Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark
Part II: Harbour porpoises

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0. Executive Summary

In 2005 we started a two-year project on the responses of harbour porpoises in the Danish offshore wind farms Horns Rev in the North Sea and Nysted in the Baltic Sea. The project is financed by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Access to the offshore wind farms was granted by the Danish Energy companies Vattenfall (formerly ELSAM eng.) and DONG energy (formerly Energi E2).
Background of this study is the question, whether there are differences in the presence, echolocation activity and behaviour of harbour porpoises between inside and outside the wind farm or between close to far away (up to 1.5 km away) from a single turbine. The study was conducted with acoustic dataloggers (T-PODs) recording harbour porpoise echolocation signals. The devices were mounted on the seabed in an array of short transects with five T-PODs in a row. Positions with T-PODs covered areas inside and outside the two wind farms Nysted and Horns Rev. In each wind farm area, two rows – totalling in ten devices – were deployed simultaneously. During the campaign, we changed the position of the rows four times, resulting in ten different experiments for each wind farm.

Calibration

An important prerequisite for T-POD study is the standardisation of the sensitivity. Test tank calibration proved that the version of T-PODs used in this study showed stable sensitivity as the differences between the single devices did not exceed beyond 3 dB re 1µPa pp. Results of field calibration show that with higher temporal resolution, a stronger correlation between test tank results and data collected in the field exists (e. g. PPM). In order to find a good compromise between high temporal resolution and small differences caused by different sensitivities, we decided to use the parameter PP10M. The remaining difference caused by the sensitivity of the T-PODs was set as a random factor when analysing the effect of the wind farm, so that we can exclude any blur caused by the method using T-PODs which are not working completely synchronised.

Natural variations

In 94 % of the total of 3,591 POD-days of recording during both years in Nysted at least one harbour porpoise signal could be detected. In Horns Rev in 98 % of the total 2,085 POD-days at least with one harbour porpoise signal was detected. This means, harbour porpoises were present inside and outside both wind farms on a nearly daily basis.
Using the parameter PP10M/day three times more harbour porpoises were recorded at Horns Rev than in the Nysted area reflecting a higher density of harbour porpoises in the Horns Rev area, which is consistent with other studies.
In both wind farm areas a high heterogeneity in recorded harbour porpoise signals at a small spatial scale of a few kilometres became evident when comparing the results of different T-POD rows, which were deployed at the same time a few kilometre away from each other. This result shows a high spatial variance in use of a specific area by harbour porpoises, most probably caused by the very dynamic hydrographic features, which govern the distribution of fish.

Effects of the wind farms

During this study no differences could be detected in harbour porpoises presence between inside and outside the wind farm in both areas Nysted and Horns Rev.

In Horns Rev there was also no difference between T-PODs at different distances to single turbines. Here, the wind farm does not seem to influence the presence of harbour porpoises at all.

In the Nysted area a weak effect was detectable between different distances of the T-PODs to single turbines with more recordings more than 700 m away from single turbines compared to T-PODs closer than 150 m to single turbines. This effect was only apparent when no additional variables, that could also effect harbour porpoise activity, were included. Wind was negatively correlated with the number of recorded PP10M/day in Nysted only. As this correlation was independent from the distance of the T-PODs to single turbines, it is unlikely that the wind farm itself and in particular the performance and noise emission of the turbines was the reason for this correlation.

The only effect of the turbines on harbour porpoises that was observed in both wind farms was an effect on the 24-hour cycle of harbour porpoise recordings. Especially in 2005 a pronounced diurnal rhythm with most recordings during the night occurred at T-PODs deployed close to single turbines in both wind farms. At the same time the diurnal pattern at T-PODs deployed more than 900 m away from single turbines showed a converse pattern with a maximum of porpoise recordings during the daylight in Horns Rev. At the same time no clear pattern between day and night could be found more than 700 m away from single turbines in Nysted. In 2006 this diurnal pattern changed in both areas and the differences between the distance groups was no longer very pronounced.

We discuss these differences in the diurnal cycle of harbour porpoise activity with regard to differences in the fish community close to single turbines, which has been demonstrated by several other studies.

From our results it can be concluded, that operating offshore wind farms are regularly incorporated into harbour porpoises habitats and do not induce significant aversive responses of these protected animals.

1. Introduction

1.1. Scope of investigations

Like other European countries, Germany promotes the extension of renewable energies in order to protect the atmosphere from harmful emissions. The Federal Government of Germany has set the target to double the energy production from renewable sources by the year 2010. Offshore wind farming is supposed to play a major role in order to achieve this target.

The installation of offshore wind farms at a large scale has raised concerns about possible impacts on nature, especially birds and marine mammals. Amongst others, there is concern that migrating birds might collide with the turbines; this may regard slow manoeuvring birds, times of limited visibility (night, fog, low clouds etc.), attraction by the turbine lights or other circumstances. The noise emissions of constructing and operating the wind farms might disturb harbour porpoises (*Phocoena phocoena*). A problem of the current discussion in Germany is that empirical research is not possible, as up to now no offshore wind turbines have been erected in German waters, though several approvals have been granted. Thus, a lack of knowledge about possible ecological problems exists and aggravates the discussion of these topics.

In Denmark, two wind farms in Horns Rev (North Sea) and Nysted (Baltic Sea) are operating since 2002 and 2003 respectively, thus offering the possibility to carry out research relevant to the German discussion about offshore wind energy, to close important gaps of knowledge and thus to provide a more solid base for further decisions. The Danish wind farms are close to German offshore wind farm projects and environmental conditions are generally comparable. In these Danish offshore wind farms we studied relevant issues for the development of offshore wind farms in Germany.

The Danish offshore wind energy activities (Elsam [now Vattenfall] at Horns Rev and Energi E2 [now DONG energy] in Nysted) are accompanied by a variety of research projects. Baseline studies, technical and progress reports are available (www.hornsrev.dk, http://uk.nystedhavmoellepark.dk). However, the Danish investigations do not cover all aspects and all possible conflicts between offshore wind farming and nature conservation which are relevant for the development in Germany but focus on the issues of greatest relevance from the Danish point of view. In co-operation with Danish scientists, our research programs were tailored to problems relevant to the development in Germany.

This report gives account of two topics relevant to these wind farms:

1) Identifying the collision risk of migrating birds;
2) Fine scaled responses of harbour porpoises.

Ad 1)

The collision risk of migrating birds is considered as a potential problem. There are no natural obstacles on the migration at sea; birds might be attracted by the lights of the turbines, which is a well known phenomena from various other illuminated structures at sea; in addition, in particular slowly manoeuvring birds and birds flying in formations might misjudge or underestimate the speed of the turbine blades; last but not least, in situations of low visibility or inclement weather birds might simply not be able to recognise the wind farm structures. These and so far unknown additional facts support the assumption, that the collision risk of birds with wind turbines at sea is higher than on land. An approval for an offshore wind farm has to be denied according to § 3 of the marine facilities ordinance (Seeanlagenverordnung[1]), if it is assumed to endanger bird migration. As no offshore wind farms have been erected in German waters and as the studies carried out in other countries are not yet sufficient to have a full view of this problem (see below), our study aims at the particular situations associated with bird migration in the direct vicinity of offshore wind farms.

Ad 2)
The project deals with the potential disturbance of harbour porpoises by the presence of wind turbines. Disturbance can be caused by noise emissions of the turbines during operation. Madsen et al. (2006) reviewed that measurements from under water noise emitted by offshore wind turbines indicate that individual turbines are audible for harbour porpoises at distances up to about hundred meters. The sound emission of wind turbines increases at certain frequencies with wind speed (Ingemansson 2003).
The responses of harbour porpoises to offshore wind farms are monitored by continuous registration of echolocation clicks of porpoises in the wind farms using Porpoise Detectors (PODs). PODs are deployed in transects from the wind farm to its surrounding in order to detect responses of the harbour porpoises to the operation of the turbines. Unlike visual observation, a deployment of PODs at the wind farms allows to relate harbour porpoise behaviour directly to the actual operation of the turbines even at high wind speeds.

The study deals with some key ecological problems which are highly relevant for the development of offshore wind farms in Germany. Thus, the results of the investigations are of a high direct value for future decisions of individual projects as well as for the general German strategy to develop offshore wind farms. In addition, the investigations will evaluate and improve the methods proposed for monitoring the ecological effects of offshore wind farms. As all approved projects are obliged to carry out monitoring programs defined as mandatory by the standard investigation concept (BSH 2007), applying the methods in practice will help to decide which results can be achieved and whether further refinements of the standards and future monitoring programs are necessary.

1.2. Cooperation with Danish partners

The studies are carried out in close cooperation with Danish scientists who conduct related studies in the wind farms. The access to the wind farms was granted from Elsam and Energi E2 to BioConsult SH.

1) Investigations of birds have been carried out in both wind farms (2001 to 2005), commissioned to the National Environmental Research Institute (NERI) by the respective

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[1] Verordnung über Anlagen seewärts der Begrenzung des deutschen Küstenmeeres (Seeanlagenverordnung -SeeAnlV), vom 23. Januar 1997 (BGBl. I S. 57).

wind farm companies. Results describe bird occurrences and activities in the areas (species composition, flock size etc.) as well as direct and indirect reactions of birds in relation to the wind farms, as there are lateral changes in migration routes and utilisation / avoidance of the wind farm areas; also, surveys of staging, moulting and wintering birds are carried out. In addition, the methods for studies on actual collision risk have been developed and tested (Desholm 2005). With the exception of the actual collision studies, these Danish investigations focus on larger birds (ducks, geese, gulls), since many of the observations and measurements (visual, radar) are made from a large distance from the wind farms. Our investigations concentrate on measuring bird occurrence, activities and behaviour in direct vicinity of the wind farms. Altitude distribution of birds as well as occurrence and behaviour of birds inside and outside the wind farm areas are the main topics; methods applied are recordings made via vertically mounted marine surveillance radar as well as visual and acoustic observations.

2) Until now harbour porpoises have been studied in both wind farms by Danish working groups at large spatial scales during ship surveys and by using T-PODs. The data of these studies are very important for our approach in order to interpret possible interannual changes in porpoise numbers and distribution which might affect the presence of these animals in the wind farms and its surrounding on the smaller spatial scale observed in our study. In turn an exchange of the data will also allow a better interpretation of the studies at larger scales which at present do not allow a direct comparison of the data with operational characteristics of the turbines. The T-PODs used were calibrated in co-operation with the German Oceanographic Museum, Stralsund under laboratory conditions as well as in the field. This assures a direct comparison of the data obtained by the different studies and highly improves the quality of the data. Data can be exchanged as raw data as well as in an analysed form (e.g. daily averages of the relevant click train parameters). Detailed weather data, especially wind strength and wind direction, have been delivered by the companies operating the wind farms, whereas hydrographical data, as water temperature and salinity in the wind farm, are not required for such a small scaled study.

1.3. Description of the offshore wind farms

1.3.1. Horns Rev

The offshore wind farm “Horns Rev” is situated in the Danish North Sea, approximately 35 km west of Esbjerg, Denmark (Fig. 1-1). The wind farm area is located in the south-eastern part of the so-called Horns Rev (“= Horn’s Reef”), some 14 km west-south-west of Blåvandshuk, a prominent headland. Geomorphologically, the Horns Rev formation is described as a terminal moraine ridge, consisting of relatively well-sorted sediments of gravel and sand. The water depth within the wind farm area ranges from 6.5 m to 13.5 m.

The formation Horns Rev is a permanently submerged sandbank. It is made of sandy materials with - especially in the western part - smaller areas of gravel. No persistent reef-like structures have been recorded. Pronounced tidal currents occur and are intensified by the shape of the sandbank. The water body is typically estuarine, with mixing freshwater from river inflow in the East and North Sea water from other directions.

In 2002, the Danish power company Elsam erected 80 turbines with an power output of 2 MW each (Fig. 1-2). As such the total installed capacity is 160 MW. The height of the turbine hub is 70 m and the rotor diameter is 80 m resulting in an overall height of 110 m above mean sea level. The minimum clearance of the rotor above the water surface is 30 m. The turbines are arranged in a rhomboid pattern with a distance of 560 m next to each other. Each corner turbine is equipped with white permanent light installed at about 10 m height to ensure visibility for ship traffic. The wind turbines are also equipped with red warning lights for the sea and air traffic safety's sake. These lights are mounted on the top of each turbine nacelle; while red lights of the outer rows are flashing (20 to 60 flashes per minute), the lights of all turbines are permanent; intensity of these illuminations is reduced when visibility exceeds 5 km. The wind farm covers an area of approximately 24 km². The turbine foundations including the scour protection cover approximately 14,500 m² of the sea bed, that is less than 0.1% of the total area of the wind farm. A dug in sea cable leads from the transformer platform to the shore. The wind farms operational phase started in autumn 2002 (Elsam Engineering & ENERGI E2 2005)

Fig. 1-1: Location of Horns Rev wind farm (white rhomboid) in the North Sea some 35 km west of the harbour city of Esbjerg, off the peninsula of Skallingen with its western headland Blåvandshuk.

Fig. 1-2: Horns Rev wind farm (photo: BioConsult SH).

The co-ordinates (latitude, longitude / WGS84) of the wind farm corners are:
55° 30.19’ N / 7° 47.78’ E
55° 30.24’ N / 7° 52.57’ E
55° 28.14’ N / 7° 53.08’ E
55° 28.10’ N / 7° 48.30’ E

1.3.2. Nysted

The offshore wind farm “Nysted” is situated approximately 10 km south and south-west respectively of the Danish cities of Nysted, Lolland and Gedser, Falster (Fig. 1-3). The wind farm area is located about 4 km south of the partly emerged sandbank Rødsand which extends over 25 km from Hyllekrog to Gedser. This formation separates a shallow lagoon area with water depths of 0.5 to 4 m. The tide is negligible (less than 0.5 m), but continuous strong winds may induce considerable currents and change the water depth by up to 2 m.

In this area, a consortium of the enterprises Energi E2, DONG energy and E.ON Sweden constructed 72 wind turbines with a power output of 2.3 MW each in 2003 (Fig. 1-4). As such the total installed capacity is 165.5 MW. The turbines have a hub height of 69 m and a rotor diameter of 82 m resulting in an overall height of 110 m above the sea. The clearance of the rotor above the water surface is 28 m. The turbines are placed in eight north-south orientated rows separated by a distance of 850 m. Each row holds nine turbines separated by a distance of 480 m. A dug in sea cable leads from the transformer platform to the shore near Nysted. The wind turbines are equipped with red warning lights for sea and air traffic safety’s sake. These lights are mounted on the top of each turbine nacelle; while red lights of the outer rows are flashing, the lights of all other turbines are shining permanently; brilliance of this illumination is adapted to visibility. The turbine foundations are concrete made gravity foundations with special protection against ice. The expected erosion around the bottom plate of the foundations is prevented by a stone protection. The foundations take up an area of about 45.000 m², corresponding to 0.2% of the total area of the wind farm (Elsam Engineering & Energi E2 2005). The wind farm officially started in normal operation December 1st 2003.

Fig. 1-3: Location of Nysted wind farm (white rhomboid) in the Baltic Sea south of the twin island of Lolland and Falster near the towns Nysted and Gedser.

Fig. 1-4: Nysted offshore wind farm (photo: Energi E2).

The co-ordinates (latitude, longitude / WGS84) of the wind farm corners are:

54° 34.20’ N / 11° 40.02’ E
54° 33.60’ N / 11° 45.54’ E
54° 31.56’ N / 11° 45.54’ E
54° 32.14’ N / 11° 40.08’ E

The sea floor at the wind farm consists of glacial sediments and the area is mainly covered by sand or silt (Hansson 2000). Areas with gravel or shells occur, but no reef-like aggregations have been recorded. The water is throughout brackish, being a mixture of saline water from Kattegat and freshwater of inner Baltic origin.

2. Harbour porpoise study – logging click sequences by means of T-PODs

2.1. Design of the harbour porpoise study

The most important question in the context of offshore wind farms and marine mammals is whether wind farm construction has an effect (positive or negative) on the mammals population size and whether or not a possible effect is acceptable. In theory, operating offshore wind farms might affect harbour porpoises in at least three different negative ways: physical habitat loss from construction, disturbance from operating turbines and disturbance from service operations. On the other hand, wind farms might attract porpoises due to higher density of prey because fishing will be prohibited inside the wind farm area and the foundations may attract fish as they function as artificial reefs.

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. Given a mean density of one or two animals per km^2 (BioConsult SH & GfN 2002, Scheidat et al. 2003, Hammond et al. 1995, Hammond 2002) the sighting rates from ship or aerial surveys are highly variable and very dependent on counting conditions, especially weather and sea state (Teilmann 2003). Due to low densities of harbour porpoises and their patchy distribution, the number of animals visible within a wind farm area of approximately 30 km² is probably too low to detect significant differences in numbers before and after the wind farms were installed. Unless there is a very marked avoidance or attraction of the wind farm area, visual surveys don't provide a sufficient control for changes in numbers or distribution within an area of wind farm size. However, visual surveys give very valuable information on large scale distribution patterns and seasonal variations in numbers as well as on distribution patterns within single days and are thus are essential for impact studies.

In consequence of the above mentioned uncertainties, we additionally applied a passive acoustic approach, using timing hydrophones with data loggers (T-PODs). Harbour porpoises use high frequency echolocation clicks of narrow bandwidth and short duration for orientation and prey capture (e. g. Amundin 1991b, Verboom & Kastelein 1995, 1997, Verfuß et al. 2005, Teilmann 2003). Akamatsu et al. (2007) showed on tagged wild harbour porpoises that they used their sonar system almost continuously with less than 4 % of the tagged time of silent periods lasting more than 50 seconds. 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. In order to compare the presence of harbour porpoises inside and outside the wind farm, devices used in this study were installed in a transect array using five hydrophones in a row with three T-PODs inside the wind farm and two T-PODs outside the wind farm up to a distance of 1,500 m to the next turbine. During data collection two T-POD-rows were always moored at the same time in each wind farm.

The main objectives of this study was an analysis of effects of an operating offshore wind farm on harbour porpoise acoustic activity at a much smaller spatial and temporal scale than other studies. Madsen et al. (2006) reviewed hearing thresholds of Odontocetes and noise emission of wind turbines and concluded that it is unlikely that harbour porpoises are able to hear operating wind turbines at distances beyond several hundred meters. A first study dealing with the influence of noise generated by wind turbines on harbour porpoises was also using passive acoustic monitoring devices (T-PODs, Koschinski et al. 2003). Thus, a small scaled approach was chosen for this study.

The time length of recorded porpoise signals is assumed to reflect the local harbour porpoise abundance, but data obtained by acoustic surveys cannot yet be transferred into absolute densities. Different studies indicate that harbour porpoise density is directly linked to T-POD recordings (Diederichs et al. 2004, Tougaard et al. 2006a, Verfuß et al. 2007). To cope with the small scaled heterogeneity, row positions were changed four times during the study period.

Working with T-PODs along transects is simple: if harbour porpoises avoid wind turbines, the instruments in the vicinity of a turbine will log significantly less porpoise clicks than those further away. As the detection range of single T-PODs is less than 300 m, a high spatial resolution of the data is assured. Due to the real-time detection of porpoise clicks by the T-PODs it is possible to correlate the presence of harbour porpoises in the vicinity of the wind turbines with their noise emission, which is primarily correlated with wind speed. In this context the high spatial and temporal resolution of the study was very useful. It is possible to analyse effects of wind turbine operating characteristics on harbour porpoise click activity, whereas no visual observations are possible at higher wind speeds, when the turbines are working at full capacity.

With the chosen design the following main questions were addressed:

Are there differences in the presence, echolocation activity and behaviour of harbour porpoises inside the wind farm or close to a single turbine and outside the wind farm area or far away from a single turbine (up to 1.5 km away)? Are potential differences related to wind speed and therefore to the performance and noise emission of the turbines?

2.2. Results of the Danish studies

Before starting construction of both wind farms in Horns Rev and Nysted, a large monitoring program on harbour porpoises was initiated (Tougaard et al. 2006a, b). Data sets of both wind farms were obtained based on acoustic recordings with T-PODs before, during and after construction of the wind farms using the BACI-approach (Before-After-Control-Impact). This approach compares the presence of animals inside an impact area (e.g. wind farm) with the presence of animals in one or more reference areas nearby. The precondition for this design is that natural variation in the two areas is similar or correlated. Variations in the data set (e. g. between T-PODs or seasonal variation) are negligible, since the comparison is done on a day by day basis, similar to a paired test.

According to the T-POD data, results show different effects for Horns Rev and Nysted. At Horns Rev area the BACI-design could only show a significant difference between semi-operation and operation phase, as indicated by harbour porpoise positive minutes (PPM, Fig.

