From: Vicki James
To: Hornsea Project Three
Subject: Hornsea Three offshore wind farm. Written questions response
Date: 14 January 2019 12:36:52
Attachments: image001.png
image002.png
image003.png
image004.png
image005.png
image006.png
image007.png
image008.png
image009.png
image010.png
WDC_Hornsea3_PINs_ResponseWrittenQuestions_Jan2019.pdf
Written question papers requested from WDC.zip

Dear Sir/ Madam,

Please find attached WDCs response to the Examining Authority's (ExA's) Further Written Questions and Requests for Information, issued 19th December, for Hornsea Three offshore wind farm.

Also attached are the papers requested as part of the questions.

Please don't hesitate to contact me if you have any queries.

Best wishes

Vicki

Vicki James
Policy officer

Telephone: +44 (0)1249 449 500

WDC, Whale and Dolphin Conservation
Brookfield House
38 St Paul Street
Chippenham
Wiltshire
SN15 1LJ
United Kingdom
whales.org

WDC WHALE AND DOLPHIN CONSERVATION

30 YEARS OF PROTECTING WHALES AND DOLPHINS

Registered with FUNDRAISING REGULATOR

Business Charity Awards 2018 Shortlist

Help us save New Zealand dolphins from extinction

Vol. 421: 205–216, 2011
doi: 10.3354/meps08888

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published January 17

Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea

Miriam J. Brandt[1,*], Ansgar Diederichs[1], Klaus Betke[2], Georg Nehls[1]

[1]BioConsult SH, Brinckmannstrasse 31, 25813 Husum, Germany
[2]Institut für technische und angewandte Physik GmbH, Marie-Curie-Strasse 8, 26129 Oldenburg, Germany

ABSTRACT: Pile driving during offshore windfarm construction goes along with considerable noise emissions that potentially harm marine mammals in the vicinity and may cause large scale disturbances. Information on the scale of such disturbances is limited. Therefore, assessment and evaluation of the effects of offshore construction on marine mammals is difficult. During summer 2008, 91 monopile foundations were driven into the seabed during construction of the offshore wind farm Horns Rev II in the Danish North Sea. We investigated the spatial and temporal scale of behavioural responses of harbour porpoises *Phocoena phocoena* to construction noise using passive acoustic monitoring devices (T-PODs) deployed in a gradient sampling design. Porpoise acoustic activity was reduced by 100% during 1 h after pile driving and stayed below normal levels for 24 to 72 h at a distance of 2.6 km from the construction site. This period gradually decreased with increasing distance. A negative effect was detectable out to a mean distance of 17.8 km. At 22 km it was no longer apparent, instead, porpoise activity temporarily increased. Out to a distance of 4.7 km, the recovery time was longer than most pauses between pile driving events. Consequently, porpoise activity and possibly abundance were reduced over the entire 5 mo construction period. The behavioural response of harbour porpoises to pile driving lasted much longer than previously reported. This information should be considered when planning future wind farm construction.

KEY WORDS: *Phocoena phocoena* · Offshore windfarm · Acoustic monitoring · Behaviour · Porpoise detectors · Construction noise · Marine mammals · Acoustic activity

INTRODUCTION

It is of vital interest for science and nature conservation to understand the ecological consequences of human use of marine habitats. Virtually all human activities at sea lead to the generation of underwater noise, which may propagate over large distances. It is well documented that noise levels in the world's oceans are increasing with expanding human activities (Andrew et al. 2002, McDonald et al. 2006). High noise levels are of special concern for cetaceans, which depend on sound as the most important source of information about their environment (Richardson et al. 1995, Nowacek et al. 2007, Southall et al. 2007, Weilgart 2007, Tyack, 2008). A growing demand for sustainable and 'environmentally friendly' energy has led a growing number of countries to explore options for the installation of offshore wind farms. However, such developments may have at least temporary negative effects on the surrounding marine environment. In particular, noise emissions during the construction phase, when steel foundations may be driven into the sea floor, can cause temporary avoidance of the area by marine mammals and at close range have the potential to inflict physical damage to their sensory system (Madsen et al. 2006, Thomsen et al. 2006, Southall et al. 2007).

---

*Email: m.brandt@bioconsult-sh.de

In the North Sea, the harbour porpoise *Phocoena phocoena* is the most abundant marine mammal and is found in all coastal and offshore waters (Reid et al. 2003). The species is listed in Annexes II and IV of the EU Habitats Directive, and deliberate killing or significant disturbance of individuals are prohibited. However, given the wide distribution of harbour porpoises in this region and the numerous wind farms, both planned and in place, it is inevitable that such developments will affect harbour porpoise habitat to some extent. In order to assess the effects of offshore windfarms on harbour porpoises, knowledge of the behaviour of the species in relation to noise levels created by offshore pile driving is essential. The main aim of this study was to describe the temporal and spatial extent of disturbance and thereby assess the spatial and temporal scale at which habitat exclusion occurs.

To our knowledge, the only published studies addressing behavioural reactions of harbour porpoises to pile driving so far were carried out by Carstensen et al. (2006), Tougaard et al. (2009) and Thompson et al. (2010). All studies used static acoustic monitoring devices (T-PODs), which allow continuous recordings of harbour porpoise echolocation activities and were deployed according to a Before After Control Impact (BACI) design aimed primarily at comparing porpoise activity during the construction period to a pre-construction and/or post-construction period. Tougaard et al. (2009) studied harbour porpoise responses to pile driving during construction of the Offshore Windfarm Horns Rev I in the Danish North Sea. This study described a clear effect of pile driving on the acoustic activity of harbour porpoises up to a distance of 20 km, with the mean time between 2 consecutive porpoise acoustic encounters (all porpoise recordings being separated by <10 min) increasing from 5.9 h to 7.5 h after pile driving. However, when comparing the affected area with a reference area, no difference in the duration of this effect was detectable. The range of the effect could therefore not be determined and the very short duration of the measured effect apparently contradicts the great distance over which it occurred. Carstensen et al. (2006) studied harbour porpoise responses during construction of the Nysted offshore windfarm in the Danish Baltic Sea. They found a longer effect, with times between porpoise encounters increasing from the normal 10–20 h to 35–50 h after construction near the windfarm, whilst a somewhat smaller effect was found in an area at a distance of about 15 km. More recently, Thompson et al. (2010) published a study assessing the effects on cetaceans during construction of 2 wind turbines off northeast Scotland. While they found some evidence that the time between consecutive porpoise detections was longer after pile driving than randomly expected in the affected area, small sample size and high variability between areas did not allow firm conclusions or statements about the duration or scale of the effect. They concluded that while passive acoustic monitoring is a useful method to assess such effects from offshore construction work on cetaceans, a gradient sampling design would offer a more promising approach than a BACI design. Here we present such a study, using a gradient sampling design where T-PODs were deployed along a transect line reaching from the pile driving site to a maximum distance of 22 km in the Danish North Sea. This design was adopted to specifically test the spatial and temporal scale of the effects of windfarm construction on harbour porpoises.

The area west of Jutland and Sylt has been identified as a location with high porpoise numbers especially during the summer months (Hammond 2006, Gilles et al. 2009). It might therefore be of high importance for harbour porpoises as a breeding and nursery ground. The offshore windfarm Horns Rev II, the largest offshore construction of its time, was constructed within this area in relatively shallow waters (Fig. 1), at a time of year when porpoise numbers are expected to be especially high. This provided us with the opportunity to test how pile driving in particular affects harbour porpoises in a high density area.

MATERIALS AND METHODS

Study area. The offshore windfarm Horns Rev II was erected north-west of the reef Horns Rev, which extends from the westernmost point of the Danish west coast at Blåvands Huk out ~40 km to the west. The reef consists of an inner and outer reef separated by the Slugen Channel (Fig. 1). The windfarm, consisting of a transformer platform and 92 2.3 MW wind turbines arranged in 7 rows in a semicircular formation, is located at the northwestern part of the reef, ~35 km west of Blåvands Huk (Fig. 1). It covers an area of ~35 km^2 with a water depth between 4 and 14 m. The top seabed layer in the windfarm area consists of predominantly medium-coarse grained sand without macrophytes.

Wind turbines were erected between 19 May and 9 October 2008 on monopile foundations. The piles had a diameter of 3.9 m, were 30 to 40 m long, had a wall thickness of 25 to 88 mm, weighed 170 to 210 t, and were driven into the seabed to depths of 20 to 25 m. The construction was performed with the aid of the jack-up barge 'Sea Jack' (A2SEA). An IHC S-1200 hydraulic hammer (IHC Hydrohammer) was used for all monopiles. The maximum applied blow energy was ~900 kJ per strike. A short ramp-up procedure with a duration of about 5 min was observed

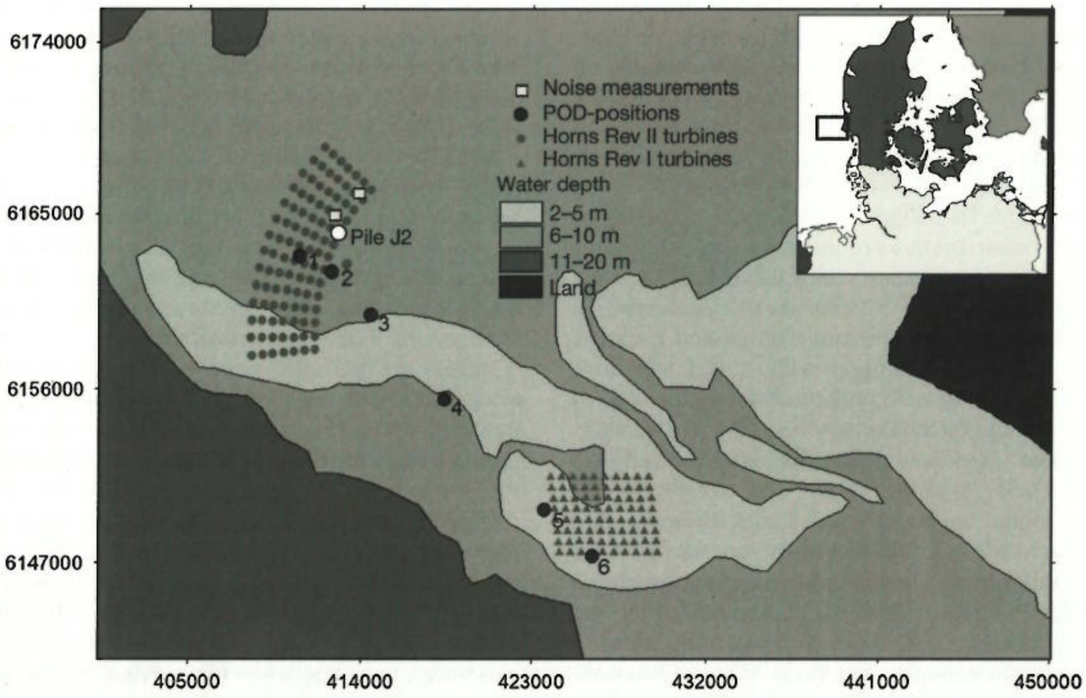


Fig. 1. Study area. Positions of the wind turbines of the windfarm Horns Rev II, where pile driving took place during this study (•), and the windfarm Horns Rev I (▲) that was already installed. ● 1 to 6 = positions of the T-PODs. □ = positions where noise measurements were conducted during pile driving of monopile J2 (○). Grid reference system is UTM 32 N

during noise measurements. Over this period, the blow rate was slowly increased from about 1 blow min^{-1} to 1 blow s^{-1}. No particular plan for ramp-up procedures existed.

Noise measurements. Noise measurements were conducted on 7 September 2008 at 2 measurement points, during installation of 1 monopile (J2). An autonomous recording buoy was deployed at 720 m distance from the pile with a hydrophone 1.5 m above the sea floor. Water depth at this position was 10 to 12 m. The system was fitted with an ITC-1001 hydrophone (International Transducer Corp.) with a recorder PMD 670 (Marantz). Recording bandwidth was 15 Hz to 20 kHz. Manual recordings were made aboard a ship at 2300 m distance from the pile using a 8105 hydrophone (Brüel & Kjær) and a HD-P2 recorder (Tascam). The bandwidth of this system was 10 to 40 kHz. The hydrophone was deployed 7 to 8 m below the sea surface. At both positions, the noise was recorded in uncompressed 16 bit wave file format. These data were later evaluated with MATLAB programs. Peak level L_{peak}, equivalent continuous sound level L_{eq} and average single-stroke sound exposure levels (SEL) were computed for the whole pile driving operation in consecutive intervals of 30 s. The peak level was derived directly from the recorded time series as follows:

$$L_{peak} = 20 \log (|p_{peak}| / p_0) \quad (1)$$

where p_{peak} is the highest positive or negative observed sound pressure in the observation interval and p_0 is the reference sound pressure, which is 1 µPa. L_{eq} and SEL were computed from one-third octave spectral analyses based on Fast Fourier Transform (FFT). A single FFT with rectangular window was performed on each whole interval. FFT length was the next highest power of 2, with reference to the number of data points, and the rest of the FFT field was filled up with zeros. For a sampling frequency of e.g. 44.1 kHz, as used in the recording buoy, the number of FFT points was thus 2 097 152. The amplitude correction for this procedure (0 to 3 dB) was applied after conversion of the FFT result to the power domain. One-third octave spectrum was then computed by summing the FFT spectral lines for each one-third octave band. Hence each of these spectra represented the L_{eq} for the particular 30 s interval. The SEL was computed from the L_{eq} according to

$$\text{SEL} = L_{eq} - 10 \log (n\, T_0/T) \quad (2)$$

where n is the number of pile driver blows within the observation interval T = 30 s, and T_0 = 1 s.

M-weighted cumulative SELs were computed following Southall et al. (2007). Frequency weighting is a sound engineering method for deriving a single-number level value that accounts for the frequency-dependent sensitivity of the auditory system. For high-frequency cetaceans, Southall et al. (2007) suggest an M-weighting curve with corner frequencies of 200 Hz and 180 kHz. Below and above these frequencies, the curve declines by 40 dB per decade whereas it is flat (i.e. no weighting) at the center frequencies.

POD settings. The responses of harbour porpoises to wind farm construction were monitored by continuous registration of echolocation clicks using T-PODs (version 4, Chelonia). A T-POD consists of a hydrophone, an amplifier, analogue electronic filters and a digital memory. They are equipped with a 128 MB non-volatile memory (up to 30 million clicks can be stored) and are powered by 2 bundles of six 1.5 V D-cell alkaline batteries. The filter settings can be set to a range of different click durations, centre and reference frequencies, signal bandwidths and signal strengths, that are characteristic for harbour porpoise echolocation clicks, in order to distinguish them from boat sonar and other sources. The T-POD is accompanied by the software package T-POD.exe (v.7.41), that uses an algorithm (train detection algorithm V3.0) to discriminate cetacean trains from other sources (for details see Verfuß et al. 2008, Bailey et al. 2010, Simon et al. 2010). We chose the following POD-settings: (1) target filter A: 130 kHz, (2) reference filter B: 90 kHz, (3) click bandwidth: 5, (4) noise adaptation switched on, and (5) scan limit for N of clicks logged: 240. The sensitivity of T-PODs has been found to differ (Dähne et al. 2006, Verfuß et al. 2007). Therefore absolute sensitivities of individual T-PODs were measured in a laboratory environment in the German Oceanographic Museum in Stralsund, Germany. During this test tank calibration, the detection threshold of each T-POD was measured and the POD-specific sensitivity, selected in order to achieve a peak to peak detection threshold of 130 dB re 1 µPa, was determined (for details see Verfuß et al. 2007). This POD-specific value was then used as the setting for T-PODs deployed in the field. The software sorts clicks into different train classifications. We only used the 2 with the highest probability of being actual harbour porpoise clicks ('CetHi' and 'CetLo'; Thomsen et al. 2005).

POD deployment. A total of 8 T-PODs were deployed at 6 positions along a transect line extending from inside the area where Horns Rev II was built (Position 1), across the reef and into the area where the windfarm Horns Rev I is located, south of the reef (Position 6) (Fig. 1, Table 1). The exact detection range of a T-POD is not accurately known. However, for version 3 T-PODs, a maximum detection distance of between 200 and 300 m has been described for harbour porpoises (Tougaard et al. 2006). In order to avoid detection of the same porpoise clicks at 2 neighbouring T-POD positions during the same minute, the positions were set with a distance of 1.5 to 8 km between them. The distance from the POD positions to individual wind turbines ranged from 0.5 to 25 km. Water depth at the T-POD positions was between 9 and 18 m.

T-PODs were placed in the water column ~1 m above the sea bottom. Each POD position was marked by an inflatable yellow buoy directly next to it and by an official yellow warning buoy at a distance of 100 to 150 m. The inflatable buoy was attached to an anchor block, which was connected to a second anchor block, to which the T-POD was attached.

During the period 8 April to 7 September 2008, a total of 728 POD-days (no. of PODs deployed × days of deployment) were achieved. During the baseline period 8 April to 18 May 2008 before pile driving activities started, no data were recorded at Position 4 due to equipment loss. At all other locations, at least 17 d of recording were achieved during the baseline period. Some further data gaps occurred due to equipment loss or damage (Fig. 2). Pile driving activities took place between 19 May and 14 October 2008. There was only 1 pause between pile driving events that was >4 d (Fig. 2), and on several occasions 2 pile driving events occurred during a single day. A pile driving event lasted on average 46 ± 14 min and the median time between them was 16 h (range: 10–309 h). During 62 pile driving events that took place between 19 May and 07 October 2008, POD data could be recorded at 3 or more POD positions during each pile driving event (Fig. 2).

To keep the animals out of the radius where physical damage from pile driving noise might occur, a seal scarer (Lofitech) and a pinger (Aquamark 100) were deployed at the construction site on average 163 ± 88 min (0–461 min) before pile driving started, and were recovered 47 ± 46 min (0–279 min) after pile driving finished. Pingers have been found to deter harbour porpoises to distances of 100 to 200 m (Kraus 1999, Barlow & Cameron 2003, Kastelein et al. 2006). The effects of the seal scarer on harbour porpoises are not well known. However, Olesiuk et al. (2002)

Table 1. Distances of POD positions (see Fig. 1) and duration of the effect on porpoise activity as found from GAM analyses. PPM/h: porpoise positive minutes per hour

POD position	Mean distance (km)	Duration of pile driving effect on PPM/h (h)
1	2.5	24 – 72
2	3.2	18 – 40
3	4.8	17 – 42
4	10.1	9 – 21
5	17.8	10 – 23
6	21.2	0

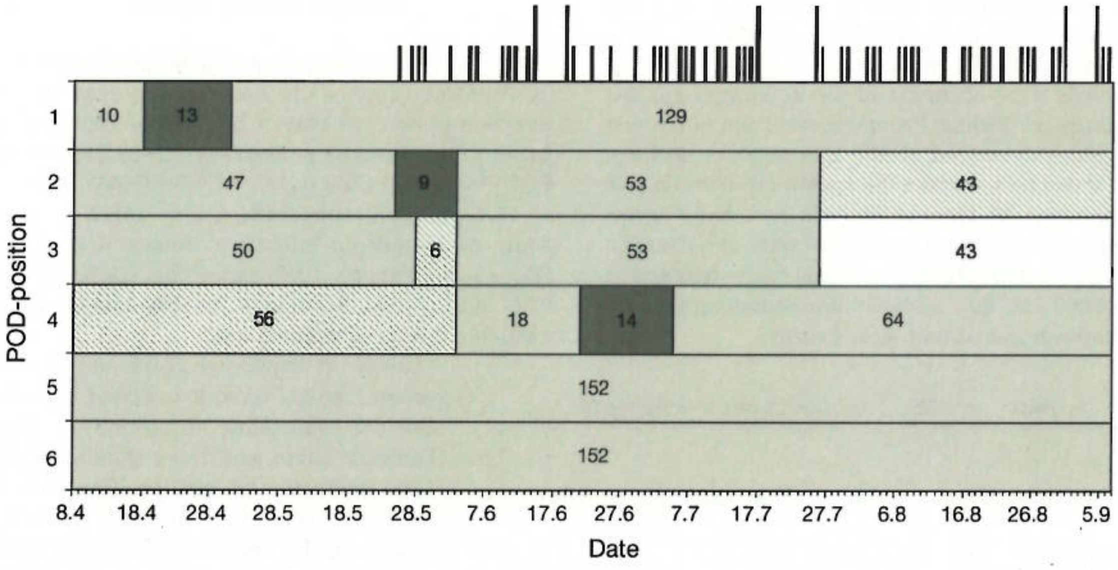


Fig. 2. Periods of T-POD deployment at the different positions (see Fig. 1). Dates given as dd.mm. Light grey bars: T-POD recorded data. Grey hatched bars: T-POD deployed but lost. Dark grey bars: T-POD deployed but did not function. White bar: no T-POD deployed. Numbers in the bars denote number of days in that period. Narrow black bars on the top of the graph show pile driving events, short bars = 1 event, long bars = 2 events during the same day

observed avoidance reactions by porpoises to the Airmar seal scarer, up to a distance of 2.5 to 3.5 km and Johnston (2002) reported a mean closest approach distance of 991 m during seal scarer activity compared to 364 m during seal scarer inactivity.

Data analysis. To determine how porpoise activity changed with respect to time after pile driving, we analysed the parameter 'porpoise positive minutes per hour' (PPM/h). This describes the number of minutes during an hour where at least 1 harbour porpoise click was recorded and can thus range from 0 to 60. Statistical analysis was conducted using the software 'R', version 2.8.1 (www.r-project.org/).

To investigate whether there was a difference in PPM per day between the baseline period from 8 Apr to 18 May 2008 before pile driving started and the pile driving period (19 May–7 Sept 2008), we calculated a non-parametric Mann-Whitney *U*-test for each POD position and applied Bonferroni correction on significant p-values to account for multiple tests on the same dataset. Only hours that were fully covered were included in the analysis.

To test for short-term effects and to determine the duration of an effect, we then proceeded by application of a Generalised Additive Model (GAM), allowing for a non-linear effect of pile driving on PPM/h, including only data from the construction period. PPM/h was chosen as the response variable and the interactions between Hour after pile driving (Hpd) and POD position, Distance to pile driving (Dpd, in km) and Time of day (Time) were chosen as non linear predictor variables, using standard settings for the number of knots specified. We also included Month as a factor. Because the interaction of Hpd with POD position was significant, and because we were interested to see how the duration of an effect differed with distance, we then recalculated the same model separately for each of the 6 different POD positions (PPM as response variable, Hpd, Dpd and Time as non-linear predictor variables and Month as a factor). Using the curve that the GAM fitted to the relationship between PPM/h and Hpd, we then defined the range between the point where PPM/h reached the overall average and where it reached the first local maximum after the initial increase. This time span we report as the possible duration of the effect of pile driving on harbour porpoise behaviour.

RESULTS

Noise measurements

During construction of monopile J2, when noise measurements were conducted, 449 blows were necessary to reach the final penetration of 21 m according to the pile driver record file. The time from the first to the last blow was 30 min (04:53:30–05:23:19). At 720 m distance, during 1 pile driving event, the peak level reached 196 dB re 1 µPa, the SEL level reached a maximum of 176 dB re 1 μPa^2 s and the M-weighted SEL (see Southall et al. 2007) reached 170 dB re 1 μPa^2 s

(Fig. 3). At a distance of 2300 m to pile driving, peak levels reached 184 dB re 1 µPa, SEL 164 dB re 1 µPa^2 s and M-weighted SEL reached 157 dB re 1 µPa^2 s. These levels were observed at the maximum applied blow energy of ~850 kJ. From the spectrum of the pile driving noise measured at 720 and 2300 m distance (Fig. 4), it can be seen that the spectral maximum was found between 80 Hz and 200 Hz and noise levels decreased at the higher frequencies until at a distance of 2300 m, background noise levels were reached at about 40 000 Hz. Fig. 5 shows the broadband sound level relative to pile driver blow energy.

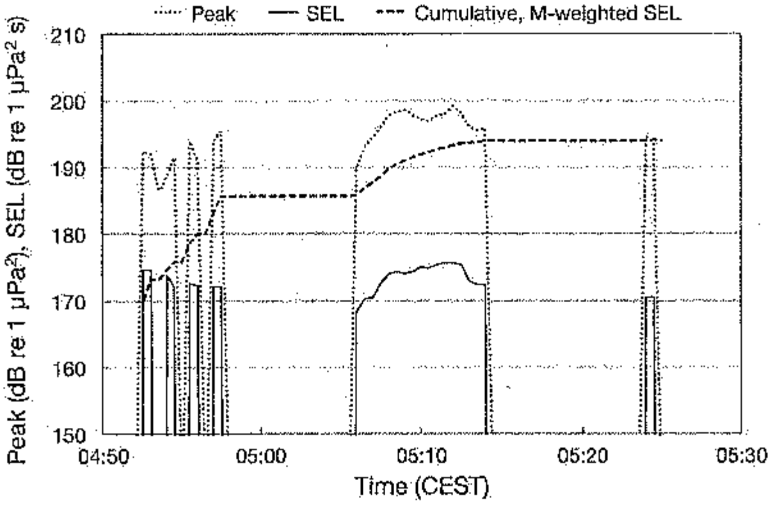


Fig. 3. Peak level and single-stroke sound exposure level (SEL) for the whole pile driving operation measured at 720 m distance. Also shown is the M-weighted cumulative SEL (the M weighting function for 'HF cetaceans' was used; Southall et al. 2007). The difference between the non-cumulative unweighted and M-weighted SEL varied from −4 to 7 dB

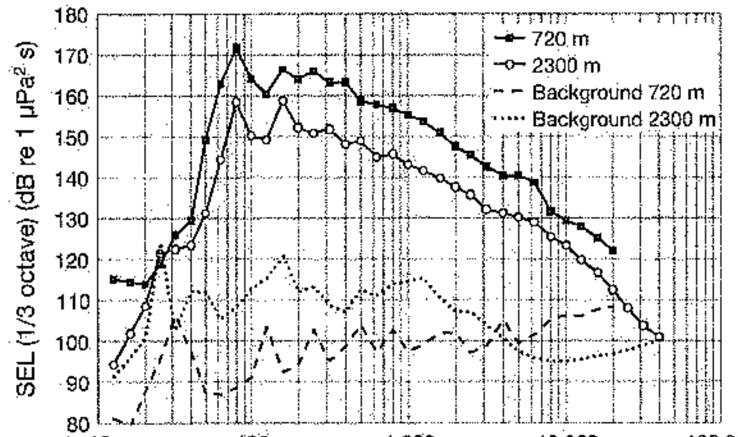


Fig. 4. Spectra of pile driving noise at the 2 measurement locations (see Fig. 1), averaged from 24, 850 kJ blows. SEL: single-stroke sound exposure level

Porpoise activity (PPM/h)

As revealed by non-parametric tests, porpoise activity (PPM/h) significantly decreased during the construction period (19 May–7 September 2008) as compared to the baseline period (8 April–18 May 2008) at POD-Positions 1 ($Z_{637,2555} = -7.47$, $p < 0.001$), 2 ($Z_{949,1355} = -11.10$, $p < 0.001$) and 3 ($Z_{973,1427} = -14.42$, $p < 0.001$), while no significant effect was found at Positions 5 ($Z_{949,2579} = -0.45$, $p = 0.66$) and 6 ($Z_{925,2580} = -0.87$, $p = 0.38$) (Fig. 6). At Position 4, no baseline data were available due to equipment loss.

The GAM explained 27.9% of the overall variance in the data. It revealed significant effects of Dpd, Time and Month on PPM/h (Table 2). There was also a significant effect of the interaction of POD position with Hpd on PPM/h (Table 2). Therefore we split the analysis up for the different POD positions and again tested for the influence of Hpd on PPM/h for each position separately while controlling for Dpd and Time and Month. Hpd, Dpd and Month had a significant effect on PPM/h at all positions, while Time only had a significant effect at some positions (Table 3). Explanatory power of the model decreased at POD positions further from the pile driving site (Table 3). The curve on the relationship between PPM/h and hour after pile driving (the parameter of main interest) that the GAM fitted to the data was of different shapes at the different POD positions. In Fig. 7, the deviation of PPM/h from the overall mean (calculated over all available hours at a given position) and how this changes with hours after pile driving can be seen for the different positions. At Position 1, PPM/h steadily increased after the pile driving event. PPM/h was substantially below the overall mean up to 24 h after pile driving. However, PPM/h continued to increase with a narrow confidence interval until reaching the first local maximum at 72 h after pile driving. At Positions 2 and 3, the pattern is similar: PPM/h steeply increased after pile driving. The overall mean was reached at 18 h (Position 2) and at 17 h (Position 3) after pile driving. At 40 h (Position 2) and 42 hours (Position 3) after pile driving, PPM/h reached the first local maximum and then fluctuated widely around the mean. At Positions 4 and 5, PPM/h increased more steeply and at 9 h (Position 4) and 10 h (Position 5) after pile driving, the overall average was reached

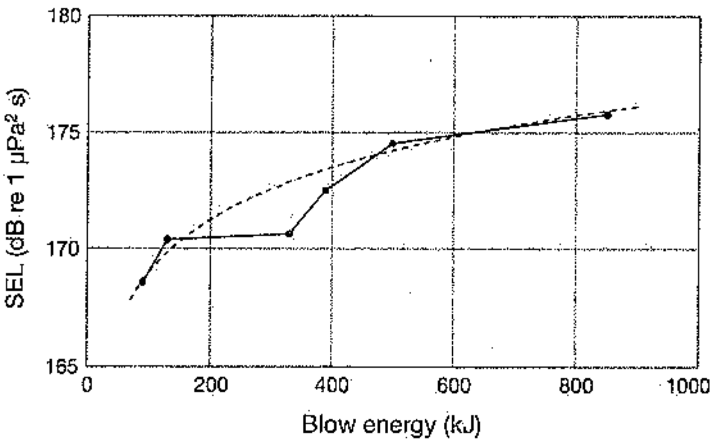


Fig. 5. Broadband sound level as a function of pile driver blow energy, observed at 720 m distance. The formula of the fitted dashed curve is SEL = 7.5 log(E) + 154. Each point represents the energetic average from between 10 and 26 blows, depending on the energy level. SEL: single-stroke sound exposure level

substantially sooner. This increase in PPM/h also levelled off sooner at these positions (21 h at Position 4 and 23 h at Position 5). At Position 6, the shape of the curve differed: PPM/h was higher than the overall mean, up to about 35 h after pile driving, while decreasing and fluctuating around the overall mean afterwards. At all POD-positions the confidence intervals for PPM/h widened substantially when more time after pile driving elapsed. This was due to a decreasing sample size as in most cases the time between pile driving events was less than 50 h. Thus, predictive power for the later periods decreased. The range of the duration of the effect of pile driving on harbour porpoises, together with the predicted sound exposure levels at the different POD positions, are given in Table 1. During the first hour after pile driving, mean porpoise activity was 0 at Positions 1 to 3, while at Positions 4 and 5 there was a reduction in porpoise activity of between 32% and 49% relative to the overall mean PPM/h value and mean PPM/h more than 70 h after pile driving (Table 4). At Position 6 (at a distance of 22 km), PPM/h decreased by 2% compared to the overall mean, but increased by 31% relative to PPM/h more than 70 h after pile driving (Table 4).

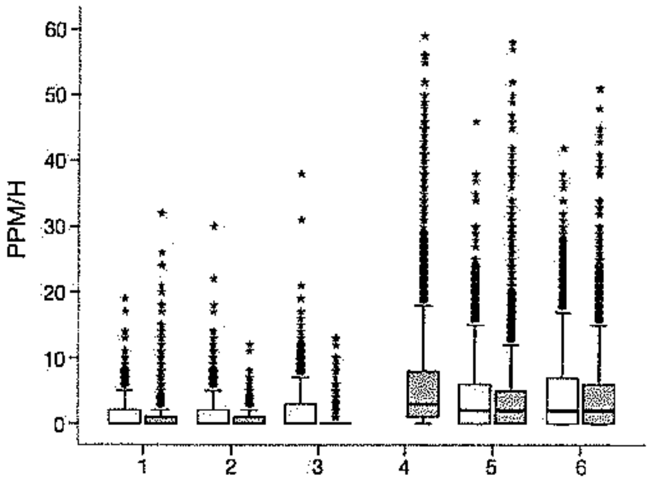


Fig. 6. Porpoise positive minutes per hour (PPM/h) during the baseline period (08 Apr–18 May 08, light bars) and the construction period (19 May–07 Sep 08, dark bars) by POD position. Dark band: mean; box: 25% quartiles; whiskers: 25% quartiles minus outliers and extremes; blobs: outliers, defined as values which are between 1.5 and 3 box lengths from either end of the box; asterisks: extremes, defined as values that are more than 3 box lengths from either end of the box

DISCUSSION

We found a clear negative effect of pile driving during wind farm construction on porpoise acoustic activity that was detectable out to a distance of 17.8 km. At the closest distance studied (2.5 km), porpoise activity was reduced between 24 to 72 h after pile driving activity, and the duration of this effect gradually declined with distance. At the furthest distance studied (21.2 km), we no longer found a negative effect of pile driving on porpoise activity; instead, activity was higher than the overall average for about 30 h after pile driving. This might indicate that porpoises at this distance showed no behavioural reaction to pile driving. Animals moving away from the construction site might have caused porpoise abundance and thus porpoise acoustic activity to temporarily increase as animals aggregated there. The lower limit we report for the duration of the effect was based on the time when porpoise activity reached the overall average. However,

Table 2. Results from the GAM on the effects of 4 independent variables on porpoise activity (porpoise positive minutes per hour, PPM/h). F-values and estimated degrees of freedom (edf) are given; the p-value of the main effect to be tested is indicated in **bold**. The model explained 27.9% of the overall variance in the data

Independent variable	F	edf	p
Hour after pile driving × POD position	13.5	28.0	**< 0.0001**
Distance	195.1	8.9	< 0.0001
Time of day	6.9	8.4	< 0.0001
Month	41.3	4	< 0.0001

Table 3. Results from the GAM on the effects of Hours after pile driving (Hpd), Distance to pile driving (Dpd), Time of day and Month on porpoise activity (porpoise positive minutes per hour, PPM/h). The *F* values for all 4 parameters are given, with significance values indicated as follows: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, ns: $p > 0.05$

POD position	Mean Dpd (km)	*F* Hpd	 Dpd	 Time	 Month	Variance explained (%)
1	2.6	56.2***	10.4***	2.3*	39.2***	24.7
2	3.2	15.9***	4.5***	0.8 ns	12.0***	15.0
3	4.8	15.8***	4.9***	0.4 ns	7.7***	13.5
4	10.1	4.6***	12.8***	3.2**	40.6***	18.8
5	17.8	7.2***	5.1***	5.1***	42.2***	14.2
6	21.7	5.7***	4.3***	9.3***	26.7***	9.6

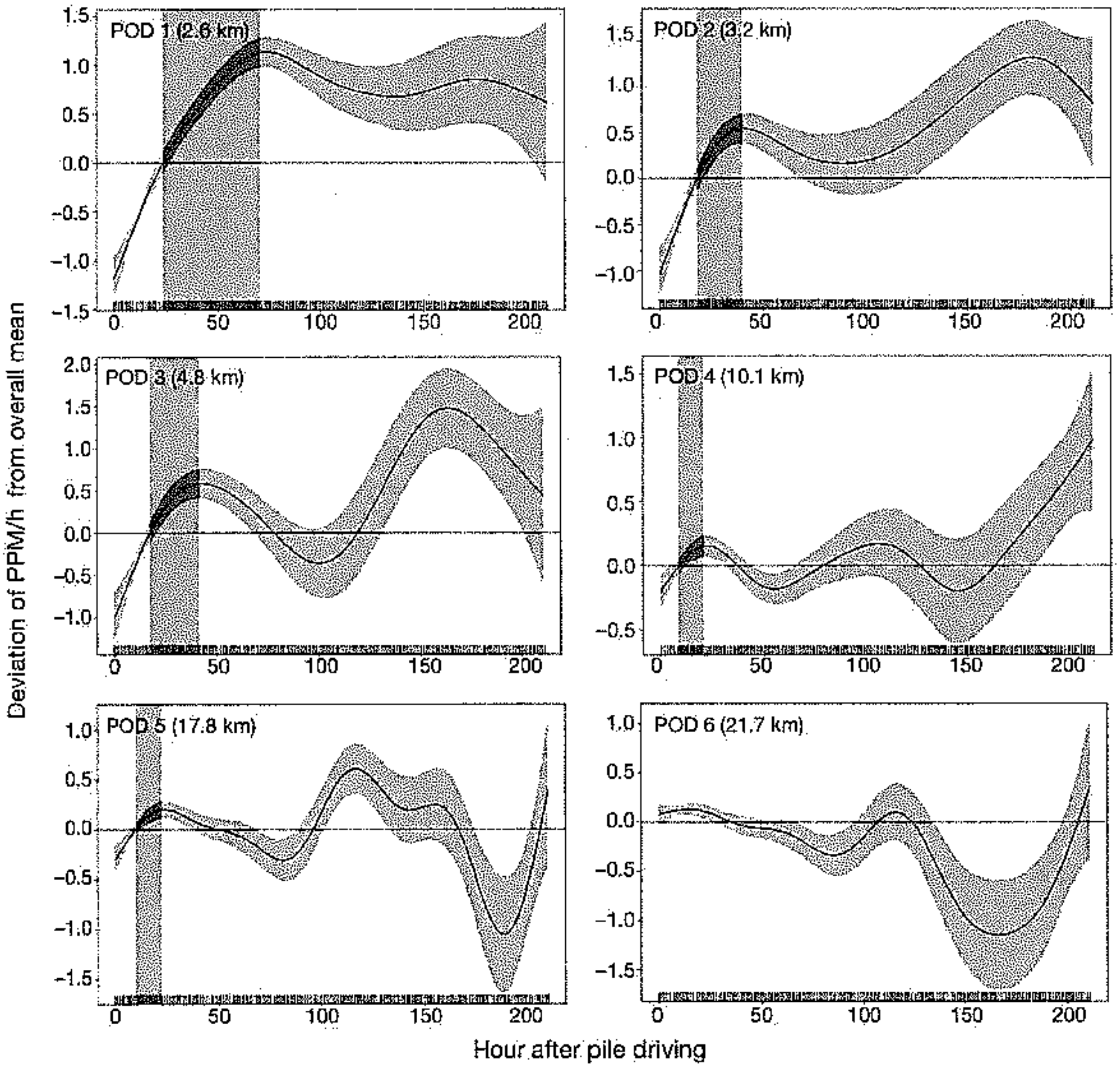


Fig. 7. Relationship between porpoise positive minutes per hour (PPM/h) and Hour after pile driving (Hpd) as fitted by the GAM. The graphs show the deviance of PPM/h from the overall mean (depicted as the horizontal line) by Hpd at each of the 6 POD positions. Grey shaded areas represent 95 % confidence intervals. Grey shaded vertical boxes indicate the area that is reported as the range of the possible duration of the effect

Table 4. Mean porpoise activity (porpoise positive minutes per hour, PPM/h) in the first hour after pile driving (Hpd), overall means and means for all hours >70 Hpd, for each POD position. Sample sizes are given in brackets. The change in PPM/h during the hour after pile driving relative to the other 2 means is also shown

POD position	Mean PPM/h			Change (%)
	1 Hpd	Overall	>70 Hpd	
1	0.0 (70)	0.9 (3192)	1.8 (356)	−100
2	0.0 (36)	1.0 (2304)	1.0 (207)	−100
3	0.0 (37)	1.1 (2400)	0.6 (232)	−100
4	3.9 (51)	6.2 (1896)	5.7 (328)	−32 to −37
5	2.9 (70)	4.3 (3528)	5.7 (356)	−33 to −49
6	4.6 (54)	4.7 (3505)	3.5 (356)	−2 to +31

the overall average includes data that are influenced by pile driving, so it cannot be seen as a 'normal' baseline value for the construction period, especially where the effects of pile driving were long lasting. As it was not possible to determine an exact baseline (due to the short time interval between pile driving events), we chose to report a range of effect duration based on mean and first maximum activity levels as the best available estimate of baseline activity during the construction period. Due to the biased average, however, the reported upper limit of the effect duration is more likely than the lower limit. It becomes clear from increasing confidence intervals in the graphs that with more time elapsing after pile driving, predictive power of the GAM decreases. This is caused by a substantial decrease in sample size, as only a few pile driving events were >50 h apart.

