CHAPTER 9

DETERMINING THE SPATIAL AND TEMPORAL EXTENT OF THE INFLUENCE OF PILE DRIVING SOUND ON HARBOUR PORPOISES

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Abstract

Piling driving sound is known to impact harbour porpoise (*Phocoena phocoena*) distribution, but to date detailed knowledge on the combined spatial and temporal components of this impact over longer time periods remains lacking. From May to September 2016, pile driving was taking place at the Nobelwind wind farm located on the Bligh Bank in Belgium. In this period, porpoise activity was recorded using passive acoustic monitoring (PAM) using Continuous Porpoise Detectors (C-PoDs), at various distances from the construction site (1 – > 55 km). In this study, we compared porpoise detections before, during and after pile driving. During piling, porpoise detections decreased at stations located up to 20 km from the location of the piling event. At larger distances (20-55 km), porpoise detections either remained the same or increased slightly during piling events, which may be due to displaced porpoises entering the area. Underwater sound levels were extrapolated for the different locations. Pile driving sound levels at the furthest distance where reductions in porpoise detections were observed were ~159 dB re 1µPa ($L_{z\text{-}p}$), which is close to the threshold level for major disturbance for harbour porpoise proposed in literature.

1. Introduction

The harbour porpoise (*Phocoena phocoena*) is the most common marine mammal in the Belgian part of the North Sea (BPNS) and is protected by both national and EU law. In the North Sea, the harbour porpoise is considered vulnerable because of high bycatch levels and increasing sound pollution. Impulsive pile driving sound originating from the construction of offshore wind farms (OWF) has been shown to affect porpoises up to distances of 20 km from the sound source (Haelters *et al.* 2013; Brandt *et al.* 2016). On the basis of seasonally high porpoise densities in Belgian waters, a pile driving ban is in force from the start of January up to the end of April (Rumes *et al.* 2011; 2012; 2014). However, The Netherlands have the Borssele offshore wind farm at only one kilometer away from the Belgian offshore wind farm zone, and do not enforce a seasonal pile driving ban. Instead, seasonally fluctuating underwater sound limits are set for construction sound (Ministerie van Economische Zaken 2015). There is a need for improved insights into the spatial and temporal extent of the impact of pile driving sound on porpoises in order to determine the consequences of pile-driving at the (local) population scale using demography-based modelling. This can then serve as a basis for a more objective assessment of the effects and stimulate better regional alignment of mitigation measures.

In this study we use continuous passive acoustic monitoring (PAM) to study the spatial and temporal extent of the influence of pile driving sound on harbour porpoises.

2. Material and methods

2.1. Data collection

Passive acoustic monitoring (PAM) of porpoises was conducted using the Continuous Porpoise Detector (C-PoD, further indicated as PoD). PoDs consist of a hydrophone, a processor, batteries and a digital timing and logging system. They continuously monitor sounds between 20 kHz and 160 kHz, and can detect all odontocetes except sperm whales (*Physeter macrocephalus*). A PoD does not record sound itself, but compresses data, generating a raw file for each click

