Blue (*Balaenoptera musculus*) and fin (*B. physalus*) whale vocalisations measured from northern latitudes of the Atlantic Ocean

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ABSTRACT

Vocalisations were recorded in the vicinity of sighted blue whales (*Balaenoptera musculus*) and fin whales (*B. physalus*) in the North Atlantic between Iceland and Greenland in August 2004 from a hydrophone towed behind a research vessel and from free floating sonobuoys. The structures of recorded calls were broadly similar to those reported from other areas, but lacked the stereotypical patterning of those signals thought to represent reproductive displays. Counts of non-patterned blue whale calls indicated low vocalisation rates, with a mean of 0.62 phrases per whale per hour (0.12 A-B and 0.49 arch phrases per whale per hour). However, vocalisations were highly clustered in time, with 80% of blue whale calls ascribed to the focal animals arriving within a single 80 second period. It is not clear what behavioural, geographical or seasonal trends may influence the vocalisation rate of large baleen whales, and thus direct comparisons between areas are difficult. However, it is hoped the results presented will be of use in interpreting remote recordings of blue whales made from the North Atlantic. Hydrophones were also monitored continuously over 7,757km of trackline using an automated detection algorithm developed for North Atlantic right whales (*Eubalaena glacialis*). However, no North Atlantic right whales were seen or heard during the study period.

KEYWORDS: BLUE WHALE; FIN WHALE; NORTH ATLANTIC RIGHT WHALE; ACOUSTICS; VOCALISATION; SURVEY–ACOUSTIC; NORTHERN HEMISPHERE; ATLANTIC OCEAN

INTRODUCTION

Passive acoustic techniques are increasingly being used to monitor cetacean populations. They have recently been used to assess issues relevant to management of mysticete populations, including density estimation (McDonald and Fox, 1999), geographic variability (McDonald *et al*., 2006; Mellinger and Clark, 2003; Stafford *et al*., 2001), seasonality (Clark and Clapham, 2004; Moore *et al*., 1998; Northrop *et al*., 1971) and migratory behaviour (Clark and Ellison, 2000; Stafford *et al*., 1999). These techniques can allow cost-effective, remote monitoring over long periods of time. However, better data on vocal behaviour, including vocalisation rates, can improve the interpretation of acoustic studies.

Passive acoustic monitoring in the waters between the United Kingdom and Iceland (Charif and Clark, 2000) has indicated seasonal patterns in the vocal activity of blue (*Balaenoptera musculus*) and fin whales (*B. physalus*). However, these seasonal trends showed different, and in some cases opposite, patterns to indicators of abundance from other data such as whaling statistics (Harwood and Wilson, 2001). The efficacy of passive acoustic monitoring to provide an index of density for these species thus requires improved knowledge of their vocal behaviour, motivation and the factors that cause variation in vocalisation rates.

Blue and fin whales are known to produce numerous types of low frequency signals (Cummings *et al*., 1986; Edds, 1988; McDonald *et al*., 2001; Thompson *et al*., 1996). Both produce long, stereotypical series of sounds, typically below 30Hz (Cummings and Thompson, 1971; Mellinger and Clark, 2003; Thompson *et al*., 1992; Watkins *et al*., 1987), which have been interpreted as seasonal breeding calls (Croll *et al*., 2002; McDonald *et al*., 2001; Watkins, 1981). The regular patterning and high source levels of these calls have allowed the tracking of individuals over vast distances (Cummings and Thompson, 1971; Stafford *et al*., 1998; Watkins *et al*., 2000; 1987). However, the problems associated with finding offshore animals that may be present in low densities and in remote locations have precluded the measurement of vocalisation rates for several whale species in many parts of the world. Despite a wealth of acoustic studies on fin whales (McDonald and Fox, 1999; Thompson and Friedl, 1982; Watkins *et al*., 1987), scant reference has been made to individual vocalisation rates, with the exception of the Gulf of California (Thompson *et al*., 1992). For blue whales, recordings have been made with consecutive sighting information off California (McDonald *et al*., 2001; Oleson *et al*., 2007; Rivers, 1997) and Chile (Cummings and Thompson, 1971). Although vocal rates have been measured in the St. Lawrence River, Canada (Edds, 1982), vocalisation rates have not been presented for Atlantic blue whales in oceanic habitats.