Another additional factor that may contribute to a comparably long-lasting effect in the immediate vicinity to the pile driving location could be increased shipping activity that continues for some time after pile driving is finished. However, this noise is unlikely to have caused effects at distances of up to 18 km. A further confounding factor is that porpoise behaviour may have changed due to the deployment of the scaring devices. Considering the scale of the observed effect, this seems unlikely. Pingers have been found to deter harbour porpoises to distances of only 100 to 200 m (Kraus 1999, Barlow & Cameron 2003, Kastelein et al. 2006). Seal scarers on the other hand were found to deter porpoises up to a distance of between 1 and 3.5 km (Olesiuk et al. 2002, Johnston 2002). The source level of the Lofitech seal scarer as reported by the manufactures is 189 dB re 1 µPa peak whereas pile driving is considerably louder. However, the main energy of the seal scarer signal is at higher frequencies (about 14 kHz) than that of pile driving. Porpoises may be more sensitive to noise at those higher frequencies because their hearing threshold at 14 kHz is at least 40 dB lower than at 500 Hz (Kastelein et al. 2002). However, during measurements at another construction site in the North Sea, where the same seal scarer model was used, the signal from the seal scarer was not found to be louder than that of pile driving at 14 kHz (Betke & Matuschek 2010). An effect of the seal scarer on porpoise activity would thus not be expected to reach as far as 18 km. Nevertheless, porpoise responses to pile driving, especially at close distances, are confounded by the use of scaring devices. However, as pile driving during windfarm construction in European waters always involves the deployment of pingers and seal scarers, the inability to differentiate these effects does not compromise conclusions about the effects of windfarm construction on harbour porpoises in Europe.

The median time between succeeding pile driving events was 16 h, during which porpoise activity did not fully recover at a distance up to about 4.8 km, as the effect of pile driving on PPM/h lasted longer than 16 h at that distance. Consequently, porpoise activity close to the pile driving site was lower than expected during the whole 5 mo of the construction period. This is indicated by a significantly lower mean value for PPM/h during the construction period as compared to PPM/h values recorded in the baseline period up to a distance of 4.8 km (POD position 3); while at greater distances the difference between baseline and construction period is less apparent due to a much shorter-lasting effect of pile driving on PPM/h.

The spatial scale of porpoise responses that we found are in line with the 20 km range that has been previously suggested (Tougaard et al. 2009, Thompson et al. 2010). However, using a gradient sampling design this study is the first to demonstrate at what distance pile driving noise no longer negatively affected porpoise activity. Furthermore, in the vicinity of the construction site, the effect demonstrated during this study lasted considerably longer than has been previously described by Carstensen et al. (2006) at Nystedt and by Tougaard et al. (2009) at Horns Rev I. Pile diameter at Horns Rev I (4 m) and thus probably source levels during pile driving were almost identical to this study at Horns Rev II, and therefore this discrepancy is surprising. However, these studies are not directly comparable because Carstensen et al. (2006), Tougaard et al. (2009) and Thompson et al. (2010) analysed the duration of waiting times between 2 consecutive porpoise encounters while we analysed PPM/h. In cases where baseline data from previous years are not available (as during this study) we find PPM/h to be a better parameter to analyse how porpoise activity is affected by pile driving, because it allows the tracking of the post-pile driving increase in porpoise activity on a fine temporal scale. T-PODs during studies by Carstensen et al. (2006), Tougaard et al. (2009) and Thompson et al. (2010) were deployed according to a BACI design, whereas we used a gradient sampling design that better enables one to detect how temporal effects differ with distance.

The PPM/h variable provides relative indices of porpoise activity but cannot at present be directly translated into porpoise density. However, previous studies have found these parameters to correlate broadly with porpoise densities obtained from porpoise sightings (Tougaard et al. 2006, Siebert & Rye 2008). So porpoise acoustic activity seems to be linked to some extent to relative changes in porpoise densities although behavioural parameters may well play a vital role here also. Considering a maximum swimming speed in harbour porpoises of about 4.3 m s^{-1}, it is surprising that we found an instant effect of pile driving on porpoise acoustic activity at distances of 18 km, and the same applies to results by Tougaard et al. (2009). If a decrease in acoustic activity reflected animals moving out of the affected area, one would assume a delayed decrease at greater distances because animals leaving the near vicinity have to pass PODs at greater distances. It might be argued that declining acoustic activity in the area does not reflect a decrease in density but simply a change in the animals' behaviour such that porpoises remain silent after pile driving and use their sonar less frequently. Studies on other cetacean species such as pilot whales, sperm whales and Cuvier's beaked whales indeed have documented such a response to other noise exposures (for review, see Weilgart 2007). Mostly, whales remained silent or reduced vocalising activity during noise exposure but resumed normal activity shortly after the noise stopped. Conversely, some studies have described an increase in vocalisation by pilot whales during noise exposure (Rendell & Gordon 1999). Two studies also addressed this issue in harbour porpoises: Koschinski et al. (2003) found no significant difference in the use of echolocation by porpoises when subjected to turbine noise; Teilmann et al. (2006) found echolocation activity of harbour porpoises to decrease in 3 out of 25 sessions when various frequency sounds with a source level of 153 dB re 1 µPa (rms) were played back to them. Although during this study, porpoises in the vicinity of pile driving might have reduced echolocation activity as a response to the sound of pile driving, we see no convincing reason why animals that rely on their sonar for orientation and foraging should cease doing so for over 20 h after pile driving noise stopped. We think that the decrease in acoustic activity is the result of a combined effect on porpoise behaviour and abundance. If animals change from foraging and resting behaviour to moving away from a noise source, this will result in a more directional movement. Considering the high directionality of the porpoise echolocation beam, this may greatly reduce the possibility of a click being recorded by the T-POD. Even if it takes some time for the animals to move out of the area, this change in behaviour will cause a direct effect on porpoise acoustic activity as recorded by T-PODs.

The difference of sound levels of about 12 dB measured between 720 m and 2300 m is quite high for the North Sea. A study conducted by the German Navy (Thiele & Schellstede 1980) suggests a level decay of ~8 dB in the major frequency range of pile driving noise over such a distance. However, the present study was located in relatively shallow water (about 4–14 m), where sound propagation is known to be highly variable and difficult to predict. As a major effect, transmission loss at low frequencies is affected by the water depth. Below a cut-off frequency, no sound propagation is possible (Jensen et al. 2000). This effect cuts off low-frequency components of the noise and can thus reduce its peak level and broadband SEL. The cut-off frequency is not only a function of water depth, but also of the impedance of the lower boundary of the propagation channel, that is, of the physical properties of the sediment. These, however, are often unknown. At 5 m water depth, for example, the cut-off can vary from about 80 to 300 Hz. The spectral maximum of the pile driving noise at Horns Rev II was found to be between 80 Hz and 200 Hz. As effects on porpoises depend highly upon sound propagation characteristics in the area, caution needs to be applied when trying to extrapolate our results to other areas.

To assess the effects of underwater noise on marine mammals, Southall et al. (2007) proposed a frequency-weighting procedure to take the hearing abilities of marine mammals into account, and a procedure to account for cumulative exposures. For the group of high-frequency cetaceans such as the harbour porpoise, the onset of hearing impairment, defined as a Temporary Threshold Shift (TTS), would be reached at 183 dB re 1 μPa^2 s SEL and Permanent Threshold Shift (PTS) at 198 dB re 1 uPa^2 s SEL (all M-weighted) (Southall et al. 2007). During this study the cumulative M-weighted SEL level reached a maximum of 194 dB re 1 μPa^2 s at 720 m distance. Therefore the noise level where Southall et al. (2007) predicted PTS to occur in high-frequency cetaceans was not reached at this distance. However, a noise level of 183 dB re 1 μPa^2 s, where they predicted TTS to occur, was reached after about 1.5 min. At 2300 m distance the cumulative M-weighted SEL level reached a maximum of 182 dB re 1μPa^2 s. This was therefore below PTS and TTS levels as predicted by Southall et al. (2007). However, recent work by Lucke et al. (2009) indicates that harbour porpoises may be more sensitive to noise exposures than was suggested by

Southall et al. (2007) for high-frequency cetaceans. Exposing 1 individual to single airgun stimulus, they found the animal to suffer TTS at 199.7 $dB_{pk\text{-}pk}$ re 1 µPa, and a sound exposure level of 164.3 dB re 1 μPa^2 s. According to this measure, a porpoise would have suffered TTS immediately at 720 m and after about 2 min at 2300 m distance during this study.

With a maximum swimming speed of about 4.3 m s^{-1} (Otani 2000), a porpoise should be able to leave the 750 m radius in about 3 min. According to both TTS criteria proposed by Southall et al. (2007) and Lucke et al. (2009) this would not be enough time for a porpoise to escape TTS. It might further be argued that animals are willing to endure potentially harmful sound levels when essential resources exist in the area. Especially in birds, many studies have shown more risk-taking behaviour when starvation risk increases (e.g. Cresswell & Whitfield 2008), and porpoises may equally endure harmful noise if by leaving the area they face a higher risk of starvation. At present, no data on this subject are available for harbour porpoises. Limited information on the levels at which anthropogenic noise causes hearing impairment in high frequency cetaceans and the discrepancies between TTS levels published by Southall et al. (2007) and Lucke et al. (2009) show that caution is required when applying TTS and PTS criteria. However, results from noise measurements during this study clearly show that mitigation measures such as the use of bubble curtains and scaring devices are to be recommended to prevent individuals from the risk of injury from pile driving operations, and further studies into the effectiveness of these measures are needed (Nehls et al. 2007).

CONCLUSIONS

Using passive acoustic monitoring, this study revealed a marked negative influence of pile driving on the acoustic activity of harbour porpoises. At 24 to 72 h in close proximity to the construction site, the temporal scale of this effect lasted much longer than found in previous studies. The duration of the effect declined with increasing distance, and no negative effect was found at a mean distance of 22 km. This information should be considered during future scheduling of pile driving activities within and between wind farms in European waters. Furthermore, sound measurements conducted during pile driving indicate that hearing impairment could potentially have occurred close to the construction site. Both the risk of hearing impairment in harbour porpoises and the far reaching disturbance effect highlight the necessity to develop suitable mitigation procedures. Here attention should especially be given to the development of measures that aim to reduce noise emission into the water.

Acknowledgements. Financial support for this study was provided by DONG Energy. We thank Christopher Honnef and the crew of the 'Tine Bødker' for their support with field work. Many thanks also go to Michael Dähne and Ursula Verfuß from the German Oceanographic Museum in Stralsund, Germany, for test-tank-calibration of the T-PODs. Special thanks go to Jakob Tougaard, Ruth Leeney and 2 anonymous referees for many helpful comments that greatly improved this manuscript.

LITERATURE CITED

Andrew RK, Howe BM, Mercer JA (2002) Ocean ambient sound: comparing the 1960s with 1990s for a receiver off the Californian coast. ARLO 3:65–70

Bailey H, Clay G, Coates EA, Lusseau D, Senior B, Thompson PM (2010) Using T-PODS to assess variations in the occurrence of bottlenose dolphins and harbour porpoises. Aquat Conserv 20:150–158

Barlow J, Cameron GA (2003) Field experiments show that acoustic pingers reduce marine mammal bycatch in the California drift gill net fishery. Mar Mamm Sci 19: 265–283

Betke K, Matuschek R (2010) Messungen von Unterwasserschall beim Bau der Windenergieanlagen im Offshore-Testfeld 'Alpha Ventus'. Final report for Stiftung Offshore Windenergie (available at: www.bsh.de/de/Meeresnutzung/Wirtschaft/Windparks/StUK3/StUK3-Schall-Bauphase-15 Mar2010.pdf)

Carstensen J, Henriksen OD, Teilmann J (2006) Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echo-location activity using porpoise detectors (T-PODs). Mar Ecol Prog Ser 321: 295–308

Cresswell W, Whitfield DP (2008) How starvation risk in Redshanks *Tringa totanus* results in predation mortality from Sparrowhawks *Accipiter nisus*. Ibis 150:209–218

Dähne M, Verfuß UK, Diederichs A, Meding A, Benke H (2006) T-Pod Test Tank Calibration and Field Calibration. In: Leeney RH, Tregenza NJC (eds) Proc Workshop Static Acoustic Monitoring of Cetaceans. 20th Annual Meeting of the European Cetacean Society, Gdynia, Poland 2 April 2006. ECS newsletter No. 46 Special Issue, p 34–36,

Gilles A, Scheidat M, Siebert U (2009) Seasonal distribution of harbor porpoises and possible interference of offshore wind farms in the German North Sea. Mar Ecol Prog Ser 383:295–307

Hammond PS (2006) Small cetaceans in the European Atlantic and North Sea (SCANS-II). LIFE project number LIFE04NAT/GB/000245, final report. biology.st-andrews.ac.uk/scans2/documents/final/SCANS-II_final_report.pdf

Jensen FB, Kupermann WA, Porter MB, Schmidt H (2000) Computational Ocean Acoustics. Springer, New York, NY

Johnston DW (2002) The effect of acoustic harassment devices on harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy, Canada. Biol Conserv 108:113–118

Kastelein RA, Bunskoek P, Hagedoorn M (2002) Audiogram of a harbour porpoise (*Phocoena phocoena*) measured with narrow-band frequency-modulated signals. J Acoust Soc Am 112:334–344

Kastelein RA, Jennings N, Verboom WC, Haan D, Schooneman NM (2006) Differences in the response of a striped dolphin (*Stenella coeruleoalba*) and a harbour porpoise (*Phocoena phocoena*) to an acoustic alarm. Mar Environ Res 61:373–378

Koschinski S, Culik BM, Henriksen OD, Tregenza N, Ellis G, Jansen C, Kathe G (2003) Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Mar Ecol Prog Ser 265: 263–273

Kraus S (1999) The once and future ping: challenges for the use of acoustic deterrents in fisheries. Mar Technol Soc J 33:90–93

Lucke K, Siebert U , Lepper PA, Blanchet MA (2009) Temporary shift in masked hearing thresholds in a harbour porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. J Acoust Soc Am 125:4060–4070

Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack PL (2006) Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar Ecol Prog Ser 309:279–295

McDonald MA, Hildebrand JA, Wiggins SM (2006) Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. J Acoust Soc Am 120: 711–718

Nehls G, Betke K, Eckelmann S, Ros M (2007) Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms. BioConsult SH, Husum, on behalf of COWRIE Ltd.

Nowacek DP, Thorne LH, Johnston MP, Tyack PL (2007) Responses of cetaceans to anthropogenic noise. Mammal Rev 37:81–115

Olesiuk PF, Nichol LM, Sowden MJ, Ford JKB (2002) Effect of the sound generated by an acoustic harassment device on the relative abundance and distribution of harbor porpoises (*Phocoena phocoena*) in retreat passage, British Columbia. Mar Mamm Sci 18:843–862

Otani S (2000) Diving behaviour and swimming speed of a free-ranging harbour porpoise, *Phocoena phocoena*. Mar Mamm Sci 16:811–814

Reid JB, Evans PGH, Northridge SP (2003) Atlas of Cetacean distribution in north-west European waters. Joint Nature Conservation Committee, Peterborough

Rendell LE, Gordon JCD (1999) Vocal response of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian Sea. Mar Mamm Sci 15:198–204

Richardson WJ, Greene CR, Malme CI, Thompson DH (1995) Marine Mammals and Noise. Academic Press, San Diego, CA

Siebert U, Rye JH (2008) Correlation between aerial surveys and acoustic monitoring. In: Wollny-Goerke, K. and K. Eskildsen (eds) Marine mammals and seabirds in front of offshore wind energy. Teubner, Wiesbaden

Simon M, Nuuttila H, Reyes-Zamudio MM, Ugarte F, Verfuß U, Evans PGH (2010) Passive acoustic monitoring of bottlenose dolphin and harbour porpoise in Cardigan Bay, Wales, with implications for habitat use and partitioning. J Mar Biol Ass UK 90:1539–1545

Southall BL, Bowles AE, Ellison WT, Finneran JJ and others (2007) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquat Mamm 33:411–414

Teilmann J, Tougaard J, Miller LA, Kirketerp T, Hansen K, Brando S (2006) Reactions of captive harbor porpoises (*Phocoena phocoena*) to pinger-like sounds. Mar Mamm Sci 22:240–260

Thiele & Schellstede (1980) Standardwerte zur Ausbreitungsdämpfung in der Nordsee. FWG-Bericht 1980–7. Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik, Kiel

Thompson PM, Lusseau D, Barton T, Simmons D, Rusin J, Bailey H (2010) Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. Mar Pollut Bull 60:1200–1208

Thomsen F, van Elk N, Brock V, Piper W (2005) On the performance of automated porpoise-click-detectors in experiments with captive harbor porpoises (*Phocoena phocoena*). J Acoust Soc Am 118:37–40

Thomsen F, Lüdemann K, Kafemann R, Piper W (2006) Effects of offshore wind farm noise on marine mammals and fish. Biola, Hamburg, on behalf of COWRIE Ltd.

Tougaard J, Rosager Poulsen L, Amundin M, Larsen F, Rye J, Teilmann J (2006) Detection function of T-PODs and estimation of porpoise densities. In: Leeney RH, Tregenza NJC (eds) Proc Workshop Static Acoustic Monitoring of Cetaceans. 20th Annual Meeting of the European Cetacean Society, Gdynia, Poland 2 April 2006. ECS newsletter No. 46, Special Issue, p 7–9

Tougaard J, Carstensen J, Teilmann J (2009) Pile driving zone of responsiveness extends beyond 20 km for harbour porpoises (*Phocoena phocoena* (L.)). J Acoust Soc Am 126: 11–14

Tyack PL (2008) Implications for marine mammals of large-scale changes in the marine acoustic environment. J Mammal 89:549–558

Verfuß UK, Honnef CG, Medling A, Dähne M, Mundry R, Benke H (2007) Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring. J Mar Biol Assoc UK 87:165–176

Verfuß UK, Honnef CG, Medling A, Dähne M, Adler S, Kilian A, Benke H (2008) The history of the German Baltic Sea harbour porpoise acoustic monitoring at the German Oceanographic Museum. In: Wollny-Goerke, K. and K. Eskildsen (eds) Marine mammals and seabirds in front of offshore wind energy. Teubner, Wiesbaden

Weilgart LS (2007) The impacts of anthropogenic noise on cetaceans and implications for management. Can J Zool 85:1091–1116

Editorial responsibility: Hans Heinrich Janssen, Oldendorf/Luhe, Germany

Submitted: July 14, 2010; Accepted: October 21, 2010
Proofs received from author(s): January 3, 2011

Vol. 321: 295–308, 2006 | MARINE ECOLOGY PROGRESS SERIES Mar Ecol Prog Ser | Published September 8

Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs)

J. Carstensen[1,*], O. D. Henriksen[2], J. Teilmann[1]

[1]National Environmental Research Institute, Denmark, Frederiksborgvej 399, PO Box 358, 4000 Roskilde, Denmark
[2]*Present address:* Oluf.dk, Stavnsbjerg Allé 55, 2730 Herlev, Denmark

ABSTRACT: Offshore wind farming is a new emerging technology in the field of renewable energies. This study investigates the potential impact of the construction of one of the first major, offshore wind farms (>100 MW) on harbour porpoises *Phocoena phocoena* by means of acoustic porpoise detectors (T-PODs) monitoring porpoise echolocation activity. The monitoring program was established as a modified BACI (before, after, control, impact) design, with 6 monitoring stations equally distributed between the impact area and a nearby reference area. Mean waiting times, defined as the period between 2 consecutive encounters of echolocation activity, increased from 6 h in the baseline period to 3 d in the wind farm area during the construction. This increase was 6 times larger than changes observed in the reference area. One specific construction activity, involving the ramming and vibration of steel sheet piles into the seabed, was associated with an additional significant increase in waiting time of 4 to 41 h, in both the construction and reference areas. Assuming that echolocation activity is related to harbour porpoise density, the analysis shows that their habitat-use changed substantially, with the porpoises leaving the construction area of the offshore wind farm. Acoustic monitoring from fixed positions provides data with a high temporal resolution, but low spatial resolution, which can be analysed at a variety of scales, and can be applied to harbour porpoises and other echolocating cetaceans.

KEY WORDS: Acoustic monitoring · BACI design · Echolocation · Environmental impact · Assessment · Harbour porpoise · Offshore wind farm · Porpoise detector · T-POD

INTRODUCTION

Offshore wind power is a rapidly expanding industry in Northern Europe, where several large offshore wind farms are under construction in nearshore waters, many having high densities of marine mammals. The construction and operation of offshore wind farms are disturbing the marine environment, and as such pose a potential threat to marine mammal habitats. In particular, shallow areas are believed to be important to the harbour porpoises *Phocoena phocoena* for calving and nursing (Koschinski 2002). The largest offshore wind farms today consist of up to 80 wind turbines covering some 20 to 30 km^2. Foundations are either steel monopiles driven into the seabed with large pile drivers, or concrete gravitational foundations placed on pebble cushion layers. The major disturbances to marine mammals arising from the construction are noise from ramming and other building activities, boats and barges, whirled-up bottom sediments, and destruction of bottom flora and fauna. Hitherto, the impacts of offshore construction work on harbour porpoises or other small cetaceans have not been studied in detail. Given the extensive plans for expanding the offshore wind energy sector, it is important to know the effect of single wind farms as well as the cumulative effect of several wind farms within the range of each marine mammal population.

In 2002 and 2003, the Nysted Offshore Wind Farm was constructed in a coastal shallow area (between 6

*Email: jac@dmu.dk

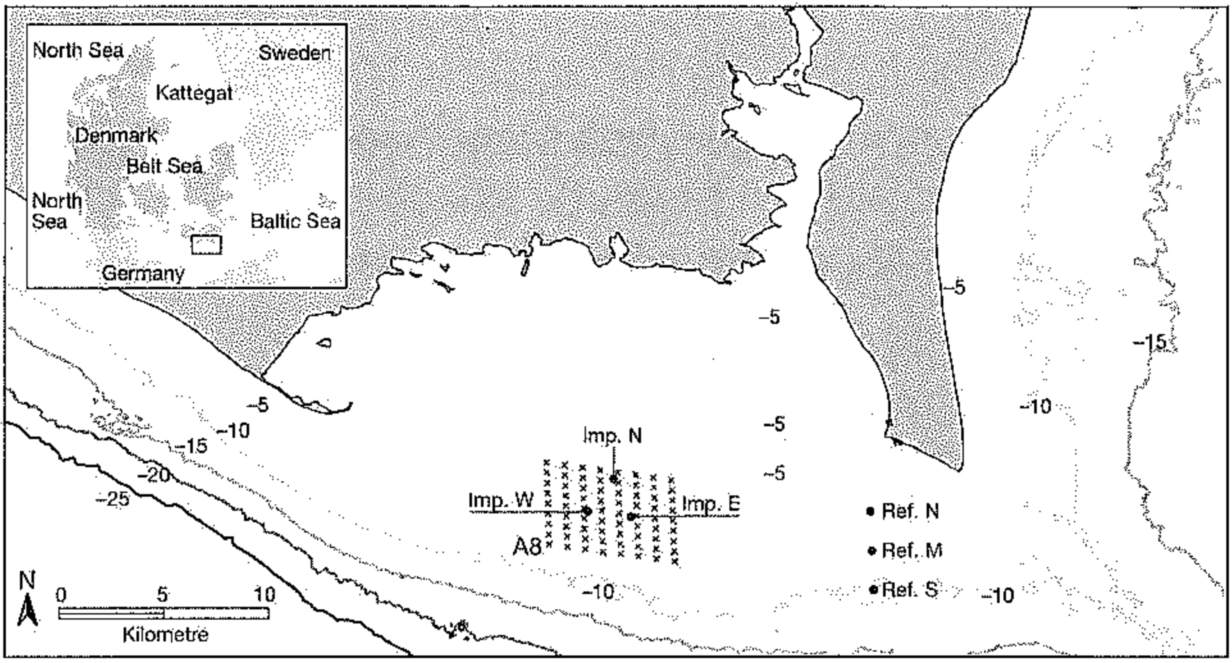


Fig. 1. Nysted Offshore Wind Farm in the western part of the Baltic Sea. The 72 wind turbines (x) are placed in a 8 × 9 grid. Foundation A8 (southwestern corner), where the sediments were stabilised with steel sheet piles, is located in the southwestern corner of the wind farm. (●) Positions of porpoise detector (T-POD) deployments (Imp. W, E, N = 3 stations examined in impact area, Ref. N, M, S = 3 stations in reference area). Depth contours (m) are shown

and 9.5 m depth) in the Danish part of the western Baltic Sea 54° 30' N, 11° 40' E (Fig. 1). The sea floor consists of glacial depositions made of sand/silt with scattered stones. The water is brackish, and salinity varies with the surface outflow from the Baltic Sea and more saline water intrusion from the North Sea through the Kattegat and the Belt Sea. Tidal amplitude is less than 0.5 m but strong winds may change water depth by an additional 1 to 2 m. In a 8 × 9 grid covering a total of ca. 24 km^2 72 wind turbines (2.2 MW each) with concrete gravitational foundations placed on pebble cushion layers, were constructed (Fig. 1).

The only dedicated surveys for harbour porpoises in the western Baltic area were carried out during the summers of 1991, 1992, and 1994 about 30 km west of the wind farm area, where an average density of 0.10 porpoises km^{-2} was found (Heide-Jørgensen et al. 1992, 1993, Hammond et al. 2002). Hence, the wind farm area is located between a relatively high density area including the Kattegat and the Great Belt (0.73 porpoises km^{-2}, Hammond et al. 2002) and the low density Baltic Proper with <0.01 porpoises km^{-2} (Koschinski 2002). In fact, the highest density of harbour porpoises (4.9 porpoises km^{-2}) for Europe was reported in a small-scale study in the Belt Sea located about 100 km from the wind farm area (Teilmann 2003). Harbour porpoises were regularly seen throughout the year during aerial bird surveys conducted in the wind farm area before the construction work started (Bach et al. 2000). Satellite tracking of 52 harbour porpoises in the inner Danish waters during 1997 to 2002 has shown that the wind farm region is regularly visited for short periods at a time, but that the normal harbour porpoise home ranges are several orders of magnitude larger than the wind farm area (Teilmann et al. 2004). The harbour porpoises in the western part of the Baltic Sea are most probably part of a greater population including the Belt Sea and the Kattegat (Teilmann et al. 2004).

Harbour porpoise monitoring has traditionally been carried out by means of shipboard surveys to calculate area- and time-specific densities. Because of the few visual observations during pilot surveys in the area, it was argued that the statistical power of this method would be low (Bach et al. 2000). Instead, we have employed a novel device, the T-POD (The POrpoise Detector) a self-contained acoustic data logger (Thomsen et al. 2005), which monitors the harbour porpoise echolocation activity continuously at fixed positions. The T-POD was chosen for this impact study, assuming that echolocation activity was related to harbour porpoise density, as suggested by the study of Koschinski et al. (2003), because it provided a wealth of data at a reasonable cost.

The objective of the present study was to assess and document the impact of the construction of the Nysted

Offshore Wind Farm on harbour porpoise density by describing (1) changes in harbour porpoise echolocation activity related to the whole construction period (medium-term response); and (2) changes in harbour porpoise echolocation activity related to steel sheet pile driving/vibration at a single wind turbine foundation (short-term response). Long-term responses to the operation of the wind farm will be investigated in the coming years.

MATERIALS AND METHODS

The construction of the Nysted Offshore Wind Farm began in mid-June 2002 and continued until the wind farm was put into operation on 1 December 2003. Main activities included excavation for, positioning and ballast-filling of concrete foundations (June 2002 to June 2003), mounting of wind turbines (May to July 2003), and digging, laying and covering of the connecting power grid (August 2002 to November 2003). Around 1 of the 72 foundations (A8, Fig. 1), the seabed had to be stabilised with steel sheet piles that were driven into the sediments using a pile driver and a barge-mounted vibrator. This activity occurred intermittently, with either the vibrator or the pile driver in continuous operation for periods of 1.5 to 10 h for a total of 25 d from 26 August to 20 November 2002. The start and ending of the ramming/vibration activity was recorded exactly to the minute. Acoustic harassment devices (harbour porpoise pinger and seal scarer) were employed near (<200 m) this foundation from 30 min before and up to the end of the ramming/vibration activity. Ambient noise levels from construction activities and harassment devices were not measured. Preliminary activities in the impact area up to 1 July 2002 were considered negligible and at least not substantially different from the normal boating activity, whereas construction activities from July 2002 to November 2003 were hypothesised to have a potential impact on harbour porpoises *Phocoena phocoena*.

T-POD monitoring. The T-POD is a self-contained submersible computer and hydrophone that recognises and logs echolocation clicks from porpoises and dolphins (Thomsen et al. 2005). Clicks (click duration and repetition rate) within the appropriate frequency bands of the harbour porpoise echolocation spectrum are logged and can be retrieved from the T-POD to a PC during maintenance visits. A software program accompanies the T-POD with an algorithm for detecting the characteristic harbour porpoise click-trains, while removing noise from boat sonars or other short duration click-like sounds having the same spectral properties as echolocation clicks (see www.chelonia.demon.co.uk for more details). It has a spatial coverage up to a radial distance of 170 m (Koschinski et al. 2003).

The porpoise echolocation activity was monitored by deploying T-PODs at 3 positions within the wind farm impact area (Imp. W, N, E) and at 3 positions in a reference area 10 km east of the wind farm (Ref. N, M, S; Fig. 1). No prior information existed on the specific porpoise densities in the impact and reference areas, and the reference area was chosen to reflect similar bathymetry, bottom features and distance from shore as the impact area. In the impact area, the T-PODs were deployed in a triangle 1.9 km apart to cover the central part of the wind farm area, whereas the reference area was chosen as a N–S transect, with 1.9 km between deployments to avoid interference with shipping lanes (Fig. 1). Distances from Foundation A8 to the deployment sites were 2.1, 4.0 and 4.0 km to Imp. W, N and E, respectively, and 15.3, 15.4 and 15.7 km to Ref. N, M and S, respectively.

The T-PODs were moored with a concrete block and a small anchor for easy recovery and maintenance of the device (Fig. 2); they were retrieved, the batteries changed (6 × 3.6V lithium D-cell batteries) and the data saved on a laptop approximately every 60 d. Technical problems resulted in some data loss (gaps in the time series), but T-PODs were in operation both before and during construction at all 6 positions. The T-POD data used in this study was separated into 2 distinct periods: a baseline period (November 2001 to June 2002) and a construction period (July 2002 to November 2003) that included the construction activities that could potentially affect the harbour porpoises in the area. Some T-PODs were lost and replaced with new ones at 3 positions (1 in the impact area and 2 in the reference area) during the course of the construction period. Each individual T-POD was deployed at the same station during the entire study to avoid con-

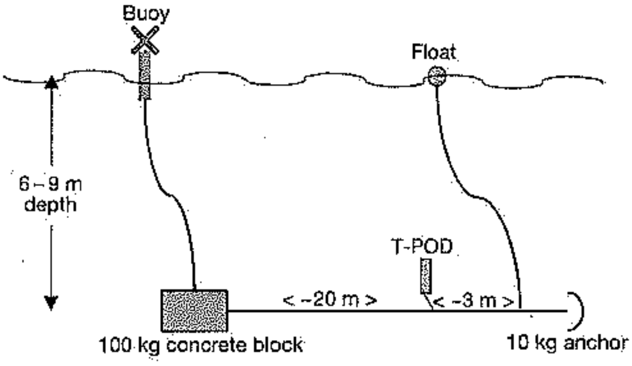


Fig. 2. T-PODs deployment. Anchor and buoy are connected to concrete block with 12 mm stainless-steel strengthened ropes. In shallow and calm waters T-POD can be retrieved by hand; should the small float be lost; the T-POD must be retrieved by diver or with a crane

founding instrument variation with temporal shift from baseline to construction, and fortunately, the T-POD replacements did not coincide with this investigated change.

All T-PODs used in this study were Version 1, equipped with external transducers and equivalent configuration. For each T-POD, all 6 channels/scans were set to the identical default values for harbour porpoises: (1) Filter A = 130 kHz; (2) Filter B = 90 kHz; (3) ratio = 5; (4) Q-value for Filter A = 5; (5) Q-value for Filter B = 18; (6) sensitivity threshold = 0; (7) maximum number of clicks = 240 clicks 9 s^{-1}; (8) minimum click duration = 10 µs. After retrieving the data from the T-PODs, harbour porpoise click-trains were identified using the 'low probability cetacean train' algorithm of the T-POD software, and the number of clicks min^{-1} was exported for subsequent data analysis (www.chelonia. demon.co.uk).

Statistical analysis. Porpoise click-trains were frequently observed as short distinct periods of high echolocation activity separated by longer periods with no activity (silent period). The exported time series of clicks per minute were converted into 'porpoise encounters', defined as a series of harbour porpoise clicks of any length when silent periods <10 min, a value chosen from examination of time series plots of data. Click series separated by silent periods of >10 min were consequently defined as 2 separate encounters. The period between harbour porpoise encounters was denoted 'waiting time' and used as a proxy indicator for harbour porpoise density in the statistical analysis. It should be stressed that because of differences in deployments at the stations and loss of T-PODs the data available for the statistical analysis was balanced in neither space nor time.

Waiting times were analysed according to a modified BACI design (Green 1979) that included station-specific, T-POD specific, and seasonal variation. The BACI (before, after, control, impact) design can be viewed as a variant of the split-plot design, since the 2 levels of the treatment (baseline versus construction) were not observed simultaneously. In the present design, the month of the observation was included as an additional blocking factor (split-split-plot design) to account for seasonal variation, such that waiting times were compared over the same months in progressive years. This is valid, because there was replication of months within the 2 yr monitoring period. The model for the waiting times (Y_t), after subtracting 10 min and log-transformation, was:

$$\begin{aligned} Y_{t(ijklmn)} = \mu &+ \underbrace{R_i + p_j + RP_{ij}}_{\text{whole-plot}} + \underbrace{m_k + RM_{ik} + PM_{jk} + RPM_{ijk}}_{\text{split-plot}} + \underbrace{a_l + RA_{il} + pa_{jl} + RPA_{ijl} + MA_{kl} + RMA_{ikl} + PMA_{jkl} + RPMA_{ijkl}}_{\text{split-split-plot(area)}} \\ &+ \underbrace{S_{m(l)} + RS_{im(l)} + PS_{jm(l)} + RPS_{ijm(l)} + MS_{km(l)} + RMS_{ikm(l)} + PMS_{jkm(l)} + RPMS_{ijkm(l)}}_{\text{split-split-plot(station)}} \\ &+ \underbrace{T_{n(lm)} + RT_{in(lm)} + PT_{jn(lm)} + RPT_{ijn(lm)} + MT_{kn(lm)} + RMT_{ikn(lm)} + PMT_{jkn(lm)} + RPMT_{ijkn(lm)}}_{\text{split-split-plot(t-pod)}} + \varepsilon_{t(ijklmn)} \end{aligned} \qquad (1)$$

where µ is the overall mean, a = area has 2 levels (control, impact), p = period has 2 levels (baseline, construction), m = month has 11 levels (February to December), S = station has 6 levels (Imp. N, W and E; Ref. N, M and S), and T = T-POD has 9 levels (T-POD identification number = 7, 14, 17, 43, 47, 48, 56, 67, 71). There were 18 different plots, denoted by R = plot in Eq. (1), where sampling was random within area, station and T-POD. Subscript letters in Eq. (1) are indices for different levels of the effects in the model. The model in Eq. (1) has 4 fixed effects (indicated by lowercase letters), where 'area' describes the spatial variation between control and impact area, 'month' describes the seasonal variation by means of monthly values and 'period' describes the stepwise change at the onset of the construction work, whereas 'area × period' describes a difference in the stepwise change between the 2 areas. The random effects of the model (indicated by uppercase letters) were 'station(area)' describing the station-specific variation nested within the 2 areas, 'tpod(area station)' describing the T-POD specific variation within the 3 stations where the equipment was replaced during construction, 'plot' describing the variation between months of monitoring, and 24 interactions. The significance of the random effects was tested and insignificant random effects were pooled with the residual variation.

The interaction area × period, also referred to as the BACI effect, therefore described a stepwise change in the impact area different from that in the reference area. Marginal means for the different factors of the model were calculated and back-transformed to mean values on the original scale using the moment's transformations of the log-transform (p. 285 in McCullagh & Nelder 1989) and adding the 10 min threshold. The BACI effect, having 1 numerator degree of freedom, was also calculated explicitly as a contrast of the marginal means for the 4 combinations of area and period, and

$$\exp(\text{BACI contrast}) = \frac{E[\text{Imp., constr.}]}{E[\text{Imp.,basel.}]} \times \frac{E[\text{Ref., basel.}]}{E[\text{Ref., constr.}]} \qquad (2)$$

where $E[\,]$ denotes the expectation values. Thus, the exponential of the contrast described the relative change from the baseline to the construction period in the impact area relative to the reference area.

The model in Eq. (1) can be formulated within the framework of general, linear, mixed models

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u} + \mathbf{e} \tag{3}$$

where **Y** is the vector of observations, **X** is the design matrix for the fixed effects, $\boldsymbol{\beta}$ is the vector of parameters for the fixed effects, **Z** is the design matrix for the random effects, **u** is the vector of random effects with covariance matrix **G**, and **e** is the vector of the residuals with the covariance matrix **R**. The temporal variation in waiting times was assumed to follow an overall, fixed, seasonal pattern described by monthly means, but fluctuations in the harbour porpoise density in the region on a shorter time scale may potentially give rise to serial correlations in the observations. For example, if a short waiting time is observed, the next waiting time is likely to be short as well. In order to account for any autocorrelation in the residuals, we formulated a covariance structure for the residuals ($\mathbf{R} \neq \sigma^2\mathbf{I}$) by means of an ARMA(1,1)-process (Chatfield 1984) subject to waiting times observed within separate deployments, i.e. complete independence was assumed across gaps in the time series. Thus, this model included an extension to the general linear theory (e.g. McCullagh & Nelder 1989) by mixing fixed and random effects (McCulloch & Searle 2001).