2-1). During semi-operation when intensive maintenance work took place, PPM reached lowest values of the entire monitoring period. Highest habour porpoise activity in both, wind farm and reference area was measured after the semi-operation phase during the operation period. In conclusion, a weak negative effect of construction and semi-operation phase could be detected, with return to baseline situation during normal operation of the wind farm.

For the Nysted area a significant effect on the abundance and behaviour of harbour porpoises could be shown, based on the acoustic recordings from T-PODs (Fig. 2-1). During construction and the two following years of operation of Nysted Offshore wind farm the abundance of harbour porpoises was significantly reduced compared to the baseline period. This effect was strongest during the construction period and also measurable in the reference area 10 km away from the wind farm. In the two following years of operation the effect decreased gradually and reached the level of the baseline period during the last year of monitoring abundances in the reference area. In the wind farm area, the number of harbour porpoise recordings is still significant lower, indicating that that less harbour porpoises use the wind farm area than before constructing the wind farm.

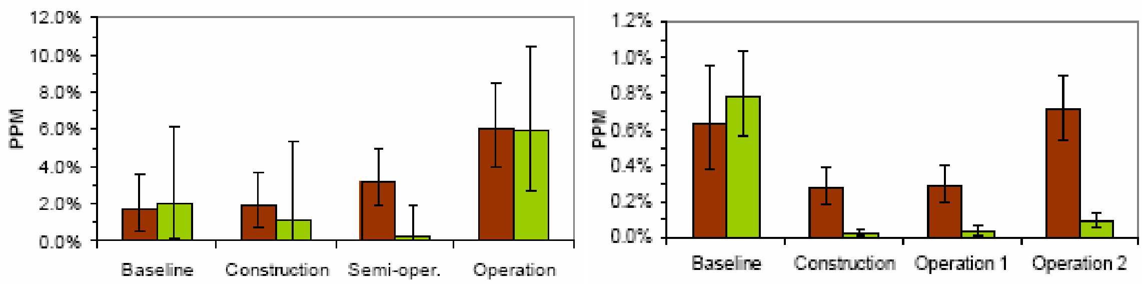


Fig. 2-1: Mean values of porpoise positive minutes (PPM, defined as minutes where porpoise clicks were logged by the T-POD) at Horns Rev (left) and Nysted (right). Data from the wind farm are shown with green bars and from the reference area with brown bars. Black lines = 95% confidence limits. Note that y-scales are different. Levels from the two areas are not entirely comparable due to different T-POD versions used in the two areas. Source: Tougaard et al. 2006a,b.

Although the design of the monitoring program was aimed only for detecting general effects of wind farm construction and operation on harbour porpoise presence, it was also possible to document specific effects of pile driving activities. The T-POD data indicate that harbour porpoises left the entire Horns Rev area during pile driving, presumably as a response to the loud impulse sound generated by this operation. After a period of 6-8 hours, harbour porpoises were again present in similar abundance as before pile driving.

2.3. Biology of the harbour porpoise

Name: Harbour porpoise (*Phocoena phocoena*), DK: Marswin, D: Schweinswal.
Order: Cetacea (Whales)
Suborder: Odontoceti (Toothed whales)

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 (Schulze 1996). 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.

2.3.1. Characteristics of harbour porpoise echolocation clicks

Sonic information is believed to be the major sense for orientation and communication of ceataceans. As a consequence, they might be sensitive to additional artificial noise sources (Richardson et al. 1995). During past decades, the marine environment has been exposed to an increasing noise emission of human activities. In particular shipping traffic contributes to the emission of low frequency noise (below one kHz). Under water, low frequency sounds with high source levels propagate very far (Urick 1967).

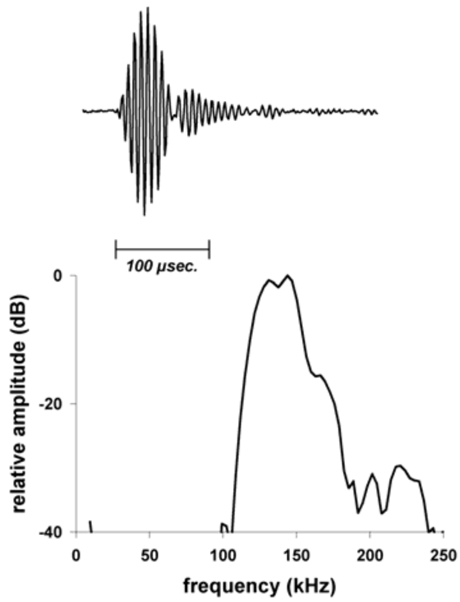


Fig. 2-2: Waveform (above) and frequency spectrum of a porpoise echo-location click (from Verfuß et al. 2004).

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. This 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. 2-2 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, Schevill et al. 1969, Verfuß & Schnitzler 2002) and presumably to some extent for communication (Verboom & Kastelein 1997, Koschinski et al. in press).

Subsequently produced clicks form specific click trains, show pulse (click) repetition frequencies or interclick-intervals between ten and 100 clicks per second. It is assumed that lower click frequencies indicate echolocation used for navigation, whereas trains with higher and accelerating values (“fast trains”) are known to be used for prey capture (Busnel & Dziedzic 1967, Kastelein et al 1997, Amundin 1991b, Verfuß et al. 2005, Koschinski et al. in press). These click trains show rapid rises in the interclick-interval commonly resulting in a minimum interclick interval below 10 µs (Fig. 2-3). High frequency click trains - buzzes - are known to be used in the final stages of prey capture. The highest frequencies recorded were approximately 1,200 clicks per second, produced from harbour porpoises during feeding bouts in T-POD trials in Yell Sound/GB in 2002 (Fisher & Tregenza 2003).

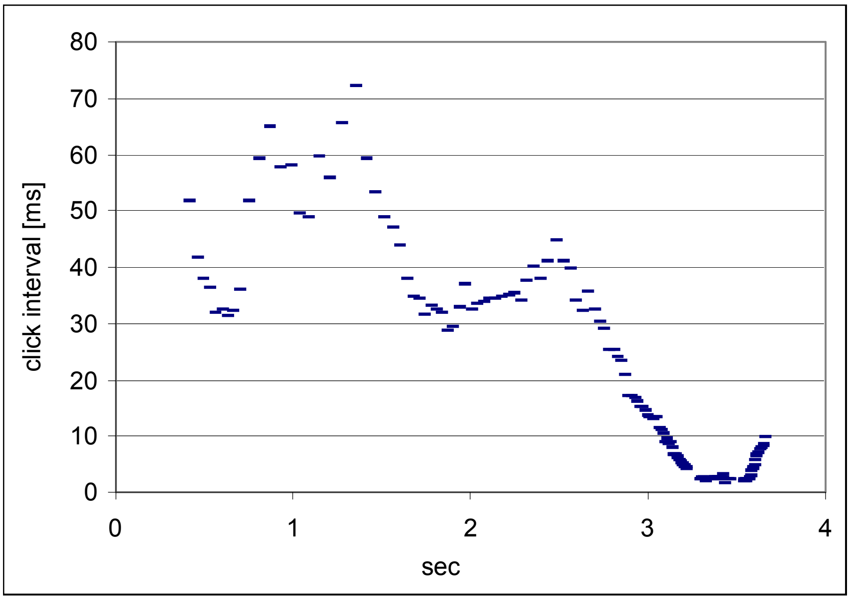


Fig. 2-3: Typical accelerating click train pattern, which is characteristic for prey capture (own data).

2.3.2. Population status and diet

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) give a review about the diet of harbour porpoises in the North East Atlantic. They show 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. Even though a wide range of species has been recorded in the diet, harbour porpoises in any area tend to feed primarily on two to four main fish species: in the German North Sea, Sole, Cod and Sandeels (Ammodytidae) have been recorded, whereas in the German Baltic Sea cod, gobies and herring were mostly found (Benke & Siebert 1996).

Harbour porpoises are often seen alone, but may aggregate in small groups when fish schools are present.

In European waters, the harbour porpoise is an endangered indigenous marine mammal (annex 2 and 4 of EU habitat directive).

Harbour porpoise occurrence at Horns Rev

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 porpoises and 230,000, respectively (Hammond et al. 1995, Hammond et al. 2002, Hammond 2007). 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 (BioConsult SH & GfN 2002, Scheidat et al. 2004, Gilles et al. 2006, Tougaard et al. 2006). Older studies from Benke et al. (1998) and Sonntag et al. (1999) indicate an area with high porpoise density and a high calve ratio west of the Northern Wadden Sea. These findings resulted in a first German whale sanctuary in 1999 west of the Island of Sylt. Recent investigations show that harbour porpoises are distributed in high numbers in a far larger area west of Sylt, which reaches up to 100 km west of the coastline (Bioconsult & GfN 2002, Diederichs et al 2004, Scheidat et al. 2004, Gilles et al. 2006). Diederichs et al. (2004) and Gilles et al. (2006) 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 (Tougaard et al. 2006a). Harbour Porpoises are also abundant around the Horns Reef area including the area now covered by the wind farm.

Little is known about factors governing temporal and spatial fine-scale distribution of harbour porpoises within a respective area. It was suggested that harbour porpoises are associated with estuarine frontal systems. The area west of the Wadden 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. 2006a).

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. Harbour porpoises probably respond to increasing prey (fish), which aggregates in the frontal regions due to the higher production and/or plankton biomass (Johnston et al. 2005).

Harbour porpoise occurrence at Nysted

The harbour porpoise is the only cetacean regularly found in inner Danish Waters and the western Baltic. It is very common in the Inner Danish Baltic Sea, with a total population in Kattegat, Belt seas and western Baltic of around 40.000 animals (Hammond et al. 1995, Hammond et al. 2002). In the Baltic Sea, varying densities of harbour porpoises occur: whereas the species is abundant in the western part, the density strongly decreases in the central or eastern Baltic Sea. Scheidat et al. (2004) described decreasing sighting rates in aerial surveys and Verfuß et al. (2004, 2007) showed decreasing echolocation activity with the help of T-PODs from the western to the eastern German Baltic Sea.

The species reaches the south-eastern limit of its main distribution range in the area south east of the islands Lolland/DK and Falster/DK. Baseline observations showed that harbour porpoises regularly use the Nysted Offshore Wind Farm area. Assessments in the EIA for the Nysted Offshore Wind Farm based on observations from a larger area concluded, that the area around the wind farm turbines probably serves as foraging grounds for harbour porpoises throughout the year (Bach et al. 2000). The population densities in the areas were characterised as low relative to other Danish waters, and information from the interviews with fishermen and from the bird censuses indicates that the wind farm area was of no greater value than the surrounding areas (Bach et al. 2000).

Satellite tracking of 60 animals in Danish waters showed that some of the tracked animals regularly visited the Rødsand area but not for very long periods (Teilmann et al. 2004).

On the basis of porpoise positive days measured by T-PODs, Verfuß et al. (2007) described a significant decline of harbour porpoise presence in the German Baltic Sea during the winter months (January – March). Recent analysis of all available data on harbour porpoise distribution in Danish Waters by Teilmann et al. (2008) showed that the Fehmarn Belt area, which is approximately 40 km west of the Nysted wind farm area is one of ten high density areas within the Inner Danish Waters. It is suggested that this area is mainly used as an important corridor to the eastern part of the Baltic with highest densities during April, June and December.

2.4. Possible impacts from offshore wind turbines on harbour porpoises

2.4.1. Noise from operating wind turbines

Turbine piles and foundations emit noise into the water column during operation. This noise could potentially have a negative effect on harbour porpoises. The noise from operating turbines in Horns Rev was measured by ITAP in 2005 and in Nysted in 2006 (Benke 2006) and the results are comparable to measurements at other turbines (see e.g. Wahlberg and Westerberg 2005). Fig. 2-4 and Fig. 2-5 show narrowband spectra and 1/3 octave spectra measured in offshore wind farms in Sweden and Denmark (Betke et al. 2004, ISD et al. 2007). All turbines are of the 2 MW class. In Nysted, 100% rated power was not reached in the observation period. However it is likely that the Nysted measurement at 70% reflects a condition near maximum sound radiation, since the turbine type is the same as in Paludans Flak, where the highest sound levels were measured at 50%. In Utgrunden and in Horns Rev, the strongest sound radiation was observed at rated power.

The frequencies are quite similar for most turbine types, since the rotor speed is almost constant if the electric power exceeds a certain limit, typically 30-40% of rated power. Since all measurements were made at 100 m distance from the turbine, a normalisation to source level according to the 15 log(R) law can be accomplished by adding 30 dB to the levels given in Fig. 2-4.

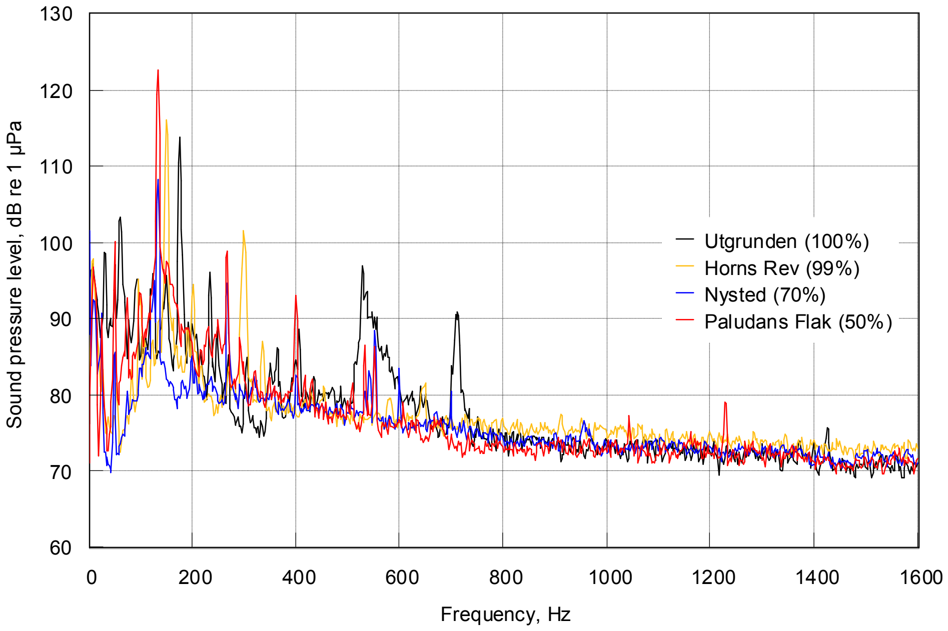
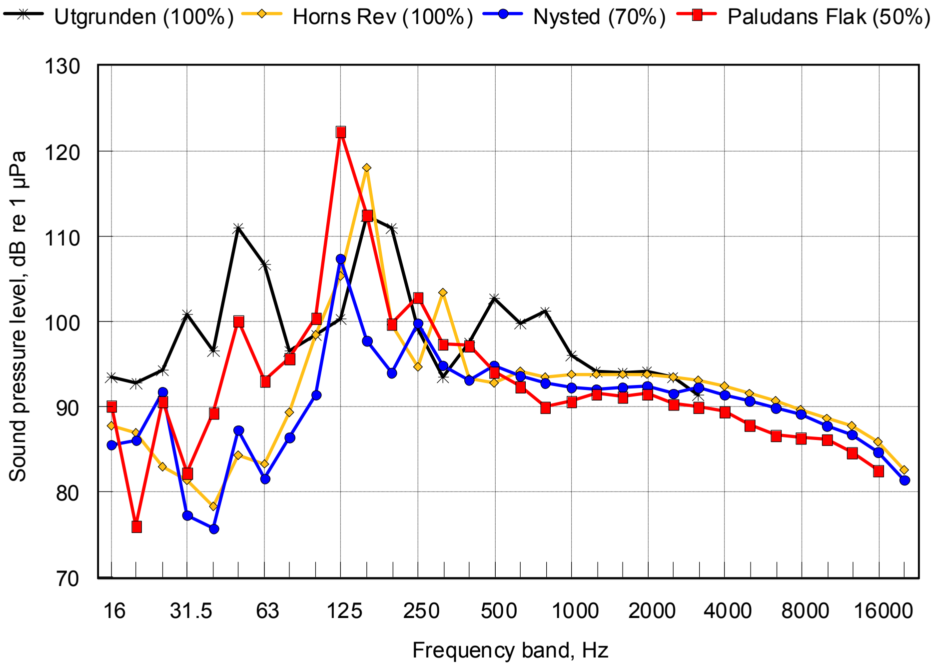


Fig. 2-4: Narrowband spectra (2 Hz resolution) of noise radiated from offshore wind turbines. All measurements were made at 100 m distance. Values in brackets are approximate operating powers of the turbine during the measurement, with respect to its maximum power (ISD et al. 2007).

In all cases, the maximum levels were found at frequencies below 200 Hz. Little or no sound radiation was observed above 1 kHz. The highest level peaks are listed in Tab. 2-1. The values in Nysted are 12 to 15 dB lower than in Paludans Flak, though the turbines are of the same type. The reason for this is probably the gravity foundation in Nysted, whereas the turbines at Paludans Flak are founded on Monopiles. Also the water depth is lower in Nysted, but this would yield only 3 to 4 dB level difference if a sound radiation proportional to pile surface is assumed.

Fig. 2-5: Spectra from Fig. 2-4 in third-octave representation.



Tab. 2-1: Highest levels measured at 100 m distance from offshore wind turbines. Source levels were computed according to 15 log(R). Level fluctuation values are based on 5-minute measurements with 2 s averaging time (ISD et al. 2007).

Wind farm	Turbine power	Frequency	Measured level (re 1 µPa at 100 m)	Source level (re 1 µPa at 1 m)	Level fluctuation
Utgrunden	100%	176 Hz	114 dB	144 dB	Not available
Horns Rev	100%	150 Hz	117 dB	147 dB	+3 / -5 dB
Nysted	70%	135 Hz	110 dB	140 dB	+4 / -6 dB
Paludans Flak	50%	134 Hz	122 dB	152 dB	+6 / -3 dB

To estimate the distance at which porpoises are able to hear the turbine noise we followed Tougaard et al. (2006). The frequency peak of turbine noise is 10-15 dB above the threshold level of the porpoise audiogram only at frequencies higher than 800 Hz. This peak should clearly be audible to the animal at a 83 meter distance. After calculations from Tougaard et al. (2006) this peak disappears below the background noise at a distance of 260 m from the turbine. Though this estimation is the best at present, it is difficult to estimate the exact range at which the turbines are audible to harbour porpoises. The general low levels of noise emitted, combined with the relatively poor hearing abilities of porpoises at low frequencies make it unlikely that they should be audible beyond a few hundred meters at best.

2.4.2. Noise from service and maintenance activities

Another potential disturbing factor is service operations on turbines. During a normal operation phase two small, fast service boats visit the wind farm nearly daily and commute between the wind turbines. In situations where seas are too rough for the boats to moor at the turbines or if fast access is needed, the turbines in the Horns Rev wind farm are accessed from a helicopter. Small fast boats are known to be very noisy, especially at cruising speeds above 15 knots (Richardson et al., 1995, Erbe 2002) so that the pure presence of these boats is likely to have a deterring effect on harbour porpoises. In contrast to the noise from the turbines, the boats noise is intermittent and overall disturbance depends on the visit duration and intervals between visits (Nehls et al. 2008).

Effects of boat traffic on harbour porpoises presence are poorly documented and while there is a general agreement that porpoises will evade individual fast motor vessels, there is no basis for concluding that high boat traffic levels in general correlate with low abundance of porpoises. Some of the highest densities of porpoises in inner Danish waters are in fact found in the busiest areas: Storebælt and Lillebælt (Kinze et al. 2003; Teilmann et al. 2004).

2.4.3. Wind farms as artificial reefs

The construction of the foundation tower and scour protection introduced new hard substrates, functioning as artificial reefs and inevitably being colonised by algae and epifauna, resulting in high biomasses e.g. of blue mussels and amphipods (Petersen and Malm 2006, Schröder et al. 2006). These will attract fishes and crustaceans and thus increase locally the biodiversity as well as potential prey available to top predators like harbour porpoises. Thus, changes in the habitat caused by the wind farm are, if anything, likely to have a beneficial effect on porpoises. Similar conclusions can be drawn from the fact that no commercial fishery is allowed in the wind farm area for safety reasons. Harbour porpoises might benefit from higher fish abundance inside the wind farm area.

2.5. Methods

2.5.1. Principle of operation and characteristics of T-PODs

The responses of harbour porpoises to offshore wind turbines were monitored by continuous registration of echo-location clicks in the wind farms using passive acoustical 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. 2-6). The vinyl material has the same impedance as seawater.

Fig. 2-6: 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, 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 sonars 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 sonars" – these noise sources are inevitably logged because boat sonars might show the same pitch as echolocation clicks of harbour porpoises.

