## Abstract

During offshore wind farms construction, abundance in harbour porpoise (Phocoena phocoena) is known to be negatively affected. From 2011 to 2013, extensive passive acoustic monitoring was conducted during research projects accompanying the construction of two wind farms in the German North Sea. Using C-PODs, we studied the effect ranges of pile driving disturbance on acoustic porpoise detections to test how these may change with different wind speeds. We found that disturbance radii highly depended on the prevailing wind speed during construction with further reaching effects at lower wind speed. Disturbance effects reached to 16 km, resp. 10 km, at wind speed of 2 m/s, resp. 5 m/s. For wind speed greater than 3 m/s, wave breaking entrains air bubbles into the upper water column assumed to form a "natural bubble curtain". At higher wind speed, (i) greater noise mitigation occurs thanks to this transient layer of bubbles in the upper water column and (ii) porpoises could also perceive piling noise as less disturbing as the signal to noise ratio decrease with higher background noise caused by waves breaking and sediment movement. Our results indicate that wind speed and possibly background noise are important factors when assessing disturbance effects of anthropogenic noise on marine mammals.
Wind creates a natural bubble curtain mitigating porpoise avoidance during offshore pile driving

A-C. Dragon, M.J. Brandt, A. Diederichs & G. Nehls – from BioConsult SH
25813 Husum, Germany, ac.dragon@bioconsult-sh.de, m.brandt@bioconsult-sh.de, a.diederichs@bioconsult-sh.de, g.nehls@bioconsult-sh.de

During offshore wind farms construction, abundance in harbour porpoise (Phocoena phocoena) is known to be negatively affected. From 2011 to 2013, extensive passive acoustic monitoring was conducted during research projects accompanying the construction of two wind farms in the German North Sea. Using C-PODs, we studied the effect ranges of pile driving disturbance on acoustic porpoise detections to test how these may change with different wind speeds. We found that disturbance radii highly depended on the prevailing wind speed during construction with further reaching effects at lower wind speed. Disturbance effects reached to 16 km, resp. 10km, at wind speed of 2m/s, resp. 5m/s. For wind speed greater than 3m/s, wave breaking entrains air bubbles into the upper water column assumed to form a “natural bubble curtain”. At higher wind speed, (i) greater noise mitigation occurs thanks to this transient layer of bubbles in the upper water column and (ii) porpoises could also perceive piling noise as less disturbing as the signal to noise ratio decrease with higher background noise caused by waves breaking and sediment movement. Our results indicate that wind speed and possibly background noise are important factors when assessing disturbance effects of anthropogenic noise on marine mammals.
1. INTRODUCTION

In Europe, offshore wind energy is rapidly developing as an alternative energy source to nuclear power and fossil fuels. During offshore wind farm construction, large steel foundations are usually driven into the sea floor by noise-intense hydraulic hammers. In the German North Sea, several research projects have been conducted to develop and test new noise mitigation methods and to evaluate the regulatory framework for conducting environmental impact assessments (Diederichs et al., 2008; Tougaard et al., 2009; Dähne et al., 2013 among others).

Marine mammal species possess a sensitive underwater hearing system and recent studies proved that pile-driving noise negatively affects seals’ and cetaceans’ natural behaviour (Hastie et al., 2015; Madsen et al., 2006; Russell et al., 2016). The harbour porpoise (Phocoena phocoena) is the only resident cetacean species known to reproduce in German waters (REID et al. 2003) and is protected under the EU habitats directive 92/43/EEC. Highly depending on echolocation for orientation and foraging (Madsen et al., 2006; Wisniewska et al., 2016), porpoise response to pile driving noise is relevant for the conservation of the species. During pile driving, some of the energy exerted on the pile is transmitted into the water column as noise. Depending on received levels, it can affect the behaviour of acoustics-reliant marine mammals and/or induce physiological effects such as temporary or permanent increase in the hearing threshold (TTS = temporary threshold shift and PTS = permanent threshold shift).