In the BACI design, the overall seasonal variation was assumed to be identical for the 2 areas, since they were located relatively close to each other and with similar bottom and depth properties. This basic assumption was investigated with the following model employed on baseline data only:

$$Y_{i(klm)} = \mu + m_k + a_l + ma_{kl} + S_{m(l)} + MS_{km(l)} + \varepsilon_{i(klm)} \tag{4}$$

where the first 2 factors of the model have the same interpretation as in Eq. (1), and the interaction area × month describes systematic differences in the seasonal variation of the 2 areas; 2 random effects, station(area) and station(area) × month, were also included. None of the T-PODs were replaced during baseline, and therefore the effect T-POD (area station) was completely confounded with station(area). There was no replication of months for the baseline data and therefore this analysis was carried out using a factorial block design. If the interaction area × month in Eq. (4) is significant, temporal variations in harbour porpoise density may not be comparable for the 2 areas, jeopardising the BACI design. Therefore, we examined the consequences for the interaction area × month by eliminating data from individual stations separately. The ARMA(1,1) covariance structure of **R** was also applied to this model (Eq. 4).

The T-POD-specific variation was nested within stations, and similarly the station-specific variation was nested within areas in Eq. (1). This implied that the factors area and station(area) were a combination of spatial variation and T-POD-specific sensitivity. However, the interaction (area × period) remained unaffected by this, because the T-PODs were not interchanged between stations during the study period and consequently the testing for a potential effect of the construction work in the impact area was not biased by differences in T-POD sensitivity. The hierarchical structure for area, station and T-POD-specific variation was chosen in favour of crossing the T-POD-specific variation with the spatial variation, because shifting the T-PODs between stations would require additional substantial effort, with a risk of the T-POD-specific variation being partly or even totally confounded with the BACI effect (area × period).

To investigate the short-term effect of ramming/vibration activity in the period from 25 August to 20 November 2002, the first and second encounter after this specific construction activity had ceased were identified, and the corresponding waiting times prior to these encounters were analysed to investigate if waiting times (first and second separately) following ramming/vibration activity were different. For each station, the distribution of first waiting times was compared to the distribution of all other observations during this specific period, and similarly, the distribution of second waiting times was compared to the distribution of all observations except first and second waiting times. For this analysis, the correlation parameters of the ARMA(1,1)-process in the covariance structure **R** were not estimated, but set to the values obtained from analysing all data according to Eq. (1), since the number of observations in this specific period was limited. In order to account for different magnitudes of variation between first, second and other waiting times, different variance parameters in **R** for these 3 categories were estimated, but the correlation parameters between observations in time were fixed.

The statistical analyses were carried out within the framework of mixed linear models (Littell et al. 1996, McCulloch & Searle 2001) by means of PROC MIXED in the SAS system. Statistical testing for fixed effects (F-test with Satterthwaite approximation for denominator degrees of freedom) and random effects (Wald Z) were carried out at a 5% significance level (Littell et al. 1996). The F-test for fixed effects was partial, i.e. considering the specific contribution of the given effect in addition to all other factors.

RESULTS

The 9 T-PODs used in this study were deployed at the 6 stations for a total of 1617 d, with approximately 47% more deployment days in the impact area than in the reference area (Table 1). During the days of deployment, 3704 waiting times were recorded at the

Table 1. Logging period showing number of days deployed, number of observations (n) and average waiting time for deployed T-PODs. Periods listed were combined of several deployments including long periods without data

Stn	T-POD no.	Logging period (d/mo/yr)	Days deployed	Baseline n	Baseline Avg. (min)	Construction n	Construction Avg. (min)
Impact area							
Imp. N	T-POD47	8/4/2002 – 8/10/2003	216	173	320	129	1707
Imp. W	T-POD56	14/11/2001 – 30/11/2003	402	509	233	319	1363
Imp. E	T-POD67	8/4/2002 – 8/8/2002	123	545	215	117	465
	T-POD71	5/2/2003 – 30/11/2003	222			66	4353
Overall			963	1227	237	631	1580
Reference area							
Ref. N	T-POD14	3/5/2002 – 23/9/2002	126	138	599	127	709
	T-POD17	12/8/2003 – 1/9/2003	21			3	7827
Ref. M	T-POD43	8/4/2002 – 30/11/2003	345	221	406	807	485
Ref. S	T-POD48	4/4/2002 – 5/4/2003	117	141	311	101	1117
	T-POD7	7/10/2003 – 30/11/2003	45			308	199
Overall			654	500	433	1346	504

6 stations with an almost equal number of observations before (n = 1727) and during (n = 1977) construction, although the T-PODs were deployed for considerably longer periods during the construction. The average waiting time increased at all stations from the baseline to the construction period, but the increase was considerably larger in the impact area (Table 1). The monitoring stations were not in continuous operation throughout the entire study period, but the time series from the different stations were overlapping to comprise combined time series for both the reference and the impact area spanning both the baseline and the construction periods. Consequently, data from the different stations were compared through the assumption of a common seasonal pattern.

The change in harbour porpoise echolocation activity in the impact area was also visible from time series plots (Fig. 3), whereby the observed waiting times never exceeded 2 d in the baseline period, but numerous encounters were separated by more than 1 wk (~10 080 min) during the construction period. In fact, at Stn Imp. W, no harbour porpoise click-train was recorded over a 38 d period from 25 February to 4 April 2003. Waiting times were generally longer in the winter period and shorter in the summer period, during both the baseline and construction periods (Fig. 3). The replacement of T-PODs at 3 stations did not introduce any clearly visible systematic shift in the waiting time levels (Fig. 3).

Investigating the spatial and temporal variations of the waiting times using baseline data only revealed that the area-specific monthly means were not common to both the control and impact area. The significance of area × month in Eq. (4) was potentially due to data from 1 of 3 stations (Imp. E, Ref. N, or Ref. S), but excluding data from Ref. N yielded the most similar seasonal means for the 2 areas (highest p-value) and the least residual variation (Table 2). Thus, the assumption of common temporal variations in harbour porpoise echolocation activity throughout the investigated area was not compromised, provided that data from Ref. N were excluded from the baseline data analysis. Removing the least significant factor, area × month, from the model (Eq. 4) of the baseline data after excluding Stn Ref. N showed a significant seasonal variation ($F_{4;56.7} = 11.60$; $p<0.0001$), but no significant variation between the reference and impact areas ($F_{1,\,2.97} = 2.00$; $p = 0.2531$). None of the random effects were significant ($\sigma^2_{\text{station(area)}} = 0.1065$; $Z = 0.97$; $p = 0.1657$ and $\sigma^2_{\text{station(area)} \times \text{month}} = 0$) and they were much smaller than the residual variation ($\sigma^2 = 2.2789$; $Z = 26.45$; $p < 0.0001$).

Table 2. *Phocoena phocoena*. Analysis of area-specific monthly means for waiting times according to Eq. (4), using baseline data only, for all stations and excluding (excl.) individual stations. Statistics for factor area × month are shown only. Denominator degrees of freedom (Den df) computed by Satterthwaite's approximation (Littell et al. 1996)

Data used in model	area × month statistics df	Den df	*F*	p	Residual variance
All stations	2	65.0	3.88	0.0257	2.3556
Excl. Imp. N	2	55.9	3.82	0.0279	2.3998
Excl. Imp. W	2	47.1	3.57	0.0359	2.3542
Excl. Imp. E[a]	2	39.9	2.63	0.0843	2.4011
Excl. Ref. N	2	62.0	2.11	0.1294	2.2757
Excl. Ref. M	2	36.7	4.91	0.0128	2.3945
Excl. Ref. S	2	65.9	2.67	0.0765	2.3359

[a] This model was run without station(area)×month to obtain convergence

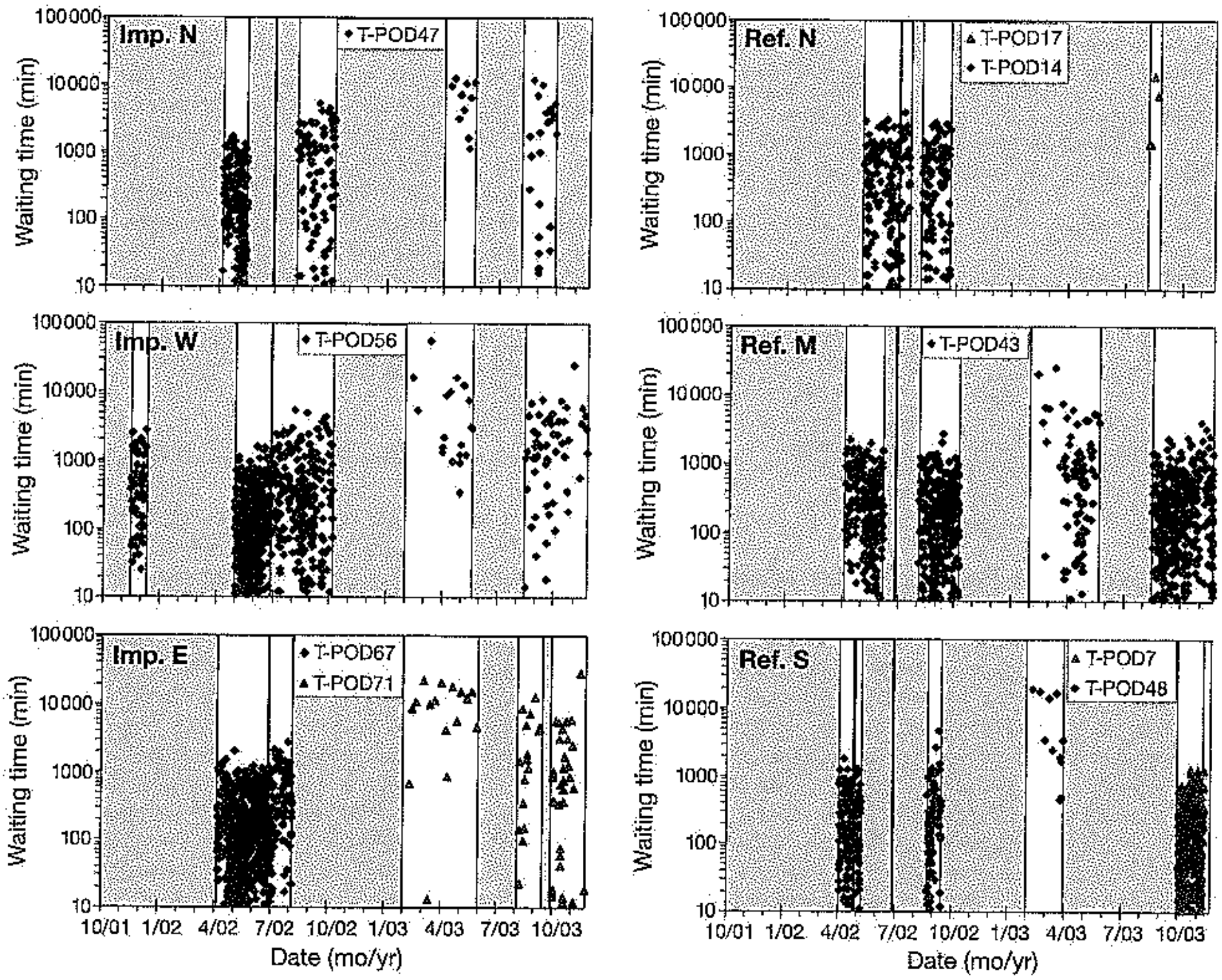


Fig. 3. *Phocoena phocoena.* Waiting times between harbour porpoise encounters in impact area (Stns Imp. N, W, E) and reference area (Stns Ref. N, M, S). Grey shading: periods with no T-POD deployments; vertical lines indicate change from baseline to construction period. Note logarithmic scale

BACI analysis

Except for 3 random (although not significant) effects, the majority of the random effect variances for the full model in Eq. (1) were zero. After pooling those effects with zero variance contribution with the residual variation, the 3 variance-contributing random effects were still insignificant (Table 3), and consequently, all random effects were pooled with the residual variation.

The fixed factors in the BACI analysis (Eq. 1) were all significant (Table 4). In the reference area, the waiting times almost doubled from the baseline to the construction period (from about 9 to 20 h), whereas waiting times in the impact area increased by more than 1 order of magnitude (from about 5.5 h to 3 d). Although the waiting times became longer during the construction in both reference and impact areas, the increase in the impact area was more than 6 times larger (BACI contrast of 1.8005) than in the reference area. In the baseline period, harbour porpoise encounters were more frequent in the impact area, but after construction began, the refer-

Table 3. Variance estimates and test for random effects in BACI (before, after, control, impact) analysis after contributing effects of zero variance have been pooled with residual variation

Variance contributing effect	Estimate	SE	Wald's Z-test	p
Period × Month (PM_{jk})	0.7109	0.8105	0.88	0.1902
Plot × Area (RA_{il})	0.1126	0.1005	1.12	0.1313
Plot × Station ($RS_{im(il)}$)	0.0729	0.0562	1.30	0.0974
Residuals	2.6208	0.0707	37.10	<0.0001

Table 4. *Phocoena phocoena*. BACI analysis of waiting times (3436 observations) between porpoise encounters at Nysted Offshore Wind Farm. Data from Stn Ref. N were not included in analysis. Tests for fixed effects are shown above; marginal means, calculated from parameter estimates and back-transformed to original scale, are shown below

Factor	df	Den df	F	p
Area	1	36.1	7.17	0.0111
Month	10	107	7.06	<0.0001
Period	1	68.5	36.09	<0.0001
Area × Period	1	41.5	35.12	<0.0001

BACI marginal means

	Reference	Impact	Overall
Baseline	542 min	337 min	427 min
Construction	1213 min	4483 min	2329 min
Overall	810 min	1219 min	

ence area had the highest (although relatively low) echolocation activity.

The seasonal variation used to compare waiting times across differences in the deployments had a pronounced pattern (Fig. 4), with long waiting times in February and March (means >1 d for both areas and periods combined) and shorter waiting times in July to November (means between 1.8 and 5.8 h for both areas and periods combined). There were no data for January, and the marginal means obtained from Eq. (1) therefore expressed the expectation value for 11 mo only. Long waiting times in February and March combined with relatively fewer deployments resulted in less than 20 observations in total for each of these 2 months, and consequently the monthly mean estimates were more uncertain. There were also few observations from July in the reference area because of the short deployment time.

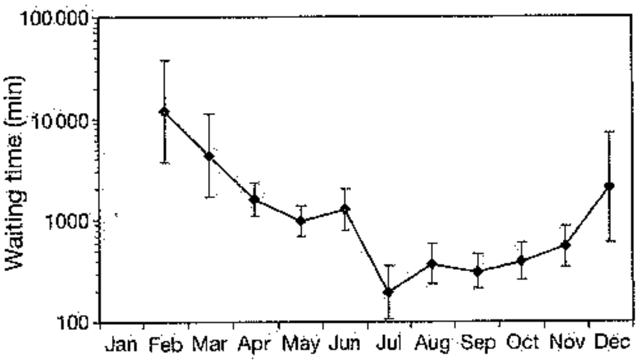


Fig. 4. *Phocoena phocoena*. Monthly mean (± 95% CL) marginal distribution of waiting times after back-transformation. Variations attributable to other significant factors in Eq. (1) have been accounted for by calculating marginal means. Note logarithmic scale

The area- and period-specific marginal means should be interpreted as the expected waiting time over 11 mo (excluding January) in both the baseline and construction periods, and the monthly marginal means should be interpreted as the expected waiting time in both areas combined. Finally, the BACI marginal means (Table 4) should be interpreted as the expected waiting time over 11 mo (excluding January) for the 4 combinations of area × period. The marginal means of the model were generally higher than the average values (Table 1) because there were considerably more observations during the summer period, with shorter waiting times.

Waiting times after ramming/vibration activity

In the period with ramming activity, 5 out of the 6 T-PODs were logging harbour porpoise echolocation activity from 25 August to 12 October, and 8.7 to 20.8% of the observations were identified as first and second waiting times for these stations. First waiting times measured the period elapsed between the first measured clicking bout after a ramming/vibration activity session and the last measured bout, and thus included some time from both before and during the session as well as immediately after. First waiting times were relatively high at all stations in both the impact and reference areas, whereas the second waiting times were on average level (Fig. 5). All 5 stations had a significantly higher first waiting time (Table 5), whereas the second waiting time after ramming/vibration activity was not different from the overall waiting time between encounters at any of the stations during this specific period (Table 6).

Waiting times for the first encounter after ramming activity had ceased increased significantly at all stations by factors of 9.0 for Imp N, 13.9 for Imp W, 9.0 for Ref. N, 3.5 for Ref. M, and 6.1 for Ref. S (Table 5). The first waiting time in the impact area was typically 35 to 50 h (means for the 2 stations) compared to the 'normal' level of 20 and 10 h for Imp. N and W, respectively (Table 5). In the reference area, mean waiting times (excluding first waiting time observations) increased from 17, 7, and 6 h to 30, 11 and 19 h for the first encounter after ramming activity for Ref. N, M and S, respectively. The increase in the waiting time was longer than the average duration of ramming/vibration activity (5.5 h), including the deployment of harassment devices, for all stations except Ref. M. The largest increase was observed at Stn Imp. W, the station closest to the site of ramming/vibration, where the first waiting times were 41 h longer than other waiting times in this specific period of ramming/vibration activity. The analysis of first and second waiting times

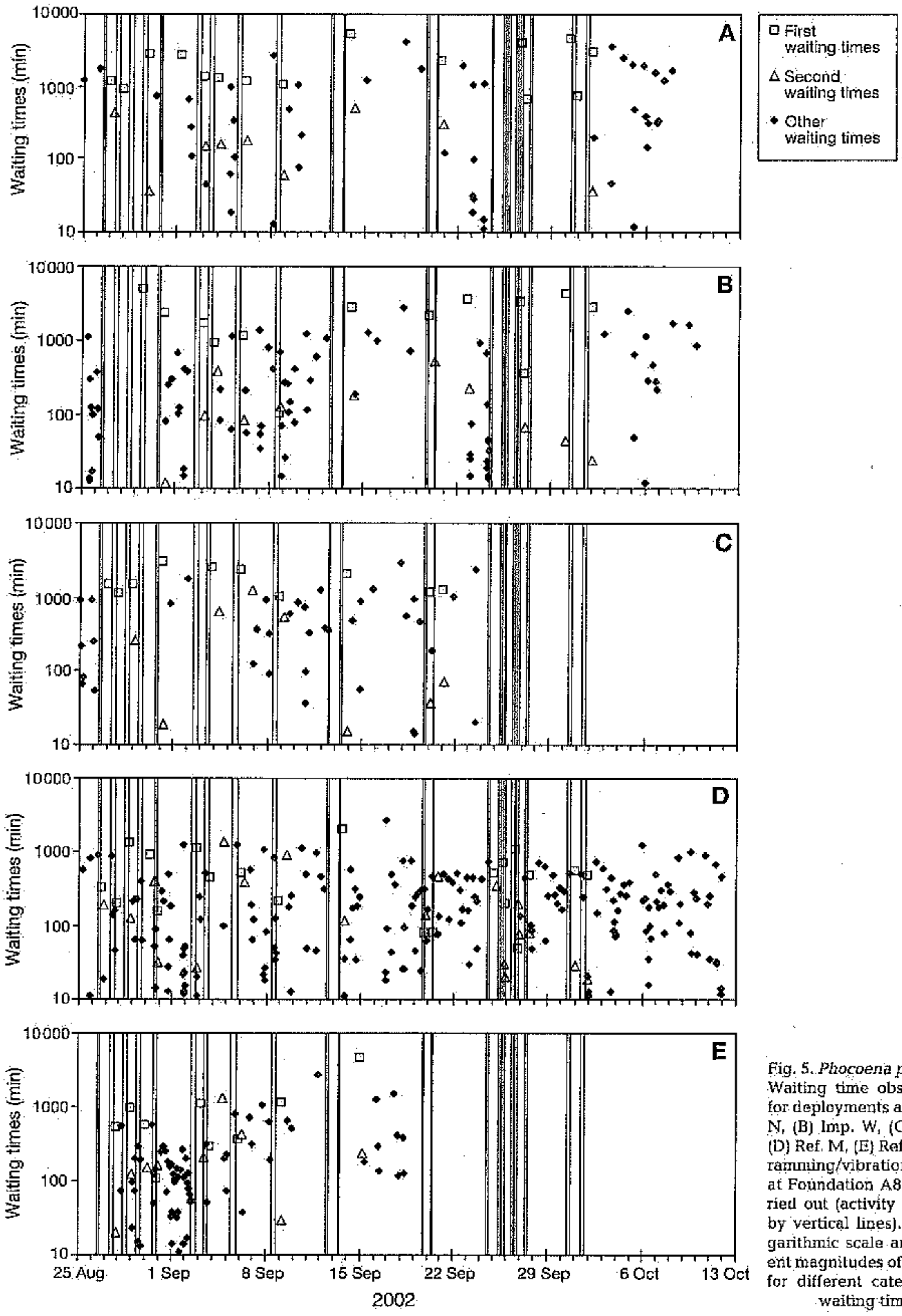


Fig. 5. *Phocoena phocoena*. Waiting time observations for deployments at (A) Imp. N, (B) Imp. W, (C) Ref. N, (D) Ref. M, (E) Ref. S, when ramming/vibration activity at Foundation A8 was carried out (activity indicated by vertical lines). Note logarithmic scale and different magnitudes of variation for different categories of waiting times

Table 5. *Phocoena phocoena*. First waiting times (min) after ramming/vibration activity had ceased versus second and other waiting times (min) from 25 August to 12 October 2002. Distributions of log-transformed data were back-transformed into median and mean waiting times by exponential function and moment transformation, respectively

Stn Waiting time	n	Log-transformed waiting time Mean	 Variance	 *F*	 p	Waiting time Median	 Mean
Imp. N							
1st	15	7.44	0.43	52.08	<0.0001	1708	2121
2nd + other	57	5.24	3.61			199	1164
Imp. W							
1st	13	7.40	1.25	52.99	<0.0001	1641	3062
2nd + other	95	4.77	3.24			128	604
Ref. N							
1st	10	7.40	0.15	55.09	<0.0001	1647	1771
2nd + other	47	5.21	3.41			193	1017
Ref. M							
1st	20	5.91	1.12	22.29	<0.0001	377	653
2nd + other	210	4.66	2.70			116	420
Ref. S							
1st	9	6.44	1.16	20.54	0.0007	639	1133
2nd + other	81	4.63	2.51			113	372

Table 6. *Phocoena phocoena*. Second waiting times (min) after ramming/vibration activity had ceased versus other waiting times (min) from 25 August to 12 October 2002. Distributions of log-transformed data were back-transformed into median and mean waiting times by exponential function and moment transformation, respectively

Stn Waiting time	n	Log-transformed waiting time Mean	 Variance	 *F*	 p	Waiting time Median	 Mean
Imp. N							
2nd	10	4.88	1.99	0.70	0.4142	141	364
Other	47	5.32	3.98			215	1506
Imp. W							
2nd	11	4.29	2.49	1.11	0.3102	83	262
Other	84	4.83	3.33			135	673
Ref. N							
2nd	8	4.58	4.31	0.93	0.3594	107	850
Other	39	5.34	3.24			218	1059
Ref. M							
2nd	19	4.61	2.35	0.03	0.8634	110	335
Other	191	4.67	2.75			117	433
Ref. S							
2nd	9	4.88	2.19	0.27	0.6121	142	403
Other	72	4.60	2.58			110	372

did not include seasonal variations during the ramming/vibration period from the end of August to the beginning of October, as these months had similar mean levels (Fig. 4).

It was not possible to estimate the entire covariance structure in the analysis of the first and second waiting times because of the limited number of observations. The covariance structure obtained from the BACI analysis (Eq. 1) implied that consecutive waiting times were positively correlated (lag 1 = 0.1870 and lag 2 = 0.1720), with a residual variance of 2.79 for the transformed waiting times, which was similar to the correlations obtained in the analysis of baseline data only (Eq. 4 without area × month) (lag 1 = 0.1330 and lag 2 = 0.1070), with a residual variance of 2.28. However, the residual variances of the first waiting times were considerably lower (0.15 to 1.25), whereas the variances of the second and other waiting times had magnitudes ranging from 2.51 to 3.61 (Table 5). These differences had repercussions for the mean back-transform using the moment transformation that included a contribution from the variance of the transformed variable (Tables 5 & 6). This was most pronounced for Imp. N, where mean levels were almost comparable although the medians differed by 1 order of magnitude.

DISCUSSION

We have employed a novel technique for monitoring the echolocation activity of harbour porpoises in order to assess the potential impact during construction of an offshore wind farm. Although standard hydrophones have been commonly used for monitoring whales in general (e.g. Au et al. 2004), documented studies using the autonomous T-POD are still few (Cox et al. 2001, Culik et al. 2001, Koschinski et al. 2003). Two T-PODs deployed in an exhibition facility in Kerteminde, Denmark (www.gounderwater.com), logged echolocation activity for about 4 to 9% of the time in which recordings were made (mean waiting times approx 40 min, encounter duration approx. 10 min; Teilmann et al. 2002) when the 2 captive porpoises were present in the pool, whereas only 3 porpoise encounters were recorded over 2 d without the captive porpoises present in the pool. These recordings may have originated from a wild porpoise approaching the enclosure, which is only separated from the sea by a net (Teilmann et al. 2002). Similar results were obtained with captive porpoises in the Netherlands (Thomsen et al. 2005). A study of wild harbour porpoises in Fortune Channel, Vancouver Island, Canada, showed that 98% of all visual observations within a distance of 150 m from a T-POD were also detected acoustically (Koschinski et al. 2003). Moreover, the echolocation rate, i.e. occurrence of click-trains, in our study (mean of 36.8 clicks min^{-1}) corresponded well with those (0 to 25 clicks min^{-1}) reported by Akamatsu et al. (1994) in a 2 wk study of 2 captive porpoises.

It is believed that harbour porpoises use their sonar mainly for navigation and catching their prey (Møhl & Andersen 1973), but there are no estimates of how frequently free-ranging porpoises use their sonar. It must be emphasised that captive individuals may not use their echolocation as much as wild individuals due to better visual conditions, no need to hunt for food, and well-known surroundings. The angular range of their sonar is rather limited (the 3 dB transmission beam width is 16°; Au et al. 1999), suggesting that the recorded echolocation activity may provide an underestimate of the 'true echolocation activity' within the T-POD range of detection, depending on the porpoises' movement patterns.

Harbour porpoise monitoring

Methods of monitoring harbour porpoises have mainly comprised abundance estimation by means of transect surveys from ship or airplane (Hiby & Hammond 1989). Estimating population sizes provides an important basis for conservation strategies in relation to the impact of bycatch in gillnet fisheries (Hammond et al. 2002). Surveys may also provide a means for environmental impact studies in localised regions such as (e.g.) offshore wind farms. However, in areas with relatively low harbour porpoise density, as in the SW Baltic Sea, density estimates will have a relatively high variance, which makes it difficult to obtain a reasonable power for statistical testing of a potential impact. Porpoise density estimates were also documented as depending on sea state (Barlow 1988, Palka 1996, Teilmann 2003). Different observers and platforms for the different surveys is another important source of variation that is not usually accounted for. Furthermore, substantial changes in diurnal and seasonal diving patterns (Teilmann et al. 2006b) are likely to bias density estimates obtained from visual surveys.

Acoustic monitoring by means of T-PODs provides high-resolution data in time, but has limited spatial coverage (Koschinski et al. 2003). New insight into seasonal, diurnal and area-specific porpoise occurrence can be obtained from this technique, particularly if the data are combined with covariates (e.g. salinity, currents) hypothesised to influence distribution patterns of harbour porpoises. As yet, echolocation activity has not been associated with density estimates, rendering this technique less useful for some management tasks. However, based on the present study we believe that echolocation activity can be regarded as a proxy estimate of relative abundance, making the T-POD an important tool for impact assessments in relatively small and defined areas.

Waiting time indicator

Continuous logging of environmental processes provides a whole new wealth of information, but places considerable demand on data processing. The echolocation activity recorded by the T-POD is a typical point process, similar to (e.g.) precipitation measured by tipping-bucket rain gauges. Although the threshold of 10 min used to separate encounters was determined empirically, this value appears reasonable from a biological point of view also. With an average swimming speed of 1.5 m s^{-1} (Teilmann 2000), a harbour porpoise would move 900 m in 10 min. With a T-POD detection range of about 170 m (Koshinski et al. 2003), it thus seems reasonable to use 10 min for separating encounters to obtain data that, although not entirely independent, are not strongly correlated. However, the autocorrelation suggests that there is still a significant probability that an individual porpoise or group of porpoises are being repeatedly recorded at successive waiting times. The estimated correlation structure shows that, beside the overall seasonal pattern, there are some systematic temporal variations at the scale of hours and days. The correlation between successive waiting times could also be due to non-stationary spatial patchiness in porpoise densities, such that during some periods there is a high density in the entire region leading to many short waiting times, and at other times a low density resulting in a few long waiting times.

The porpoise-click recordings could potentially be aggregated into lower frequency time series, e.g. daily observations, and the BACI analysis carried out using an appropriate transformation and distribution. However, in areas with a generally low density of harbour porpoises, several consecutive days with zero observations might result, and daily observations potentially reflect severe serial correlation. Therefore, the level of temporal aggregation should depend upon the area-specific porpoise echolocation activity. Encounters and waiting times have the advantage that these data can be combined with short-term disturbances such as ramming/vibration activity, whereas it is not possible to detect potential impacts on the time scale of 24 h or less from daily observations.

Monitoring designs

The T-POD deployments were planned as a symmetrical design with 3 stations in both the impact and reference areas. The exclusion of data from Stn Ref. N in combination with data losses from some deployments resulted in an uneven distribution of data over time and space. Applying the waiting time definition to the click-train recordings added to this skewness, with considerably more data in the summer months. Applying a seasonal variation in the BACI analysis allowed comparison of data sampled across different time periods. This asymmetry in both time and space sampling is a modification of the original BACI design (Green 1979), which did not consider several locations, and the 'Beyond BACI' design (Underwood 1994), which considered spatial replication in an asymmetrical design, but with the given process being considered as sampled at the same time at all locations. These designs have successfully been employed in a variety of different impact studies such as sewage outfall construction and removal (Archambault et al. 2001, Bishop et al. 2002), demersal trawling (Schratzberger et al. 2002, Rosenberg et al. 2003) and marine constructions (Lewis et al. 2002).

Another modification of the traditional BACI design was to incorporate a covariance structure for the residuals by means of a stochastic process. The large amount of data enabled consistent estimates of the covariance structure in the different analyses. Attempts to estimate the ARMA (autoregressive moving average) parameters in the analysis of the first and second waiting times after ramming activity were not successful due to convergence problems of the optimisation algorithm. Lack of data could be one reason why temporal correlations are generally ignored in BACI analyses and independent observations are assumed from re-sampling the same location. Another approach to accommodate temporal correlations is the application of repeated-measures designs (Green 1993).

Construction impact

The present study documents a substantial effect on the harbour porpoise echolocation activity from construction activities in general (medium-term response) and from specific ramming/vibration activities (short-term response). The data indicate that the porpoises avoided the construction area to a large extent or, alternatively, that their density remained unchanged but that they used their echolocation signals much less due to (e.g.) noise from construction activities. However, Koschinski et al. (2003) found that harbour porpoises used their echolocation more intensively when wind-turbine noise was played back to them in the wild. Teilmann et al. (2006a) found no change in echolocation activity in captive harbour porpoises when various high frequency sounds (100 to 140 kHz, 153 dB re 1 µPa (RMS) at 1 m) were played back, except during the first exposure to these relatively loud sounds, when the porpoises almost refrained from echolocating for the full 5 min sound exposure. Based on these experiments, it is unlikely that the harbour porpoises in our impact area would have echolocated less than in the reference area over the entire construction period. We contend that the recorded decrease in echolocation activity was related to a decrease in the density of the harbour porpoises.

The impact of ramming and vibration activity had a substantial, but short-lived effect on harbour porpoise activity at all stations, with significant increases in the first waiting times only. These 2 sources of acoustic disturbance during these construction activities had quite different properties. Frequency range and noise levels associated with the ramming/vibration activity were not measured. Noise from similar pile-driving operations was reported by Würsig et al. (2000), who measured broad-band noise in the frequency range 100 Hz to 25.6 kHz. The maximum octave band noise level measured was 170 dB re 1 µPa (400 Hz centre frequency) 250 m from the pile-driving site. Assuming pure cylindrical spreading in the shallow water area around the pile-driving site, this corresponds to a source level of approximately 194 dB re 1 µPa.

The harbour porpoise pinger deployed near Foundation A8 in connection with the ramming/vibration activity transmitted 8 different frequency modulated signals in the 20 to 160 kHz frequency bands, with a maximum source level of 145 dB re 1 µPa (www.aquatec.demon.co.uk). This sound device can be sensed by the harbour porpoises at a maximum range of 1600 m at Sea State 0 (Teilmann 2000). Given that distances from Foundation A8 to the monitoring stations were at least 2 km, it is unlikely that the harbour porpoise pinger could affect the recorded echolocation activity. The seal scarer used a source level of 189 dB re 1 µPa in the 10 to 15 kHz range (www.lofitech.no) that may have affected the harbour porpoises over greater distances. Hence, noise from the ramming/vibration activity and the seal scarer were most probably of similar magnitude, but considering that the higher frequencies of this harassment device are attenuated more quickly than the low frequencies of the construction works (Urick 1983), the sound level of this activity is likely to be higher in the reference area. However, harbour porpoise responses to different noise frequencies have not yet been documented.

Increases in waiting times were longer (4 to 41 h) than the duration of the ramming/vibration activities (1.5 to 10 h), with a tendency of relatively longer first waiting times in the impact area. This indicates that the ramming/vibration activities had a spatially declining effect on harbour porpoise densities, extending most probably beyond the 3 stations in the reference area (located >15 km from Foundation A8). If the porpoises were affected by noise from the construction over such long distances, this could explain that the first waiting times at the reference stations increased by several hours. Furthermore, if the reference stations were affected by the specific ramming/vibration activity, it is also likely that other construction activities may have influenced their density in the reference area. Although the BACI analysis assumed the reference area to be unaffected by the construction activities, the doubling of the waiting times in this area (Table 4) could potentially be associated with the construction of the wind farm. This implies that waiting times in the impact area may have increased by more than a factor of 6. Although we have established empirical evidence that construction activities reduced the echolocation activity of harbour porpoises in this study, and most probably reduced porpoise density also, the underlying cause–effect mechanisms still need to be investigated. Future years of monitoring will show if the harbour porpoise population in the Nysted Offshore Wind Farm region will recover.

The development of offshore activities is increasing rapidly, giving rise to a demand to assess their effect on the marine environment. The method developed in this study may be modified to study other echolocating cetaceans and determine the potential effect from offshore constructions or other human activities within a specified area.

Acknowledgements. We are grateful to Gregers Glendorf, Svend-Erik Rasmussen and Jan Simonsen from the cutter MS 'Amigo' for help with the T-POD deployments and their invaluable expertise on offshore equipment. We thank our colleagues Susi Edrén and Thomas Dau Rasmussen for help in the field, Ib Krag Petersen for providing the map, and Jakob Tougaard for constructive discussions on the acoustics. Nick Tregenza (Chelonia) is acknowledged for kind and prompt responses related to the T-PODs. We thank Charlotte Boesen, Per Hjelmsted Pedersen, Hans Ohrt and Pernille Holm Skyt from Energi E2 A/S for valuable comments on the manuscript and providing all necessary information and support in relation to the construction work. These investigations were funded by Danish public service obligations under contract with Energi E2 A/S. The manuscript was improved by valuable comments by anonymous reviewers.