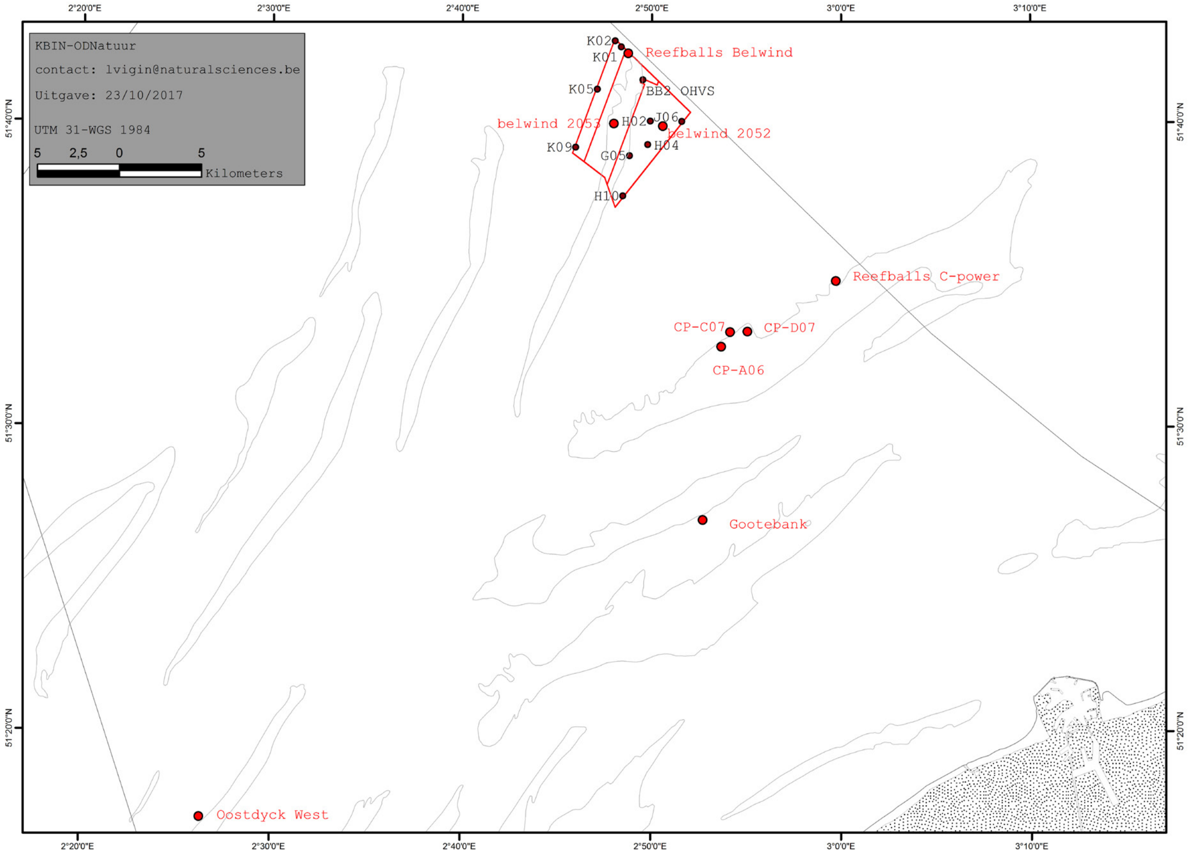


Figure 1. Location of the PoD deployments used in this study with indication of the Nobelwind wind farm (red outline) and the locations of the piling events used in this study.

Table 1. Overview of PoDs used in this study with indication of their location, deployment period, mooring type and range of distance from the piling events. Two additional PoDs deployed inside the Belwind windfarm on 4 April 2016 remain lost at sea.

Station	Latitude	Longitude	Start record	End record	Mooring type	Range
Belwind 2052	51°39.875'	02° 50.590'	11 August 2016	22 February 2017	Bottom	Inside
Belwind 2053	51°39.956'	02°47.999'	4 April 2016	1 July 2016	Bottom	Inside
Reefballs Belwind	51°42.265'	02°48.756'	14 July 2016	9 September 2016	Bottom	2-10 km
Reefballs C-Power	51°34.800'	02°59.729'	30 August 2016	4 October 2016	Bottom	10–20 km
CP-A06	51°32.639'	02°53.687'	24 April 2016	18 August 2016	Bottom	10–20 km
CP-C07	51°33.116'	02°54.150'	24 April 2016	27 May 2016	Bottom	10–20 km
CP-D07	51°33.137'	02°55.067'	24 April 2016	17 August 2016	Bottom	10–20 km
Gootebank	51°26.950'	02°52.720'	28 June 2016	24 October 2016	Surface Buoy	20-30 km
Oostdyck West	51°17.150'	02°26.320'	27 June 2016	13 October 2016	Surface Buoy	45-55 km

characteristics such as time of occurrence, duration, dominant frequency, bandwidth and sound pressure level. Using dedicated software, the raw file can be objectively analysed to find click trains and to classify these into trains produced by odontocetes and trains that originate from other sources such as boat SONAR. Distinction can be made between harbour porpoises, a species producing narrow-band, high frequency clicks, and dolphins, producing more broadband clicks with a lower frequency. The maximum detection range for porpoises is approximately 400 m. PoDs have autonomy of up to 200 days (www.chelonia.co.uk).

For this study, data were used from PoDs deployed at nine locations in the BPNS, five of which were specifically deployed for this study with the other four forming part of the VLIZ EU Lifewatch observatory (Flanders Marine Institute 2015; fig. 1). Mooring locations were divided into five range classes: inside the piling area, 2 to 10 km from the piling events, 10-20 km distance, 20 to 30 km distance and 45 to 55 km.

As PoDs were anchored in different ways and at different depths, which influence detection rates (Sostres, Alonso & Nuuttila 2015), comparisons of detections between those PoDs are not justified. Therefore, we limited ourselves to comparing the relative differences in detection rates through time at the different stations. Data from different locations was only aggregated when the same type of anchoring was used.

2.2. Data selection and analysis

Pile driving for the Nobelwind wind farm comprised 51 piling events from 16 May 2016 up to 22 September 2016. Pile diameter ranged from 4.5 to 6.8 m, penetration depth lay between 29 to 39 m and total piling time varied between 1.27 h and 4.31 h. The contractor was legally obliged to turn on an acoustic deterrent device (ADD; in this case a Lofitech Seal Scarer was used) 30 min before the start of piling and to use a soft start procedure.

