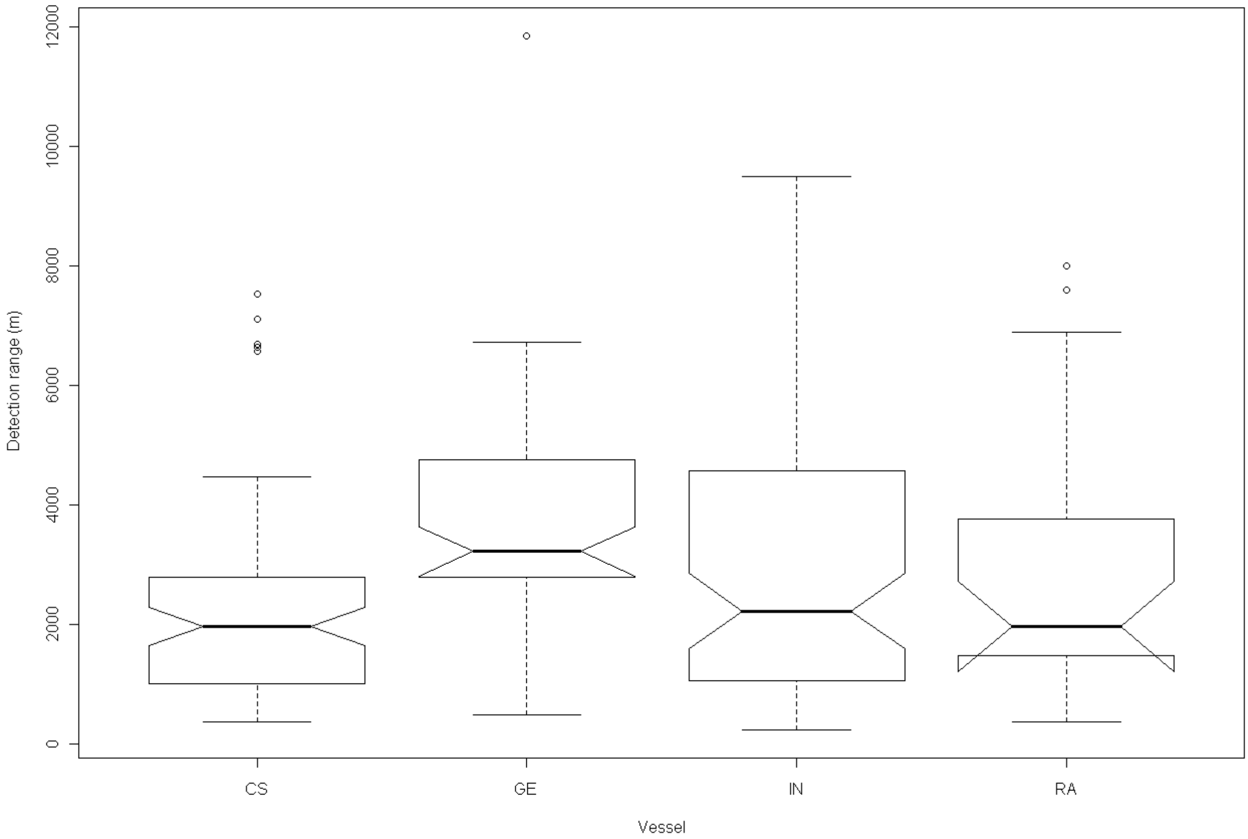

Figure 3. Boxplot showing the variation in mean and maximum detection range between vessels. Abbreviations for vessel names are CS = Cornide de Saavedra, GE = Germinal, IN = Investigador, and RA = Rari.

