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Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals

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ABSTRACT

Marine renewable developments have raised concerns over impacts of underwater noise on marine species, particularly from pile-driving for wind turbines. Environmental assessments typically use generic sound propagation models, but empirical tests of these models are lacking. In 2006, two 5 MW wind turbines were installed off NE Scotland. The turbines were in deep (>40 m) water, 25 km from the Moray Firth Special Area of Conservation (SAC), potentially affecting a protected population of bottlenose dolphins. We measured pile-driving noise at distances of 0.1 (maximum broadband peak to peak sound level 205 dB re 1 μPa) to 80 km (no longer distinguishable above background noise). These sound levels were related to noise exposure criteria for marine mammals to assess possible effects. For bottlenose dolphins, auditory injury would only have occurred within 100 m of the pile-driving and behavioural disturbance, defined as modifications in behaviour, could have occurred up to 50 km away.

1. Introduction

Exposure to anthropogenic noise can cause detrimental effects to both humans and wildlife (Reijnen et al., 1996; Öhrström et al., 2006). Many aquatic species are capable of generating and detecting sound, for example crustaceans, fish and marine mammals (e.g. Au et al., 1974; Popper et al., 2004; Henninger and Watson, 2005). Anthropogenic noise may consequently pose a serious threat within the marine environment (Parsons et al., 2008), and this should be considered in environmental impact assessments (Croll et al., 2001). These assessments typically involve predicting source levels (sound level measured or estimated 1 m from the noise source) and using generic models to estimate transmission loss (reduction in sound level with distance). Received levels, and the potential effects of these on marine species, can then be estimated. Although such assessments are now made regularly, the actual underwater noise levels produced are rarely measured (Southall et al., 2007). Furthermore, little is known about the accuracy of different sound propagation models, particularly at longer ranges from source and in shallow coastal waters.

In the marine environment, seismic surveys and pile-driving produce some of the most intense anthropogenic noises (Richardson et al., 1995; Gordon et al., 2003). Over the last decade there has been a growing interest in marine renewable energy production, resulting especially in the rapid development of offshore wind power (Gaudiosi, 1999; Gill, 2005). Construction of these fixed structures generally involves pile-driving, which has raised concerns about the resulting environmental impact of high sound levels on species such as fish and marine mammals (Madsen et al., 2006; Wilhelmsson et al., 2006).

The area over which anthropogenic noise may adversely impact marine species depends upon how well the sound propagates underwater, its frequency characteristics and duration. Information on received levels and spectral content at different distances from source can be compared with hearing thresholds of species of interest and local ambient noise levels. Together, these data can be used to determine the likelihood that species will be impacted at different distances from the source.

Sound propagation within the deep ocean has been reasonably well documented, but is more complicated in shallow water environments (<200 m deep) (Urick, 1983). Variability in depth, sediment type, temperature and salinity, as well as repeated reflections off the surface and bottom, make sound transmission difficult to model (Marsh and Schulkin, 1962). Similarly, there is little information on background noise levels in shallow water (Nedwell et al., 2003). Since the majority of human activities occur within the coastal zone, the limited empirical data from these areas currently constrains efforts to predict and mitigate the impacts of construction noise on coastal wildlife populations.

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Several reviews (e.g. Richardson et al., 1995; Gordon et al., 2003; Madsen et al., 2006) have identified the need for more comprehensive measurements of anthropogenic sound sources that have a reasonable likelihood of causing injury, or adversely affecting marine mammals' hearing or behaviour. We therefore made empirical measurements of pile-driving noise levels during the installation of two offshore wind turbines close to a Special Area of Conservation (SAC) designated to protect a population of bottlenose dolphins. We consequently aimed to determine: (1) accurate estimates of received levels at a range of distances from the source, (2) the validity of the propagation model and predicted received levels in the environmental assessment, (3) the potential impacts on marine mammals based on noise exposure criteria and in comparison with local background noise measurements.

2. Method

2.1. Study area

The study was carried out in the Moray Firth, NE Scotland, when Talisman Energy (UK) Ltd. (Talisman) and Scottish and Southern Energy installed two 5 MW wind turbines in 2006 to assess the potential for deep water offshore windfarms. The turbine site (58°06′ N, 03°04′ W) was 25 km from the nearest coastline and in water 42 m deep (Fig. 1).

This area supports an internationally protected population of bottlenose dolphins (*Tursiops truncatus*), and the Moray Firth Special Area of Conservation (SAC) is a Marine Protected Area (MPA) (Fig. 1) that was designated to protect this population through the EU Habitats Directive (Thompson et al., 2000). The outer boundary of the SAC is 25 km from the turbine site. Nevertheless, the potential both for underwater noise to travel long distances, and for dolphins to travel outside the SAC boundary, meant that the potential impacts of the development on this small protected population was a key concern for the developer and environmental stakeholders. In addition, several other marine mammal species also frequent the area (Table 1), including common (*Phoca vitulina*) and grey seals (*Halichoerus grypus*), harbour porpoises (*Phocoena phocoena*) and minke whales (*Balaenoptera acutorostrata*) (Thompson et al., 1996; Hammond et al., 2002; Hastie et al., 2003).

2.2. Background noise recordings

Prior to the commencement of the pile-driving operations, recordings of background noise were made with a Brüel and Kjaer 8106 hydrophone, sampling at 300 kHz and 24 bit depth (giving an effective frequency range up to 150 kHz). The hydrophone has an in-built 10 dB preamplifier, 7 Hz high-pass filter, and is capable of recording noise levels well below sea state zero. This 8106 hydrophone is less sensitive at very low frequencies and at high frequencies above 80 kHz. The majority of background noise tends to occur at frequencies below 10 kHz (Wenz, 1962). The background noise data was therefore summed over the frequency range 10 Hz to 120 kHz without correcting for the high frequency roll off above 80 kHz. This hydrophone, and all others used in this study, were calibrated with a Brüel and Kjaer Type 4223 Pistonphone Calibrator.

