Harbour porpoise responses to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea

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Content

1. Summary

During summer 2008, 92 monopile foundations of 3.9 m diameter were rammed into the seabed of the Danish North Sea west of Esbjerg to construct the offshore wind farm Horns Rev II. The aim of this study was to investigate the spatial and temporal scale of the effects of underwater noise from pile driving on harbour porpoises (*Phocoena phocoena*). Using passive acoustic monitoring devices (T-PODs) to record porpoise echolocation clicks, we found a clear impact of pile driving activities during construction of the wind farm on porpoise acoustic activity.

The percentage of porpoise positive ten minutes per hour (PPM/day) decreased from the baseline period to the piling period at the POD-positions close to the construction site, while no effect or even a small increase was found at further distances. Analysing porpoise positive ten minutes per hour (PPM/H), a negative effect of piling was also observed at close proximity but no effect or a slight increase was found at the furthest distances.

Analysis of the duration of waiting times between porpoise encounters offered the best method to define the duration of an effect. It appeared that harbour porpoises completely left the area next to the construction site for a medium time of 16.6 hours and for a maximum of 74.2 hours after piling. Here it took about 22.7 hours until waiting times returned to normally expected durations. A sudden decrease in the length of effect was found at POD-positions south of the reef at distances of at least about ten km, where the first waiting time after piling only doubled from about 30 min to about one hour. Here the effect was limited to the time of pile driving. This sudden decrease is probably linked to differences in sound transmission at different water depths, as sound was probably attenuated to a large degree in the shallow waters of the reef.

The relatively long recovery time that we found near the construction site was almost as long as the time between piling events, and consequently porpoise activity and possibly density was reduced near the construction site over the entire five months that pile driving took place. However, based on these results, porpoise density is expected to recover in the area within one to two days after construction is finished.

The change in acoustic activity most likely relates to changes in porpoise density rather than to changes in acoustic behaviour. Thus the animals had probably left the impact area during pile driving and during a considerable time afterwards. The temporal scale of the effect was much longer than what was found during studies on pile driving effects on porpoises at Horn Rev I and from what was predicted in the EIA for Horns Rev II, while the spatial scale over which it was observed was considerably smaller. This difference might in part be explained by differing topography and consequently sound transmission and maybe also by differing habitat suitability.

Mitigation procedures that consisted of the application of scaring devices that aim to keep the animals out of a zone, where physical injury might occur, seem to have succeeded. Based on noise measurements near the construction site, injury would only have occurred at distances of up to 2 km. No animal was detected at distances less than 3 km during pile driving, and thus mitigation measures were probably effective.

2. Introduction

In 2008, DONG Energy, Copenhagen, constructed the offshore wind farm Horns Rev 2 in the Danish North Sea west of Esbjerg. The wind farm consists of 92 turbines and a transformer platform based on mono-pile foundations. Pile driving activities to construct offshore wind farms cause high underwater noise emissions, which may adversely affect marine mammals such as harbour porpoises (Madsen et al. 2005). The Horns Rev area has been identified as an area with high porpoise numbers (Tougaard et al. 2006a, Skov & Thomsen 2006) and the wind farm was constructed right within this area in relatively shallow waters at a time when porpoise numbers are observed to be especially high. In December 2007 DONG energy contracted BioConsult SH to investigate the behavioural reactions of harbour porpoises to pile driving of foundations for Horns Rev II.

2.1. Project background

Offshore wind farming is a rapidly extending industry and several new wind parks are constructed in the North Sea and in the Baltic Sea at present. This raises the question how construction and operation of offshore wind farms effect marine mammals. Until today we know little about the spatial and temporal scale with which these activities affect the population of harbour porpoises (*Phocoena phocoena*), the only regularly occurring cetacean species in the German and Danish North Sea and Baltic Sea.

Some studies have investigated behavioural reactions of harbour porpoises to the construction and operation of wind farms and found somewhat differing results. While porpoise activity in the area around Horns Rev I decreased during the construction phase but returned to normal activity during operation of the wind farm (Tougaard et al. 2006a), there seemed to be a longer lasting effect at Nysted wind farm in the Baltic Sea (Tougaard et al. 2006b). However, it was not exactly clear whether this effect was really due to the wind farm or due to other natural parameters. When comparing porpoise activity outside the operating wind farm to inside the wind farm, Diederichs et al. (2008) found no difference at either Horns Rev I or Nysted. However, daily activity rhythms seemed to be affected by the proximity to single turbines, and the authors speculated that this might be linked to differences in porpoise feeding behaviour at the pile foundations. Based on a play back experiment Lucke et al. (2007) concluded that the impact of sound transmission of operating wind farms on harbour porpoises will be small.

While the effect of operating wind turbines might be negligible, underwater noise from pile driving activities, when mono-pile foundations have to be rammed into the sea floor that goes along with considerable noise emission may have a more pronounced negative effect on marine mammals (Madsen et al. 2005). Especially toothed cetaceans rely on echolocation for orientation and prey capture, and high levels of sound might interfere with their echolocation system via masking effects or possibly even physical injury of their sensory system. It may further cause elevated stress levels and / or avoidance of an area, which might have consequences for the animals' fitness. Avoidance reactions in response to noise have been documented for a variety of cetacean species (for review see Richardson et al. 1995, Nowacek et al. 2007 and Weilgart 2007).

Madsen et al. (2005) calculated that noise from pile driving might be detectable by harbour porpoises from a distance of more than 1000 km while injury might occur at a distance of up to 2 km assuming injury at source levels exceeding 180 dB re 1 μPa_{rms}. Thomsen et al. (2006) estimated audibility of piling noise to harbour porpoises up to a distance of 2000 km. Up to what distance a behavioural reaction is to be expected is more difficult to predict.

To our knowledge the only empirical studies addressing behavioural reactions of porpoises to pile driving were carried out by Tougaard et al. (2006a) during the construction of the Offshore Wind farm Horns Rev I in the Danish North Sea and by Carstensen et al. (2006) during construction of the offshore wind farm Nysted in the Danish Baltic Sea. Both studies used static acoustic monitoring devices (PODs), which allow continuous recordings of harbour porpoise echolocation activities. Tougaard et al. (2006a) found a strong effect of piling activities on the activity of harbour porpoises at Horns Rev in a distance of up to 15 km with a relatively short lasting effect of only about four hours. They were, however, unable to determine the distance up to which this effect was observable as they did not find a spatial gradient in the observed changes. Further, the long distance but relatively short time frame that they identified for the effect of piling on porpoise activity seems somewhat contradictory. Carstensen et al. (2006) found that in Nysted the effect lasted much longer, with times between porpoise encounters increasing from the normal 10-20 hours to 35-50 hours after construction near the wind farm and a somewhat smaller effect in an area at a distance of about 15 km. Here waiting time increased from 6-17 to 11-30 hours. However, turbines were erected using gravity foundations and ramming was restricted to a few steel sheet piles for stabilising the seabed around one foundation. This was mainly done by using a barge-mounted vibrator, where noise emissions are probably considerably lower than during pile driving. It is surprising therefore, that the effect on porpoises lasted so much longer than during pile driving at Horns Rev I. There might be considerable differences between areas of generally low porpoise activity like in the Baltic Sea and areas with generally high porpoise activity like at Horns Rev in the North Sea, and water depth, sea floor topography and geology will probably also cause major differences. Many questions on the interplay of topography and sound transmission, porpoise density and the effect of noise emission on porpoise behaviour remain unanswered.

The construction of the offshore wind farm Horns Rev II in 2008 by DONG Energy provided us with the opportunity to test how pile driving in particular affects harbour porpoises in an area with high abundance of these animals, and we designed a study to specifically test the spatial and temporal scale, with which piling activities affect this species.

Based on an experiment of Kastelein et al. (2005) on reactions of harbour porpoises to different signals around 12 kHz, Skov and Thomsen (2006) predicted in their EIA for Horns Rev II that behavioural reactions of porpoises to pile driving will occur at a distance up to 7.5

km. Using different estimates from Nedwell et al. (2003) and Madsen et al. (2004), they calculated a reaction zone of up to 25 km. Based on investigations of Tougaard et al. (2003, 2005a) on responses of Harbour porpoises to piling at Horns Rev I, they predicted a relatively short lasting effect of only a few hours (Skov and Thomsen 2006).

2.2. Biology of the harbour porpoise

Harbour porpoises inhabit coastal areas of the northern hemisphere, including the North Sea and the Baltic Sea. Their life expectancy is about 18 years and females reach sexual maturity at the age of four (Benke et al. 1998). Being a small cetacean the harbour porpoise reaches a body length of 149 – 160 cm (Schulze 1996, Benke et al. 1998).

The mating season of harbour porpoises in the North Sea and the Baltic Sea is assumed to be June to August (Benke et al. 1998). Most adult females reproduce annually, giving birth to a single calf between May and July and nurse their calves for eight to ten months (Schulz 1984). Both, mating and reproduction periods can differ regionally and as mating takes place between June and August, most adult females are pregnant and lactating at the same time, resulting in a high energetic need during this period.

Harbour porpoises are capable of diving to depths of more than 100 m (Teilmann 2000), however, they are regularly found in shallow waters and are often seen foraging very close to shore, even in the surf zone. Harbour porpoises are generalists and opportunistic in their feeding behaviour (Koschinski 2002, Santos & Pierce 2003). Santos & Pierce (2003) showed that harbour porpoises feed mainly on small shoaling fishes from both, demersal and pelagic habitats. Many prey items are probably taken on, or very close to the sea bed.

Harbour porpoises are distributed throughout the entire North Sea, and comparable high densities are found in the eastern German Bight. The SCANS surveys in the North Sea and the English Channel from 1994 and 2005 estimated 250,000 and 230,000 porpoises, respectively (Hammond et al. 1995, Hammond et al. 2002, Hammond 2006). Data from both SCANS surveys as well as a number of other smaller scaled studies reveal a large area west of Jutland as a high density area (Benke et al. 1998 and Sonntag et al. 1999, BioConsult SH & GfN 2002, Scheidat et al. 2004, Gilles et al. 2006, Teilmann et al. 2008, Tougaard et al. 2006a, Brandt et al. 2008). Diederichs et al. (2004), Gilles et al. (2006) and Brandt et al (2008) showed a consistent marked seasonal distribution pattern with low densities during winter and maximum numbers between May and July for this area. Similar observations on density and seasonal distribution of harbour porpoises at Horns Reef within the framework of impact studies for the Horns Rev wind farm showed, that this area is part of the large high density area west of Jutland and highest numbers were also observed during the summer months (Tougaard et al. 2006a, Skov & Thomsen 2006). Harbour Porpoises are also abundant around the Horns Reef area including the areas now covered by the wind farms Horns Rev I and Horns Rev II. Little is known about factors governing temporal and spatial fine-scale distribution of harbour porpoises within a respective area. Skov & Thomsen 2006 found that harbour porpoises around Horns Reef are associated with local up welling systems and their distribution differed with tidal flows. Topography, frontal systems and tidal currents seem to be important in predicting porpoise distribution and thus porpoise habitat suitability (Skov &Thomsen 2006).

2.3. Conservation status of the harbour porpoise

The harbour porpoise is listed in Annex II and IV of the EU-habitat directive. Article 12 of the EU habitat directive prohibits the “deliberate capture or killing of this species as well as the deliberate disturbance especially during the period of breeding, rearing and migration”. It also prohibits the “deterioration or destruction of breeding and resting habitats”. The harbour porpoise is further listed in appendix II of the “Convention on the Conservation of Migratory Species of Wild Animals” (CMS, Bonn 1979) that includes migratory species that would significantly benefit from international co-operation. The convention encourages the range states to conclude global or regional agreements for the conservation and management of these species. In consequence the “Agreement on the Conservation of Small Cetaceans in the Baltic and North Seas” (ASCOBANS) was concluded in 1991 and entered into force in 1994. Following its conservation and management plan, work towards “effective regulation to reduce the impact on the animal, of activities which seriously affect their food resources” and towards “prevention of other significant disturbance, especially of an acoustic nature” is required. It also requires research to be conducted to “identify present and potential threats” to this species.

2.4. Characteristics of harbour porpoise echolocation clicks

Sonic information is believed to be the major sense for orientation and communication of cetaceans. As a consequence, they might be sensitive to additional artificial noise sources (Richardson et al. 1995). Madsen et al. (2006) state that small toothed whales can hear frequencies over a range of 12 octaves, with their most sensitive hearing-range in a frequency band roughly overlapping the frequency content of their echolocation clicks (Au 1993, Richardson et al. 1995). The detection of a signal by a marine mammal ear is affected by interference from noise in frequency bands near that received signal, which is a typical effect for biological receivers in general.

In contrast to other odontocetes, harbour porpoises do not whistle. Compared with dolphin clicks, porpoise clicks are relatively long and highly tonal.

Fig. 1 shows the waveform (above) and spectrum (below) of a porpoise echo-location click with the scale units being kHz. The click beam has a three dB width of 16 degrees (Au et al. 1999). The click spectrum does not change much at increasing angles from the centre of the beam (Au et al. 1999).

Harbour porpoises produce short high frequency echolocation clicks of a narrow bandwidth centred near 130 kHz, with little energy below 100 kHz (Verboom & Kastelein 1997). These characteristics make signals suitable for automatic remote detection. Harbour porpoises use echolocation clicks for orientation (Verfuß et al. 2005), prey capture (Busnel & Dziedzic 1967, Verfuß & Schnitzler 2002) and presumably to some extent for communication (Verboom & Kastelein 1997, Koschinski et al. in press).

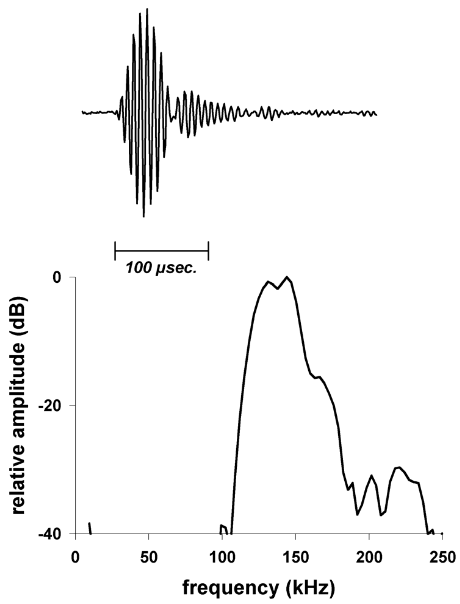

Fig. 1: Waveform (above) and frequency spectrum of a porpoise echo-location click (from Verfuß et al. 2004).

2.5. Potential impacts of pile driving on harbour porpoise

Noise emissions of pile driving may harm or disturb marine mammals (Madsen et al. 2005, Nehls et al. 2008). Apart from the possibility that in close proximity, the noise might lead to permanent or temporary hearing loss, it might also cause the animal to change behaviour at further distances. Richardson et al. (1995) discriminated between four different impact zones (Fig. 2). The zone of audibility defines the zone where the sound is detectable by the animal. The zone of masking defines the zone where the sound might interfere with the detectability of other sounds like communication or echolocation signals. Probably somewhere below that lays the zone of responsiveness, where the animals respond to a noise by changing their behaviour. At close range there will be a zone, where a temporal threshold shift of hearing might occur (TTS) and finally a permanent threshold shift (PTS), where the animal suffers permanent physical damage.

Harbour porpoises have good hearing abilities at frequencies from about 200 Hz to about 140 kHz (Kastelein et al. 2002) with best hearing abilities from 16-140 kHz, where the hearing threshold is at approximately 32-46 dB_{rms} re 1µP. A considerable part of noise emitted during pile driving usually falls into that frequency band. Using a worst case scenario Madsen et al. (2005) calculated that noise from pile driving might be detectable by harbour porpoises from a distance of more than 1000 km while injury might occur at a distance of up to 2 km assuming injury at source levels exceeding 180 dB re 1 μPa_{rms}. Up to what distance a behavioural reaction is to be expected is more difficult to predict and studying this is the aim of this study.

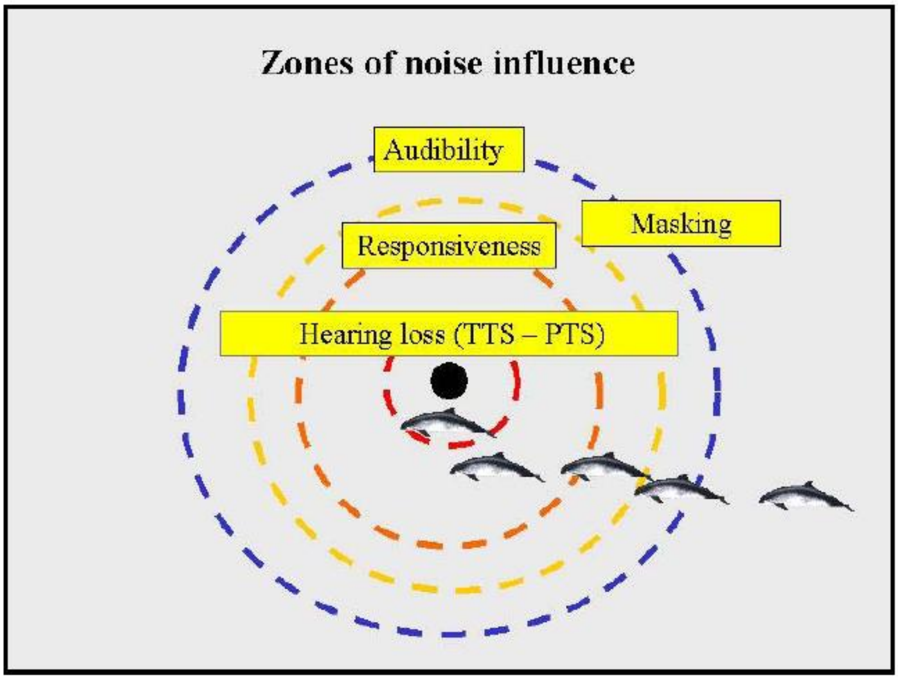

Fig. 2: Zones of noise influence (after Richardson et al. 1995).

2.6. Design of the harbour porpoise study

Detecting and quantifying numerical and spatial changes in the distribution of species that roam widely in offshore waters like the harbour porpoise, remains a difficult task (Diederichs et al. 2008). Sighting rates from ship or aerial surveys are highly variable and very dependent on counting conditions, especially weather and sea state (Teilmann 2003). Further it is logistically almost impossible to time surveys with the exact timing of the piling activity, and aerial surveys will provide only a snapshot of the porpoise distribution at a given point in time. Aerial surveys provide useful data on changes in absolute density but are unsuitable for determining the temporal scale over which an effect of pile driving is apparent.

As identifying the temporal time scale with which piling effects harbour porpoises is crucial for deciding whether or not the effect is acceptable, we decided to use a technique that enables the determination of both the temporal and spatial scale at which an effect is observable. We applied passive acoustic monitoring, using timing hydrophones with data loggers especially designed to detect harbour porpoise echolocation clicks (T-PODs). Harbour porpoises use high frequency echolocation clicks of narrow bandwidth and short duration for orientation and prey capture (e. g. Verboom & Kastelein 1995, 1997, Verfuß et al. 2005, Koschinski et al. in press). Akamatsu et al. (2007) showed that tagged wild harbour porpoises used sonar almost continuously, and silent periods lasting longer than 50 seconds made up less than 4 % of the time of investigation. Their sound characteristics make the echolocation signals of harbour porpoises unique and well suited for remote acoustical monitoring. Hydrophones receive the specific echolocation signals and log single clicks. T-

PODs continuously record acoustic signals produced by harbour porpoises within an area smaller than approximately 0.6 km². While this enables to detect relative changes over time and space it does not, however, enable us to make inferences about absolute densities as this method is not yet sufficiently calibrated with survey data. However, different studies indicate that harbour porpoise density is directly linked to T-POD recordings (Diederichs et al. 2004, Tougaard et al. 2006c, Verfuß et al. 2007, Siebert and Rye 2008).

In order to study spatial and temporal changes in the presence of harbour porpoises during and after pile driving we deployed eight T-PODs in a transect line along six different positions leading from inside the area where Horn Rev II was to be built across the reef up to a distance of about 20 km in the area of Horns Rev I south of the reef. The study period covered one month of baseline investigations before piling activities started and four month during which pile driving was carried out almost continuously. With the chosen design the following main questions were addressed: Over what spatial scale will avoidance of the impact area by harbour porpoises due to pile driving occur? How long will such an effect last?

3. Methods

3.1. Study area

The offshore wind farm Horns Rev II was erected north west of the reef Horns Rev, which extends from the westernmost point of the Danish west coast at Blavands Huk approximately 40 km to the west. The reef consists of an inner and outer reef separated by the Slugen channel. The wind farm consists of 95 2.3 MW wind turbines erected at the north western part of the reef approximately 35 km west of Blavands Huk and a platform to the east of the wind park. The turbines are arranged in 7 rows of a semicircular shape (Fig. 6) and cover an area of approximately 35 km² with a water depth of between 4-14 m. In a minimum distance of 14 km exists the wind park Horns Rev I, that is already in operation since 2003 and located in the south eastern part of the reef. At Horns Rev II turbines were erected using mono-pile foundations, which were driven into the sea bed using an IHC 1200 hammer. Mono-piles had a diameter of 3.9 m, were 30-40 m long, had a wall thickness of 25-88 mm and weighted 170-210 tons. They were driven into the seabed up to a depth between 20-25 m. The top sea layer in the wind farm area consists of predominantly medium-coarse grained sand without bottom vegetation. The Horns Ref area is known to support high numbers of Harbour porpoises especially during the summer months (Hammond 2006, Tougaard et al. 2006 and Diederichs et al. 2008).

3.2. Principle of operation and characteristics of T-PODs

The responses of harbour porpoises to wind farm construction were monitored by continuous registration of echo-location clicks using hydrophones with data logger (Porpoise Detectors, T-PODs, version 4 with the associated software T-POD.exe v7.41). T-PODs are self-contained automated echolocation sound logger with click timing manufactured by N. Tregenza, www.chelonia.demon.co.uk.

The housing of a T-POD is made of PVC pipe of 730 mm in length and 88 mm in diameter. A screwing lid closes the device at one end and a vinyl encapsulated hydrophone (piezoceramic transducer) is attached on the other end (Fig. 3). The vinyl material has the same impedance as seawater.