Previous studies on the effects of offshore wind farm construction on harbour porpoises used passive acoustic monitoring devices (e.g. C-PODs) that continuously record harbour porpoise echolocation, i.e. clicking activity. Passive acoustic devices allow comparing porpoise detections during the construction period to those of a preconstruction and/or post-construction period at high temporal resolution. Porpoise detections were shown to decrease significantly during piling up to 20 km around wind farm construction sites (Tougaard et al., 2009b; Brandt et al., 2011; Dähne et al., 2013). In the absence of noise mitigation during pile driving, negative effects lasted up to two days within close vicinity of the foundations (Brandt et al., 2011b; Rose et al., 2014; Tougaard et al., 2009b). Brandt et al. (2016) shows in a recent study that the spatiotemporal effect ranges of piling can differ widely between wind farm projects which cannot only be explained by differences in sound levels emitted. Furthermore, several studies analysed the distribution and behaviour of porpoises in relation to piling noise levels and tried to identify the noise level at which porpoise detections or abundance during piling significantly decreased compared to a given baseline period before or after piling. The onset of a behavioural reaction during pile driving (change in detection rates, density or observable behaviour) was estimated to occur at noise levels between 140 and 152 dB (Brandt et al., 2016; Dähne et al., 2013; Diederichs et al., 2008; Rose et al., 2014).

Regarding noise mitigation, a number of studies have demonstrated that bubble curtains effectively attenuate pile-driving noise (Diederichs et al., 2014; Lucke et al., 2011; Nehls et al., 2016; Würsig et al., 2000). Noise attenuation in marine waters is positively influenced by wind conditions due to increased air-bubbles in the water column (Dol et al., 2012; Farmer and Lemon, 1984; Mandal et al., 2016; Mathias et al., 2016; Thiele and Schellstede, 1980; Wanninkhof, 1992). We therefore hypothesise that avoidance distances by porpoises during pile driving also depend on the prevailing wind speed, with further reaching effect radii at lower wind speed. This study tested this hypothesis by investigating wind characteristics and the fine-scale effects of pile driving on porpoise detections.
2. MATERIAL & METHODS

i. Data Collection & Preparation

The present study looks at construction effects on harbour porpoises from two wind farms that were built using tripod piles in the German North Sea between 2011 and 2013. Figure 1 presents Trianel Offshore Windpark Borkum, phase 1 (BWII) and Global Tech I (GTI). In this study, data of porpoise occurrence were available from passive acoustic monitoring devices (C-POD, Chelonia Limited) that record porpoise echolocation clicks. At GTI, C-PODs were deployed at 14 positions and at BWII, C-PODs were deployed at 19 positions. C-PODs are located in the water column 5-10 m above the sea floor. The C-POD position is fixed at the sea floor with a mooring system and kept in the water column by a buoy (see details in Brandt et al., 2016).

Data was analysed for the periods of pile driving activities, i.e. from September 2011 to May 2012 at BWII and from October 2012 to December 2013 at GTI. Data screening was thoroughly conducted as C-PODs also record tonal signals originating from other sources than porpoise echolocation activity (e.g. sonar, sediment suspension, waves). To focus only on porpoise clicks, a strict exclusion criterion was applied to only keep the data when the number of “non-porpoise” clicks was under the threshold of 100,000 clicks per hour. In addition, the variable number of “non-porpoise” clicks was included in the statistical analyses to control for potential impacts of background noise on porpoise detection by C-PODs (see details in Brandt et al., 2016). Finally, wind speed, wind direction and sea-surface temperature values were gathered from NOAA open source databases (http://www.esrl.noaa.gov/psd/) and extracted to match the spatiotemporal resolution of C-POD data. Sediment type has been derived from EMODnet data (http://www.emodnet-seabedhabitats.eu/).

In order to describe the short-term effects of pile driving on porpoise activity at a small spatial scale we used the parameter detection positive hours (DPH) as indicator for porpoise presence. DPH describes whether or not a porpoise click-train was recorded and identified during a given hour and is thus a binary variable (with the values 0 or 1). Porpoise detection data were merged with pile driving data, wind characteristics and the other georeferenced environmental information (i.e. sea surface temperature, sediment type). For the present analyses we only selected data collected during the hours when piling activity occurred at one of the two wind farms and only from C-POD-positions up to a maximum distance of 60 km from a piling site.
Figure 1. Map of the study area depicting all wind farms operating, under construction or for which construction has been approved in the German North Sea. The two wind farms studies Global Tech 1 (GTI) and Trianel Windpark Borkum (BWII) are illustrated in orange and mint green respectively. POD stations are indicated by dark green dots.

ii. Statistical Analyses

First, we combined all data from both wind farms to investigate the overall effects of wind speed on avoidance radii during piling (dataset hereafter referred to as the combined dataset). Second, we ran “project-specific models” in order to look potential differences in the effects of wind on avoidance radii between the two study areas. Dealing with biological processes, we expected the input (environmental covariates) and output (residuals) time series of statistical models to display temporal autocorrelation. Considering the model residuals, previous investigations showed that significant autocorrelation originated from the DPH response variable and not from environmental covariates.