As in Brandt *et al.* (2016), we selected only those piling events where at least 96 h had passed since the end of the previous pi-

Table 2. Overview of the Nobelwind piling events included in this study

Location	Pile order	Date	Time started	Time stopped	Total blows	Latitude	Longitude
K01	1	16 May 2016	14:11	18:15	3539	51° 42.477' N	2° 48.381' E
K02	2	21 May 2016	05:02	09:29	3510	51° 42.676' N	2° 48.064' E
K05	5	4 June 2016	01:08	04:00	3211	51° 41.088' N	2° 47.118' E
K09	9	15 June 2016	11:10	14:36	3921	51° 39.177' N	2° 45.981' E
J06	13	28 June 2016	01:15	03:30	2894	51° 40.032' N	2° 51.590' E
BB2 OHVS	25	25 July 2016	18:46	23:19	5157	51° 41.400' N	2° 49.531' E
G05	26	31 July 2016	20:56	23:08	3215	51° 38.906'	2° 48.830' E
H04	32	15 August 2016	10:35	13:58	3955	51° 39.271' N	2° 49.792' E
H02	35	23 August 2016	03:08	05:20	3098	51° 40.039' N	2° 49.926' E
H10	40	5 September 2016	08:45	10:10	3603	51° 37.582' N	2° 48.478' E

ling event. Our analyses are limited to the time period starting 48 h prior to the start of the activation of the ADD up to a maximum of 48 h after the end of a piling event. The time period was shorter when there was a consecutive piling within 48 h of the previous event. Hours during which the ADD was turned on or during which piling took place were counted as 0. All this was done in order to minimize the effect of consecutive piling events, *i.e.*, we assumed that harbour porpoise densities had returned to the original level 48 h after piling ended. Details on the piling events included in our analysis are listed in table 2.

PoD data were automatically processed with the proprietary software C-POD.exe version 2.044 (Tregenza 2011) using the KERNO classifier and the settings for "porpoise-like" click sequences in the classes "Hi" and "Mod" . For the analysis we used the following measures for porpoise presence:

- detection positive minutes per day (DPM/d), or the number of minutes in a day, in which porpoise click trains were detected; also detection positive 10 min per hour (DPM10/h) was used;
- click intensity per hour represents the number of porpoise clicks recorded during that hour;
- waiting time (WT) is the interval length of periods of more than 10 min without detections and thus a measure for the amount of time between different porpoise encounters (Dähne *et al.* 2013).

We compared click intensity per hour, DPM/d, DPM10/h and WT between encounters and at various distances from the piling event.

All analyses were executed using R (version 3.4.0, The R Foundation for Statistical Computing) and Rstudio (2009-2016 Rstudio, Inc.).

2.3. Underwater sound

Impulsive underwater sound was measured during piling operations in the framework of the RBINS wind farm monitoring programme using a calibrated moored hydrophone (B&K 8104 hydrophone with a