LITERATURE CITED

Akamatsu T, Hatakeyama Y, Kojima T, Soeda H (1994) Echolocation rates of 2 harbor porpoises (*Phocoena phocoena*). Mar Mamm Sci 10:401–411

Archambault P, Banwell K, Underwood AJ (2001) Temporal variation in the structure of intertidal assemblages following the removal of sewage. Mar Ecol Prog Ser 222:51–62

Au WWL, Kastelein RA, Rippe T, Schooneman NM (1999) Transmission beam pattern and echolocation signals of a harbour porpoise (*Phocoena phocoena*). J Acoust Soc Am 106:3699–3705

Au WWL, Ford JKB, Horne JK, Allman KAN (2004) Echolocation signals of free-ranging killer whales (*Orcinus orca*) and modeling of foraging for chinook salmon (*Oncorhynchus tshawytscha*). J Acoust Soc Am 115:901–909

Bach S, Teilmann J, Henriksen OD (2000) Environmental impact assessment (EIA) of offshore wind farms at Rødsand and Omø Stålgrunde, Denmark. Virum, Rambøll (also available at: www.nystedhavmoellepark.dk/upload/pdf/Ramboll_2_Pebr.pdf)

Barlow J (1988) Harbor porpoise, *Phocoena phocoena*, abundance estimation for California, Oregon and Washington. I. Ship surveys. Fish Bull (Seattle) 86:417–432

Bishop MJ, Underwood AJ, Archambault P (2002) Sewage and environmental impacts on rocky shores: necessity of identifying relevant spatial scales. Mar Ecol Prog Ser 236: 121–128

Chatfield C (1984) The analysis of time series—an introduction, 3rd edn. Chapman & Hall, London

Cox TM, Read AJ, Solow A, Tregenza N (2001) Will harbour porpoises (*Phocoena phocoena*) habituate to pingers? J Cetacean Res Manag 3:81–86

Culik BM, Koshinski S, Tregenza N, Graeme ME (2001) Reactions of harbor porpoises (*Phocoena phocoena*) and herring (*Clupea harengus*) to acoustic alarms. Mar Ecol Prog Ser 211:255–260

Green RH (1979) Sampling design and statistical methods for environmental biologists. Wiley, New York

Green RH (1993) Application of repeated-measures designs in environmental-impact and monitoring studies. Aust J Ecol 18:81–98

Hammond P, Benke H, Berggren P, Borchers DL and 7 others (2002) Abundance of harbour porpoises and other cetaceans in the North Sea and adjacent waters. J Appl Ecol 39:361–376

Heide-Jørgensen M, Mosbech A, Teilmann J, Benke H, Schultz W (1992) Harbour porpoise (*Phocoena phocoena*) densities obtained from aerial surveys north of Fyn and in the Bay of Kiel. Ophelia 35:133–146

Heide-Jørgensen M, Teilmann J, Benke H, Wulf J (1993) Abundance and distribution of harbour porpoises, *Phocoena phocoena*, in selected areas of the western Baltic and the North Sea. Helgol Meeresunters 47:335–346

Hiby AR, Hammond PS (1989) Survey techniques for estimating abundance of cetaceans. Rep Int Whal Comm Spec Issue 11:47–80

Koschinski S (2002) Current knowledge on the harbour porpoises (*Phocoena phocoena*) in the Baltic Sea. Ophelia 55: 167–197

Koschinski S, Culik B, Henriksen OD, Tregrenza N, Ellis G, Jansen C, Kathe G (2003) Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Mar Ecol Prog Ser 265: 263–273

Lewis LJ, Davenport J, Kelly TC (2002) A study of the impact of a pipeline construction on estuarine benthic invertebrate communities. Estuar Coast Shelf Sci 55:213–221

Littell RC, Milliken GA, Stroup WW, Wolfinger RD (1996) SAS system for mixed models. SAS Institute, Cary, NC

McCullagh P, Nelder JA (1989) Generalized linear models, 2nd edn. Monographs on statistics and applied probability, 37. Chapman & Hall/CRC, Boca Raton, FL

McCulloch CE, Searle SR (2001) Generalized, linear, and mixed models. Wiley series in probability and statistics. Wiley, New York

Møhl B, Andersen S (1973) Echolocation: high-frequency component in the click of the harbour porpoise (*Phocoena ph.* L.). J Acoust Soc Am 54:1368–1373

Palka D (1996) Effects of Beaufort sea state on the sightability of harbor porpoises in the Gulf of Maine. Rep Int Whal Comm 46:575–582

Rosenberg R, Nilsson HC, Gremare A, Amouroux JM (2003) Effects of demersal trawling on marine sedimentary habitats analysed by sediment profile imagery. J Exp Mar Biol Ecol 285:465–477

Schratzberger M, Dinmore TA, Jennings S (2002) Impacts of trawling on the diversity, biomass and structure of meiofauna assemblages. Mar Biol 140:83–93

Teilmann J (2000) The behaviour and sensory abilities of harbour porpoises (*Phocoena phocoena*) in relation to bycatch in gillnet fishery. PhD thesis, University of Southern Denmark, Odense

Teilmann J (2003) Influence of sea state on density estimates of harbour porpoises (*Phocoena phocoena*). J Cetacean Res Manag 5:85–92

Teilmann J, Henriksen OD, Carstensen J, Skov H (2002) Monitoring effects of offshore wind farms on harbour porpoises using PODs (porpoise detectors). Tech Rep. National Environmental Research Institute, Roskilde (also available at: http://www.hornsrev.dk/Engelsk/default_ie.htm)

Teilmann J, Dietz R, Larsen F, Desportes G and 5 others (2004) Satellitsporing af marsvin i danske og tilstødende farvande. Tech Rep. National Environmental Research Institute, Denmark, Roskilde. (In Danish with English summary.) (Also available at: http://www2.dmu.dk/1_viden/2_Publikationer/3_fagrapporter/rapporter/FR484_samlet.pdf)

Teilmann J, Tougaard J, Miller L, Kirketerp T, Hansen K, Labberté S (2006a) Reaction of captive harbour porpoises (*Phocoena phocoena*) to pinger-like sounds. Mar Mamm Sci 22:240–260

Teilmann J, Larsen F, Desportes G (2006b) Time allocation and diving behaviour of harbour porpoises (*Phocoena phocoena*) in Danish and adjacent waters. J Cetacean Res Manag (in press)

Thomsen F, van Elk N, Brock V, Piper W (2005) On the performance of automated porpoise-click-detectors in experiments with captive harbor porpoises (*Phocoena phocoena*) (L). J Acoust Soc Am 118:37–40

Underwood AJ (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecol Appl 4:3–15

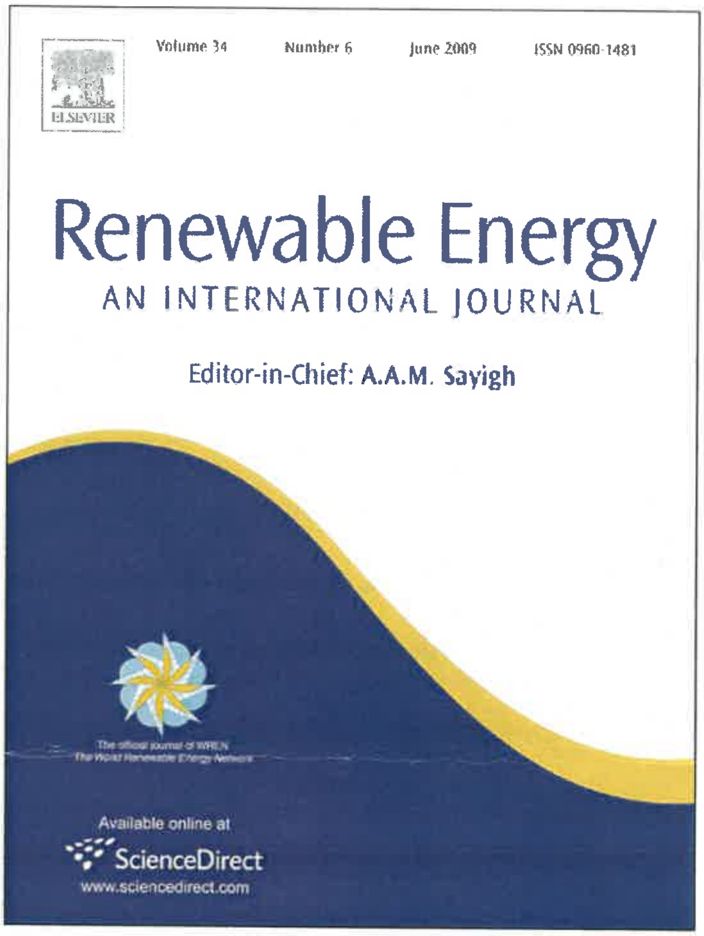
Urick RJ (1983) Principles of underwater sound. McGraw-Hill, New York

Würsig B, Greene CR Jr, Jefferson TA (2000) Development of an air bubble curtain to reduce underwater noise of percussive piling. Mar Environ Res 49:79–93

Editorial responsibility: Howard I. Browman (Associate Editor-in-Chief), Storebø, Norway

Submitted: July 14, 2004; Accepted: January 21, 2006
Proofs received from author(s): August 16, 2006

EV- 245-27



Volume 34 Number 6 June 2009 ISSN 0960-1481

ELSEVIER

Renewable Energy
AN INTERNATIONAL JOURNAL

Editor-in-Chief: A.A.M. Sayigh

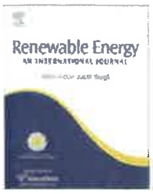
The official journal of WREN
The World Renewable Energy Network

Renewable Energy 34 (2009) 1567–1578

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Ecological and economic cost-benefit analysis of offshore wind energy

Brian Snyder*, Mark J. Kaiser

LSU Center for Energy Studies, Energy Coast and Environment Building, Baton Rouge, LA 70803, United States

A R T I C L E I N F O

Article history:
Received 18 September 2008
Accepted 9 November 2008
Available online 25 December 2008

Keywords:
Offshore wind economics
Ecological impacts
Cape wind

A B S T R A C T

Wind energy has experienced dramatic growth over the past decade. A small fraction of this growth has occurred offshore, but as the best wind resources become developed onshore, there is increasing interest in the development of offshore winds. Like any form of power production, offshore wind energy has both positive and negative impacts. The potential negative impacts have stimulated a great deal of opposition to the first offshore wind power proposals in the U.S. and have delayed the development of the first offshore wind farm in the U.S. Here we discuss the costs and benefits of offshore wind relative to onshore wind power and conventional electricity production. We review cost estimates for offshore wind power and compare these to estimates for onshore wind and conventional power. We develop empirical cost functions for offshore wind based on publicly reported projects from 2000 to 2008, and describe the limitations of the analysis. We use this analysis to inform a discussion of the tradeoffs between conventional, onshore and offshore wind energy usage.

1. Introduction

Over the past 10 years, the onshore wind industry in the U.S. has grown dramatically and as a result developers, citizens and the U.S. Congress have expressed interest in the development of an offshore wind industry. Several companies have developed plans for offshore wind projects and the U.S. Mineral Management Service (MMS) is in the process of reviewing these applications and developing regulations for the industry while the state of Texas has already leased lands for at least one and possibly several additional offshore wind farms. Lawmakers, government agencies, corporations, non-governmental organizations and private individuals are deciding whether or not to support or participate in the development of an offshore wind industry, and the relative level of support or encouragement to give this new industry. In making these decisions, stakeholders will have to balance the ecological costs and benefits of offshore wind against its economic costs and compare to offshore wind energy's most realistic competitors. The decision is complex and requires balancing local and global environmental issues, historical conservation and economic costs.

Offshore wind energy competes with both onshore wind energy and conventional fossil-fueled electricity. Onshore wind power and natural gas fired power are the two fastest growing segments of the electricity market. Coal power is the largest current producer of electricity in the U.S. Offshore wind will thus displace either coal, natural gas or onshore wind.

Given the uncertainties associated with global climate change, it is difficult to compare the societal costs and benefits of wind energy to fossil-fueled energy. However, one way to develop a first-order comparison of these costs would be include the costs of market based carbon offsets in the costs of conventional electricity. This assumes that the costs of carbon emission credits accurately reflect their ecological value which would occur if carbon credits actually represent a reduction of the specified amount of carbon dioxide from the atmosphere.

It is perhaps less difficult to compare the costs of onshore and offshore wind energy since they both have similar carbon emissions. In this case, one could simply compare the economic and ecological costs of onshore and offshore wind.

There are several reasons why developers or lawmakers might prefer offshore wind power over fossil-fueled power or onshore wind power. Offshore wind power could be less expensive than its competitors, either at a local or national scale, it could have the potential to be less expensive than its competitors, or it could have less severe social and environmental impacts than its competitors.

In this paper, we seek to address the question, "Is investment in offshore wind power preferred over investments in fossil-fueled or onshore wind power?" We focus primarily on coal-fired power as representative of fossil-fueled power since it is the dominant source of electricity in the U.S. and it is both inexpensive and a major source of greenhouse gases.

We begin with an overview of the commonly expressed criticisms and benefits of offshore wind power. We discuss cost models for offshore wind power and compare them to onshore wind power and conventional power. We also discuss the factors that lead to higher costs through a first-order empirical cost function and

---

* Corresponding author. Tel.: +1 225 578 4559.
E-mail address: snyderb@lsu.edu (B. Snyder).

0960-1481/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2008.11.015

discuss how these costs can be decreased. We discuss the environmental impacts of offshore wind power and how these factors can be mitigated. We end the paper with the conclusions of the analysis.

2. Criticisms of offshore wind power

There have been a number of criticisms on offshore wind power in the U.S., mostly associated with the Cape Wind project (Table 1, [1,2]). The environmental impacts are discussed in more detail below, the rest of the concerns are discussed here.

2.1. Navigational safety

Any structure placed in federal water must receive a permit from the Army Corps of Engineers (ACE). The ACE, through the Rivers and Harbors Act (RHA), has the authority to regulate obstructions to navigation in federal waters. The ACE considers a multitude of factors in making RHA decisions, however, their primary responsibility is protecting navigation, therefore they are unlikely to permit offshore wind projects that pose serious threat to U.S. shipping lanes. However, densely spaced wind turbines could provide a problem for recreational boats and small fishing vessels attempting to navigate through a wind farm. Typically, turbines in a wind farm are spaced 500–1000 m apart and have blades that at their lowest point are at least 20 m above the water. Small boats should therefore have no problem navigating among these turbine in good weather, however, some critics of the Cape Wind project have pointed out that the coast of Massachusetts is infamous for bad weather and shipwrecks. This is likely to be the case in many places in which offshore turbines are particularly profitable (i.e. areas with high winds).

2.2. Federal subsidies

Opponents of offshore wind projects claim that offshore wind power is not economically viable without federal "subsidies", by which they mean federal tax credits for renewable energy. The federal Production Tax Credit (PTC) gives a tax credit of \$0.02/kW h of produced electricity for the first ten years of production from any renewable source, including wind.[1] Opponents of the PTC argue that its original purpose was to help the renewable energy industry become established and because it originally became law in 1992, it should now be allowed to expire. In fact, the PTC did expire in 2000, 2002 and 2004 and is currently set to expire at the end of 2008. Interestingly, the pattern of wind capacity growth in the U.S. seems to closely follow the expiration of the PTC [3]. In each of the years in which the PTC was allowed to expire, the growth in wind capacity slowed markedly. Given the relatively unfavorable economics of offshore wind, it is reasonable to suggest that offshore wind energy projects will need the continuation of the Production Tax Credit (PTC) in order to be competitive.

2.3. Aesthetics

Opponents to wind power claim that wind turbines mar the landscape or seascape. This is especially an issue for the Cape Wind project in which local activists are concerned about the views from historic landmarks. There are some aesthetic issues that are beyond the scope of analytic tools, however, the effects of wind farms on property values has been analyzed. Sterzinger et al. [4] analyzed property values in the viewshed of onshore wind turbines and found that in eight out of ten cases the property values in the viewshed increased faster than the values in control sites. Furthermore, in nine of ten cases the rate of property value increase rose after the placement of the wind farm. Thus, there is no empirical evidence to suggest that wind farms negatively influence property values.

In Denmark, Ladeenburg and Dubgaard [5] estimated the willingness of citizens to pay for moving turbines further from shore. They found that respondents were willing to pay 46, 96 and 122 Euros per year per household in order to move a theoretical wind farm to 12, 18 or 50 km away from the coast, relative to an 8 km baseline [5]. Huaghton et al. [6] conducted a similar study on Cape Cod and found that 22% of respondents were willing to pay, on average, a onetime cost of \$286 for windmills to not be built, while 9% were willing to pay an average of \$112 for windmills to be built. The average net willingness to pay per person was \$75. These data suggest that on average the public views offshore wind turbines as visual disamentities, at least before they are built.

2.4. Cost and risk

The offshore environment is significantly more uncertain and difficult than onshore, and thus, more costly and risky. The offshore environment involves personnel traveling to and from offshore turbines; this increases equipment and time costs as well as insurance costs due to increased risks. Offshore work involves increased risks of storms which affect the amount of time available for maintenance and installation which in turn influence capital and operation costs. Offshore environments are corrosive to electrical and structural equipment and require turbines to be marinized with cathodic and humidity protection. Capital expenditures for offshore wind projects depend on marine vessel dayrates which are unpredictable, and offshore foundations require more steel for jackets and pilings than onshore foundations.

2.5. Unpredictable power

One of the most substantive criticisms of wind power is that it is unable to provide constant, predictable power to the grid. The electricity grid is designed to send a constant AC load to consumers and it relies on large power plants producing predictable and steady electricity. Wind energy is not steady and varies on the scale of minutes, hours, days and months and the changes in wind power output are difficult to predict ahead of time [7]. Therefore, integrating wind power into the electricity grid will require backup systems (especially natural gas fired power plants) that can respond quickly to changing production from wind farms [8]. This increases the total national cost of electricity. The DOE has estimated that the supply up to 20% of the nation's electrical use from wind power would cost up to \$5/MW h in integration costs [9].

3. Benefits of offshore wind power

Offshore wind power shares all of the same benefits of onshore wind power relative to conventional power sources (Table 1). Most notably, wind power has very low carbon emissions over its lifecycle, as well as negligible emissions of mercury, nitrous oxides and sulfur oxides. Wind power does not use fuel and is therefore freed from the price volatility associated with electricity generated from oil, natural gas, biomass, nuclear and coal. Wind power does not rely on large sources of freshwater as conventional sources of power do [9]. In the near term, offshore wind power will be more expensive than onshore wind power, however, there are several benefits of offshore wind power that are not shared by onshore wind; these benefits may or may not justify the additional costs.

---

[1] For example, if a 400 MW wind farm has a capacity factor of 50%, then it would produce about 1.7 billion kW h of electricity annually, and would qualify for 35 million dollars in tax credits each year for the first ten years of its operational life.

Table 1
Summary of arguments for and against offshore wind and comparison to onshore wind.

	Applies to onshore wind power	Validity
Arguments against offshore wind		
Ruins special/historic seascape	Y	Aesthetics subjective, but wind turbines are visual disamenity to most. No effect on property values.
Kills birds	Y	Expected death rate 1–10 birds per MW. Difficult to compare effects of wind and fossil fuels on bird populations on a per MW h basis.
Harms fisheries	N	Likely to be significant impacts on local fisheries during construction, especially if monopiles are used. During operation fishing success may increase.
Harms marine mammals	N	Likely to have impacts on marine mammals during construction, especially if monopiles are used, potentially including mortality. During operation impacts will be negligible.
Requires subsidies	Y	Offshore wind power not economically competitive with onshore wind or fossil-fueled power.
Endangers shipping/navigation	N	Site dependent. USACE must permit projects and decide if they threaten navigation.
Hurts tourism	N	Offshore wind projects have caused net increases in tourism.
Arguments for offshore wind power		
Mitigates climate change	Y	Wind power produces very little greenhouse gas emissions over its life cycle.
Decreases water use	Y	Each MW of wind capacity can offset 0.7–2.1 million gallons of water consumed per year
Improves air quality	Y	Cape wind estimated to prevent 11 mortalities per year (Kempton et al., 2005), but depends on fuel mix of power actually displaced.
Reduces foreign fuel dependence	Y	Roughly 50% of U.S. electricity comes from coal; U.S. exports more coal than it imports. Roughly 20% of electricity from natural gas. Roughly 20% of this natural gas is imported, almost entirely from Canada.
Creates jobs	Y	The Cape Wind project will create about 50 permanent jobs, plus 100 indirect jobs. Construction will create several hundred additional jobs.
Creates electrical price stability	Y	Wind power provides price stability since cost of producing energy can be forecast, but even most ambitious plans only imagine 20% of U.S. electricity supply to come from wind in 2030.
Close to population centers	N	Offshore sources are closer to population centers than onshore wind sources, but it is probably cheaper to build new transmission systems from high-wind onshore sites.
Higher winds offshore	N	Winds are more powerful offshore, but COE of offshore wind is higher than COE of onshore wind, suggesting that higher wind speeds do not make up for higher capital costs.
Reduced user conflicts	N	Site and plan specific; seems to be occurring in Texas, not in Cape Cod.

3.1. *Location*

Onshore wind resources in the U.S. are localized in the middle of the country, far away from large population centers. Offshore wind power is physically close to the major population centers of the coastal United States, thereby removing the need for expensive high voltage transmission [10]. However, with a large enough investment, it may be more efficient to build these transmission lines then it would be to invest in offshore wind power. Recent studies have evaluated the costs of producing 20% of the nation's electricity from wind (primarily onshore wind). The cost to transmit this electricity from the wind centers of the west and midwest to the population centers on the coasts has been estimated to be about $20 to $26 billion. This would add about $120 to $180 to the capital costs of new construction making total capital costs about $2000/kW, below current offshore costs of around $3000–4000/kW [9].

Onshore wind power, in some cases, has been stalled by local opposition due to conflicts between alternative land uses [11]. One potential benefit of offshore wind is that it may reduce this conflict [12]. Wind turbines can be placed far enough from the shore to be inaudible and, potentially, invisible. Local opposition to the Cape Wind project remains strong, but does not seem to be the case in the Galveston Offshore Wind Project [13].

3.2. *Power*

Offshore winds are generally stronger and more constant than onshore winds. As a result, turbines are expected to operate at their maximum capacity for a larger percentage of the time, and the constancy of wind speed reduces wear on the turbine and provides a more constant source of power to the electrical grid reducing the need for other sources of electricity to serve as backups [14]. The increase in wind speed leads to a 150% increase in electricity production for offshore wind turbines [15] and an increase in the capacity factor of the wind farm from about 25 to 40% [16].

3.3. *Transport and construction*

The marine cranes developed for the offshore oil and natural gas industry are capable of handling larger equipment than onshore cranes, thus allowing for larger turbines to be efficiently erected at sea. The transportation of the required enormous pieces of equipment is also made significantly easier at sea [17]. The size of onshore turbines is limited by the ability to transport the blades, tower and nacelles of the turbines. As a result, cost reductions due to the economics of scale are limited. However, at sea these constraints are not an issue and wind turbines already exceed 5 MW and may eventually exceed 10 MW. These larger turbines may make offshore wind power more economically attractive due to the economies of scale.

3.4. *Design considerations*

Offshore wind power also has several potential benefits that have not yet been realized due to its nascent nature; these benefits are related to the potential for new turbine designs optimized for the offshore environment [18].

Turbine noise is an oft-cited criticism made by opponents to onshore wind power [19]. The offshore wind power industry does not have to be as concerned about turbine noise as does the onshore industry. As a result, the offshore industry can use far larger turbines [17]. These larger turbines should make offshore wind power more economically attractive due to scale economies. Additionally, if offshore turbines are freed from constraints of noise, then turbine manufacturers could build turbines with downwind rotors, that is, rotors that are located behind (with respect to the wind direction) the support tower and nacelle. In upwind rotors, extreme wind speeds could deflect the blades back toward the tower. Thus the blades have to be made very stiff, increasing their price and weight (the increased weight also increases the expense of the tower, foundation and construction). In a downwind rotor the blade can be more flexible. However, as the blades pass through the wind shadow caused by the tower they create a low frequency noise. Offshore wind farms would not need to be as concerned with this noise [20].

Offshore wind farms located over the horizon could also make use of lattice towers instead of tubular towers. These lattice towers require less material and are therefore lighter and cheaper than the more common tubular towers, however, they are rare for aesthetic reasons [21]. Similarly, two bladed turbines were rejected by the European market for aesthetic reasons [20], however they are lighter (and therefore less expensive) than three bladed turbines.

4. Cost estimates of wind power

The economic costs of conventional, onshore and offshore wind power are shown in Table 2. The estimate for conventional power comes from an average of all power generation in the U.S. There is a great deal of variation in the estimates for offshore wind costs which is due to the assumptions of the analysts and the year in which the estimates were performed. Commodity prices have increased significantly in recent years, and the costs of turbine construction and installation have also increased, both onshore and offshore. Additionally, the methodology through which cost estimates are made, and their potential application can differ significantly. What is clear is that the costs of onshore wind power are competitive with conventional power sources, but that the costs of offshore wind power are more expensive than either onshore or conventional electricity perhaps by a factor of 2–3. The exact price of the premium is time and site specific, but may be up to \$50/MW h. Since onshore wind is cost competitive with conventional electricity, the premium is similar for both energy sources and may be higher for onshore wind than for conventional power.

4.1. Costs of onshore wind power

Data on the costs of offshore wind power is relatively sparse due the limited number of installations and the lack of reporting. Data on onshore wind power costs are more readily available. The price of onshore wind generated electricity (cost of energy; COE) declined from 1999 to 2005 from approximately \$63/MW h in 1999 to \$36/MW h in 2005. However, in 2006 the price began to rise again and in 2007 the price of wind generated electricity was \$40/MW h (all prices in 2007 dollars). Even with this increasing price, wind power is competitive with conventional power sources; since 2003 wind generated electricity has been at or below the average national wholesale price of power.

Table 2
Capital costs and cost of energy of offshore wind farms.

Wind farm or type of estimate	Year of prediction/ estimate	Cost of energy (\$/MW h)	Capital costs (\$/kW)	Source
Generating costs of coal-fired electricity	2003	49		[60]
National average wholesale price of power (primarily coal, gas and nuclear)	2008	58		[22]
Generic estimate based on empirical data (Onshore)	2008	40	1710	[22]
Generic estimate based on small set of empirical data	2005	40–95	1600–2600	[64]
Theoretical w/3 MW turbine	2006	95	2100	[23]
Theoretical 500 MW farm, 5 MW turbines, 15 miles from coast	2004	54	1200	[17]
LIOWP (cancelled)	2007	291	5231	[25]
Generic estimate for future wind farm	2007		4000	[25]
General based on empirical data	2007	100	3200	[33]
Cape Wind	2007	122		[65]
Estimates from proposed wind farms	2001	48–70		[66]
Generic estimate based on all available empirical data	2008		3354	Data in Table 3
Middelgrunden	2005	70		[26]
Theoretical Generic estimate	2006		3500	[18]
Empirical data	2003		2200–2600	[62]

Part of this rising price is attributed to the rising capital costs of wind farms. From the early 1980s to the early 2000s, capital costs of wind farms declined by \$2700/kW. From 2001 to 2003 the capital costs for onshore wind farms averaged about \$1450/kW; by 2007 these costs had risen to \$1710/kW. These increasing project costs are due to increasing turbine costs which have increased as demand and commodity prices have grown.

The primary drivers of the COE are the capital costs of a wind farm and the capacity factor. COE increases with the capital costs and decreases with the capacity factor [22].

4.2. Offshore cost estimates

Musial and Butterfield [17] developed a model of the costs of offshore wind farms. They modeled a hypothetical 500 MW wind farm composed of 100, 5 MW turbines. The farm was in shallow water, 15 miles from the coast. They assumed that the turbines would cost \$340 million, the foundations \$100 million and the electrical connections \$160 million. This gave a total construction cost of \$1200/kW and a cost of energy of \$54/MW h.

Fingersh et al. [23] modeled the costs of a single 3 MW turbine in shallow water, but included the per turbine costs of electrical interconnection. The cost of electricity was a function of the annual expenses divided by the annual energy production. The annual expenses included the rate of return on the initial capital investment (11.85%) times the initial capital required (\$6.3 million; \$2100/kW) plus the land lease costs (\$12,000), operation and maintenance costs (\$215,000 per year), and replacement and overhaul costs (\$55,000 per year). Fingersh et al. assumed a capacity of 38% and predicted the total costs to be \$95/MW h. They used a similar method to estimate the costs of onshore wind power and found them to be roughly half the costs of offshore wind power.

In the now defunct Long Island Offshore Wind Park (LIOWP) agreement between FPL Energy and the Long Island Power Authority (LIPA), LIPA agreed to pay \$94.97/MW h for offshore produced wind power. This rate was designed to increase annually at 2.75% [24]. PACE Global Energy Services conducted an independent report for LIPA and found that the costs of construction were approximately \$750 million (\$5231/kW). This translated into a cost of energy of \$291/MW h. PACE also estimated the costs of a future (2010) generic European offshore wind farm at \$4000/kW. This high cost is due to the increasing price of materials [25].

4.3. Cost components

The primary component costs for on and offshore wind based on empirical studies are shown in Fig. 1. The primary capital cost for onshore wind projects is the turbine; installation costs make up about 14% of the total capital costs. For offshore wind projects, the costs of installation is higher, approximately 20% of the total costs and the costs of building and installing the foundations account for another 20% of capital costs. For offshore wind, operation and maintenance costs make up a larger proportion of the overall components of the COE [23]. This is likely due to the costs of accessing offshore wind farms and maintaining turbines in operating condition.

5. Offshore cost functions

5.1. Data source

We have compiled data from a variety of public sources on the costs of offshore wind farms built in Europe (Table 3). Construction

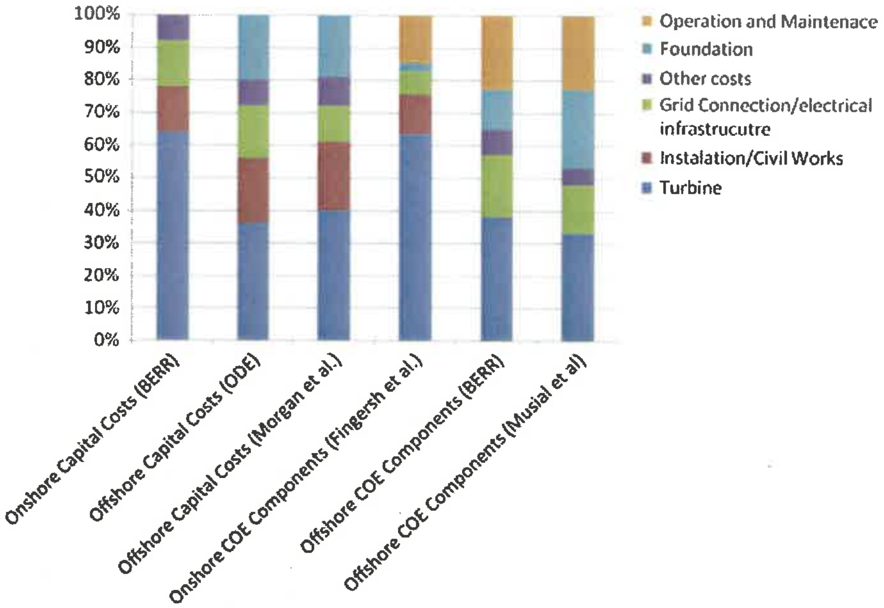


Fig. 1. Costs of onshore and offshore wind. Sources: [23,31,33,62,63].

costs have ranged in price from $1462 to $7000/kW of capacity and average $3354/kW of capacity. Excluding Beatrice, estimated costs for not yet completed wind farms and developments built before 2000, construction costs for wind farms built between 2001 and 2007 ranged from $1462 to $3125/kW. We believe the smaller sample is more representative of general trends and use it for all further analyses.

These data come from a variety of sources including developer websites which we cannot independently verify. These data may not reflect the entire costs of construction in all cases such as the cost of transmission studies and permitting. The cost data were inflated to 2008 dollars by converting the original cost to dollars using the average exchange rate in the year in which the estimate was given (assumed to be the year of construction unless otherwise indicated), then inflating to 2008 dollars using the U.S. Bureau of Labor Statistics calculator.

5.2. Model specification

We created multiple regression models of capital cost based on several factors. We hypothesized a cost model in which the predictor variables were total capacity, water depth, distance to

Table 3
Costs of offshore wind farms in Europe.

Wind farm	Nation	Year constructed	Capacity (MW)	Total cost[a] (million)	Depth (m)	Turbine size (MW)	Number of turbines	Distance to shore (km)
Vindeby	Denmark	1991	5	11.2	3.5	0.45	11	1.5
Lely	Netherlands	1994	2	4.8	7.5	0.5	4	0.8
Tuno Knob	Denmark	1995	5	11.2	4	0.5	10	3
Dronten	Netherlands	1996	11	28.6	1.5	0.6	19	0.03
Bockstigen	Sweden	1997	3	4.8	6	0.55	5	
Blyth	UK	2000	4	7	8.5	2	2	1
Middlegrunden	Denmark	2001	40	53	6	2	20	2
Utgrunden	Sweden	2001	10	14	8.6	1.425	7	
Yttre Stengrund	Sweden	2001	10	18	8	2	5	
Horns Rev	Denmark	2002	160	500	10	2	80	14
Nysted	Denmark	2003	158	373	7.75	2.3	72	10
Samso	Denmark	2003	23	52	20	2.3	10	3.5
North Hoyle	UK	2003	60	148	12	2	30	7
Ronland	Denmark	2003	17.2	26	1	2.3	8	
Scroby Sands	UK	2004	60	155	16.5	2	30	2.5
Arklow	Ireland	2004	25	70	3.5	3.6	7	10
Kentish Flats	UK	2005	90	217	5	3	30	10
Barrow	UK	2006	90	190	17.5	3	30	7.5
Egmond aan Zee	Netherlands	2006	108	334	18	3	36	10
Burbo Bank	UK	2007	90	185	5	3.6	25	6.5
Beatrice	UK	2007	10	70	45	5	2	22
Lillgrund	Sweden	2007	110	300	7	2.3	48	10
Q7	Netherlands	2007	120	590	21.5	2	60	23
Lynn/Inner Downsing	UK	2008	90	600	9.5	3.6	54	5
Robin Rigg	UK	2008	180	765	5	3	60	9
Throton bank	Belgium	2008	300	1250	14	5	60	27

Sources: [18,26,64,66–75].

[a] Adjusted for inflation using the Bureau of Labor Statistics calculator and exchange rates at the time of construction.

shore, year constructed, turbine size, and number of turbines. We had no reason to assume that any interaction or higher-order terms would be appropriate.

5.2.1. *Total capacity*

Obviously, increasing the size of development will increase the capital costs of the project and this parameter is needed in the model in order to control for varying sizes of developments. However, the costs are unlikely to scale linearly with the size of development. Installation costs, and grid connection costs, and even turbine costs are unlikely to scale linearly with the size of the wind farm. For example, for orders of over 100 turbines there is approximately a 30% reduction in the list price [16]. Nonetheless, we expect that the total capital costs will increase with increases in total capacity.

5.2.2. *Turbine capacity*

There is a clear trend toward increasing turbine size in onshore [22] and offshore applications. This could decrease costs since larger capacity turbines would require fewer foundations for the same sized wind farm, however, larger components require larger barges and cranes for construction which are less common and more expensive than smaller barges. There is no relationship between turbine capacity and the per kW capital costs of offshore wind farms (Fig. 2) and so we do not hypothesize relationship between increasing turbine capacity and capital costs.

5.2.3. *Distance to shore*

The distance to shore influences both the construction and operation and maintenance costs. During construction the ships will have to make a number of trips between the site and shore to load additional equipment. This travel period is costly and therefore the closer an offshore site is to an industrial port facility, the less expensive installation will be. Furthermore, the distance to shore also dictates the amount of transmission cabling required. During operation a maintenance crew will need to make regular trips to the wind farm to monitor the foundations, towers and turbines [26]. Locating this crew as close as possible to the wind farm will decrease both the environmental impacts and the costs of maintenance. We expect distance to shore to be positively related to capital costs.

5.2.4. *Water depth*

Water depth is a primary factor in most offshore operations in the oil and gas industry, and thus we suspect water depth will also eventually play an important role in determining costs as offshore wind farms are installed in ever deeper water. Increasing depths increase the price of construction by making monopile and gravity foundations impractical and potentially requiring the use of expensive, jacketed foundations and expensive marine vessels for installation. Shallow water can restrict the access of some large barges which could also restrict operations. Many cable laying vessels have deep drafts (up to 8 m); therefore shallow water may necessitate the use of remotely operated vehicles (ROVs) for cable laying operations. Use of ROVs and divers in offshore construction will significantly impact costs.

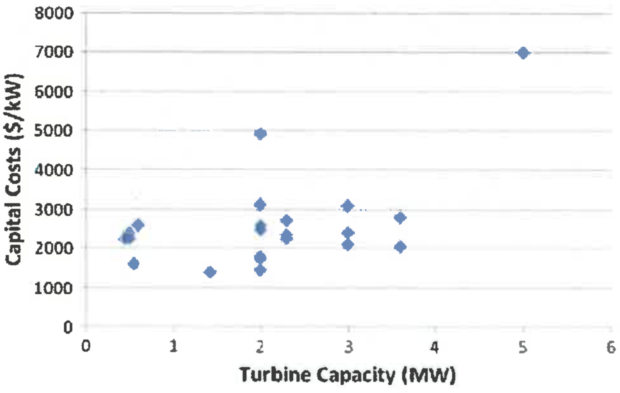


Fig. 2. Capital costs versus turbine size.

5.2.5. *Year of construction*

There is a general expectation that technological learning will cause the cost of offshore wind installations to decrease [16]. This has occurred in the onshore wind industry with consequent expansion in capacity, and there is a great deal of expectation that a similar phenomenon will occur in the offshore wind industry. Year of construction may be negatively associated with capital costs, but we do not suspect that the sample set is sufficiently large to detect such effects.

5.3. *Model results*

We checked the variables for colinearity using a correlation matrix and found no parameters with correlation coefficients greater than 0.7. Therefore, we left all parameters in the model and applied various combinations of the 5 parameters and ranked the models according to their adjusted R^2 value. The models and their parameter estimates are given in Table 4.

Three variables common to all three of the best models were total capacity, distance to shore, and turbine size. As expected, costs increased with increases in total capacity and distance to shore, and decreased with increases in turbine size. The year of construction and water depth were not significant in any of the models. The water depth value from the sample set ranged from 1 to 21 m which is not sufficient to detect depth effects. The cost element is also too gross to expect time to play a significant role in the model.

5.4. *Limitations of analysis*

The capital costs of offshore wind farms is governed by conditions unique to the structure, site contractor and country as well as the prevailing environmental, engineering, market, operational, and regulatory conditions at the time of the operation. The unique nature of the offshore operations and construction objectives drives the variability observed and can only be partially explained through factor analysis.

6. Managing costs

With a COE of up to $100/MW h (Table 2), offshore wind is not currently cost competitive with either onshore wind or conventional electricity. However there are a number of factors which may

Table 4
Parameter estimates from the three best models from multiple regressions.

Total cost (million $) = $\beta_0 + \beta_1^*$ (year) + β_2^* (distance to shore (m)) + β_3^* (turbine size(MW)) + β_4^*(capacity (MW)) + β_5^*(water depth (m))

Parameter	Model 1	Model 2	Model 3
β_0	−21,029 (0.2281)[a]	18.02 (0.6929)	−19,293 (0.2890)
β_1	10.53 (0.2271)		9.66 (0.2887)
β_2	9.28 (0.015)	9.97 (0.0007)	8.43 (0.0111)
β_3	−56.14 (.0204)	−39.06 (0.0346)	−57.68 (0.0229)
β_4	2.45 (<0.0001)	2.65 (<0.0001)	2.53 (<0.0001)
β_5			1.05 (0.5825)
Adj R^2	0.92 (<0.0001)	0.91 (<0.0001)	0.91 (<0.0001)

[a] *P*-values reported in parenthesis.

lead to significant cost reductions in the future and there are many factors that may make offshore wind locally attractive.

The COE for offshore wind power is determined by the capital costs of installation, the interest rate, the operation and maintenance costs, and the energy produced. Offshore wind developers have little control over some of these factors (e.g., the interest rate), but site selection and project planning can reduce costs and increase revenues. Furthermore, the costs of offshore wind may decrease over time due to technological learning.

6.1. *Factors influencing revenue*

The wind profile at a site determines the COE and the revenue to a wind farm operator by determining the number of kW h sold. Since wind power scales with the cube of wind velocity, the velocity of the air is likely to be the most important single factor in determining the placement of offshore wind farms and their profitability. The strongest winds offshore of the U.S. occur in the Aleutian Islands in Alaska, off the coast of northern California and southern Oregon, and in the Atlantic Ocean off the southern and eastern coasts of Massachusetts. In all of these places wind speeds at 50 m average 8.8–11.1 m/s [10]. While these are the largest concentrations of strong winds, there may also be areas of class 7 winds (the most powerful wind class, considered superb by NREL for energy production) at 80 m off the coasts of Texas, Louisiana, North Carolina and Long Island [27], however, these winds were not identified by some other studies [10].

The value of energy is also determined by the time of the day in which these winds blow. Electricity is not equally valuable throughout the day and developers interested in site selection need to know not just the mean annual wind speed, but the time of day and time of year in which the wind is strongest.

Revenue is determined by costs of energy at the local level. In the U.S. the average retail price of electricity ranges from 4.92 to 20.72 cents/kW h [28]. Thus an offshore wind farm may not be practical in Washington (average retail price of electricity is 6.14 cents/kW h) but may be very profitable in Hawaii where the average price is over 3 times higher (20.72 cents/kW h).

Revenue is also impacted by what other marketable products the wind farm generates. In states with Renewable Portfolio Standards (RPS), wind farm operators could sell renewable energy credits (RECs). States with RPS include most of the states with offshore wind potential with the exception of Ohio, Georgia, Louisiana and Michigan. The prices of RECs vary dramatically with the most expensive RECs being about $45 to $55/MW h in Massachusetts, Connecticut and Rhode Island.

The differences in local prices for electricity and RECs mean that the Cape Wind project may be able to sell its electricity for about 13 cents/kW h (average wholesale price of electricity in New England in 2007 was 7.7 cents/kW h; average REC price is 5.5 cents/kW h), while the Galveston Offshore Wind project may only be able to sell electricity at half that rate (average wholesale price of electricity in Texas in 2007 was 5.7 cents/kW h; average REC price is 0.5 cents/kW h; [22,28]). These differences in revenue could determine if a wind farm would be competitive with fossil-fueled fired electricity or not.

6.2. *Site selection impacts*

Previously, we discussed the possible impacts of water depth and distance to shore on capital costs, however, other factors associated with the site selection will also impact capital costs, for example, seafloor geology. Most offshore wind farms have been established using driven monopiles, however, monopiles are impractical in rocky soil since they may require drilling. Suction caissons have been employed as foundations for some turbines and they have been installed in both clay and sandy soils, but, firmer substrates require larger pressure difference between the outside and inside of the basket. Therefore, suction foundations may be impractical in some shallow water applications.

Areas with extreme weather events, and even areas with a high frequency of moderate weather events, can also influence costs. Moderate waves (above 2 m) can delay construction and effect the proportion of time that maintenance crews can access the turbines.

Hurricanes could dramatically influence the costs of construction and insurance. Current onshore towers are built to withstand 120 mph winds; hurricanes often have winds that significantly exceed this threshold. WEST, a company interested in building an offshore wind farm off the coast of Texas, has developed plans for a wind turbine that could withstand winds in excess of 150 mph [29]; it is unclear how much this might add to the cost of a turbine. Given the frequency of hurricanes in the Gulf of Mexico and the 20–30 year lifetime of a wind farm, it seems prudent for any wind farm to plan on being impacted by one or more hurricanes over its lifetime.