The continental shelf waters to the west of Iceland are known for concentrations of blue and fin whales (Pike *et al*., 2003; Víkingsson *et al*., 2002) and as such represent a promising study area for combined visual and acoustic investigations of these species. The aim of this study was to relate visual observations of blue and fin whales at the surface with data from continuous acoustic monitoring in order to further develop passive acoustic techniques for these species and derive vocalisation rates where possible. In addition, the survey provided a valuable opportunity to investigate the occurrence of North Atlantic right whales (*Eubalaena glacialis*) in these waters. Whaling records suggest the eastern stock of North Atlantic right whales migrated from northern Europe to northwest Africa (Perry *et al*., 1999). However, very little is known about the current status and distribution of this stock, although individual right whales have been occasionally reported off Iceland (Jacobsen *et al*., 2004; Sigurjónsson *et al*., 1991).

METHODS

Visual and acoustic search effort was conducted between June and September 2004 in waters to the north and west of Iceland from *Song of the Whale*, a 21m auxiliary-powered sailing research vessel. The search track of the vessel was chosen to maximise the chances of encountering species of interest based on prior knowledge and on recent information provided by whale watch operators. The trackline of the survey vessel was broken to investigate large whale sightings or to identify distant blows (Fig. 1).

Acoustic surveying

Acoustic monitoring was conducted whenever water depth was sufficient (>50m) using a 200m dual-element towed array. The array consisted of two *Benthos* AQ-4 elements spaced 3m apart, mounted close to preamplifiers with a gain of 29dB. The overall response of the system was flat from 10Hz to 15kHz. Noise from the vessel's engine was reduced by noise-dampening mounts, an exhaust separation system and a five-bladed propeller. The signals from the hydrophone were passed through Behringer graphics equalisers with 1000Hz low pass filters, to a *National Instruments* PCI-6013 data acquisition board sampling at 2000Hz. The output from the board was recorded directly to hard-disk for subsequent analysis using a database program. In addition, a real time implementation of an algorithm for detecting right whales (Gillespie, 2004) was run at all times. When appropriate, *Plessey* 906 sonobuoys were deployed from the vessel and the resulting signals were recorded using *Yaesu* VHF receivers connected to the National Instruments acquisition board. Thus, four-channel recordings could be made to hard disk using the twin-element array and two sonobuoys broadcasting on different frequencies. Sonobuoys were recovered before the preset sink time of six hours had elapsed.

Visual surveying

When visual surveying conditions were appropriate (absence of fog and Beaufort Sea states of ≤4) two dedicated observers searched for cetaceans during the daytime from a platform with an eye height of approximately 5.3m above sea level. At other times, a single observer kept watch from deck level when there was sufficient light. Close approaches to whales were only made for the purposes of photo-identification (ID) and no whale was approached closer than 50m.

Data analysis

Continuous hard-disk recordings were examined for periods when baleen whales were observed; in total 22% of all 501 recordings were examined (98 out of 454 hours of data). Spectrograms of the recordings were examined for evidence of whale signals using a Matlab interface (*XBAT*, *www.xbat.org*; 2048 FFT; 94% overlap; sample rate 2000Hz; Hanning window). The time and frequency bounds of candidate vocalisations were recorded and all signals graded from 1 to 4 according to visual clarity in the spectrogram, after Mellinger and Clark (2003). Quality 1 phrases were extremely clear whilst quality 4 signals had very low signal-to-noise ratios (SNRs). The SNRs were subsequently measured for all sounds. Signal level was taken as the maximum within any spectrogram time partition of the summed energy within the given frequency band. Since sounds often occurred in sequences, one minute of signal was taken either side of each sound to calculate noise levels. The energy within the given frequency band was summed and the values of the energy for each time partition sorted in ascending order. The noise level was then taken as the median of the ordered noise statistic.

The two hydrophone elements in the towed array were too close to allow useful bearings to be obtained for low frequency vocalisations. When sonobuoys were deployed, relative bearings were derived by calculating possible source locations for each measured time delay. Bearings derived by acoustic techniques could thus be compared with bearings taken from visual sightings of whales at the surface.

RESULTS

During the study period, there were four blue whale encounters, six fin whale encounters and no right whale sightings. Of these, only one blue and one fin encounter were of sufficient duration to allow collection of instructive acoustic data. A summary of the types and qualities of calls recorded from both blue and fin whales is given in Table 1.