During recordings, the hydrophone was attached to an anti-heave buoy and suspended at a depth of approximately 5 m below sea level. The survey vessel's engines and other equipment that might have interfered with the measurements, such as an echosounder, were switched off and the boat allowed to drift. The sounds were listened to before recording began to ensure that self-noise caused by cable strum, own-ship noise and electrical interference

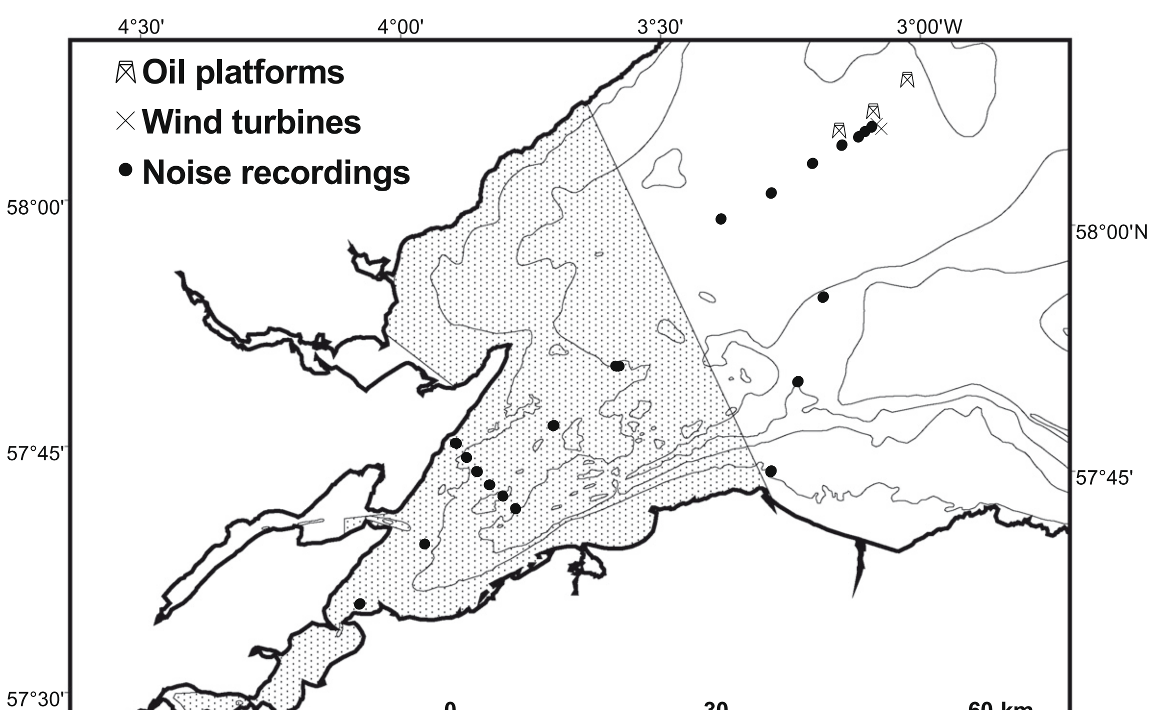

Fig. 1. Location of the wind turbines and sound recordings during pile-driving in the Moray Firth, NE Scotland. The Marine Protected Area is shaded and contour lines indicate water depth at 20 m intervals.

Table 1
Marine mammal species known to occur in the Moray Firth, Scotland (Reid et al., 2003).

Common	Occasional
Bottlenose dolphin (*Tursiops truncatus*)	Common dolphin (*Delphinus delphis*)
Harbour porpoise (*Phocoena phocoena*)	White-beaked dolphin (*Lagenorhynchus albirostris*)
Minke whale (*Balaenoptera acutorostrata*)	White-sided dolphin (*Lagenorhynchus acutus*)
Common seal (*Phoca vitulina*)	Striped dolphin (*Stenella coeruleoalba*)
Grey seal (*Halichoerus grypus*)	Risso's dolphin (*Grampus griseus*)
	Killer whale (*Orcinus orca*)
	Pilot whale (*Globicephala melas*)
	Humpback whale (*Megaptera novaeangliae*)
	Fin whale (*Balaenoptera physalus*)
	Northern bottlenose whale (*Hyperoodon ampullatus*)

was at a minimum. All sound recordings were also monitored both during recording and in post analysis for quality control. Sound recordings were made at pre-defined sites within the vicinity of the wind turbines and in the MPA to investigate spatial variability in background noise levels and frequency characteristics.

2.3. Pile-driving technical details

The two 88 m tall wind turbines had 63 m long blades, and were mounted 700 m apart on four-legged steel jackets fixed to the seabed using four (44 m × 1.8 m diameter) tubular steel piles. Unlike conventional monopole turbine construction, these tubular steel piles were driven almost entirely into the substrate to 'pin' the turbine jacket to the seabed at each of its four corners. Pile-driving operations were estimated to take two hours for each pile, resulting in a total duration of 16 h for the two wind turbines, to take place over several days.

In the project's Environmental Statement (Talisman, 2005) to assess the potential environmental impacts, sound propagation models indicated that, within the MPA, received levels of noise from the pile-driving would have fallen to a level at which an avoidance reaction was no longer expected. However, high noise levels would be experienced close to the site. Consequently, an environmental protection plan was developed by Talisman, which ensured that marine mammals were not within 1 km of the operation. This was achieved using trained marine mammal observers (MMOs) using both visual and passive acoustic detection to monitor activity. This mitigation was augmented by adopting a "soft start" whereby the force of piling was gradually increased to alert animals in the vicinity to the commencement of the operations. The soft start consisted of five strokes of the hammer at low energy separated by 5, 3, 2 and then 1 min, followed by a slow increase in the hammer energy over a period of 20 min. Full blow impact piling then continued until the pile was installed.

2.4. Pile-driving noise recordings

Noise recordings during the pile-driving operations were made by two teams, working from two separate boats. Noise recordings close to the source were made within 100 m to 2 km of the pile-driving, and also measured variation in sound levels during the soft start period. Sound recordings were made using a Brüel and Kjaer 8105 hydrophone and a Brüel and Kjaer 2635 charge amplifier, and recorded directly onto a laptop computer using a National Instruments LabVIEW program. Sampling was at 350 kHz, 24 bit depth and with a 1 Hz high-pass filter (giving an effective frequency range of 1 Hz to 170 kHz).

Further noise recordings were taken from 500 m out to a range at which the sound could no longer be distinguished from background noise. Spatial variability in sound propagation was also investigated by taking noise recordings along a line of stations along an arc 60 km from the pile-driving at 2 km intervals (Fig. 1). Sound recordings were made with a Brüel and Kjaer 8104 hydrophone and Brüel and Kjaer NEXUS charge conditioning amplifier. This was connected to a hard disk recorder (Sound Devices 722) sampling at 192 kHz, 24 bit depth and with a 10 Hz high-pass filter (giving an effective frequency range of 10 Hz to 96 kHz). Recordings were all made at 5 m depth with the survey vessel's engines and echosounder switched off. All sound recordings were monitored prior to and during recording to ensure minimum self-noise and for quality control. A GPS position was taken for each recording and at least five 30-second recordings were made at each station.