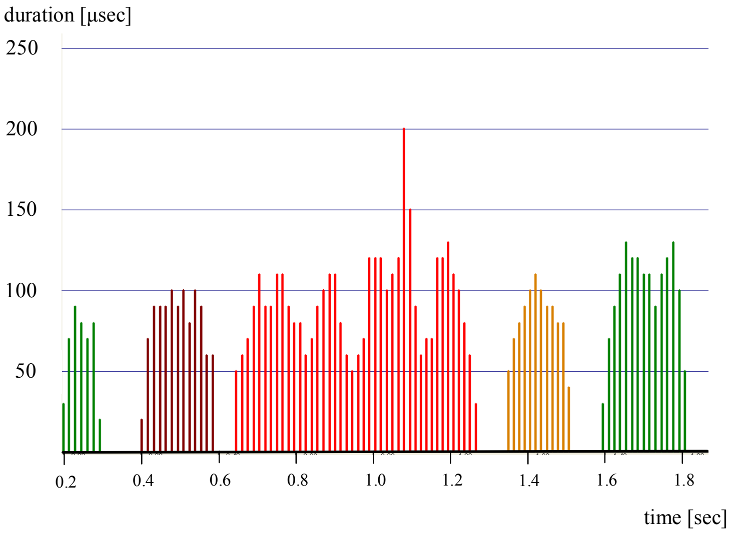


Fig. 2-7: Example of a registered porpoise click sequence divided by different click trains, shown as series of vertical bars (clicks), whereas the time [sec] is shown on the X–axis and the duration of a click is shown on the Y-axis.

All other clicks that did not occur in trains or did not fit into the scheme above are rejected and will not be shown.
The software presents different train classifications in different colours of clicks on the screen (Fig. 2-7). Red = CetHi; yellow = CetLo; green = doubtful; grey = very doubtful.
Special attention must be given to the classification "doubtful". In relatively quiet environments like in the Nysted area most of the trains classified as "doubtful" were neighboured by trains of higher classification categories. It is therefore obvious that click trains of this classification were also produced by harbour porpoises and could be included into data analysis.
In the Horns Rev area a lot of ambient noise clutter was recorded, possibly caused by moving sediments during periods of high current speeds. Especially grains of sand hitting the hydrophone produced high frequency noise which passed the filter and caused thousands of clicks within a few seconds. Fig. 2-9 shows that the number of clicks recorded is highly correlated with wind speed. As soon as a wind speed threshold of approximately 8 m/sec is

reached the number of recorded clicks shot up to values of more than 200 clicks per minute. The scan limit of 1440 clicks per minute was reached during periods of more than 12 m/sec wind speed (Fig. 2-10). The fact that increasing noise clutter occurred approximately three to four hours after increasing wind speed, indicates that it was most likely produced by moving sand (it takes a while before the inert sand groins come in motion).

In these noisy periods a lot of click trains classified as “doubtful” are likely to have a non-cetacean origin. In order to cope with this ambient noise clutter, threshold values were identified to define times at which harbour porpoise click sequences are possibly masked. The thresholds were set arbitrarily and need to be tested in future studies.

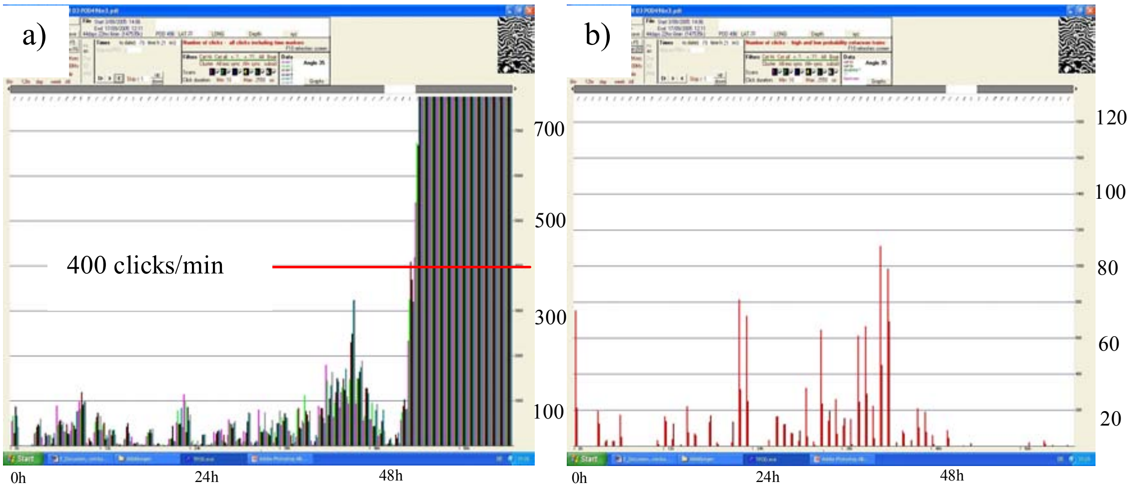


Fig. 2-8: Example of empirical identification of threshold assessing the logging effort: a) all clicks b) identified harbour porpoise clicks. Ambient noise clutter masks harbour porpoise echolocation click sequences and logging periods with more than 4,000 clicks per ten min were deleted. Be aware of different scale in Y-axis in a) and b).

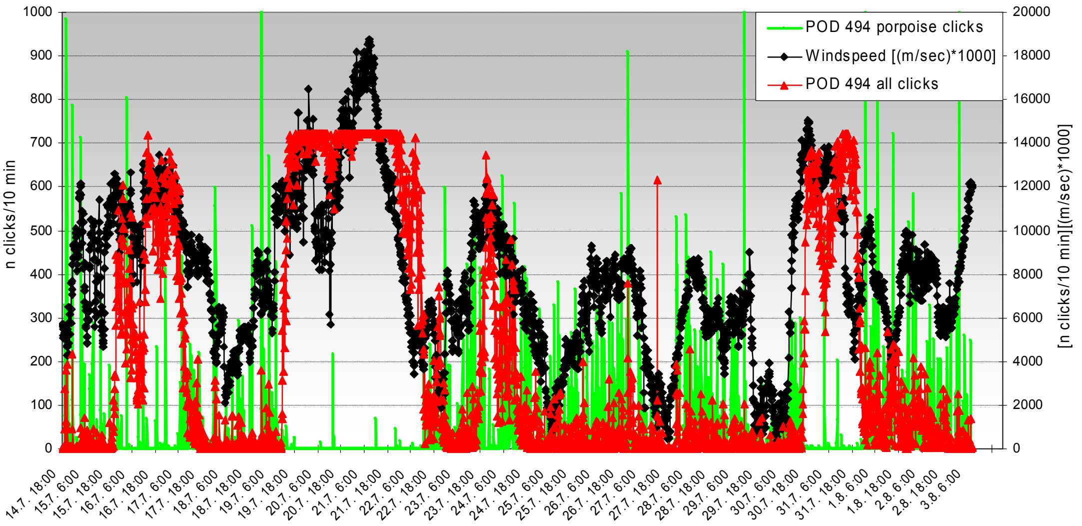


Fig. 2-9: Wind speed, all recorded clicks and harbour porpoise click trains identified by the algorithm of T-POD 494 in the time period July, 14th to August, 3rd.

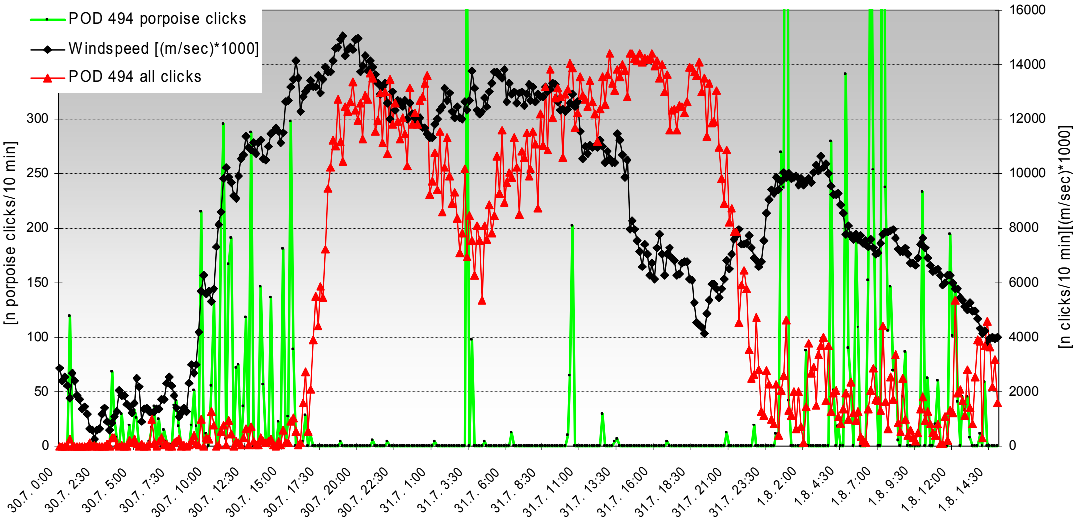


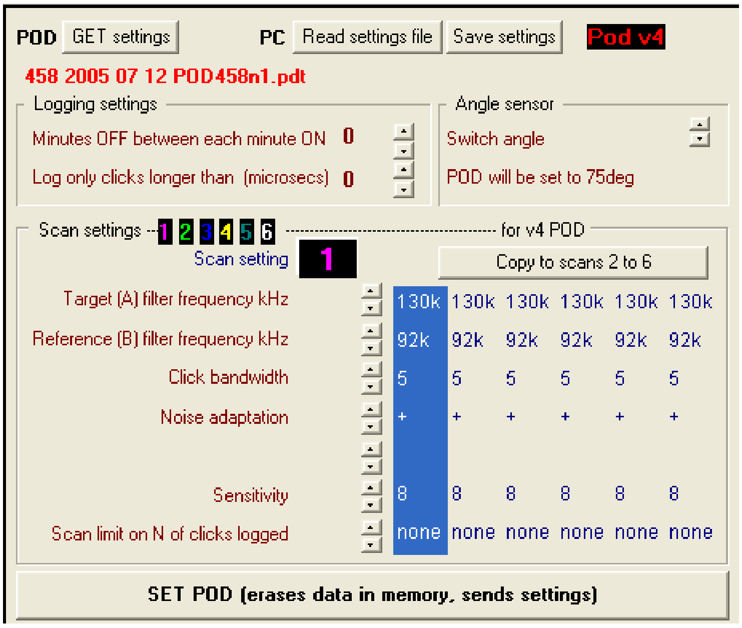
Fig. 2-10: Wind speed, all recorded clicks and harbour porpoise click trains identified by the algorithm of T-POD 494 in the time period July, 30th to August, 1st (extraction of fig. 33)

When no scan limit was set, we skipped logging periods with more than 14,000 clicks per minute (equivalent to 233 clicks per scan). Later, we introduced a scan limit and excluded periods with more than 400 clicks per minute (equivalent to 67 clicks per scan, Fig. 2-8). These times were identified and omitted from the logging effort. To keep both areas comparable we used only “CetHi “and “CetLo” click trains for this report, following the same method like our Danish colleagues (Tougaard et al. 2006a, b, 2005, 2004, Teilmann et al. 2001, 2002).

The TPOD.exe software enables to choose specific settings to cope with different target species and environments (Fig. 2-11):
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 (++ = on) and deactivated in the calmer conditions of the Nysted wind farm area (+ = off).
- 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.



458 2005 07 12 POD458n1.pdt

Logging settings

Minutes OFF between each minute ON 0

Log only clicks longer than (microsecs) 0

Angle sensor

Switch angle

POD will be set to 75deg

Scan settings -- 1 2 3 4 5 6 -------- for v4 POD

Scan setting 1

Target (A) filter frequency kHz	130k	130k	130k	130k	130k	130k
Reference (B) filter frequency kHz	92k	92k	92k	92k	92k	92k
Click bandwidth	5	5	5	5	5	5
Noise adaptation	+	+	+	+	+	+
Sensitivity	8	8	8	8	8	8
Scan limit on N of clicks logged	none	none	none	none	none	none

Fig. 2-11: Scan settings of the T-PODs. With the exception of the scan limit the settings were identical in the two wind farm areas Horns Rev/DK and Nysted/DK.

The noise adaptation facility has been developed recently and has not been approved so far. It was therefore not used in this study to keep the data set coherent and comparable. An influence of the perception of different intensities of echolocation clicks under variable ambient noise has not been addressed so far. (The screenshot of the settings shows a single '+' for noise adaptation OFF, instead of '++' for noise adaptation ON.)

The sensitivity was set to “8” (the medium value within the range from 1 to 16) in order to reduce overlapping recording ranges of single T-POD devices.

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°

Due to a considerable ambient noise at Horns Rev, probably caused by moving sediments (see above) the device settings were changed during the investigated period. To avoid memory replenishment within a few days due to millions of click clutter, a scan limit of 240 clicks within a scan of 9.4 second duration was set after July, 13th. In the Nysted area the environment is much calmer and no scan limit was activated (“none” in Fig. 2-11).

As we cut off times with a lot of disturbance by noise in the Horns Rev area, this difference in settings had no influence on the analysis of echolocation activity parameter, used in this report.

2.5.2. Mooring of T-PODs at sea

Within both wind farms, we used two arrays consisting of five T-PODs to investigate, whether harbour porpoises react either to a single wind turbine or to the entire wind farm (Fig. 2-12).

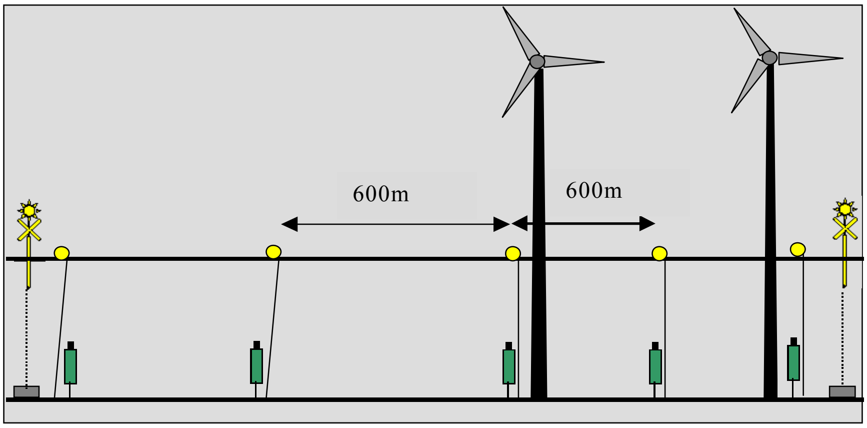


Fig. 2-12: Linear array of T-PODs (transect) from outside (left) to inside the wind farm (right). T-PODs inside the wind farm with different distances to the wind turbines.

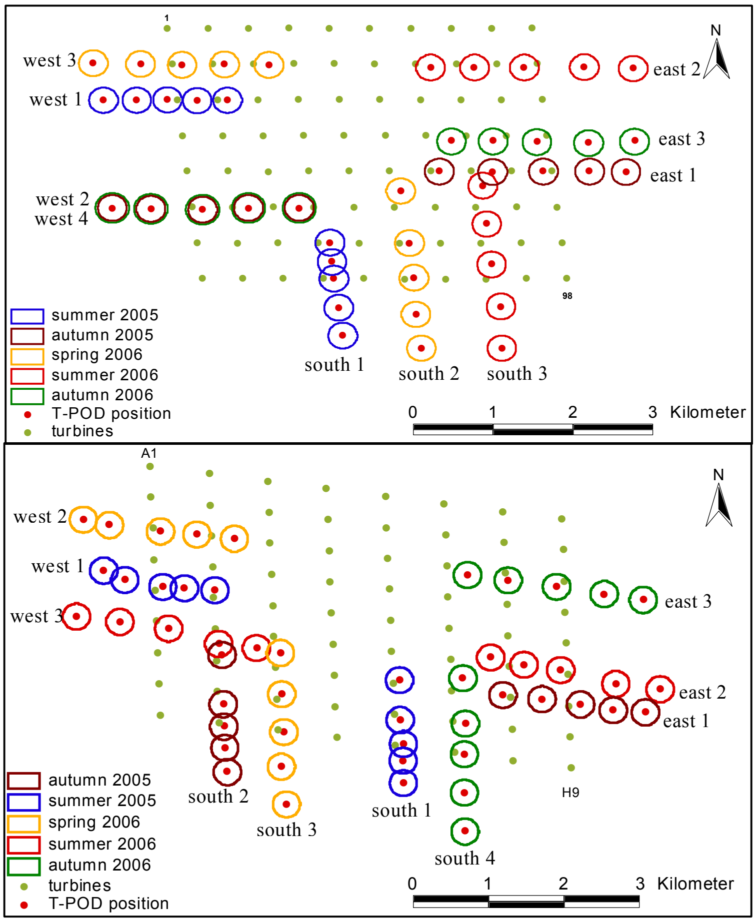


Fig. 2-13: Positions of T-PODs in 10 different rows in the wind farms during the investigation period with 200 m diameter around each T-POD. Two rows (10 T-PODs) were moored at the same time. Names of rows are used in the results. Top: Horns Rev. Below: Nysted.

One array consists of a row with five T-PODs placed approximately 600 m apart from each other. Two of the T-PODs within a row were moored inside the wind farm closer than 200 m to a single wind turbine, a third T-POD inside the wind farm was positioned in between two wind mills. The last two T-PODs were moored outside the wind farm up to a maximum distance of 1,400 m apart from the outer line of wind turbines and from noise measurements at operating turbines it is assumed, that they were placed outside the range of any possible disturbance from noise emissions.

Four times during the whole study period the two rows in both wind farms were changed to new positions (Fig. 2-13) in order to avoid site-specific gradients caused by differences in sea bed or depth and resulting in differences in the echolocation activity of harbour porpoises.

The exact detection range of a T-POD is not accurately known. However, with a known absolute detection threshold and a given sound absorption in sea water of 0.04dB/m at 135 kHz (Fisher & Simmons 1977) a theoretical maximum detection distance can be assessed following the passive sonar equation (equation 1,Villadsgaard et al. 2007).

$$(1) \qquad DT = SL - TL = SL - 20\log(R) - 0.04R$$

DT = detection threshold, SL = Source level, TL = Transmission lost, R = detection distance.

With a mean detection threshold (DT) of 127 db re 1µPa (peak to peak), measured by the DMM for the 24 T-PODs used in this study and a source level of 165 dB re 1µPa pp for a porpoise signal measured by Kastelein et al. (1999) the detection threshold would reach only 61 m. Measurements by Villadsgaard et al. (2007) revealed mean source levels from wild harbour porpoises of 191 dB re 1µPa pp. Referring to this source level, the detection distance would steeply increase to 413 m. Following the manufacturers instructions, the T-POD version 4 logs porpoise echolocation clicks up to a distance of 270 m when the sensitivity is set to “8” (www.chelonia.co.uk). As the porpoise signal is highly directional with a beam width of approximately 16° at 3 dB (Au et al. 1999), the maximum detection distance can only be received when the sonar of the harbour porpoise points towards the hydrophone of the T-POD. Therefore the detection range is supposed to decrease significantly if the sonar beam is not directed to the hydrophone. Tougaard et al. (2006) could show that the detection probability strongly decreased with distance of the animal to the T-POD. For version 3 T-PODs the authors determined an effective detection radius of 107 m with recordings in a maximal distance of slightly more than 300 m.

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-PODs during the same minute, the T-PODs were employed at a medium sensitivity and located with a distance of about 600 m from each other (Fig. 2-13). While handling the T-PODs under rough sea conditions, it was not always possible to deploy the T-POD systems at exactly equal distances from each other.

In both wind farm areas, we placed the T-PODs in the water column approximately one meter above the sea bottom (Fig. 2-14).

Fig. 2-14: Deployment of a T-POD at sea.

The T-POD normally has a sufficient buoyancy for staying in an upright position, but considerable inclination may occur with strong currents – especially in the North Sea. Inflatable yellow buoys indicate the position of the T-POD. A row of five hydrophone positions is marked by two official yellow warning buoys in the Baltic and three in the North Sea respectively.

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

Fig. 2-15: T-POD mooring system with two anchor blocks (tyres with concrete).