Blue whales

On 21 August, a pair of blue whales was encountered at 65°28'N 29°25'W and followed for eight hours until visual contact was lost in failing light. The whales were moving on a steady course at a mean speed of 8.5km hr^{-1}, with variable dive lengths between 30 seconds and 13 minutes (mean=5.5 minutes). The swim speeds of the focal animals were in keeping with previous reports of singing blue whales tracked either visually or acoustically (2-10km hr^{-1}); (Kibblewhite *et al*., 1967; McDonald *et al*., 2001; 1995; Northrop *et al*., 1971; Thode *et al*., 2000). Due to the steady movement of the whales, it was not practical to deploy sonobuoys and recordings were only made on the towed array. During post-process analysis, 30 separate phrases typical of North Atlantic blue whales (Charif and Clark, 2000; Mellinger and Clark, 2003; Nieukirk *et al*., 2004) were evident (Table 1; Fig. 2). The SNR and the call quality are shown in Fig. 3 plotted as a function of range. The calls with a high SNR were all quality 1 signals and show a reduction in SNR as a function of range to the focal animals. Lower quality calls had low SNR and did not show such a reduction. Therefore the lower quality calls were not thought to have come from the focal animals.

A-B phrase structure

The contours of the lowest frequency vocalisations were similar to others reported for the Atlantic (Edds, 1982; Mellinger and Clark, 2003). It is possible that the blue whales of the Atlantic represent two separate stocks (Sears and Calambokidis, 2002) and as such these phrases offer potential as a stock identification parameter. In general, most A-B phrases were composed of a period of constant frequency (typically 18Hz) followed by a steady decrease in frequency (to 16Hz; Table 1). The waveforms of phrases were tonal in structure, lacking the amplitude modification observed in the Pacific (Rivers, 1997; Stafford *et al*., 1998; Thompson *et al*., 1996) and the Indian Ocean (McCauley *et al*., 2004). The louder phrases possessed harmonics at multiple integers of the fundamental frequency, often with relatively high energy levels (second harmonic typically 8-10dB less than that of the fundamental frequency).

None of the phrases recorded in this study shared the truncated structure reported from the northwest Atlantic (Berchok *et al*., 2006; Mellinger and Clark, 2003), the Pacific Ocean (McDonald *et al*., 2001; Rivers, 1997; Stafford *et al*., 2001; Thompson *et al*., 1996) or Antarctica