The Brüel and Kjaer 8104 and 8105 hydrophones have a linear response from 0.1 Hz to 100 kHz with variability +1 to −6 dB. The sensitivity variation at high frequencies was not corrected. However, the response is flat over the range 10 Hz to 10 kHz, the frequency of most of the pile-driving noise.

2.5. Sound analysis

Sounds were analyzed in Avisoft-SASLab Pro (version 4.39). Absolute sound pressure levels (SPL) were calculated using the standard equation (Richardson et al., 1995):

$$\mathrm{SPL} = 20\log_{10}(P/P_0) \tag{1}$$

where P_0 is the reference pressure, the standard being 1 μPa in underwater acoustics, and P is the sound pressure measured (μPa). SPL is therefore given in units of dB re 1 μPa. Hereafter, unless otherwise stated, background noise is given as the root mean square (rms) level calculated over a period of 30 s, and pile-driving noise is expressed as a peak to peak level, the maximum variation in pressure from positive to negative within the wave.

2.6. Estimating the source level and sound propagation model

Sound propagation is described by the equation:

$$\mathrm{SPL}(r) = \mathrm{SL} - \mathrm{TL} \tag{2}$$

where SPL(r) is the sound pressure level at distance r from the source (m), SL is the sound level at 1 m from the source (source level) and TL is the transmission loss. Transmission loss may be expressed as (Urick, 1983):

$$\mathrm{TL} = N\log_{10}(r) + \alpha r \tag{3}$$

where N is a factor for spreading loss and α is the absorption coefficient (dB m^{-1}). The peak to peak sound levels were measured for each piling blow and a sound propagation model (Eq. (2)) fitted by nonlinear least-squares regression. To provide a more accurate measure of the source level, and noise within the range at which injury to marine mammals may occur, the measured data within 1 km of the pile-driving operation was also analysed as a separate subset.

In the Environmental Statement (Talisman, 2005), the predicted peak to peak source level was calculated using the equation by Nedwell et al. (2005):

$$\mathrm{SL} = 24.3D + 179 \tag{4}$$

where D is the pile diameter (m). In this development, where the piles were 1.8 m, this resulted in a predicted source level of 225 dB re 1 μPa at 1 m. Transmission loss was assumed to be caused by geometrical spreading with a spreading loss term of 15, which is intermediate between spherical and cylindrical spreading to reflect the source being in relatively deep water but in close proximity to the shallow coastal zone. This resulted in a predicted sound level of 159 dB re 1 μPa at the SAC boundary, 25 km from the source (Talisman, 2005). These predicted values were compared with the recorded sound levels and estimated propagation model during the pile-driving.

2.7. Potential impact on marine mammals

The potential impacts on marine mammals were categorised, in order of decreasing severity, as: (1) Auditory injury or permanent threshold shift (PTS) in hearing, (2) Temporary threshold shift (TTS), (3) Behavioural disturbance, (4) Audibility. Since it is unknown which sound metric is best associated with the likelihood of injury, Southall et al. (2007) proposed a dual criterion based on peak sound pressure level and sound exposure level (SEL), and the level that is exceeded first is used as the operative injury criterion. SEL is a measure of energy that incorporates both sound pressure level and duration. The spectral content can also be taken into account by an M-weighting of the SEL, which is a frequency weighting to allow for the functional hearing bandwidths of different marine mammal groups (Southall et al., 2007).

No data exist for the onset of PTS in marine mammals so it was instead estimated as 6 dB above the SPL (unweighted) and 15 dB above the SEL (M-weighted for the relevant marine mammal group) onset of TTS and assumed that the pile-driving represents a multiple pulse sound (Southall et al., 2007). Southall et al. (2007) propose SPL criteria of 230 dB re 1 μPa (peak broadband level) for PTS onset in cetaceans (in this case most at risk were bottlenose dolphins, harbour porpoises and minke whales) and 218 dB re 1 μPa for pinnipeds (including common and grey seals). TTS onset is expected at 224 dB re 1 μPa (peak broadband level) and 212 dB re 1 μPa for cetaceans and pinnipeds respectively (Finneran et al., 2002; Southall et al., 2007). The SEL criteria proposed are TTS onset at 183 dB re 1 μPa^2 -s for cetaceans and 171 dB re 1 μPa^2 -s for pinnipeds, and PTS onset is expected at 15 dB additional exposure.

Behavioural disturbance is difficult to quantify as reactions are highly variable and context specific making them less predictable (Southall et al., 2007). SPL fails to account for the duration of the exposure, but it is the metric that has most often been estimated during disturbance studies (Southall et al., 2007) and is therefore used as the criteria here (Table 2). These values were based on those for multiple pulse sounds for all species, except for the harbour porpoise where all of the studies reviewed in Southall et al. (2007) were classified as nonpulses (intermittent or continuous sounds that can be tonal, broadband or both). These criteria are precautionary as only a small number of controlled studies have been performed, few field studies estimate received levels and a limited number of species are represented. The long-term implications of these behavioural responses have also not been determined.

Although the effective filter bandwidth in mammals varies, it can be coarsely approximated as one-third of an octave. The zone of audibility is defined as the point at which the sound's received level equals the level of background noise in the same one-third-octave band (David, 2006). A mean of the one-third-octave band levels of the background noise were used for comparison with the pile-driving levels. One-third-octave band levels of the pile-driving noise were calculated over a 3 s period for the frequencies 1 and 10 kHz at a range of 96 m to 70 km from the source to compare with published data on marine mammal hearing thresholds, as they are most sensitive to higher frequencies. The audiograms for bottlenose dolphins (Johnson, 1967), harbour porpoises (Kastelein et al., 2002) and common seals (Møhl, 1968) were selected for the analysis, as the species most likely to be impacted in the Moray Firth (Thompson et al., 1996; Hastie et al., 2003). Unfortunately no direct measurements of hearing exist for baleen whales, such as minke whales (Richardson et al., 1995).