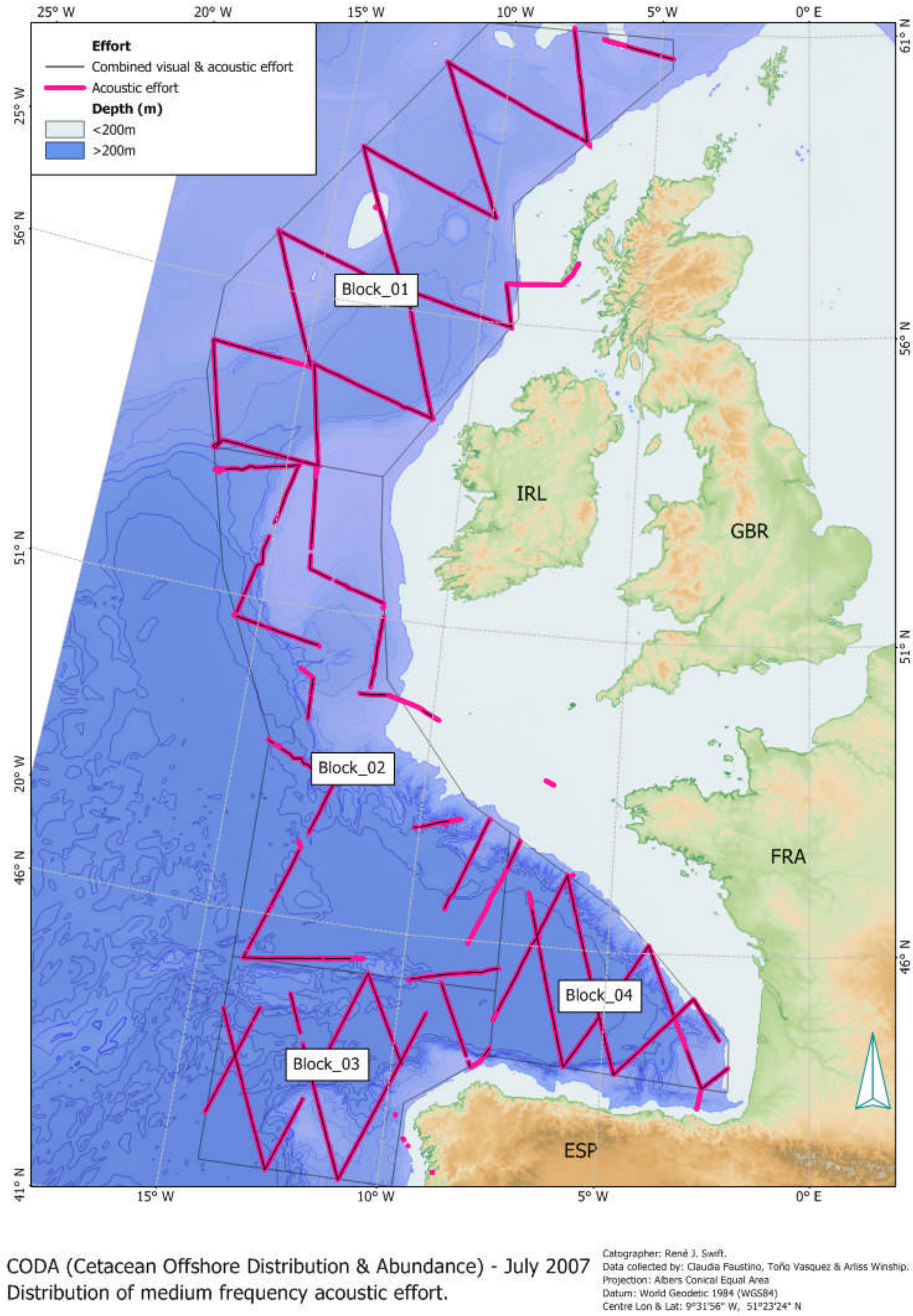

Figure 4. Distribution of acoustic and visual effort.