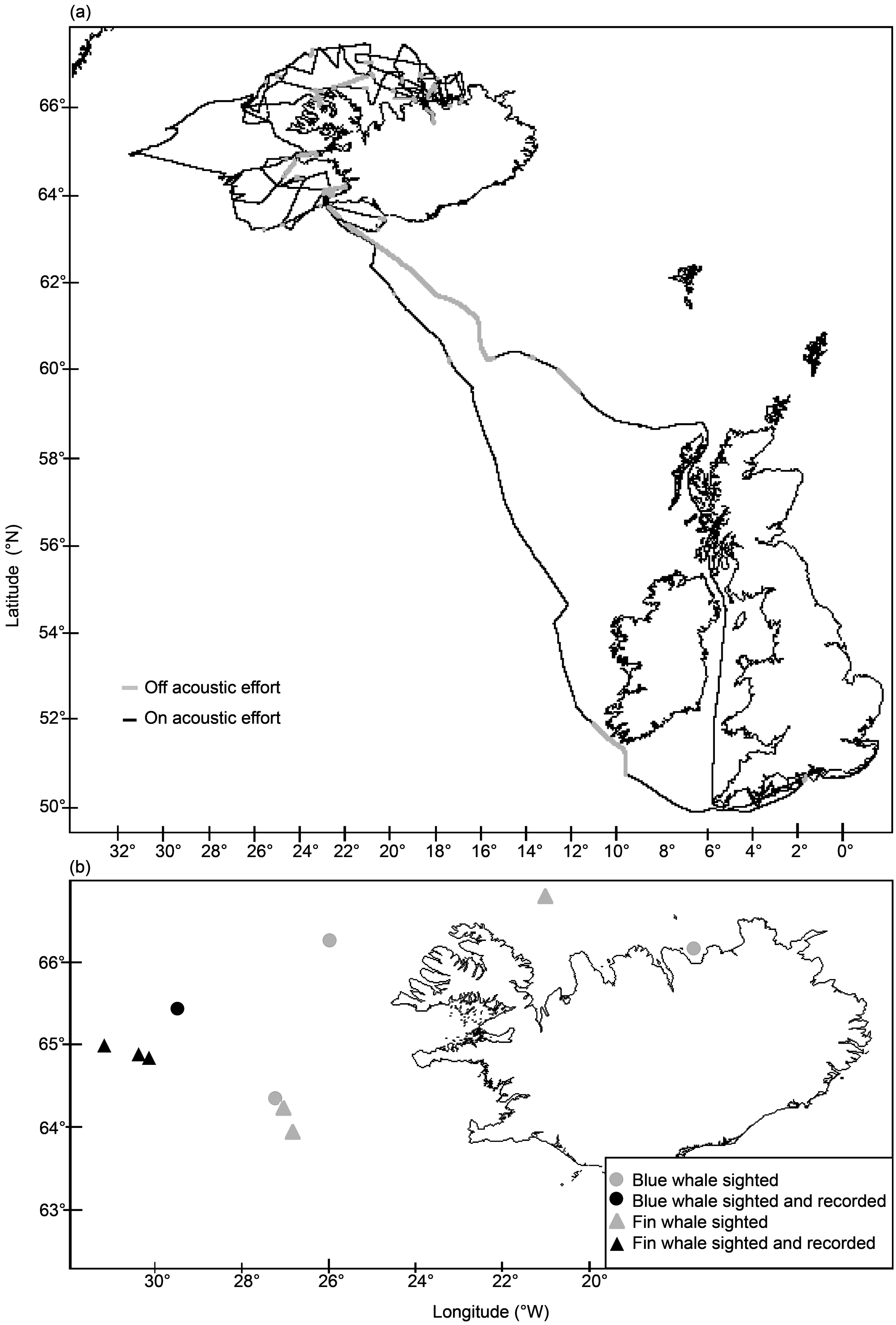

Fig. 1. Map showing the track of *Song of the Whale* between 8 June and 4 September 2004 (a), including those periods when the hydrophone was deployed and monitored. Sightings of blue and fin whales are shown (b), including the encounters for which recordings were made.

(Rankin *et al*., 2005). However, the phrases were of similar duration and bandwidth to the contiguous A-B phrases described by Mellinger and Clark. Overall, the phrases in this study seem most similar to the narrowband downsweeps described from the St. Lawrence River (Berchok *et al*., 2006; Edds, 1982). The A-B phrases in this study also lacked the predictable patterning reported elsewhere (Mellinger and Clark, 2003). The period from one phrase onset to the next was highly variable, ranging from 20 seconds to over an hour. Although Mellinger and Clark were not explicit about the timing of sequences in the North Atlantic, they defined them as 'stereotyped, regularly

Table 1

Mean values (and standard deviations) for parameters measured from all blue and fin whale phrases. Frequencies described in Hz; time information in seconds. Peak times listed as a proportion of call duration. The phrase interval for the fin whale Type III calls (*) were measured from just two calls and is likely to be an underestimate.

Phrase	Qlty 1	Qlty 2	Qlty 3	Qlty 4	Duration	Start freq	Peak freq	Peak time	End freq	Freq range	Phrase period
Blue (A-B)	2	0	3	9	14.3	18.5	17.0	0.6	16.3	2.2	941
n=14					(4.3)	(0.6)	(0.8)	(0.2)	(1.0)	(0.8)	(1,256)
Blue (Arch)	8	1	7	0	1.5	76.8	90.6	0.3	41.4	49.1	533
n=16					(0.5)	(15.8)	(12.6)	(0.2)	(12.9)	(11.9)	(1,021)
Fin (Type I)	2	23	38	16	0.50	27	22.8	0.5	18	9	19
n=79					(0.14)	(1)	(1.5)	(1.3)	(1)	(2)	(39)
Fin (Type II)	14	19	4	0	1.05	73	51.8	0.5	34	39	117
n=37					(0.62)	(15)	(15.0)	(0.2)	(9)	(14)	(478)
Fin (Type III)	2	1	2	0	0.96	84	33.3	0.5	52	33	36*
n=5					(0.64)	(14)	(17.7)	(0.2)	(16)	(15)	(42)

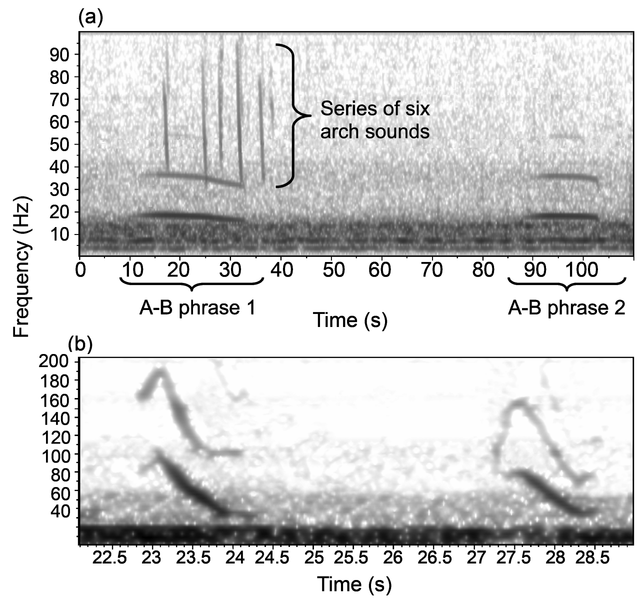

Fig. 2. Examples of blue whale phrases recorded on the towed array on 21 August 2004. Two separate A-B phrases are shown (a); FFT (Fast Fourier Transform) 2048, hop length $^1/_8$, Hanning window. All A-B phrases recorded were within the bandwidth of 14 to 30Hz. The contours and harmonics of two of the arch sounds are shown in more detail below (b); FFT 512, hop length $^1/_{32}$, Hanning window.