2.5.3. 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).

$$(2) \quad \text{Porpoise positive time per time unit [\%]} = \frac{\text{Number of time units with clicks}}{\text{Total number of time units}} = \frac{N\,\{x_t > 0\}}{N_{\text{total}}}$$

The parameter “porpoise positive time” has already been identified as a powerful tool to describe harbour porpoise click activity (Teilmann et al. 2001, 2002, 2003, Tougaard et al. 2004, 2005, 2006, Diederichs et al. 2004, 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, 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. With increasing time resolution a new problem especially in comparative studies occurs: Even small differences in the sensitivity of T-PODs used at the same position may result in significant differences between these PODs especially with smaller time units and in areas with low porpoise density. That means in areas with only a few recordings of harbour porpoises two T-PODs at the same position may log the same number of porpoise positive days (for example 3 days out of 10) but one could may log many more numbers of minutes with porpoise clicks than the other. Due to a slightly higher sensitivity one T-POD may log always a few minutes more during a “porpoise event” than the other T-POD. This difference may become more pronounced with smaller time units and lower porpoise density.

We therefore conducted a specific field calibration to find differences between the T-PODs used and to decide which time unit should be used for this study.

For an area west of Sylt, Diederichs et al. (2004) showed a high similarity between seasonal attendance patterns of porpoises derived from PPM/day with those based on densities calculated from observations during monthly aerial surveys. Such a relation of harbour porpoise density and PPM/day could also be statistically proofed by Rye et al. 2007. Tougaard et al. 2006 could calculate a first detection function for T-PODs on the basis of PPM and thus calculated absolute densities from T-POD data. The assumptions made in this study have to be validated in the future and cannot be translated to data of other studies.

However, they provide evidence that the parameter PPM is strongly correlated with porpoise density.

By comparison of results in different time units (for example PPH with PPM) it is possible to draw some conclusions about the activity of porpoises in an area. A high value of PPH in combination with a low value of PPM may indicate a high turnover rate with a short duration of stay. In contrast, a low value of PPH in combination with a high PPM may describe a longer duration of stay and a low turn over rate.

We analysed the diurnal rhythm of echolocation activity by considering PPM per hour in order to get the highest resolution. Because the daily click activity was compared with data from the same T-POD, the parameter PPM can be chosen for this analysis without causing imprecision by different T-POD sensitivities.

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. 2-16).

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.

Three parameters were extracted to describe porpoise activity on the basis of encounters (Fig. 2-16):

Encounter duration = number of minutes between two silent periods longer than ten minutes.

Number of encounter = number of encounters per day.

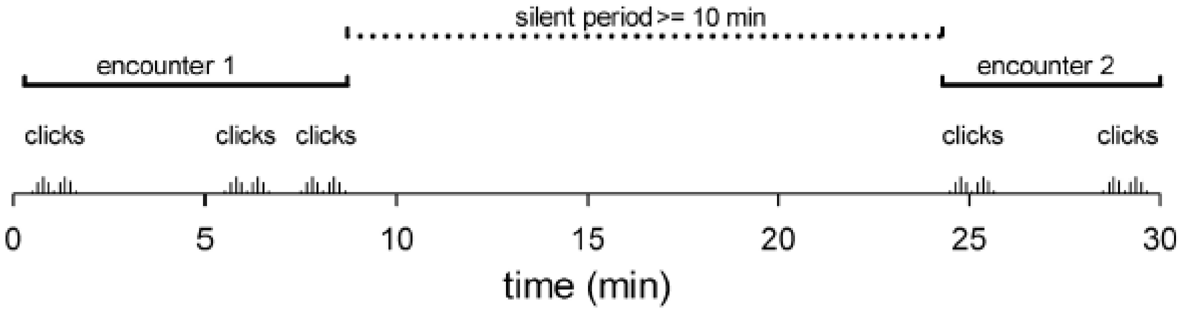


Fig. 2-16: Definition of “encounter” and “silent periods (= waiting time)” (from Benke et al. 2003).

Waiting time (= silent periods)

The time period between two encounters is defined as waiting time and to some extent related to the parameter encounter. The waiting time is the time interval in minutes between two encounters and per definition not shorter than ten minutes.

Because all parameters are highly correlated with each other and all describe a factor for relative abundance of harbour porpoises, we decided to analyse only ‘Porpoise Positive Time Units’ as the strongest parameter in relation to absolute density values.

2.5.4. Abiotic Parameter used for analysis

Results from T-PODs were related to different abiotic data on different time scales. From both wind farms, wind speed data were provided in a 10 minute resolution. Thus, all T-POD data based on days (PP10M/day) and hours (PPM/hour) could be correlated to the daily average and maximum of wind speed and to the hourly average and maximum wind speed, respectiveley.

For Horns Rev data of the water temperature in 4 m water depth were also available.

For the Nysted wind farm we analysed the power production of single turbines, which were in close range to deployed T-PODs, using a 10 minute time resolution. Due to a very close correlation between wind speed and power production we also used this data to find days where the turbines stood still although slow wind was blowing.

2.5.5. Calibration of T-PODs

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, Benke et al. 2002, Diederichs et al. 2002, Tougaard et al. 2005, Kyhn et al. 2006). Especially for this study, which focused on comparisons between single locations on a small temporal and spatial scale, it is necessary to ensure that each hydrophone produces comparable data. Therefore two different ways of calibration set ups were carried out for all hydrophones used in this study.

The absolute sensitivity of individual T-PODs was measured in a laboratory environment (tanks in Roskilde/DK and Stralsund/D). Additionally, *insitu* measurements of the relative sensitivity of single hydrophones were carried out by deploying a set of T-PODs close together in the field. To avoid losing T-PODs during field calibrations, these were conducted while a ship was anchoring a few hundred metres away for investigation on bird migration.

Test tank calibration

Testing cetacean click detection in a test tank, some general problems have to be considered: Tanks are mostly subject to significant reverberation. Therefore it is very important that threshold measurements will relate only to the directly transmitted signal with the highest intensity. So, echoes from the tank sides and the water surface should always be weaker and thus cannot be detected at sound pressure levels close to the transmitted signal. Due to the problem that sound sources and receivers are still mostly subject to significant resonance it is essential to make sure that the results of test tank calibrations are reproducible and do not vary with equipment or test numbers. Settings of the T-POD filters during test tank calibration should be identical to settings used for deployment in the field. In the beginning of this project, only two research groups were able to conduct test tank calibrations: The National Environmental Research Institute in Roskilde, Denmark and the German Oceanographic Museum (DMM) in Stralsund. T-PODs for this study were calibrated at both locations. Due to several measurements before and after the field season at the DMM, only data from there were analysed in more detail for this study.

NERI (Roskilde/DK)

In June 2005 colleagues from NERI calibrated 17 of 24 T-PODs used in the two wind farm areas in a laboratory test tank in order to measure their absolute sensitivity.

The calibration set-up was developed by NERI and an exact description can be found in Tougaard et al. (2005). In short, 108 artificial porpoise signals per minute were pulsed into the water by a waveform generator (18 pulses per every T-POD's nine seconds lasting scan). The sound level of these signals was stable during that minute and was decreased stepwise by 1 db re 1Vrms/µPa each minute. Calibration was started with sound levels well above the threshold of the T-POD hydrophone. The signal threshold was defined as the sound level where less than 50 % of the 108 clicks/minute were recorded by the T-POD.

The horizontal directionality of T-PODs was measured by sequentially measuring the T-POD sensitivity at four different angles of incidence in steps of 90 degrees.

German Oceanographic Museum (Stralsund/D)

Due to a co-operation agreement with the German Oceanographic Museum in Stralsund, we calibrated all 24 T-PODs, which had been used in the area, in a 0.7 m x 1.0 m x 1.0 m test tank at the Museum in Stralsund (Fig. 2-17). The concept of this test tank calibration was very similar to that of the NERI in Roskilde, using a series of real porpoise clicks with decreasing amplitude as calibration signal. For details we refer to Verfuß et al. 2004.

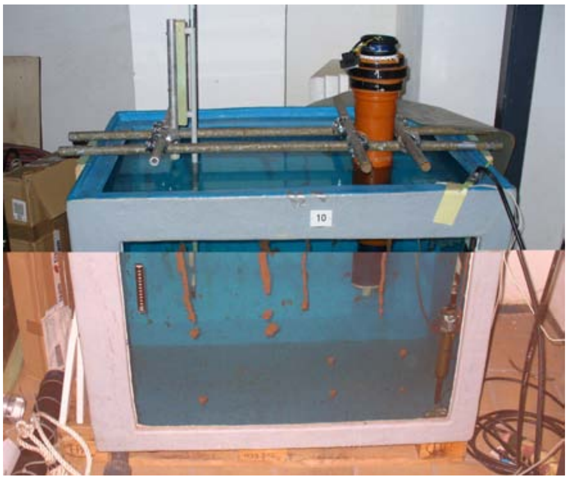


Fig. 2-17: Testtank setup

Field calibration

Up to now, it has not been possible to analyse the results of the test tank calibration with respect to potential differences in recorded echolocation activity parameters as for instance, “porpoise positive time per time unit”.

To be able to compare data from T-PODs of different sensitivity, we performed *insitu* inter-calibration experiments of bundled T-PODs in both wind farm areas. The aim of the experiments was to test for a correlation between the parameter recorded by different devices, allowing the calculation of correction factors to compare the results of different T-PODs despite varying sensitivities.

The calibration arrangement was similar to the general deployment. In order to minimise effects of interference or shadow up to six T-PODs were fixed together in a plastic frame and deployed 1.5 m above the sea bottom to a concrete anchor block (Fig. 2-18). In this frame the distance between the T-PODs ranged from 35 cm to 80 cm. During every session the composition of T-PODs within the plastic frame was different apart from the standard T-POD 475 which was used as reference and therefore fixed during every calibration experiment.

Fig. 2-18: Plastic frame for inter calibration experiments with 6 T-PODs during recovery.

For data analysis following parameters were extracted:

- Number of all clicks per hour (raw data without applying the algorithm);
- Number of PPM/hour using all porpoise classes defined by the algorithm (CetHi, CetLo, '?', '??');
- Number of PP10M/6 hours;
- Number of PPH/12 hours.

In a first step, the total calibration time for every single T-POD with the sum of the listed parameters was counted and compared with results of the standard T-POD.
In a second step, every T-POD was compared to the standard T-POD by calculating the slope of regression for the listed parameters. Every experiment was handled as an independent event.

2.5.6. Statistical analysis

Statistical treatment was performed using the software “R”, version 2.5.1 (http://www.r-project.org/).
To test whether different variables like wind, season, sensitivity, etc. have a significant effect on the presence of harbour porpoises a Generalised Additive Model (GAM, Hastie and Tibshirani 1990, Wood 2006) was fitted using the quasi-Poisson function and the MGCV package (Wood 2004) in R.
For testing if the variable wind has a significant effect on the presence of harbour porpoises dependent on the distance of the T-PODs to the turbines, a T-test comparing both distance

groups (inside/outside and close/far to turbines) was performed. A possible correlation of wind speed and power production of the turbines was tested by a Spearman-Rank correlation.

The influence of position of the T-PODs (inside or outside the wind farm) on presence of porpoises was first tested by applying a Generalised Linear Model (GLM; MCCULLAGH & NELDER 1989, CRAWLEY 2002) fitted to a quasi-Poisson distribution in R. Furthermore, we tested the effect of the T-PODs positions (inside or outside the wind farm and distance to the next turbine) on presence of porpoises comparing two Generalised Linear Mixed Effects Models (GLMM, e.g. Faraway 2006) applying the library lme4 (Bates and Sarkar 2007) fitted also to a quasi-Poisson distribution. In model 1, the fixed effect was substituted for one, the variables wind, sensitivity (= detection threshold from test tank calibration), year, month and (only in Horns Rev water temperature) were set as random effects to exclude possible effects on the distribution. In model 2 the variable ‘inside/outside the wind farm’ or ‘close/far away to the next turbine’ was added as a fixed effect including all random effects from model 1. We compared both models using ANOVA (Wood 2006). If the ANOVA for the two models is significant the factor PP10M must differ significantly between inside and outside the wind farm, or between distance close to single wind turbines and further away.

Analysing the echolocation activity during a 24-hour day the 24 hours of a day formed the predictor variable in a Generalised Additive Model (GAM, Hastie and Tibshirani 1990, Wood 2006) fitted to a quasi-Poisson distribution and the MGCV package (Wood 2004) in R.

Correlation between results of the calibration experiments in the test-tank and in the field were tested using a Spearman Rank correlation.

Significance limits for all statistical treatments were defined as follows (Tab. 1-2-2).

Tab. 1-2-2: Definition of significance levels:

Error probability p	Level of significance
≥ 0,05	not significant
< 0,05 (*)	significant
< 0,001 (***)	highly significant

2.6. Results

2.6.1. Calibration of T-PODs

Test-tank calibration

Due to different measuring instruments and different units used by NERI and DMM (e. g. “peak to peak” instead of “root mean square (rms)” for sound pressure levels) we decided to use only the results from Stralsund for further analyses. Here we tested all T-PODs used in this study. Both test tank calibrations showed consistency in the results, so that the differences in sensitivity between T-PODs within the POD generation V4 are rather small compared to older T-POD versions (Verfuß et al. 2004, Dähne et al. 2006). Fig. 2-19 shows the absolute detection threshold of all 24 T-PODs used in this study measured with sensitivity settings of 8. Mean threshold of the 22 T-PODs (V4) was at 127.5 dB re 1µPa pp.

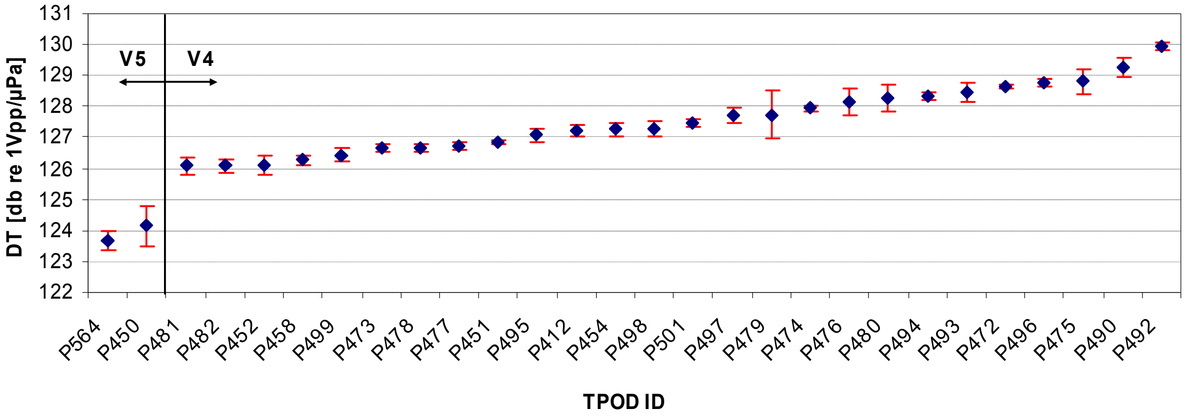


Fig. 2-19: Absolute detection thresholds (dB re 1Vpp/µPa) of all T-PODs used in this study with standard settings. The accuracy of measurement is about 2 db.

Maximum difference between highest and lowest sensitive T-POD (only V4) was 3.9 dB re 1µPa pp (Fig. 2-20). Verfuß et al. (2004) give a measurement error of approximately 2 dB, indicating that most of the T-PODs have no differences regarding the detection threshold. The two version 5 T-PODs with a modified type of hydrophone show on average a 3 dB lower detection threshold at sensitivity setting 8 of 124 dB re 1µPa pp.

Following equation 1 (p. 26) the theoretical detection distance between the highest and lowest sensitive T-POD (v4) varies about 16 % (67 m, with a source level for porpoise clicks of 191 dB re 1µPa pp, Villadsgaard et al. 2007) or about 31 % (21 m, with a source level for porpoise clicks of 165 dB re 1µPa pp, Kastelein et al. 1999). However, a translation of differences in detection thresholds regarding the parameter received by field measurements is not yet known.

Another result of the test tank is that nearly no T-POD showed deviation from a uniform omni-directional receiving beam pattern in the horizontal plane. Only three out of 24 T-PODs showed a standard deviation of more than one dB measured from 8 different positions. Two of these relative noncircular T-PODs are the least sensitive T-PODs No. 490 and 492 (Fig. 2-19).

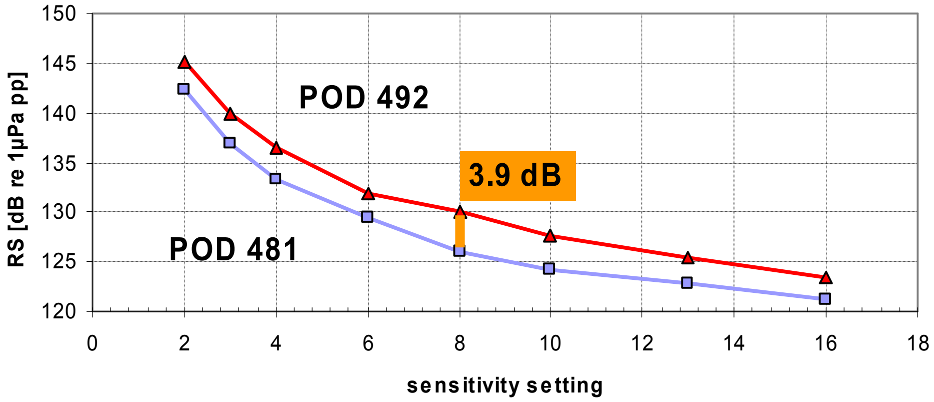


Fig. 2-20: Receiving sensitivities for the least sensitive V4 T-POD (red line) and the most sensitive V4 T-POD (blue line) in relation to different sensitivity settings. Sensitivity of 8 was used in this study.

In order to decide whether field data should be corrected for their differences in absolute sensitivities, a combined approach was used and the absolute detection threshold data were related to results of field calibrations.

Field calibration

Altogether, 17 field calibration experiments between spring 2005 and autumn 2006 were conducted. All T-PODs used in this study were moored next to the standard T-POD for one experiment (maximum: 5 experiments). Tab. 2-3 sums up the results from the field calibration experiments. With 101 hours (4.2 days) T-POD No. 496 had the shortest calibration time and T-POD No. 458 had the fewest recordings of porpoises with only 28 PPM during 116 hours (4.8 days). Therefore data from this T-POD were excluded from analysis of the parameter PP10M and PPH. T-POD No. 479 recorded more than one million clicks but only 45 minutes with porpoises during 138 hours (5.8 days). This is due to very noisy conditions during the calibration experiments when T-POD 479 was involved. The results for this T-POD are therefore possibly affected by false positive recordings and therefore also excluded from analysis relating test-tank to field calibration.

In a first step, field calibration data were analysed separately. All recorded clicks per hour (raw data) and, (after applying the algorithm of TPOD.exe), the parameters PPM per hour, PP10M per 6 hour and PPH per 12 hour of every calibrated T-POD were related to the standard T-POD 475. Each field calibration experiment was handled as an independent event. In Fig. 2-21 an example for the T-POD 481 is given for the parameter PPM/h. With $R^2 = 0.89$ a close correlation between the standard T-POD and POD 481 was found.

The regression slope of 1.075 differs slightly from 1 (when both PODs would have recorded exact the same) and indicates a slightly higher sensitivity of POD 481 compared to the standard T-POD.

Tab. 2-3: Results from field calibration experiments.

POD-ID	Calibration time [hours]	no. of clicks (raw data)	no. of PPH	no. of PP10M	no. of PPM
412	183	376689	133	383	1063
452	176	556424	41	64	129
458	116	21730	10	10	28
473	356	203125	54	67	137
474	220	489101	122	301	763
476	123	559225	85	274	793
477	238	57173	33	43	95
478	238	468077	34	46	96
479	138	1377712	20	29	45
480	210	205366	85	239	624
481	302	158457	33	44	101
482	174	521083	64	124	345
490	268	786700	42	66	126
492	164	825378	47	86	213
493	171	225673	82	166	460
494	175	469363	75	144	355
495	161	57604	27	38	77
496	101	396524	43	83	215
497	220	344912	30	50	96
498	171	208591	79	169	446
499	202	366857	44	71	135
501	264	1105381	87	170	424
564	124	798865	40	88	247

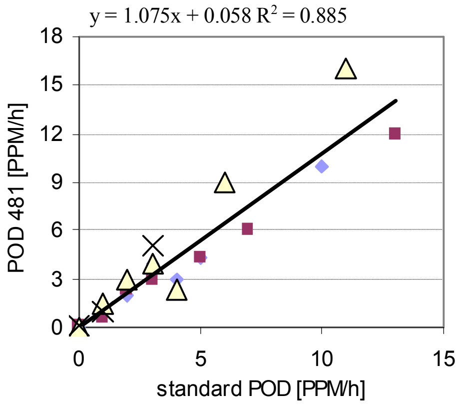


Fig. 2-21: Observed relationship of PPM per hour between the standard T-POD 475 (x-axis) and the T-POD 481. Different colours represent different calibration experiments.