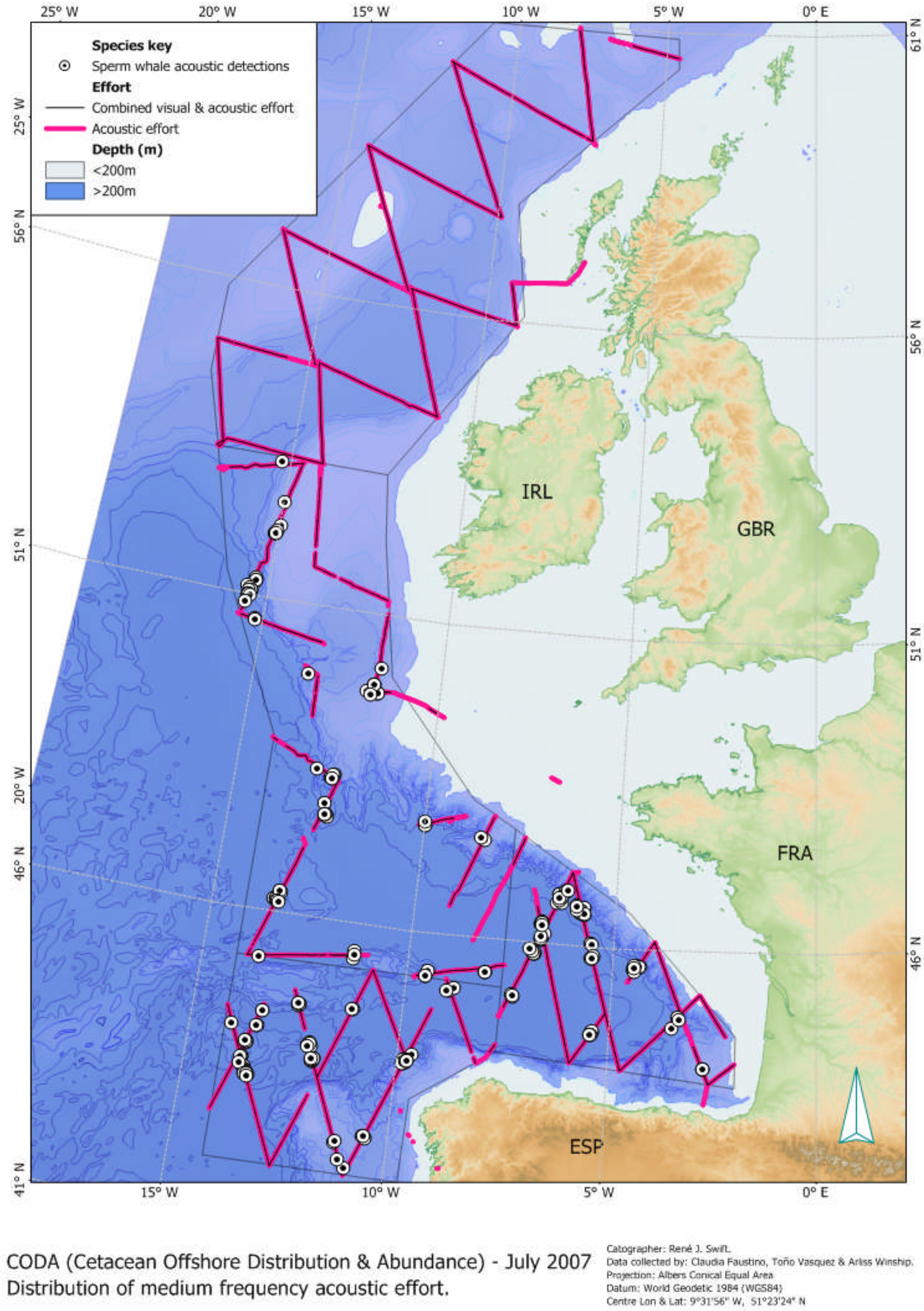

Figure 5. Distribution of acoustic effort and sperm whale acoustic detections.