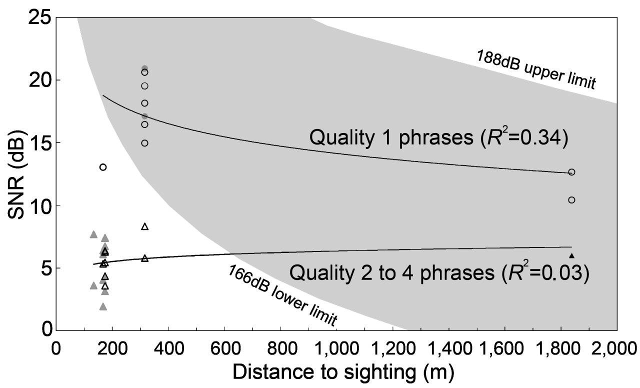

Fig. 3. Signal to noise ratios (SNRs) of all blue whale phrases in relation to the estimated distance from the hydrophone. Solid symbols represent A-B phrases; clear symbols represent arch sounds. All quality 1 phrases (circles) had SNR values >10dB; all lower quality phrases (triangles) had SNR values <10dB. Logarithmic regression lines and corresponding R^2 values are shown. The shaded area represents SNR expected under spherical spreading using the average background noise value of 104 dB for A-B phrases (the upper and lower source levels reported in the literature are used to bound the plot). The increase in SNR with distance for the low quality phrases suggests they were not produced by the focal animals.

repeating series of sounds', consisting of between 1 and 25 phrases. The phrases recorded in this study were produced in seven short sequences of between 1 and 4 phrases with little evidence of stereotyped spacing.

Arch sounds

Numerous instances of a second call type were recorded, ostensibly similar to the arch sounds reported from the North Atlantic (Mellinger and Clark, 2003; Nieukirk *et al*., 2004), the D sounds from the northeast Pacific (Bass and Clark, 2003; Oleson *et al*., 2007; Thompson *et al*., 1996), sound IV of the northwest Pacific (Stafford *et al*., 2001), the arch sound of Australia (Ljungblad *et al*., 1997) and the high-frequency downsweep of Antarctica (Rankin *et al*., 2005). It has been proposed that arch sounds may act as contact calls (McDonald *et al*., 2001; Oleson *et al*., 2007).

The arch sounds in this study had similar frequency contours to those previously reported from the North Atlantic, starting at 77Hz, rising to a peak frequency of 91Hz before a slow descent to 41Hz (cf. 56, 69 and 35Hz in Mellinger and Clark, 2003). The arch sounds typically occurred in sequences (one to seven phrases), as did those reported by Mellinger and Clark (four to eight). However the arch sounds in this study were much briefer (1.5s) than those reported from the Atlantic (6.3s) (Mellinger and Clark, 2003) and the northwestern Pacific (7.8s) (Stafford *et al*., 2001). Indeed, the arch sounds in this study are closer in duration to those reported from the northeastern Pacific (1s); McDonald *et al*. (2001).

In marked contrast to the findings of Mellinger and Clark, the arch sounds in this study were recorded consecutively with A-B phrases. Four of the A-B phrases overlapped with one or more arch sounds, suggesting either that separate whales were responsible for each sound type (as suggested by 2001) or that the same whale produced both phrases consecutively within the vocal apparatus. The two focal animals present during the recordings were closely associated and it was not possible to assign individual calls to either animal.

Other sounds
No evidence was seen of the 9Hz sound reported at the end of A-B phrases in the North Atlantic (Mellinger and Clark, 2003). However, 9Hz would have been at the extreme low end of the recording bandwidth. Furthermore, ambient noise levels below 10Hz were often high in the course of this study (Fig. 2) and thus any 9Hz sounds could easily have been overlooked. Similarly, no evidence was found for the 16Hz tone preceding A phrases, nor the 10-12Hz or 300-500Hz precursors of B phrases reported from the northeastern Pacific (Clark and Fristrup, 1997; Cummings and Thompson, 1971; McDonald *et al*., 2001; Stafford *et al*., 1999). The 18-20Hz moan that typically preceded arch sounds in the northwestern Pacific (Stafford *et al*., 2001) was also not heard in this study, nor were the highly-variable AM calls of the northeast Pacific (Oleson *et al*., 2007).