3. Results

3.1. Background noise

Background noise recordings were made at 25 sites in the Moray Firth in Beaufort sea state 3 or less (Fig. 2a). Comparison with a test recording confirmed that the ambient noise was greater than the self-noise of the hydrophone system at all sites. The 30 s rms SPL ranged from 104 to 119 dB re 1 μPa in the MPA. At the time, increased boat activities relating to construction activity meant that background levels were higher within 1 km of the wind turbine site, reaching 138 dB re 1 μPa, than close to the operating oil platform (121 dB re 1 μPa). The background noise mainly consisted of low frequencies less than 1 kHz. There were higher noise levels in the outer than in the inner Moray Firth, particularly at 100–500 Hz where the spectral levels were typically 20 dB higher (Fig. 2b).

3.2. Pile-driving noise

The pile-driving operation took 108–157 min (Mean = 135 min) for each pile on five separate days. Each pile required 5000–7000 blows of the hammer (Mean = 6223 blows) resulting in a mean total energy of 1,912,100 kJ per pile. During pile-driving, the pile was struck about once every second (Mean = 0.8 strikes per second, SD = 0.09). Noise recordings were made at 100 m to 80 km distance from the pile-driving (Fig. 1). There was a decrease in sound pressure and an increase in duration with increasing distance from the source (Fig. 3). At close ranges, the initial peak of the waveform was very pronounced, lasting approximately 10 ms within 1 km of the source (total waveform duration 200 ms). However, the duration of this peak increased to 200 ms at 40 km (total duration approximately 600 ms).

Close to source (up to 2 km distance), the sound was highly broadband. Peak sound energy occurred at 100 Hz to 2 kHz, but there was substantial energy up to 10 kHz (Fig. 4). High frequen-

Table 2
Noise exposure criteria for behavioural disturbance for the marine mammal species most commonly found in the Moray Firth and the maximum distance from the pile-driving within which this sound level was exceeded based on our recordings (distances estimated from Eq. (5) in parentheses). In cases where the response is highly variable, minor disturbance has been used to indicate some animals may be sensitive to this level whereas major disturbance is likely to elicit a strong reaction.

Species	Threshold for behavioural disturbance (peak to peak broadband level)	Max. distance from pile-driving	Reference for threshold
Bottlenose dolphin (mid-frequency cetacean)	140 dB re 1 μPa	50 km (43 km)	(Southall et al., 2007)
Harbour porpoise (high-frequency cetacean)	Minor disturbance: 90 dB re 1 μPa	Minor: 70 km (70 km)	(Southall et al., 2007)
	Major disturbance: 155 dB re 1 μPa	Major: 20 km (21 km)	
Minke whale (low-frequency cetacean)	143 dB re 1 μPa	40 km (38 km)	(Gordon et al., 2003)
Harbour and grey seal (pinnipeds in water)	Minor disturbance: 160 dB re 1 μPa	Minor: 14 km (15 km)	(Harris et al., 2001)
	Major disturbance: 200 dB re 1 μPa	Major: 215 m (300 m)	