In Fig. 2-22 for all T-PODs the regression slopes are plotted together with their CV for the parameter PPM/h. For 7 (of 23) PODs the deviation (inclusive the CV) is more or less than one. That means, for these 7 PODs a significant deviation from the standard T-POD is assumed and recordings of the parameter PPM from these PODs should always be beyond or beneath the values received by the standard T-POD. In order to proof our assumption - that with decreasing time resolution in the used parameter the differences between T-PODs caused by different sensitivities will also decrease - we compared all clicks for the four parameters PPM, PP10M and PPH regarding their deviation from the standard T-POD.

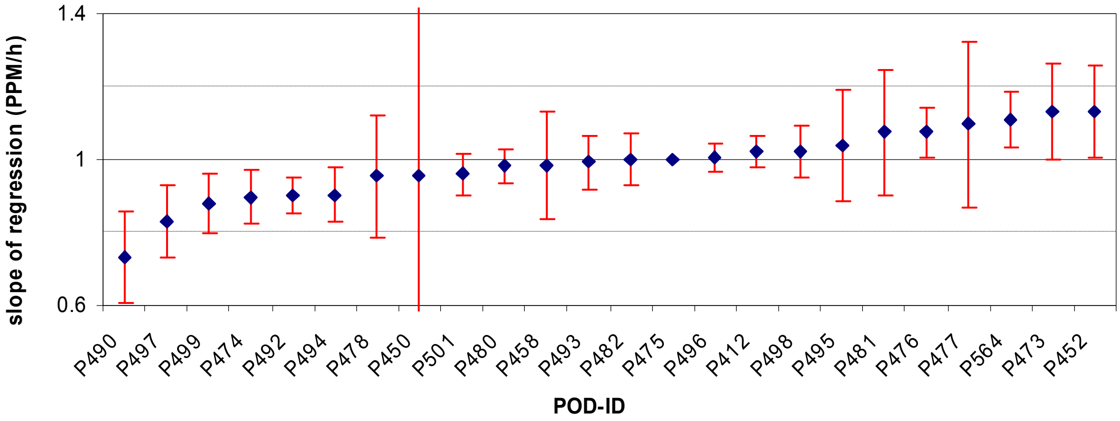


Fig. 2-22: Relationship of PPM per hour between the standard T-POD 475 and the field calibrated T-PODs used in this study expressed by the slope of regression incl. the 95 % confidence interval (red line).

The results show that the median deviation from the standard T-POD decrease from 13 % to 5 %, from the parameter “all clicks per hour” (as the parameter with the highest resolution) to PPH (as the most insensitive parameter on a time scale, Fig. 2-23).

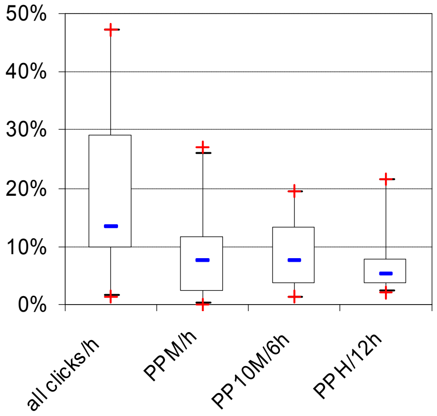


Fig. 2-23: Median (blue), Min, Max (red), 5/95 % (black) and 25/75 % (box) percentile for the deviation from the standard T-POD for four different parameter.

Although with 5 % PPH the smallest median deviation from the standard T-POD is still high. With more than 20 % the distance between minimum and maximum deviation is also still high for PPH and even higher than for the more sensitive parameter PP10M. PP10M is the parameter with a high time resolution and the smallest deviation between minimum and maximum and a relative small medium deviation of 7 %. For experimental studies like this, a medium deviation of 7 % is still very high, implying that differences between single T-PODs below that threshold could also be caused by differences in the sensitivity of the T-PODs. This difference between single T-PODs was further minimised by distributing the T-PODs randomly.

In a next step we related our findings from the field calibration to the absolute detection threshold measured in the test tank (Fig. 2-24).

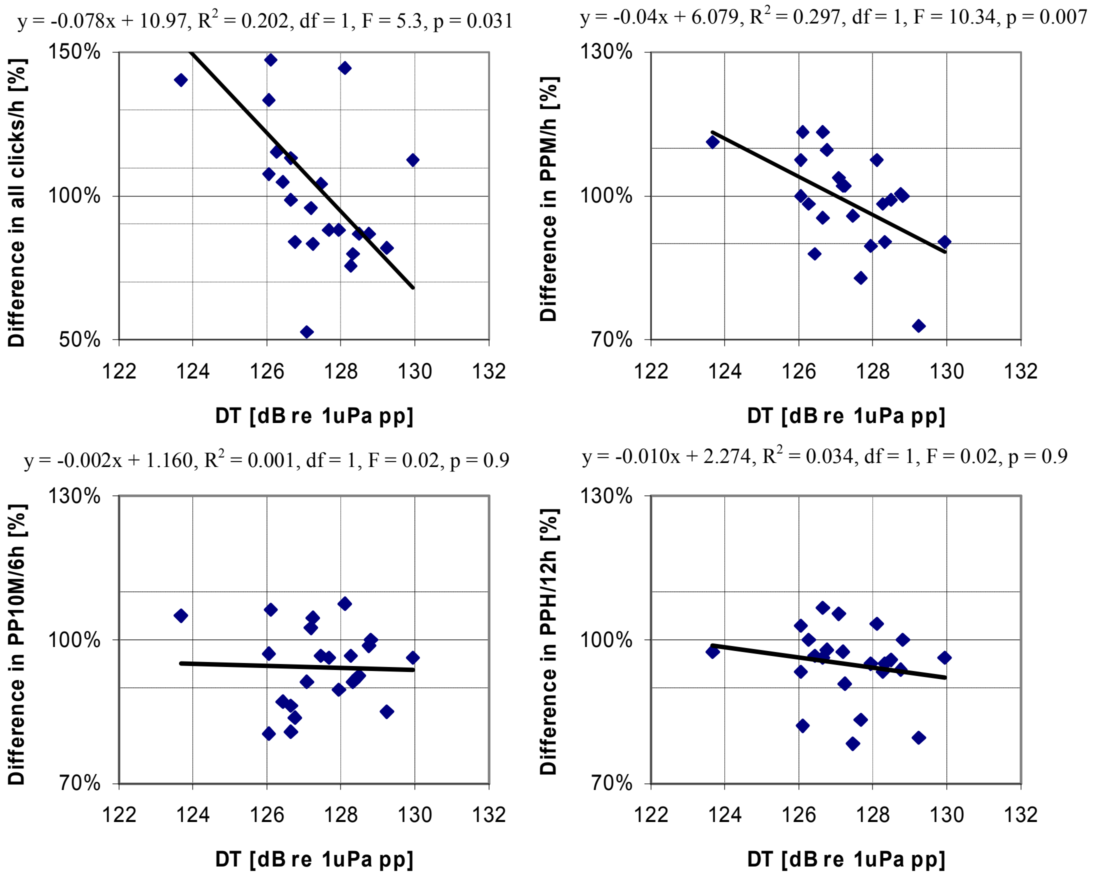


Fig. 2-24: Observed relationship between field calibration and acoustic sensitivity measured in a test-tank. Top left: All clicks/h to detection threshold; top right: PPM/h to detection threshold; bottom, left: PP10M/6h to detection threshold; bottom right: PPH/12h to detection threshold.

For the parameter “all clicks/hour”, a significant correlation between absolute detection threshold and number of recorded clicks occurred (Spearman-Rank, df=1, F=12.21, p=0.002). Also for the next parameter with a high temporal resolution PPM/hour, a weaker but still significant correlation between the absolute detection threshold and number of PPM/hour is apparent (Spearman-Rank, df=1, F=5.91, p=0.023).

Looking at the parameter PP10M/6hour and PPH/12hour, no correlation appears. As shown before, the deviation of 7 % on average from the standard T-POD is still high (Fig. 2-23), but the deviation is completely independent from the absolute detection threshold (Spearman-Rank, df=1,F=0.016, p=0.90).

We therefore decided to choose PP10M/day as a the best parameter to compare different T-PODs without any correction factors. It is a good compromise between a temporally high-scaled resolution and an adequate scale to avoid huge blur caused by small sensitivity differences of different devices.

Furthermore, results from field calibrations are strongly influenced by the duration of calibration and the number of harbour porpoises in the vicinity of the T-PODs. The more animals are recorded and the longer the T-PODs were calibrated, the more exact the measurements. Therefore, we recommend a larger field calibration data base for further comparable studies on the basis of T-PODs.

In order to check if our prediction, that the number of PP10M/day is not correlated with the T-POD specific detection threshold, we compared PP10M/day-values recorded in the Nysted area with the T-POD specific detection thresholds, measured in the test-tank at DMM. A Spearman's Rank correlation shows that in both data sets the correlation between PP10M/day and detection threshold is highly significant (Nysted: R= -0.087, n=3,595, p<0.001; Horns Rev: R= -0.079, n=2,038, p<0.001), which gives a clear indication that the measured detection thresholds show different sensitivities in the right direction. A Generalized Additive Model with PP10M per day as a function of the theoretical detection threshold when sensitivity is set to '8', is shown in Fig. 2-25.

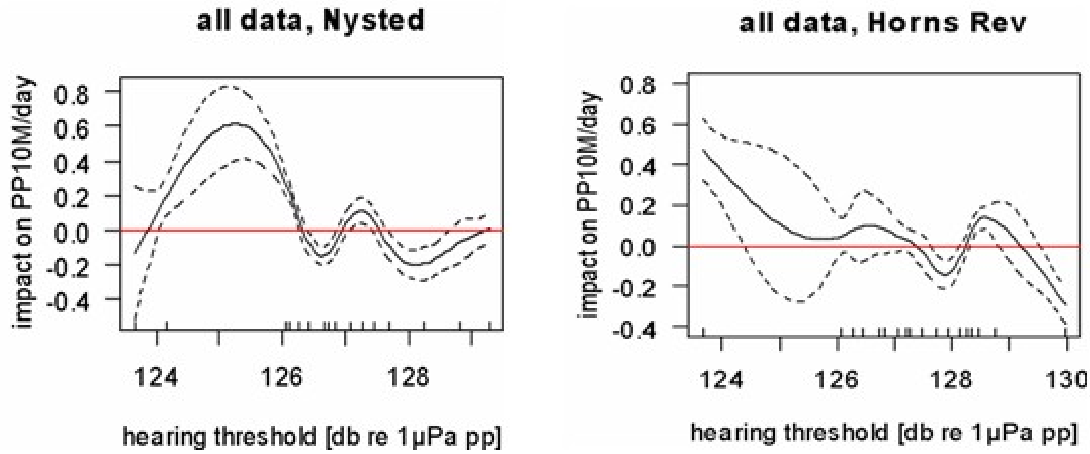


Fig. 2-25: GAM smoothing curves fitted to the individual sensitivity (detection threshold) of every single POD used in this study on the presence of harbour porpoises (pp10m/day) on the basis of all data from Nysted (left) and Horns Rev (right). Dashed lines represent 95% confidence intervals around the main effects. Sensitivity had a significant effect on the results.

According to a GAM, sensitivity expressed by the theoretical detection threshold has a high significant impact on the number of recorded PP10M/day (Nysted: F=14.09, p<0.001, n=3,595; Horns Rev: F=11.69, p<0.001, n=2,036). The non linear curve in both cases indicates that other factors may play important roles and/or that not all sensitivity measurements in the test tank can be translated into a more or less sensitive T-POD regarding the number of recorded PP10M/day. In conclusion, PP10M/day is a parameter, which gives a high temporal resolution of the data while a correlation with the POD specific detection thresholds still exists. In order to avoid that sensitivity cause an error when estimating the influence of the wind farm it should be incorporated into the models as an explanatory variable.

2.6.2. Nysted

POD deployments

From June, 12th 2005 to November 10th 2006, a total of 17 T-PODs were deployed in the area of the offshore wind farm Nysted. We changed the rows four times, which resulted in a total of 10 different row experiments (Fig. 2-26). The T-PODs logged continuously for periods of several weeks. Over both years, all T-PODs recorded 3,591 days in total where POD-data were obtained resulting in more than 84,000 hours or over 5 millions minutes. Separated by years, the T-PODs recorded a sum of 1,627 days in 2005 and 1,964 days in 2006. Only during the last survey between September, 12th and mid of November 2006 losses of data and/or devices led to one position without any data recordings (position 2 in row east3).

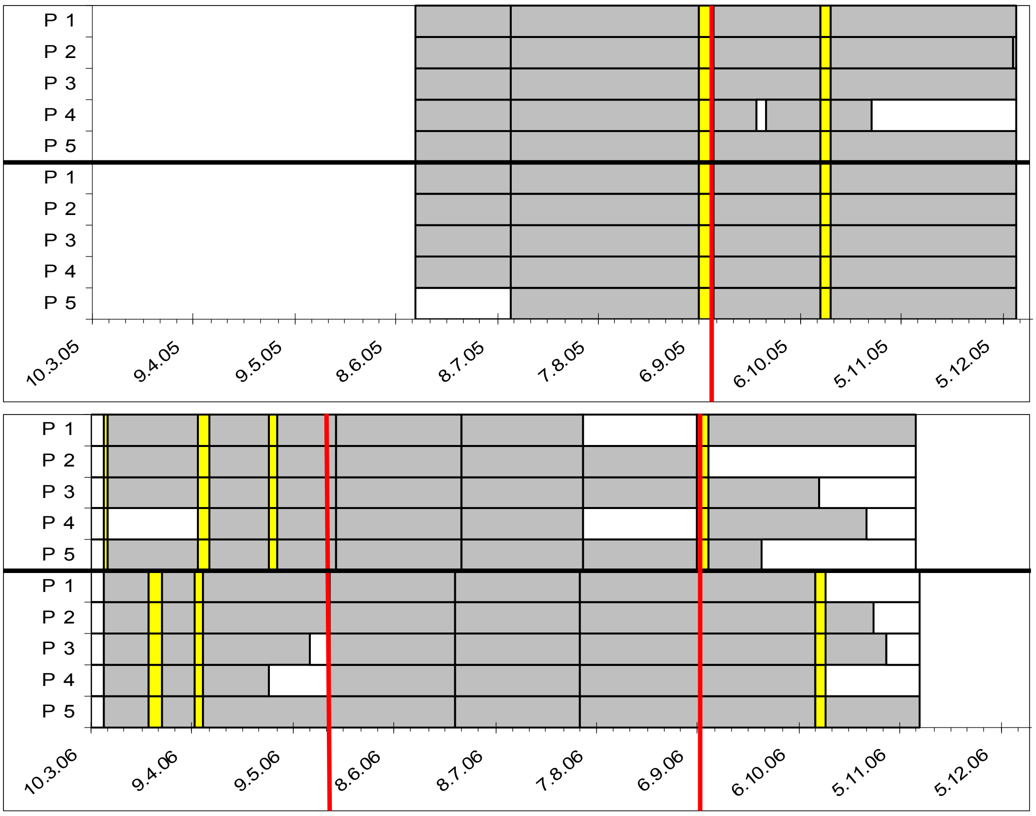


Fig. 2-26: Recorded data of PODs in the years 2005 (above) and 2006 (below) placed in the offshore wind farm Nysted. P1-P3 = within the offshore wind farm; P4, P5 = outside of the offshore wind farm. Vertical red lines show changes of rows. Grey bars: gathered POD-data; white bar: no data; yellow bar: field calibration.

Although some further data gaps occurred due to equipment loss or damage, for all 10 experiments enough data were collected for a robust analysis.

2.6.2.1. Temporal distribution pattern

The first analysis of „porpoise positive time“ as the parameter for the presence of harbour porpoises showed that the T-PODs recorded harbour porpoises nearly daily at all positions inside and outside the wind farm area (94 %, Fig. 2-27). If the temporal solution of days is elevated to the smallest analysed unit of minutes, it can be seen that their presence within the investigation area of the PODs was on average very short. In the offshore wind farm Nysted, harbour porpoise signals were recorded on average at 43 minutes of a 24-hour day distributed over 7.4 hours. This lead to an average stay of the animals in the detection radius of the T-PODs of 5.8 minutes. Seven percent of all “10-minute blocks” were recorded with at least one porpoise signal. We use this parameter in the following sections for the data analysis.

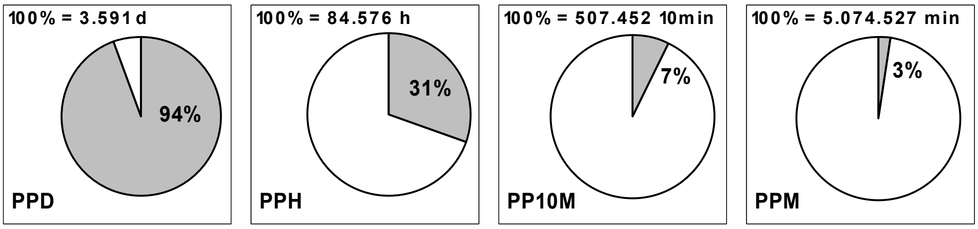


Fig. 2-27: Sum of “porpoise positive time” of all devices for different time units in the offshore wind farm Nysted

Before we compare the number of recorded PP10M between inside and outside the wind farm in order to assess the influence of the wind farm on harbour porpoises we check the effect of different factors beside the wind farm itself.

2.6.2.2. Seasonality

Recordings of the presence of harbour porpoises show clear seasonal effects within the whole study area (Fig. 2-28, Fig. 2-29). Seasonal differences with a maximum in summer and a minimum in autumn/winter as well as differences between years could be shown. In the area of Nysted, the highest number of harbour porpoise contacts were measured in July 2005 as well as in October 2005. In the following year, only one maximum of the recorded time with porpoise signals was measured in July (Fig. 2-28). The variance in the figure shows that the daily values are highly variable. Days with many porpoise recordings may be followed by days with only very few recordings. This variability is much more pronounced during summer resulting from higher porpoise density in the area.

The same data from Fig. 2-28 were fitted in a GAM with “months” forming the predictor variable, separated by the years 2005 and 2006 (Fig. 2-29). The figure confirms that seasonality has a strong influence on the occurrence of harbour porpoises in the Nysted area. Over both years, the model explained 12.4% of the total variance of the data.

To cope with this factor in the comparison between inside and outside the wind farm, a twofold approach was used: First, we compared results of experiments, each not lasting for longer than 8 weeks, in order to avoid a strong seasonal influence. Second, for a more global trend, a mathematical solution was applied by using Linear Mixed-Effects Models (lmer, Crawley 2002). This allows for different intercepts for the different months as a random effect.

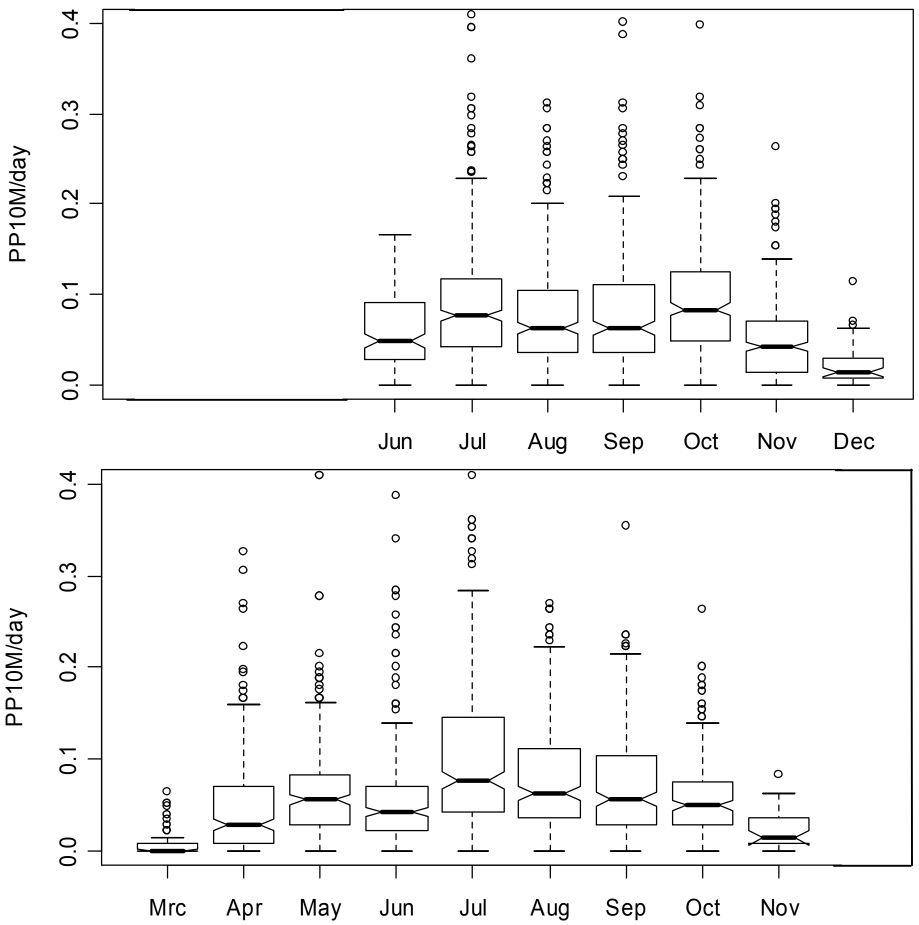


Fig. 2-28: Seasonal medians (months) for the indicator "Porpoise positive 10minutes per day" (PP10M/day) for the years 2005 and 2006 in the Nysted wind farm.