Vocalisation rate
When calculating vocalisation rates it is essential to incorporate only those periods of time when focal animals are within detectable range (Matthews *et al*., 2001). To calculate the vocalisation rate for the encounter on 21 August, the period between the first and last sightings of the two blue whales was considered (estimated ranges of 1,840m and 290m respectively). As reported source levels for blue whale vocalisations are typically high (166 to 188dB re 1μPa); (Cummings and Thompson, 1971; McDonald *et al*., 2001; Moore, 1999; Thode *et al*., 2000) it is assumed that both whales would be audible to the recording system throughout the encounter (the mean range estimated from the hydrophones to the whales at the surface was 299m). The received levels of calls were low and this is in part due to low-frequency engine noise from the research vessel and flow noise over the hydrophones. The average noise level in the A-B frequency band was 104dB; in the arch frequency band the average value was 93dB. Assuming spherical spreading and using average SNR values for quality 1 vocalisations (19.0 for A-B phrases; 15.7 for arch sounds), theoretical source levels of 173dB for A-B phrases (from the mean distance of 316m) and 165dB for arch sounds (from the mean distance of 678m) were derived. These values are in keeping with reported source levels.

Only phrases of quality 1 were used for the purposes of calculating vocalisation rates as SNRs of these signals were consistently above 10dB (Fig. 3). During the encounter period (8hr 7min) a total of two A-B phrases and eight arch sounds of quality 1 were recorded from the two focal whales, representing a total vocalisation rate of 0.62 phrases per whale h^{-1} (0.12 A-B and 0.49 arch phrases per whale h^{-1}). However, it should be noted that the calls were highly clustered in time, with most quality 1 calls being recorded in a period of just 2min. No other candidate blue whale calls were identified in the additional 90hr of recordings examined, strengthening the premise that a number of the detected calls were from the focal whales. It would appear the calls not ascribed to the focal animals were from other whales clustered in space, a tendency noted for this species (McCauley *et al*., 2004; McDonald *et al*., 2001; Rankin *et al*., 2005).

Fin whales

On 22 August, a pair of fin whales was encountered at 64°57'N 31°7'W and was followed for six hours. Despite unpredictable consecutive surfacings, there was a net movement in a northeasterly direction at a speed of 1-10km hr^{-1}. Both whales dived continually throughout the encounter and the average dive time was a little over 5min. No vocalisations were recorded when either of the focal animals were seen at the surface.

Sonobuoy recordings
During the course of the encounter with the fin whales, two sonobuoys were deployed. Although only three calls were identified from the recording of the first sonobuoy, a further 118 calls were identified from the second sonobuoy. The recorded sounds all had downswept frequency contours, and could be categorised into three call types (Table 1; Fig. 4). The majority were the typical 20Hz downsweeps reported from other fin whale populations (Edds, 1988; McDonald and Fox, 1999; Watkins, 1981), with 63% of calls having a start frequency below 30Hz. These type I calls were 0.2-1.25 in duration (mean 0.5s) and typically swept downwards from 28 to 18Hz (maximum 32Hz, minimum 14Hz). There was little evidence of the stereotyped 'doublet' patterning reported for this call type in other studies (Thompson *et al*., 1992; Watkins *et al*., 1987), although individual phrases were often recorded in clusters. Inter-call intervals were highly variable, typically less than 20s, although gaps of up to 2min were recorded.

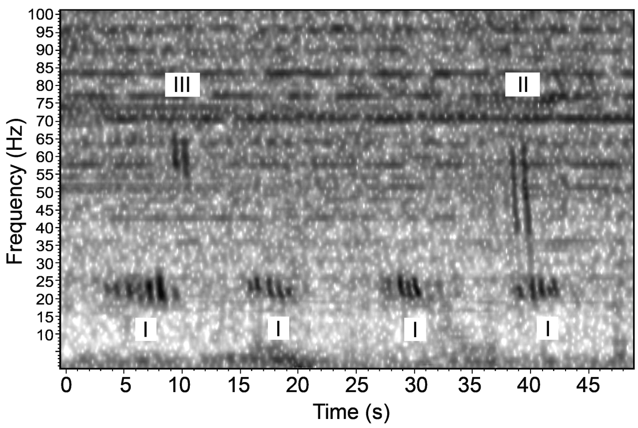

Fig. 4. Example sonobuoy spectrogram (2048 FFT; 94% overlap; sample rate 2000Hz) showing the three fin whale call types identified in this study. Type I is synonymous with the 20Hz call reported from other studies; type II typically downsweeps from 72 to 34Hz; type III from 84 to 52Hz. Note multipath effects on all.