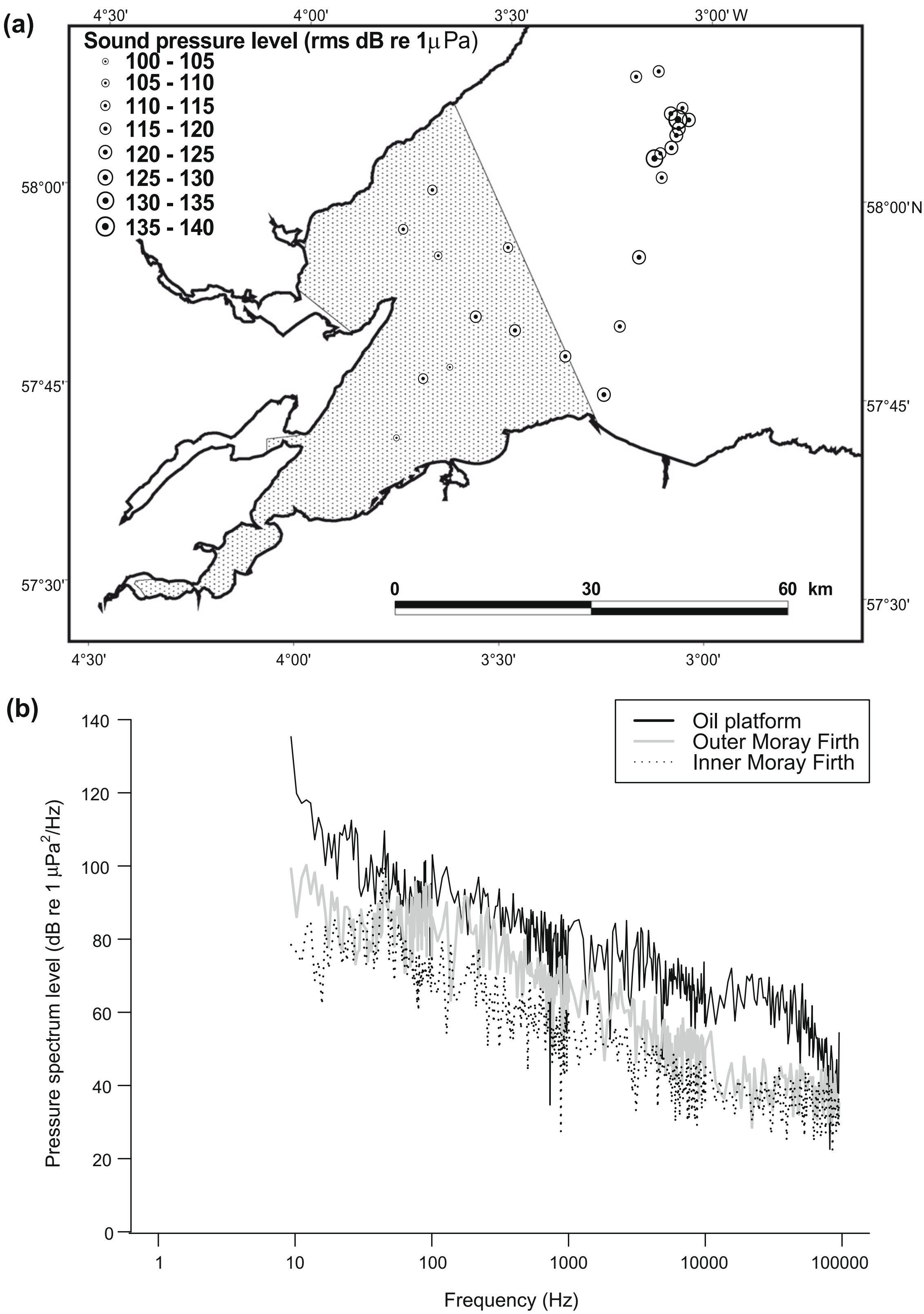

Fig. 2. (a) Location and sound pressure level (root mean square) of background noise measurements, the Marine Protected Area is shaded, (b) Power spectral density of three seconds of background noise measured in the vicinity (800 m distance) of the operating oil platform, at the outer boundary of the Marine Protected Area (outer Moray Firth) and within the Marine Protected Area (inner Moray Firth). Recordings of background noise were made with a Brüel and Kjaer 8106 hydrophone, sampling at 300 kHz and 24 bit depth. The data was summed over the frequency range from 10 Hz to 120 kHz without correcting for the high frequency roll off above 80 kHz.

cies were rapidly attenuated with distance and beyond 4 km the majority of the sound consisted of frequencies less than 5 kHz.

Measured broadband peak to peak sound levels reached 205 dB re 1 µPa at 100 m from the pile-driving (Fig. 5a). At 80 km away,

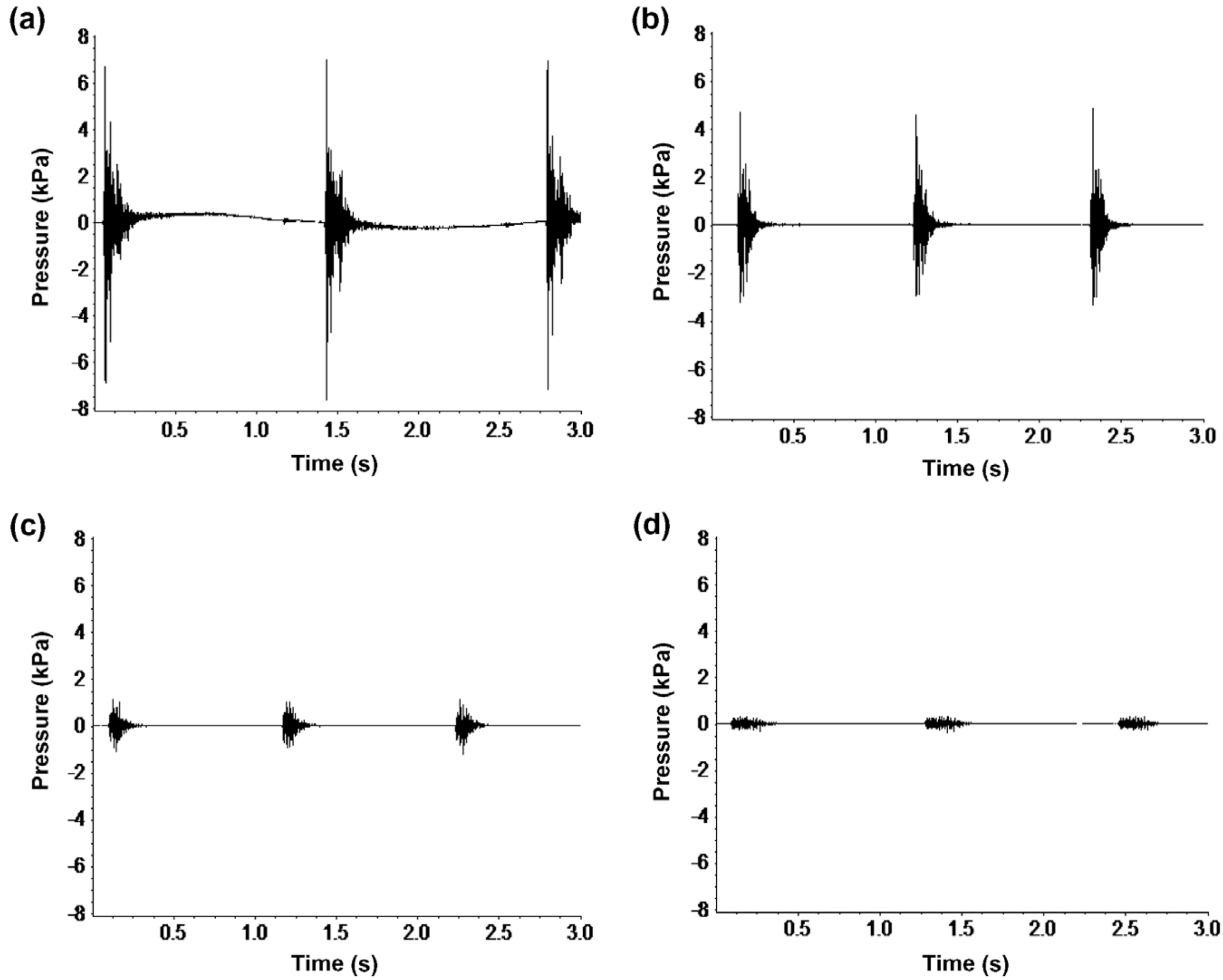

Fig. 3. Three-second time histories of underwater pile-driving noise at a distance of (a) 100 m, (b) 710 m, (c) 1520 m, (d) 4550 m.

received levels were no longer distinguishable above background noise.

Recordings were made at six stations along a line 60 km from the pile-driving in water depths of 14.5–51.4 m (Fig. 1). There was a significant difference in the received levels between recording stations (ANOVA: $F = 107.4$, df = 5, 22, $p < 0.001$). Tukey's post hoc tests showed that the three stations on the eastern side of the transect, closer to the coast, had significantly higher peak to peak sound levels than the three on the west side (Fig. 1), but received levels were not linearly related with the depth of water in which the sound measurements were taken (Linear Regression: $F = 1.90$, df = 1, 26, $p = 0.180$).