Preliminary analyses were conducted to investigate different ways of taking autocorrelation into account and determine the most parsimonious autocorrelation patterns to be taken into account in further analyses. The definition of a differenced covariate (DPH at t-1) acting as an auto-regressive component of the first order (Bestley et al., 2010) was found to significantly reduce the autocorrelation pattern in the combined dataset as well as in each of the two wind farm project-specific datasets. With the software R (R Core Team, 2015), the function bam (Wood and Wood, 2015) was used because of its fast-computing ability of large datasets and GAM analyses being less time-consuming (Wood et al., 2015). C-POD position was included as a random effect to take into account the geographical location, hence geographically-related characteristics. We ran GAMs including year, day of year, hour of day, wind direction, sea surface temperature, noise clicks recorded by the C-POD and sediment type. Finally, GAMs
included the interaction of distance with wind speed in order to test whether the distance where porpoise detections start to decline is related to wind speed. Wind speed could affect noise propagation under water as well as background noise level. The selection of the optimal model is based on the Akaike Information Criterion (AIC, Akaike, 1974) and on a graphical investigation of the autocorrelation (ACF) and partial autocorrelation (PACF) functions of model residuals.

3. RESULTS

iii. Wind characteristics

Figure 2 illustrates the frequency of wind speed values for the complete study period and when piling activity occurred at both wind farms. During piling at GTI, seasonal wind speed average values vary between 6.4 m/s in summer and 9.4 m/s in winter with a yearly mean wind speed of 7.0 m/s (standard deviation = 2.9 m/s). During piling at BWII, seasonal wind speed average values vary between 8.0 m/s in spring and 8.9 m/s in autumn with a yearly mean wind speed of 6.3 m/s (sd = 2.4 m/s). Seasonal variations are more important at GTI than at BWII but average wind speed during piling is higher for BWII, potentially due to the lack of piling during summer for this wind farm.
iv. Wind speed reduces porpoise response to piling

Figure illustrates DPH during piling from the GAM outputs over the complete dataset including the interaction between wind speed and distance to the piling site. The interaction of wind speed with distance was highly significant showing that decreases in DPH occurred at larger distances from construction sites when wind speed was lower during piling. In addition, the increase of DPH occurs not only with increasing distance to the piling site but also increasing wind speed values. DPH rates reach a maximum at about 14 m/s. With no wind, the disturbance radius, i.e. the area where porpoise detections are below the overall average (isoline 0) as estimated from the model outputs, is about 17 km. At wind speed of about 2 m/s, DPH reaches
the overall average at about 16 km. At wind speed of 8 m/s, the global average is reached at about 5 km. This points to large differences in effect ranges of piling depending on wind speed.

**Figure 3.** GAM outputs over the combined dataset showing the interaction of wind speed (m/s) with distance to piling site on DPH. Shown are the predicted absolute values for DPH with 95% confidence intervals (dotted lines). Histograms on the x- and y-axes illustrate data availability

Similarly, Figure illustrates the effect of the interaction between wind speed and distance to piling site on porpoise detections during piling separately for each of the two wind farms. The interaction of wind speed with distance was highly significant showing that decreases in DPH occurred at larger distances from construction sites when wind speed was lower during piling. With no wind, the radius of the area where porpoise detections are below the overall average as estimated from the model outputs is about 16 km for both GTI and BWII wind farms. At GTI, the disturbance radii during piling range from 16 km at 2 m/s wind speed to 5 km at 8 m/s wind speed. At BWII, the disturbance radii during piling range from 16 km at 2 m/s wind speed to 10 km at 8 m/s wind speed.
4. DISCUSSION