Fig. 3: The housing of the T-POD with external hydrophone.

The T-POD is equipped with a 128 MB non-volatile memory (up to 30 million clicks can be stored) and is powered by two bundles of six 1.5 volt D-cell alkaline batteries. Data logging stops when the voltage drops to 5.2 volts. The standard alkaline batteries ensure a logging

period of more than six weeks. The memory is filled in highly variable times depending on echolocation activity, ambient noise and specific software settings.
Furthermore, the T-POD consists of a hydrophone, an amplifier, analogue electronic filters and a digital memory to store click times. Potential aging of the ceramics forming the active part of the hydrophone is negligible. Static pressure has - especially in the onsite shallow waters - no influence on the sensitivity of the hydrophones. The hydrophones are omnidirectional in the horizontal plane with the highest sensitivity at 120 kHz, but especially tidal currents cause inclination of the T-POD and may influence the sensitivity to an unknown extent. In the range of normal onsite water temperatures the hydrophone is insensitive to temperature. The filter settings can be set to a range of different click duration, centre and reference frequencies, signal bandwidth and signal strength, that are characteristic for harbour porpoise echolocation clicks, in order to distinguish them from noises from boat sonar and other sources (e. g. propeller cavitations, shifting sediments in tidal areas like Horns Rev).
The T-POD detects harbour porpoise sonar clicks by the continuous comparison of the output of two bandpass filters. Each filter blocks all frequencies except those around its centre frequency. The start of a click is defined by the output level of the target frequency filter exceeding the reference level by some selected factor. The logger can scan through six channels (scans) during one minute whereas the settings of each channel can be set individually. In each scan, the T-POD logs for 9.4 seconds using the set of chosen values.
The device processes recorded signals with specialised software in real-time and logs time and duration of each click with a resolution of ten microseconds on a PC. Overall click timing accuracy is lower due to clock drift of approximately one minute per week, but would be sufficient for logged events to be correlated with timed visual data.
Click detection by the T-PODs is followed by train detection and classification using the software T-POD.exe (v.7.41). This software uses an algorithm (train detection algorithm V3.0) to discriminate cetacean trains from other sources. The difficulty of train classification is to distinguish between “false positives” and “true negatives”. False positives are click trains from other sources than porpoises but the algorithm identifies this train as porpoise click trains. Respectively true negatives are real porpoise click trains which are not identified by the algorithm. The T-POD.exe software deals with that problem by distinguishing between different click train classes with different probability to origin from porpoises.
The software sorts clicks into the following train classifications:
“CetHi” – (Cetaceans high): click trains with very high probability of coming from harbour porpoises.
“CetLo” – (Cetaceans low): less distinctively harbour porpoise click trains, but still with a high probability of porpoise origin.
“?” – (Cetaceans doubtful): trains, which in noisy environment are likely to have a non-cetacean origin.
“??” – (Cetaceans very doubtful): trains, which include trains that may have come from porpoises but cannot be reliably identified as having that origin. These trains have often been subject to multiple reflections and may contain multiple clicks in clusters.
“Boat sonar” – these noise sources are inevitably logged because boat sonar might show the same pitch as echolocation clicks of harbour porpoises.

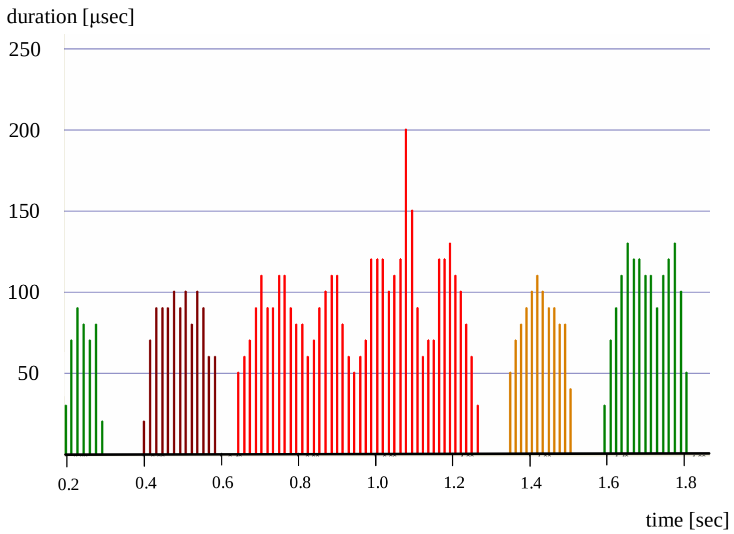

Fig. 4: Example of a registered porpoise click sequence divided by different click trains, shown as series of vertical bars (clicks), where the time [sec] is shown on the x–axis and duration of a click on the y-axis.

All other clicks that did not occur in trains or did not fit into the scheme outlined above are rejected and will not be shown. The software presents different train classifications in different colours of clicks on the screen (Fig. 4). Red = CetHi; yellow = CetLo; green = doubtful; grey = very doubtful. In order to avoid that false positives, which can often occur during times of stormy weather, affect the results, we decided to use a conservative approach and included only clicks of the two highest classes (CetHi and CetLo) in the analysis. This is the same method Tougaard et al. (2004, 2005, 2006a, b) and Teilmann et al. (2001, 2002) also used.

The TPOD.exe software enables to choose specific settings to cope with different target species and environments (Fig. 5):
For each 9.4 second interval of each minute the following operational parameters can be set:

- Target frequency (16 steps from 9 kHz to 170 kHz).
- Reference frequency (same).
- Bandwidth (8 steps).
- Sensitivity (16 steps).
- Noise adaptation. This reduces the maximum bandwidth logged when the ambient noise level (reference filter output) is high. This function was activated in the Horns Rev wind farm area.
- Maximum number of clicks logged in each scan and minute. This helps making memory use more predictable.
- In addition the minimum click duration can be set for all scans

With a focus on harbour porpoises, we set the target (A) filter to 130 kHz and the reference (B) frequency filter to 92 kHz and the click bandwidth to 5 kHz.

The sensitivity of single hydrophones differs as a result of the production process (N. Tregenza pers. comm.). Different authors therefore recommend T-POD calibrations (Teilmann et al. 2001, Diederichs et al. 2002, Dähne et al. 2006, Kyhn et al. 2006). The absolute sensitivity of individual T-PODs was measured in a laboratory environment in the German Oceanographic Museum in Stralsund, Germany. During this test tank calibration the theoretical detection threshold of each T-POD was tested and the POD-specific sensitivity was determined that has to be chosen in order to achieve a theoretical detection threshold of 130 db. This POD-specific value was then used as setting for T-PODs deployed in the field. Field calibrations by Diederichs et al. (2008) revealed that data collected by different PODs were generally well comparable.

The T-PODs were operating only while floating in a more or less upright position. The logger switched off when the angle of inclination ranged between 75 and 295°

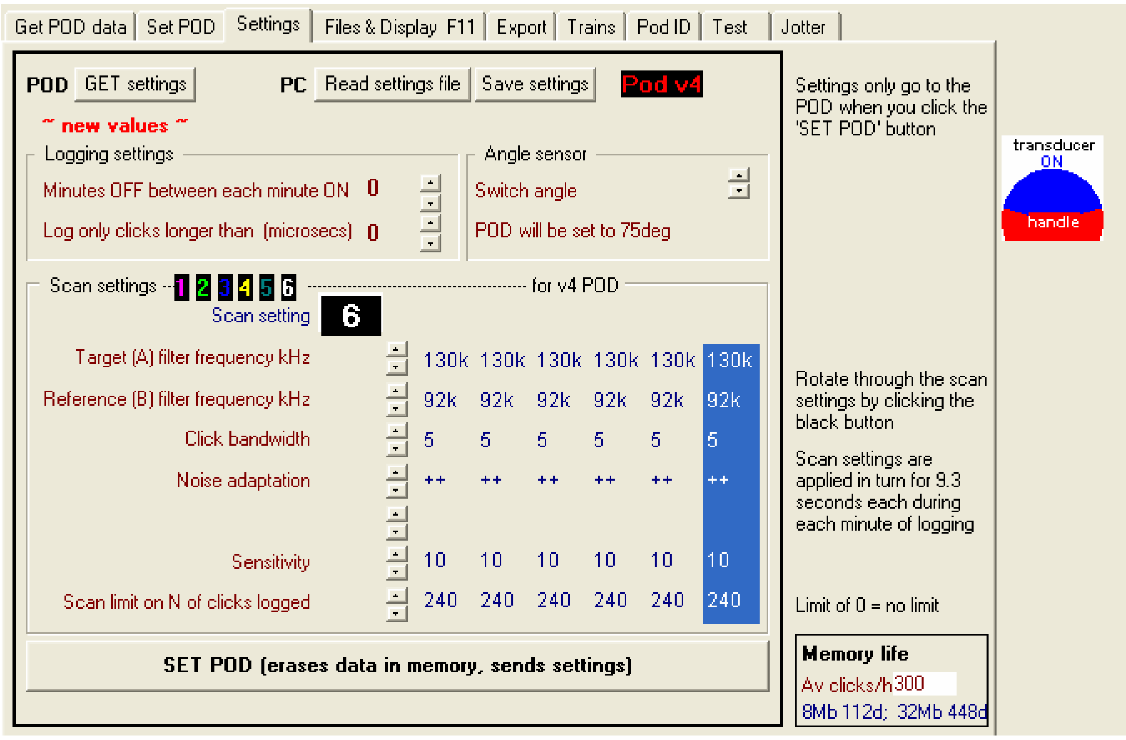

Fig. 5: Scan settings of the T-PODs. Sensitivity was set specifically for each T-POD.

3.3. T-POD deployment

Eight T-PODs were deployed at six positions along a transect line reaching from inside the area where Horns Rev II was to be built (position 1) across the reef into the area where Horns Rev I is located south of the reef (position 6) (Fig. 6).

The exact detection range of a T-POD is not accurately known. However, for version 3 T-PODs a detection distance of 200-250 m is assumed by different authors (Tregenza pers. com., Henriksen et al. 2003, Benke et al. 2003, Koschinski & Culik 2001, Diederichs et al. 2002). In order to avoid detection of one animal by two neighbouring T-POD-positions during the same minute, the positions were set with a minimum distance of 1.5 km between them.
The distance between T-POD-positions was between 1.5 and 8 km and the distance of the POD-positions to a single wind turbine that was to be constructed ranged from 0.5 to 25 km. Water depth at the T-POD-positions was between 9 and 18 m. Two T-PODs each were deployed at Position 1 and 6, one T-POD each was deployed at positions 2-5. This approach was chosen to maximise the chance to gain data from the positions nearest and furthest from the construction site, should data loss due to equipment loss or malfunction occur.

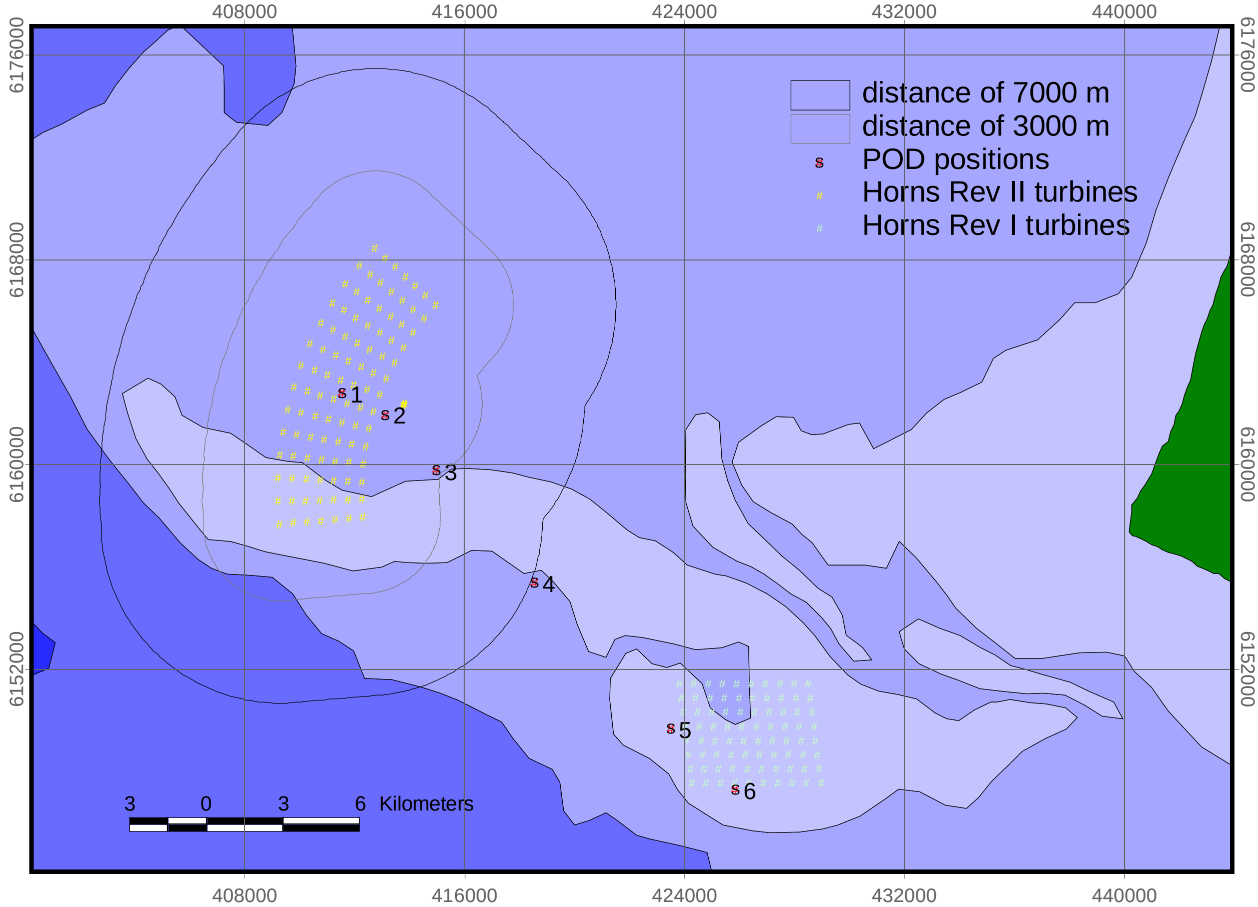

Fig. 6: Study area and position of wind farms and PODs.

T-PODs were placed in the water column approximately one meter above the sea bottom (Fig. 7). The T-POD normally has sufficient buoyancy for staying in an upright position, but considerable inclination may occur with strong currents – especially in the North Sea. Inflatable yellow buoys indicated the position of the T-POD. Each POD-position was additionally marked by an official yellow warning buoy deployed at a distance of 100-150m to the T-POD-position. The mooring system for the T-POD consisted of the inflatable yellow buoy, which was attached to an anchor block. This anchor block was connected to a second anchor block, to which the T-POD was attached (Fig. 7, 8).

The locations of the T-PODs were stored by the ships GPS system with approximately five meter accuracy.

T-PODs were changed approximately every four weeks, data were extracted and PODs changed between positions when redeployed. This activity took about one hour per position.

Fig. 7: Deployment of a T-POD at sea.

Fig. 8: T-POD mooring system with two anchor blocks (tyres with concrete).

During the period 08.04.2008-07.09.2008, a total of 871 POD-days (no of PODs deployed x days of deployment) were achieved. During the baseline period 08.04.08-18.05.08 before pile driving activities started, no data could be recorded at position 4 and 1a due to equipment losses or damage. At every other location at least 17 days of recording where achieved during the baseline period. Although some further data gaps occurred during the pile driving period, enough data were collected for a robust analysis (Fig. 9).
The POD position denoted as POD T3.1 stand for a second POD deployed at position 3 because the other POD was thought to be lost but was later recovered and had also recorded data. Data from 3 and 3.1 were pooled for position 3 in the analysis. Periods were no PODs were deployed occurred because boys were lost so that no PODs could be deployed. Periods with deployed PODs but without data occurred because the devices were not functioning properly or were damaged.

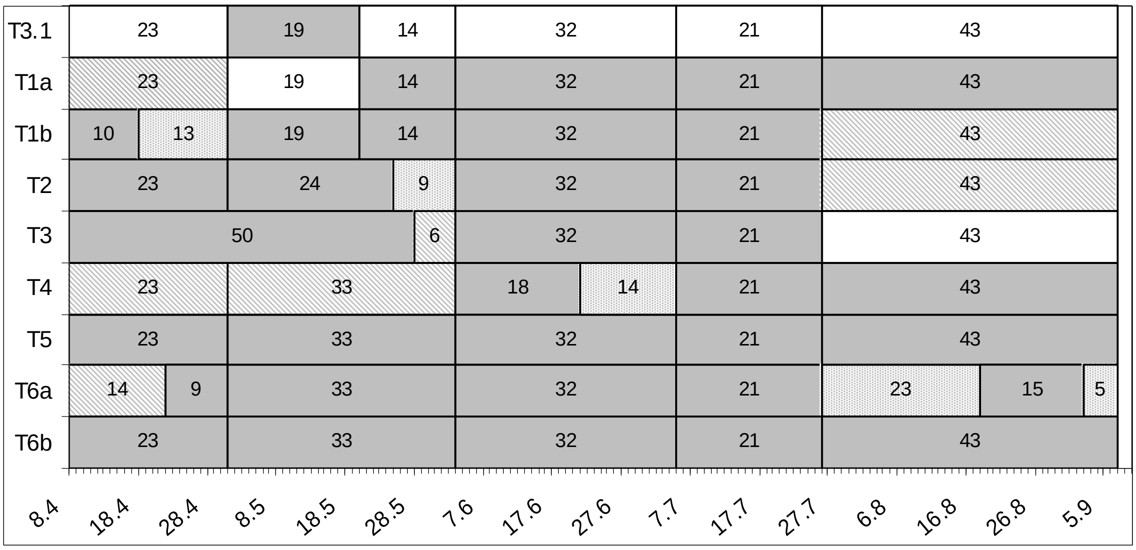

Fig. 9: Recorded data of PODs placed at different positions in relation to the offshore wind farm Horns Rev II. Vertical black lines show changes of PODs. Grey bars: POD recorded data, hatched bars: POD deployed but lost, dotted bars: POD deployed but did not record data; white bars: no POD deployed.

Piling activities started at the 19.05.2008 and continued until 14.10.2008. During this period there was only one pause between piling events that was longer than four days. This occurred between piling at the 14.07.08 and 23.07.08 and was thus eight days long (Fig. 10). A period with a break lasting four days occurred at only two times, all others were shorter than that. On several occasions two piling events occurred during one day. A piling event lasted on average 46 ± 14 min. Mean time between piling events (measured from the end of a piling event to the start of the next piling event) was 38 ± 45 hours.
In order to minimise the risk of physical damage to harbour porpoises and seals, mitigation procedures were applied. These consisted of the deployment of two scaring devices at the area of construction some time before piling started to keep the animals out of the radius where physical damage from piling noise might appear. Scaring devices used during construction of Horns Rev II consisted of a seal scarer (Lofitech) and pinger (Aquamark 100).

Seal scarers are usually used to keep seals away from fishing gear while pingers are used to deter harbour porpoises from fishing gear. Both these devices produce sound that was shown to deter harbour porpoises. The pinger used here produces sounds at of low intensity (up to 145 dB re 1 µP @ 1 m) at high frequencies of about 20-160 kHz, which was found to deter harbour porpoises to distances of 100-200m (Kraus et al. 1999, Laake et al. 1998, Larsen 1999, Trippel et al. 1999, Larsen et al. 2002, Barlow and Cameron 2003, Kastelein et al. 2006). The seal scarer used during construction (Lofitech) emits strong acoustic signals of 189 dB re 1 µP @ 1 m at frequencies of 13.5-15 kHz. Its effectiveness for harbour porpoises is not really known but Olesiuk et al. (2002) observed avoidance reactions by porpoises to the Airmar seal scarer, which produces a 5 dB louder noise, up to a distance of 2.5-3.5 km. Scaring devices were deployed on average 163 ± 88 min (0-461 min) before piling activities started and were recovered 47 ± 46 min (0-279 min) after piling was finished.

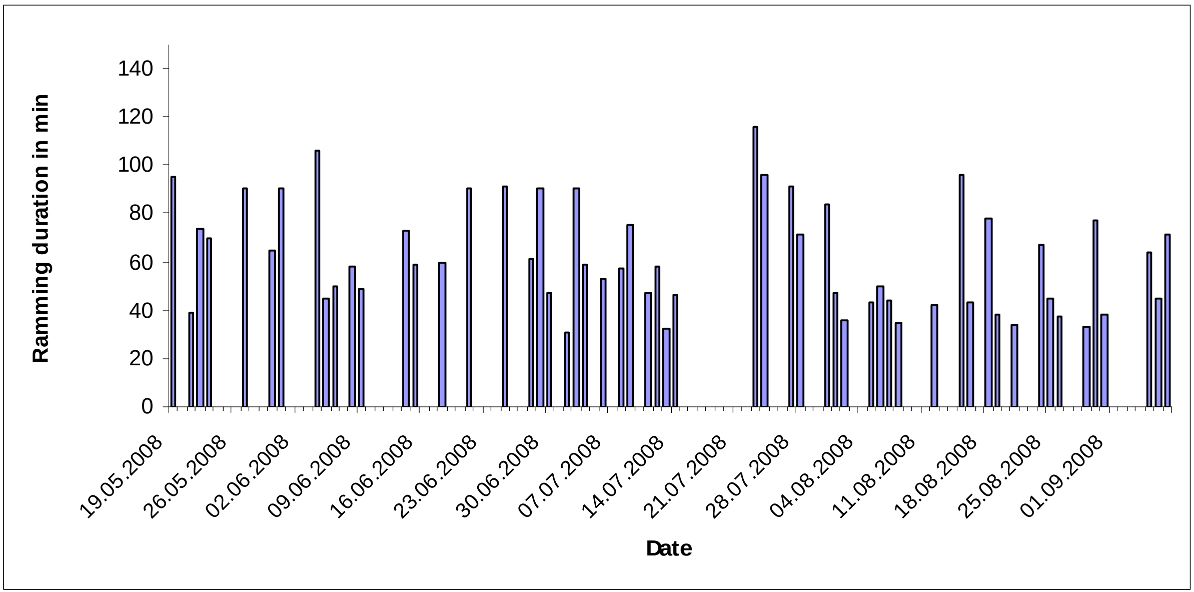

Fig. 10: Timing of piling events depicted as number of minutes that pile driving took place on the day where an event was finished.