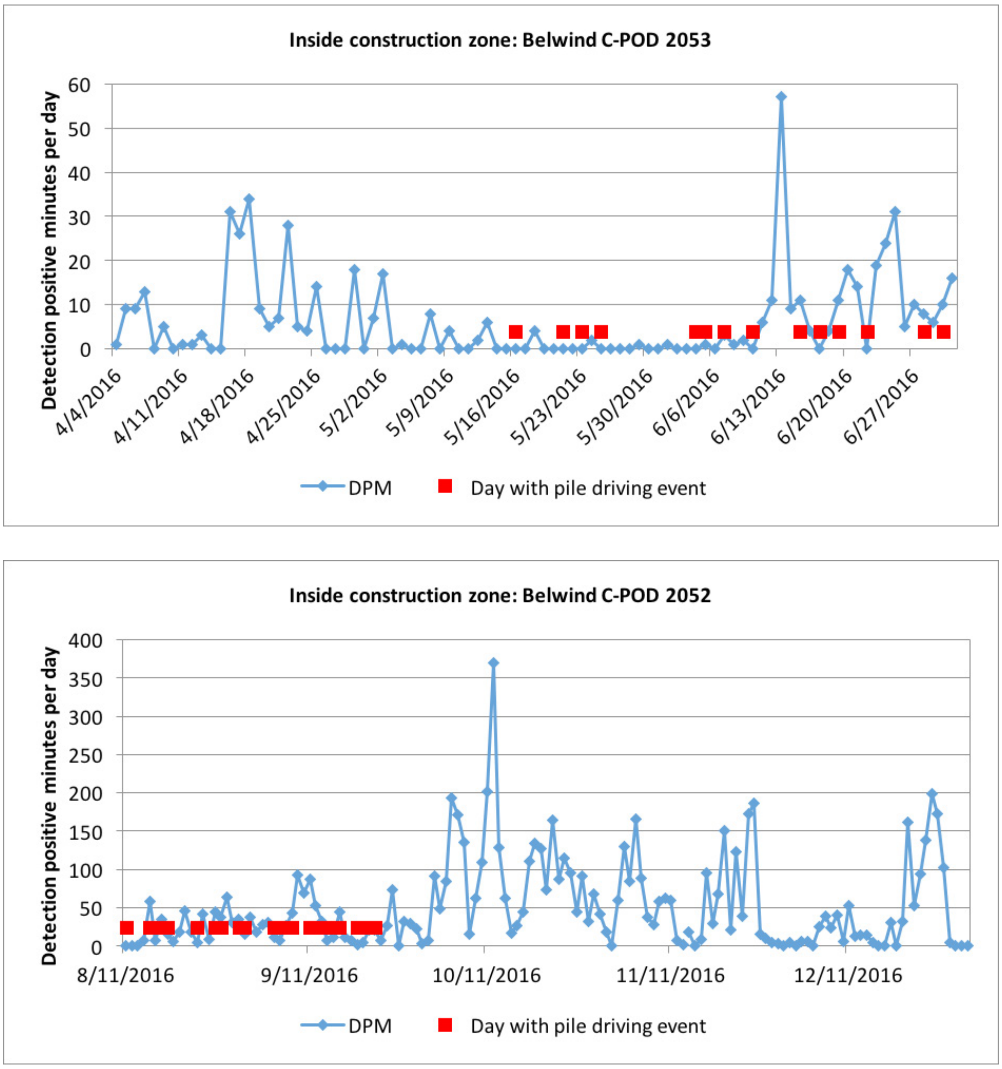


Figure 2 (part one). Detection positive minutes per day for the two PoDs moored inside the pile driving area.

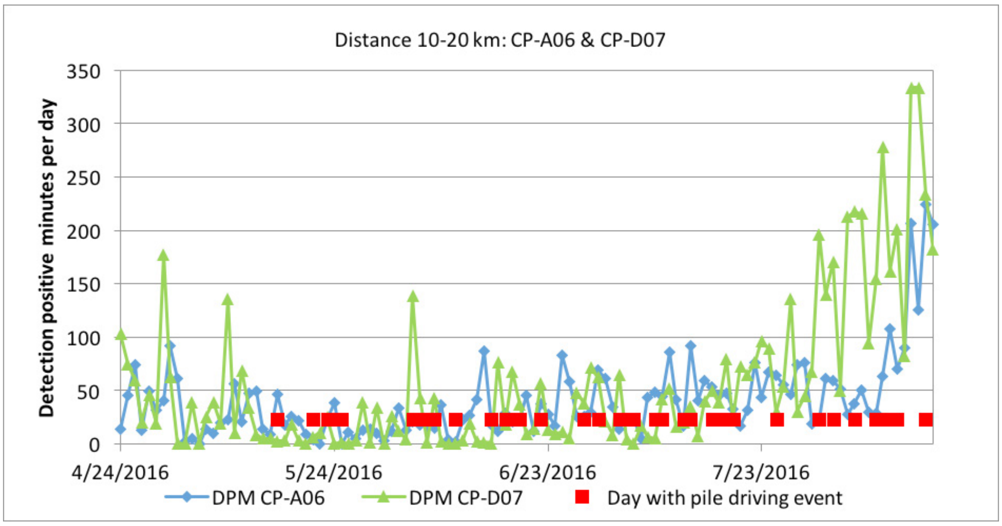
RTsys EA-SDA14 recorder) located within the Nobelwind area (at the same location as the Belwind 2052 PoD). The recorder was operated at a sampling rate of 78,125 Hz. Using reference signals, the sound level and frequency distribution (spectral analysis) of selected sections of the recordings were analysed. Zero to peak level (L_{z-p}) as well as Sound exposure level for siggle strike SEL_{ss} and cumulative sound exposure level SEL_{cum} were calculated using MATLAB. A propagation model (Norro *et al.* 2013) was used to extrapolate the sound levels at various distances from the source.

3. Results

3.1. Passive acoustic monitoring

3.1.1. Detection positive minutes per day

The interannual variability and seasonal patterns in harbour porpoise densities in the Southern North Sea make it difficult to interpret changes in porpoise detections throughout the piling period. A visual inspection of the DPM/d vs piling does illustrate the range in variability present in the dataset. Inside the work area, we observed on average lower detection rate (DPM/d) during piling days (fig. 2, part 1). There was no clear



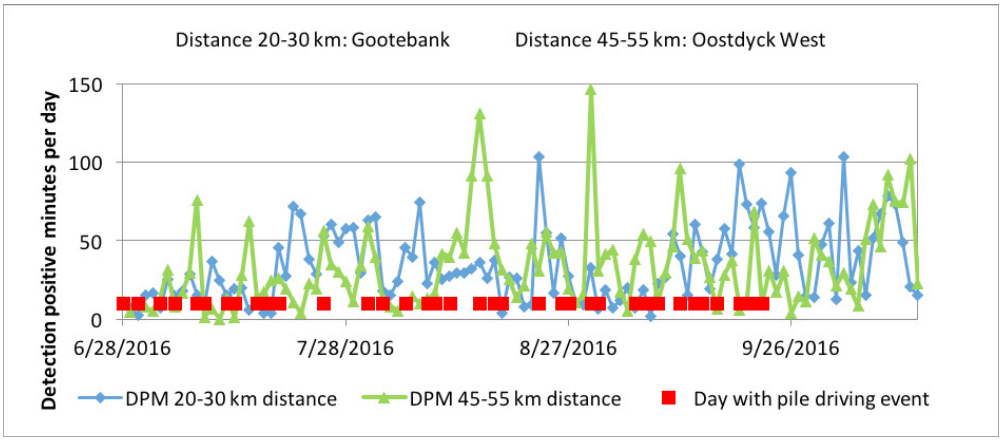


Figure 2 (part two). Detection positive minutes per day for the PoDs moored at increasing distances from the pile driving area.2.1.2 Click intensity per hour

relation between detection rate and piling at the other stations, with natural variability in density probably playing a major role (fig. 2, part 2).