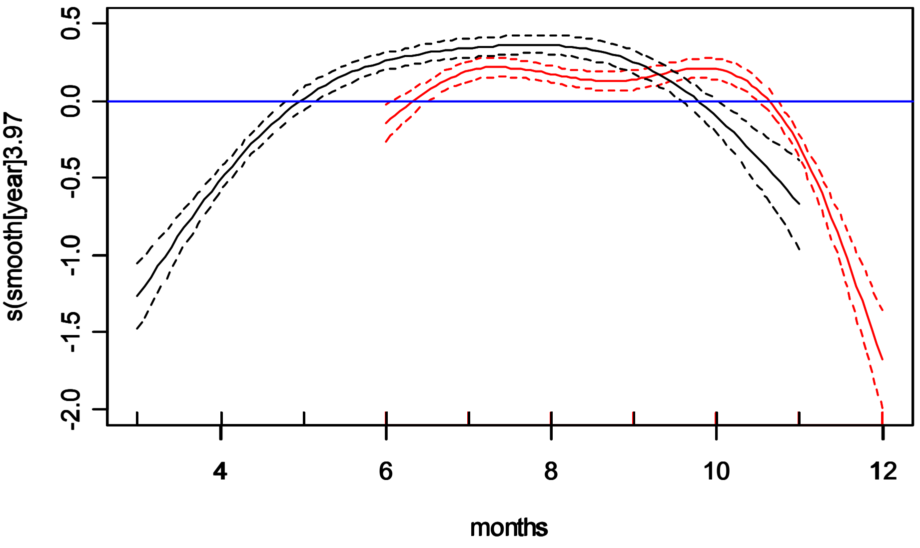


Fig. 2-29: GAM smoothing curves fitted to months of a year on the presence of porpoises (pp10m/day) during the years 2005 (red line) and 2006 (black line) for the Nysted wind farm area. Dashed lines represent 95% confidence intervals around the main effects. Seasonality had a strong effect on presence of harbour porpoises.

2.6.2.3. Influence of wind speed and turbine power production

The influence of wind speed on the daily amount of PP10M was tested by using a GAM setting with "daily average wind speed" as explanatory factor. Looking at all data, this parameter significantly influenced porpoise recordings (F=16.96, p<0.001, n=3,595). Days with wind speed below 6 m/sec had a distinct positive effect on porpoise recordings whereas days with wind speed between 7 and 9 m/sec and above 11 m/sec had a slightly negative effect on the number of recorded PP10M/day (Fig. 2-30).

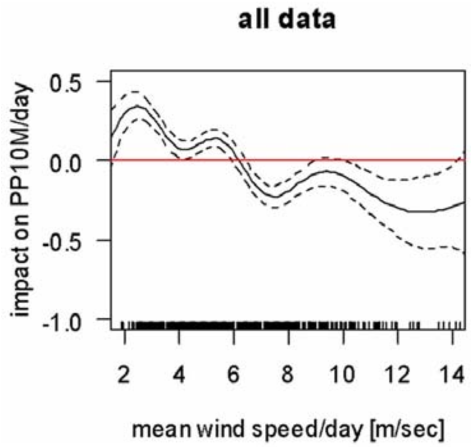


Fig. 2-30: GAM smoothing curves fitted to mean wind speed per day as an explanatory variable on PP10M/day. Porpoise density is represented as a function of wind speed depicted for a GAM. Dashed lines represent 95 % confidence intervals around the main effects.

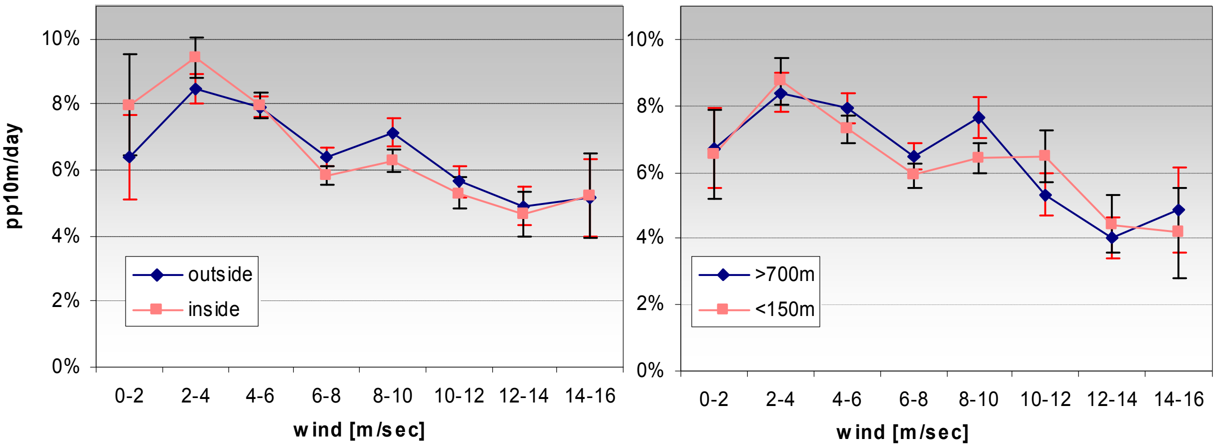


Fig. 2-31: Number of recorded PP10M/day during different wind speeds close to a single turbine and more than 700 m away from a turbine (right) and inside the wind farm compared to outside the wind farm (left). Error bars indicate standard error.

The general picture of the influence of wind speed on the recorded number of PP10M is very similar comparing T-PODs close to single turbines with T-PODs more than 700 m away and also comparing T-PODs deployed inside the wind farm with T-PODs deployed outside the wind farm (Fig. 2-31). No statistical significant difference is detectable between the different distance classes (T-test: inside/outside: T=0.104, df=14, p=0.919; <150m/>700m: T= -0.045, df=14, p=0.964). Comparing the curves of ‘inside’ with ‘outside the wind farm’ (Fig. 2-31, left) the only period when a slight difference in PP10M/day is remarkable was at the two lowest intervals between 0 and 4m/sec. In this case a strong correlation exists between wind speed and number of recorded PP10M/day (Spearman Rank, inside: R= -0.119, n=1412 p<0.001; outside: R= -0.116, n=1372, p<0.001) with most harbour porpoise recordings at low wind speeds between 2 and 4 m/sec and less recordings with increasing wind speed. Minima were reached during the two highest wind speed classes above 12 m/sec. For the factor ‘distance to the turbines’ (Fig. 2-31, right) a significant correlation between wind speed and number of recorded PP10M/day was observable (Spearman Rank, <150m: R= -0.082, n=903, p=0.006; >700m: R= -0.111, n=738, p=0.001) with the same direction: The more wind the less recordings of harbour porpoises, independent from the distance of the T-POD to the turbines. This finding is independent from season as in the summer months like July the effect is still highly significant with more recordings during low wind speed (Sperman Rank; R= -0.132, n=275, p=0.014).

The same result was found for the influence of turbine power production (Fig. 2-32): A significant correlation between power production and number of recorded harbour porpoises occurred for all distance classes (Spearman Rank, inside: R= -0.138, n=1044, p<0.001; outside: R= -0.112, n=1400, p<0.001; Spearman Rank, <150m: R= -0.114, n=908, p<0.001; >700m: R= -0.106, n=759, p=0.002).

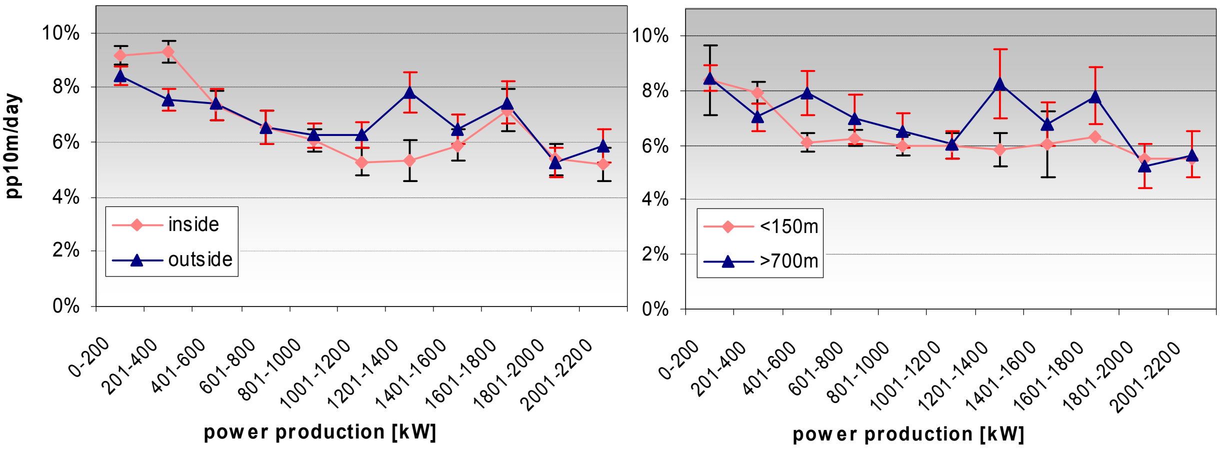


Fig. 2-32: Number of recorded PP10M/day during times with different power production close to a single turbine and more than 700 m away from a turbine (right) and inside the wind farm compared to outside the wind farm (left). Error bars indicate standard error.

During days with high power production, fewer porpoises were recorded than during days with low power production. This finding is not surprising given a significant interaction between wind speed and power production analysed by a GAM (F=3.83, p<0.001). The strong, positive correlation between wind speed and power production (Spearman Rank: R=0.908, p<0.001, n=3,133) supports this result. A maximum in recorded PP10M was always observable during times with low power production. However, even though no statistical significant difference between the distance classes was detectable (T-test, inside/outside: T= -0.437, n=14, p=0.667; <150m/>700m: T= -1.435, n=14, p=0.167), for the PODs outside the wind farm, inside the wind farm (but here less pronounced) and for the PODs far away from single turbines, the number of recorded porpoises increased again with higher power productions. Only close to single turbines no difference was detectable between times when the turbines were producing more than 400 kW energy.

Turbine power production was used for finding days when the turbine next to the T-PODs stood nearly still (< 100 kW power production), independent of weather conditions. In Fig. 2-33 days without power production of turbines next to the T-PODs were compared with days when turbines were operating close to full capacity. There was still no difference in PP10M/day comparing two Linear Mixed Effects Models by an ANOVA with season (month), years and sensitivity as random factors (days with turbine power below 100 kW: Chi²=0.6906, df=1, p=0.4060, n=239, days with turbine power beyond 1,500 kW: Chi²=0.3748, df=1, p=0.5404, n=227).

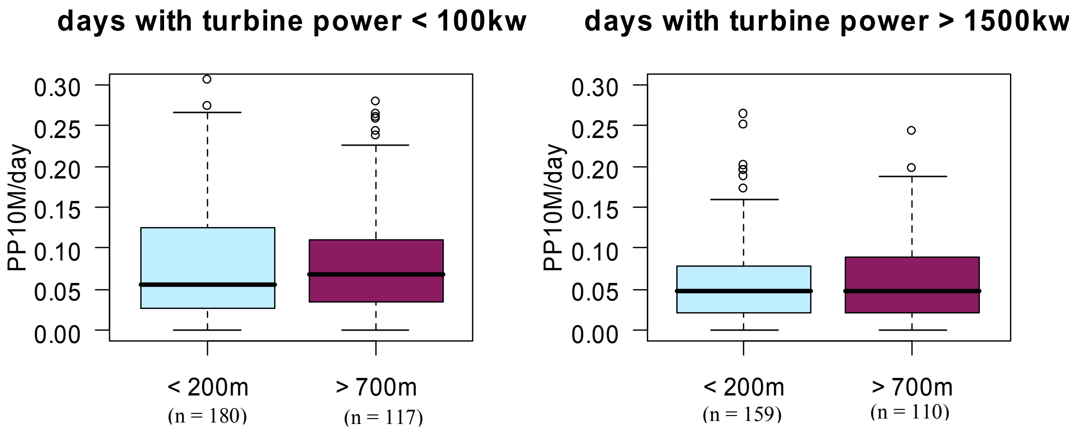


Fig. 2-33: Median PP10M/day close (< 200 m) and far away (> 700 m) to the next wind turbine in the Nysted wind farm area separated for days without power production (turbine stand still, left) and high power production (right).

The picture between inside/outside and close/far away from turbines is very conform. A maximum in number of recorded PP10M/day was always reached at low wind speeds (< 4 m/sec) and a minimum was always reached at high wind speeds (> 11 m/sec). The same picture is evident for the comparison of power production with PP10M/day. All this findings show that wind and parallel to wind also turbine power production have a significant effect on the number of porpoise recordings. This effect is independent of the position of the T-PODs in relation to the wind farm.

Between June 25 and July 2, 2006 all turbines in the offshore wind farm Nysted were temporarily shut down due to maintenance. This special case was assessed for possible changes of presence of harbour porpoises within the wind farm area. In the week of the shut down, the mean presence of harbour porpoises was determined and the results were compared to three weeks before and after (Fig. 2-34). Inside the row east2 no difference at all could be detected between the 7 weeks (ANOVA, F=1.940, n=97, p=0.08). Outside the wind farm the only significant difference of week 0 occurred to the week after this event (ANOVA, F=4.32, n=97, p<0.001). In row west3 was no difference of week 0 for both groups detectable compared to the three weeks before that event. Week 1 and 3 after the week with stand still of all turbines showed in both cases significant more activity (ANOVA, inside: F=9.04, n=97, p<0.001; outside: F=9.00, n=97, p<0.001). Traffic of service ships did not differ from the ordinary service traffic as always two installation ships per day visit the wind farm. Whereas in the row east2 in 6 of 7 weeks more activity was measured outside the wind farm, was it converse in row west3, when at 6 of 7 weeks more activity was measured inside the wind farm.

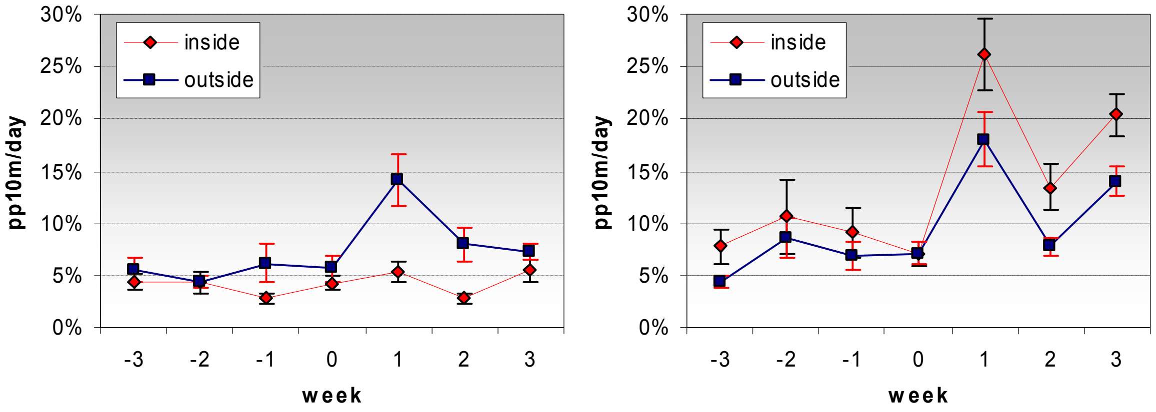


Fig. 2-34: Presence of harbour porpoises inside and outside of the offshore wind farm Nysted in the rows east2 (left) and west3 (right) in different weeks before and after the shut down of turbines (week 0).

We modelled the daily porpoise activity measured by PP10M per day as a function of these explanatory variables using General Additive Models (GAM) with non-parametric smoothers (Crawley 2002). According to this GAM, we can conclude that the variables wind speed, the interaction of wind speed with power production, seasonality (months) and specific detection threshold of the single T-PODs (sensitivity) have a significant impact on the number of recorded PP10M per day (Tab. 2-4). All variables as well as the interaction between wind and power production appear highly significant, but still only 24 % of the deviance can be explained by this model.

Tab. 2-4: Results of the GAM-statistics for the smoothing terms ‘wind’, ‘thresh’ and ‘season’ (months).

smoothing term (n = 3,133)	F	p
T-POD sensitivity	14.39	< 0.001***
windspeed	9.68	<0.001***
interaction (windspeed, power production)	3.83	<0.001***
season (month)	89.14	<0.001***

2.6.2.4. Influence of the wind farm:

Spatial distribution pattern (Intra-row comparisons)

For the comparison of harbour porpoise presence inside and outside the wind farm, we pooled the data from the two innermost T-PODs and plotted them against the pooled data from the two T-PODs outside the wind farm (Fig. 2-35). According to the GLM, there is no difference within data from both years in the distribution pattern between inside and outside the wind farm (n=2,839, p=0.627).

This picture is still present after randomising the effects of wind, year, T-POD specific sensitivity and seasonality (months) using a Generalized Linear Mixed Effect Model (LMER) and comparing both models by applying an ANOVA (Chi²=0.1312, df=2, p=0.937, n=2,840).

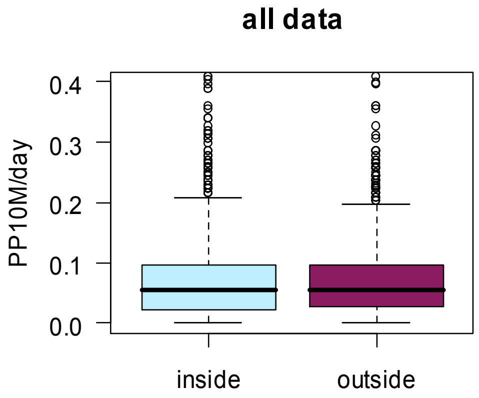


Fig. 2-35: Median PP10M/day outside and inside the Nysted wind farm area for all data pooled from 2005 and 2006 (n = 2,840).

In order to avoid overlooking site specific differences in porpoise activity between inside and outside the wind farm, we compared the recorded PP10M per day for 10 experiments by dividing the data set into the 10 single rows. For every comparison within a row a Generalised Linear Model (GLM) was calculated. In eight experiments a significant difference between inside and outside the wind farm occurs according to the GLM (for statistics see Fig. 2-36). But the pattern is not consistent. Five of ten rows show a higher porpoise density outside the wind farm but three rows show more time with recorded porpoises inside the wind farm. Two rows show no difference at all.

In a next step the variables wind, season and sensitivity were incorporated into the analysis by calculating two LMER for each row, comparing inside with outside the wind farm. After the comparison of both models by an ANOVA in any row no more difference between inside and outside the wind farm is apparent (Tab. 2-5). The variable ‘inside’ or ‘outside’ the wind farm does not have any influence on the number of recorded PP10M/day.