3.4. Parameter from T-POD signals

Different parameters from T-POD signals were proposed for describing harbour porpoise echolocation activity. For porpoise presence and as a measure for porpoise density the parameter “porpoise positive time” per time unit (days/hours/10minutes or minutes) was analysed. The parameter “porpoise positive time” means the proportion of time units (minutes/hours/days) with porpoise activity logged compared with the total number of time units in which the T-POD was active (equation 2, xt = number of clicks during time unit).

(1) $$\text{Porpoise positive time per time unit [\%]} = \frac{\text{Number of time units with clicks}}{\text{Total number of time units}} = \frac{N\ \{x_t > 0\}}{N_{\text{total}}}$$

The parameter “porpoise positive time” has already been identified as a powerful tool to describe harbour porpoise click activity (Teilmann et al. 2001, 2002, Diederichs et al. 2004, Tougaard et al. 2004, 2005, Verfuß et al. 2007). The different time units from days to minutes give different information about the echolocation activity of harbour porpoises. The number of porpoise positive days (PPD) as the roughest unit gives information about the utilisation of low density areas. It answers the question: how many days are porpoises present in this area. This unit is useful to describe seasonal attendance pattern in areas with low densities like the eastern German Baltic (Verfuß et al. 2004, 2007). In high density areas, where harbour porpoises are present nearly every day, like in the Horns Rev area, it is recommended to apply a higher resolution. The more detailed units, porpoise positive hours (PPH), porpoise positive ten-minutes (PP10M) and porpoise positive minutes (PPM) express the utilisation of a specific area with increasing precision. We used the parameter “PP10M/day” in order to get an estimation of general porpoise activity in the area during the baseline and the construction period and used the parameter “PPM/H” to get a higher resolution that we could then more specifically link to each piling event.

A different approach of analysing T-POD signals is used for considering their temporal pattern and to separate periods with click activity from periods without click activity. In this sense, a click event or encounter is defined as a period with click activity separated by a silent period of at least ten minutes without any click activity (Fig. 11). In consequence, two click sequences separated by a silent time of nine minutes do per definition still belong to the same encounter and thus the maximal number of encounters within one hour is five. The interval of ten minutes for separating events or encounters was suggested by Teilmann et al. (2002) as an appropriate choice after inspecting high-resolution graphs of POD signals. The parameter that we used in this study in order to investigate low long after piling it will take until the first porpoise reappears in the impact area and in order to study how long it might last until porpoise activity is back to normal was the length of time between two porpoise encounters called “waiting time” (= silent periods) (Fig. 11). Waiting time is thus defined as the time period between two encounters and is per definition not shorter than ten minutes.

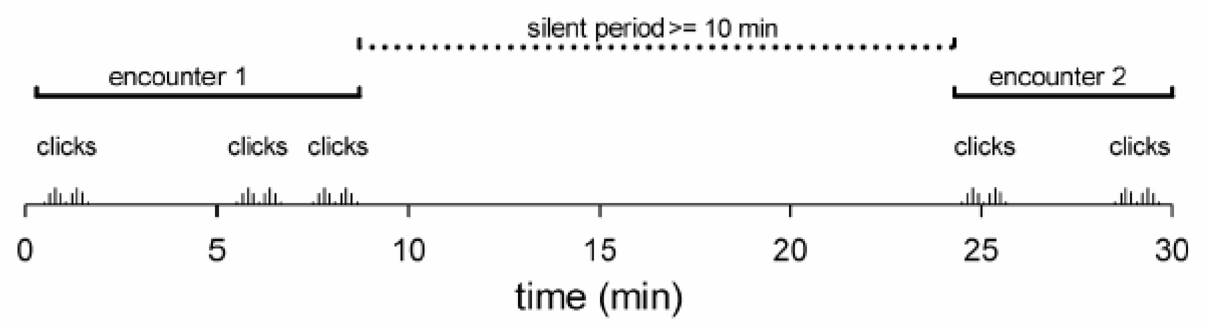

Fig. 11: Definition of “encounter” and “silent periods (= waiting time)” (from Benke et al. 2003).

3.5. Statistical analysis

Statistical treatment was mostly performed using the software “SPSS13”. For analysis using a GLM fitted to a Poisson distribution we used the software “R”, version 2.8.0 (http://www.r-project.org/).

3.5.1. Porpoise positive ten minutes per day (PP10M/day)

For the parameter PP10M/day we calculated the percentage of PP10M/day relative to the amount of hours covered during that day. This was 24 hours in most cases, only when PODs were deployed, recovered or changed, there were a few hours missing during that day. Data were log-transformed to achieve near normal distribution for further analysis.

To investigate whether there was a difference in PP10M/day between the baseline period from 09.05.08-18.05.08 before piling activities started and the piling period (19.05.-07.09.08), we calculated a General Linear Mixed Model (GLMM) where the dependent variable was “PP10M/day” (the log-transformed percentage of porpoise positive ten minutes per day). “Month” and “POD-ID” were entered as random factors to control for their potential influence, and “period” (baseline versus piling period) and “position” (location of the PODs from 1 to 6) were entered as fixed factors as these were the variables we were interested in. As we assumed that the parameter might show different changes between periods at the different locations, we also included the interaction term of “period” with “position” in the model. In cases where an interaction term was not found to have a significant influence it was then dropped from the model to look at the effect of the two parameters alone. In cases where the interaction term was found to be significant, we split the data into corresponding subsets of data and again analysed them with a GLMM.

In a second step we were interested in whether the parameter differed between days during the baseline period, days between piling events and days during which piling took place (Tab. 1). The date of pile driving was assigned to the day where the activity was finished. Days between such events were defined as days where at least 24 hours had passed since the piling event was finished. This means that days during piling consisted of the day where piling happened and the following day while days between piling where those from the second day after piling to the day before the next piling event started. This conservative approach was chosen as piling could take place at any time of the day and PP10M/day was always counted from 0:00 - 23:59. In the instance that piling occurred during the evening an effect of piling is expected at the day following the day of piling rather than during that day itself. Only by following this approach we could therefore achieve comparability of the days between and days during piling. This means however, that a conclusion about the time period over which a potential effect is observable is rather limited.

To test for differences between baseline-days, piling-days and non-piling-days we calculated another GLMM similar to the one described above only that instead of “period” we now entered “piling” (baseline-days, days between piling events and days during piling) as a fixed factor and also the interaction term of “piling” with “position”. Following the approach described above we split the data into subgroups for further analysis if the interaction term was found to be significant.

Tab. 1: definition of the parameter piling used to investigate the effect of piling on PP10M/day

States of the parameter piling	Definition
Before piling	Days during the baseline period (8.04.-18.05.2008) before construction started
Between piling	Days at least two days after a piling event and before the next piling event started
During piling	Days during which a piling event took place and the first days following it.

3.5.2. Porpoise positive minutes per hour (PPM/hour)

Analysis of PP10M/day only gives a crude indication on how porpoise activity during the day of piling decreases but it does not give an indication on how long an effect lasts. This can be analysed in more detail using PPM/H, which can better be linked to the exact timing of the piling event. Data from the baseline period were not used for this analysis and only hours that were fully covered were included in the analysis. Hours were assigned to their occurrence after the last piling event and grouped into ten hour intervals after piling. To test whether piling had an effect on the parameter PPM/H we then proceeded by calculating a GLMM with “PPM/H” entered as the dependent variable. Similar to the approach described for PP10M/day above, “Month”, “POD-ID” and “Hour” were included as random factors while “POD-position” was included as a factor and “time since piling” as a covariate assuming a linear directional effect. The interaction of the latter two variables was also included. We then followed the same procedure as described for PP10M/day above.

In order to test how long the effect of piling is observable at the different stations we further used a non parametric Mann-Whitney-U-test for two independent samples to compare each 10 hour period after piling to all following 10 hour periods. The first ten hours after piling were thus compared to all hours later than 10 hours after piling, then the 10-20 hours after piling where compared to all hours later than 20 hours after piling and so on. In this way we aimed to find out when after piling porpoise activity no longer increases but stagnates. As we calculated six such tests on the same dataset we corrected significance levels using the Bonferroni method (Sokal and Rohlf 1995) meaning that derived p-values were multiplied with the number of tests conducted (six in this case).

As the distance of POD-positions to the construction site was not constant (due to the different locations of mono-piles that were to be erected), and also the gradient of the distance to the construction site varied between the first three POD-positions (sometimes position 1, 2 or 3 was the closest location), to each value of PPM/H we also assigned the distance from the last mono-pile that was erected, where we used the following distance intervals: 0-3 km, 3.1-6 km, 6.1-9 km, 9.1-12 km, 12.1-18 km, 18.1-25 km. We then calculated the same GLMM as described above but with “distance” (distance group of the POD-position to the erected mono-pile) entered as the covariate instead of “POD-position”.

3.5.3. Waiting times

Waiting times were assigned to each piling event by sorting them according to their order of occurrence after the piling event. The first waiting time after piling was defined as the first waiting time, which end occurred after the piling event was finished. The first waiting time after piling might therefore cover the whole time a piling event lasted and in some cases also some time before piling started. All waiting times after the ninth waiting time were grouped into “waiting time ≥10” because sample size after the ninth waiting time decreased severely due to the next piling event already starting in many occasions.

As waiting time data were not normally distributed (but near Poisson distributed) we calculate statistics using median waiting times. However, as in the literature waiting times are mostly given as means, we also show mean waiting times in a different table.

First we tested for the influence of the piling on the duration of waiting times by calculating a GLM fitted to a Poisson distribution and allowing for overdispersion with “waiting time” (in min) entered as the dependent variable, “month”, “POD-ID” and “POD-position” included as fixed factors and “order” (order of waiting time after piling event) as a covariate assuming a linear effect. Further we also tested for in interaction of “POD-position” with “order”, as we assumed the effect of order to differ with the POD-position relative to the location of the erected mono-pile. Because the interaction term was significant we split the data up for POD-position in a second step and again calculated the model for each position separately. Note that here we could not control for POD-ID at each position, because at some positions not enough different PODs were used for analyses to be valid.

In order to test when after the piling event waiting times returned to “normal” duration we further used a non parametric Mann-Whitney-U-test for two independent samples to compare each waiting time to all following waiting times excluding earlier ones. As we calculated six such tests on the same dataset we corrected significance levels using the Bonferroni method (ref), meaning that derived p-values were multiplied with the number of tests conducted (six in this case).

After finding out up to which waiting time a significant difference was found, we summed up the duration of all the first waiting times that were different to gain an estimate on how long after piling it takes until waiting times have returned to “normal” values.

As with the analysis of PPM/H we also recalculated the same model with “distance” (to erected mono-pile) in the model instead of “POD-position” and then followed the same procedure as described for POD-position above.

3.5.4. Porpoise encounter

In order to investigate at what distance porpoises were recorded during pile driving events we also studied all instances where porpoises were recorded while piling occurred and assigned these encounters the distance (1 km resolution) of the POD-position where a recording occurred to the mono-pile that was driven into the seabed at that time.

4. Results

4.1. Porpoise positive ten minutes per day (PP10M/day)

There was a clear seasonal pattern in harbour porpoise acoustic activity measured as PP10M/day at positions 4-6. Activity gradually increased from April to July, when it reached levels between 34-44 % PP10M/day. Activity remained high in August at position 4 but declined again at positions 5 and 6. At position 1-3 activity was highest in April and remained at comparatively low levels from May to August. Note that pile driving started in mid May and continued until September (Fig. 12 a). Seasonal patterns found at POD-positions 4-6 at Horns Rev II was similar to those found by Diederichs et al. (2008) in the area around Horns Rev I (Fig. 12 b). Here porpoise acoustic activity also increased from April to July and remained high during the summer months.

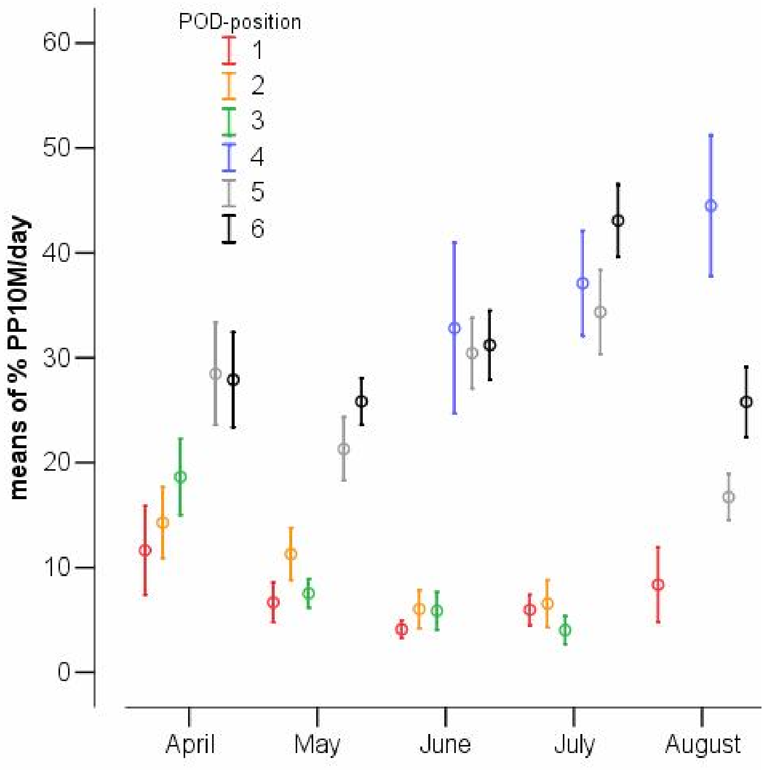

Fig. 12: Seasonal change in PP10M/dy at the different POD-positions around Horns Rev II.

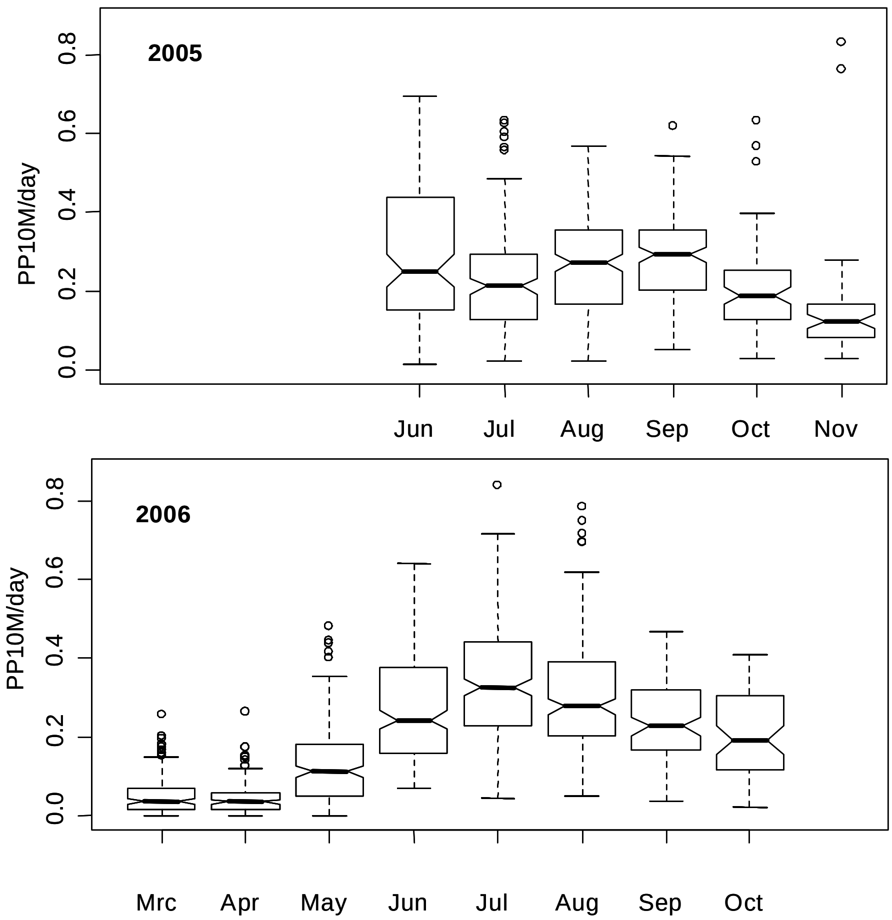

Fig. 12b: Seasonal change in PP10M/day during 2005 and 2006 in the area around Horns Rev I.

As revealed by a GLMM, there was a significant effect of the interaction of period (baseline versus time during piling activities) with position of the T-POD on PP10M/day (Tab. 2**)**. This means that PP10M/day differed significantly between the baseline and the piling period, but not in the same manner at all POD-positions. PP10M/day was generally higher at positions 4-6 south of the reef than at positions 1-3 north of the reef during both baseline and piling period (Fig.13, Tab. 3). During the baseline period PP10M/day was between 26-28 % at positions 5-6 and thus about 2.5 times higher than at positions 1-3, where it lay between 11-13 %. From the baseline period (08.04.08 – 18.05.08) to the piling period (19.05.08 – 07.09.08) PP10M/day decreased at positions 1, 2, 3 and 5 but not at position no 6. For position no 4 this could not be tested because no baseline data are available. The effect was similar at locations 1-3 with a decrease of more than 50 %, but much weaker at position 5 (Fig. 13, Tab. 3). This became even clearer when the analysis was split into positions 1-3 and 5-6. This revealed no significant interaction of period*position for positions 1-3 ($F_{2,416}$=2.2, p=0.11, model 1.1, Tab. 4) nor for positions 5-6 ($F_{1,401}$=1.8, p=0.18, model 1.2, Tab. 4). So while the effect was similar between positions 1, 2 and 3 and between 5 and 6, there seemed to be a difference in the influence of piling activities between the area north of the reef and close to the construction site (position 1-3) as compared to the area south of the

reef further from the construction site (positions 4-6). After removing the non significant interaction term from the model the influence of period remained highly significant with a negative effect from baseline to piling period at positions 1-3 ($F_{1,418}$=11.9, p≤0,01, model 1.1a, Tab. 4) but no effect at positions 5-6 ($F_{1,402}$=2.8, p=0.1, model 1.2a, Tab. 4). Thus, a difference in the PP10M/day between baseline and piling period existed north of the reef at positions 1-3 close to the construction site but not at positions 5-6 south of the reef further from the construction site.
In all GLMMs the random variables month and POD-ID were found to have a highly significant effect on PP10M/day (Tab. 2, 4) underlining the necessity to control for these variables.

Tab. 2: Results from the GLMM on the effects of period and position on % of PP10M/day. The p-value of the main effect to be tested is indicated in bold numbers.

Dependent variable: Log(% PP10M/day)					
Independent variable		**Type III Sum of squares**	**df**	**F**	**p**
Intercept	Hypothesis	344.8	1	1025.4	≤0.001
	Error	4.6	13.6		
Month	Hypothesis	2.0	5	4.9	≤0.001
	Error	74.7	907		
POD-ID	Hypothesis	4.9	14	4.2	≤0.001
	Error	74.7	907		
Period	Hypothesis	2.2	1	27.3	≤0.001
	Error	74.7	907		
POD-position	Hypothesis	16.6	5	40.3	≤0.001
	Error	74.7	907		
Period*POD-position	Hypothesis	2.2	4	6.5	**≤0.001**
	Error	74.7	907		

Tab. 3: Means, standard deviation and sample size for PP10M/day between baseline and piling period for each POD position.

Position	Period	Mean	SD	N
1	baseline	11.35	5.8	29
	piling	5.9	6.8	179
2	baseline	13.3	6.7	41
	piling	6.6	5.6	61
3	baseline	11.9	8.5	59
	piling	5.5	4.2	66
4	baseline			0
	piling	37.6	17.0	84
5	baseline	26.2	10.9	41
	piling	25.5	12.0	112
6	baseline	28.0	10.6	68
	piling	31.9	14.2	197

Tab. 4: Results from different GLMMs. Given is the p-value for all variables entered into the model. P-values of the main effects to be tested are indicated as bold if they were significant and as bold italics if there were not significant. Main results are highlighted in yellow. The model of first order represents the main model, models of second order test data subsets of the main model die to a significant interaction and models of third order are calculated if an interaction term in second order models was not significant, in which case the interaction term was removed.