In case of a low density of porpoises, such as usually in early summer months in Belgian waters (Haelters *et al.* 2016), the number of porpoise clicks per hour is often zero. This notwithstanding, we could still observe a reduction in the number of porpoise detections (to virtually 0) inside the work area during the hours of acoustic deterrence and piling. At locations further away detections were higher during these time intervals (fig. 3).

In the run up to and during the piling event, click intensity decreased strongly inside of the piling area only to recover less than 48 h later (fig. 4). A smaller reduction in click intensity was observed in the vicinity (2-10 km distance) of the piling area. At larger distances, click intensity either remained largely the same or it temporarily increased (fig. 4).

3.1.2. Detection Positive 10 minutes per hour (DPM10/h)

In the run up to and during the piling events, porpoise detections (DPM10/h) decreased both inside and at distances up to 20 km from the piling area, with the decrease starting later further away from the work area. In contrast, at larger distances (> 20 km distance) DPM10/h increased during the piling events (fig. 5).

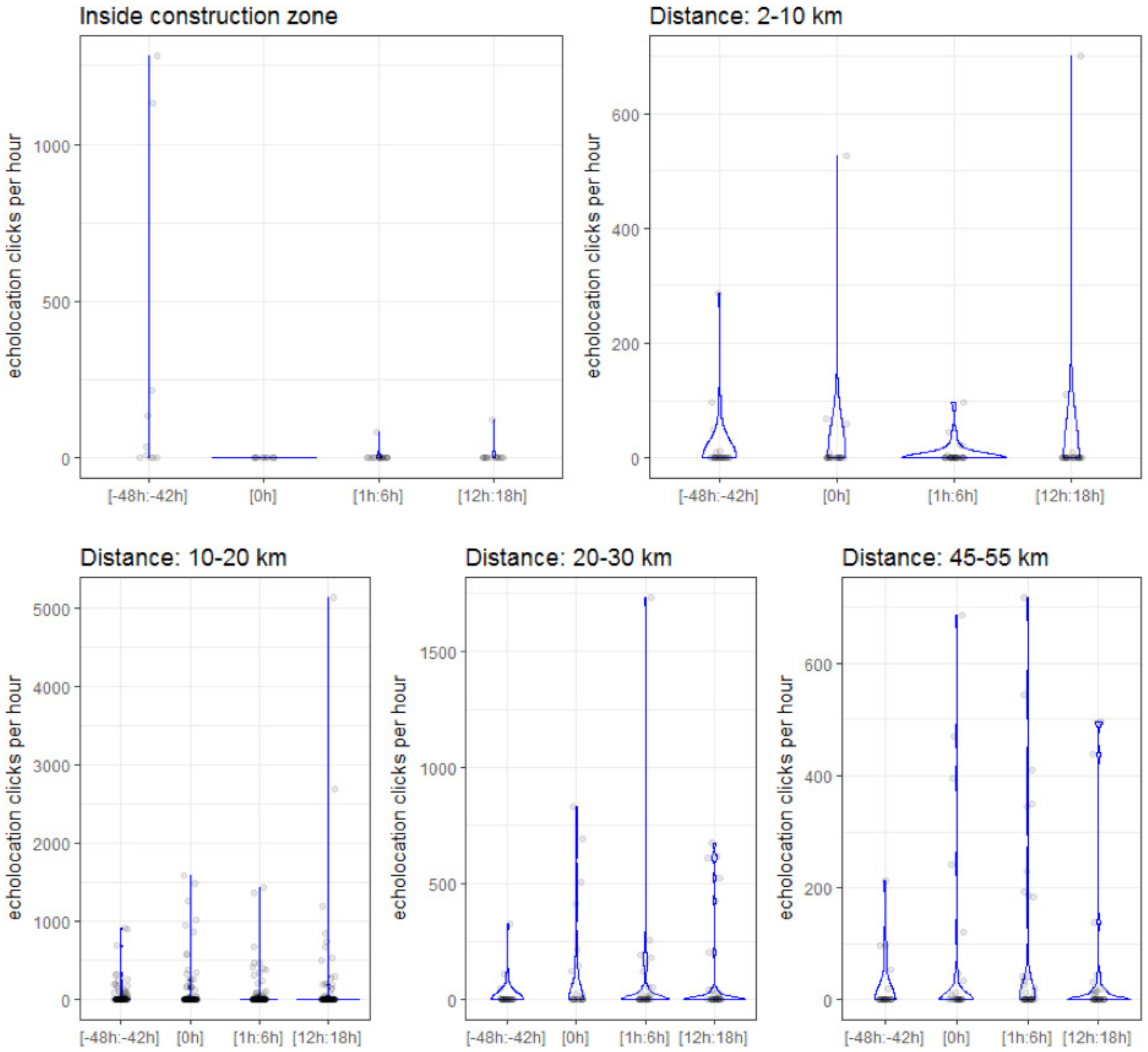