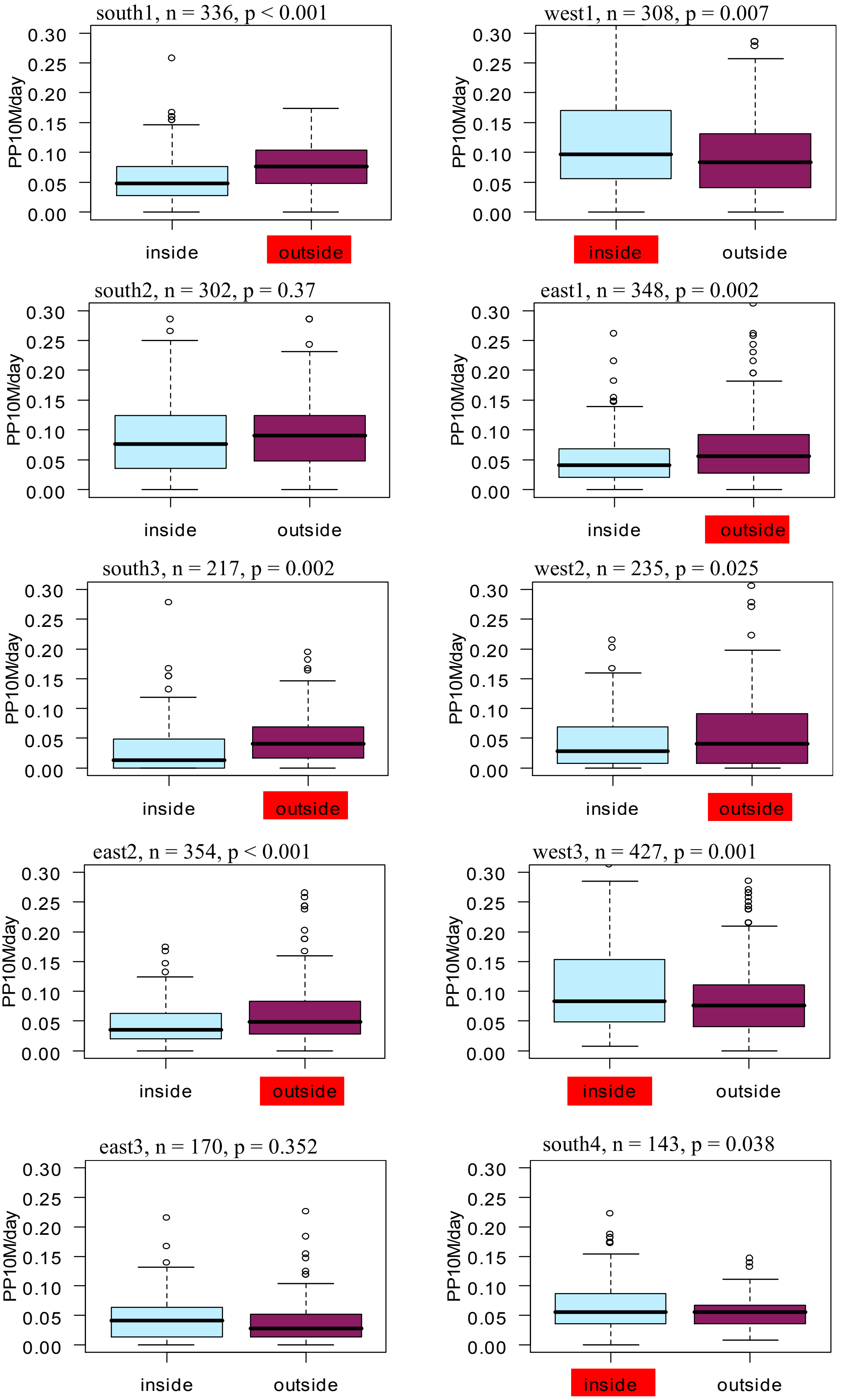


Fig. 2-36: Median PP10M/day outside and inside the Nysted wind farm area for 10 experiments. Two rows in a line were deployed during the same time. The wind farm site with significantly more recorded porpoises is marked by a red bar.

Tab. 2-5: Results of the ANOVA comparing the two Linear Mixed Effect Models with wind, season and sensitivity as random factors for inside and outside the wind farm.

experiment	Chi²	Df	n	p
south1	0.4237	1	336	0.5151
west1	0.4189	1	308	0.5175
south2	0.0358	1	302	0.85
east1	0.3939	1	348	0.5303
south3	0.4989	1	217	0.48
west2	0.3494	1	235	0.5544
east2	0.5662	1	354	0.4518
west3	0.5113	1	427	0.4746
east3	0.0234	1	170	0.8784
south4	0.1199	1	143	0.7291

For every deployed T-POD the exact distance to the next turbine was stored in the database. In order to check if the devices, which were moored in close vicinity to single turbines, recorded less porpoises than the T-PODs which were moored in a distance of more than 700 m to the next turbine, we compared porpoise density (expressed by PP10M/day) for distances beyond 150 m to single turbines with distances over 700 m.

When splitting the data set into 2005 and 2006 for both years, a difference with significantly more recorded porpoises at a larger distance to the turbines occurred (Fig. 2-37, GLM, 2005: n=855, t=2.498, **p=0.0127**; 2006: n=742, t=3.137, **p<0.00177**). After inclusion of the variables wind, season and sensitivity this difference is no longer apparent (ANOVA, 2005: Chi²=0.3329, n=855, p=0.564, 2006: Chi²=0.4775, n=1,045, p=0.4896).

Analysing single experiments, the non-consistent picture from the comparison of inside to outside the wind farm changes slightly: According to a GLM, in five experiments (out of 10) significantly more porpoise positive time was measured at larger distances and only in one experiment it was converse. In four experiments no difference at all could be verified. Incorporating the variables wind, season and sensitivity by calculating LMERs, leads to no differences at all. All 10 experiments show no significant difference between the harbour porpoise activity measured close to single turbines compared with the activity measured far away (Tab. 2-6).

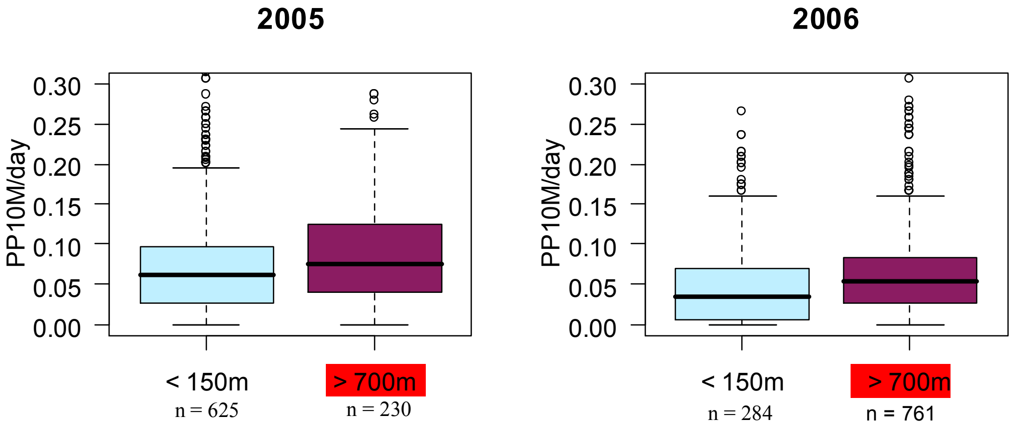


Fig. 2-37: Median PP10M/day close (< 150 m) and far away (> 700 m) to the next wind turbine in the Nysted wind farm area separated for the years 2005 (left, n = 855) and 2006 (right, n = 1,045). The area with significantly more recorded porpoises calculated by a GLM is marked by a red bar.

Tab. 2-6: Results of the ANOVA comparing the two Linear Mixed Effect Models with wind, season and sensitivity as random factors for T-PODs deployed < 150 m and > 700 m to the next turbine.

experiment	Chi²	Df	n	p
south1	0.557	1	196	0.4555
west1	0.0602	1	224	0.8063
south2	0.1997	1	261	0.655
east1	0.4293	1	174	0.5123
south3	0.5741	1	179	0.4486
west2	1.2707	1	88	0.2596
east2	0.1007	1	249	0.751
west3*)	0.0929	1	214	0.7605
east3	3.2369	1	96	0.072
south4	0.0298	1	96	0.863

*) In row west3 values < 200 m were included.

In conclusion, for the Nysted area a very weak effect of the distance of the T-PODs could be shown with more recordings of harbour porpoises at larger distances to single turbines. This effect is only apparent when no variables affecting the recordings are included. If so, no more differences can be recognised.

Inter-row comparisons

By comparing the relative porpoise density measured by PP10M/day between the different rows (when T-PODs were deployed at the same time) a clear difference between these areas in four experiments (out of five) showed up, according to a GLM (Fig. 2-38,Tab. 2-7). The average of the two rows deployed at the same time differs up to factor 2, which is a much greater difference than between inside and outside the wind farm during the same time.

Tab. 2-7: Results of the GLM statistics for the comparisons of PP10M/day of different rows during the same time.

Experiment No.	rows	n	t	p
time 1	west1/south1	812	11.65	<0.0001***
time 2	south2/east1	824	-5.97	<0.0001***
time 3	south3/west2	575	3.66	0.0003***
time 4	east2/west3	995	12.19	<0.0001***
time 5	east3/south4	389	-0.79	0.4305

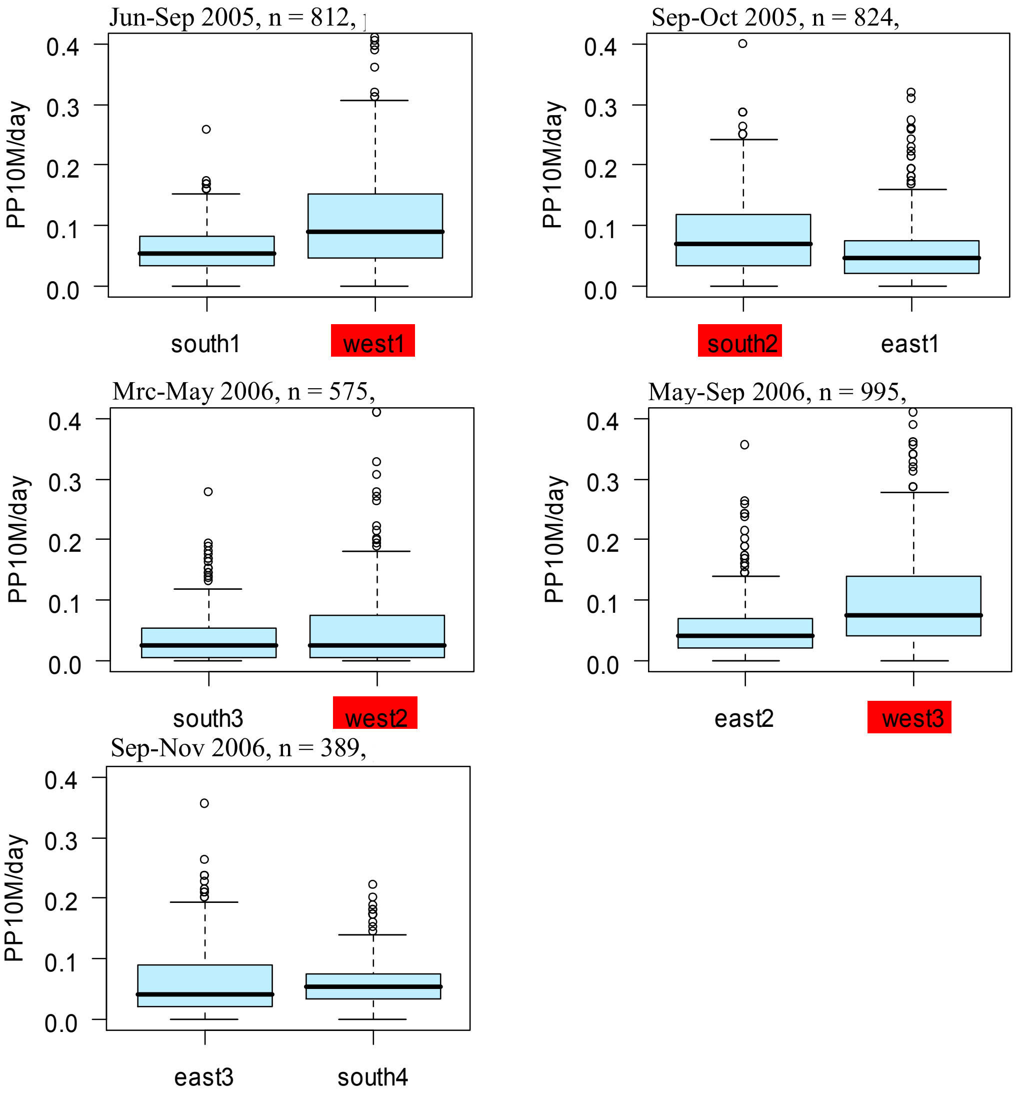


Fig. 2-38: PP10M/day in the Nysted wind farm area for two rows in five different time periods. All data from one row are pooled. The row with significantly more recorded porpoises is marked by a red bar.

These differences remain stable in only two experiments when the variables wind, season, sensitivity and distance to the next turbine are set as random effects to exclude possible effects on the distribution (Tab. 2-8). In conclusion, the differences between single rows, which are placed with a distance of one to three kilometres from each other, is much more distinct than differences within single rows.

Tab. 2-8: Results of the ANOVA statistics comparing two Generalised Mixed Effect Models.

Experiment No.	rows	n	Chi²	p
time 1	west1/south1	812	5.270	0.0217*
time 2	south2/east1	824	1.446	0.2290
time 3	south3/west2	575	0.840	0.3595
time 4	east2/west3	995	7.555	0.0060**
time 5	east3/south4	389	0.017	0.8967

2.6.2.5. Diurnal rhythm

For the complete data set a 24-hour-rhythm with presence of harbour porpoises was assessed by a GAM on the basis of „porpoise positive minutes per hour within day“ (Fig. 2-39). A clear day-night-rhythm with high activity during the night and low activity between 5 AM and 7 PM turned out in the offshore wind farm Nysted.

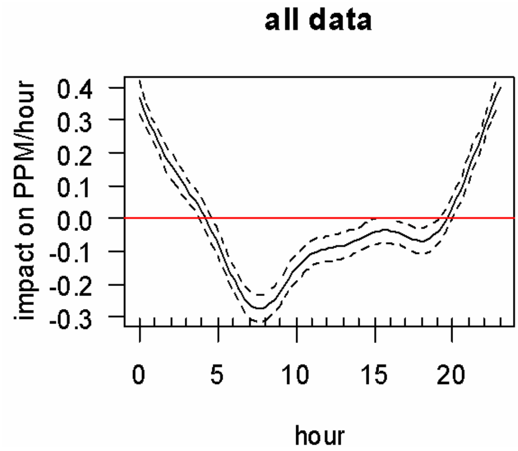


Fig. 2-39: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/hour) including all data. Dashed lines represent 95% confidence intervals around the main effects. Day time had a strong effect on presence of harbour porpoises.

With respect to the complete data set this pattern is very clear inside the wind farm (Fig. 2-40). Outside the wind farm this pattern is still noticeable but not very distinct. Still, during night a higher activity was measured but during daytime the confidence interval differs from the daily average only for two short time intervals: In the morning and evening (from 6 AM to 9 AM and from 6 PM to 7 PM) fewer porpoises were recorded.

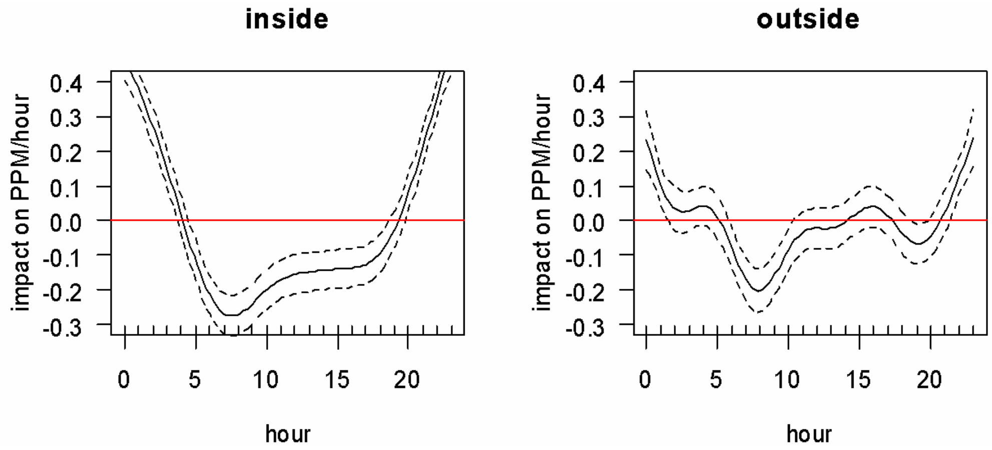


Fig. 2-40: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/hour) inside (left) and outside the wind farm (right). Dashed lines represent 95% confidence intervals around the main effects.

In order to avoid that possible effects are masked by the influence of years or season, we separated the data set into the two different years 2005 and 2006 and analysed only data between July and October, the time span with highest harbour porpoise recordings. Then the pattern with high activity during night and low activity during day is still very similar inside the wind farm, but much more distinct in 2005 (Fig. 2-41, left). In 2006 the lower activity inside the wind farm starts 2 hour early (3 AM) and lasts not that long (until 2 PM) compared to 2005 when until 6 PM significantly fewer activity was measured. hour

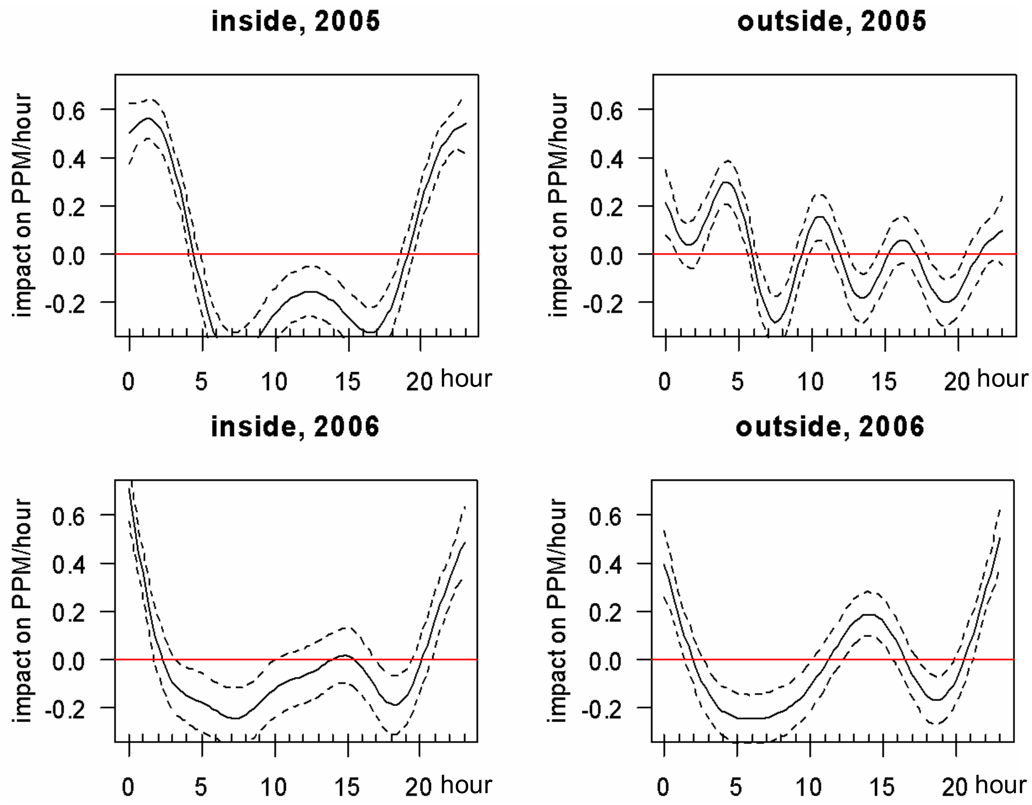


Fig. 2-41: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/hour) inside (left) and outside the wind farm (right) separated by the years 2005 (top) and 2006 (below). Only data between July and October were used. Dashed lines represent 95% confidence intervals around the main effects.

Outside the wind farm the daily activity pattern is different from the T-PODs inside the wind farm for 2005 as well as the pattern in 2005 does not correspond to the pattern in 2006 (Fig. 2-41, right). In 2005, a regular change in daily porpoise activity from a peak to a low occurred approximately every 3 hours, starting with an activity peak at midnight. In 2006 the pattern is very similar to inside the wind farm with highest activity during night between 9 PM and 2 AM and low activity during the day between 4 AM and 11 AM.

In order to test for the influence of single turbines to the 24-hour-rhythm of harbour porpoises the presence of the animals was assessed by a GAM with data from T-PODs deployed closer than 150 m to the next turbine and compared to the data from T-PODs deployed more than 700 m away from the next turbine (Fig. 2-42). In this case, a clear day-night rhythm with high activity during night and low activity during day is even more pronounced close to single wind turbines. In both years, significantly fewer PPM/h were recorded between 4 AM and 19 PM in 2005 and between 7 AM to 16 PM in 2006. More than 700 m away from the turbines this pattern is not detectable in 2005, when a similar regular change in daily activity occurred like inside the wind farm in Fig. 2-41. In contrast to the year 2005 the activity pattern in 2006 is without any changes between close and far away from single turbines.