Model No	POD positions used in the model	Month	POD-ID	Period (baseline or piling)	Position	Period* position
1	1 - 6	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	**≤ 0.001**
1.2	1 - 3	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.01	***0.11***
1.2.a	1 - 3	≤ 0.001	≤ 0.001	**≤ 0.001**	≤ 0.001	
1.3	5 - 6	≤ 0.001	≤ 0.001	0.26	≤ 0.001	***0.18***
1.3.a	5 - 6	≤ 0.001	≤ 0.001	***0.1***	≤ 0.001	

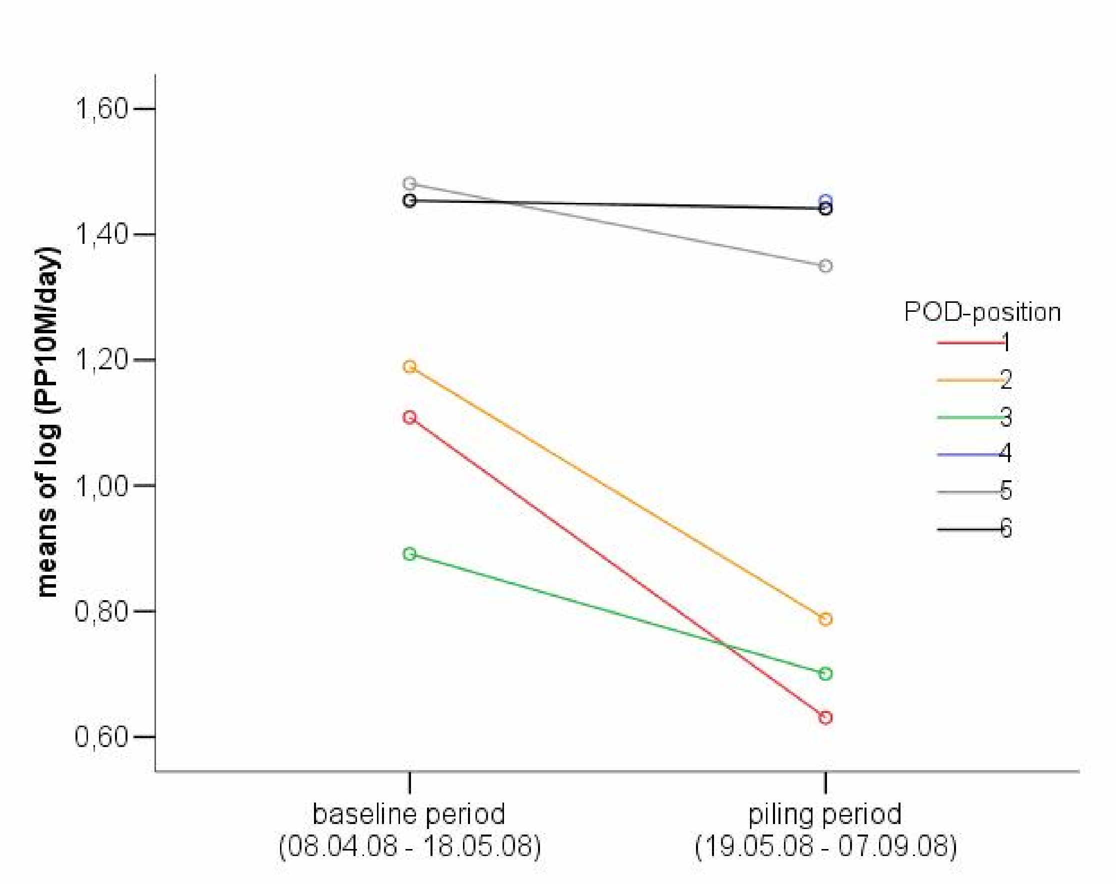

Fig. 13: Means of log-transformed porpoise positive ten minutes / day during the baseline and pile driving period as predicted by the model.

To look at the effect of piling on PP10M/day more closely, we then compared days during the baseline period with days between and days during piling events (this factor will be called "piling" from now). There was a significant effect of the interaction of piling with POD-position on PP10M/day (Tab. 5). As visualised in Fig. 14 a-b this was mainly due to a marked increase in PP10M/day from days during piling to days between piling at positions 1-3. This effect was less clear at positions 4-6. We therefore split the model into positions 1-3 and positions 4-6. At positions 1-3 the interaction of piling*position was no longer significant ($F_{4,413}$=1.0, p=0.40, model 1.1, Tab. 6). When the interaction term was removed from the model, piling still had a significant effect ($F_{2,417}$=37.9, p≤0.001, model 1.1.a Tab. 6). At positions 4-6 however, the interaction term remained significant ($F_{3,480}$=5.0, p p≤0.01, model 1.2 Tab. 6), but the effect was in opposite directions at position 5 and 6 and generally quite weak (Fig. 14 a-b).

To define the exact effect of piling we further split the analysis and only used days before and between piling events in a first step and only days during piling and between piling in a second step. In this way we aimed to determine whether the observed effect of piling on PPP10M/day was confined to days during piling mostly, or whether it lasted over a longer period. We further aimed to determine whether the POD-positions are affected differently.

When only using days before and between piling events, the interaction between piling and position was not significant in the model ($F_{4,407}$=0.5, p=0.73, model 2 Tab. 6). After removal of the interaction term there was also no difference between days before and days between piling events ($F_{1,411}$=0.1, p=0.81, model 2a Tab. 6). Thus PP10M/day did not significantly differ between days during the baseline and days between piling events at any POD-position. When only using the days between and during piling events there was a significant effect of piling*position on PP10M/day ($F_{5,670}$=11.3, p≤0.001, model 3 Tab. 6). We therefore again split the model into positions 1-3 and 4-6. For positions 1-3 the interaction was no longer significant ($F_{2.288}$=0.3, p=0.73, model 3.1 Tab. 6). After removal of the interaction term, piling remained to have a significant effect ($F_{1,290}$=56.2, p≤0.001, model 3.1a Tab. 6) with PP10M/day decreasing from days between piling to days during piling (Fig.14 a-b, Tab. 7). At positions 4-6 the interaction piling*position remained significant ($F_{2,376}$=5.9, p≤0.01, model 3.2 Tab. 6). We therefore looked at the effect of piling for each of these positions separately. At position 4 there was no significant effect ($F_{1,78}$=0.77, p=0.38, model 3.2a Tab. 6), at position 5 PP10M/day decreased significantly from days between to days during piling ($F_{5,670}$=11.29, p≤0.001, model 3.2b in Tab. 6, Tab. 7, Fig. 14 a-b), while at position 6 the opposite effect was observed ($F_{5,670}$=11.29, p≤0.001, model 3.2c in Tab. 6, Tab. 7, Fig. 14 a-b).

In summary PP10M/day was generally higher at POD-positions 4-6 south of the reef than at positions 1-3 north of the reef. PP10M/day significantly decreased by more than 50 % from the baseline period to the piling period at POD-positions 1-3 but no significant effect was found for position 5 and 6.
When refining the analysis to split the piling period into days during and days between piling events, no significant change in PP10M/day occurred between baseline and days between piling events at any position. From days between to days during piling events PP10M/day significantly declined at positions 1, 2, 3 and 5, while it increased at position 6. No effect was observed at position 4.

Tab. 5: Results from the main GLMM on the effects of piling (as days before, between and during piling events) and POD-position on % of PP10M/day. The P-value of the main effect to be tested is indicated in bold numbers.

	Dependent variable: Log(% of PP10M/day)				
Independent variable		**Type III Sum of squares**	**df**	**F**	**p**
Intercept	Hypothesis	448.0	1	1048.1	<0.001
	Error	5.2	112.1		
Month	Hypothesis	2.0	5	5.4	<0.001
	Error	67.5	901		
POD-ID	Hypothesis	4.9	14	4.7	<0.001
	Error	67.5	901		
Piling (days before, between or during piling)	Hypothesis	5.4	2	36.1	<0.001
	Error	67.5	901		
POD-position	Hypothesis	16.6	6	49.3	<0.001
	Error	67.5	901		
Piling*POD-position	Hypothesis	6.4	9	9.4	**<0.001**
	Error	67.5	901		

Tab. 6: Results from different GLMMs calculated to test for the influence of piling (as days before, between and during piling events) and POD-position on % of PP10M/day. Given is the p-value for all variables entered into the model. P-values of the main effects to be tested are indicated as bold if they were significant and as bold italics if there were not significant. Main results are highlighted in yellow. First order models represents the main models, models of second order test data subsets of the main model due to a significant interaction and models of third order are calculated if an interaction term in second order models was not significant, in which case the interaction term was removed.

Model	POD positions used in the model	Days used in relation to piling	Month	POD-ID	Piling	Po-sition	Piling* position
1	1 - 6	before, between, during	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	**≤ 0.001**
1.1	1 - 3	before, between, during	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	***0.40***
1.1.a	1 - 3	before, between, during	≤ 0.001	≤ 0.001	**≤ 0.001**	≤ 0.001	
1.2	5 - 6	before, between, during	≤ 0.001	≤ 0.001	0.47	≤ 0.001	**≤ 0.001**
2	1 - 6	before, between	≤ 0.001	≤ 0.001	0.91	≤ 0.001	***0.73***
2.a	1 - 6	before, between	≤ 0.001	≤ 0.001	***0.81***	≤ 0.001	
3	1 - 6	between, during	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	**≤ 0.001**
3.1	1 - 3	between, during	≤ 0.001	≤ 0.01	≤ 0.001	≤ 0.05	***0.73***
3.1.a	1 - 3	between, during	≤ 0.001	≤ 0.01	**≤ 0.001**	≤ 0.05	
3.2	4 - 6	between, during	≤ 0.001	≤ 0.05	0.45	0.1	**≤ 0.01**
3.2.a	4	between, during	≤ 0.01	0.5	***0.39***		
3.2.b	5	between, during	≤ 0.001	0.20	**≤ 0.05**		
3.2.c	6	between, during	≤ 0.001	1.0	**≤ 0.01**		

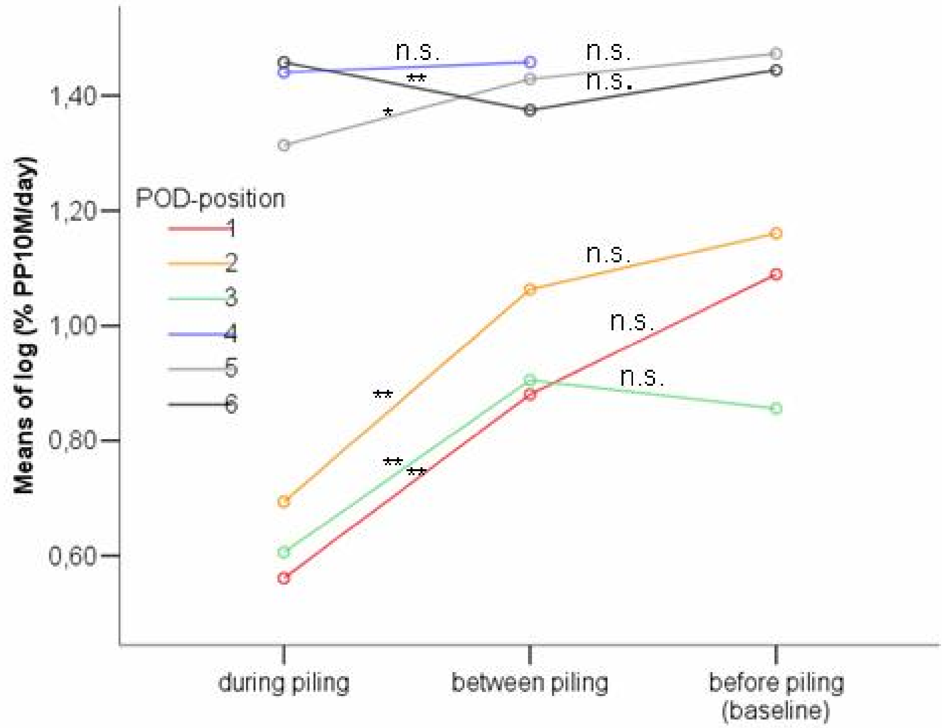

Fig. 14 a: Means of log-transformed % of PP10M/day for all POD-positions on days before, between and during pile driving events as predicted by the model.

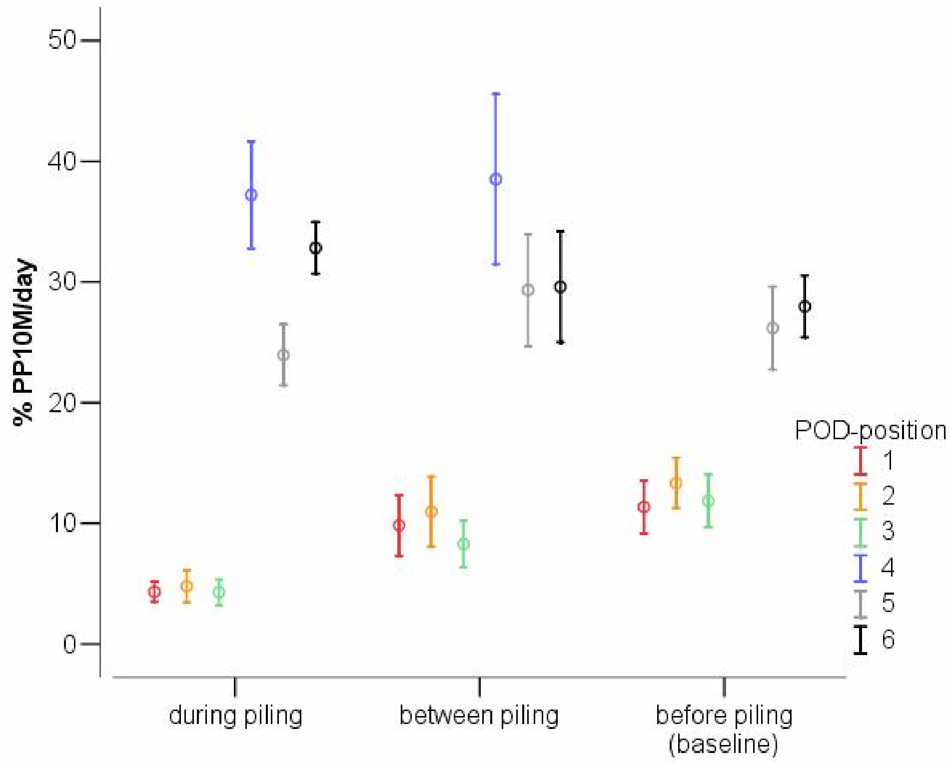

Fig. 14 b: Means and 95 % confidence intervals of % of PP10M/day for all POD-positions on days before, between and during pile driving events.

Tab. 7: Means, standard deviation and sample size for % of PP10M/day on days before (baseline), between and during piling events.

Position	Piling	Mean	SD	Min	Max	N
1	before	11.4	5.8	0	23	29
	between	9.8	9.0	0	37	52
	during	4.3	4.7	0	22	127
2	before	13.3	6.7	0	33	41
	between	11.0	5.9	3	23	18
	during	4.8	4.4	0	19	43
3	before	11.9	8.5	0	42	59
	between	8.3	4.1	1	15	19
	during	4.3	3.7	0	15	47
4	before					
	between	38.5	16.7	6	69	24
	during	37.2	17.2	4	85	60
5	before	26.2	10.9	4	49	41
	between	29.3	12.7	12	62	31
	during	24.0	11.5	0	52	81
6	before	28.0	10.6	0	51	68
	between	29.6	17.0	6	87	55
	during	32.8	12.9	6	69	142

4.2. Porpoise positive minutes per hour (PPM/H)

There was a significant influence of the interaction of hours after piling with POD-position on PPM/H (Tab. 8). This means that PPM/H changed in a linear pattern after the piling event but differently at the 6 POD-positions (Fig. 15 a-b). Therefore we calculated a new GLMM for each POD-position separately. At positions 1, 2 and 3 PPM/H increased significantly with hours after piling, at position 4 and 5 no effect was found and at position 6 PPM/H significantly decreased with hours after piling (Tab. 9, Fig. 15 a-b).

To test more specifically how long after the piling event the increase / decrease in PPM/H existed at the different positions, we further compared each value for a 10 hour period with all values after that time (e.g. PPM/H for 0-10 hours after piling were compared to PPM/H from 11 to the last hour after piling). This also reveals possible non-linear effects. By entering hours after piling as a covariate into the GLMM we are assuming a linear effect of this factor on PP10M. However, as PPM/H might only increase for a short time after the piling event this might not necessarily be the case. As it turned out PPM/H was significantly lower up until 40 hours after piling than during later hours at position 1 (Tab. 10). At position 2 and 3 this effect lasted until about 20 hours after piling and at position 4 and 5 until about 10 hours after piling. At position 6 there was a decreasing effect of PPM/H after the piling event. PPM/H was significantly higher than during later time periods up until 30 hours after piling (Tab. 10, Fig. 15 a-b). It has to be bared in mind that the resolution of these estimates is only 10 hours so real effects can be slightly longer or shorter than found with this method.

Tab. 8: Results from the GLMM on the effects of time elapsed after the piling event and POD-position on PPM/hour. The p-value of the main effect to be tested is indicated as bold numbers.

Dependent variable: PPM/hour					
Independent variable		**Type III Sum of squares**	**df**	**F**	**p**
Intercept	Hypothesis	3737	1	19.5	≤0.001
	Error	2191.7	11.5		
Month	Hypothesis	5603	4	44.6	≤0.001
	Error	495033.5	15770		
POD-ID	Hypothesis	9924	13	24.3	≤0.001
	Error	495034	15770		
Hour	Hypothesis	2737	23	3.8	≤0.001
	Error	495034	15770		
POD-position	Hypothesis	10394	5	66.2	≤0.001
	Error	495034	15770		
Hours after piling	Hypothesis	257	1	8.2	≤0.01
	Error	495034	15770		
Hours after piling *POD-position	Hypothesis	1688	5	10.8	**≤0.001**
	Error	495034	15770		

Tab. 9: Results from different GLMMs calculated to test for the influence of time elapsed after the piling event and POD-position on PPM/H. Given is the p-value for all variables entered into the model. P-values of the main effects to be tested are indicated as bold if they were significant and as bold italics if there were not significant. Main results are highlighted in yellow. The model of first order represents the main model and models of second order test data subsets of the main model due to a significant interaction.

Model	**POD positions used in the model**	**Month**	**POD-ID**	**Hour**	**Hour after piling**	**POD-position**	**Hour after piling*POD-position**
1	1 - 6	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.01	≤ 0.001	**≤ 0.001**
1.1	1	≤ 0.001	≤ 0.01	0.6	**≤ 0.001**		
1.2	2	≤ 0.05	≤ 0.05	0.44	**≤ 0.001**		
1.3	3	0.07	0.70	0.96	**≤ 0.001**		
1.4	4	≤ 0.001	≤ 0.001	0.45	***0.63***		
1.5	5	≤ 0.001	≤ 0.001	≤ 0.001	**0.25**		
1.6	6	≤ 0.001	≤ 0.001	≤ 0.001	**≤ 0.01**		

Tab. 10: Means, standard deviation and sample size for PPM/H at different time intervals after the piling event and results from non parametric statistics to compare each time period to the later ones. This shows when the increasing or decreasing effect appears or disappears. Significant p-values are indicated as bold numbers.

Position	Hours after Piling	Mean	SD	N	Z	p	p after Bonferroni	Direction of effect
1	0-10	0.21	0.96	1175	-13.1	≤ 0.001	**≤ 0.001**	-
(0.5-6km)	11-20	0.38	1.27	732	-8.1	≤ 0.001	**≤ 0.001**	-
	21-30	0.49	1.22	470	-5.1	≤ 0.001	**≤ 0.001**	-
	31-40	0.85	2.06	376	-3.2	≤ 0.01	**≤ 0.01**	-
	41-50	1.17	2.59	325	-0.1	0.95		
	≥ 50	1.27	3.10	1013				
2	0-10	0.20	0.65	388	-8.5	≤ 0.001	**≤ 0.001**	-
(0.5-6km)	11-20	0.57	1.25	258	-3.6	≤ 0.001	**≤ 0.001**	-
	21-30	0.72	1.35	171	-1.4	0.16		
	31-40	0.89	1.70	122	-1.4	0.15		
	41-50	0.96	1.75	90	-0.1	0.90		
	≥ 50	0.94	1.56	326				
3	0-10	0.24	0.89	409	-6.8	≤ 0.001	**≤ 0.001**	-
(3-9km)	11-20	0.31	0.75	258	-4.2	≤ 0.001	**≤ 0.001**	-
	21-30	0.76	1.59	171	-0.5	0.65		
	31-40	0.81	1.62	129	-0.0	0.99		
	41-50	0.98	1.48	100	-2.3	≤ 0.05		
	≥ 50	0.72	1.72	371				
4	0-10	5.89	9.23	546	-2.7	≤ 0.01	**≤ 0.05**	-
(7-14.5km)	11-20	7.96	10.81	308	-2.0	≤ 0.05		
	21-30	6.12	8.53	185	-0.9	0.37		
	31-40	5.79	7.23	166	-0.1	0.96		
	41-50	6.82	10.42	145	-0.4	0.69		
	≥ 50	5.51	7.45	536				
5	0-10	3.41	6.04	754	-5.4	≤ 0.001	**≤ 0.001**	-
(14.5-22km)	11-20	5.02	8.18	453	-0.4	0.72		
	21-30	4.46	6.45	295	-0.6	0.57		
	31-40	4.37	6.45	239	-0.2	0.84		
	41-50	4.74	6.85	205	-1.3	0.21		
	≥ 50	4.33	6.80	633				
6	0-10	5.30	7.23	1293	-3.3	≤ 0.001	**≤ 0.01**	+
(18-25km)	11-20	5.32	6.62	802	-4.6	≤ 0.001	**≤ 0.001**	+
	21-30	5.28	7.00	533	-3.5	≤ 0.001	**≤ 0.01**	+
	31-40	4.69	6.37	429	-1.8	0.07		
	41-50	3.99	5.62	360	-0.6	0.52		
	≥ 50	4.67	7.64	1070				

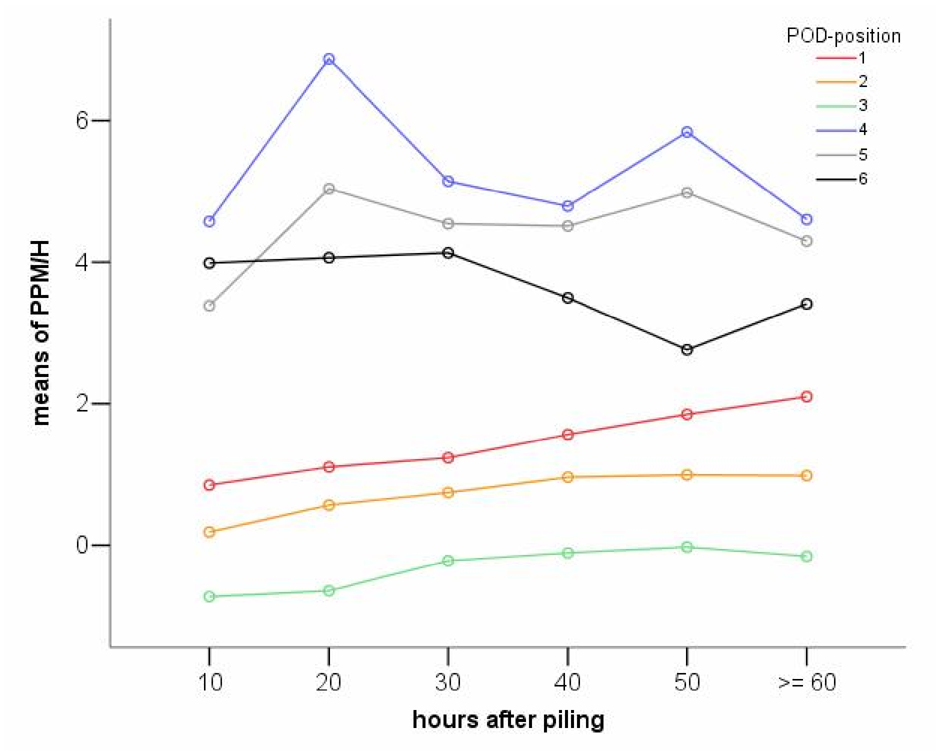

Fig. 15 a: Estimated marginal mean of PPM/Hour for the different POD-positions with time after the piling event in 10 hour steps as predicted by the model.