3.3. Source level and sound propagation model

Based on the recorded sound measurements, the best-fit sound propagation model gave a source level of 250 dB re 1 μPa at 1 m (95% CI ± 3.5), a spreading loss of 20 (95% CI ± 1.2) and absorption loss coefficient of 0.4 dB km^{-1} (95% CI ± 0.06):

$$\mathrm{SPL}(r) = 250 - 20\log_{10}(r) - 0.0004r \quad (5)$$

This source level probably greatly over-estimates the actual source level as inspection of the data in Fig. 5a highlights that this fit exceeds the majority of the measured data at close range

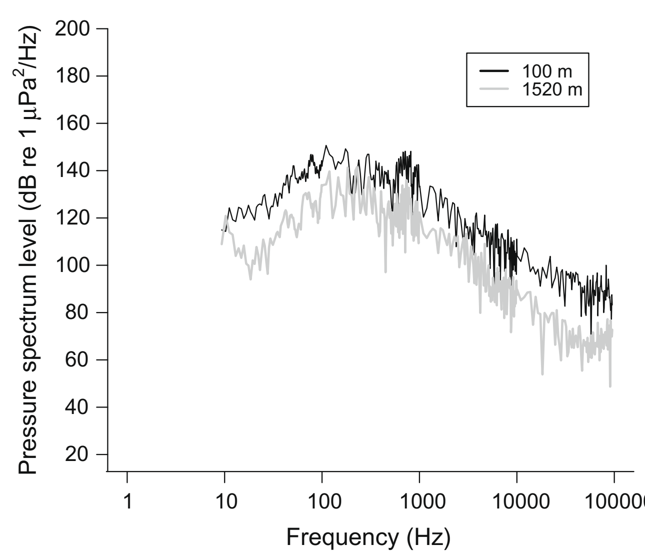

Fig. 4. Power spectral density of three seconds of pile-driving noise at 100 m and 1520 m distance. Recordings of pile-driving noise were made with Brüel and Kjaer 8104 and 8105 hydrophones. The data was over the frequency range 10 Hz to 96 kHz without correcting for sensitivity variations above 10 kHz.

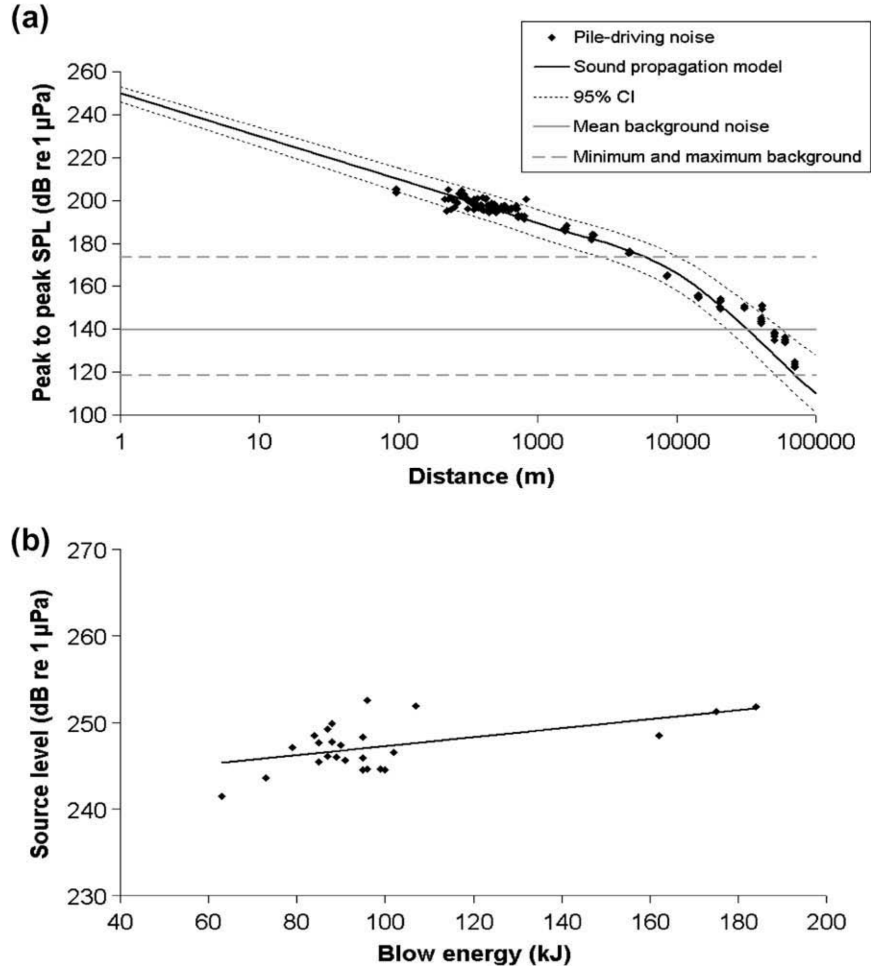

Fig. 5. (a) Broadband peak to peak sound pressure levels of pile-driving in relation to distance from the noise source and the best-fit sound propagation model. Peak to peak background noise levels are shown for comparison only. (b) Relationship between estimated peak to peak source level of pile-driving noise and blow energy of piling hammer with least-squares regression line.

(100–300 m), but under-estimates the sound at ranges from 500 m to 1000 m. The source level calculated for the subset of data closest to the pile-driving (up to 1 km) was 226 dB re 1 μPa at 1 m (95% CI ± 14.2), which is similar to that predicted (225 dB re 1 μPa at 1 m) in the Environmental Statement (Talisman, 2005). It was also predicted that the received level would be 159 dB re 1 μPa at the MPA boundary 25 km from the pile-driving (Talisman, 2005). Based upon the fit to our measured data (Eq. (5)), the received level at 25 km distance was lower than this estimate at 152 dB re 1 μPa and would only have exceeded 159 dB re 1 μPa within 15 km of the source. Although we did not record at 25 km distance, our mean measured sound level at 20 km (at two different locations, Fig. 1) was 152 dB re 1 μPa and at 30 km away was 150 dB re 1 μPa.

The soft start period lasted for 20 min and used a reduced blow force that slowly increased from an energy of about 63 kJ per blow up to 200–400 kJ (maximum 510 kJ) during full strength pile-driving (Talisman Energy (UK) Ltd.). The transmission loss from the sound propagation model in Eq. (5) ($20\ \log_{10}(r) - 0.0004r$) was used to calculate the predicted peak to peak source level for each noise recording during the soft start. The source level was estimated to be 242 dB re 1 μPa when the piling blow energy was 63 kJ (the lowest energy level for which we had sound recordings) and 252 dB re 1 μPa at 184 kJ blow energy. Lower blow strength during the soft start period therefore resulted in a reduction of 10 dB in the source level noise. A significant positive linear relationship was found between the peak to peak source level and blow energy of the pile-driving (Linear Regression: $F = 10.1$, df = 1, 23, $p = 0.004$) (Fig. 5b).