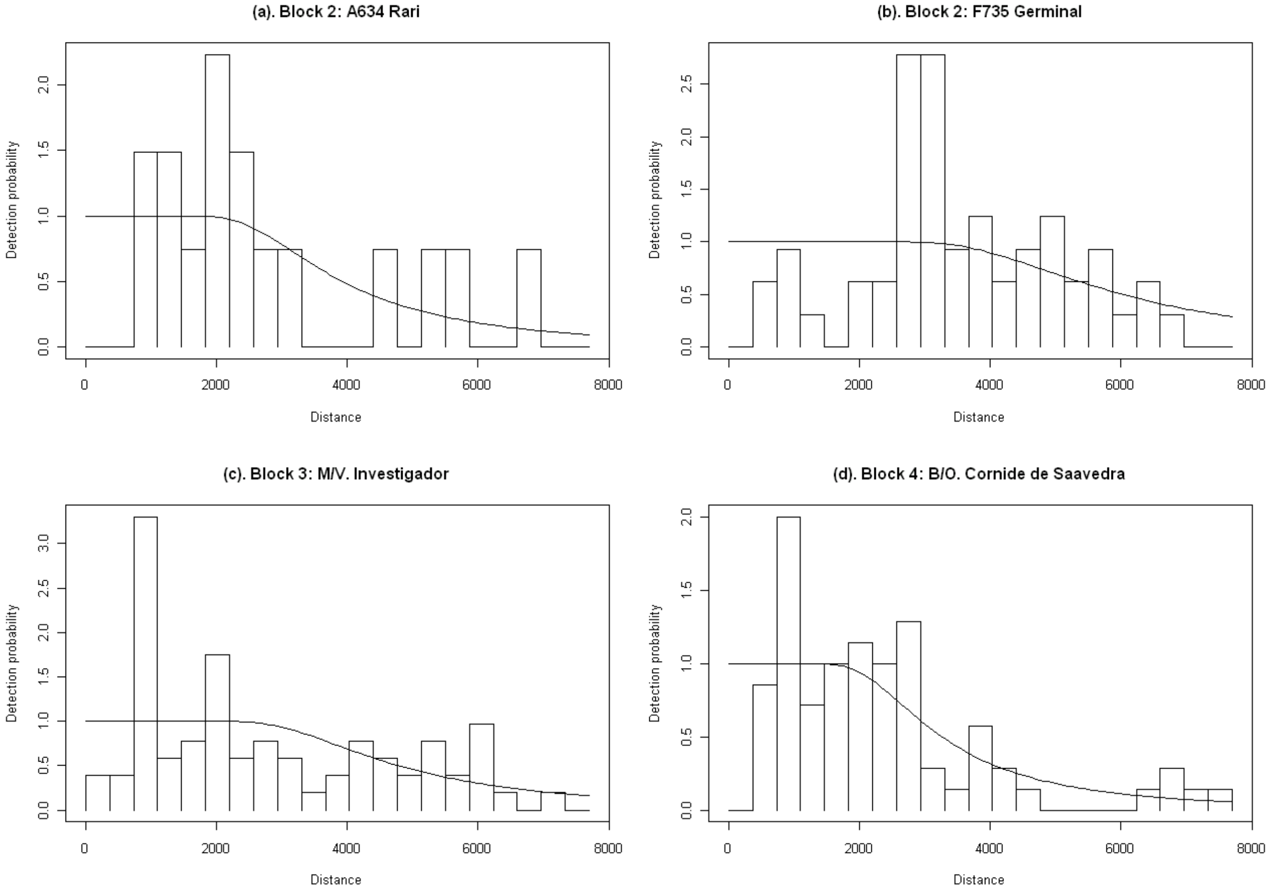

Figure 6. Acoustic detection functions for the platforms used to survey (a, b) Block 2, (c) Block 4 and (d) Block 3. The data were right truncated at a detection probability of 0.1, equivalent to a distance of 7,700 m.