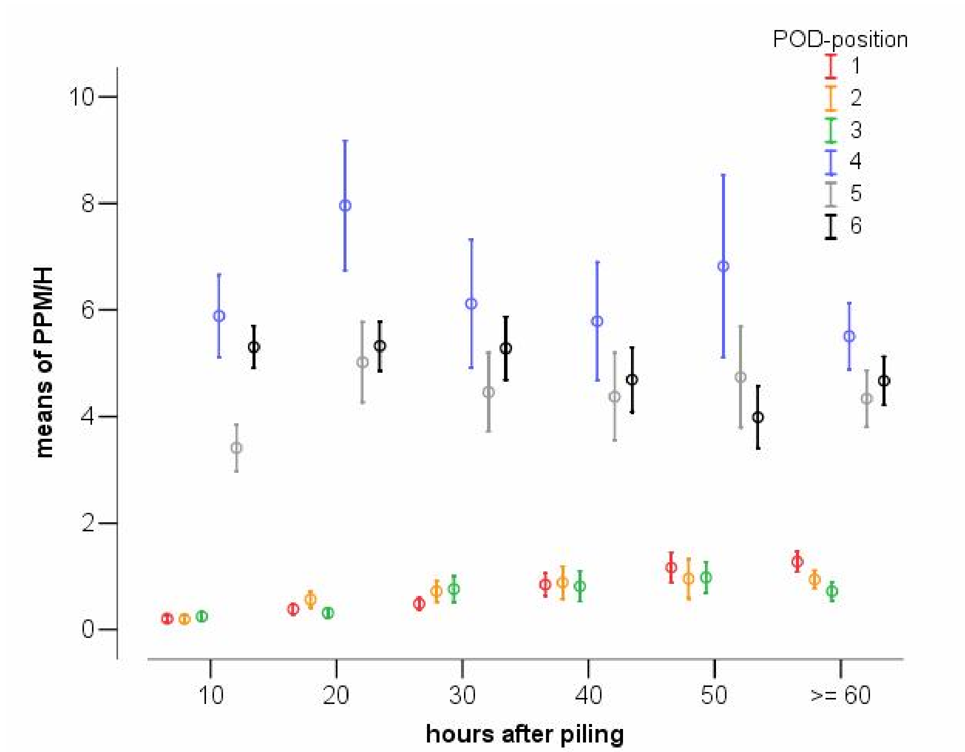

Fig. 15 b: Raw means and 95 % confidence intervals of PPM/Hour for the different POD-positions with time after the piling event in 10 hour steps.

In summary PPM/H was negatively affected by piling at POD-positions 1-5 where the time length with which the effect is observable decreased with distance from the piling location. About 40 hours of significantly lower values were observed at the POD-location with the closest proximity to most piling locations (POD-position 1) and this decreased to about ten hours at position 4, which was between 14.5 and 22 km from the piling locations. At POD-position 6 furthest from the piling location (about 18-25 km) we found a positive effect of piling on PPM/H that lasted for about 30 hours after the piling event (Tab. 11).

Tab. 11: Summary of the effect of piling on PPM/H at the different POD-positions.

POD position	Distance to piling location in km	Direction of effect from piling on PPM/H	Estimated length of effect of piling on PPM/H in 10 hour steps
1	0.5 - 6	-	40
2	0.5 - 6	-	20
3	3 - 9	-	20
4	7 - 14.5	-	10
5	14.5 - 22	-	10
6	18 - 25	+	30

4.3. Waiting time between porpoise encounters

The duration of waiting time was significantly influenced by the interaction of its order after the last piling event and POD-position (Tab. 12. 13). The duration of waiting time decreased after piling but in different ways at the six positions (Fig. 16). When calculating a GLMM for each position separately it turned out that there was a significant decrease in waiting time at all positions (Tab. 13).

When comparing a median waiting time to all other later waiting times, the first four waiting times after a piling event were significantly different at position 1 (Tab. 14). At position 2 it was only the first, at position 3 the first and fourth and at position 4-6 it was the first two waiting times that significantly differed from the following waiting times (Tab. 14). Durations for the first and second waiting time in relation to the other waiting times at the different POD-positions can be seen in Tab. 15a,b and Fig. 17 a-f. However, the effect on the first waiting time was much more pronounced than on the second waiting time or those following it (Tab. 14, Fig. 16, 17 a-f).

If we sum the duration of the significant median waiting times up, we gain an estimate on how long it took until the time between porpoise encounters returned to “normal” values (those that we found furthest away in time from the piling events). At position 1 it took a median time of 23.5 hours (mean: 33.4) until waiting times were back to normal, at position 2 and 3 it took 13.9 (mean: 17.3) and 16.4 hours (mean: 15.9), while at position 4-6 this value drastically declined to between only 0.8-2.6 hours (mean: 2.7-4.7) (Tab. 15 a-b, Fig. 17 b). Therefore, there seemed to be a long lasting effect of over 13 and up to 24 hours at position

1-3 north of the reef, while south of the reef at positions 4-6 at distances of 7-25 km from the piling location this effect was rather small and did not clearly decline with positions at further distances (Tab. 15 a-b, Fig. 15, Fig. 17 b).

The median time elapsing after a piling event until the first porpoise was again encountered ranged between 14 and 17 hours north of the reef and between 1.0 and 2.4 hours south of the reef (Tab. 15a, Fig. 18 a). The maximum waiting time occurred at position 1 directly after piling and was 74.2 hours long. By contrast the longest waiting time south of the reef was only about 15.2 hours and was recorded at position 5 directly after piling. The median waiting time at least 10 waiting times after piling lay between 1.1-1.2 hours at positions 1-3 and between 0.4-0.6 hours at positions 4-6. This is close to the waiting times recorded during the baseline which lay around 1 hour at positions 1-3 and between 0.5-1 hour at positions 4-6 (Tab. 15 a).

We compared waiting times after piling to those later after piling because there was no marked difference between baseline data and waiting times long after piling. Baseline data were not available for position 4 and we also considered it to be more reasonable to compare data directly after piling to those late after piling rather than to baseline data in order to keep seasonal influences as small as possible. This method was also preferable over using the last waiting time before piling started, which is what Carstensen et al. (2006) used, because in our case the last piling event was often less than 24 hours ago, so that this waiting time was possibly still influenced by the last piling event.
The first median waiting time after piling increased 16 fold at position 1, 14 fold at position 2 and 13 fold at position 3. At position 4 to 6 it increased 2-4 fold compared to normal (those later than the tenth waiting time after piling) waiting times (Tab. 15 a).
Thus almost no decrease in the duration of the first waiting times was found at positions with increasing distances to the piling location north of the reef, but waiting times steeply declined to the positions south of the reef, where again there was no declining affect with increasing distance (Fig. 18 a).

Tab. 12: Results from the GLM (fitted to a Poisson distribution and allowing for overdispersion) on the effect of piling on the duration of waiting time. The p-value of the main effect to be tested is indicated as bold numbers.

	Dependent variable: PPM/hour		
Independent variable	**df**	**Chi²**	**p**
Month	4	89.8	≤0.001
POD-ID	12	113.1	≤0.001
POD-position	5	719.4	≤0.001
Order after piling	1	1841.0	≤0.001
Order after piling*POD-position	5	607.2	**≤0.001**

Tab. 12: Results from different GLMs (fitted to a Poisson distribution and allowing for overdispersion) calculated to test for the influence of the order of a waiting time after the piling event and POD-position on the duration of waiting time between porpoise encounters. Given is the p-value for all variables entered into the model. P-values of the main effects to be tested are indicated as bold if they were. Main results are highlighted in yellow. The model of first order represents the main model and models of second order test data subsets of the main model due to a significant interaction.

Model	POD positions used in the model	Month	POD-ID	Order after piling	POD-position	Order after piling*POD-position
1	1 - 6	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	**≤ 0.001**
1.1	1	≤ 0.001	0.06	**≤ 0.001**		
1.2	2	≤ 0.05		**≤ 0.001**		
1.3	3	≤ 0.05		**≤ 0.001**		
1.4	4	≤ 0.001		**≤ 0.001**		
1.5	5	≤ 0.001	0.45	**≤ 0.001**		
1.6	6	≤ 0.001	≤ 0.01	**≤ 0.001**		

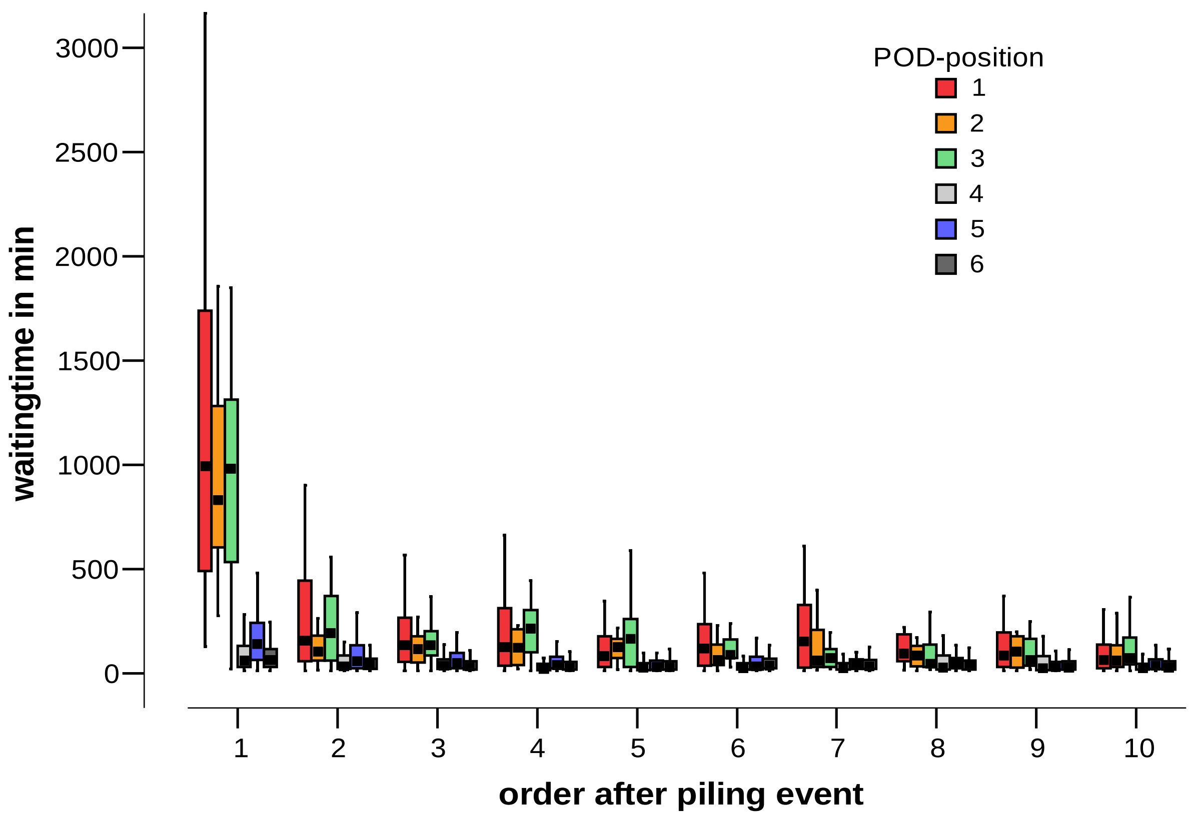

Fig.16. Boxplots showing medians and 95 % confidence intervals for duration waiting time in min between porpoise encounters by their order after the last piling event and the different POD-positions.

Fig. 16 a: Duration of waiting time between porpoise encounters in min by date of occurrence for POD-position 1.

Fig. 17 b: Duration of waiting time between porpoise encounters in min by date of occurrence for POD-position 2.

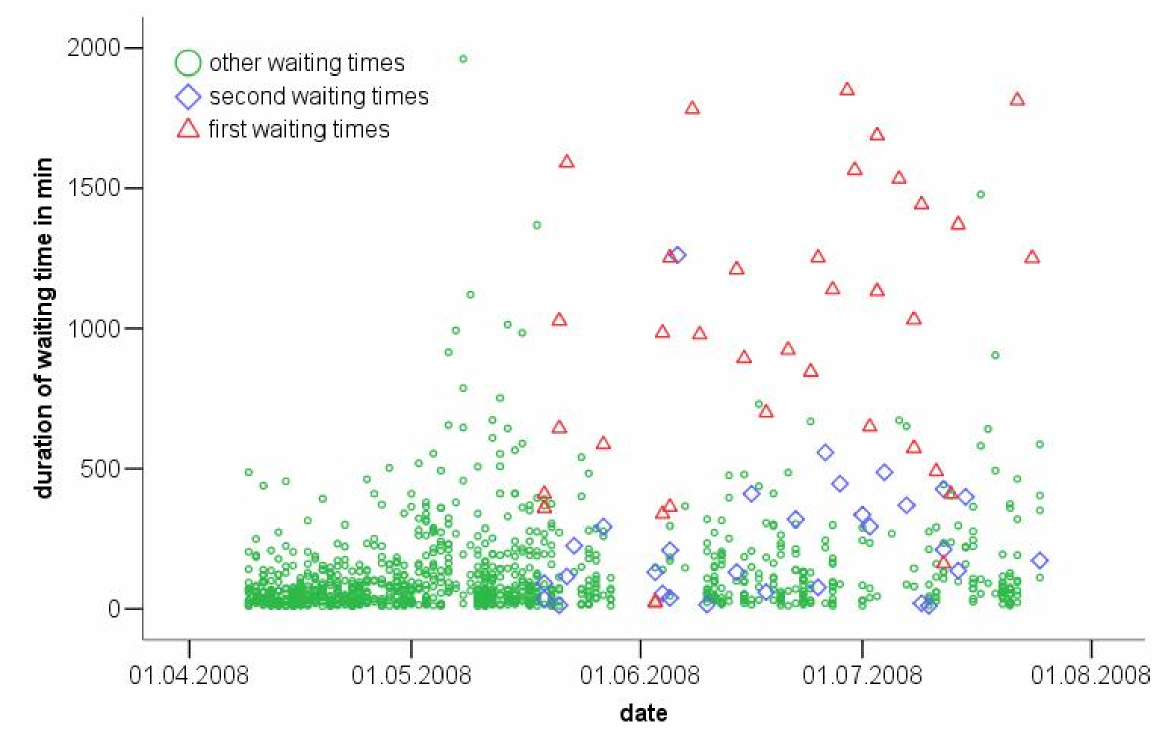

Fig. 17 c: Duration of waiting time between porpoise encounters in min by date of occurrence for POD-position 3.

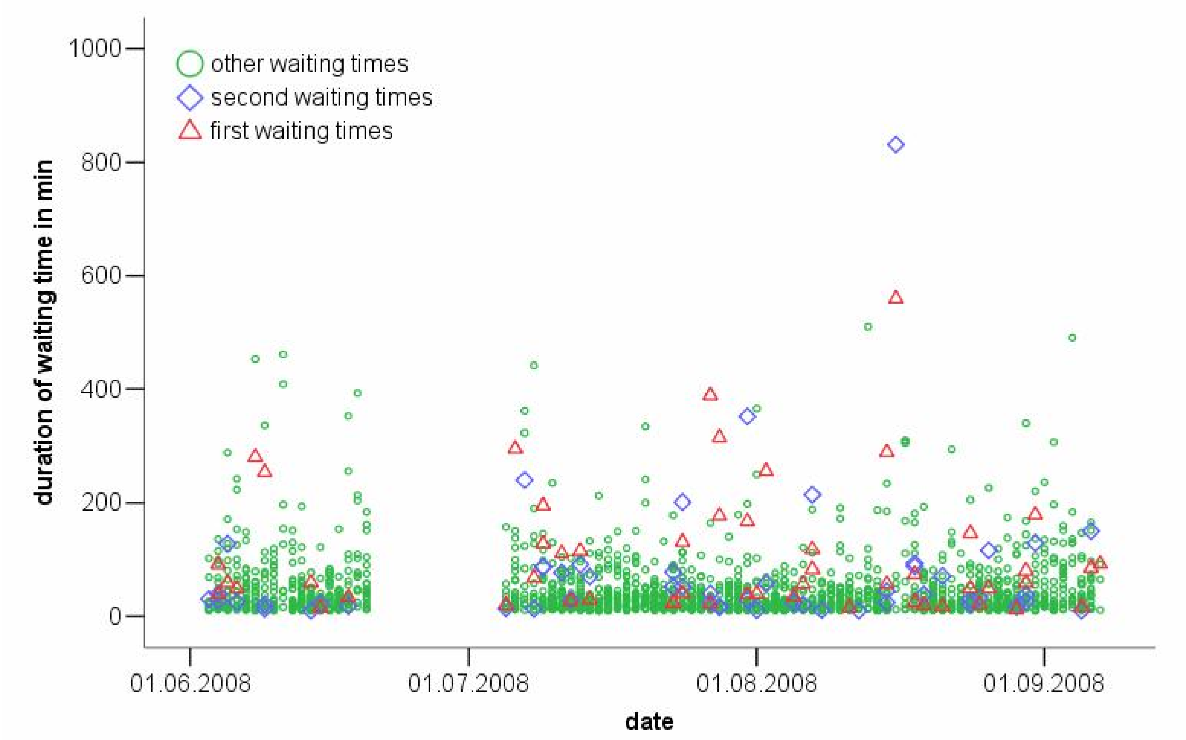

Fig. 17 d: Duration of waiting time between porpoise encounters in min by date of occurrence for POD-position 4.

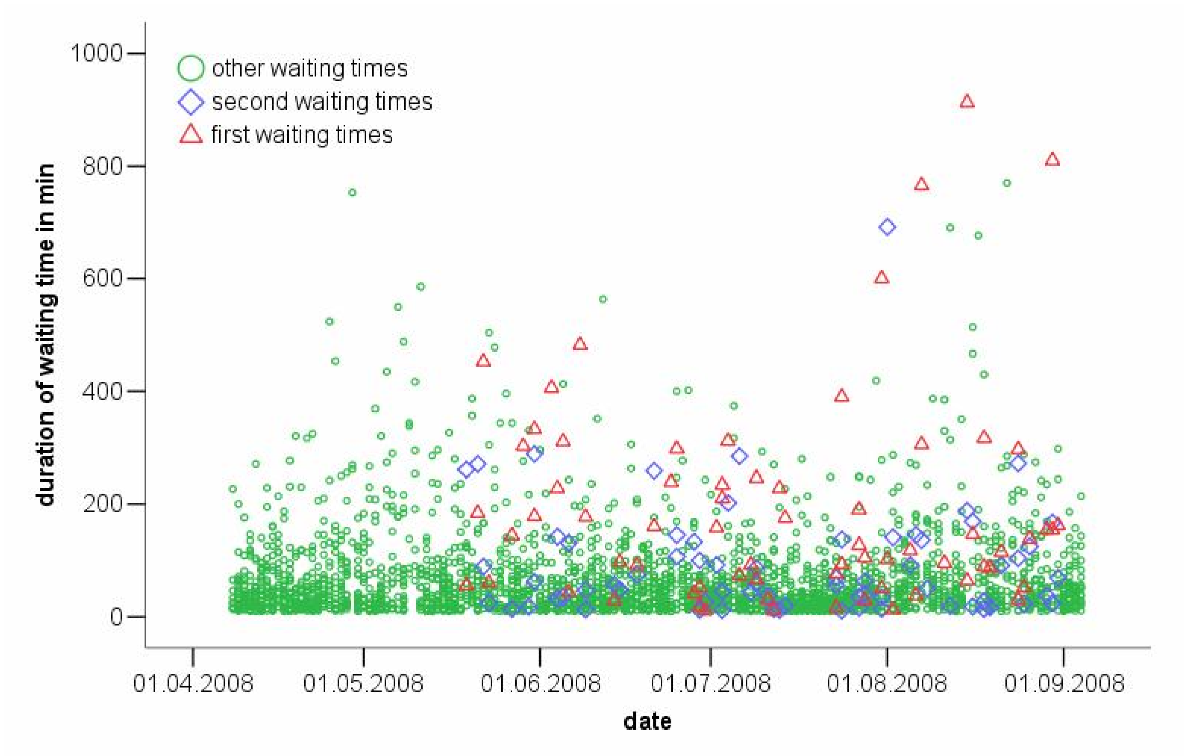

Fig. 17 e: Duration of waiting time between porpoise encounters in min by date of occurrence for POD-position 5.

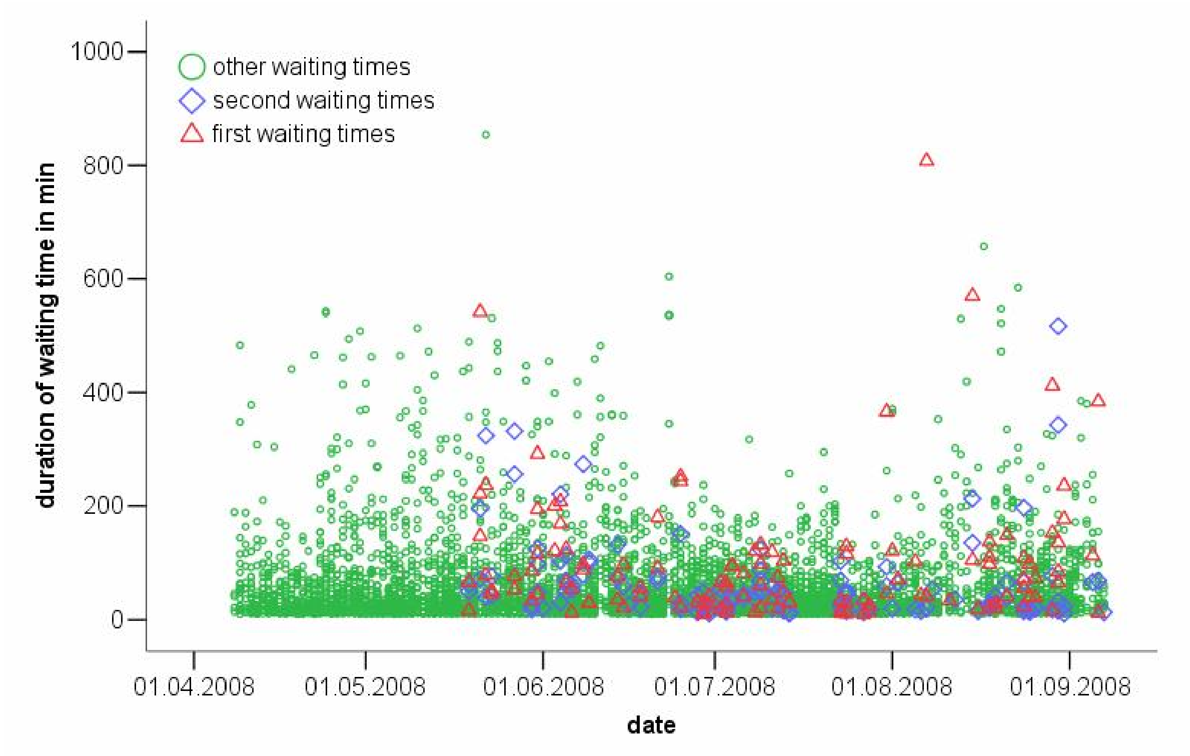

Fig. 17 f: Duration of waiting time between porpoise encounters in min by date of occurrence for POD-position 6.