6.3. *Project specific impacts*

The costs of installation are partly determined by how many of the components are assembled on land. In some cases, developers have assembled components and even complete turbines on land and then shipped them to the installation site. This may decrease the time in which barges are needed but increase the sizes of the barges needed for construction. Barge costs are determined by the market; if wind farm development increases barge utilization then demand conditions will likely increase dayrates. Contracts with barges can be on either a turnkey or dayrate basis. Turnkey contracts transfer the operational risks associated with construction to the contractor; the party who holds weather related delay is determined by the terms of the contract.

6.4. *Economies of scale*

The largest wind turbines in the world are built by two German companies, Enercon and Repower. Enercon is building a 6 MW prototype land-based turbine while Repower sells a 5 MW turbine. Physical principles suggest that these larger machines should be more expensive per kW than smaller turbines because the material needed for a turbine should scale with the third power of rotor diameter while the power should scale with the square of rotor diameter [16,20]. However, empirical data suggest that the cost per kW of capacity has stayed relatively constant with increasing rotor diameter due to technological innovation [20] and the weight of the blades and the nacelles has scaled with the exponents 2.3 and 1.5 respectively, rather than the cube as expected [16]. This, combined with the fact that operation and maintenance costs are lower for wind farms with fewer, larger turbines, means that as the scale of wind farms increases, the costs of energy may decrease [30]. These cost reductions reach a limit for land-based wind farms due to the high costs of transporting huge turbines and blades. For offshore turbines transportation over roadways is not an issue, and it is likely that the size of offshore turbines may continue to increase above 5 MW [9]. We would expect that wind farms using large turbines would therefore be cheaper on a per kW capacity basis, but so far this has not occurred (Fig. 2).

We might also expect larger wind farms to be less expensive on a per MW basis than smaller wind farms [31]. This could occur through discounts with large turbine purchases, through learning associated with installation of foundations, through operation and maintenance efficiencies or through decreasing per MW electrical connection costs. However, neither the data for onshore wind farms seem to support this expectation [32] nor do the data for offshore wind farms (Fig. 3).

6.5. Technological learning

Musial and Butterfield [17] predicted that the COE for an offshore wind farm in shallow water would decline from \$54/MW h in 2006 to \$32/MW h 2025 based on technological learning and independent of cost reductions through scale economies.

There are several ways in which technological learning could take place; it could occur through incremental developments, the development of new main components, or through the development of entirely new turbine concepts [18]. Incremental development consists of developing new methods for turbine installation, advanced blade materials, easier access to the turbines, and more reliable electronic components, and is expected to be the major source of future price reductions[2] [18,33]. Other options for technological cost reductions include the use of DC transmission, the mass production of jacketed structures, and the assembly of turbine components onshore [16,18,33].

7. Environmental impacts of offshore wind power

Offshore wind power has both positive and negative environmental consequences. The negative environmental consequences are generally local, whereas the positive environmental consequences are global and exist only insofar as offshore wind power displaces other forms of electricity generation. The environmental impacts studied in the Cape Wind EIS are shown in Table 5, but note that the U.S. Fish and Wildlife Service has objected that the data used to make the determinations in the table were not adequate. In general, the environmental impacts of offshore wind are similar to those from onshore wind, however, offshore wind has additional environmental impacts, primarily associated with the effects of noise on marine animals, that onshore wind does not share.

7.1. Impacts on birds

One of the primary concerns surrounding wind farms is the risk that they will cause excessive avian mortality through collisions. The birds most at risk of collision will be seabirds, and in some cases migrating passerines. While bird mortality increases due to the risk of colliding with offshore turbines, the rate of mortality is relatively low, from 0.01 to 23 mortalities per turbine per year (these data are from both on and offshore wind farms; [34]). On a per MW basis, fatalities range from 0.95 to 11.67 deaths per year [35]. Altamont pass in California became notorious for its bird mortality. While the annual collision rate per turbine was low (0.02–0.15 collisions per year), mortality was still sizable due to the fact that 7000 turbines were involved and many of the birds killed were golden eagles, a charismatic species [34]. These data suggest that the fatality rate may be highly dependent on site specific factors.

The estimates above were generally taken from studies in which mortality was measured by counting dead birds found near turbines and, in some cases, correcting for birds removed by scavengers. In the offshore environment counting carcasses is likely to be very difficult due to the fact that many carcasses will not be found [36]. At Nysted, a thermal imaging system was placed on one of the turbines and could monitor 30% of the swept area for bird collisions. Using these data, it was predicted that approximately 0.02% of birds would collide with turbines.

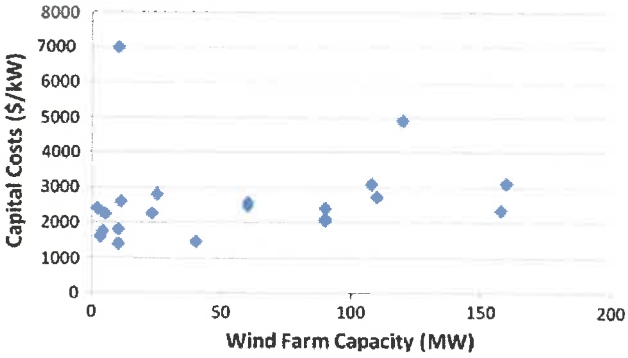


Fig. 3. Capital costs as a function of wind farm size.

Wind farms can also pose barriers to birds. Birds often seem to avoid flying through wind farms; this likely decreases their mortality [37]. However, birds that avoid a wind farm must expend a significant amount of energy flying around it, especially since offshore wind farms can be quite large (tens of square miles). This could be of particular importance if a wind farm is located in between rookeries and feeding grounds [34].

Table 5
Environmental impacts associated with Cape Wind development according to the EIS.

	Affected resource	Construction impacts[a]	Operation impacts
Oceanography	Currents	No measurable impacts	Minor
	Waves	No measurable impacts	No measurable impacts
	Salinity	No measurable impacts	No measurable impacts
	Temperature	No measurable impacts	No measurable impacts
	Sediment transport	Minor	Minor
	Water depth	Minor	Minor
Birds	Raptors	No measurable impacts	No measurable impacts
	Passerines	Minor	No measurable impacts to Minor
	Coastal species	No measurable impacts to Minor	No measurable impacts to Moderate
	Marine birds	Minor to Moderate	Minor to Moderate
Invertebrates	Benthic invertebrates	Minor	Minor
	Shellfish	Minor	Minor
	Plankton	No measurable impacts	Minor
Fisheries	Finfish	Minor	No measurable impacts to Minor
	Demersal eggs and larvae	Moderate	
	Fish habitat	No measurable impacts to Minor	No measurable impacts to Minor
Marine Mammals	Marine Mammals	Minor to Moderate	No measurable impacts to Moderate
Endangered Species	Sea turtles	No measurable impacts to Minor	No measurable impacts to Minor
	Cetaceans	No measurable impacts to Minor	No measurable impacts to Minor
	Birds	No measurable impacts to Minor	No measurable impacts to Moderate

[a] Minor impacts are those that can be completely mitigated against or are small enough that the resource can recover completely on its own. Moderate impacts occur if either the impact is immitigable but the resource could recover on its own, or if the impact can be partially mitigated and the resource could then recover on its own. Major impacts occur if the impact is immitigable, the viability of the resource is threatened and the resource would not fully recover.

---

[2] One example of this could be the learning that occurred during the Horns Rev installation. Eighty turbines were installed at Horns Rev. At the start of construction the average installation time was 3 days; by the end of the construction period an average of 1.4 turbines was installed per day [16].

Finally, wind farms can remove essential habitat from seabirds. Many seabirds have restricted areas in which they can successfully feed and in many cases these areas are shallow sand banks appropriate for wind farm development. If birds avoid wind farms, then even though the footprint of a wind turbine foundation is very small, very large areas of habitat may be inaccessible to birds. This seems to have occurred among diving birds at the Horns Rev wind park and long-tailed ducks at Nysted wind park. Similar patterns are seen for terns and auks at Horns Rev, although the trends are not significant [38].

7.2. Impacts on marine mammals

Many cetaceans use echolocation to find food and many more communicate via acoustic signals. As a result many cetaceans, particularly porpoises, have very sensitive hearing which can be damaged by the loud noises associated with wind farms, particularly the sounds of pile driving. At the site of construction, the sound pressure level of pile driving a monopole for a 1.5 MW turbine is 228 dB [39]. Four-hundred meters away from pile driving the sound pressure level is 189 dB. This would cause hearing loss in seals. Hearing loss for porpoises would likely extend 1.8 km away from the source. Pile driving would be audible to porpoises and seals for at least 80 km and might cause behavioral responses up to 20 km away [39]. This sound pressure level is similar to, but slightly less intense than that used in naval sonar which has been implicated in the mass stranding of beaked whales [39]. During wind farm operation the noise from the turbines may be detectable for porpoises and seals up to about 1 km from the source [39].

At the Nysted Wind farm the population of harbor and grey seals was monitored before, during and after construction. Wind farm operation did not seem to significantly impact seal abundance, however, piling driving operations that occurred at one foundation site (Nysted uses gravity foundations) did decrease the number of seals observed at a nearby breeding site. Also, while the total annual population remained stable, after construction fewer harbor seals were present on nearby land sites in June (the breeding season) but more were present in July and August. This could suggest that fewer seals are using the area around the wind farm for breeding which could have an important effect on the viability of the population.

Harbor porpoises were shown to occur less frequently in the area around a wind farm during construction at both Nysted [40] and Horns Rev [38]. Presumably this is primarily due to animals fleeing the noise. At Horns Rev, the porpoises seemed to return following the construction period, however, even two years later porpoises at Nysted are less numerous then they were in baseline [38].

7.3. Impacts on fish

Wind farms could have both positive and negative impacts on fish. These effects could cascade up the food web to have either positive or negative effects on the birds and marine mammals that consume them.

As with marine mammals, fish can be very sensitive to loud sounds and could be displaced during wind farm construction; however, there is a great deal of variability among fish auditory systems and different species of fish will respond differently to noise from underwater construction. Furthermore, bottom-dwelling will be affected differently from fish swimming in the water column due to the different propagation of sound through sediment [39].

There have been few studies on the effects of pile driving on fish (reviewed in [41]). In general, these studies have placed fish in cages at various distances from the piles being driven and measured mortality and other injuries through non-microscopic necropsy. Abbott and Bing-Sawyer [42] studied Sacramento blackfish and found that fish placed in cages close to the sound source (45 m) experienced more damage than animals further away and that damage was only found in animals exposed to 193 dB or more. CALTRANS [43] studied shiner surfperch and steelhead and compared damage between fish experimentally exposed to pile driving and fish that were transported to the site but not exposed to noise. They found that fish exposed to pile driving noise experienced more damage than unexposed animals, but that there was no significant difference in mortality rates between control and experimental animals. CALTRANS [44] also conducted an observational study of fish mortality during pile driving for the San Francisco–Oakland bay bridge and found dead fish out to 50 meters around the construction. Finally, Abott [45] and Marty [46] studied the effects of a relatively small pile (2 feet in diameter) being driven close (32 feet) to cages of shiner perch, Chinook salmon and northern anchovies and they used control fish subjected to the same conditions but without noise. They found no difference in either mortality or pathology.

There have also been a few studies on the effects of noise on stress levels in fish. Chronic noise exposure is known to increase stress levels in humans with consequential effects on health. Smith et al. [47] studied the effects of a continuous 170 dB noise on corticosterone (a stress hormone) levels in goldfish and found no statistically significant results.

More subtle effects on fish behavior could also occur. Engas et al. [48] and Engas and Lokkeborg [49], found that the catch rate of haddock and cod decreased in areas after air gun use but returned to normal several days later suggesting that fish left the area and gradually returned. Nedwell et al. [50] calculated the zones around which salmon and cod would show significant avoidance behavior to be 1.4 km and 5.5 km, respectively.

The only clear conclusions which can be drawn from this research is that pile driving will effect fish; the degree of this effect will vary and is not at all clear. Very close to pile driving some mortality may occur for some species and fish may temporarily leave the area.

Many species of fish are also sensitive to electric and magnetic fields which can be caused by buried underwater cables. Fish use their perception of electric and magnetic fields for orientation and prey detection. Species that contain magnetic material, potentially for navigational purposes include several species of economically important fish including yellow fin tuna, and Chinook and sockeye salmon [51]. There is some evidence that the fish in the area of the Nysted wind farm may be affected by the electromagnetic fields produced by the wind farm. Baltic herring, common eels, Atlantic cod and flounder all showed asymmetries in the catch rate on either side of the cables suggesting that the cables may retard migration [38].

In addition to these negative effects, there has been some discussion of the potential for positive impacts from offshore wind farms on fish and fisheries. After construction of an offshore wind farm, turbine foundations could act as fish aggregating devices (FADs). The foundations could add three dimensional complexity to the environment and serve as a substrate for benthic invertebrates, thereby attracting fish. Offshore oil platforms are well known for this property. Although monopiles lack the structure of offshore oil and gas platforms, Wilhelmsson et al. [52] have shown that they act as fish aggregating devices at the Yttre Stengrund and Utgrunden wind farms. At the Horns Rev and Nysted wind farms there was no clear difference between fish densities inside and outside of the wind farms [38]. The difference in these results is likely due to the different methodologies employed. The Swedish studies used scuba divers to monitor fish while the Danish studies used hydro-acoustic sampling. As a result, the Danish studies may have overlooked some of the smaller species observed in the Swedish wind farms.

7.4. Environmental benefits of offshore wind power

Wind power is considered to be among the most environmentally benign sources of electricity available today and it is important to consider the negative environmental impacts of wind power in the context of alternative sources of electricity. For example, concerns about the impacts of wind power on birds should be compared to the impacts of fossil fuel use on birds on a per MW basis.

7.4.1. Greenhouse gases

The primary environmental benefit of wind power is its negligible contribution to global climate change. The only greenhouse gases produced by the establishment of a wind farm are those used in the construction and operation of the wind farm. The greenhouse gases released from construction and operation of an offshore wind farm are likely to be dominated by CO_2 released from the ships used in construction of the wind farm and the manufacturing of the steel used in the turbine towers and foundations. To our knowledge there is no estimate of these emissions for offshore wind farms, but for onshore wind farms these emissions decrease the CO_2 offset by 1–2% [53]. It is not clear whether offshore turbines would have higher or lower per MW CO_2 output from construction. In general, transportation via ship is more efficient than over land, but the operation and maintenance emissions may be higher for offshore wind. Assuming an offshore wind turbine replaces electricity generation from fossil sources at a rate equal to that for onshore wind farms, then each MW of wind capacity should displace about 1800 tons of CO_2 per year [54].

It is extremely difficult to predict the effects of climate change per ton of CO_2. While we can predict a per MW bird mortality associated with wind power, we cannot make a comparable prediction for fossil fuel use. Studies have indicated that climate change may be associated with high rates of species extinction. Climate change is predicted to cause between 11 and 45% of all species to become extinct [55]. For birds, the subject of so much concern over wind power, it is estimated that 950–1800 species of terrestrial birds (out of 8750 studied) will be threatened due (in part) to climate change [56]. It is critically important, however, that there has been very few studies of the adaptation of biodiversity to climate change, thus these estimates must be taken as preliminary [57]. Still, the fact that climate change may imperil the survival of species, especially species endemic to high and low altitudes and latitudes and restricted geographical ranges, is in contrast to wind power which has no demonstrated population or species level effects on biodiversity.

7.4.2. Water

In many parts of the U.S. water resources are stressed. The six world climate models used in the Intergovernmental Panel on Climate Change (IPCC) generally predict that the U.S. will become drier by 2050. One of the models predicts that precipitation over virtually the entire U.S. will decline by over 30% while the other five models show more modest declines [57]. Forty-eight percent of total water withdraws and nine percent of total water consumption (68 billion liters per day) is used by thermoelectric power plants (powered by coal, natural gas, nuclear, oil and biomass; [9]). Ethanol production also uses large quantities of water, from 3.5 to 6 l of water for every liter of ethanol produced [58]. Wind power directly uses no water. Per kW h, the amount of water used in fossil-fueled plants ranges from about 0.2 to 0.6 gallons depending on the technology employed [59]. Assuming a 40% capacity factor, 1 MW of offshore wind power can offset the use of between 0.7 and 2.1 million gallons of freshwater per year.

7.4.3. Value of ecological benefits

Onshore and offshore wind have nearly identical ecological benefits on a per MW h basis. We can attempt to place a dollar value on the ecological services, in terms of water unused and carbon not emitted, of offshore wind power relative to traditional fossil-fueled power. The actual costs of offsetting a ton of carbon are not known, but governments have set up trading systems in which offsets are exchanged. The costs of these offsets will be set by supply and demand, and are expected to increase in the future. Current prices for the offset of one metric ton of CO_2 are around $30. Each MW h of coal-fired electricity produces 0.839 metric tons of CO_2 [60]. Thus, per MW h, the value of avoided CO_2 emissions may be about $25.

8. Ecological mitigation

8.1. Mitigation through site selection

Potential sites are avoided due to their potential impacts on the environment. Certain areas are known to be bottlenecks on the migratory routes of large numbers of birds. Cape May, New Jersey, Delaware Bay, Grays Harbor Washington, Point Reyes, California, and the Barrier Islands of Louisiana are all important areas for avian migration and may be considered unacceptable for offshore wind power development. Similarly, planners for the LIOWP took the migration routes of Right Whales into consideration in selecting a site. Whale migration routes will likely need to be considered on the Pacific coast as well.

Placing offshore wind farms near nesting sites for seabirds may also be ecologically hazardous. Seabirds generally avoid using the Horns Rev wind farm and direct mortality from collision with turbines is relatively rare and in many cases not significant. However, because seabirds avoid entering offshore wind farms, their existence may reduce available foraging habitat or force birds to expend energy to fly around the wind farm. Both of these could have population level impacts on bird species. Offshore wind farm construction could also have similar impacts on nearby populations of marine mammals.

From the perspective of conserving biodiversity, it is perhaps most important for developers to avoid areas considered essential habitat for threatened or endangered species. The endangered species act requires that critical habitat for any listed species be identified and it requires federal agencies that permit activities consider the effects of permitting on these habitats. While there are procedures in which the government may permit activities that are detrimental to the critical habitat of an endangered species, it would seem prudent for developers to exclude critical habitats of endangered species from development plans, if not out of a perceived ethical responsibility for conservation, then out of the risk of the failure of the permitting process and the associated financial losses.

The areas of critical habitat for species managed by NOAA are listed at http://www.nmfs.noaa.gov/pr/species/criticalhabitat.htm and species managed by FWS are listed at http://crithab.fws.gov/. The critical habitat of the North Atlantic Right Whale and the Stellar Sea Lion, both managed by NOAA, are the most likely to influence offshore wind placement. The critical habitat of the North Atlantic Right Whale includes areas off the coast of southern Georgia and the Atlantic Coast of Northern Florida as well as areas off the Northern and Eastern coasts of Cape Cod. The areas of critical habitat that may conflict with offshore wind power development for the Stellar's sea lion consist of five small zones off the coast of northern California and Oregon.

The impacts on local culture should also be considered. One of the primary criticisms of the Cape Wind project is that it will spoil the views from historic areas. Similarly, some areas of interest for offshore wind development may be located near shipwrecks. These issues should be noted by wind power developers for two reasons. First, the MMS, in their guidelines on development of the OCS, adopted a policy of consulting with State Preservation Authorities before permitting development and it is therefore possible that MMS would decline a permit for offshore wind energy if there were significant cultural issues. Secondly, even if MMS were to allow development, construction can be seriously slowed by local community resistance. For example, the Cape Wind project will, if completed, have taken at least a decade to develop and have required at least one protracted legal battle (*Alliance to Protect Nantucket Sound v. United States Army*). In contrast, WEST's plans to build a wind farm off the coast of Texas have proceeded rapidly, despite less favorable wind conditions. This may be due to acceptance by the local community, many of whom are familiar with offshore structures from experience with the oil and gas industry [13].

8.2. Mitigation through technology

Most of the offshore wind turbines constructed to date have used monopole foundations. The ecological effects of the piling operations are a concern, however, there are alternavites to pile-driven foundations. One option would be to use gravity foundations, as were used in the Nysted and Middlegrunden wind farms. Gravity foundations are simple concrete structures with large diameter bottoms that rest on the sea floor. They weigh thousands of tons and use their weight to stabilize the turbine. Gravity foundations do not require piling operations and therefore have less potential to disturb marine mammals and fish. Also, gravity foundations have more three dimensional structure than monopiles; this may provide additional habitat for benthic organisms.

Another alternative would be to use suction foundations, such as those considered in the Beatrice demonstration project. Suction foundations are simple steel baskets that are placed on the seafloor and form a seal with the ocean bottom. Suction is then applied to the inside of the basket and the resulting pressure difference causes the basket to bury itself in the sediment, much like a driven monopile. Again, installation is much quieter allowing for fewer environmental effects.

Technologies are also being developed to allow the use of deeper water. Using deeper water would allow offshore wind farms to be sited further from shore, increasing the wind speed and decreasing the possibility of conflicts with local human and animal populations. A survey conducted in New Jersey showed visitors and residents simulated images of offshore wind farms at varying distances from shore and found that as the distance increased the percentage favoring development increased [61]. Deep water turbines could be placed over the horizon and thus be invisible from shore. This would also decrease their impact on seabirds which generally do not feed in the open ocean, and on migratory birds, which, with the exception of birds flying over the GOM, do not migrate over open ocean. Additionally, these turbines are placed on floating foundations that will likely have fewer environmental impacts during construction.

One of the leading developers of floating foundations for offshore wind turbines is Blue H Technologies. They have recently installed an offshore wind turbine in 108 m of water 20 km off the coast of Italy and also applied to MMS for a permit to study the potential for a wind farm 23 miles off the southern coast of Cape Cod. If this technology becomes economically viable it could decrease conflicts with coastal communities and would lessen the environmental impacts of wind farms.

9. Conclusion

The higher economic costs of offshore wind power relative to onshore wind power could be justified if the ecological or social costs of offshore wind were significantly different from onshore wind power, but this seems not to be the case. Both on and offshore wind power face local opposition due to user conflicts. The ecological impacts of offshore wind power affect a very different ecosystem than onshore wind power and, as a result, their ecological impacts are not directly comparable. However, like onshore wind, it is clear that offshore wind power does have ecological impacts with the potential for population level effects.

Decreasing commodity costs or legislation capping greenhouse gas emissions could increase the profitability of offshore wind but would not change the fact that onshore wind will be a less expensive alternative, even when transmission costs are included. Until land use conflicts in high-wind onshore sites become severe, or the technology develops so that the higher offshore winds balance the higher costs of installation, there seems to be little incentive for a large offshore wind industry in the U.S. In sum, we do not envision offshore wind producing a significant portion of the U.S. electricity production until at least 2020.

It is much more difficult to analyze the ecological and economic costs and benefits of offshore wind power relative to fossil-fueled power. Including a premium on coal-fired power of $25/MW h to offset emissions may make coal and offshore wind power nearly price competitive, depending on the specific capital costs of offshore wind. This $25/MW h premium would give coal and offshore wind similar greenhouse gas emissions, however, coal would still use more water than offshore wind and would be associated with significant health effects. However, this would be balanced against the ecological impacts of offshore wind in terms of bird and bat mortality and marine mammal impacts. Thus, it is not clear that offshore wind is preferable to coal-fired power, if the emissions from the coal plant are offset.

Based on the analysis in this paper, it seems clear that the economic and ecological costs of offshore wind power are site specific. These costs can be mitigated with current technology and detailed site selection. It therefore seems imprudent to conclude that all offshore wind development is inferior to all onshore wind development or fossil-fueled power. Instead, a more nuanced approach which weighs the site specific costs and benefits of offshore wind power is necessary. In some cases, offshore wind power may be able to cheaply produce electricity with negligible environmental impacts, however, in many more cases, offshore wind power will be more expensive than its competitors, even when the costs of carbon offsets are included.

Acknowledgements

This paper was prepared on behalf of the U.S. Department of the Interior, Mineral Management Service, Gulf of Mexico OCS region, and has not been technically reviewed by the MMS. The opinions, findings, conclusions or reccomendations expressed in this paper are those of the authors and do not neccisarily reflect the views of the MMS. Funding for this research was provided through the U.S. Department of the Interios and the Coastal Marine Institute, Louisiana State University.

References

[1] Firestone J, Kempton W. Public opinion about large offshore wind power: underlying factors. Energy Policy 2007;35(3):1584–98.
[2] Firestone J, Kempton W, Krueger A. Delaware opinion on offshore wind power. University of Delaware college of marine and earth studies, interim report; January 2007.
[3] Bird L, Bolinger M, Gagliano T, Wiser R, Brown M, Parsons B. Policies and market factors driving wind power development in the United States. Energy Policy 2005;33(11):1397–407.
[4] Sterzinger G, Beck F, Kostiuk D. The effect of wind development on local property values. Renewable energy policy project – analytical report; 2003.
[5] Ladenburg J, Dubgaard A. Willingness to pay for reduced visual disamenities from offshore wind farms in Denmark. Energy Policy 2007;35(8):4059–71.
[6] Haughton JH, et al. Blowing in the wind: offshore wind and the cape cod economy. Boston: Beacon Hill Institute at Suffolk University; 2003.

[7] Hirst E, Hild J. The value of wind energy as a function of wind capacity. The Electricity Journal 2004;17(6):11–20.
[8] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30(13):2402–12.
[9] DOE. 20% Wind energy by 2030. Washington, D.C.: Department of Energy; 2008.
[10] NREL. Wind powering America; 2008. Available from: http://www.eere.energy.gov/windandhydro/windpoweringamerica/wind_maps.asp.
[11] Righter RW. Exoskeletal outer-space creations. In: Pasqualetti M, Gipe P, Righter RW, editors. Wind Power in View: Energy Landscapes in a Crowded World. San Diego: Academic Press; 2002.
[12] Pasqualetti MJ. Wind power: obstacles and opportunities. Environment 2004;46(7):22–38.
[13] Patterson J. Press conference on offshore wind lease. Austin: Texas General Land Office; 2005.
[14] IEA. Offshore wind experiences. Paris; 2006.
[15] Vattenfall. Horns rev offshore wind farm; 2007. Available from http://www.vattenfall.com/www/vf_com/vf_com/365787ourxc/366203opera/555848newpo/557004biofu77761/557004biofu/index.jsp.
[16] Junginger M, Faaij A, Turkenburg WC. Cost reduction prospects for offshore wind farms. Wind Engineering 2004;28(1):97–118.
[17] Musial W, Butterfield S. Future for offshore wind energy in the United States: preprint. In: EnergyOcean 2004. Palm Beach FL; 2004.
[18] Lemming JK, Morthorst PE, Clausen N. Offshore wind power: experiences, potential and key issues for deployment. Copenhagen, DK: Riso National Laboratory; 2007.
[19] Pedersen E, Waye KP. Perception and annoyance due to wind turbine noise—a dose–response relationship. The Journal of the Acoustical Society of America 2004;116:3460.
[20] Butterfield CP, Musial W, Jonkman J. Overview of offshore wind technology: preprint. In: Chinese renewable energy industry association conference. Shanghai; 2007.
[21] Gipe P. Wind power: renewable energy for home, farm, and business. Chelsea Green Pub Co; 2004.
[22] Wiser R, Bolinger M. Annual report on U.S. wind power installation, cost and performance trends: 2007. NREL; 2008.
[23] Fingersh L, Hand M, Laxson A. Wind turbine design cost and scaling model. Golden, CO: National Renewable Energy Laboratory; 2006.
[24] Greer M. A financial analysis of the proposed long island offshore wind farm. Oakdale, NY: Dowling College; 2007. p. 8.
[25] PACE. Assesment of offshore wind power resources. Fairfax, VA: Long Island Power Authority; 2007. p. 26.
[26] Larsen JHM, et al. Experiences from Middelgrunden 40 MW offshore wind farm. Copenhagen offshore wind conference; 2005. p. 26–8.
[27] Archer CL, Jacobson MZ. Evaluation of global wind power. Journal of Geophysical Research 2005;110(D12110):1–20.
[28] EIA. Official energy statistics from the U.S. Government. Energy Information Administration; 2008.
[29] Schellestede H. Personal communication; 2008.
[30] Grimley B. Offshore wind energy. In: Southeastern regional offshore wind power symposium. Clemson, SC; 2007.
[31] BERR. Offshore wind background; 2004. Available from: http://www.offshore-sea.org.uk/site/scripts/documents_info.php?documentID = 6&pageNumber = 2.
[32] Wright SD, et al. Transmission options for offshore wind farms in the United States. Proceedings of the AWEA annual conference; 2002. p. 1–12.
[33] ODE. Study of the costs of offshore wind generation. Department of Trade and Industry; 2007.
[34] Drewitt AL, Langston RHW. Assessing the impacts of wind farms on birds. Ibis 2006;148(s1):29–42.
[35] Strickland D, Johnson D. Overview of what we know about avian/wind interaction. In: National wind coordinating collaborative wildlife workgroup research meeting. San Antonio, TX; 2006.
[36] Bennett EO. Alternate energy-related uses on the outer continental shelf – 1010-AD30. US FWS; 2006.
[37] Desholm M, Kahlert J. Avian collision risk at an offshore wind farm. Biology Letters 2005;1(3):296–8.
[38] DONG, et al. Danish offshore wind – key environmental issues. Copenhagen: DENA; 2006.
[39] Thomsen F, et al. Effects of offshore wind farm noise on marine mammals and fish. Report funded by COWRIE (Collaborative offshore wind research into the environment). Available from www.offshorewind.co.uk.
[40] Carstensen J, Henriksen OD, Teilmann J. Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Marine Ecology Progress Series 2006;321:295–308.
[41] Hastings MC, Popper AN. Effects of sound on fish. Report to Jones and Stokes for California Department of Transportation; January 2005.
[42] Abbott R, Bing-Sawyer E. Assessment of pile driving impacts on the Sacremento blackfish (Orthodon microlepidotus). CALTRANS; 2002.
[43] CALTRANS. Fisheries and hydroacoustic monitoring program compliance report for the San Francisco–Oakland Bay bridge east span seismic safety project; 2004.
[44] CALTRANS. Pile installation demonstration project. Fisheries impact assessment. San Francisco–Oakland Bay bridge east span seismic safety project; 2001.
[45] Abbott R. Progress report: monitoring the effects of conventional pile driving on three species of fish. CALTRANS; 2004.
[46] Marty GD. Necropsy and histopathology of three fish species exposed to concrete pile driving in the port of Oakland. Draft report 2004, Port of Oakland; August 2004.
[47] Smith ME, Kane AS, Popper AN. Noise-induced stress response and hearing loss in goldfish (Carassius auratus). Journal of Experimental Biology 2004;207(3):427–35.
[48] Engas A, et al. Effects of seismic shooting on local abundance and catch rates of cod(Gadus morhua) and haddock(Melanogrammus aeglefinus). Canadian journal of fisheries and aquatic sciences(Print) 1996;53(10):2238–49.
[49] Engås A, Løkkeborg S. Effects of seismic shooting and vessel-generated noise on fish behaviour and catch rates. Bioacoustics 2002;12(2/3):313–6.
[50] Nedwell J, Langworthy J, Howell D. Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise. Subacoustech report reference 544R0424; November, 2004.
[51] Öhman MC, Sigray P, Westerberg H. Offshore windmills and the effects of electromagnetic fields on fish. AMBIO: A Journal of the Human Environment 2007;36(8):630–3.
[52] Wilhelmsson D, Malm T, Ohman MC. The influence of offshore windpower on demersal fish. ICES Journal of Marine Science: Journal du Conseil 2006;63(5):775.
[53] White D, Kulsinski G. Net energy payback and CO_2 emissions from wind generated electricity in the midwest. Madison, WI: University of Wisconsin; 1998.
[54] Awea. Wind energy basics. Washington, D.C.: American Wind Energy Association; 2008.
[55] Thomas CD, et al. Extinction risk from climate change. Nature 2004;427(6970):145–8.
[56] Jetz W, Wilcove DS, Dobson AP. Projected impacts of climate and land-use change on the global diversity of birds. PLoS Biol 2007;5(6):e157.
[57] IPCC. Climate change 2007: synthesis report. In: Core Writing Team, Pachauri RK, Reisinger A, editors. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. Geneva, Switzerland: IPCC; 2007.
[58] Keeney D, Muller M. Water use by ethanol plants: potential challanges. Minneapolis, Minnesota: Institute for Agriculture and Trade Policy; 2006.
[59] Force CAT. The last straw: water use by power plants in the arid west, Hewlett foundation energy series. Boston, MA: Clean Air Task Force; 2003.
[60] Sims REH, Rogner HH, Gregory K. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy 2003;31(13):1315–26.
[61] Mills D, Rosen H. New Jersey shore opinion study about off shore wind turbines. Great Neck, NY; 2006.
[62] Morgan CA, Snodin HM, Scott NC. Offshore wind: economics of scale, engineering resource and load factors. Department of Trade and Industry; 2003.
[63] Musial W, Butterfield S, Ram B. Energy from offshore wind: preprint, Offshore technology conference. Houston, TX: NREL; 2006.
[64] IEA. Projected costs of generating electricity. Paris: International energy agency; 2005.
[65] Mense RSD. Draft evalutation of the cape wind energy project proposed site and alternatives with the offshore wind energy project model: a microsoft excel cash flow spreadsheet. Herndon, VA: Minerals Management Service; 2007.
[66] Barthelmie RJ, Pryor S. A review of the economics of offshore wind farms. Wind Engineering 2001;25(4):203–13.
[67] A2Sea. Taking windpower offshore; 2008. Available from: http://www.a2sea.dk/SEEEMS/2.asp.
[68] Beurskens LWM, Noord M. Offshore wind power developments. An overview of realisations and planned projects; 2003. ECN policy studies.
[69] DONG. Nysted Havmollepark; 2008. Available from: http://uk.nystedhavmoellepark.dk/frames.asp.
[70] Econcern and Eneco. Windpark Q7; 2008. Available from www.q7wind.nl.
[71] Gerdes G, Tiedmann A, Zeelenberg S. Case study: European offshore wind farms – a survey for the analysis of the experiences and lessons learnt by developers of offshore wind farms. DENA; 2007.
[72] IEA. Offshore wind experiences. Paris: International Energy Agency; 2005.
[73] OffshoreWindEnergy.org. Map of existing and planned windfarms in North–West Europe; 2007. Available from: www.offshorewindenergy.org.
[74] Power-Technology. Industry projects; 2008. Available from: http://www.power-technology.com/projects/.
[75] Vattenfall. Wind; 2008. Available from: http://www.vattenfall.com/www/vf_com/vf_com/365787ourxc/366203opera/555848newpo/557004biofu77761/index.jsp.

Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow recovery

2012 Environ. Res. Lett. 7 045101

(http://iopscience.iop.org/1748-9326/7/4/045101)

OPEN ACCESS
IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **7** (2012) 045101 (10pp) doi:10.1088/1748-9326/7/4/045101

Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow recovery

Jonas Teilmann and Jacob Carstensen

Department of Bioscience, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark

E-mail: jte@dmu.dk

Received 18 July 2012
Accepted for publication 12 November 2012
Published 6 December 2012
Online at stacks.iop.org/ERL/7/045101

Abstract
Offshore wind farms constitute a new and fast growing industry all over the world. This study investigates the long term impact on harbour porpoises, *Phocoena phocoena*, for more than 10 years (2001–12) from the first large scale offshore wind farm in the world, Nysted Offshore Wind Farm, in the Danish western Baltic Sea (72 × 2.3 MW turbines). The wind farm was brought into full operation in December 2003. At six stations, acoustic porpoise detectors (T-PODs) were placed inside the wind farm area and at a reference area 10 km to the east, to monitor porpoise echolocation activity as a proxy of porpoise presence. A modified statistical BACI design was applied to detect changes in porpoise presence before, during and after construction of the wind farm. The results show that the echolocation activity has significantly declined inside Nysted Offshore Wind Farm since the baseline in 2001–2 and has not fully recovered yet. The echolocation activity inside the wind farm has been gradually increasing (from 11% to 29% of the baseline level) since the construction of the wind farm, possibly due to habituation of the porpoises to the wind farm or enrichment of the environment due to reduced fishing and to artificial reef effects.

Keywords: static acoustic monitoring, long term effect, BACI design, echolocation, *Phocoena phocoena*, offshore wind farm, Nysted Offshore Wind Farm, porpoise detector, T-POD

1. Introduction

Like other toothed whales (odontocetes) harbour porpoises have good underwater hearing and use sound actively for navigation and prey capture (echolocation). They produce short ultrasonic clicks (130 kHz peak frequency, 50–100 μs duration; Møhl and Andersen 1973, Teilmann *et al* 2002) and are able to navigate and find prey even in complete darkness. Porpoises tagged with acoustic data loggers indicate that they use their echolocation almost continuously (Akamatsu *et al* 2007, Linnenschmidt *et al* 2012).

Several studies on porpoises in the western Baltic Sea have used autonomous acoustic dataloggers (T-PODs) that record the echolocation sound of porpoises. Verfuss *et al* (2007) used T-POD data from a large number of permanent stations throughout the German part of the Baltic Sea to estimate the relative abundance. During the environmental assessment program at Nysted Offshore Wind Farm T-PODs was also used to monitor the effect of the construction and operation (Carstensen *et al* 2006). They reported a strong decrease in porpoise echolocation activity following the construction and first years of operation.

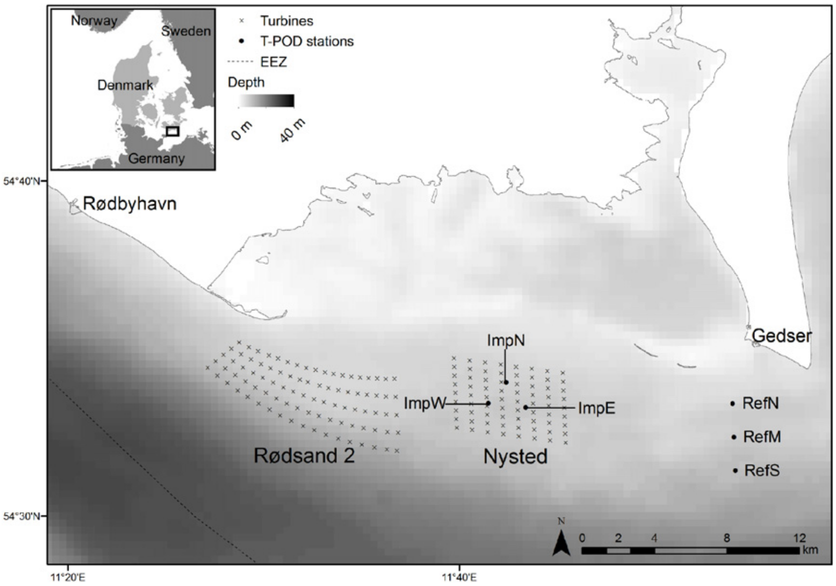


Figure 1. Study area with Nysted and Rødsand 2 Offshore Wind Farm. Wind turbines are shown with an 'X' and T-POD monitoring stations with solid circles. Three stations (ImpW, ImpN and ImpE) are located inside the wind farm and three stations (RefN, RefM and RefS) are located in a reference area about 10 km east of the wind farm.