When analysing porpoise detections during offshore pile driving, we find increasing porpoise detections with increasing distance from piling for the combined dataset as well as for both wind farm specific datasets. During piling activities, an increase in porpoise detection rate can be directly interpreted as a decreased disturbance effect on harbour porpoises. Furthermore, our results reveal that porpoise detection rates during offshore pile driving increase with increasing wind speed at both wind farms. Depending on wind speed, the radii of avoidance estimated from the model outputs range from 5 to 17 km, the maximum of which is of the same order of magnitude than effect ranges for unmitigated pile driving in the literature (Brandt et al., 2011a; Dähne et al., 2013; Tougaard et al., 2006). Given differences in wind speed between seasons and projects, it is expected to observe varying effect range estimates between different wind farm projects. In a recent study Brandt et al. (2016) found differing effects on porpoises between wind farms that stem partially from local environmental characteristics (e.g. sediment type, wind
conditions). In comparison to the wind farm BWII, there was for instance more variability in wind speed during the construction period at GTI and larger differences in disturbance radii between low- and high-wind speed conditions.

Considering distance to construction site, our results confirm our initial hypothesis that further reaching effects are observed at lower wind speed. This is likely due to piling noise travelling further at low wind speed, thus leading to a further reaching deterrence effect on porpoises. Numerous studies have found sea state to affect noise propagation (e.g. Jones et al., 2009; Thiele and Schellstede, 1980). Noise attenuation increases with wind speed as wind increases the natural aeration of the water column by leading to more air-bubbles especially in the upper water layer. Heinis et al. (2015) also show evidence for noise to travel further at lower wind speed due to stronger reflection of noise by a smooth water surface. Higher sea state especially mitigates frequencies above 1 kHz where porpoise hearing is more sensitive (Jones et al., 2009).

In addition to differences in sound propagation at varying wind speed, variations in porpoises’ hearing would contribute to explaining why disturbance radii decrease at higher wind speed. High-wind conditions are associated with increased waves breaking and sediment movements, responsible for increased ambient noise especially at higher frequencies where porpoise hearing is best. With regards to porpoises perceiving piling noise, higher wind speed causes a lower signal-to-noise ratio such that piling becomes more difficult for porpoises to differentiate from other noise or causes them to perceive it as less disturbing. This might further contribute to decreased disturbance radii during piling. Piling noise and preparation noises (e.g. shipping) in times of high-background noise may disturb less the porpoises than when noises occur in a quieter environment. The magnitude with which those physical and biological processes interact and how much each of these contributes to explain the decreased disturbance effects at higher wind speed remain to be investigated in more details.

Disturbance effects from pile driving on porpoises are very clear which might be due to their occurring mostly during calm weather conditions. Besides pile driving, harbour porpoises may also respond to other anthropogenic noise sources such as shipping activities. Shipping occurs during a whole range of weather conditions so that the North Sea receives continuous shipping activities causing all year round noise. Few studies have investigated shipping noise and harbour porpoises (Wisniewska et al., 2016) and still little is known about the specific effects of shipping noise on porpoise behaviour. While shipping sound emissions differ in frequency and intensity from the loud and sudden impulses of piling noise, we expect shipping noise sources to also be naturally mitigated thanks to high wind conditions. Indeed, Thiele and Schellstede (1980) have pointed out that the strongest effects of sea state were found during winter at wind speeds above 15 m/s, when water layering was substantially less expressed than in summer. On average, shipping might then be more attenuated than piling because it can also occur when wind speed is high. When addressing the general effects of shipping in future work, it may therefore be of high importance to consider the effects of wind and weather as well and not restrictively focus on good weather conditions.
5. CONCLUSION

Pile driving during the construction of offshore wind farms is known to negatively affect acoustic porpoise detections and porpoise abundance around construction sites. Considering varying wind conditions, we investigated the spatial effects of pile driving on porpoise detections. We demonstrated that the spatial extent of porpoise disturbance during offshore pile driving is influenced by the prevailing wind conditions with further reaching disturbance radii at low wind speed. Porpoise detections increase with wind speed values and distance to piling site. Our results suggest that porpoise disturbance not only depends on piling noise levels but also on how this noise is naturally attenuated in the environment. They also raise the question of how porpoises perceive the noise of piling activities with varying environmental background noise. There are pronounced changes in sound propagation and noise perception at different weather conditions (e.g. low wind speed) that so far have seldom been considered when assessing the effects of anthropogenic noises on acoustic-reliant marine mammals.
REFERENCES