3.4. Potential impact on marine mammals

Based on the broadband peak to peak sound level calculated from Eq. (5), PTS onset would have occurred within 5 m of the pile-driving operation for cetaceans and 20 m for pinnipeds. The level for TTS onset would have been exceeded within 10 m and 40 m of the pile-driving for cetaceans and pinnipeds respectively. The closest measurement of the pile-driving noise recorded at 100 m, had a M-weighted SEL of 166 dB re 1 μPa^2 -s. This is less than the PTS and TTS SEL criteria for cetaceans and pinnipeds, and indicates that no form of injury or hearing impairment should have occurred at ranges greater than 100 m from the pile-driving operation.

Wild and captive observations indicate that harbour porpoises can be highly sensitive to noise (Southall et al., 2007) and it is therefore possible that behavioural disturbance could occur up to 70 km from the pile-driving, the limit at which it could be distinguishable from background noise. However, the analysis of the measured data in this study, compared with the exposure criteria (Table 2) indicates that strong avoidance behaviour would only be expected within 20 km of the noise source. The zone of impact for pinnipeds is expected to be smaller, within 14 km of the source. Bottlenose dolphins and minke whales may exhibit behavioural disturbance within 50 km and 40 km respectively of the pile-driving.

The maximum distance at which the pile-driving would be audible to marine mammals extended to the range at which components of the noise remained above the auditory threshold, and was distinguishable from background noise. The pile-driving noise at 1 kHz would be audible to bottlenose dolphins up to 40 km from the source (Fig. 6a). Harbour porpoises and common seals have higher sensitivities at these frequencies and are limited by the level of background noise rather than their hearing threshold. All three marine mammal species may be capable of hearing the pile-driving sound at the frequency 10 kHz, at which their hearing is more sensitive, until it reached background levels at about 70 km distance (Fig. 6b). At this frequency, the average background noise level was greater than their hearing thresholds and would limit the detection distance.

4. Discussion

As the marine renewables industry develops, our understanding of the noise produced and potential effects on marine species must be improved so that appropriate mitigation procedures can be developed. We measured noise levels produced during pile-driving for two wind turbines and showed that it was detectable above background underwater noise levels for a distance of 70 km. It is possible this sound could have been audible to marine mammals over that entire range. Bottlenose dolphins and minke whales (and other mid- and low-frequency hearing cetaceans) may exhibit behavioural disturbance up to 50 km away. This would include parts of the Moray Firth SAC. The measurements of piling noise indicate that any zones of auditory injury (PTS) and TTS were likely to have been within a range of 100 m of the pile-driving operation, and such impacts should have been prevented by the use of MMOs, who were there to ensure that there were no marine mammals within 1 km of the pile-driving.

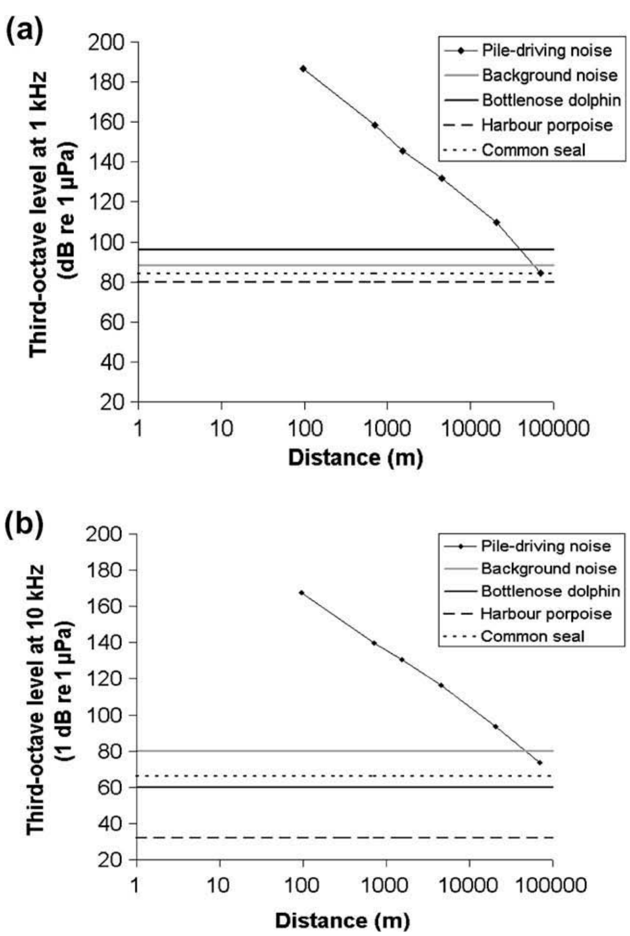

Fig. 6. Third-octave band sound levels for pile-driving at 96 m to 70 km range, the mean third-octave band background noise levels and hearing thresholds for bottlenose dolphins, harbour porpoises and common seals at (a) 1 kHz and (b) 10 kHz.

The potential impact of specific sounds on marine species depends on the level of background noise, but these levels are rarely measured. In the Moray Firth there was spatial variation in both the sound level and frequency characteristics of the background noise. It was generally louder outside than inside the MPA, with the higher frequency sounds in the outer Moray Firth probably resulting from wave noise levels and long range shipping (Richardson et al., 1995). Amoser et al. (2004) found that ships less than 60 m in length elevated the natural background noise by 10–40 dB in a shallow (90 m) lake. Background noise in shallow water is generally subject to wide variations that correspond to the wind and wave conditions (Richardson et al., 1995). Pressure spectrum levels in our study are similar to those found by Knudsen et al. (1948) and Wenz (1962) at sea states 2–3, but considerably higher than those recorded in deeper water. For example, off southern California at a depth of 1106 m, the mean pressure spectrum levels were 65–85 dB re 1 μPa^2/Hz (McDonald et al., 2006). The majority of the background sound we recorded was below 1 kHz.

The source level for pile-driving was estimated both from the whole dataset and a subset of the measurements, within 1 km of the pile-driving. The peak to peak source level calculated from the whole dataset (250 dB re 1 μPa at 1 m) is likely to be a considerable over-estimate of the actual source noise. The measurements close to the pile-driving are likely to give a more appropriate estimate (226 dB re 1 μPa at 1 m) and was similar to that predicted in the Environmental Statement (225 dB re 1 μPa at 1 m) (Talisman, 2005). The highest measured broadband peak to peak sound level was 205 dB re 1 μPa at 100 m from the pile-driving.