Offshore wind energy has grown exponentially in European waters since the first 11 offshore turbines were erected at Vindeby in Denmark. To be economically sustainable wind farms are growing in size and the largest to date will be London Array Offshore Wind Farm with 175 turbines and a capacity of 630 MW, enough for 470 000 British homes. This wind farm cover 100 km^2 and comprises only a minor part of the present and planned wind farms in European waters (www.4coffshore.com/offshorewind/). It has been shown that the harbour porpoise (*Phocoena phocoena*) can be both positively and negatively affected by the construction and operation of offshore wind farms (Carstensen *et al* 2006, Scheidat *et al* 2011). As harbour porpoises mainly live in shallow continental shelf waters in the northern hemisphere (Hammond *et al* 2002, SCANS-II 2008) and as they are protected under annex II and IV of EU's Habitats Directive, it is important to fully understand the potential effects of offshore wind farms, either directly through disturbing the animals or indirectly through affecting their habitat.

In 2002–3 Nysted Offshore Wind Farm was constructed in the Danish part of the western Baltic Sea. Together with Horns Rev Offshore Wind Farm, it was part of a national demonstration program to test the feasibility and economy of large scale offshore wind power and address potential negative effects on the marine environment by initiating an ambitious environmental monitoring program, parallel to the construction and operation. The present study is a continuation of this monitoring program and will test the long term effect of the wind farm on harbour porpoises. In 2009–10 another large offshore wind farm (Rødsand 2, www.eon.dk/Rodsand-2) comprising 90 turbines was constructed only about 3 km west of Nysted wind farm. The potential effect of this additional wind farm in the study area will also be discussed.

2. Material and methods

2.1. Study area

The Nysted wind farm area is located south of the islands Lolland and Falster in the western Baltic (figure 1). The area is dominated by two large sand barriers (Eastern and Western Rødsand), which borders a shallow lagoon from the deeper Fehmern Belt and Kadet Trench. This narrow sandbar runs about 25 km from Hyllekrog to Gedser and is partly exposed at normal water levels in the middle. The shallow lagoon area (depths 0.5–7 m), is an important area for fish, birds, seals and coastal fishery.

The sea floor south of Rødsand at depths shallower than 10 m consists primarily of glacial depositions. The largest part of the area is covered by sand/silt bottom with larger and smaller ridges and with aggregations of pebbles, gravel and shells scattered throughout the area. A small natural stone reef (Schönheiders Pulle) is located east of Nysted Offshore Wind Farm.

The water in the area is brackish and salinity varies with the freshwater surface flow from the Baltic Sea and influx of more saline bottom water from the Kattegat. The tide is weak in the area (less than 0.5 m) and variations in water level are mainly determined by wind and barometric pressure differences between the Baltic Proper and the Kattegat/Danish Straits.

2.2. Acoustic monitoring

The T-POD or POrpoise Detector is a small self-contained battery operated data-logger that logs echolocation clicks from harbour porpoises and other cetaceans (Chelonia, UK). In this study we deployed the T-PODs about 1 m above the seafloor and downloaded data and changed batteries every 1–2 months. It is programmable and can be set to specifically detect and record the echolocation signals from harbour porpoises.

The T-POD consists of a hydrophone, an amplifier, a number of band-pass filters and a data-logger that logs echolocation clicks. It processes the recorded signals in real-time and only logs time and duration of sounds fulfilling a number of acoustic criteria set by the user. These criteria relate to click length (duration), frequency spectrum and intensity, and are set to match the specific characteristics of echolocation clicks of harbour porpoises.

The T-POD relies on the highly stereotypical nature of porpoise sonar signals. These are unique in being very short (50–150 μs) and containing virtually no energy below 100 kHz. Main part of the energy is in a narrow band 120–150 kHz, which makes the signals ideal for automatic detection. Most other sounds in the sea, with the important exception of boat echosounders, are characterized by being either more broadband (energy distributed over a wider frequency range), longer in duration, with peak energy at lower frequencies or combinations of the three. In addition echosounders have a more regular pattern than porpoise echolocation. The actual detection of porpoise signals is performed by comparing signal energy in a narrow filter centred at 130 kHz with another narrow filter centred at 90 kHz. Any signal, which has substantially more energy in the high filter relative to the low and with a duration less than 200 ms is highly likely to derive either from a porpoise or an echosounder. However, porpoise click trains are recognizable by a gradual change of click intervals throughout a click sequence, whereas boat echosounders have highly regular repetition rates (almost constant click intervals). Clicks of other origin tend to occur at random, thus with highly irregular intervals.

The T-POD operates with six separate and individually programmable channels. In this study all channels had identical settings for each type of T-POD (table 1). Each of the six channels records sequentially for 9 s, with 6 s per minute assigned for change between channels. This gives an overall duty cycle of 90% (54 s $\min^{-1}$). In order to minimize data storage requirements only the onset time of clicks and their duration are logged. This is done with a resolution of 10 μs. The absolute accuracy of the timing of each recording is much less, due to drift in the T-PODs clock during deployment (a few minutes per month). Clicks shorter than 10 μs and sounds longer than 2550 μs were discarded. The hydrophone of the T-POD has a resonance frequency of 120 kHz and is cylindrical and thus in principle omnidirectional in the horizontal plane.

Table 1. T-POD filter settings used in this study.

	T-POD V1	T-POD V5
A filter frequency (kHz)	130	130
B filter frequency (kHz)	90	92
Ratio A/B	5	—
A filter sharpness (au)	5	4
B filter sharpness (au)	18	
Sensitivity	0.35	8–11[a]
Noise filter	–	+
Scan limit	240	None
Minimum click length (μs)	10	10
Switch angle	254	75

[a] Value depend on calibration.

2.3. Data collection

To assess the long term effect of Nysted Offshore Wind Farm T-PODs were deployed before, during and after construction (2001–12) at three stations in the wind farm area (impact) and at three stations 10 km east of the wind farm (control). Data collection was partitioned into 6 distinct periods: (1) baseline period (November 2001–June 2002), (2) construction period (July 2002–November 2003), (3) operation period 1 (December 2003–December 2004), (4) operation period 2 (January 2005–December 2005), (5) operation period 3 (September 2008–February 2009), and (6) operation period 4 (September 2011–March 2012). The operation period was divided into four periods of approximately same length to investigate a potential gradual recovery in porpoise density, assuming that the animals may over some time habituate to changed habitat conditions with the introduction of hard substrate turbine foundations in a soft-sediment environment.

In an earlier study (Carstensen *et al* 2006), it was found that one of the reference stations (RefN) was apparently strongly affected by the nearby Gedser Harbour and therefore unsuitable as reference. Moreover, the T-POD deployment was discontinued at ImpN after operation period 2 for logistical reasons. As a consequence, the statistical analysis included data from five stations for the first 4 periods and data from four stations in the last two periods. Given the length of the study it was necessary to replace the older T-POD version 1 (V1) with the newer T-POD version 5 (V5) when instruments were lost or malfunctioned. However, to account for potential differences in sensitivity between the two versions in the statistical model (see below), both T-POD versions were deployed simultaneously at four stations (ImpE, ImpW, RefS and RefM, figure 1).

Under normal conditions battery capacity and memory in the T-PODs is sufficient for continuous operation for at least one month and in practice even longer than this. The time series obtained from the T-POD signals contained some gaps where the T-PODs were not deployed or specific T-PODs were not operating properly for various technical reasons. The T-PODs have consistently been deployed at the same positions. Thus, there has not been any shifting of T-PODs between positions that could bias the statistical analyses due to differences in T-POD sensitivity.

Prior to the first deployment the T-PODs were calibrated in a circular cedar wood tank, 2.8 m deep, 3 m diameter located at University of Southern Denmark's research facility in Kerteminde. T-PODs were fixed in a holder with the hydrophone pointing downwards and placed 0.5 m below the water surface. A projecting hydrophone (Reson TC4033) was placed in the same depth, 1 m from the T-POD. Calibration signals were 100 μs pulses of 130 kHz pure tones, shaped with a raised cosine envelope. Signals were generated by an Agilent 33250A arbitrary waveform generator. Projector sensitivity was measured prior to calibration by placing a reference hydrophone (Reson TC4034) at the position of the T-POD hydrophone.

T-PODs were presented with groups of 130 kHz pulses of decreasing sound pressure. Threshold was defined as the sound pressure level at which 50% of the transmitted pulses were recorded by the T-POD. Thresholds were determined for 6 out of the 16 possible sensitivity settings and for four different angles of incidence (all in the horizontal plane). V1 T-PODs had a significantly lower sensitivity compared to V5 T-PODs (see also intercalibration section below) and were only used with the most sensitive settings. Following calibration the settings of V5 T-PODs were adjusted to match as closely as possible a sensitivity of 127.5 dB re 1 μPa.

The V1 T-PODs were equipped with 8 MB memory and powered by 6 D-cell type batteries, providing power for a little more than one month. V5 T-PODs have 128 MB memory and are powered by 15 D-cell type batteries, which can power the unit for up to 60 days. The memory will normally fill in 1–2 months depending on echolocation activity, background noise and software settings. Data was downloaded with the T-POD.exe program (version 5.1 for V1 T-PODs and 8.23 for V5 T-PODs) designed for communication with the T-POD and subsequent analysis of data. Harbour porpoise echolocation clicks were extracted from the background noise using a filtering algorithm that filters out non-porpoise clicks such as cavitation noise from boat propellers, echo sounder signals and similar high frequency noise. This filter has several classes of confidence of which the second highest class ('cetaceans all') was used. Data were exported in ASCII format for statistical analysis after filtering.

The detection range of the V1 and V5 T-POD has been determined in the field and shows a maximum range of 350 m from the T-POD, with a detection function decreasing with increasing distance (Kyhn *et al* 2012), However, the detection function is strictly dependent on the detection threshold of the individual T-POD.

Field experiments and sound propagation models have shown that detection of porpoise echolocation may depend on the deployment depth of the T-PODs (DeRuiter *et al* 2010). To avoid variability due to depth, all T-PODs in this study were deployed at similar water depth (6–9 m) and moored 1 m above the bottom.

2.4. Porpoise activity indicators from T-POD signals

Four indicators were extracted from T-POD signals having a constant frequency of 1 min. This signal, denoted x_t, described the recorded number of clicks per minute and consisted of many zero observations (no clicks) and relatively few observations with click recordings. The click intensity per minute was aggregated into daily observations of:

$$\text{PPM} = \text{Porpoise Positive Minutes} = \frac{\text{Number of minutes with clicks}}{\text{Total number of minutes}} = \frac{N\{x_t > 0\}}{N_{\text{total}}}$$

$$\text{CPPM} = \text{Clicks per Porpoise Positive Minute} = \frac{1}{N\{x_t > 0\}} \sum_{x_t>0} x_t.$$

Another approach was to consider the recorded click as a point process, i.e. separate events occurring within the monitored time span. Therefore, we considered x_t as a sequence of porpoise encounters within the T-POD range of detection separated by silent periods without any clicks recorded. Porpoise clicks were often recorded in short term sequences consisting of both minute observations with and without clicks. Such short term sequences were considered to belong to the same encounter although there were also silent periods (no minute clicks) within the sequence. We decided to use a silent period of 10 min to separate two different encounters from each other. This threshold value was determined from graphical investigation of different time series of x_t. Thus, two click recordings separated by a 9 min silent period would still be part of the same encounter. Converting the constant frequency time series into a point process resulted in two new indicators for porpoise echolocation activity.

$$\text{Encounter duration} = \text{Number of minutes between two silent periods}$$

$$\text{Waiting time} = \text{Number of minutes in a silent period} > 10\ \text{min.}$$

This implied that waiting times had a natural lower bound of 10 min, and that encounters potentially included zero minute recordings. Encounter duration and waiting times were computed from data from each T-POD deployment individually identifying the first and last encounters and the waiting times in-between. Consequently, each deployment resulted in one more observation of encounter duration, since the silent periods at beginning and end of deployment were truncated (interrupted) observations of waiting times. Encounter duration and waiting time observations were temporally associated with the time of the midpoint observation, i.e. a silent period starting 30 September at 12:14 and ending 1 October at 1:43 was associated with the mean time of 30 September 18:59 and categorized as a September observation.

2.5. Statistical analysis

The indicators were analysed according to a modified BACI design (Green 1979) that included station-specific and seasonal variation as well. Variation in all four indicators reflecting different features of the same porpoise echolocation activity were assumed to be potentially affected by the following factors (4 fixed and 2 random) and combinations thereof.

- *Area* (fixed factor having 2 levels) describes the spatial variation between control and impact area. The factor is fixed because inference is made for these two areas only.

Table 2. List of transformation, distributions and back-transformation employed on the four indicators for harbour porpoise echolocation activity.

Indicator	Transformation	Distribution	Back-transformation
Daily intensity (PPM)	Logarithmic—$\log(y)$	Normal	$\exp(\mu+\sigma^2/2)$[a]
Daily frequency (CPPM)	Angular–$\sin^{-1}(\sqrt{y})$	Normal	$\sin^2(\mu)$
Encounter duration	Logarithmic—$\log(y)$	Normal	$\exp(\mu+\sigma^2/2)$[a]
Waiting time	Logarithmic—$\log(y-10)$	Normal	$\exp(\mu+\sigma^2/2)+10$[a]

[a] The back-transformation of the logarithmic transformation can be found in e.g. McCullagh and Nelder (1989), p 285.

- *Station (area)* (random factor having five levels) describes the station-specific variation (ImpW, ImpN, ImpE, RefM and RefS) within area. This factor is random in order to infer for all possible spatial sampling locations within the two areas.
- *Period* (fixed factor having 6 levels) describing the difference between baseline, construction and 1–4 operation periods. The factor is fixed because inference is made for these six periods only.
- *Month* (fixed factor having 12 levels (all months)) describes the seasonal variation by means of monthly values. The factor is fixed because all levels are sampled.
- *Podtype* (fixed factor having 2 levels) describes the difference between V1 and V5 T-PODs. The factor is fixed because inference is made for these two types only.
- *Podid* (random factor having 14 levels) describes the random variation between different T-PODs for V1 and V5 separately. This factor is random in order to infer for the deployments of various T-PODs in general instead of the 14 used in the present study.

Three of the fixed factors (main factors area, period, month), and their four interactions, described the spatial–temporal variation in the echolocation activity, whereas podtype described a potential difference in the indicators obtained with V1 versus V5 T-PODs. The use of different T-POD versions was assumed not to interact with the spatial–temporal variation, and consequently interactions between podtype and all the spatial–temporal components (first four factors in the list above) were disregarded in order to limit the model. Thus, variations in the echolocation indicators, after appropriate transformation, were assumed Normal-distributed with a mean value described by the equation for:

$$\mu_{ijkl} = \text{area}_i + \text{period}_j + \text{area}_i \times \text{period}_j + \text{month}_k + \text{area}_i \times \text{month}_k + \text{period}_j \times \text{month}_k + \text{area}_i \times \text{period}_j \times \text{month}_k + \text{podtype}_l. \quad (1)$$

Random effects of the model included station (area) and any derived interactions with the fixed spatial–temporal factors as well as podid (podtype) that had a version-specific variance, i.e. different magnitude of variation between T-PODs for V1 and V5.

The temporal variation in the indicators was assumed to follow an overall fixed seasonal pattern described by monthly means, but fluctuations in the harbour porpoise density in the region on a shorter timescale may potentially give rise to serial correlations in the observations. For example, if a short waiting time is observed the next waiting time is likely to be short as well. Similar arguments can be proposed for the other indicators. In order to account for any autocorrelation in the residuals we formulated a covariance structure for the random variation by means of an ARMA(1,1)-process (Chatfield 1984) subject to observations within separate deployments, i.e. complete independence was assumed across gaps in the time series.

Transformations, distributions and back-transformations were selected separately for the different indicators by investigating the statistical properties of data (table 2). The data comprised an unbalanced design, i.e. uneven number for the different combinations of factors in the model, and arithmetic means by averaging over groups within a given factor may therefore not reflect the 'typical' response of that factor because they do not take other effects into account. Typical responses of the different factors were calculated by marginal means (Searle *et al* 1980) where the variation in other factors was taken into account.

Waiting times had a natural bound of 10 min imposed by the encounter definition, and we therefore subtracted 9 min from these observations before taking the logarithm in order to derive a more typical lognormal distribution. Applying the log-transformation had the implication that additive factors, as described in equation (1), were multiplicative on the original scale. This meant that e.g. the seasonal variation was described by monthly scaling means rather than additive means. Variations in the four indicators were investigated within the framework of generalized linear mixed models (McCullagh and Nelder 1989), and the significance of the different factors in equation (1) was tested using the F-test (type III SS) for the normal distribution (SAS Institute 2003).

The factor area × period, also referred to as the BACI effect, described a step-wise change (e.g. from baseline to post-construction) in the impact area different from that in the reference area. Marginal means for the different factors of the model were calculated and back-transformed to mean values on the original scale. For log-transformed indicators such contrasts can be interpreted by calculating:

$$\exp(\text{BACI contrast}) = \frac{\text{E[Impact, post-construction]}}{\text{E[Impact, baseline]}} \times \frac{\text{E[Control, baseline]}}{\text{E[Control, post-construction]}} \quad (2)$$

i.e. the exponential of the contrast describes the relative change from the baseline to the construction period in

Table 3. Significance testing of fixed effects in equation (1) for the four indicators after removing non-significant fixed and random effects, while the main effects and factors related to the BACI analyses were retained.

	Click PPM			PPM		
Fixed effects	DFs	F	P	DFs	F	P
Area	174.6	26.04	<0.0001	1 127	101.05	<0.0001
Period	583.4	1.98	0.0901	5 133	17.13	<0.0001
period × area	572.5	4.37	0.0016	5 122	7.10	<0.0001
Month	11 221	4.23	<0.0001	11 325	15.38	<0.0001
Podtype	1 165	8.67	0.0037	1 208	30.62	<0.0001
	Encounter duration			Waiting time		
Fixed effects	DFs	F	P	DFs	F	P
Area	128.1	2.96	0.0964	165.9	57.22	<0.0001
Period	538.8	3.12	0.0185	586.5	9.50	<0.0001
Period × area	529.1	1.30	0.2893	568	3.65	0.0055
Month	1137	1.24	0.2952	1180.5	10.07	<0.0001
Podtype	1429	11.84	0.0006	1350	11.30	0.0009

the impact area relative to the reference area. Similar calculations were carried out for the BACI contrasts for different combination of periods.

The statistical analyses were carried out within the framework of mixed linear models (Littell *et al* 1996) by means of PROC MIXED in the SAS system. Statistical testing for fixed effects (F-test with Satterthwaite approximation for denominator degrees of freedom) and random effects (Wald Z) were carried out at a 5% significance level (Littell *et al* 1996). The F-test for fixed effects was partial, i.e. taking all other factors of the model into account, and non-significant factors were removed by backward elimination and the model re-estimated, although effects pertaining to the BACI testing (period and area) were retained for displaying their level of significance.

3. Results

The T-PODs were deployed for a total of 1422 days, while porpoise echolocation data were extracted for on average 817 days on each station, equalling 57% of the time. The backward elimination approach resulted in all random factors, except for the ARMA(1,1) covariance structure for all four indicators and period × month × station (area) for encounter duration and waiting time, were found insignificant and removed from the model. The random variation among stations was not significant, indicating that there was no smaller-scale spatial variation in echolocation activity within the reference and impact area. Moreover, for all four indicators the fixed factors area × month, period × month and area × period × month were also not significant and consequently removed from the model, and this suggests that the echolocation activity followed the same seasonal pattern in both the reference and impact area as well as across the different periods. After removing non-significant interactions and re-estimating the model (equation (1)), all main factors and the BACI effect were all significant for PPM and waiting time, whereas not all of these factors were significant for CPPM and encounter duration (table 3). Significant variation between T-POD V1 and V5 were found for all indicators, clearly demonstrating that V5 T-PODs were more sensitive and recorded higher echolocation activity than V1 T-PODs.

4. Seasonal patterns

Three of the four indicators had a highly significant seasonal variation (table 3) with a similar and pronounced unimodal seasonal pattern (figure 2). In fact, only encounter duration was not changing over the seasons. Few porpoises were encountered during winter months (January–March), with on average about three encounters at each T-POD per week, compared to the peak during summer, where several encounters were recorded daily. The seasonal variations were comparable to those reported in Carstensen *et al* (2006). CPPM varied from a mean of 26 clicks min^{-1} in February to 56 clicks min^{-1} in May, PPM varied from 0.13% in February to 0.78% in September, encounter duration varied, albeit not significantly, from 2.6 min in February to 4.2 min in April, and waiting times varied from 59 h in February to 5.6 in August. In general, the largest seasonal variations were observed for PPM and waiting times.

4.1. Long term assessment

Echolocation activity was significantly higher in the reference area than in the impact area for all indicators except encounter duration (table 3), with 49.1 versus 36.1 clicks min^{-1} for CPPM, 0.71% versus 0.25% PPM, and 8.8 versus 22.3 h for waiting time. Based on PPM and waiting time the mean echolocation activity was almost three times higher in the reference area. Significant changes were also found across the six periods (baseline, construction and operation 1–4) for all indicators except CPPM. Echolocation activity was highest during the baseline for all indicators and lowest during the construction period for all indicators except encounter duration (figure 3). During the four operation periods there was a tendency of increasing echolocation activity, particularly in the impact area, although operation period 2 had the highest PPM and encounter duration. The BACI effect

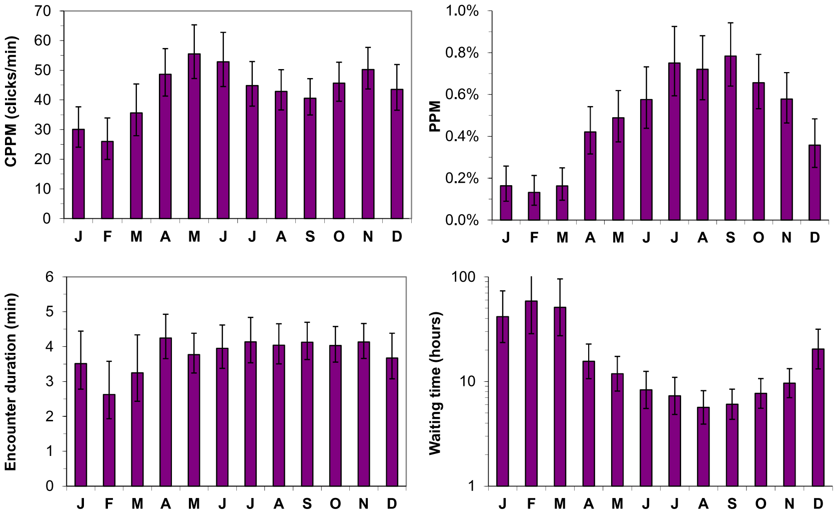


Figure 2. Monthly means at Nysted reference and impact areas combined showing the four indicators after back-transformation. Error bars show 95% confidence limits of the mean values. The covariation with other factors in equation (2) has been accounted for by calculating marginal means.

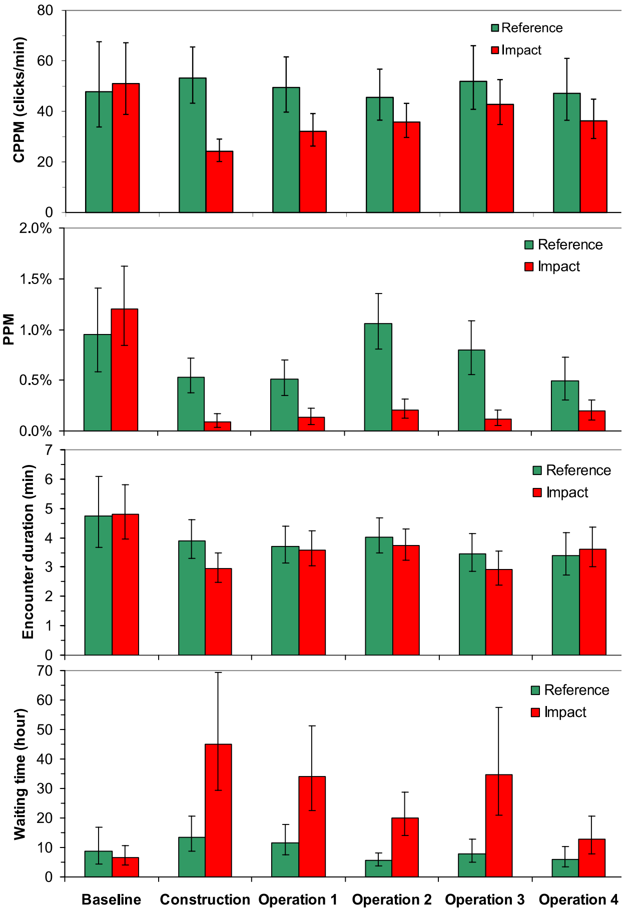


Figure 3. Mean values for the four indicators back-transformed to the original scale for combinations of the two areas and the six periods (baseline Nov 2001–Jun 2002, construction Jul 2002–Nov 2003, operation 1 Dec 2003–Dec 2004, operation 2 Jan–Dec 2005, operation 3 Sep 2008–Feb 2009 and operation 4 Sep 2011–Mar 2012). Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in months and T-POD versions have been accounted for by calculating marginal means.

was significant for all indicators except encounter duration (table 3). However, this factor only described that there were significant relative changes between the impact and reference areas across all periods, whereas which specific periods may have caused this significant change were demonstrated by calculating BACI contrasts (table 4). The relative changes across periods are shown in figure 3. The significant BACI effect for CPPM was mainly caused by a 57% relative decline in the impact area from the baseline to construction period and a 70–80% increase from the construction period to operation periods 2–4. PPM was reduced in the impact area relative to the reference area by a factor of 5–10 from the baseline to the other periods, except for the operation period 4 when the relative change was only a factor of 3.5 lower. There was a relative reduction in PPM from operation period 1 to operation period 2, followed by a relative increase from operation period 2 and 3 to operation period 4. There was no overall relative change between the impact and reference area across periods for encounter duration, albeit one of the contrasts was borderline significant. Waiting times in the impact area increased 4–6 times relative to the reference area from the baseline to the construction and operation periods 2 and 3, whereas the relative change from baseline to the operation period 4 only decreased about a factor of three and was borderline significant (table 4).

5. Discussion

This study has successfully collected acoustic data on harbour porpoise echolocation activity for more than 10 years in one of the first large scale offshore wind farms in the world. It is also the first long term study of effects of offshore wind farms on harbour porpoises. The results show that the echolocation activity declined in Nysted Offshore Wind Farm after the baseline in 2001–2 (Carstensen *et al* 2006) and has not fully recovered yet. However, when comparing the wind farm area with the reference area in operation period 4

Table 4. The relative change between the impact and reference area from one period to another given as percentage (cf equation (2)) and the *P*-value for the contrast. Significant BACI contrasts are highlighted in bold.

BACI contrast	Click PPM		PPM		Encounter duration		Waiting time	
Baseline–construction	**43%**	**0.0004**	**11%**	**<0.0001**	74%	0.0950	**475%**	**0.0011**
Baseline–operation1	**61%**	**0.0373**	**20%**	**0.0002**	95%	0.7842	**397%**	**0.0027**
Baseline–operation2	74%	0.1954	**16%**	**<0.0001**	92%	0.5939	**495%**	**0.0004**
Baseline–operation3	77%	0.3076	**11%**	**<0.0001**	84%	0.3657	**599%**	**0.0005**
Baseline–operation4	72%	0.2048	**29%**	**0.0047**	108%	0.7035	**287%**	**0.0406**
Construction–operation1	**143%**	**0.0343**	178%	0.2458	128%	0.0892	84%	0.6303
Construction–operation2	**173%**	**0.0014**	140%	0.1869	123%	0.1193	104%	0.9026
Construction–operation3	**181%**	**0.0021**	99%	0.3277	113%	0.4449	126%	0.5852
Construction–operation4	**169%**	**0.0088**	262%	0.0931	**145%**	**0.0364**	61%	0.2579
Operation1–operation2	121%	0.2661	**79%**	**0.0186**	96%	0.7601	125%	0.5077
Operation1–operation3	127%	0.2215	55%	0.0596	88%	0.4400	151%	0.3224
Operation1–operation4	118%	0.4044	147%	0.4661	113%	0.4743	72%	0.4558
Operation2–operation3	105%	0.8086	70%	0.8891	92%	0.5742	121%	0.6285
Operation2–operation4	98%	0.9078	**186%**	**0.0078**	117%	0.3140	58%	0.1871
Operation3–operation4	93%	0.7488	**265%**	**0.0230**	128%	0.1897	48%	0.1268

(2011–2), there is a relatively higher echolocation activity than during the construction period (2002–3) and operation period 1–3 (2004–6 and 2008–9), showing a significant increase from construction to operation period 4 in click PPM and encounter duration as well as significant increases in PPM from operation periods 2 and 3 to operation period 4. It is therefore likely that the strong negative effect on porpoises in Nysted Offshore Wind Farm is gradually diminishing possibly due to a habituation of the porpoises to the wind farm or enrichment to the environment favourable to porpoises due to less fishing and artificial reef effects (Petersen and Malm 2006).

Although T-PODs have been deployed at several different locations in Danish waters and elsewhere, it is not possible to compare measurements directly. Different versions and settings of T-PODs have been used in different studies and it is not possible to translate these data into exact number of animals in the area. Nevertheless, fewer animals in general are present in the Nysted area, compared to a high density area such as Horns Reef in the North Sea where porpoise clicks were recorded by T-PODs about ten times more often than in the Nysted area (Tougaard *et al* 2006). Also the density of harbour porpoises in the south western Baltic Sea (0.101 animals km^{-2}) was estimated to be about seven times lower than in the adjacent waters to the north (Danish straits, Kattegat and Skagerrak 0.725 animals km^{-2}) and about eight times lower than around Horns Reef (0.812 animals km^{-2}, Hammond *et al* 2002). The annual variation found at Nysted was similar to what was found at Horns Reef although not as pronounced (Tougaard *et al* 2006). At the Dutch offshore wind farm Egmond aan Zee in the North Sea a strong seasonal high peak was found from December–March and almost complete absence in summer (Scheidat *et al* 2011). The biological reason behind the observed decrease in abundance in winter is unknown.

The effects of large scale offshore wind farms on harbour porpoises have been studied at four wind farms. At Nysted (72 turbines, gravity foundations) and Horns Rev I (80 turbines, mono piles) both construction and operation was studied, while at Horns Rev II (91 turbines, mono piles) only construction was studied and at Egmond aan Zee (36 turbines, mono piles) only the operation was studied. At Horns Rev I and II, there was a weak negative effect of the construction period as a whole and strong, but short lived reactions to pile driving operations out to at least 20 km and for up to 24 h (Tougaard *et al* 2006, 2009, Brandt *et al* 2011). At Nysted, despite only limited pile driving at one foundation, there were strong negative reactions to the construction as a whole, where animals left the wind farm area almost completely. Also the reference site 10 km away appeared affected (Carstensen *et al* 2006). Nysted was constructed with gravity foundations, which takes longer to construct than mono pile foundations, but the loud impulsive sounds from pile driving are avoided.

The population effect of constructing and operating the four wind farms has not been assessed. In general, however, at Horns Rev a large number of animals were affected, but for a limited period of time during the construction period. At Nysted comparatively fewer porpoises were affected. However, when evaluating the total impact from the entire study period, a higher proportion of the population at Nysted was probably affected because the response to the wind farm was stronger and because the duration of the disturbance was considerably longer than at Horns Rev.

Contrary to the findings at Nysted, no significant negative or positive effects were found at Horns Rev I during the operation of the wind farm. In contrast to both Nysted and Horns Rev I, the results from Egmond aan Zee showed a pronounced and significant increase in harbour porpoise acoustic activity inside the operating wind farm, compared to the baseline. The cause for this increase is unknown, however, the area is known for heavy ship traffic and intensive trawling, so the ban of shipping and fishing inside the wind farm may have provided a 'sanctuary' for the porpoises (Scheidat *et al* 2011).

The monitoring programs were all designed to use a BACI design to determine if the animals avoided the wind farm areas both during construction and/or operation of the wind farms. This is probably the most powerful testing analysis to apply, but the data do not reveal the underlying causal factors, i.e. whether noise, presence of the turbines, boat traffic or change in prey availability were responsible for the observed effects. The only exception is pile drivings during construction (Carstensen *et al* 2006, Tougaard *et al* 2009). However, it is likely that the negative effect on porpoises from the construction could be due to a combination of disturbance from the different construction activities, involving boat traffic, with associated underwater noise, as well as disturbance to the seabed with resuspension of sediment etc. Secondary effects, where prey species of fish were deterred by the construction and operation activities are also possible. There are no clear explanations to the slow recovery at Nysted and why this negative effect was not observed at Horns Rev and Egmond aan Zee. Whether the difference in construction methods between the three wind farms (pile driving at Horns Rev and Egmond aan Zee and gravitation foundations at Nysted) affected the porpoises differently is also unknown. Like at other offshore wind farms, a smaller fast moving service boat has daily visits to Nysted wind farm, which passes the reference area on the way between Gedser Harbour and the wind farm (see figure 1). Fishing activity was limited in Nysted wind farm area before the wind farm was constructed and changes in fisheries is therefore not expected to have any impact on the porpoises in the area. Similarly, other human activities seem to be unchanged over the period of the study. One possible explanation to the stronger response at Nysted may be that the area is a less important habitat to porpoises than Horns Rev and Egmond aan Zee and that the lower porpoise density at Nysted implies less competition for food resources and thereby that the porpoises do not necessarily have a strong incentive to search for food in an area with disturbances. In other words, the porpoises at Horns Rev and Egmond aan Zee may be more tolerant to disturbance, if the area is of great importance to their survival, whereas the porpoises around Nysted may not be particularly interested in the area, as indicated by satellite tracks in the area (Sveegaard *et al* 2011) and may simply avoid the area if disturbed, without any larger consequences than the need to swim around the wind farm. Another possible explanation is that the Nysted wind farm is located in a relatively sheltered area in the Baltic, whereas Horns Rev and Egmond aan Zee has a high exposure to wind and waves in the North Sea resulting in higher natural background noise. Thus, at Nysted the signal to noise ratio is higher and therefore the relative noise level from the turbines is louder and more audible to the porpoises at greater distances than at Horns Rev and Egmond aan Zee. Since the effects on harbour porpoises were different in magnitude at the three wind farms, we conclude that harbour porpoises may react differently to similar disturbances, like wind farms. This is an important conclusion in future monitoring of wind farms. Until more information is available on the actual cause of the observed difference no generalization of the results to other wind farms can be recommended.

Cumulative effects are an important issue when more wind farms are built within the same range of a harbour porpoise population. In 2009–10 (between Operation 3 and 4) another large offshore wind farm (Rødsand 2, www.eon.dk/Rodsand-2) comprising 90 turbines was constructed using gravity foundations (like Nysted) only about 3 km west of Nysted wind farm. All construction and maintenance activities for this wind farm were based in Rødbyhavn west of Nysted offshore wind farm and ships did therefore not go through the Nysted wind farm or the reference area (see figure 1). Since there was no monitoring of harbour porpoises during the construction the effect of this cannot be evaluated. The cumulative effect of the operation of both wind farms in Operation 4 (2011–2) showed a relative increase in porpoise presence inside Nysted wind farm compared to the reference stations. The reference area for the present study was 10 km east of Nysted wind farm (away from Rødsand 2 wind farm) and is therefore less likely to be influenced by Rødsand 2 than Nysted wind farm. The gradual return of the porpoises to Nysted wind farm started before Rødsand 2 wind farm was constructed and we do not see a strong cumulative effect of an additional adjacent wind farm. We therefore suggest that the gradual return of porpoises in Nysted wind farm is unlikely to be related to the construction and operation of Rødsand 2 offshore wind farm.

Future monitoring will show if harbour porpoises in Nysted wind farm will fully recover over time and return to the level prior to construction or if the wind farm has caused permanent habitat loss. Also focus should be given to determining cumulative effects of several wind farms to be able to set threshold levels in disturbance tolerance of harbour porpoises under various ecological and geographical conditions. Finally, studies explaining why, and at what distances, porpoises react negatively or positively to operating wind turbines, under different habitat conditions are lacking.

Acknowledgments

We are grateful to Gregers Glendorf, Svend-Erik Rasmussen and Jan Simonsen from the cutter M/S Amigo and HH Enterprise for help with the T-POD deployments and their invaluable expertise on offshore equipment. We thank our colleagues Jakob Tougaard, Susi Edrén, Thomas Dau Rasmussen, Nikolaj Ilsted Bech, Lars Renvald, Jan Damgaard and Anders Galatius from Department of Bioscience (former NERI) for their enthusiastic participation in preparation of the equipment, during the field work and reporting. Nick Tregenza (Chelonia) is acknowledged for kind and prompt responses related to all sorts of questions related to the T-PODs. We thank Charlotte Boesen, Per Hjelmsted Pedersen, Hans Ohrt and Pernille Holm Skyt from Energi E2 A/S and Esben Tarpgaard from NIRAS A/S for help and fruitful discussions during the project. The study was funded from 2001 to 2005 by the Danish Energy Authority under contract with Energi E2 A/S, through the PSO-programme and from 2008–12 by E.ON Vind Sverige AB. Farvandsvæsnet, Søfartsstyrelsen and DONG Energy gave permission to the deployments. The map was kindly provided by Signe Sveegaard.