Figure 3. Violin plot of the number of Harbour porpoise (*Phocoena phocoena*) echolocation clicks per hour for four time intervals (48-42 h before the start of deterrence – used here as the baseline, during acoustic deterrence or piling, 1-6 h after piling ended and 12-18 h after piling ended) at five distance ranges from the piling event.

3.1.3. Waiting time (WT)

Waiting time, a measure for the amount of time between different porpoise encounters, temporarily increased both inside and at distances up to 20 km from the piling area (fig. 5). At larger distances WT (temporarily) decreased in this time period.

3.2. Underwater sound

3.2.1. Underwater sound levels inside the pile driving area

Underwater sound was recorded during the construction period using a moored hydrophone (B&K 8104 hydrophone with a RTsys EA-SDA14 recorder). During the piling events extremely high sound levels were recorded (up to L_{z-p} 198 dB re 1µPa and SEL_{ss} 174 in dB re 1µPa^2 s both @ 750 m, Norro, this volume). For the BPNS, ambient underwater sound levels were documented

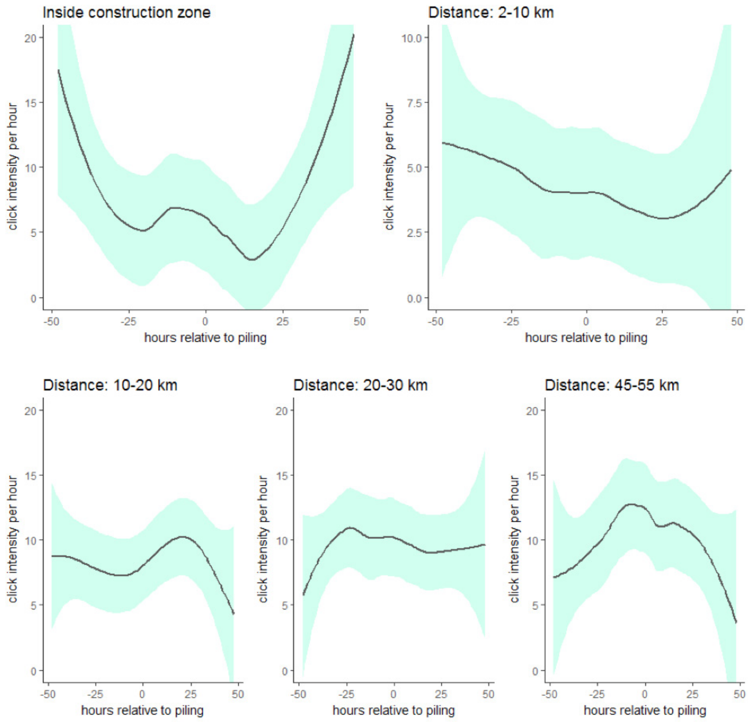


Figure 4. Click intensity per hour for a time period starting 48 h before acoustic deterrence started and ending 48 h after piling was terminated at five distance ranges from the piling event. All data from the time period starting with the start of deterrence and ending with the end of piling is included in the 0 h data point. Error bars (shaded area) represent the 95% confidence interval. For the distance interval 10-20 km data from CP-A06 was used.