The second call type comprised calls with relatively large bandwidths, typically downsweeping from 72 to 34Hz. Type II calls were recorded intermittently, and although they were usually produced just prior to 20Hz calls, they were also produced individually (33% occurred more than 20s before a 20Hz call). The third call type only contained relatively high frequency energy, and was typically downswept from 84 to 52Hz. Only five of the type III calls were recorded and they did not appear to be produced in close conjunction with the first two call types.

Call positions
Of the 121 fin whale vocalisations recorded, 12 were recorded on both the hydrophone towed behind *Song of the Whale* and the second sonobuoy. Differences in arrival time at the sonobuoy and the towed array were measured from spectrograms (256-point FFT (Fast Fourier Transform); 99% overlap; 1.3ms time resolution) and used to calculate bearings to the 12 multi-channel calls. There was broad agreement between bearings estimated from arrival-time differences, suggesting the vocalisations were generated to

the south of the trackline. However, the bearings measured from the vocalisations were rarely in keeping with the bearings estimated to surfacing whales. The SNRs measured from many of the vocalisations were low with a high degree of variability (1-18dB), suggesting more than just the two focal animals were recorded. As such, it is not prudent to calculate vocalisation rates for this encounter as the number of whales within acoustic range is uncertain.

Right whales

The real-time right whale detection algorithm was run at all times when the hydrophone was deployed. Throughout the 700hr of recordings (7,757km of trackline) no acoustic detections were made of right whales and no right whales were seen. Previous acoustic surveys for right whales suggest small aggregations are less likely to be detected (Matthews *et al*., 2001). Thus quiet solitary animals could easily avoid detection during periods of poor visibility (e.g. night-time or elevated sea states).

DISCUSSION

This study describes vocalisations for fin and blue whales from single encounters with small groups. Although other solitary blue and fin whales were encountered, vocalisations were not identified from these lone animals. It is possible that low frequency calls produced by these individuals were masked (by engine noise, for example) but it is unlikely that the *Song of the Whale* recording system would be unable to record these signals when within 2km (the maximum estimated distance to a fin/blue sighting). The production of social calls in these species may be related to whale density, with isolated individuals less likely to produce vocalisations.

A significant obstacle in the recording of free-ranging cetaceans is the determination of caller identity. The use of multiple hydrophone elements allows estimation of bearings and/or relative positions to vocalising animals. This approach, combined with measurements of SNRs, made it possible to ascertain if sighted animals were being recorded. During the blue whale encounter, only some of the calls recorded could be ascribed to the focal pair, while none of the signals recorded during the fin whale encounter could be ascribed to the focal animals with any confidence. All other recordings made in the presence of baleen whales were examined but no vocalisations were identified (98hr of recordings from 216 sightings).

Blue whales

The vocal rates reported are based on two closely associated animals, of which the lead animal (approximately 23m as calculated using the photogrammetrical techniques described by Gordon *et al*. (1986) appeared larger than the other. It is possible they were a male-female pair, as adult males are typically shorter in length than adult females (Lockyer, 1981). Thus the two different call types may have been produced by different animals. This is in part supported by the hypothesis that the A-B call type is a breeding call produced exclusively by adult males (Oleson *et al*., 2007; Watkins *et al*., 2000) and also by evidence suggesting blue whales rarely mix call types (McDonald *et al*., 2001; Thode *et al*., 2000). The A-B phrases produced by the focal pair lacked the stereotypical patterning of song, as noted for closely-associated blue whales recorded in the northeast Pacific that produce singular A-B calls but not song (Oleson *et al*., 2007). In that study, female whales were exclusively paired with singular A-B calling males. Although it is assumed that blue whales use the waters off Iceland in the summer for feeding, individuals in the eastern Pacific and the Gulf of St. Lawrence have been observed in male-female pairs during the feeding season (Oleson *et al*., 2007; Sears, 2002). On these feeding grounds, pairing increases as the breeding season approaches, with some pairs remaining stable for at least several weeks. Thus mate selection in blue whales may not be seasonally confined.