References

Akamatsu T, Teilmann J, Miller L A, Tougaard J, Dietz R, Wang D, Wang K, Siebert U and Naito Y 2007 Comparison of echolocation behaviour between coastal and riverine porpoises *Deep-Sea Res.* II **54** 290–7

Brandt M J, Diederichs A, Betke K and Nehls G 2011 Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea *Mar. Ecol. Prog. Ser.* **421** 205–16

Carstensen J, Henriksen O D and Teilmann J 2006 Impacts on harbour porpoises from offshore wind farm construction: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs) *Mar. Ecol. Prog. Ser.* **321** 295–308

Chatfield C 1984 *The Analysis of Time Series—An Introduction* 3rd edn (London: Chapman and Hall) p 286

DeRuiter S L, Hansen M, Koopman H N, Westgate A J, Tyack P L and Madsen P T 2010 Propagation of narrow-band-high-frequency clicks: measured and modeled transmission loss of porpoise-like clicks in porpoise habitats *J. Acoust. Soc. Am.* **127** 560–7

Green R H 1979 *Sampling Design and Statistical Methods for Environmental Biologists* (New York: Wiley)

Hammond P S, Berggren P, Benke H, Borchers D L, Collet A, Heide-Jørgensen M P, Heimlich S, Hiby A R, Leopold M F and Øien N 2002 Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters *J. Appl. Ecol.* **39** 361–76

Kyhn L A, Tougaard J, Thomas L, Poulsen L R, Steinbæk J, Desportes G, Amundin M and Teilmann J 2012 From echolocation clicks to animal density—acoustic sampling of harbour porpoises with static dataloggers *J. Acoust. Soc. Am.* **131** 550–60

Linnenschmidt M, Teilmann J, Akamatsu T, Dietz R and Miller L A 2012 Biosonar, dive and foraging activity of satellite tracked harbour porpoises (*Phocoena phocoena*) *Mar. Mam. Sci.* at press (doi:10.1111/j.1748-7692.2012.00592.x)

Littell R C, Milliken G A, Stroup W W and Wolfinger R D 1996 *SAS System for Mixed Models* (Cary, NC: SAS Institute) p 633

McCullagh P and Nelder J A 1989 *Generalized Linear Models* 2nd edn (Boca Raton, FL: Chapman & Hall/CRC Press)

Møhl B and Andersen S 1973 Echolocation: high-frequency component in the click of the harbour porpoise (*Phocena ph. L.*) *J. Acoust. Soc. Am.* **54** 1368–72

Petersen J K and Malm T 2006 Offshore windmill farms: threats to or possibilities for the marine environment *Ambio* **35** 75–80

SCANS-II 2008 Small cetaceans in the European Atlantic and North Sea (SCANS-II) *Final Report to the European Commission Under Project LIFE04NAT/GB/000245* (St Andrews: University of St Andrews) (http://biology.st-andrews.ac.uk/scans2/inner-finalReport.html)

Scheidat M, Tougaard J, Brasseur S, Carstensen J, Petel T V P, Teilmann J and Reijnders P 2011 Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea *Environ. Res. Lett.* **6** 025102

Searle S R, Speed F M and Milliken G A 1980 Populations marginal means in the linear model: an alternative to least squares means *Am. Stat.* **34** 216–21

Sveegaard S, Teilmann J, Tougaard J, Dietz R, Mouritsen K N, Desportes G and Siebert U 2011 High density areas for harbor porpoises (*Phocoena phocoena*) identified by satellite tracking *Mar. Mam. Sci.* **27** 230–46

Teilmann J, Miller L A, Kirketerp T, Kastelein R, Madsen P T, Nielsen B K and Au W W L 2002 Characteristics of echolocation signals used by a harbour porpoise (*Phocoena phocoena*) in a target detection experiment *Aquat. Mamm.* **28** 275–84

Tougaard J, Carstensen J, Wisz M S, Teilmann J, Bech N I and Skov H 2006 Harbour porpoises on Horns Reef in relation to construction and operation of Horns Rev Offshore Wind Farm *Technical Report to Elsam Engineering A/S* (Roskilde: National Environmental Research Institute)

Tougaard J, Carstensen J, Teilmann J, Skov H and Rasmussen P 2009 Pile driving zone of responsiveness extends beyond 20 km for harbour porpoises (*Phocoena phocoena*, (L.)) *J. Acoust. Soc. Am.* **126** 11–4

Verfuss U K, Honnef C G, Meding A, Dähne M, Mundry R and Benke H 2007 Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring *J. Mar. Biol. Assoc. UK* **87** 165–76

Marine Mammal Science

Letters

MARINE MAMMAL SCIENCE, 34(1): 265–270 (January 2018)

DOI: 10.1111/mms.12463

Response to "Resilience of harbor porpoises to anthropogenic disturbance: Must they really feed continuously?"

Danuta Maria Wisniewska, Hopkins Marine Station, Stanford University, 120 Ocean View Boulevard, Pacific Grove, California 93950, U.S.A., Zoophysiology, Department of Bioscience, Aarhus University, Building 1131, C. F. Moellers Alle 3, DK-8000 Aarhus C, Denmark and Marine Mammal Research, Department of Bioscience, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark; **Mark Johnson**, Scottish Oceans Institute, East Sands, University of St Andrews, St Andrews KY16 8LB, Scotland; **Jonas Teilmann**, Marine Mammal Research, Department of Bioscience, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark; **Laia Rojano-Doñate**, Zoophysiology, Department of Bioscience, Aarhus University, Building 1131, C. F. Moellers Alle 3, DK-8000 Aarhus C, Denmark; **Jeanne Shearer**, Scottish Oceans Institute, East Sands, University of St Andrews, St Andrews KY16 8LB, Scotland; **Signe Sveegaard,** Marine Mammal Research, Department of Bioscience, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark; **Lee A. Miller**, Sound and Behaviour Group, Institute of Biology, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark; **Ursula Siebert**, Institute for Terrestrial and Aquatic Wildlife Research, University of Veterinary Medicine Hannover, Werftstrasse 6, 25761, Buesum, Germany; **Peter Teglberg Madsen**, Zoophysiology, Department of Bioscience, Aarhus University, Building 1131, C. F. Moellers Alle 3, DK-8000 Aarhus C, Denmark and Murdoch University Cetacean Research Unit, School of Veterinary and Life Sciences, Murdoch University, Perth, Western Australia, 6150, Australia.

Our recent paper on harbor porpoise (*Phocoena phocoena*) foraging (Wisniewska *et al.* 2016) has sparked an interesting discussion that has been thoughtfully summarized by Hoekendijk *et al*. (2018). In their correspondence, these authors commend our methodological approach but point out some potential shortcomings. Specifically, their concerns pertain to the small sample size used in our study, the biased age structure of porpoises examined, the potential impacts of the tagging procedure, and the short period of monitoring after tagging. Moreover, the authors put in doubt our

---

[1] Corresponding author (e-mail: danuta@stanford.edu).

findings of little overlap between the diet of the tagged porpoises and commercial fisheries, and suggest that the ability to feed at high rates makes porpoises resilient to anthropogenic disturbance. In this note, we address these points of critique.

There is, unfortunately, no unbiased way to assess the prey preference and dietary intake of free-ranging marine mammals like harbor porpoises. Although the traditional approach involving stomach content analysis of stranded and bycaught individuals provides important information, animals must either end up on a beach (*e.g.*, due to illness or navigation error) or in a net (*e.g.*, potentially due to a preference for the prey targeted by the fishery) in order to be sampled. In our paper, we took a novel and complementary approach involving analysis of echo information from prey targeted by instrumented porpoises as they hunt freely. As a result, we are reliant on animals incidentally live caught in commercial pound nets to be temporarily restrained for tagging, resulting in a small sample size comprising mostly young individuals. Although we would of course have preferred a broader sample, this does not lessen the significance of our results. Specifically, even if the "ultra-high" foraging rates demonstrated in our paper are only typical of young animals, the resulting higher vulnerability to disturbance will still give rise to a bottleneck effect: all animals are young at some point in their lives. Moreover, animals of 2 yr and younger constitute a significant proportion of the porpoise population (Lockyer and Kinze 2003).

This high proportion of young porpoises, perhaps combined with their inexperience, may explain why this age class prevails in pound nets. Unfortunately, very few of our suction cup tag deployments on adult porpoises have extended beyond a few hours without considerable sliding or detachment of the tag. However, data from an adult female of 170 cm, tagged since our paper was drafted, revealed buzz rates ranging from 35 to 140 buzzes per hour with an average of 73 buzzes per hour over the 13 h deployment, similar to the 86 buzzes per hour that we reported for another adult female in Wisniewska *et al.* (2016) (Table 1). While the buzz rates of these adults are on average lower than for juveniles (125 per hour), they, nonetheless, appear to target some 1,500–2,000 small fish per day (Table 1). Thus, although our adult sample size is small, Hoekendijk *et al.*'s concern that high feeding rates are only found in juvenile porpoises does not seem to be supported by our data.

Table 1. Buzz rates of the five harbor porpoises in Wisniewska *et al.* (2016) and two new animals not presented previously (in bold), ordered by size. Buzz rates were computed as averages of buzz counts in complete recording hours, *i.e.*, excluding the first and last incomplete hours of the recording. Time before the first foraging buzz was assumed to be the recovery period. Hence, tag duration represents here the time from start of foraging to the end of tag deployment. Total tag recording time is provided in brackets.

ID	Sex	Deployment date	Standard length (cm)	Tag duration (h)	No. of feeding buzzes	Buzzes per hour
hp16_316a	♂	11 Nov 2016	113	39.1 (39.5)	5,715	146
hp13_102a	♂	12 Apr 2013	114	22.7 (23.7)	3,405	162
hp12_272a	♀	28 Sep 2012	122	17.8 (21.9)	1,821	106
hp13_170a	♂	19 Jun 2013	122	15.3 (15.3)	1,222	60
hp14_226b	♂	14 Aug 2014	126	19.8 (20)	3,234	153
hp12_293a	♀	19 Oct 2012	163	16.4 (17.7)	1,346	86
hp15_116a	♀	24 Apr 2015	170	12.4 (13)	906	73
Mean buzz rate juveniles						125.4
Mean buzz rate adults						79.5

We also note that these authors mistakenly extrapolate the extreme value of foraging rate reported in our paper to infer that individual porpoises must be taking ">10,000 fish per day." We clearly stated in our paper that 550 prey capture attempts per hour was the maximum hourly rate recorded from any of our porpoises. In figure 1 of the paper, we showed how the hourly buzz rate changed throughout the deployment and reported the total buzz count for each tagged individual. The mean buzz rate for juveniles in our study of 125 per hour (Table 1) leads to a much lower daily ration than that erroneously inferred by Hoekendijk *et al.* Assuming the weight of each small fish to be around 1 g, and a 90% prey capture success rate, our porpoises would have consumed about 2.7 kg/24 h, which is roughly 10% of the body weight of a young porpoise (Lockyer *et al.* 2003). These numbers are consistent with stomach content analyses (Leopold 2015, Andreasen *et al.* 2017): Leopold (2015) states that "young porpoises quickly become very efficient foragers on gobies. We have seen many stomachs containing hundreds, and 30 containing the remains of over one thousand gobies (the record-holder had remains of 5,369 gobies in its stomach)." This is very much in line with our findings even if not from the same area or population.

Hoekendijk *et al.* go on to suggest that "the entire recording time period (15–23 h period after tagging) on which the authors base their conclusions should be considered as poorly representative of a 'normal behavior' since the porpoises released after being trapped should still be recovering from stress and starvation." This is again an extreme interpretation for which Hoekendijk *et al.* provide no supporting evidence. Porpoises likely swim into pound nets following prey, and there is always fish in the nets where the animals are trapped. We do not know to what extent porpoises feed while in the pound net nor whether they have an elevated stress level during this time. We did, however, make every effort to minimize stress during tagging. Porpoises were typically only restrained for 5 min while being instrumented with the suction cup tags and were not followed after release. Given the uncertain state of hunger of porpoises at the time of release, and the scant data on how porpoises respond to stress and starvation, it is not possible to refute Hoekendijk *et al.*'s assertion. But, it certainly seems a bit constructed to argue that the entrapped porpoises do not feed in the net and *therefore* must feed a lot after tagging (for the entire recording time) and *therefore* show large room for compensation and, *hence*, resilience to disturbance. Since our paper was published we have tagged a juvenile porpoise for 39.5 h (Fig. 1, Table 1) providing an opportunity to explore whether potential responses to tagging might attenuate over a longer interval. That animal targeted an average of 145 fish per hour, producing 2,841 buzzes in the first 24 h after release, and 2,874 buzzes in the following 15.5 h, entirely consistent with our other tagged juveniles. Although this could be interpreted as a prolonged response to the tagging circumstances, such an argument becomes increasingly difficult to sustain and we suggest that it is more tempered to view the tag data as largely representative of normal behavior of the animals sampled.

In common with many tag-based studies, our data represent a small and brief sample from a single location. While these data provide the first insight into the search and prey capture behavior of any porpoise, we certainly do not expect (nor claim in the paper) that our results must apply to porpoises as a whole. Harbor porpoises are opportunistic foragers with dietary preferences that likely differ between geographical areas, seasons, and individuals. However, we reiterate that diet analyses based on stomach contents also have several sources of bias, with the most important limitation being short and differential gastric passage time (Kastelein *et al.* 1997, Christiansen *et al.* 2005, Ross *et al.* 2016). While our tag data represent a brief period of

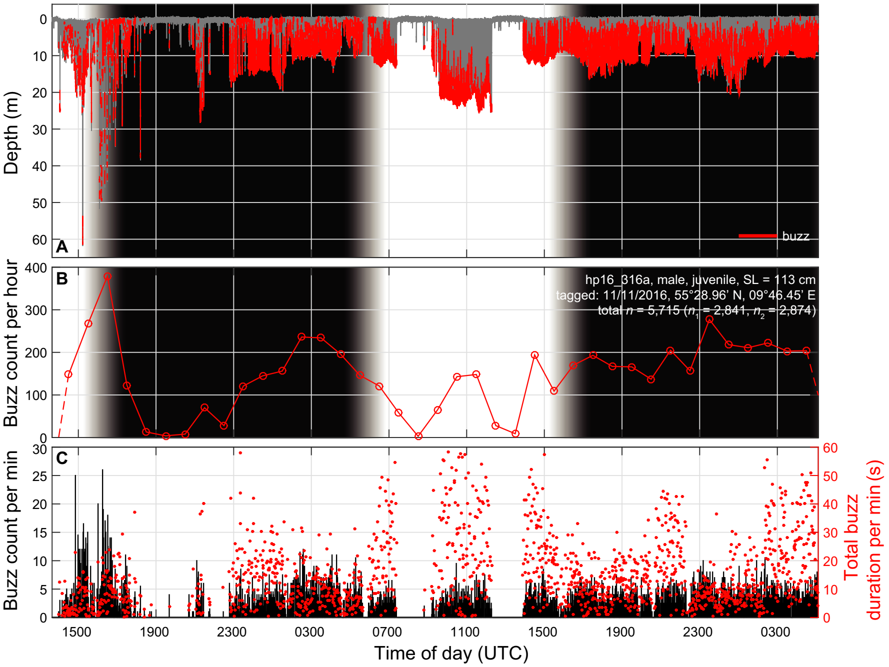


Figure 1. Foraging behavior of a juvenile harbor porpoise during a 39.5 h DTAG deployment. (A) Dive profile. Individual buzzes are marked in red. The shaded area represents twilight (gray) and night (black). See Wisniewska *et al.* (2016) for detailed methodology. (B) Hourly buzz counts as recorded by the attached tag. Numbers for the first and last incomplete hours are depicted with dashed lines. The animal's sex, age class, standard length (SL), tagging date, and location, as well as the number of buzzes recorded during the first 24 h (n_1) and the following 15.5 h (n_2) are listed in the panel. The digits in the names of the individuals indicate the year and Julian day of tag deployment. (C) Minute-wise buzz counts (black bars) and total buzz durations (red circles) illustrating the different foraging strategies employed by the porpoise with numerous short buzzes during pelagic dives, and fewer longer buzzes when targeting benthic or demersal prey.

monitoring for each animal, stomach contents represent an even shorter interval of foraging spanning a maximum of 5 h (Christiansen *et al.* 2005, Ross *et al.* 2016). This rapid digestion process contributes to the scarcity of data from stranded animals, which are often found with empty stomachs (Neimanis *et al.* 2004). Consequently, most inferences about porpoise diet are based on stomachs from individuals bycaught in fishing nets (but see, *e.g.*, Andreasen *et al.* 2017), which are likely biased towards prey in the nets they were targeting. There may also be a bias towards detecting remains of larger prey in stomach contents, as smaller otoliths may deteriorate faster (Christiansen *et al.* 2005, Ross *et al.* 2016), possibly as fast as within an hour for the 1–1.5 mm otolith of a 5 cm black goby (*Gobius niger*) (Härkönen 1986, Christiansen *et al.* 2005). Most diet studies have not accounted for the differential residence time of otoliths in the forestomach of porpoises (but see Ross *et al.* 2016 and Andreasen *et al.* 2017), therefore likely overestimating the share of larger species in porpoise diet (Ross *et al.* 2016). Thus, a complete picture of porpoise foraging will only be achieved by combining insights from a range of different methods.

Finally, we wish to clarify two important misapprehensions of Hoekendijk *et al.* (2018) with regard to our paper. Nowhere in our paper do we make the claim that porpoises do not feed on species of commercial interest: our echo analysis method provides little information on the prey species targeted. While we see how our sentence "the consistently small fish targeted by the four porpoises with measurable echograms suggest that their diet has little overlap with commercial fisheries" could have been misunderstood, our intended message was that there was little overlap, and hence competition, with commercial fisheries in terms of the sizes of targeted fish. This conclusion tallies with data from bycaught animals, as Hoekendijk *et al.* (2018) also point out: with the exception of herring (*Clupea harengus*) and sandeels (*Ammodytes tobianus*), the majority of fish found in stomachs of porpoises from Inner Danish Waters are below the sizes of commercial interest for the given species (Sveegaard *et al.* 2012). Likewise, we do not intend to dispute or draw attention away from bycatch as the prevalent anthropogenic threat to porpoises in European coastal waters, and we wonder how that conclusion can be reached from our paper. Like Hoekendijk and colleagues, we consider efforts to mitigate incidental catches of porpoises in commercial fisheries to be of paramount importance. We sincerely hope that our studies using fine-scale biologging data will complement other study methods to better define the factors that lead to such elevated bycatch and so aid in the conservation of this species.

Literature Cited

Andreasen, H., S. D. Ross, U. Siebert, N. G. Andersen, K. Ronnenberg and A. Gilles. 2017. Diet composition and food consumption rate of harbor porpoises (*Phocoena phocoena*) in the western Baltic Sea. Marine Mammal Science. https://dx.doi.org/10.1111/mms.12421.

Christiansen, J. S., A.-G. G. Moen, T. H. Hansen and K. T. Nilssen. 2005. Digestion of capelin, *Mallotus villosus* (Müller), herring, *Clupea harengus* L., and polar cod, *Boreogadus saida* (Lepechin), otoliths in a simulated seal stomach. ICES Journal of Marine Science 62:86–92.

Härkönen, T. 1986. Guide to the otoliths of the bony fishes of the northeast Atlantic. Danbiu Aps, Hellerup, Denmark.

Hoekendijk, J., J. Spitz, A. Read, M. Leopold and M. Fontaine. 2018. Resilience of harbor porpoises to anthropogenic disturbance: Must they really feed continuously? Marine Mammal Science 34.

Kastelein, R. A., S. H. Nieuwstraten and M. W. A. Verstegen. 1997. Passage time of carmine red dye through the digestive tract of harbour porpoises (*Phocoena phocoena*). Pages 265–275 *in* A. J. Read, P. R. Wiepkema and P. E. Nachtigall, eds. The biology of the harbour porpoise. De Spil Publishers, Woerden, The Netherlands.

Leopold, M. F. 2015. Eat or be eaten: Porpoise diet studies. Ph.D. thesis, Wageningen University, Wageningen, The Netherlands. 239 pp. Available at https://www.wur.nl/en/activity/Eat-and-be-eaten-porpoise-diet-studies-1.htm.

Lockyer, C., and C. Kinze. 2003. Status, ecology and life history of harbour porpoise (*Phocoena phocoena*) in Danish waters. Pages 143–175 *in* T. Haug, G. Desportes, G. A. Vikingsson and L. Witting, eds. Harbor porpoises in the North Atlantic. Volume 5. NAMMCO Scientific Publications, Tromso, Norway.

Lockyer, C. H., G. Desportes, K. Hansen, S. Labberté and U. Siebert. 2003. Monitoring growth and energy utilisation of the harbour porpoise (*Phocoena phocoena*) in human care. NAMMCO Scientific Publications 5:107–120.

Neimanis, A. S., H. N. Koopman, A. J. Westgate, L. D. Murison and A. J. Read. 2004. Entrapment of harbour porpoises (*Phocoena phocoena*) in herring weirs in the Bay of Fundy, Canada. Journal of Cetacean Research and Management 6:7–17.

Ross, S. D., H. Andreasen and N. G. Andersen. 2016. An important step towards accurate estimation of diet composition and consumption rates for the harbor porpoise (*Phocoena phocoena*). Marine Mammal Science 32:1491–1500.

Sveegaard, S., H. Andreasen, K. N. Mouritsen, J. P. Jeppesen and J. Teilmann. 2012. Correlation between the seasonal distribution of harbour porpoises and their prey in the Sound, Baltic Sea. Marine Biology 159:1029–1037.

Wisniewska, D. M., M. Johnson, J. Teilmann, *et al*. 2016. Ultra-high foraging rates of harbor porpoises make them vulnerable to anthropogenic disturbance. Current Biology 26:1441–1446.

Received: 15 September 2017
Accepted: 15 October 2017

PROCEEDINGS B

rspb.royalsocietypublishing.org

Research

Cite this article: Wisniewska DM, Johnson M, Teilmann J, Siebert U, Galatius A, Dietz R, Madsen PT. 2018 High rates of vessel noise disrupt foraging in wild harbour porpoises (*Phocoena phocoena*). *Proc. R. Soc. B* **285**: 20172314. http://dx.doi.org/10.1098/rspb.2017.2314

Received: 18 October 2017
Accepted: 22 January 2018

Subject Category:
Ecology

Subject Areas:
behaviour, ecology, environmental science

Keywords:
anthropogenic disturbance, exposure rates, behavioural response, fitness consequences, foraging, DTAG

Author for correspondence:
Danuta Maria Wisniewska
email: danuta.wisniewska@bios.au.dk

Electronic supplementary material is available online at https://dx.doi.org/10.6084/m9.figshare.c.3991632.

THE ROYAL SOCIETY
PUBLISHING

High rates of vessel noise disrupt foraging in wild harbour porpoises (*Phocoena phocoena*)

Danuta Maria Wisniewska[1,3], Mark Johnson[4], Jonas Teilmann[1], Ursula Siebert[5], Anders Galatius[1], Rune Dietz[1] and Peter Teglberg Madsen[1,2]

[1]Department of Bioscience, and [2]Aarhus Institute of Advanced Studies, Aarhus University, Aarhus, Denmark
[3]Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA
[4]Sea Mammal Research Unit, University of St Andrews, St Andrews, UK
[5]Institute for Terrestrial and Aquatic Wildlife Research, University of Veterinary Medicine Hannover, Buesum, Germany

DMW, 0000-0002-3599-7440; MJ, 0000-0001-8424-3197; JT, 0000-0002-4376-4700; US, 0000-0002-2556-3948; AG, 0000-0003-1237-2066; RD, 0000-0001-9652-317X; PTM, 0000-0002-5208-5259

Shipping is the dominant marine anthropogenic noise source in the world's oceans, yet we know little about vessel encounter rates, exposure levels and behavioural reactions for cetaceans in the wild, many of which rely on sound for foraging, communication and social interactions. Here, we used animal-borne acoustic tags to measure vessel noise exposure and foraging efforts in seven harbour porpoises in highly trafficked coastal waters. Tagged porpoises encountered vessel noise 17–89% of the time and occasional high-noise levels coincided with vigorous fluking, bottom diving, interrupted foraging and even cessation of echolocation, leading to significantly fewer prey capture attempts at received levels greater than 96 dB re 1 μPa (16 kHz third-octave). If such exposures occur frequently, porpoises, which have high metabolic requirements, may be unable to compensate energetically with negative long-term fitness consequences. That shipping noise disrupts foraging in the high-frequency-hearing porpoise raises concerns that other toothed whale species may also be affected.

1. Introduction

Toothed whales rely on sound for communication, navigation and searching for food by echolocation [1], and may therefore be impacted negatively by increased levels of noise associated with human activities in the marine environment [2,3]. Effects may include physical damage and hearing loss for powerful transient noise sources, such as explosions or seismic airguns [2,4], whereas more frequent, lower-level noise exposures can cause masking and behavioural disruption that may be hard to detect, but can have cumulative long-term effects on populations [3]. Recent research efforts have focused on how odontocetes [5–9] respond to transient noise sources, including pile driving, airguns and military sonars, but little is known about the effects of shipping noise—the dominant anthropogenic noise source in the world's oceans [10]. The few studies on the effects of shipping noise have primarily focused on baleen whales owing to their communication, and thus probably sensitive hearing, at low frequencies that overlap with the maximum power outputs of large cargo vessels [11–13]. However, it has recently been shown that a diverse range of vessels produce substantial noise levels at even very high frequencies, where toothed whales hear well and use sound [14,15]. Moreover, boat traffic in many coastal areas is dominated by smaller vessels that generate noise at higher frequencies than large cargo vessels [16], raising the possibility that vessel noise may actually be a significant, but so far overlooked problem for odontocetes [17]. This concern may be particularly relevant for

Table 1. Tag deployment and data summary. (The age classes of the porpoises were determined using growth curves established for Danish porpoises [26].)

animal ID	hp12_272a	hp12_293a	hp13_102a	hp13_170a	hp14_226b	hp15_117a	hp16_264a
deployment date	28 Sep 2012	19 Oct 2012	12 Apr 2013	19 Jun 2013	14 Aug 2014	26 Apr 2015	20 Sep 2016
age class and sex	juvenile ♀	adult ♀ (with a calf)	juvenile ♂	juvenile ♂	juvenile ♂	adult ♀	adult ♀ (with a calf)
standard length (cm)	122	163	114	122	126	170	163
handling time (min)	15	3	5.5	3.5	7.5	12	10
recording duration (h)	21.9	17.7	23.7	15.3	21.7	13	11.9
time to first foraging buzz (h)	4.1	1.4	1	0.1	0.2	0.6	0.2

porpoises that live in areas with some of the highest shipping densities in the world [10].

Although data are sparse, harbour porpoises have been reported to react to ships at long ranges (800–1000 m) [18,19], where noise, rather than the physical presence of the vessel, is more likely to deliver the negative stimulus. Furthermore, recently, captive individuals have been shown to respond behaviourally to low levels of relatively high-frequency vessel noise [20]. This led us to hypothesize that broadband shipping noise may cause behavioural disruptions in porpoises despite them having poor low-frequency hearing compared with most other cetaceans [21]. As small marine mammals that live in cold water requiring high feeding rates year round [22,23], porpoises may be particularly vulnerable to disruption of, or increased energy expenditures associated with, foraging. Behavioural reactions that affect foraging time [24] and increase energy expenditure over short time periods may accumulate over repeated exposures and impact the long-term fitness of animals. In spite of these concerns, very little is known about vessel encounter rates, exposure levels and avoidance reactions of any small odontocetes in the wild, including porpoises. To address this, we here use sound recording tags to study the foraging rates of harbour porpoises as a function of the vessel noise they experience. We show that the tagged porpoises were exposed to vessel noise between 17 and 89% of the time, and that they interrupted foraging in the presence of high-noise levels, which may have adverse effects on populations in industrialized coastal waters.

2. Results

Wideband sound and movement recording tags (DTAGs [25]) were deployed on seven porpoises yielded high-quality recordings (i.e. with little sliding of the suction cup-attached tag, clear buzzes, low flow noise and long duration of between 11.9 and 23.7 h, table 1; electronic supplementary material, figure S1).

(a) Foraging rates

The seven porpoises performed short (1–3 min long) foraging dives to depths of 5–50 m (e.g. figure 1), where they produced a total of 380–3400 buzzes (table 2), an indication of prey encounters [23], with an hourly rate of 0–550 buzzes. Excluding time intervals with rain (e.g. figure 1) or non-vessel sound transients, for example, owing to water splashing, the proportion of 1 min intervals with at least one buzz ranged from 18 to 76% and averaged approximately 50% (table 2; electronic supplementary material, table S1). While few data were collected during night-time for hp13_170a and hp16_264a, all but one porpoise (hp15_117a) seemed to forage primarily after dusk (table 2 and figure 1).

Prey pursuits involved significant increases in flow noise in the tag recordings, in some cases even at high frequencies (greater than 50 kHz) (electronic supplementary material, figure S2). However, 0.5 s averages of one third octave levels (TOLs, i.e. the root mean square (rms) sound pressure level in one third octave bands) in the 16 kHz band during foraging (i.e. 5 s before the start of each buzz and until the end of the buzz) were largely independent of the animals' swimming activity and rarely exceeded 90 dB re 1 µPa (figure 2; electronic supplementary material, figure S2).

(b) Vessel noise exposure

The proportion of time in which vessel noise was audible to expert listeners varied widely across the tagged animals, from approximately 17% for two animals to more than 65% for four animals (table 2 and figure 1). The high exposure rates of the latter individuals may be a consequence of the areas in which these animals stayed. Three of these porpoises were tagged in the narrow and heavily trafficked Great Belt (electronic supplementary material, figure S1) while the dive and movement profiles of the fourth animal (figure 1) suggest that it swam south to a narrow, relatively deep-water shipping route to Aarhus Harbour, the largest container port in Denmark (electronic supplementary material, figure S1; table 1). Vessel noise occurred primarily during daytime (table 2).

Most of the received vessel noise was of relatively low level at the frequencies that could be measured reliably, with L_{10} values (i.e. the noise level exceeded 10% of the time) in the 16 kHz third octave band 1–10 dB (median of 6 dB) above baseline (i.e. periods without foraging or vessel noise; figure 2*a*–*g*). Although for one animal (hp12_272a), only low-level vessel noise was recorded, the remaining animals experienced occasional high TOLs associated with vessel passes (maximum 1 min 16 kHz TOLs of 102–118 dB re 1 µPa rms, figure 2; electronic supplementary material, table S2). These high-noise events seemed to coincide with the absence of buzzes (figure 2, purple overlaid with black outline), raising the question of whether high-level exposures led to reduced foraging.

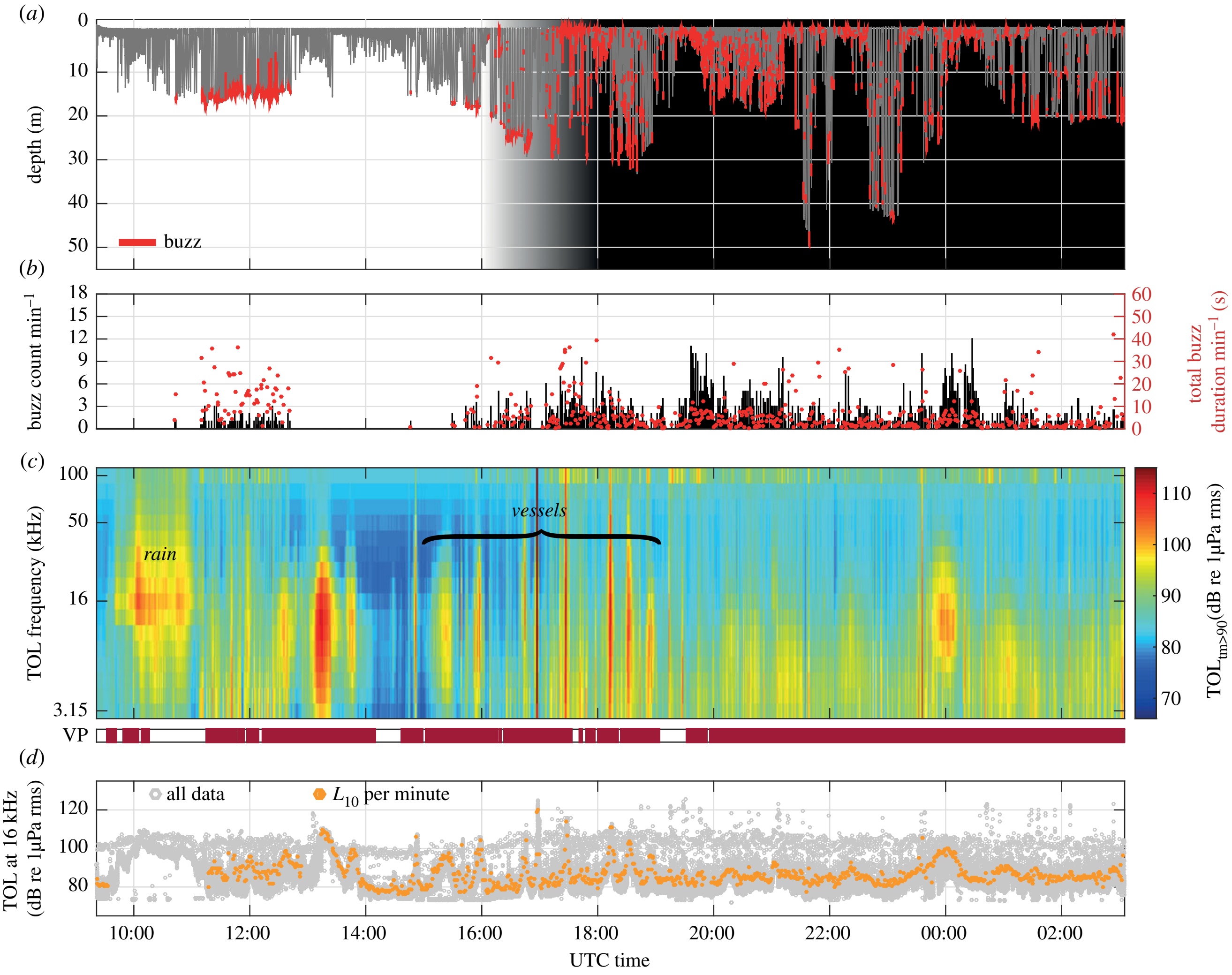


Figure 1. Data from DTAG deployment on porpoise hp12_293a. (*a*) Dive profile. Individual buzzes are marked in red. Shading represents twilight and night. Given the bathymetry of the area, dives deeper than 25 m must have been performed in deeper-water channels. (*b*) Buzz counts per minute (black bars) and buzz durations, in seconds, summed in each minute (red circles). (*c*) TOLs. Shown are the TOL_{10}, i.e. the noise levels in each third octave that are exceeded 10% of the time within each minute, excluding time spent by the animal at the surface during respirations and logging, which emphasizes the highest exposure levels, that is the levels most likely to explain any behavioural reaction. Periods with audible noise from vessels are marked in scarlet in the lower panel (vessels present, VP). (*d*) Noise levels in the third octave band centred at 16 kHz. Light-grey circles show 0.5 s trimmed mean averages prior to exclusion of segments dominated by loud transients (e.g. surface splashes, see Material and methods). Orange circles show 1 min TOL_{10} noise levels.

Table 2. Overview of foraging buzz data, excluding time intervals dominated by rain, splashing and loud transients (see also electronic supplementary material, table S1), and estimates of vessel exposure rates for the entire recording period. (Night was assumed to start after civil dusk.)

animal ID	hp12_272a	hp12_293a	hp13_102a	hp13_170a	hp14_226b	hp15_117a	hp16_264a
total buzz count	1856	1381	3408	1222	3232	906	383
number of minutes analysed	897	907	1160	306	690	700	493
buzz-positive minutes	352 (39.2%)	532 (58.7%)	565 (48.7%)	217 (70.9%)	523 (75.8%)	402 (57.4%)	88 (17.8%)
daytime buzz-positive minutes	65 (17.7%)	83 (27.1%)	124 (17.8%)	114 (60.0%)	383 (73.0%)	304 (64.1%)	22 (5.9%)
night-time buzz-positive minutes	287 (54.2%)	449 (74.7%)	441 (95.0%)	103 (88.8%)	140 (84.9%)	98 (43.4%)	66 (55.0%)
vessel noise exposure rate (%)	37	70	89	17	18	89	66
vessel noise exposure rate-day/night (%)	51/17	55/81	88/92	3/87	22/10	88/93	77/45

(c) Porpoise behaviour during high-level exposures

The behaviour of the porpoise that received the maximum noise exposure (hp12_293a) is shown in figure 3 and the electronic supplementary material, video S1. Vessel automatic identification system (AIS) data at the time of the noise exposure, together with the rapid increase and decrease in noise, suggest that the source was one of the fast ferries moving between the island of Zealand and the Jutland Peninsula (electronic supplementary material, figure S1). Doppler-shift analysis of the signal recorded by the tag indicates a

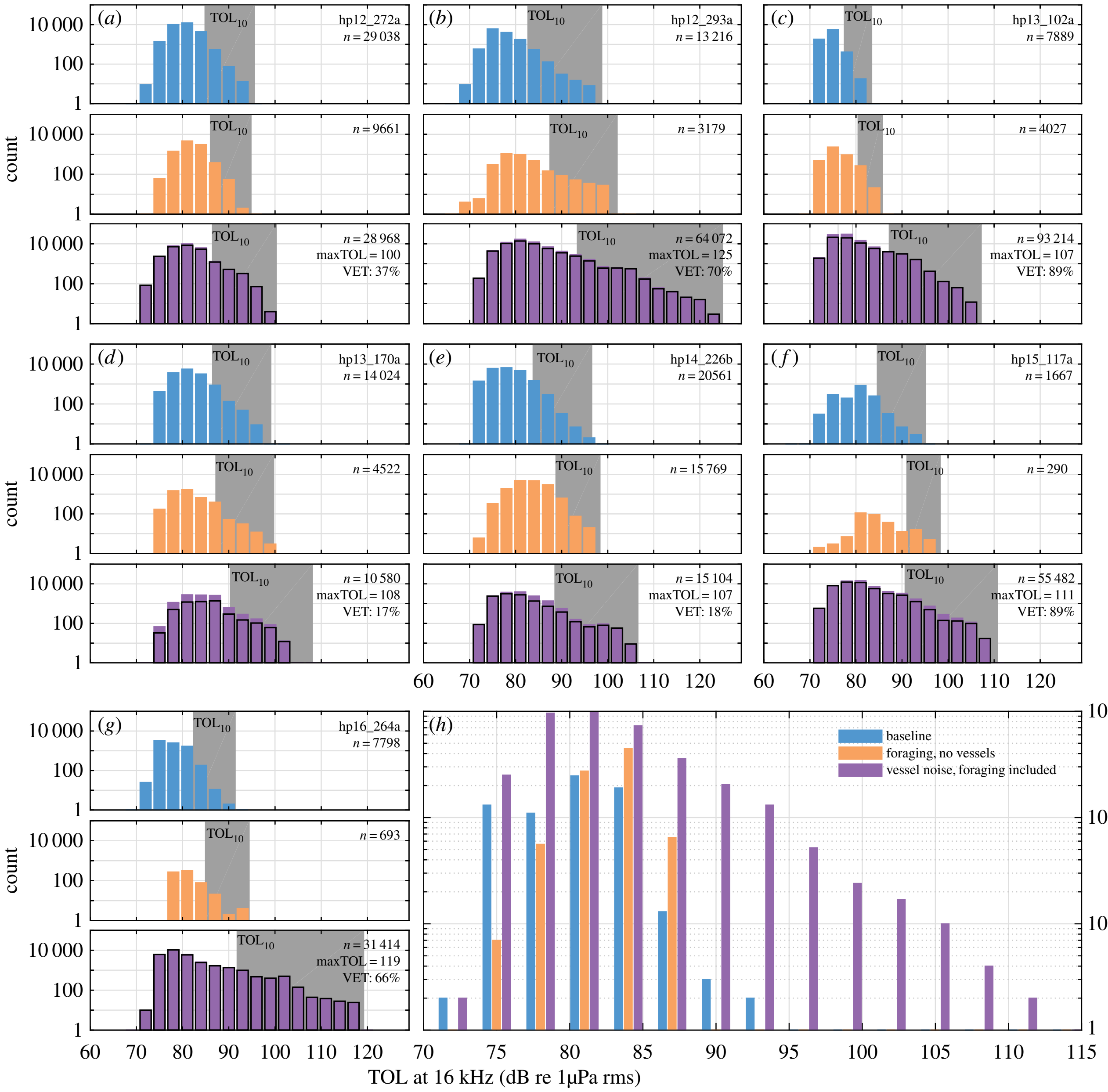


Figure 2. Noise levels recorded on the seven porpoises (*a–g*) during three time categories: (i) baseline (i.e. outside of foraging or vessel noise exposure as judged by expert listeners; blue), (ii) during prey pursuit but outside of periods of vessel noise exposure (orange), and (iii) during vessel noise exposure, whether or not the porpoise was foraging (purple). The distribution of noise levels in the last category is overlaid with an outline of the distribution of levels during vessel noise exposure with time of prey pursuits excluded (black solid line) to illustrate the relative contribution of noise from vessels only. Noise levels are the 0.5 s trimmed mean average rms received levels in a 16 kHz third octave band for periods free of loud transients. The shaded areas correspond to the 16 kHz TOL exceeded 10% of the time, i.e. TOL$_{10}$. VET gives per cent of audible vessel exposure time. (*h*) Distributions of 1 min TOL$_{10}$ noise levels within the three categories with all individuals pooled.

speed of 33 knots and a closest approach to the porpoise of 140 m. Moreover, the spectral characteristics of the noise (figure 3*c*) strongly resemble those of the same fast ferries recorded at similar ranges [14]. This porpoise had been echolocating and foraging continuously prior to the exposure, but ceased regular echolocation at about the time when the ferry became audible in the recording (figure 3*b*), approximately 7 min before the point of the closest approach. Given the estimated speed of the vessel, this time corresponds to a reaction distance of approximately 7 km. As the 0.5 s 16 kHz TOL increased to 100 dB re 1 µPa, the porpoise dove away from the surface while fluking vigorously (figure 3*c–f*). When the noise levels decreased again, the animal resurfaced (figure 3*c–f*). Regular foraging behaviour resumed 8 min later, 15 min after it was first interrupted.