Tab. 13: Medians, means and sample size for waiting time in min between porpoise encounters by their order after the last piling event for each POD-position. Shown are statistical results for testing whether a waiting time was significantly different from all following waiting times. Also shown is the sum of all the first median waiting times that were found to significantly differ for that position.

Posi-tion	Order after Piling	Median waiting time in min	Mean waiting time in min	SD	Min	Max	N	Z	p	p after Bonfe-rroni	Direc-tion of effect	Sum of sig. waiting time in min
1	baseline	67	119	153	10	1325	318					
	1	994	1305	1051	128	4451	74	-13.2	≤ 0.001	**≤ 0.01**	+	
	2	155	294	308	11	1364	56	-4.3	≤ 0.001	**≤ 0.01**	+	
	3	134	212	225	11	1073	52	-3.3	≤ 0.001	**≤ 0.01**	+	
	4	125	195	197	11	740	48	-2.6	≤ 0.01	**≤ 0.05**	+	2006
	5	81	155	204	10	923	45	-0.7	0.48			
	6	118	179	188	11	668	44	-1.9	0.06			
	≥10	64	109	138	10	1719	667					
2	baseline	57	95	113	10	1185	590					
	1	831	1035	605	275	2859	31	-9.1	≤ 0.001	**≤ 0.01**	+	1035
	2	104	152	151	15	553	26	-1.7	0.08			
	3	115	138	119	11	443	20	-1.4	0.15			
	4	122	212	314	21	1282	18	-1.8	0.08			
	5	125	177	177	16	688	18	-2.5	≤ 0.05			
	6	64	133	148	11	530	17	-0.6	0.58			
	≥10	60	98	103	10	680	286					
3	baseline	58	109	162	10	1961	732					
	1	981	952	521	21	1850	36	-8.4	≤ 0.001	**≤ 0.01**	+	952
	2	192	245	251	11	1263	30	-2.5	≤ 0.05			
	3	133	148	100	12	404	27	-1.6	0.12			
	4	213	231	184	11	673	22	-2.8	≤ 0.01	**≤ 0.05**	+	
	5	163	180	160	11	587	19	-1.1	0.27			
	6	88	131	93	31	351	17	-1.3	0.20			
	≥10	74	138	174	11	1478	201					

Tab.14 continued

Position	Order after Piling	Median waiting time in min	Mean waiting time in min	SD	Min	Max	N	Z	p	p after Bonferroni	Direction of effect	Sum of sig. waiting time in min
4	1	59	106	112	12	560	53	-6.0	≤ 0.001	**≤ 0.01**	+	
	2	33	76	125	10	831	53	-2.6	≤ 0.01	**≤ 0.05**	+	182
	3	34	63	85	11	442	53	-2.4	≤ 0.05			
	4	21	40	52	11	336	53	-1.2	0.23			
	5	26	43	54	10	323	53	-0.3	0.73			
	6	23	42	54	10	340	53	-0.1	0.96			
	≥10	25	40	46	10	510	1667					
5	baseline	38	67	80	10	753	765					
	1	141	189	201	11	913	66	-8.4	≤ 0.001	**≤ 0.01**	+	
	2	58	94	88	11	692	68	-3.4	≤ 0.001	**≤ 0.01**	+	283
	3	47	78	80	10	467	66	-2.3	≤ 0.05			
	4	40	75	101	10	514	64	-1.8	0.07			
	5	29	60	44	10	691	63	-0.3	0.80			
	6	32	60	80	11	400	62	-0.2	0.90			
	≥10	36	62	64	10	770	1625					
6	baseline	33	62	79	10	543	1335					
	1	63	97	105	10	808	124	-6.7	≤ 0.001	**≤ 0.01**	+	
	2	42	65	81	11	517	123	-3.4	≤ 0.001	**≤ 0.05**	+	162
	3	32	46	46	10	264	123	-0.45	0.60			
	4	28	46	60	11	268	121	-2.3	0.82			
	5	31	46	72	10	213	121	-0.7	0.52			
	6	37	65	58	10	489	121	-3.2	≤ 0.001	**≤ 0.01**		
	≥10	28	50	64	10	854	3494					

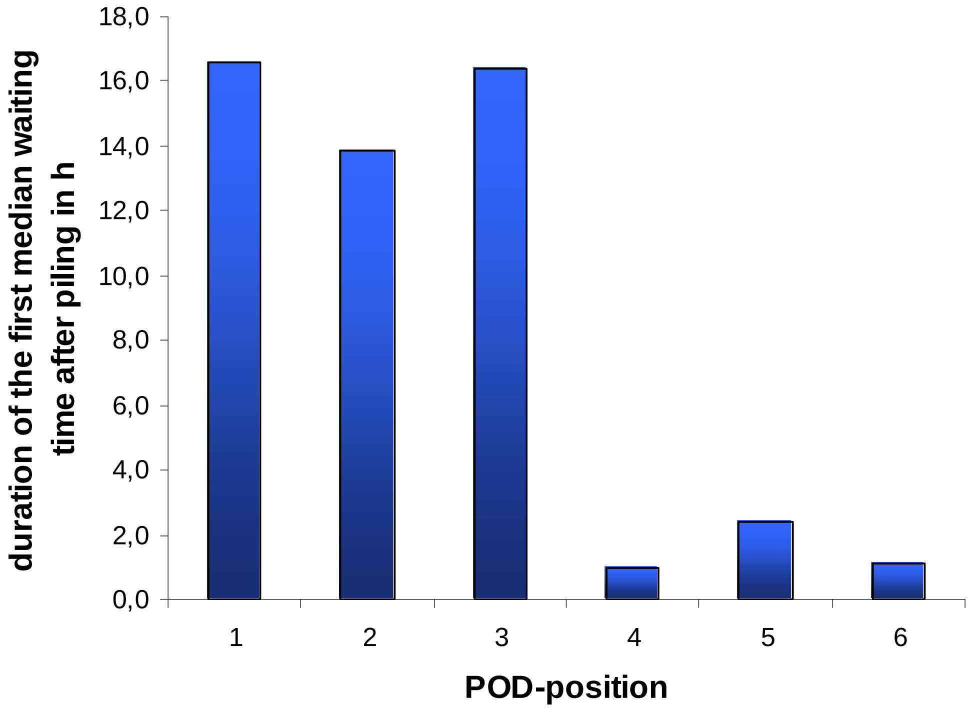

Fig. 17 a: Duration of the first median waiting time after piling for the different POD-positions.

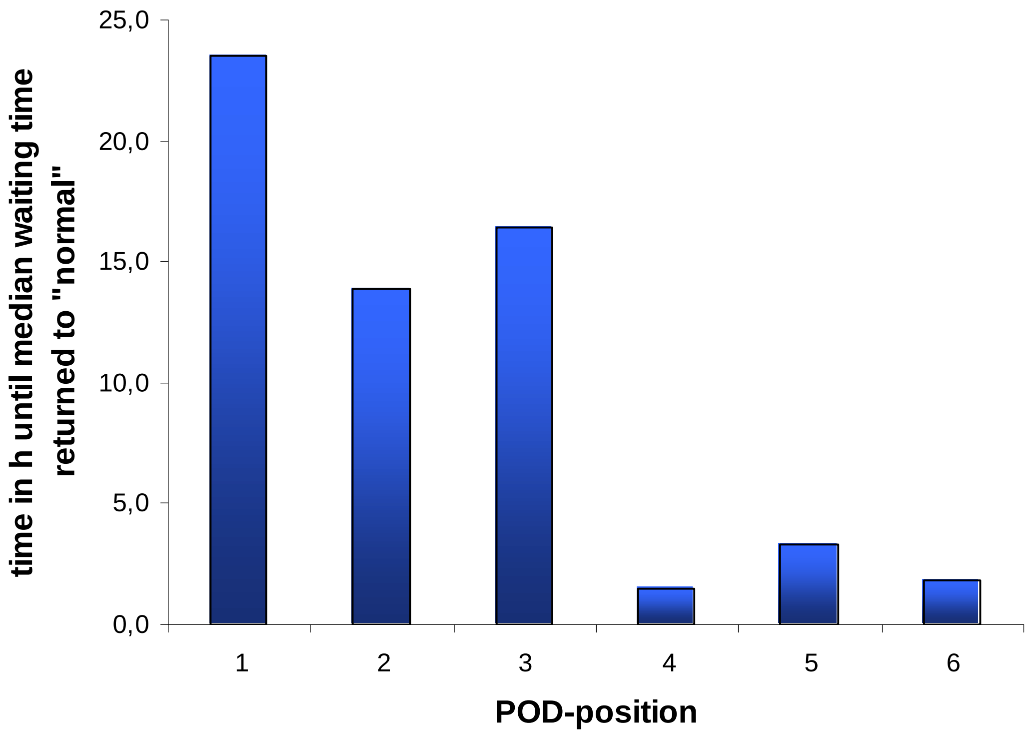

Fig. 18 b: Time in hours that it takes for median waiting times to return to “normally expected” values at the different POD-positions.

Tab. 15 a: Summary of results on the influence of piling on median waiting time between porpoise encounters. For each POD-position is shown: the time until the first porpoise encounter after piling (first waiting time after piling), the "normal waiting time" (Sum of all waiting times after the 9th waiting time after piling), the sum of the first waiting times that significantly differed from later ones, this sum minus the mean piling duration (which essentially is the time it takes for the waiting times to return to "normal") and the time that the latter is longer than would usually be expected from "normal waiting times".

POD position	Distance to piling location in km	First waiting time after piling in min (h)	"normal waiting time" in min (h)	Sum of significant waiting times in min (h) = time until waiting times are back to "normal"	Time until waiting times are back to "normal" minus mean piling time in min (h)
1	0.5 - 6	994 (16.6)	64 (1.1)	1408 (23.5)	1362 (22.7)
2	0.5 - 6	831 (13.3)	60 (1.0)	831 (13.9)	785 (13.1)
3	3 - 9	981 (16.4)	74 (1.2)	981 (16.4)	935 (15.6)
4	7 - 14.5	59 (1.0)	25 (0.4)	92 (1.5)	46 (0.8)
5	14.5 - 22	141 (2.4)	36 (0.6)	199 (3.3)	153 (2.6)
6	18 - 25	36 (1.1)	28 (0.5)	105 (1.8)	59 (1.0)

Tab. 15 b: Summary of results on the influence of piling on mean waiting time between porpoise encounters. For each POD-position is shown: first waiting time after piling, the "normal waiting time", the sum of the first waiting times that significantly differed from later ones, this sum minus the mean piling duration and the time that the latter is longer than would usually be expected from "normal waiting times".

POD position	Distance to piling location in km	First waiting time after piling in min (h)	"normal waiting time" in min (h)	Sum of significant waiting times in min (h) = time until waiting times are back to "normal"	Time until waiting times are back to "normal" minus mean piling time in min (h)
1	0.5 - 6	1305 (21.8)	109 (1.8)	2006 (33.4)	1960 (32.7)
2	0.5 - 6	1035 (17.3)	98 (1.6)	1035 (17.3)	989 (16.5)
3	3 - 9	952 (15.9)	138 (2.3)	952 (15.9)	906 (15.1)
4	7 - 14.5	106 (1.8)	40 (0.7)	182 (3.0)	136 (2.3)
5	14.5 - 22	189 (3.2)	62 (1.0)	283 (4.7)	237 (4.0)
6	18 - 25	97 (1.6)	50 (0.8)	162 (2.7)	116 (1.9)

As the distance between POD-positions and piling locations and also the distance gradient between positions differed with piling event due to the different positions of mono-piles, we assigned the distance of each POD to the piling location for every piling event. We then categorised them into distance categories and calculated the same statistics as above only with distance instead of POD-position included in the model.

When repeating the above analysis with distance categories instead of POD-positions, duration of waiting time was also significantly influenced by the interaction of its order after the last piling event and the distance from the piling location (Tab. 16). Waiting time decreased after piling but in different ways at the seven distance categories (Fig. 19). When calculating a GLMM for each distance category separately it turned out that there was a significant decrease in waiting time at all distance categories (Tab. 16) but that the decrease was more pronounced at the first three categories (0-9 km distance) than at the other ones (Fig. 19).

When comparing a median waiting time to all other waiting times following it, the first three waiting times after a piling event were significantly longer at 0-3 km distance, the first four at 3-6 km distance, only the first at 6-9 km distance and the first two at 9-12 km distance. At 12-15 km and at 15-18 km distance it was again only the first and at 18-25 km the first two and also the sixth waiting time that were significantly longer than the later ones (Tab. 17). Again, the effect on the first waiting time was very pronounced whereas only a slight effect was observed on the second and later occurring waiting times (Fig. 18).

After summing the first significantly different median waiting times up we found that it lasted about 20.6 hours at 0-3 km distance until waiting times were back to normal, 21.7 hours at 3-6 km distance, and this declined to 3.5 hours at 6-12 km distance (Tab. 18 a, Fig. 19, Fig. 20 a). After this the effect somewhat stagnated with no further decrease up to the distance category 18-25 km (Fig. 20 b).

Duration of the first median waiting times lasted about 16.6 hours at 0-3 km distance, which gradually declined to 0.9 hours at 9-12 km distance (Tab. 18, Fig. 20 a). After this duration of first waiting times stagnated with no further decrease up to the distance category 18-25 km. There was thus a somewhat discontinuous effect at greater distances, with a slight effect still observable at the greatest distance (Fig. 20 a).

Tab. 16: Results from different GLMs (fitted to a Poisson distribution and allowing for overdispersion) calculated to test for the influence of the order of a waiting time after the piling event and distance from the piling location on the length of waiting time between porpoise encounters. Given is the p-value for all variables entered into the model. P-values of the main effects to be tested are indicated as bold if they were significant. Main results are highlighted in yellow. The model of first order represents the main model and models of second order test data subsets of the main model due to a significant interaction.

Model	Distance category	Month	POD-ID	Order after piling	POD-position	Order after piling*POD-position
1	0 – 25 km	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001	**≤ 0.001**
1.1	0 – 3 km	≤ 0.001	0.06	**≤ 0.001**		
1.2	3.1 – 6 km	0.20		**≤ 0.001**		
1.3	6.1 – 9 km	0.30		**≤ 0.001**		
1.4	9.1 – 12 km	0.87		**≤ 0.001**		
1.5	12.1 – 15 km	≤ 0.001		**≤ 0.01**		
1.6	15.1 – 18 km	≤ 0.01	0.59	**≤ 0.001**		
1.7	18.1 – 25 km	≤ 0.001	≤ 0.001	**≤ 0.001**		

Tab. 14: Medians, means and sample size for waiting time in min between porpoise encounters by their order after the last piling event for each POD-position. Shown are statistical results for testing whether a waiting time was significantly different from all following waiting times. Also shown is the sum of all the first median waiting times that were found to significantly differ for that position.

Distance category in km	Order after piling	Median waiting time in min	Mean waiting time in min	Min	Max	N	Z	p	p after Bonfe-rroni	Direc-tion of effect	Sum of sig. waiting time in min
0-3	1	995	1354	128	4451	67	-12.7	≤0.001	**≤0.01**	+	
	2	159	257	12	1364	52	-3.9	≤0.001	**≤0.01**	+	
	2	129	199	11	1073	47	-2.7	≤0.01	**≤0.05**		1283
	4	124	186	11	740	43	-2.3	≤0.05			
	5	84	154	10	923	42	-0.8	0.41			
	6	107	159	11	668	42	-1.4	0.15			
	≥10	62	107	10	1719	562					
3.1-6	1	905	970	21	3017	68	-12.4	≤0.001	**≤0.01**	+	
	2	140	224	11	1033	54	-3.1	≤0.01	**≤0.05**	+	
	2	130	157	12	642	46	-2.8	≤0.01	**≤0.05**	+	
	4	175	231	11	1282	39	-3.3	≤0.001	**≤0.01**	+	1350
	5	119	171	12	688	35	-2.1	≤0.05			
	6	107	160	11	568	31	-2.0	≤0.05			
	≥10	64	109	10	3017	528					
6.1-9	1	254	436	22	1564	21	-5.3	≤0.001	**≤0.01**	+	254
	2	40	150	11	263	22	-1.6	0.12			
	2	51	101	11	442	22	-1.9	≤0.05			
	4	45	96	11	366	22	-0.4	0.69			
	5	27	104	11	587	21	-0.33	0.75			
	6	22	54	10	351	21	-1.0	0.33			
	≥10	32	67	10	1478	385					
9.1-12	1	53	85	12	560	32	-4.0	≤0.001	**≤0.01**	+	
	2	39	82	10	831	32	-3.0	≤0.01	**≤0.05**	+	92
	2	29	49	11	305	32	-1.1	0.28			
	4	18	30	11	122	32	-1.6	0.10			
	5	27	38	10	185	32	-0.0	0.98			
	6	27	44	12	168	32	-1.3	0.18			
	≥10	23	36	10	831	998					

Tab. 17 continued

Distance category in km	Order after Piling	Median waiting time in min	Mean waiting time in min	Min	Max	N	Z	p	p after Bonfe-rroni	Direc-tion of effect	Sum of sig. waiting time in min
12.1-15	1	80	94	21	190	7	-2.7	≤0.01	**≤0.05**	+	80
	2	35	55	11	129	7	-0.9	0.35			
	2	38	42	18	82	7	-1.0	0.31			
	4	46	84	14	248	7	-1.3	0.18			
	5	29	33	14	67	7	-0.1	0.94			
	6	29	102	11	340	7	-0.8	0.44			
	≥10	25	43	10	491	343					
15.1-18	1	112	162	11	600	38	-6.3	≤0.001	**≤0.01**	+	112
	2	52	91	11	692	38	-1.7	0.09			
	2	43	69	10	430	38	-1.8	0.07			
	4	41	62	11	287	38	-1.0	0.33			
	5	31	68	10	691	37	-0.0	0.97			
	6	28	62	11	400	37	-0.1	0.92			
	≥10	36	53	10	564	812					
18.1-25	1	66	121	10	913	153	-8.3	≤0.001	**≤0.01**	+	
	2	46	72	11	517	152	-4.4	≤0.001	**≤0.01**	+	112
	3	33	54	10	467	150	-1.0	0.33			
	4	30	53	10	514	146	-0.8	0.44			
	5	31	47	10	243	146	-0.4	0.69			
	6	37	62	11	400	145	-2.7	≤0.001	**≤0.01**	+	
	≥10	29	51	10	854	4298					

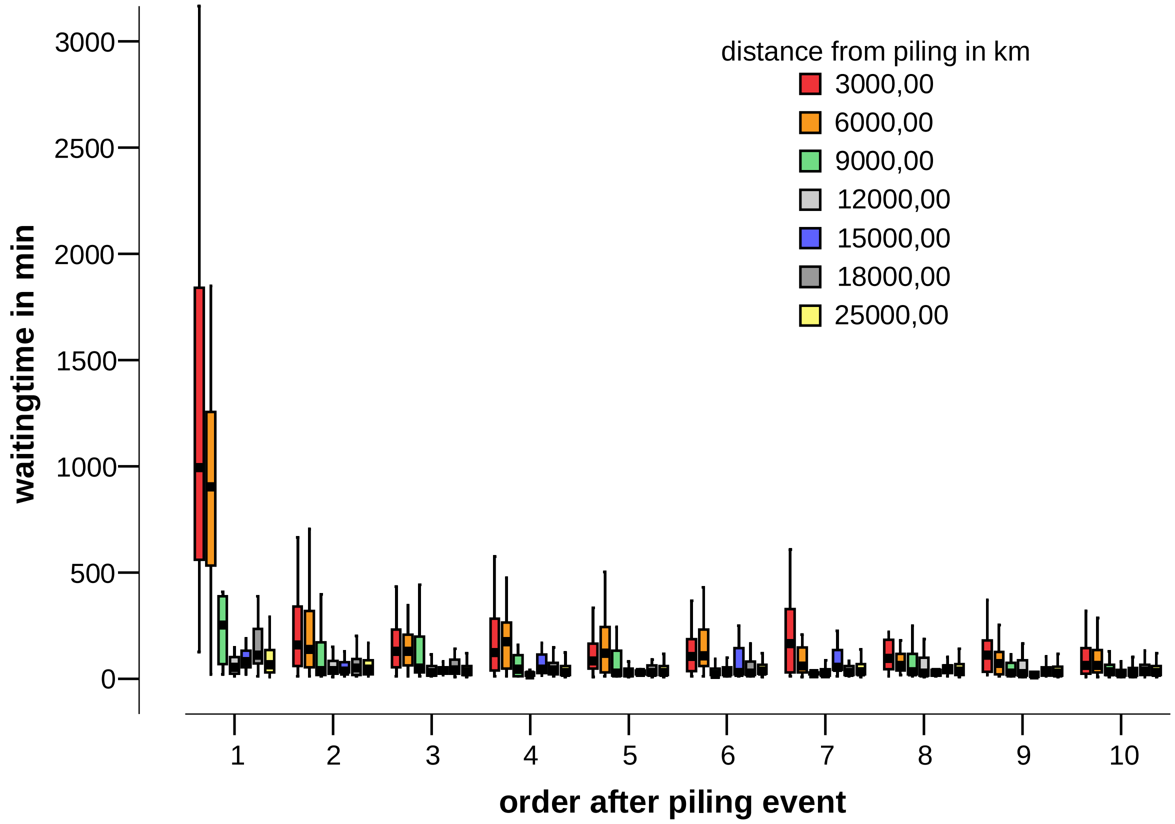

Fig. 18: Boxplots showing medians and 95 % confidence intervals of duration of waiting time in min between porpoise encounters by their order after the last piling event and the different distance categories.