Offshore windfarms have never before been installed in water this deep (42 m), and the estimate of transmission loss (geometric spreading loss factor of 20) more closely approximated spherical spreading typical of deeper water (Urick, 1983). Our measurements also showed the importance of absorption in reducing the sound level beyond 10 km from the source. Since studies have generally only made recordings at closer range, this is rarely incorporated in the analysis of pile-driving noise or other loud impact sounds and was not included in the transmission loss model in the original Environmental Statement for this project (Talisman, 2005). The sound propagation model used in our study (Eq. (2)) is the accepted model used in underwater acoustics for describing sound propagation in the field of a noise source (Urick, 1983). Close to the source, in the near field, this model breaks down, and rapid variations in acoustic pressure are often experienced over comparatively short distances. The data presented in Fig. 5a indicates a high level of measurement repeatability at each position and therefore suggests that the effects of varying blow force, substrate characteristics, pile radiating surface area, and seabed and sea surface interactions were minimal.

Seabed topography can have a strong effect on the propagation of sound resulting in different sound levels according to direction from the source. The water depth will affect the degree of interaction of the sound between the seabed and sea surface, and may explain the differences found at the sites along the transect 60 km from the source. For example, there is a sand bank ahead of the recording stations on the eastern side that may have absorbed or reflected some of the sound (Fig. 1a). Since the measurements were not made simultaneously (it took approximately 1 h to record at all of the stations along the transect), it is also possible that the differences were caused by the transmission characteristics varying over time, e.g. due to changes in tidal state. Long-term parallel recordings at multiple sites would be required to account for all of the potential variables that may have influenced the sound level and propagation, but this would present enormous logistic challenges in this offshore environment.

Intentionally precautionary criteria were used to estimate zones of injury and behavioural disturbance. Although dual criteria (SPL and SEL) were considered (Southall et al., 2007), SEL was found to be the most conservative in estimating the zones of PTS and TTS. SPL was used to define the zone of behavioural disturbance as there is very limited information on acoustic exposure and behavioural reactions with which to estimate appropriate SEL criteria (Southall et al., 2007). The disadvantage with using broadband SPL is that it is not frequency weighted. Since the peak energy of the pile-driving sound was predominantly below 2 kHz and this decreased with distance, the actual impact ranges are likely to be much shorter than those predicted (Table 2) for mid- (e.g. bottlenose dolphin) and high-frequency hearing cetaceans (e.g. harbour porpoise). Our definition of behavioural disturbance also included modifications in behaviour that indicated a response, but not necessarily an avoidance reaction to the sound. These distances should therefore be considered maximum estimates for any behavioural response. Given the size of these zones (Table 2), we recommend that studies to investigate noise impacts on marine mammals include observing systems sufficiently distant from the source.

We have shown that pile-driving sound can be detected at ranges of up to 70 km. Comparison of the measured data with the noise exposure criteria indicates that behavioural disturbance may have occurred up to a distance of 50 km for bottlenose dolphins (Table 2). However, the review by Southall et al. (2007) indicated that there was no clear relationship between increasing received noise levels and the severity of the behavioural response for mid-frequency hearing cetaceans exposed to multiple pulses. Other factors, such as the noise duration and behaviour of the animals at the time of exposure, are therefore likely to be involved. Noise may also reduce an animal's ability to detect other sounds by masking (Gordon et al., 2003). David (2006) estimated that pile-driving sound would be capable of masking strong vocalisations by bottlenose dolphins within 10–15 km and weak vocalisations up to 40 km. However, there is currently no empirical information on the extent to which pile-driving or seismic pulses mask biologically significant sounds for marine mammals.

During the construction of a 72 turbine windfarm in the Baltic Sea, a reduction in the detection of harbour porpoise clicks was recorded up to 16 km away, indicating a change in behaviour (Carstensen et al., 2006). This is within the 20 km expected for a strong avoidance reaction from this study (Table 2). Little is known of the hearing or behavioural responses of minke whales, but they are likely to be more sensitive to these low frequency sounds (Nowacek et al., 2007).

The soft start to the pile-driving was a key measure of the developer's Environmental Protection Plan. Our measurements showed that it successfully resulted in the gradual increase of sound pressure, which could potentially have alerted animals before levels became harmful and enabled them to swim away, although no studies have documented this. Additional mitigation measures such as the use of bubble curtains can reduce the radiated sound levels of piling in shallow waters, particularly at 400–6400 Hz (Würsig et al., 2000). Bubble curtain systems were investigated by the developer in our study, but they could not be used because of the complexities of the installation operation in water 42 m deep. However, improvements in enclosed bubble curtains means they may have application for pile-driving in deep water in the future and should be investigated in areas of high cetacean activity.

This study has made detailed physical measurements of pile-driving noise. However, our understanding of marine species' hearing and response thresholds is still relatively poor. Audiograms are based on small sample sizes that make no consideration for variation as a result of differences between individuals, age or sex (Nedwell et al., 2004; Houser and Finneran, 2006). The difficulty of observing and surveying marine species, especially offshore, also makes it difficult to determine responses of free-ranging animals. A better knowledge of these biological processes will greatly improve our understanding of the effects of underwater noise.

The noise levels recorded in this study make it clear that the sound from pile-driving extends over a large area, and any studies making physical or biological measurements should take this into consideration (Madsen et al., 2006). The higher background levels recorded at the turbine site (Fig. 2) are likely to be a result of the presence of the piling vessel and support ships, highlighting the importance of considering all construction phases in terms of their environmental impact. In this study, only two wind turbine bases were installed, but the potential environmental effects may be greater where the construction activity associated with larger windfarms extends over longer periods. We hypothesise that the sound levels for a full-scale windfarm would be similar to those we recorded and would therefore cause injury to marine mammals only within the very close vicinity of the windfarm site (within 100 m). However, the much greater duration of these sounds (over a period of several months rather than several days) could potentially lead to avoidance of the area up to 20 km away by harbour porpoises, the species most likely to be impacted as they frequently use this area near the turbine site (Bailey et al., 2009). Future assessments of the significance of any impacts on harbour porpoises, or on other marine mammals using potential windfarm sites, will require a more detailed understanding of the nature and extent of behavioural responses to anthropogenic noise.

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