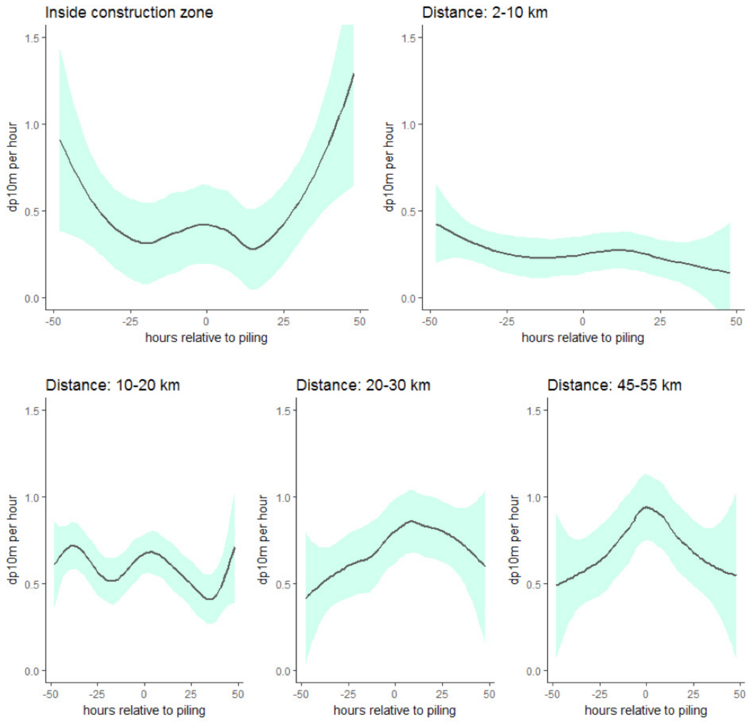


Figure 5 (part 1). Detection Positive 10 minutes per hour (0-6) for a time period starting 48 h before acoustic deterrence started and ending 48h after piling was terminated at five distance ranges from the piling event. All data from the time period starting with the start of deterrence and ending with the end of piling is included in the 0 h data point. Error bars (shaded area) represent the 95% confidence interval.

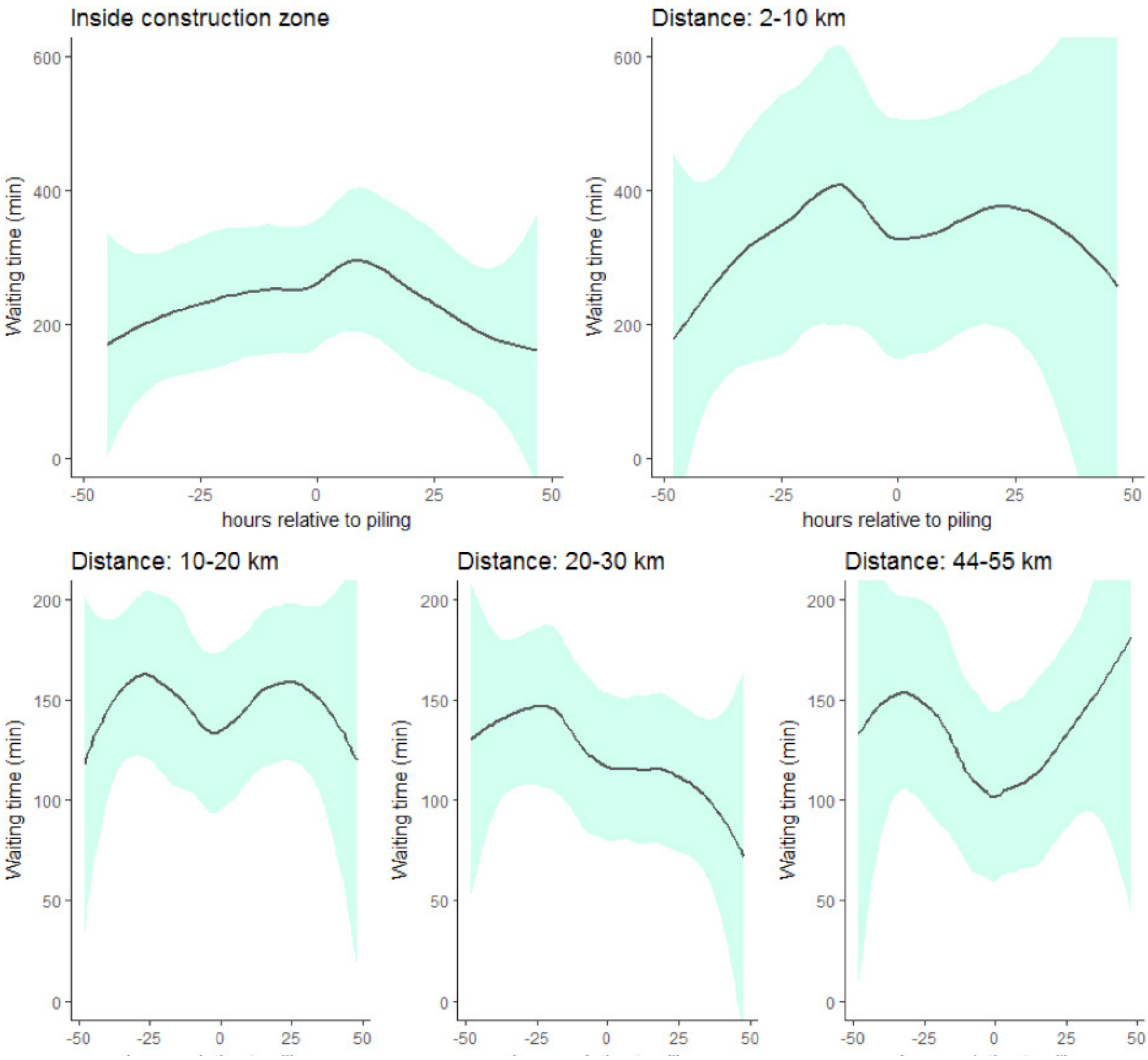


Figure 5 (part two). Waiting time for a time period starting 48 h before acoustic deterrence started and ending 48 h after piling was terminated at five distance ranges from the piling event. All data from the time period starting with the start of deterrence and ending with the end of piling is included in the 0 h data point. Error bars (shaded area) represent the 95% confidence interval. Note the difference in scale between the top two and bottom three locations.

prior to wind farm construction with reference to sound pressure levels (SPL) of about 100 dB re 1 µPa at the Thornton Bank and Bligh Bank (Henriet *et al.* 2006; Haelters *et al.* 2009). Underwater sound levels in the construction area also temporarily increased outside of piling events with extended periods of near continuous sonar when the pile driving vessel was on site.