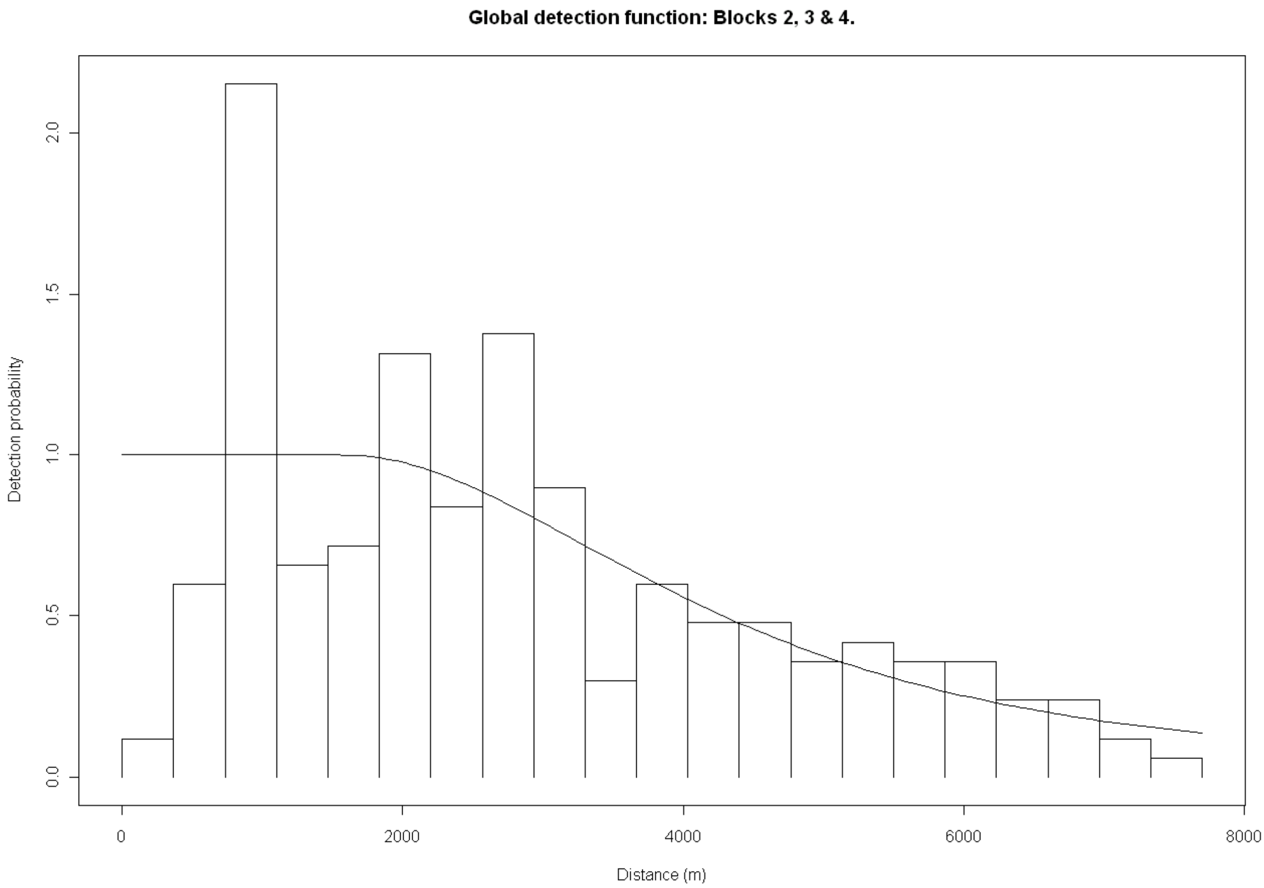

Figure 7. Acoustic detection function for sperm whales in Blocks 2, 3 and 4. The data were right truncated at a detection probability of 0.1, equivalent to a distance of 7,700 m.