A total of 0.12 A-B and 0.49 arch phrases were produced per whale hr^{-1}. This is much lower than vocalisation rates reported from the northeast Pacific. The three whales observed by McDonald *et al*. (2001) produced between 31.2 and 39.6 phrases per whale hr^{-1} (from Fig. 4; October, latitude 33°N). In the South Pacific, rates of 24.7 and 25.6 were reported for three-part ABC sequences from two individual whales (Cummings and Thompson, 1971); (from Table 1; May, latitude 43°S). In the St. Lawrence River, a rate of 36.7 has been reported for seven 'narrow-band low frequency moans' recorded from a single whale (Edds, 1982); (from Table 1; August, latitude assumed to be 47°N). As the whales followed in this study were at higher latitudes (65°N) and in open water habitats (>150 miles from land) it is hard to draw any direct parallels. However, the rates described above were all measured from long, stereotypical sequences of phrases that were not present in this study. It is not clear from previous studies what the vocalisation rate might be for sounds that are not produced as part of a patterned sequence. It may be that paired animals produce infrequent calls at signal levels considerably below those of 'continuously' singing whales. The low vocal rate may also relate to recording in northern latitudes where blue whales are likely to be travelling or foraging. Thus, the continuous singing reported from males at the start of the breeding season is unlikely to be heard in these waters.

Fin whales

The vocalisations reported were recorded in the presence of two closely associated animals. However, it is likely that several of the calls were produced by non-focal animals. Fin whales producing calls are typically part of a group (Watkins, 1981) and although no other whales were seen near the focal animals, it is certainly possible animals out of visible range were recorded. The low SNR values suggest any calls produced by the focal animals were not intended for broadcast over large distances. It has been suggested that whales dispersed by more than 15-20km do not produce higher frequency calls (such as the type II call in this study), which have measured source levels of 155-165dB re 1μPa @ 1m (Watkins, 1981). Thus the type II calls recorded in this study may have been social signals directed at nearby conspecifics.

Of interest is the high number of type I (20Hz) calls recorded in this study, a call traditionally described as a reproductive call produced from autumn to spring (Watkins *et al*., 1987). Although there is growing evidence that 20Hz sequences are produced only by males (Croll *et al*., 2002), the data obtained in this study suggest individual 20Hz calls are not restricted to lower latitudes or winter months. The high seasonality of 20Hz calls reported in previous studies (Watkins *et al*., 1987) seems to relate only to highly repetitive sequences. Indeed, individual 20Hz calls have been reported from the North Atlantic in all calendar months except July (Patterson and Hamilton, 1964; Walker, 1964; Watkins *et al*., 1987; Weston and Black, 1965), which may reflect a lack of research effort in the most northern latitudes.

Right whales

Right whales were once common in waters off Iceland, although sightings in recent decades have been extremely rare. No right whales were seen and none were heard during the present study. A study carried out in 2005 using the same vessel and equipment in the Gulf of Maine (an area more commonly frequented by right whales) found that acoustic detection rates were the same as visual detection rates (IFAW, 2006). In the Gulf of Maine visual detection rates were lower than they would be in Iceland due to considerable fog. It can however be assumed that the right whale detection equipment was functioning and would have detected vocally active right whales. Based on historical records, Smith *et al*. (2006) suggest that the Loppa Sea off northern Norway 'seems a good candidate as an unrecognised summering ground for some of the right whales that are born in the calving ground along the southeastern United States'. The acoustic methods used in this study would appear well suited to further investigation of known historical right whale habitat.

CONCLUSIONS

The vocalisation rates estimated in this study for non-patterned blue whale calls tend to be low. It is not clear what behavioural, geographical or seasonal trends may influence the vocalisation rate of large baleen whales and thus direct comparisons between areas are difficult. However, it is hoped the presented results will be of use in calibrating remote recordings made from the North Atlantic. Future work should endeavour to record patterned stereotypical calls with sighting information for blue/fin whales of the North Atlantic. These data would be of particular use for calibrating SOSUS array recordings (Clark, 1994; Mellinger and Clark, 2003). A persistent problem in acoustic density estimation is the ability to allow for silent whales within the study area. It is perhaps not insignificant that eight of the ten blue/fin sightings were lone animals that appeared to be silent. Complementary visual and acoustic techniques will be required in future to provide a more accurate estimate of the proportion of silent animals within a study area.

The research vessel used in the study, *Song of the Whale*, was commissioned in 2004 having been designed specifically for research purposes. Particular attention had been given in the design brief to low noise levels under power including the hull, propeller and engine-mounting design. The ability to be able to monitor around the 20Hz frequency range from a hydrophone on a relatively short towing cable (200m), while steaming at speeds of 6 knots ($3ms^{-1}$), is a rather unique characteristic of this vessel.

Based on the very limited number of recent observations in the study area, it is not particularly surprising that North Atlantic right whales were not detected. Nevertheless, these data are valuable in contributing to an overall understanding of the distribution of this species in view of its endangered status and the lack of knowledge of parts of the population at certain times of year. The development of automated acoustic detection algorithms for this species now allows surveillance for this species over extended areas to be conducted from vessels involved in other studies, which are essentially platforms of opportunity.

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