3.2.2. Pile driving sound levels at various distances

Using the updated propagation model of Norro *et al.* (2013) and recorded pile driving sound levels we extrapolated pile driving sound levels to the different spatial ranges (table 3). Bailey *et al.* (2010) propose 149 dB SPL $L_{z\text{-}p}$ re 1 µPa as the threshold level for major disturbance for harbour porpoise.

Table 3. Extrapolated pile-driving sound level from the Nobelwind pile driving operations (propagation model of Norro *et al.* 2013)

Distance to source (in km)	Pile driving sound level ($L_{z\text{-}p}$ in dB re 1µPa)	Pile driving sound exposure level (SEL $_{ss}$ in dB re 1µPa^2 s)
1	196	172
2	187	163
10	168	144
20	159	136
30	155	131
45	150	126
55	147	124

4. Discussion

4.1. Spatial extent of deterrence

Elevated levels of underwater sound can affect harbour porpoise in several ways ranging from injury and death to discomfort and the masking of communication (Kastelein & Jennings 2012). While the thresholds for these impacts are as of yet unknown, it is well-established that porpoises will temporarily vacate too noisy areas even if these are otherwise suitable (Culik *et al.* 2000). In this study, we observed a reduction in detections of porpoises at stations up to 10-20 km from the location of the piling event. We extrapolated that pile driving sound levels at this distance were ~159 dB re 1µPa ($L_{z\text{-}p}$) (SEL_{ss} = 136 dB re 1 µPa^2 s) which is close to the threshold level for major disturbance for harbour porpoise proposed by Bailey *et al.* (2010). Previously, Haelters *et al.* (2013) using aerial survey data, found decreased porpoise densities up to 20 km from the piling event. The observed spatial extent of deterrence is consistent with the results of similar research in other parts of the North Sea (Brandt *et al.* 2011; 2016; Tougaard *et al.* 2006; 2009)

At larger distances, porpoise detections either remained the same or increased slightly, which may be due to displaced porpoises entering the area. In the German waters, Dähne *et al.* (2013) showed a negative impact of pile-driving on relative porpoise detection rates at distances less than 10.8 km and increased detection rates were at 25 and 50 km distance, suggesting that porpoises were displaced towards these positions.

4.2. Temporal extent of deterrence

Inside the work area detections decreased well before the start of piling works. This is in line with results from the German Bight (Brandt *et al.* 2016) and suggests that porpoises leave prior to the start of pile-driving possibly due to increased work vessel traffic sound and sonar which act as a deterrent. In fact, overall detections inside the construction area decreased throughout the entire construction period whether there was pile driving ongoing or not. This may be due to the effect of consecutive pile driving events which prevent the stabilisation of porpoise densities. However, this may also be due to seasonal fluctuations in porpoise densities with decreasing numbers in function of time at the start of the construction period (Haelters *et al.* 2016).

With increasing distance from the pile driving event we would expect changes in porpoise detections to be less pronounced, start later, and last shorter (as in Diederichs *et al.* 2010; Brandt *et al.* 2011; 2016). However, while this appears to be correct for the stations at 15-20 km distance further stations (25-55 km distance) do not follow this trend. As argued in Tougaard *et al.* (2009), this may be due to limited data availability.

4.3. Future work

In order to more accurately assess the spatial and temporal extent of pile-driving induced deterrence of harbour porpoise we need to understand the consequences of repeated piling events. Although Thompson *et al.* (2010) suggested that the distance over which cetaceans are disturbed becomes larger with each successive piling event, no such effect was observed in the German Bight (Brandt *et al.* 2016). In our current study, we avoided this issue by selecting only those piling events where there was an interval of at least 96 h between the end of the previous piling event and the start of acoustic deterrence. However, this meant we limited ourselves to only 10 out of 51 piling events. Our next step is to use generalized additive modelling to also take into account the effects of successive piling events, seasonality, and diurnal patterns on porpoise detections.

As we gain insight into both the seasonally fluctuating porpoise densities in the BPNS (Haelters *et al.* 2016) as well as the spatial and temporal extent of pile-driving induced deterrence we can start to more accurately determine the number of porpoises affected by wind farm construction. This is part of the information we need to determine the consequences of pile-driving at (local) population scale using demography-based modelling, such as the interim *Population Consequences of Disturbances* (PCoD; Harwoord *et al.* 2014) and the *Disturbance Effects on the Harbour Porpoise Population in the North Sea* (DEPONS; Van Beest *et al.* 2015). Both models will be applied to estimate the cumulative effects of the planned piling in the BPNS and are expected to contribute to the choice of appropriate sound mitigation measures.

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