Tab. 15 a: Summary of results on the influence of piling on median waiting time between porpoise encounters. For each POD-position is shown: the time until the first porpoise encounter after piling (first waiting time after piling), the "normal waiting time" (Sum of all waiting times after the 9th waiting time after piling), the sum of the first waiting times that significantly differed from later ones, this sum minus the mean piling duration (which essentially is the time it takes for the waiting times to return to "normal") and the time that the latter is longer than would usually be expected from "normal waiting times". All waiting times are given in min.

Distance to piling location in km	POD posi-tions	First median waiting time after piling in min (h)	"Normal median waiting time" in min (h)	Sum of significant median waiting times in min (h) = time until waiting times are back to "normal"	Time until median waiting times are back to "normal" in min (h) – mean duration of piling (46 min)
0.5 - 3	1 - 2	995 (16.6)	62 (1.0)	1283 (21.4)	1237 (20.6)
3.1 - 6	1 - 3	905 (15.1)	64 (1.1)	1350 (22.5)	1304 (21.7)
6.1 - 9	3 - 4	254 (4.2)	32 (0.5)	254 (4.2)	208 (3.5)
9.1 - 12	4	53 (0.9)	23 (0.4)	92 (1.5)	46 (0.8)
12.1 - 15	4 - 5	80 (1.3)	25 (0.4)	80 (1.3)	34 (0.6)
15.1 - 18	5	112 (1.9)	36 (0.6)	112 (1.9)	66 (1.1)
18.1 - 25	5 - 6	66 (1.1)	29 (0.5)	112 (1.9)	66 (1.1)

Tab. 16 b: Summary of results on the influence of piling on mean waiting time between porpoise encounters. For each POD-position is shown: the time until the first porpoise encounter after piling (first waiting time after piling), the "normal waiting time" (Sum of all waiting times after the 9th waiting time after piling), the sum of the first waiting times that significantly differed from later ones, this sum minus the mean piling duration (which essentially is the time it takes for the waiting times to return to "normal") and the time that the latter is longer than would usually be expected from "normal waiting times". All waiting times are given in min.

Distance to piling location in km	POD posi-tions	First mean waiting time after piling in min (h)	"Normal mean waiting time" in min (h)	Sum of significant mean waiting times in min (h) = time until waiting times are back to "normal"	Time until mean waiting times are back to "normal" in min (h) – mean duration of piling (46 min)
0.5 - 3	1 - 2	1354 (22.6)	107 (1.8)	1810 (30.2)	1565 (26.1)
3.1 - 6	1 - 3	970 (16.2)	109 (1.8)	1582 (26.4)	1536 (25.6)
6.1 - 9	3 - 4	436 (7.3)	67 (1.1)	436 (7.3)	390 (6.5)
9.1 - 12	4	85 (1.4)	36 (0.6)	167 (2.8)	121 (2.0)
12.1 - 15	4 - 5	94 (1.6)	43 (0.7)	94 (1.6)	48 (0.8)
15.1 - 18	5	162 (2.7)	53 (0.9)	162 (2.7)	116 (1.9)
18.1 - 25	5 - 6	121 (2.0)	51 (0.9)	193 (3.2)	147 (2.5)

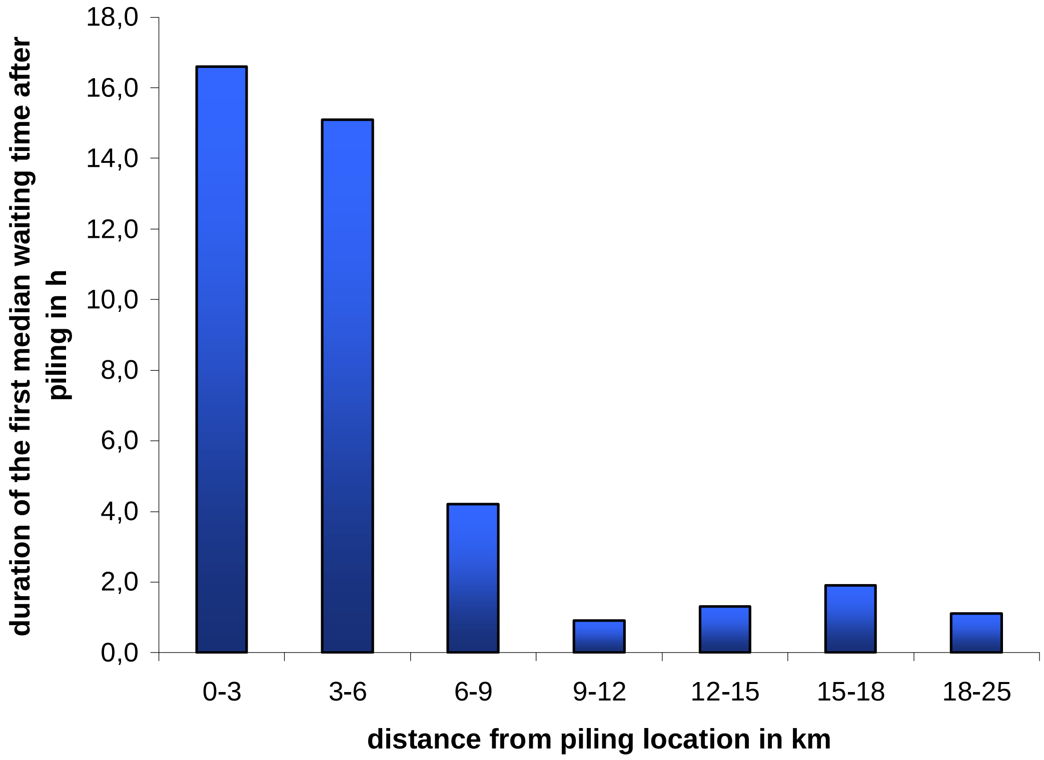

Fig. 19 a: Duration of the median first waiting times after piling by distance in km from the piling location.

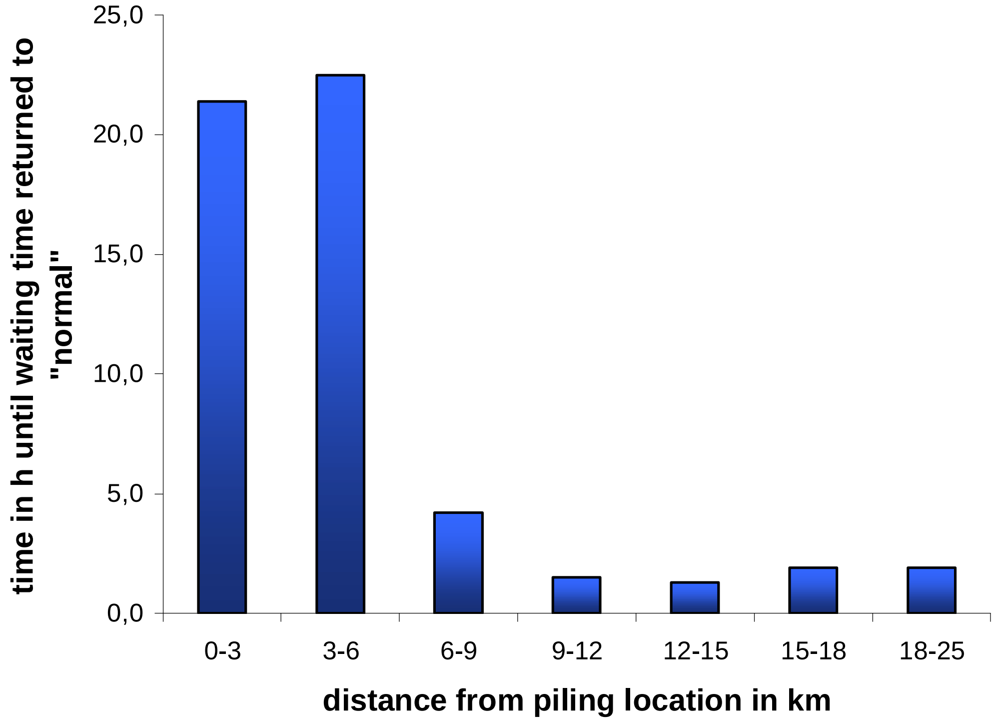

Fig. 20 b: Time in hours that it takes for median waiting times to return to “normally expected” values by distance in km from the piling location.

4.4. Porpoise encounters

In order to investigate how close to the piling location porpoises occurred while pile driving took place, we investigated how many times porpoises were recorded at the POD-positions during piling and measured the distance of the recording POD to the piling location. During all 92 piling events a total of 194 porpoise encounters were recorded at all six POD-positions. Of these only five occurred at position 1-3 near the wind park. Three were recorded at a distance of 3-4 km from the piling location, all others occurred at a distance greater than 6 km. Thus the minimum distance where a porpoise was detected during piling was at a distance of 3 km to the piling location (Tab. 19). The number of piling events PODs were recording data at the different distance categories is shown in Tab. 20.

Tab. 17: Number of encounters during piling and their distance from the piling location during all 92 piling events.

Distance to piling location in km	POD positions	Number of encounters
0-1		0
1-2		0
2-3		0
3-4	1, 2	3
4-5		0
5-6		0
6-7	3	2
7-8	3, 4	4
8-9	4-6	5
9-10	4-6	10
>10	4-6	172

Tab. 18: Number of piling events during which porpoise activity was recorded at the different distance categories.

Distance to piling location in km	POD positions
0-3	37
3.1-6	38
6.1-9	20
9.1-12	33
12.1-15	8
15.1-18	37
18.1-25	63

4.5. Summary of main results

Porpoise activity expressed in PP10M/day was significantly higher at POD-positions south of the reef than at POD-positions north of the reef during both baseline and piling period. PP10M/day increased from April to June at the POD-positions south of the reef but declined at POD-positions north of the reef. North of the reef this seasonal effect was probably linked to the effect of piling activities.

Compared to the baseline period PP10M/day significantly decreased to less than 50 % during the piling period at positions north of the reef, while no effect was found at the positions south of the reef. If the piling period is split into days during piling and days between piling events (with a minimum of 24 hours to the last piling event) this difference was no longer present if comparing the baseline period to days between piling events. However, here a slight decrease in PP10M/day from days between piling events to days during piling was also present at position 5 south of the reef while at position 6 porpoise activity increased. While a negative effect of piling is thus apparent at distances of up to somewhere around 14.5-22 km (distance from position 5 to the construction site) it generally seemed to disappear 1-2 days after piling.

When looking at porpoise activity on a finer resolution using PPM/hour, a clear effect of piling was visible at the positions 1-3 north of the reef, while at positions 4-6 south of the reef it was much less pronounced or even in the opposite direction. Porpoise activity remained significantly lower up to 40 hours after piling at position 1 and up to 20 hours at position 2 and 3. At positions 4-5 south of the reef this lasted only up until about 10 hours after piling, while at position 6 it was significantly higher up until about 30 hours after piling. A negative effect of piling on PP10M/H was observable up to about 12 km, while at further distances activity increased shortly after piling.

Analysing the duration of time between two porpoise encounters (waiting time) enables to define the length of the effect of piling on porpoise activity more precisely. It turned out that at position 1 it took about 24 hours until waiting times returned to normal values, while at position 2 and 3 it was 14-16 hours. At positions 4-6 south of the reef this effect rapidly declined to about 1-3 hours. A strong negative effect on porpoise activity was thus observable at distances of up to 9 km from the piling location, while at greater distances the duration of this effect rapidly declined. However, with this high time resolution analysis a short lasting negative effect of about 1 hour was still present at the greatest distances studied, which is 18-25 km.

It is important to note, that the recovery time of porpoise activity next to the construction area measured as median waiting times is about 2/3 of the average interval between piling events (which is 38 hours). If taking the mean waiting times (33 hours) is almost of the same length than this interval.

5. Discussion

The aim of this study was to investigate the spatial and temporal scale of the effects pile driving might have on the behaviour of harbour porpoises (*Phocoena phocoena*) at the area around the offshore wind farm Horns Rev II in the Danish North Sea. Using passive acoustic monitoring devices (T-PODs) we found the area around the reef to be used by harbour porpoises with a relatively high frequency. With an average of 11-28 % of porpoise positive ten minutes per day (PP10M/day) for the six POD-positions during the baseline period in April, porpoise activity during this study was very similar to the 4-30 % of PP10M/day that were found by Diederichs et al. (2008) in the area around Horns Rev I between April and August in 2005 and 2006. They found porpoise activity to slightly increase from March to July, when maximum porpoise activity was recorded, and this also corresponds to findings by Tougaard et al. (2006) for the same area. This supports previous findings that Horns Rev is continuously used by harbour porpoises, with a relatively high frequency especially during the summer months, and porpoise activity here is much higher than for example around Nysted in the Baltic Sea (Tougaard et al 2006a, Diederichs et al. 2008).

Analysing porpoise acoustic activity, we found a clear impact of piling activities during construction of the wind farm on porpoise acoustic activity. Porpoise activity measured as porpoise positive ten minutes per day (PP10M/day) significantly declined from the baseline period before construction to the construction period at POD-positions next to the wind farm in 0.5-9 km distance from single mono-piles. No such effect was found at POD-positions south of the reef at a distance of about 7-25 km. When further refining the analysis by splitting the piling period up into days during (including the day following the day of piling) and days between piling events (from the second day after piling onwards) it appeared that this decline was due to a decline at the days of piling activities only. No difference was found between the baseline period and days between piling events. However, the decline during days of piling was also apparent at the POD-position 5 in a distance of 14.5-22 km to a single mono-pile, while at the position furthest from the construction location (18-25 km) PP10M/day slightly increased.
PP10M/day gives a crude estimate of daily porpoise activity in the area around a POD. While it clearly shows that at some POD-positions piling had a negative impact, and that this impact disappeared at about the second day after piling, conclusions about fine time scales are not possible and short lasting effects might not be detected. The relatively crude time resolution based on a 24 hour period means that effects lasting only a fraction of this time might not come out significantly analysing the parameter PP10M/day. By using PP10M/day it is also not possible to directly link porpoise activity to the exact time of piling, because PP10M/day is always counted from 0:00 to 23:59 while piling could happen at any time of the day.

We therefore also used a second parameter to analyse porpoise activity, which was porpoise positive minutes per hour (PPM/H). This parameter could directly be linked to a piling event on the basis of a one hour resolution. Hours of porpoise activity were then pooled into 10 hour periods after piling to enable the comparison of different time periods, giving a resolution of 10 hours. Here we found a negative effect of piling on porpoise acoustic activity that lasted around 20-40 hours at the POD-positions near the wind farm north of the reef and about 10 hours at the POD-positions 4 and 5 south of the reef. At the furthest POD-position no. 6 south of the reef at a distance of 18-25 km PPM/H was significantly higher during the first 30 hours after piling compared to the time later after piling. This indicates a strong negative effect of piling on porpoise activity in close vicinity to the piling location that declined with distance to the piling location, until at a distance of 18-25 km a positive effect was found. However, there was a sudden decrease in the effect between position 3 north of the reef and position 4 south of the reef that may not be explained by an increase in the distance from piling alone.

As a resolution of ten hours was apparently still not sufficient to define the effect of the duration satisfyingly, we further analysed the duration of waiting time between porpoise encounters. This also revealed a strong effect of piling on porpoise activity near the construction site with a gradually declining effect at further distances. At the positions closest to the piling site waiting times increased 16 fold from the usual 1.1 to 16.6 hours directly after piling, and this effect only slightly decreased to a 14 fold increase at position 2 and 3 (from 1.0 to 13.9 hours and from 1.2 to 16.4 hours respectively) 3-9 km from the piling location. The effect steeply declined at greater distances south of the reef with waiting times after piling only being about twice as long (about 1-2 hours) as usual. This effect was still observable at the greatest distance (18-25 km) and did no longer decline at the positions south of the reef at distances to piling sites from 7 km to 25 km.
The time until waiting times returned to normal duration was slightly longer than the first waiting times and lasted 13.1-22.4 hours at the POD-positions north of the reef and 0.8-2.6 hours south of the reef. At all position this time and also the first waiting time after piling exceeded the average duration of pile driving, which was 46 min and north of the reef they also exceeded the average time duration of seal-scarer and pinger activity, which lasted on average 163 min before and 47 min after piling (256 min in total). At least north of the reef the effect was thus not limited to the time of noise exposure from piling and pinger and seal-scarer activity but lasted a considerable period after exposure had ended. As waiting times only doubled south of the reef, where normal waiting times were less than one hour, it is possible that here it was mainly during pile driving itself that porpoise activity was reduced.
To what extend the observed effect on porpoise activity was caused by pile driving or by the scaring devices can not be resolved at present. According to the Olesiuk (2002) seal scarer might deter porpoises up to a distance of 2.5-3.5 km. Its impact would thus be expected to only occur at the first distance category of 0-3 km. However, only three porpoises being recorded at distances up to 6 km during pile driving might indicate that the scaring devices were effective over a much larger area and this should be tested in future studies.

PP10M/day and PPM/H give relative estimates of porpoise activity but cannot directly be translated into porpoise density. However, previous studies have found these parameters to correlate with porpoise densities obtained from porpoise sightings (Diederichs et al. 2004, Tougaard et al. 2006c, Verfuß et al. 2007, Siebert and Rye 2008). While directly translating activity values into densities is not possible at present, they do seem to be linked to relative in- or decreases in densities such that they can serve as a parameter to study the influences of an activity on porpoise density. Conducting surveys simultaneously would be desirable but is often limited by financial aspects and weather conditions. Waiting times are also correlated to PP10M/day and PPM/H to some extend but their relation to porpoise density has not yet been studied. However, results obtained from PPM/H fit the results from analysing waiting times, such that we feel confident that the increase in waiting time that we found after a piling event is linked to reduced porpoise density in the area. Waiting times have the advantage, that they can directly be linked to the time of piling and provide the smallest resolution in time to estimate the duration of an effect.

The 16 fold increase of the first waiting time closest to the piling location from 1.1 to 16.6 hours was much greater during this study than what was found by Tougaard et al. (2006a) during the construction of Horns Rev I, where it only increased 3 fold to a waiting time of about 8 hours and did not decline up to a distance of 25 km. In contrast we found a gradient in the extend of the effect with distance, and the effect almost disappeared at a distance of about 10 km south of the reef already. Thus the effect we found was much longer but over a much smaller spatial scale than what Tougaard et al. (2006a) described. However, while there was no clear decline with distance north of the reef, the effect suddenly almost disappeared south of the reef at POD-positions 4-6, where only a very small effect without a spatial gradient existed. This could be due to differences in water depth, as sound has to travel through much shallower water to reach the area south of the reef. Sound transmission is known to substantially differ with water depth and attenuation is significantly higher in shallow waters (Medwin and Clay 1998). Therefore sound levels reaching the area south of the reef were probably much reduced to what occurred in the area north of the reef. A considerably smaller effect of piling on porpoise activity at position 4 directly south than to what was observed at position 3 directly north of the reef might thus be due to sound being attenuated to a large degree when travelling across the reef where water depths is only about 3 m in parts. Sound transmission and with it the effect of piling on porpoise activity might thus be substantially different towards the north of Horns Rev II, where water depth continuously increases. A further reaching effect might exist towards that direction and here the spatial scale of the effect might have been very similar to what was found by Tougaard et al. (2006a), who found no decline in the effect at more than 15 km distance from the noise source. Here only a small fraction of the reef lay between the sound source and the POD-stations where porpoise activity was measured and thus sound transmission might have been substantially different with a smaller attenuation effect. Substrate at Horns Rev II mainly consists of soft sandy sediment and this might also lead to a stronger attenuation than elsewhere. However, while the different spatial scales found by Tougaard et al. (2006a) and by us might be explained by water depth the different time scales of the effect found remain to be somewhat contradictory.

Tougaard et al. (2006a, 2006b) only found the first waiting time to significantly differ from normal waiting times while in our study it was also some later waiting times that were longer than usual. This might simply be due to a sample size effect. As with larger sample size the chance to detect a significant effect increases, this might be the reason for this discrepancy.

Their sample size was considerably smaller and might not have been sufficient to detect subtle changes in duration. Like during the study of Tougaard et al. (2006a, b) a very large effect of piling was found on the first waiting time, which at distance category 0-3 km increased more than 16 fold during our study. The second waiting time after piling only about doubled as compared to normal waiting times giving a marked decrease in the effect of piling. Thus the effect on the first waiting time will be detectable with a very small sample size already, while for the subtle changes in the following waiting times larger sample sizes are needed.

Even though our study area was right next to the area, where Horns Rev I was constructed our results are more similar to those found by Carstensen et al. (2006) during the construction of Nysted wind farm in the Baltic Sea. They found waiting times to increase 6 fold from the normal 10-20 hours to 35-60 hours in the vicinity of the piling location and from 6-17 hours to 11-30 hours at a distance of about 15 km. Here there was also a declining effect at greater distances, and the twofold increase in waiting times at a distance of about 15 km was similar to our finding at that distance. Total waiting time however, was much longer both normally and directly after piling than during our study. Porpoise density in this part of the Baltic Sea is known to be much lower than at the area around Horns Rev (Tougaard et al. 2006a, Diederichs et al. 2008) such that this is not surprising. While during the summer months densities of up to 3.5 animals / km² have been described for the area just south of the reef west of Sylt and Amrum (Gilles et al. 2007), density was only about 1 animal per km² in the area of the Baltic sea around Nysted (Gilles et al. 2007). A shorter waiting time after piling in Horns Rev II than at Nysted is probably also caused by higher porpoise density there. As found by radio-tracking porpoises use extensive areas in the North and Baltic Sea (Teilmann et al. 2008). The chance that an animal, that was not directly subjected to noise from pile driving, might occur in the area where this activity took place a few hours ago is therefore much greater at Horns Rev than at Nysted. Porpoise activity returning to normal values does not necessarily mean that the same animals have returned but simply that some animals again occurred in the impact area. How long an individual that was directly exposed to the noise might avoid the area is not known. If however, that effect is considerably longer than the effect on porpoise activity in general, this will lead to a considerably longer effect in areas with low porpoise density compared to areas with high density. Duration of first waiting times after piling being much shorter in Horns Rev than at Nysted seem to point in this direction.