A similar reaction was recorded from another porpoise (hp14_226b), 2 years later (electronic supplementary material, figure S3*c–f*). The Doppler-shift method gave a speed estimate of 14.5 knots and a closest approach distance of 80 m, consistent with a maximum 0.5 s 16 kHz TOL of 107 dB re 1 µPa rms for this exposure. This porpoise also interrupted foraging and dove to deeper water when the vessel noise became audible; it resumed foraging soon after the vessel passed (electronic supplementary material, figure S3). Aurally and temporally, this vessel encounter and several others from the same recording (electronic supplementary material, figure S3*a,b*) were consistent with a fast ferry, implying that this porpoise was repeatedly passed by fast ferries during the 21.7 h tag attachment.

(d) Effects of vessel noise on foraging rates

To investigate whether repeated exposures to high-level vessel noise led to a pattern of reduced foraging, we performed a

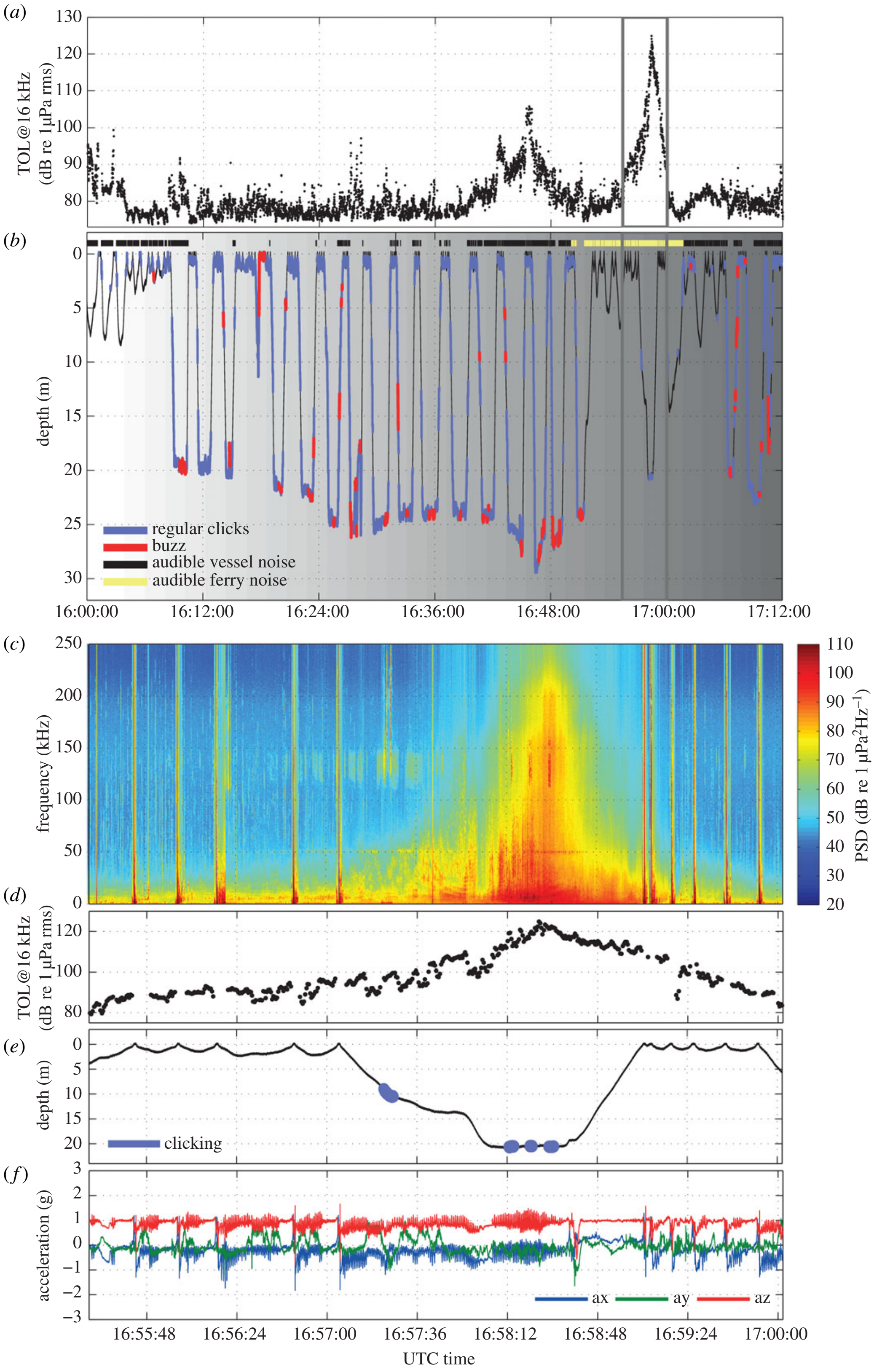


Figure 3. Diving and foraging behaviour of porpoise hp12_293a around the time of passage of a presumed fast ferry. (*c–f*) A close-up of the period delineated by the grey frame in (*a*,*b*). (*a*,*d*) 16 kHz TOLs (0.5 s trimmed mean averages over 1 ms measurements). (*b*,*e*) Dive profile with the time during which the porpoise produced regular and buzz clicks marked in blue and red, respectively. The thick black lines above the profile in (*b*) show the times with audible vessel noise in the recordings. The yellow overlay marks the period when the ferry noise was clearly audible above other vessel noise. Shading marks the civil twilight and night-time. (*c*) Spectrogram composed of power spectral densities in 1 Hz bands. The broadband vertical bands indicate noise when the porpoise surfaces. (*d*,*e*) Detail of TOL and dive profile during the close-up interval. (*f*) Acceleration. The oscillations in the *x*- and *z*-axes (i.e. the animal's longitudinal and ventro-dorsal axes, respectively) indicate propulsive motions.

series of permutation tests, which compared the buzz count and total buzz duration in minutes with high- and low-level noise. This requires defining a threshold to separate high- and low-noise intervals. When averaged over 1 min, the vast majority of activity-related flow noise in the 16 kHz third octave band was below 90 dB re 1 μPa (figure 2; electronic supplementary material, table S2), making 96 dB the lowest usable threshold allowing a minimum 6 dB difference between low and high levels. Tougaard *et al*. [3] suggest that the threshold for behavioural reaction of porpoises to anthropogenic noise is approximately 100 dB re 1 μPa rms (averaged over 125 ms window) at 16 kHz making this a reasonable choice. Six of the seven porpoises were exposed to greater than 96 dB 16 kHz TOLs for a minimum of 5 min (electronic supplementary material, table S3). Of those, one individual produced significantly longer buzzes in the high-noise group, but showed no significant differences in buzz counts between the low- and high-noise groups. Another individual showed no significant differences in buzz count or duration. The four remaining porpoises produced fewer buzzes in the minutes with high-level vessel noise, with the differences being significant ($p < 0.05$, 10 000 permutations) at thresholds of 96 dB re 1 μPa for three animals and at 102 dB re 1 μPa for the fourth porpoise. For these four individuals, buzzes tended to be longer in the low-noise group, significantly so for three of them at a threshold of 96 dB re 1 μPa (electronic supplementary material, table S3). The exposure time to vessel noise levels that exceeded the threshold for reduced foraging was relatively short, ranging from 0.9 to 4.3% of the analysed minutes (electronic supplementary material, table S3).

3. Discussion

Worldwide shipping, the primary source of underwater anthropogenic noise, is contributing to chronic acoustic pollution in many marine habitats [27,28]. But the overall impact of this large-scale environmental modification is difficult to assess because of the lack of comparable control areas without noise pollution. Effects are only measureable when there are step changes in the noise level above the gradually increasing baseline levels [28–30], e.g. owing to changes in vessel speed or routing. The few available reports on the effects of vessel activity on cetaceans mention short-term avoidance reactions [18,19], physiological stress responses [31] and habitat displacement [32]. Such reports have raised awareness of a potential problem (e.g. [33]) and have led to long-term noise monitoring programmes, e.g. as required to evaluate habitat quality under the European Marine Strategy Framework Directive [34–36]. However, data on how often individual toothed whales encounter vessels, the resulting noise exposure levels and the frequency and severity of reactions are scarce. Most importantly, almost nothing is known about whether vessel activity interferes with vital behaviours such as feeding (but see [37]) and if this occurs often enough to have biologically significant effects on the fitness of individuals and populations [38,39].

The present study addresses these knowledge gaps by measuring the vessel noise budget of free-ranging harbour porpoises under natural conditions in relation to their fine-scale foraging behaviour; to our knowledge the first for any toothed whale. Throughout data collection, we deliberately did not follow the tagged animals to avoid adding to their vessel noise exposure. This means that our results represent the actual authentic noise budget, but also that we are reliant on tag data both to measure exposure and to infer response. The multiple tag sensors and stereotyped acoustic behaviour of porpoises, verified in captive studies (e.g. [40,41]), make it possible to quantify their foraging behaviour with high accuracy. Quantifying noise exposure on free-ranging animals is more complicated owing to the presence of noise from water flowing around the tag, surface splashes and impact sounds, as well as sounds originating from the animal itself. We manually marked splash and impact events in all of the recordings and excluded these from spectral analysis. Clicks from the tagged animal were excluded by taking the trimmed mean of spectra computed over successive short intervals. Flow noise was minimized by using measurements at high frequencies as proxies for the total noise exposure. These frequencies, while falling on the low edge of the best hearing range of porpoises [21], and thus being highly relevant to these high-frequency specialists, make our results difficult to compare with long-term noise data, because most monitoring studies do not extend that high (e.g. [36]). However, given the typical spectra of vessel noise that decrease with increasing frequency, high levels at high frequencies very likely translate into higher levels at lower frequencies [14]. Our methodology does not allow for exploring the cues porpoises may use to assess the immediacy of threat from vessels. However, our aim was not to investigate such explanatory scenarios, but rather to assess whether wild porpoises respond to vessel passes and what impact responses could have. We argue that to achieve this objective, the proxy chosen here, i.e. the noise level actually experienced by the animal, is reasonable and can be measured robustly enabling comparison with other studies.

Evaluation of the tag recordings by experienced listeners revealed that the porpoises encountered vessels frequently (table 2), albeit primarily at long ranges, as indicated by the prevailing low received levels (figure 2; electronic supplementary material, table S2). The resultant lack of baseline data and the variable foraging strategies of porpoises (table 2; [23]) make statistical testing of effects of ship encounters on foraging rates challenging. Despite this, the data reveal a statistically significant decrease in prey capture attempts during exposures to vessel noise at values closely matching the reaction threshold predicted by Tougaard *et al*. [3], albeit with some interindividual variability (electronic supplementary material, table S3). While these results should be interpreted with caution owing to the small relative number of minutes with high-noise level (electronic supplementary material, table S3) and the lack of baseline noise-free periods, they strongly indicate that exposed porpoises produce fewer foraging buzzes in the presence of high-level vessel noise, whether the received noise level is an explanatory factor for the responses, or merely a corollary of vessel proximity [37]. Under the assumption that the foraging rates recorded under less acute exposure conditions reflect unperturbed foraging rates, the fact that relatively few disturbances were recorded by the tags would suggest a minimal fitness cost of exposure. Crucially, however, that assumption may be wrong and even just a few per cent of decrease in foraging may have significant effects on fitness of these small animals that must keep warm in cold waters [22,42,43], especially when accumulated with other disturbances [44]. The generally shorter total buzz duration during high-noise exposure (electronic supplementary material, table S3) suggests little if any increased effort per prey in the form of a longer pursuit, or perhaps premature termination of prey pursuits. Thus, a lower energy intake could result from lost foraging opportunities, a shift to an easier, lower quality prey, or failed prey captures, these effects probably being additive, context-dependent and accompanied by higher energy expenditure owing to increased swimming activity.

Two specific examples involving porpoises of different ages and sexes demonstrate energetic responses to close vessel passes despite their frequent exposure to more distant boat noise (table 2). In both cases, vessel noise had spectral and temporal characteristics consistent with a fast ferry (figure 3; electronic supplementary material, figure S3). Both animals dove deeper, increased swimming effort and interrupted their foraging activities during the vessel pass with one of them abandoning echolocation altogether. The responses therefore caused not only missed foraging opportunities, but also increased energy expenditure, as well as potentially a greater risk of swimming into fishing nets that would normally be detected by echolocation. The estimated reaction distance of 7 km for one of the porpoises, together with the poor underwater visibility in Danish waters (less than 10 m) and the very small fraction of time spent by the animals with their eyes out of the water, reinforces the notion that threat from vessels was primarily perceived acoustically [37], whether the response was triggered by noise level, rate of change of noise level, noise spectrum or all of the above. The observation of a 15 min cessation of foraging associated with a single close vessel pass suggests that the impact of vessels may extend longer than the interval in which noise levels exceed a high threshold, and the vessel is close. Those 15 min would correspond to 23 prey capture attempts, if the animal continued to buzz at the average rate recorded just prior to and just after the exposure, and up to 88 attempts, if maximum 15 min buzz count for this animal was assumed. Given the frequency of the fast ferry service in the area chosen by these animals for foraging, it is likely that they experience close passes often (electronic supplementary material, figure S3). Thus, the strong responses to high-level vessel passes reported here suggest that these animals have not habituated to the noise. This is in agreement with the findings of Dyndo *et al.* [20], who observed that porpoises showed a robust and stereotypical porpoising reaction to some boats, despite their long-term residence in a harbour enclosure.

AIS records for the study area indicate a wide spatial variation in traffic density consistent with the complex coastline and varying bathymetry (electronic supplementary material, figure S1). In particular, large ship traffic concentrates in deeper channels that allow access to ports or open water. Tagged porpoises did not appear to avoid such highly trafficked areas, perhaps because these overlapped with important foraging habitats. Locally deep waters may aggregate fish and offer distinctive and valuable resources (e.g. [45]). For porpoises, they may thus constitute 'acoustic hotspots' where noisy anthropogenic activities overlap with important habitats [46].

The spatial variability of vessel encounter rates (table 2; electronic supplementary material, figure S1) and the wide range of received noise levels (electronic supplementary material, table S2; figure 2) probably also reflect differences in the type of boat traffic. Vessel, engine and propeller design [14,16], as well as speed and load [14,15,47], all affect the spectral characteristics of the generated noise and the duration of the exposure. Such a wide range of noise sources may require animals to develop a number of strategies to cope with exposure. Many behavioural reactions may be subtle and so go unnoted, even though cumulatively they could represent a significant disturbance. As a result, convincingly demonstrating behavioural responses to noise under natural conditions is notoriously difficult (e.g. [6]), especially because the history of the animal's exposure to vessel noise is rarely known. In the consistently noisy inner Danish Waters, porpoises may have developed behavioural strategies and/or compensatory mechanisms, e.g. an increase in vocalization amplitude [48], to combat elevated noise levels, and the absence of a control population makes it impossible to assess the full cost of these. Here, we focus on the additional loss of foraging effort owing to close vessel passes as the most reliably quantifiable and biologically relevant response variable. In doing so, we probably underestimate the full effect of vessel noise on porpoises.

4. Conclusion

We quantified the vessel noise budget of seven harbour porpoises in their natural environment, to our knowledge the first time this has been achieved for any toothed whale. We show that porpoises in a busy coastal habitat are frequently exposed to vessel noise. Although most exposures are at low levels, occasional high-level exposures with rapid onset occur when vessels pass close to animals or at high speeds. Observed reactions to such vessel passes involved vigorous fluking, interrupted foraging and even cessation of echolocation. Such exposures led to a general pattern of reduced foraging effort in the presence of noise levels greater than 96 dB re 1 μPa rms in the 16 kHz third octave band, although we probably underestimate the total impact of noise because animals may have already adjusted to the elevated average noise levels or be affected by them offering no real baseline. Given the high metabolic requirements and near continuous foraging reported for porpoises in this area, missed foraging opportunities during frequent boat passes could have a significant cumulative effect on body condition and vital rates. As high-frequency echolocators, porpoises use signals well beyond the low frequencies predominantly produced by vessels, and thus, our results raise concerns about the effects of vessel noise on other lower-frequency toothed whale species.

5. Material and methods

(a) Study area

The study was conducted in the inner Danish waters of Kattegat and the Belt seas (electronic supplementary material, figure S1), which are relatively shallow with depths rarely exceeding 50 m and averaging 23 m. The Sound, Great Belt and eastern Kattegat serve as narrow, deeper-water connections between the Baltic Sea and the North Sea, making these straits heavily trafficked at all times of the day by large ships, such as tankers and bulk freighters, but also diverse smaller vessels, including fishing boats [49]. Ship traffic in southern Kattegat between the Jutland Peninsula and the island of Zealand includes a fast passenger ferry line operating up to 24 passes a day. From late spring to early autumn, the coastal waters are occupied by widespread leisure boating activities.

(b) Data collection

Between September 2012 and September 2016, 19 porpoises incidentally trapped in pound nets set by local fishermen were equipped with DTAG-3 tags [25]. Tagging was carried out within 24 h of discovering a porpoise in the net. For tagging, the porpoise was carefully lifted onboard a fishing boat and placed on a soft pad. Its sex was determined, body condition evaluated and morphometric measurements were taken. Only animals that seemed in good health from an external examination were equipped with a tag. The porpoise was handled on the boat for no more than 15 min (table 1) before being released several hundred metres from the net.

The suction cup-attached tag was placed dorsally approximately 5 cm behind the blowhole to ensure good quality recordings of the low-level clicks of foraging buzzes [40] and to minimize noise associated with the animal's propulsion. The tags measured 7 × 17 × 3.5 cm and weighed 221–321 g in air and were slightly positively buoyant in water to facilitate recovery. They sampled 16 bit stereo audio at 500 kHz (179 dB re 1 µPa clip-level; approximately flat frequency response at 0.5–150 kHz), as well as three-dimensional orientation and pressure sensors at 250–625 Hz (16 bit). To avoid biased estimates of noise pollution, the DTAG-equipped porpoises were not followed after release; the tags were detached actively or passively after 12 to more than 24 h and were recovered with the aid of aerial VHF radio tracking and in some cases ARGOS satellite telemetry.

(c) Data analysis

Data processing and analysis were performed using MATLAB R2013b (MathWorks, Inc.). Tag acoustic recordings were evaluated by headphone-listening and visual inspection of spectrograms (Hamming window, fast Fourier transform (FFT) size = 512, 75% overlap) computed over consecutive 5 s segments of the data. A corresponding dive profile was displayed in the same plot (for MATLAB code, see www.soundtags.org). All intervals with detectable vessel noise, rain or loud transients were marked, as were respirations, logging periods at the sea surface and high-repetition-rate click sequences. The high-rate click sequences were classified as pulsed communication calls [50] or foraging buzzes accompanying prey capture attempts by the tagged animal [40] using published criteria [23].

Intervals with audible vessel noise were checked on a dive-by-dive basis to remove short periods when the tag was out of the water from the total exposure time. Similarly, the durations of all respirations and logging events (with a 0.5 s guard window to account for masking when animals break the surface) were subtracted from the time with no detectable vessel noise. Periods when vessel noise was uncertain, for example, owing to masking during rain or high sea state, were considered vessel-free. Our vessel exposure rates are, therefore, conservative estimates.

Foraging and noise measures were quantified in consecutive 1 min segments of the data. This interval spans the approximate duration of a typical porpoise dive in the area and allows reliable estimates of rapidly fluctuating noise levels from vessels passing at high speeds. A dip in the distributions of inter-click-intervals at 15 ms was used to detect the start and end of buzzes [23]. Data prior to the first foraging buzz were excluded to allow for a post-tagging recovery period [6] and thereby minimize the potential for confound owing to a stress response to handling. This time interval varied from 0.2 to 4.1 h (table 1), but a minimum time of 1 h after tagging was excluded. As the animals switched between benthic, demersal, pelagic and surface foraging, they adapted their acoustic behaviour resulting in prolonged buzzes in some foraging modes. Such buzzes could represent a long pursuit of a repeatedly escaping prey, or a series of captures on several schooling prey. To allow for both possibilities, foraging effort was quantified by both the number of buzz sequences and their total duration in each 1 min segment. Noise level was quantified in a two-step procedure; to eliminate sound energy from the animal's powerful 100 µs clicks, the noise level was first measured in 1 ms intervals and averaged over a 0.5 s time window as a trimmed mean discarding the highest 10th percentile of the data in each one third octave band (see below). To estimate the highest noise level, i.e. the level most likely to explain any behavioural reaction, the 0.5 s averages were ordered within each minute and the 90th percentile identified. This corresponds to the L_{10} statistical noise level, a robust estimate of the highest noise level. Time spent by the animal at the surface with the tag out of the water during breathing and resting (typically 0.5–30 s) was excluded in each minute before ordering. Similarly, recording blocks dominated by rain, splash noise from the animal breaking the surface, breaking waves down to 2 m depth or loud transients that were not judged to come from vessels, but rather zero padding of rare undecodable data chunks or debris hitting the hydrophones, were excluded from further processing. Finally, time intervals dominated by the animal's calls or loud air recycling sounds were also excluded. If more than 40 s of a given 1 min segment were discarded, the whole minute was excluded.

Noise level was quantified as one third octave levels, which approximate the filter-bank model of the mammalian auditory system [2,51]. Third octave bands with centre frequencies at 63 and 125 Hz have been suggested as proxies for general levels from shipping [34]. However, harbour porpoises have poor low-frequency hearing [21] with signal detection thresholds below 1 kHz probably higher than the ambient TOLs in southern Kattegat [14]. As porpoises have been shown to react to the high-frequency components of vessel noise [20], a third octave band centred at 2 or 10 kHz has been proposed as a more appropriate indicator of shipping noise relevant for these high-frequency specialists [14,52]. However, sound recordings made on a moving animal contain significant activity-dependent flow noise at low-to-mid frequencies, which complicates the measurement of ambient noise, especially during energetic pursuits of prey. To determine the lowest third octave band that is relatively free of flow noise in most activities, we examined the relationship between TOLs recorded in the absence of vessel noise, and $\log(J)$ a proxy for swimming activity (electronic supplementary material, figure S2), where J is the rms jerk [53] in a 0.5 s time window. For the 1 min averages, we computed the 90th percentile of the 0.5 s jerk measurements corresponding to the intervals included in the noise analysis. From this analysis, we chose the 16 kHz third octave band to characterize ambient noise.

Relative speed and closest point of approach (CPA) to the tagged animal were estimated for a subset of eligible vessels, by measuring the Doppler shift of tones generated by the vessels' engines, gearboxes and propellers [54] and recorded by the tag. The inflection point of the frequency shift of the tone was identified in the spectrogram of the vessel recording and a sigmoid curve was fitted to the data. Vessel velocity and CPA were estimated using the Doppler equation, assuming a stationary receiver and a sound speed of 1500 m s^{-1}. The method requires high-quality recordings of the tones, which limited the dataset to less than 10 of the recorded vessels. In the remaining vessel passes, the tones were masked by cavitation noise and other broadband contributions from the vessel movement.

(d) Statistical analysis

Statistical analyses were carried out using R v. 3.3.2 (http://www.R-project.org) with the perm package.

Following an exploratory analysis of model fitting, we split the 1 min measurements for each animal into groups with low- and high-level noise and then tested for a difference in the distribution of buzz count and total buzz duration between groups using a two-sample permutation test corresponding to the central Fisher's exact test [55]. The noise level threshold for identifying the high-level group was increased stepwise in 3 dB intervals. An initial 6 dB buffer was used between the high- and low-level groups, i.e. minutes with average noise levels < threshold, but ≥(threshold-6 dB) were excluded from the analysis. The low-level group remained constant, i.e. number of minutes in the buffer increased as the high-level threshold increased. A one-sided permutation t-test evaluated whether minutes with high-level noise contained a lower number of buzzes than minutes with low-level noise. A two-sided test was used for total buzz duration, because more buzzing time could indicate an increased foraging activity, or an increased effort per prey. The permutation test was run if at least 5 min exceeded the threshold level for each animal. The p-values were estimated from 10^4 replications.

Ethics. Tagging was carried out under permission from the Danish Forest and Nature Agency (NST-3446-00016) and the Animal Welfare Division (Ministry of Justice, 2010-561-1801).

Data accessibility. Scripts used to analyse the data and example datasets were deposited at doi:10.5281/zenodo.898733.

Authors' contributions. D.M.W., M.J., P.T.M., J.T. and U.S. designed the study. M.J. designed the measurement devices and processing software. D.M.W., J.T., P.T.M., A.G. and R.D. collected the data. D.M.W., M.J., P.T.M. and J.T. conducted data analysis and interpretation. D.M.W., P.T.M., M.J. and J.T. drafted the manuscript, and all authors contributed to finalize it.

Competing interests. We declare we have no competing interests.

Funding. This work was funded by the German Federal Agency for Nature Conservation via a grant to U.S., J.T. and M.J. (contract Z1.2-5330/2010/14 and BfN-Cluster 7) and in part by grants from the Carlsberg Foundation and FNU to P.T.M. Tag development was supported, in part, by the Marine Alliance for Science and Technology Scotland and a Marie Skłodowska-Curie Career Integration Grant to M.J.

Acknowledgements. We thank S. Sveegaard, L. Mikkelsen, M.V. Jensen, L. Hermannsen, S. Elmegaard, M. de Freitas, L. Doñate-Rojano, M. Dyndo, B. McDonald, A. Hansen and B. Hansen as well as all the helpful fishermen and the skilled pilot (U. Gosewinkel) involved in tag deployments and recoveries. L. Doñate-Rojano, M. Dyndo, S. Videsen and A. Schrøder helped with data processing. T. Hurst at Woods Hole Oceanographic Institution and R. Swift at the University of St Andrews helped construct the tags. We thank L.A. Miller and J. Tougaard for comments on an earlier version of this manuscript.

References

1. Tyack PL, Clark CW. 2000 Communication and acoustic behavior of dolphins and whales. In *Hearing by whales and dolphins* (eds WWL Au, R Fay), pp. 156–224. New York, NY: Springer Handbook of Auditory Research Series.
2. Richardson WJ, Greene Jr CR, Malme CI, Thomson DH. 1995 *Marine mammals and noise*. London, UK: Academic Press.
3. Tougaard J, Wright AJ, Madsen PT. 2015 Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. *Mar. Pollut. Bull.* **90**, 196–208. (doi:10.1016/j.marpolbul.2014.10.051)
4. Gray H, van Waerebeek K. 2011 Postural instability and akinesia in a pantropical spotted dolphin, *Stenella attenuata*, in proximity to operating airguns of a geophysical seismic vessel. *J. Nat. Conserv.* **19**, 363–367. (doi:10.1016/j.jnc.2011.06.005)
5. Tougaard J, Carstensen J, Teilmann J, Skov H, Rasmussen P. 2009 Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.)). *J. Acoust. Soc. Am.* **126**, 11–14. (doi:10.1121/1.3132523)
6. Miller PJO, Johnson MP, Madsen PT, Biassoni N, Quero M, Tyack PL. 2009 Using at-sea experiments to study the effects of airguns on the foraging behavior of sperm whales in the Gulf of Mexico. *Deep Sea Res. Part I Oceanogr. Res. Pap.* **56**, 1168–1181. (doi:10.1016/j.dsr.2009.02.008)
7. Miller P, Kvadsheim P, Lam F. 2012 The severity of behavioral changes observed during experimental exposures of killer (*Orcinus orca*), long-finned pilot (*Globicephala melas*), and sperm (*Physeter macrocephalus*) whales to naval sonar. *Aquat. Mamm.* **38**, 362–401. (doi:doi:10.1578/AM.38.4.2012.362)
8. DeRuiter SL *et al.* 2013 First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biol. Lett.* **9**, 20130223. (doi:10.1098/rsbl.2013.0223)
9. Miller P *et al.* 2015 First indications that northern bottlenose whales are sensitive to behavioural disturbance from anthropogenic noise. *R. Soc. open sci.* **2**, 140484. (doi:10.1098/rsos.140484)
10. Hildebrand J. 2009 Anthropogenic and natural sources of ambient noise in the ocean. *Mar. Ecol. Prog. Ser.* **395**, 5–20. (doi:10.3354/meps08353)
11. Payne R, Webb D. 1971 Orientation by means of long range acoustic signaling in baleen whales. *Ann. NY Acad. Sci.* **188**, 110–141. (doi:10.1111/j.1749-6632.1971.tb13093.x)
12. Croll DA, Clark CW, Calambokidis J, Ellison WT, Tershy BR. 2001 Effect of anthropogenic low-frequency noise on the foraging ecology of Balaenoptera whales. *Anim. Conserv.* **4**, 13–27. (doi:10.1017/S1367943001001020)
13. Castellote M, Clark CW, Lammers MO. 2012 Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. *Biol. Conserv.* **147**, 115–122. (doi:10.1016/j.biocon.2011.12.021)
14. Hermannsen L, Beedholm K, Tougaard J, Madsen PT. 2014 High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (*Phocoena phocoena*). *J. Acoust. Soc. Am.* **136**, 1640–1653. (doi:10.1121/1.4893908)
15. McKenna MF, Ross D, Wiggins SM, Hildebrand JA. 2012 Underwater radiated noise from modern commercial ships. *J. Acoust. Soc. Am.* **131**, 92–103. (doi:10.1121/1.3664100)
16. Jensen FH, Bejder L, Wahlberg M, Soto NA, Johnson M, Madsen PT. 2009 Vessel noise effects on delphinid communication. *Mar. Ecol. Prog. Ser.* **395**, 161–175. (doi:10.3354/meps08204)
17. Pirotta E, Milor R, Quick N, Moretti D, Di Marzio N, Tyack P, Boyd I, Hastie G. 2012 Vessel noise affects beaked whale behavior: results of a dedicated acoustic response study. *PLoS ONE* **7**, e42535. (doi:10.1371/journal.pone.0042535)
18. Barlow J. 1988 Harbor porpoise, *Phocoena phocoena*, abundance estimation for California, Oregon, and Washington: I. Ship surveys. *Fish. Bull.* **86**, 417–432.
19. Palka DL, Hammond PS. 2001 Accounting for responsive movement in line transect estimates of abundance. *Can. J. Fish. Aquat. Sci.* **58**, 777–787. (doi:10.1139/cjfas-58-4-777)
20. Dyndo M, Wisniewska DM, Rojano-Doñate L, Madsen PT. 2015 Harbour porpoises react to low levels of high frequency vessel noise. *Sci. Rep.* **5**, 1–9. (doi:10.1038/srep11083)
21. Kastelein RA, Hoek L, de Jong CAF, Wensveen PJ. 2010 The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz. *J. Acoust. Soc. Am.* **128**, 3211–3222. (doi:10.1121/1.3493435)
22. Lockyer CH, Desportes G, Hansen K, Labberté S, Siebert U. 2003 Monitoring growth and energy utilisation of the harbour porpoise (*Phocoena phocoena*) in human care. *NAMMCO Sci. Publ.* **5**, 107–120. (doi:10.7557/3.2743)
23. Wisniewska DM *et al.* 2016 Ultra-high foraging rates of harbor porpoises make them vulnerable to anthropogenic disturbance. *Curr. Biol.* **26**, 1441–1446. (doi:10.1016/j.cub.2016.03.069)
24. Pirotta E, Brookes KL, Graham IM, Thompson PM. 2014 Variation in harbour porpoise activity in response to seismic survey noise. *Biol. Lett.* **10**, 20131090. (doi:10.1098/rsbl.2013.1090)
25. Johnson M, Aguilar Soto N, Madsen PT. 2009 Studying the behaviour and sensory ecology of marine mammals using acoustic recording tags: a review. *Mar. Ecol. Prog. Ser.* **395**, 55–73. (doi:10.3354/meps08255)
26. Lockyer C, Kinze C. 2003 Status, ecology and life history of harbour porpoise (*Phocoena phocoena*), in Danish waters. *NAMMCO Sci. Publ.* **5**, 143–176. (doi:10.7557/3.2745)
27. Malakoff D. 2010 A push for quieter ships. *Science* **328**, 1502–1503. (doi:10.1126/science.328.5985.1502)
28. Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C, Popper AN. 2010 A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends Ecol. Evol.* **25**, 419–427. (doi:10.1016/j.tree.2010.04.005)
29. Andrew RK, Howe BM, Mercer JA, Dzieciuch MA. 2002 Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. *Acoust. Res. Lett. Online* **3**, 65–70. (doi:10.1121/1.1461915)
30. Tournadre J. 2014 Anthropogenic pressure on the open ocean: the growth of ship traffic revealed by altimeter data analysis. *Geophys. Res. Lett.* **41**, 7924–7932. (doi:10.1002/2014GL061786)

31. Rolland RM, Parks SE, Hunt KE, Castellote M, Corkeron PJ, Nowacek DP, Wasser SK, Kraus SD. 2012 Evidence that ship noise increases stress in right whales. *Proc. R. Soc. B* **279**, 2363–2368. (doi:10.1098/rspb.2011.2429)
32. Bejder L *et al.* 2006 Decline in relative abundance of bottlenose dolphins exposed to long-term disturbance. *Conserv. Biol.* **20**, 1791–1798. (doi:10.1111/j.1523-1739.2006.00540.x)
33. Sutherland WJ *et al.* 2013 Identification of 100 fundamental ecological questions. *J. Ecol.* **101**, 58–67. (doi:10.1111/1365-2745.12025)
34. European Commission. 2008 Directive 2008/56/EC of the European Parliament and of the Council of 17th June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), OJ L 164, 25.6.2008, pp. 19–40.
35. Merchant ND, Pirotta E, Barton TR, Thompson PM. 2014 Monitoring ship noise to assess the impact of coastal developments on marine mammals. *Mar. Pollut. Bull.* **78**, 85–95. (doi:10.1016/j.marpolbul.2013.10.058)
36. Merchant ND, Brookes KL, Faulkner RC, Bicknell AWJ, Godley BJ, Witt MJ. 2016 Underwater noise levels in UK waters. *Sci. Rep.* **6**, 1–10. (doi:10.1038/srep36942)
37. Pirotta E, Merchant ND, Thompson PM, Barton TR, Lusseau D. 2015 Quantifying the effect of boat disturbance on bottlenose dolphin foraging activity. *Biol. Conserv.* **181**, 82–89. (doi:10.1016/j.biocon.2014.11.003)
38. National Research Council. 2005 *Marine mammal populations and ocean noise: determining when noise causes biologically significant effects*. Washington, DC: National Academy Press.
39. New LF *et al.* 2013 Modelling the biological significance of behavioural change in coastal bottlenose dolphins in response to disturbance. *Funct. Ecol.* **27**, 314–322. (doi:10.1111/1365-2435.12052)
40. DeRuiter SL, Bahr A, Blanchet M-A, Hansen SF, Kristensen JH, Madsen PT, Tyack PL, Wahlberg M. 2009 Acoustic behaviour of echolocating porpoises during prey capture. *J. Exp. Biol.* **212**, 3100–3107. (doi:10.1242/jeb.030825)
41. Verfuß UK, Miller LA, Pilz PKD, Schnitzler H-U. 2009 Echolocation by two foraging harbour porpoises (*Phocoena phocoena*). *J. Exp. Biol.* **212**, 823–834. (doi:10.1242/jeb.022137)
42. Kastelein RA, Hardeman J, Boer H. 1997 Food consumption and body mass of harbour porpoises (*Phocoena phocoena*). In *The biology of the harbour porpoise* (eds AJ Read, PR Wiepkema, PE Nachtigall), pp. 217–233. Woerden, The Netherlands: DeSpil Publishers.
43. MacLeod CD, Santos MB, Reid RJ, Scott BE, Pierce GJ. 2007 Linking sandeel consumption and the likelihood of starvation in harbour porpoises in the Scottish North Sea: could climate change mean more starving porpoises? *Biol. Lett.* **3**, 185–188. (doi:10.1098/rsbl.2006.0588)
44. Nabe-Nielsen J, Sibly RM, Tougaard J, Teilmann J, Sveegaard S. 2014 Effects of noise and by-catch on a Danish harbour porpoise population. *Ecol. Modell.* **272**, 242–251. (doi:10.1016/j.ecolmodel.2013.09.025)
45. Nilsson L, Thygesen UH, Lundgren B, Nielsen BF, Nielsen JR, Beyer JE. 2003 Vertical migration and dispersion of sprat (*Sprattus sprattus*) and herring (*Clupea harengus*) schools at dusk in the Baltic Sea. *Aquat. Living Resour.* **16**, 317–324. (doi:10.1016/S0990-7440(03)00039-1)
46. McCarthy E. 2004 Hotspots: sensitive areas of intense acoustic activity. In *International regulation of underwater sound: establishing rules and standards to address ocean noise pollution* (ed. E McCarthy), pp. 62–81. Boston, MA: Kluwer Academic Publishers.
47. McKenna MF, Wiggins SM, Hildebrand JA. 2013 Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. *Sci. Rep.* **3**, 1–10. (doi:10.1038/srep01760)
48. Hotchkin C, Parks S. 2013 The Lombard effect and other noise-induced vocal modifications: insight from mammalian communication systems. *Biol. Rev.* **88**, 809–824. (doi:10.1111/brv.12026)
49. Stankiewicz M, Backer H, Nikolay Vlasov. 2010 Maritime activities in the Baltic Sea. An integrated thematic assessment on maritime activities and response to pollution at sea in the Baltic Sea region. *Balt. Sea Environ. Proc.* **123**, 1–65.
50. Clausen KT, Wahlberg M, Beedholm K, Deruiter S, Madsen PT. 2010 Click communication in harbour porpoises *Phocoena phocoena*. *Bioacoustics* **20**, 1–28. (doi:10.1080/09524622.2011.9753630)
51. Fletcher H. 1940 Auditory patterns. *Rev. Mod. Phys.* **12**, 47–65. (doi:10.1103/RevModPhys.12.47)
52. Hermannsen L, Tougaard J, Beedholm K, Nabe-Nielsen J, Madsen PT. 2015 Characteristics and propagation of airgun pulses in shallow water with implications for effects on small marine mammals. *PLoS ONE* **10**, e0133436. (doi:10.1371/journal.pone.0133436)
53. Ydesen KS, Wisniewska DM, Hansen JD, Beedholm K, Johnson M, Madsen PT. 2014 What a jerk: prey engulfment revealed by high-rate, super-cranial accelerometry on a harbour seal (*Phoca vitulina*). *J. Exp. Biol.* **217**, 2239–2243. (doi:10.1242/jeb.100016)
54. Holz F, Schuster M. 2016 Tag data analysis regarding ship distance and speed. Auswirkungen des Unterwasserschalls der Offshore-Windenergieanlagen auf marine Säuger—Unterwasserschall Effekte (UWE).
55. Fay M. 2010 Two-sided exact tests and matching confidence intervals for discrete data. *R J.* **2**, 53–58.