Noise emissions from pile driving were measured at two distances (720 m, 2300 m) at 7.9.2008 (Betke 2008). Source levels were about 236 dB_{peak} and 213 dB_{SEL}. Attenuation appeared to be stronger than expected and noise levels fell below 150 dB_{SEL} within the range of the PODs (Tab 20). To account for transmission losses in shallow waters 5 dB were subtracted from these estimates to gain values for POD positions in the area south of the reef. The furthest distance of a POD-position north of the reef from a rammed mono-pile was 9 km, and here SEL was 161 dB. At this distance a pronounced response of porpoises to piling, that lasted considerably longer than the piling event itself, was still observed. At the first POD-position south of the reef the reaction was roughly limited to the time of sound exposure by piling and was also of a lower magnitude here. Many porpoises were still encountered at the PODs during piling. In order to reach a POD-position south of the reef sound had to travel across the shallow waters of the reef. The first POD south of the reef lay in a distance of 7-14.5 km such that SEL at that position ranged somewhere between 150-156 dB. Thus at a sound level somewhere between 150 and 161 dB the reaction was limited to the duration of sound exposure. However, a reaction was still observed at the furthest distance category, where SEL ranges between 144-147 dB.

Tab. 19: Sound exposure levels in deep and shallow water at the different distance categories based on measurements from Betke (2008).

Distance in km	SEL dB in deep water	SEL dB in shallow water
0.5-3	166-178	
3.1-6	161-166	
6.1-9	158-161	153-156
9.1-12	156-158	151-153
12.1-15	154-156	149-151
15.1-18	152-154	147-149
18.1-25	149-152	144-147

It might be argued that declining acoustic activity in the area might not reflect a decrease in density but simply a change in the animals' behaviour such that porpoises remain silent after piling activities and use their sonar less frequently. Studies on other cetacean species such as pilot whales, sperm whales and Cuvier's beaked whales indeed documented such a response to noise exposure (for review see Weilgart 2007). Mostly, whales remained silent or reduced vocalising activity during noise exposure but resumed with normal activity shortly after the noise stopped. On the contrary other studies even found an increase in vocalisation by pilot whales during noise exposure (Rendell and Gordon 1999). Two studies also addressed this issue in harbour porpoises: Koschinski et al. (2003) found that harbour porpoises used their echo location system more intensely when subjected to turbine noise. Teilmann et al. (2006) found no changes in echolocation activity of harbour porpoises when various frequency sounds (100-140 kHz re 1 µP at 1 m) were played back to them except during the first exposure to relatively loud sounds, when porpoises remained silent during the 5 min of sound exposure. While during this study porpoises in the vicinity of pile driving might have reduced echolocation activity due to masking effects or as a response to the sound of pingers and seal-scarers we believe that it is highly unlikely that such a change in behaviour would resume for as long as 20 hours after the noise stopped. Further Madsen et al. (2005) and Thomsen et al. (2006) concluded that due to the different frequency of the echolocation clicks to that of piling noise significant masking effects are unlikely to occur. There is further no convincing reason why animals that rely on their sonar for orientation and foraging should cease doing so after being subjected to piling noise unless their sensory system was damaged. This, however, could only occur at close range of up to a maximum of 2 km (Madsen et al. 2005). Therefore we conclude that the change in acoustic activity of harbour porpoises found during pile driving reflects a change in porpoise densities rather than a change in acoustic behaviour.

Only very few porpoises were recorded during piling at the POD-positions in close proximity to the noise source, and the closest encounter was at a minimum distance of 3 km. While we cannot rule out that animals fall silent at close proximity to the noise we believe that these data show that it is unlikely that any animal would have suffered physical damage during piling. Scaring devices were deployed prior piling started and these seem to have succeeded in keeping the animals at a minimum distance of 3 km. Madsen et al. (2005) estimated a zone of injury up to a distance of 2 km, and this was based on a worst case scenario. During piling of one mono-pile at Horns Rev II Betke (2008) measured a sound exposure level (SEL) of about 176 dB re 1 µPa at a distance of 720 m from the piling location and about 164 dB re 1 µPa at a 2300 m distance. Both values are below 180 dB re 1 µPa, where Madsen et al. (2006) assume the zone of injury for cetaceans.

In a recent publication Southall et al. (2007) reviewed the available literature on the impacts of underwater noise on marine mammals and derived criteria to assess the onset of hearing impairment defined as a Temporary Threshold Shift (TTS) or a Permanent Threshold Shift (PTS). They further 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 a TTS would be reached at 183 dB_{SEL} and PTS at 193 (M-weighted). Betke (2008) calculated weighted and unweighted cumulative noise levels for the two distances, where he conducted noise measurements during pile driving (Fig. 21): According to these calculations, a harbour porpoise swimming at a distance of 720 m to the piling operation would have received a cumulative noise level causing TTS within a few minutes and a cumulative noise level causing PTS within 20 minutes. At a distance of 2300 m the cumulative noise level would have caused TTS after 20 minutes but would not have been sufficient to cause PTS during the piling operation. As no animals have been detected during pile driving at a distance less than 3 km, it appears unlikely that these could have caused hearing impairments of harbour porpoises. However, the data show that mitigation measures such as the use of scaring devices are necessary to prevent individuals from the risk of injury. Recent investigations of Lucke et al. (2008) indicate that harbour porpoises may be more sensitive to noise exposures than other ‘high-frequency cetaceans” and caution is the required to avoid injuries from pile driving operations.

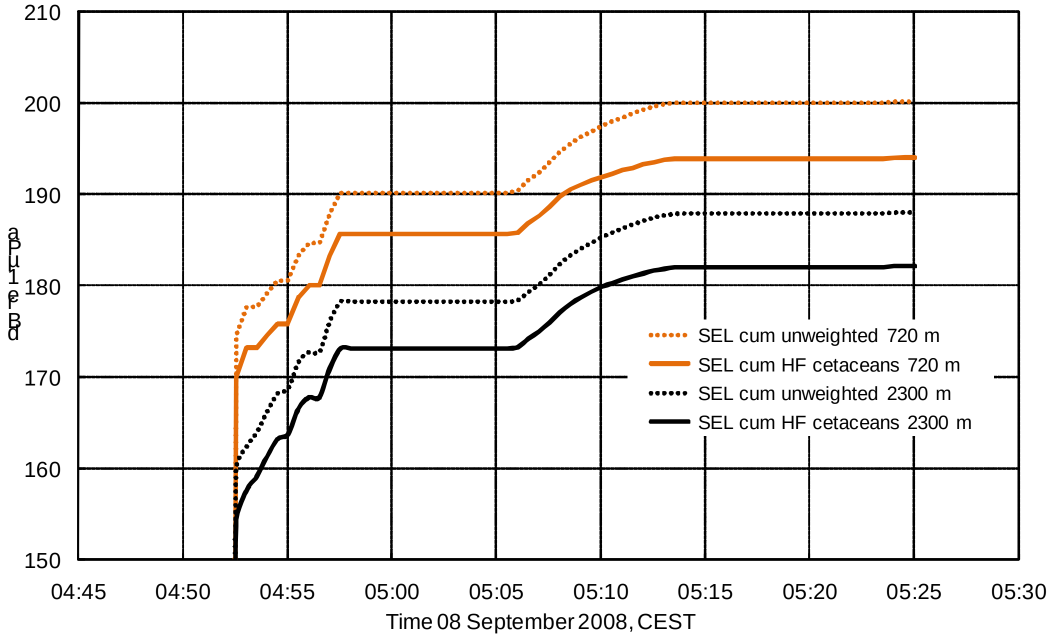

Fig. 21: Cumulative SELs for two measurement distances during pile driving (from Betke 2008).

It is noteworthy that while waiting times were still twice as long as usual directly after piling at the greatest distance from the piling location (1.1 hours) PPM/H was significantly higher during the first 30 hours after piling than later on. At first this seems somewhat contradictory. However, the increase in waiting time was small, being only about 30 min longer, and the time until waiting times returned to normal length was only about one hour. This effect is probably to short for being detected at a time resolution of ten hours, which is what we used for analysing PPM/H. An increase in waiting time directly after piling at that position but higher activity during the first ten hours after piling might indicate that porpoises rapidly left the area during piling, but that flight reaction was small at the greatest distance and probably ceased when animals had reached the furthest distance studied here. If animals present at that distance do not show a strong flight reaction and animals flee from near the piling location to these distances, porpoise density and thus activity might temporarily increase in that area as porpoises aggregate there for a short period of time. This further supports our argument that at a distance of over 10 km south of the reef behavioural reactions tend to minimal.

It has to be bared in mind also, that we found large differences in harbour porpoise activity between the area north and the area south of the reef already during the baseline period. This might be caused by differences in habitat suitability as prey abundance might differ. The North Sea is dominated by large riverine freshwater inflow, predominantly from the rivers Scheldt, Ijssel, Rhine and Elbe. The mixing zone of estuarine waters with more saline North Sea water runs along a frontal zone reaching offshore from the Wadden Sea, with Horns Reef marking the northern edge of this frontal system (Krause et al. 1986, Tougaard et al. 2005). Piscivorous birds – e. g. divers (*Gavia sp.*) - are often associated with estuarine frontal systems in the German Bight (Skov & Prins 2001). A study from the Bay of Fundy, Canada, also confirms a strong association of harbour porpoises with hydrographical fronts and eddies formed by strong tidal currents (Johnston et al. 2005). As the Horns Reef area is part of the complex hydrographical feature in the German Bight with fronts and eddies, which is most probably even amplified by the reef structure, it is likely that hydrography plays a major role in determining the fine-scale distribution of harbour porpoises in that area, including the wind farm. Krause et al. (1986) assume gradients and frontal systems being important for concentrating nutrients and plankton, which would then determine fish distribution also. Skov et al. (2008) showed via modelling of frontal systems that suitability of foraging habitat might differ locally around Horns Rev and might also change with the tidal cycle. They located up welling systems at the whole southern part of the reef during incoming north-flowing tide and an up welling system in the north-western part of the reef during outgoing south-flowing tide (Fig. 22). A habitat suitability map that they created from ship-based observations seemed to match these predictions (Fig. 23). Following their maps it is especially the area in the south-western part of the reef that is characterised by a pronounced up welling system during north flowing tide and that might be of high importance for porpoises, while during south flowing tide it is the area in the north-eastern and south-eastern part of the reef that is of medium suitability but of the relatively highest suitability in the reef area (Fig. 23). POD-position 4 was located right next to the up welling system during north-flowing tide that was modelled as being of high suitability for porpoises, and here highest porpoise activity was recorded during the piling period (no baseline data are available for this position). Positions 5 and 6 were located in close proximity to the area modelled as being of medium suitability, and slightly lower porpoise activity was recorded here than at position 4. POD-positions 1-3 were located north-west of the reef where Skov et al. (2008) found low habitat suitability, and during our study least porpoise activity was recorded there. Our POD-data thus seem to roughly match their predictions and findings. However, even though major differences exist between the positions, relative changes between times during and after piling are comparable. However, the relatively shorter lasting effect of piling on waiting times at POD-position 4 than at 5 and 6, even though it was closer to the piling site than 5 and 6 might be explained by high motivation of porpoises to return to these area, due to high prey availability. This could also in part explain the shorter effect of piling on porpoise acoustic activity found during construction of Horns Rev I, where PODs were mainly placed at positions, where habitat was modelled to be of higher suitability.

POD-positions north of the reef and south of the reef are therefore not directly comparable and this might further complicate the interpretation of the sudden decrease in the effect from the area north to the area south of the reef as this could partly be due to differences in porpoise density also. We clearly need more data on changes in porpoise behaviour in response to piling at areas differing in porpoise density, water depth and topography before these questions can be solved. Also measurements on how sound transmission varies with water depth, soil composition and topography are needed for predicting the influence of future wind farm construction on marine mammals in other areas.

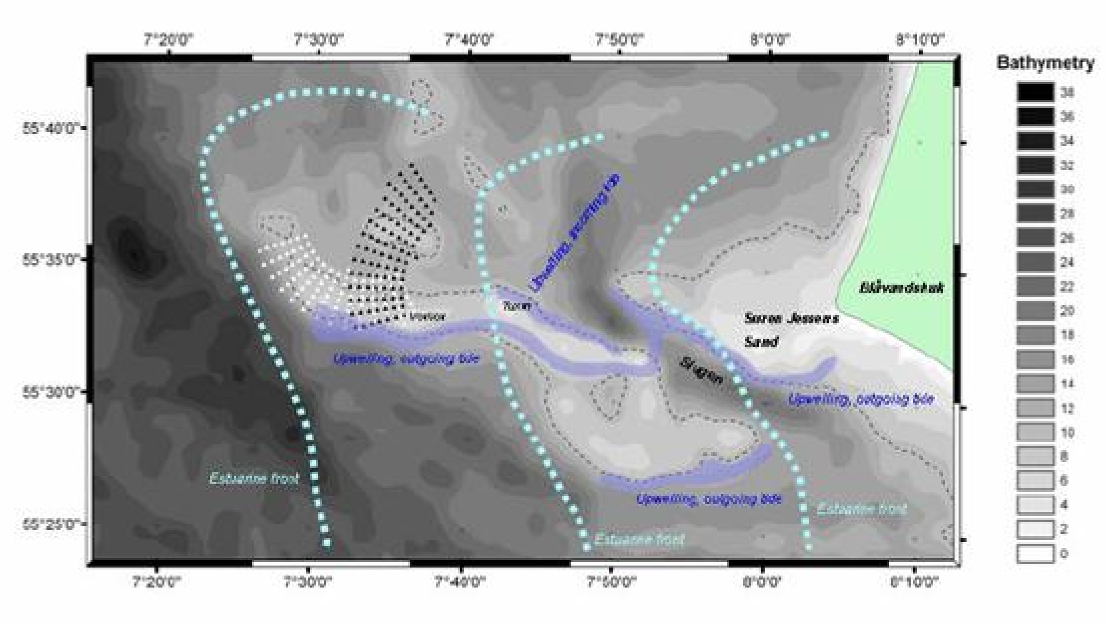

Fig. 22: Map showing the physical environment of Horns Rev. The 10 m (dotted line) depth contour, typical up-welling zones (blue raster) and potential position of the estuarine front (light blue dotted line) are indicated. Taken from Skow et al. (2008).

The seasonal pattern that we found south of the reef, where porpoise activity gradually increased from April to July is in line with findings by Tougaard et al. (2006a), Skov & Thomsen (2006) and Diederichs et al. (2008), where porpoise activity was also found to be highest during the summer months. In contrast no such seasonal pattern was observed at the POD-positions north of the reef, where porpoise activity declined from April to June and remained low afterwards. As Skov & Thomsen (2006) described similar seasonal patterns at the different POD-positions around the Horns Rev area, it can be assumed that the seasonal pattern north of the reef should be similar to that south of the reef. The difference we found is thus likely to be caused by piling activity at Horns Rev II. As we found an effect of piling on porpoise activity that lasted about 23 hours (33 hours when using mean waiting times) next to the piling location this probably causes porpoise density to be lower than would be expected without piling over the whole piling period. The mean time between piling events was 38 hours. This is only one third longer than the time it takes for porpoise activity to recover. Therefore, it can be concluded that porpoise density was reduced within the impact area north of the reef over the whole piling period, which in this case lasted over 5 months. A full recovery of porpoise numbers in the area can be expected after construction and no impacts are assumed for the operation of the wind farm. However, regarding future developments of offshore wind farming in Europe this aspect needs to be considered for spatial and temporal planning of wind farm construction.

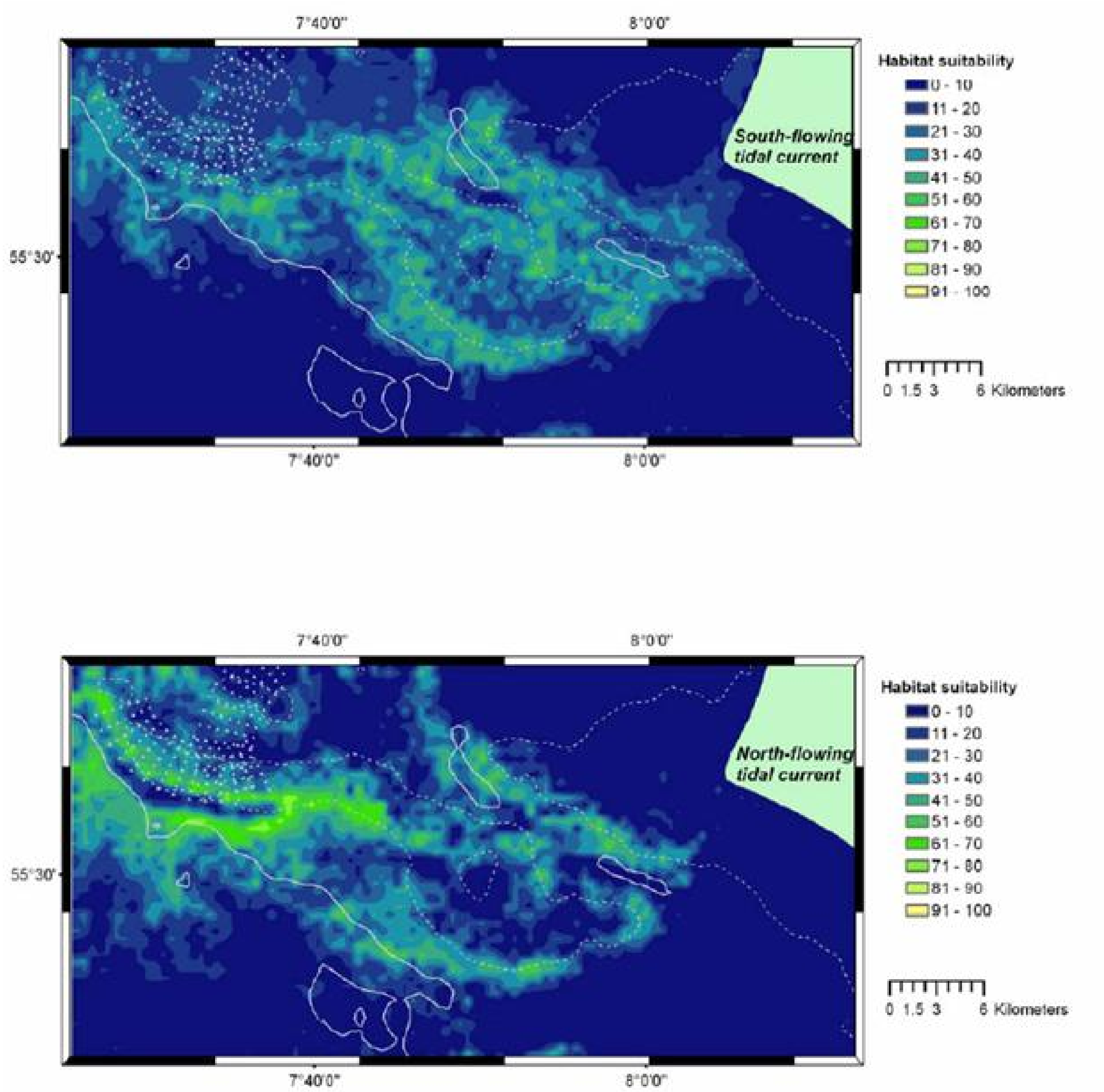

Fig. 23: Habitat suitability of harbour porpoise modelled from ship-based sightings during periods of south-flowing (above) and north-flowing (below) tidal currents (selected surveys). Taken from Skov et al. (2008).

5.1. Conclusions

This study successfully demonstrated temporal and spatial responses of harbour porpoises to the construction of the Horns Rev II offshore windfarm. Using Passive Acoustic Monitoring, a marked influence of pile driving on the acoustic activity of harbour porpoises was apparent. The change in acoustic activity most likely relates to changes in porpoise density rather than to changes in acoustic behaviour. Thus, it is assumed that the animals left the impact area during pile driving and during a considerable time afterwards. The temporal scale of the effect was longer than predicted from previous studies during the construction of Horn Rev I and from what was predicted in the EIA for Horns Rev II. It lasted about 23 hours in close proximity to the construction site. The duration and magnitude of the effect only slightly declined with distance from the construction site north of the reef but a clearly diminished effect was found south of the reef, which is possibly linked to differences in sound transmission at different water depths. A somewhat further reaching effect might therefore have occurred towards the north of the construction site where water depths gradually increase. Another parameter likely to influence the reaction of harbour porpoises is habitat suitability. A small effect was still observable at greater distances of 9-25 km at the POD-positions south of the reef, but here it was restricted to the time of pile driving. More data are needed on how sound transmission and with it the behavioural reactions of harbour porpoises differ with water depth, topography and habitat suitability in order to describe the spatial extent of porpoise responses to pile driving more precisely.

The mean time between piling events was only slightly longer than the recovery time for porpoise activity close to the piling location. Consequently, porpoise activity was reduced over the whole construction period, which lasted five months, in an area up to 9 km from the construction site. However, porpoise activity can be assumed to recover within one to two days after construction is finished and a longer lasting effect seems unlikely. Previous investigations in the Horns Rev 1 windfarm revealed no avoidance behaviour of habour porpoises (Diederichs et al. 2008) during operation of the widfarm and it thus assumed, that porpoise numbers in the Horns Rev 2 windfarm will be back to natural levels very soon after the termination of the construction activities.

Before and during pile driving, scaring devices were used to keep marine mammals out of the vicinity of the construction area. No animals were recorded during pile driving within a 3 km radius around the piling site. This shows that the scaring devices were most probably successful in keeping the animals at a distance where physical injury can safely be excluded. Thus, mitigation methods used during this project seemed to have been effective and no injury of harbour porpoises is expected.

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