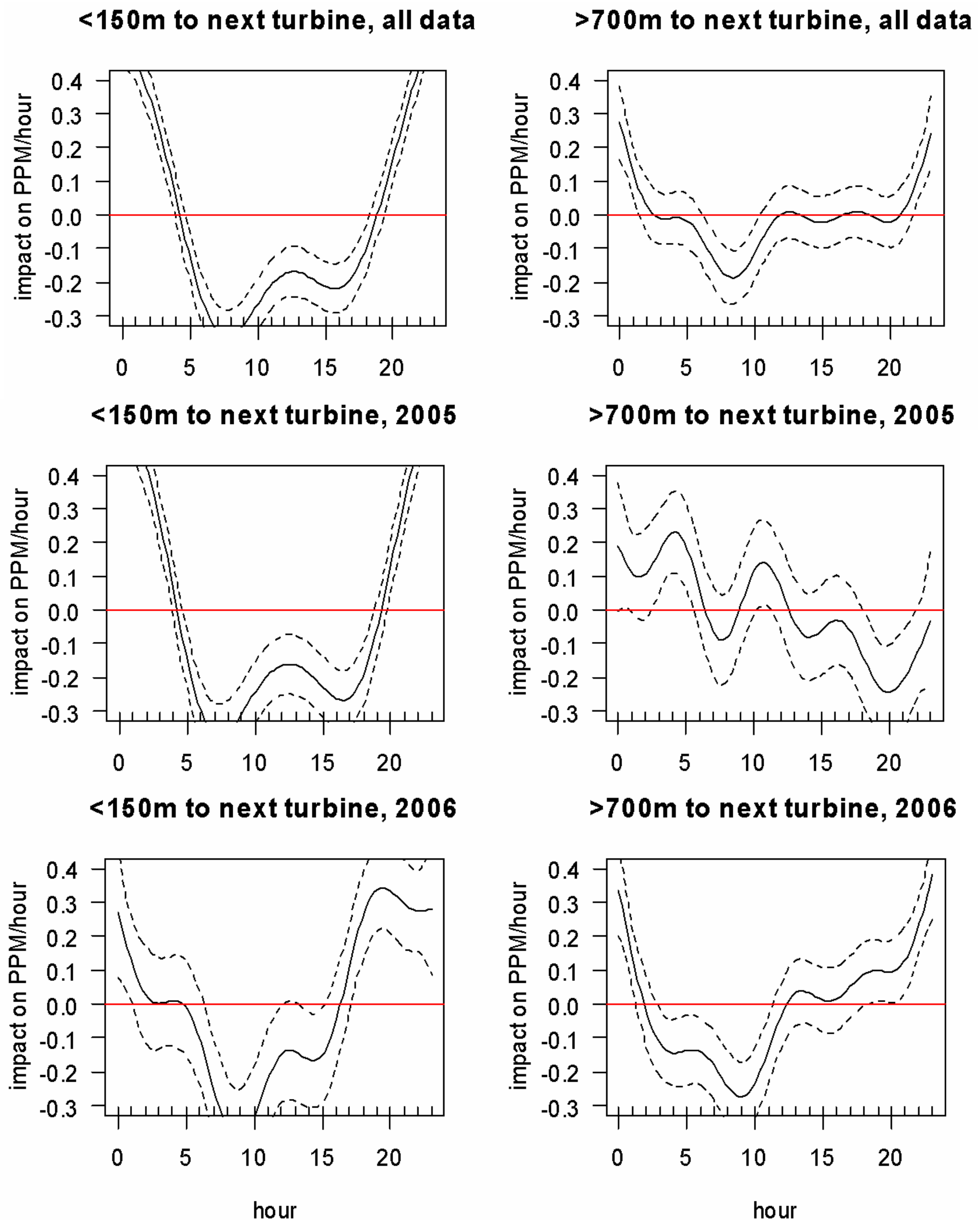


Fig. 2-42: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/hour) closer than 150 m to the next turbine (left) and more than 700 m away from the next turbine (right) separated by the complete data set (top), July to October 2005 (middle) and July to October 2006 (below). Dashed lines represent 95% confidence intervals around the main effects.

In a next step we assessed the behaviour of the animals by applying a GAM on the mean inter click interval per hour of a 24-hour day (Fig. 2-43). Also for this factor a clear daily rhythm occurred with a rhythm that differs to the pattern of the parameter "PPM/hour": The daily pattern was dependent on the distance of the T-PODs to single turbines.

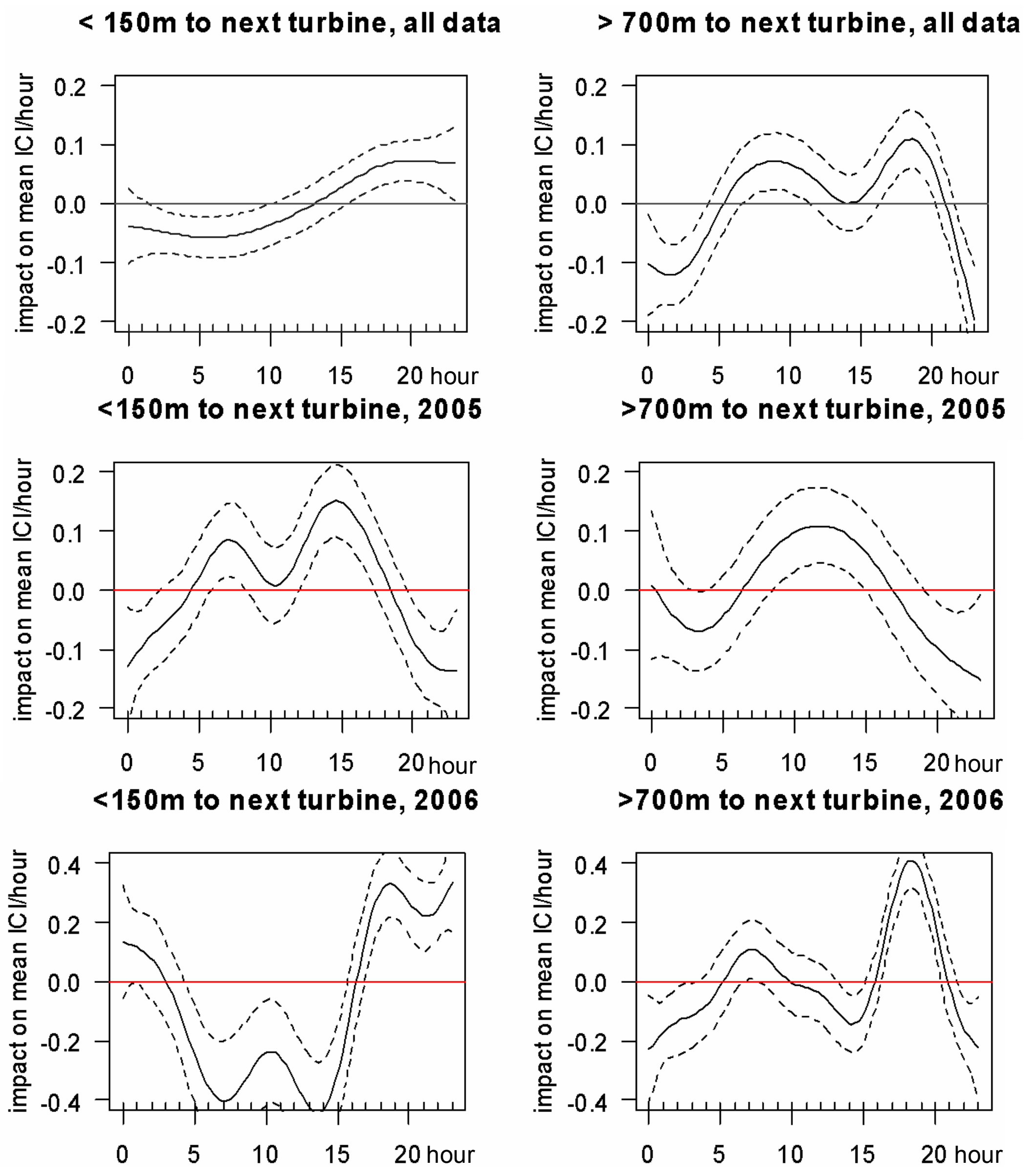


Fig. 2-43: GAM smoothing curves fitted to the 24 hours of a day on the performance of the click trains of harbour porpoises measured by mean inter click interval/hour closer than 150 m to the next turbine (left) and more than 700 m away from the next turbine (right) separated by the complete data set (top), July to October 2005 (middle) and July to October 2006 (below). Dashed lines represent 95% confidence intervals around the main effects.

Significant smaller inter click intervals than the average intervals were measured during night at all positions, which were far away from single turbines. Accordingly longer intervals than the average occurred during day time, in 2005 between 8 AM and 3 PM and 2006 at two smaller peaks, at 7 AM only for a very short time and again in the evening between 5 PM and 8 PM with a very distinct peak. Close to single turbines the pattern differs from each other between the two years: In 2005 a distinct pattern occurred similar to that away from the turbines: Small click intervals during night and longer intervals between 6 AM and 5 PM during daylight. But in 2006 this pattern changed completely to long intervals during evening/night from 5 PM to midnight and smaller intervals during daytime between 4 AM and

3 PM. This pattern does not correspond with the pattern more than 700 m away from the turbines.

2.6.3. Horns Rev

POD deployments

Deployments of T-PODs in the area of the offshore wind farm Horns Rev and useful data obtained through the entire study period are shown in Fig. 2-44. We changed the rows four times. Thus, a total of 10 different row experiments were conducted. Due to severe weather conditions and strong currents affecting the data collection by producing a lot of clutter, the recordings were often interrupted for a few hours up to some days. In the data analysing we therefore only included 24hour days without any interruption. As a consequence we gained much less data than in the Nysted area. From June 15th 2005 to 18th October 2006, 21 different T-PODs were deployed in the Horns Rev area. In 2005 the T-PODs recorded a sum of 751 days with some larger gaps from October to December. Data of 1,334 days were collected in the year 2006.

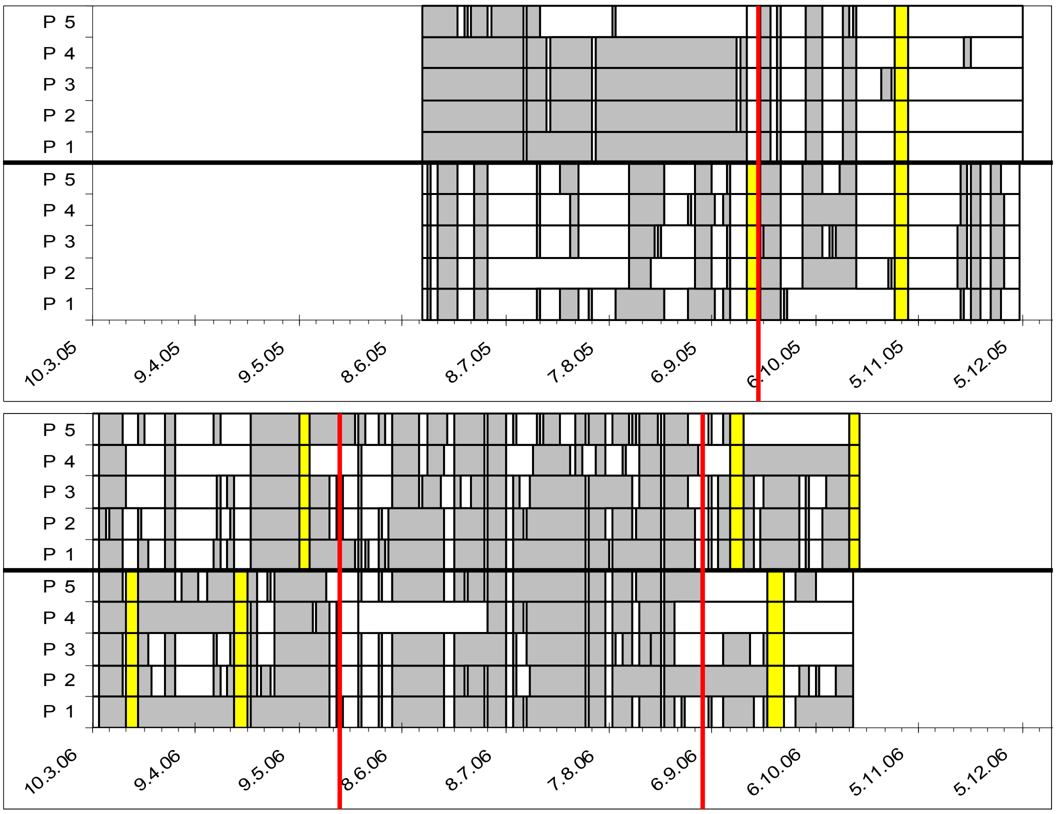


Fig. 2-44: Recorded data of PODs in the years 2005 (above) and 2006 (below) placed in the offshore wind farm Horns Rev. P1-P3 = within the offshore wind farm; P4, P5 = outside of the offshore wind farm. Vertical black lines show changes of rows. Grey bars: gathered POD-data (only 24hour-days); white bar: no data; yellow bar: field calibration.

2.6.3.1. Temporal distribution pattern

The analysis of „porpoise positive time“ as a parameter for the presence of harbour porpoises shows that the T-PODs recorded harbour porpoises nearly daily at all positions inside and outside the wind farm area (Fig. 2-45). If the temporal solution of days is elevated to the smallest analysed unit of minutes, it can be seen that the devices recorded harbour porpoises almost daily but also, similar to the Nysted area, that the presence of the animals within the study area of the T-PODs was on average very short. Compared to Nysted harbour porpoises visit the area more regularly. In approximately 14 hours of the 24-hour day at least one porpoise could be recorded. On average, the stay of an animal in the detection radius of a T-POD lasted 6.4 minutes, which is close to the results of Nysted. PP10M (the parameter we use in the following chapter) were recorded on 22 % of all 10 minute blocks.

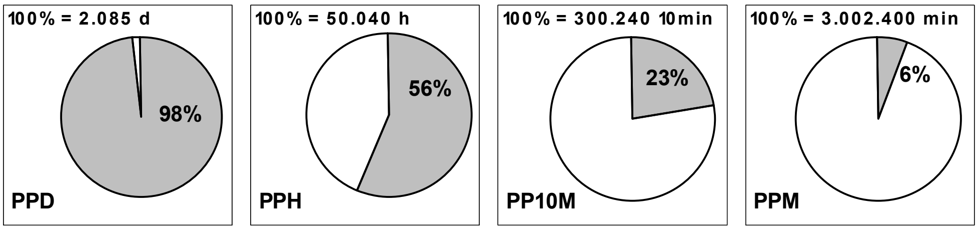


Fig. 2-45: Sum of “porpoise positive time” of all devices for different time units in the offshore wind farm Horns Rev.

2.6.3.2. Seasonality

Monthly medians of PP10M/day show a clear variation across months with a peak in summer and only few recordings during autumn and early spring (Fig. 2-46). Mean PP10M/day was lowest in March and April 2006 with approximately 5 % and peaked in July 2006 with approximately 34 %. The general trend of the seasonal variation was similar in both years. However, slight difference occurred with respect to the summer peak. In 2005 when the campaign started in June, peak values were reached in August and September, whereas in 2006 only one distinct peak occurred in July.

Similar to the Nysted wind farm, the daily values vary strongly from day to day. By fitting the data in a GAM with “months” forming the predictor variable, separated by the years 2005 and 2006 (Fig. 2-47) seasonality has a strong effect on the occurrence of harbour porpoises in the Horns Rev area. Due to some outlier in October and November 2005, the model explains only 9 % of the deviation for 2005. For 2006 the model explains 51 % of the deviation. Including the different sensitivity of the T-PODs in the model increases the explanatory power to 18 % in 2005 and 53 % in 2006. This strong effect of seasonality has to be considered when evaluating the effect of the wind farm or of single turbines either by randomising this effect or by comparing time spans not lasting longer than a few weeks. In the following we use both approaches.

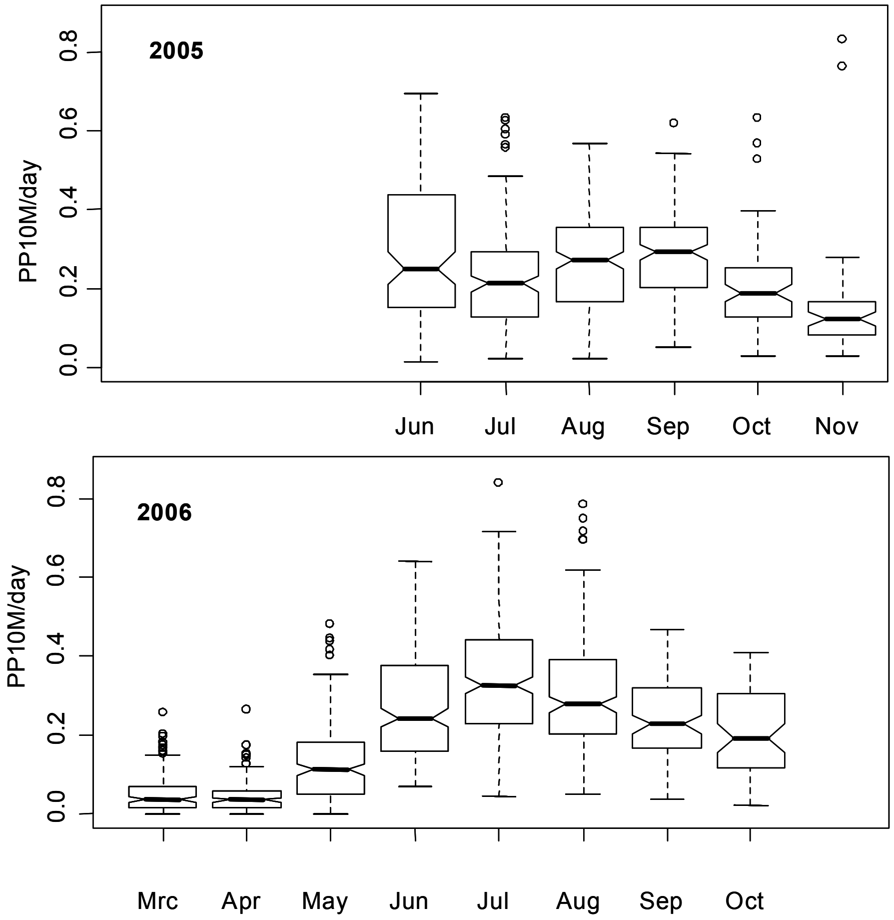


Fig. 2-46: Seasonal medians (months) for the indicator "Porpoise positive 10minutes per day" (PP10M/day) for the years 2005 and 2006 in the Horns Rev area.

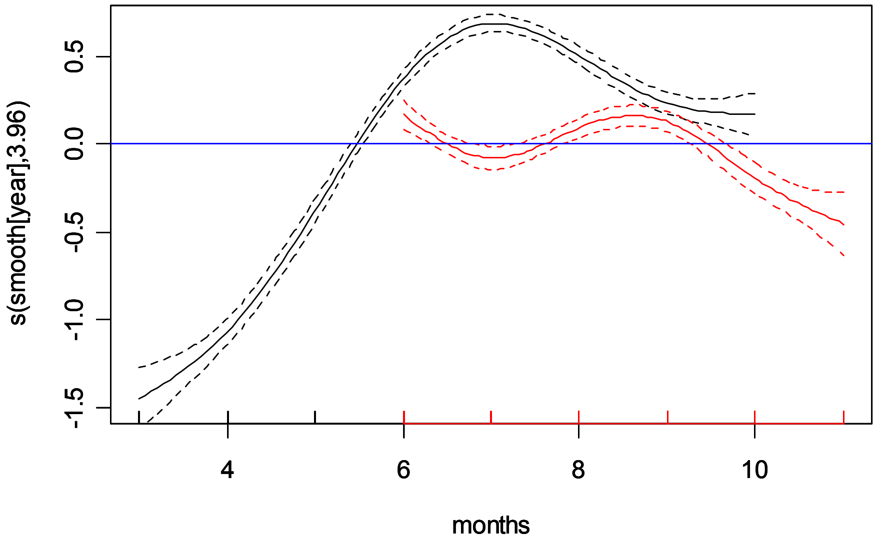


Fig. 2-47: GAM smoothing curves fitted to months on the presence of harbour porpoises (pp10m/day) during the years 2005 (red line) and 2006 (black line) in the Horns Rev area. Dashed lines represent 95% confidence intervals around the main effects. Seasonality had a strong effect on presence of harbour porpoises.

2.6.3.3. Influence of water temperature, wind speed and turbine power production

Using all data, mean daily wind speed has a significant effect on PP10M/day according to a GAM including T-POD specific sensitivity (n=2,036, F=4.74, p<0.001, Fig. 2-48). However, the deviance shows no clear pattern and only 2 % (6 % together with sensitivity) of the deviance can be explained by the model. Significantly less than the mean PP10M/day was recorded during low wind speed at 2 m/sec but two further minima occur at higher windspeeds at 6 and at 9 m/sec.

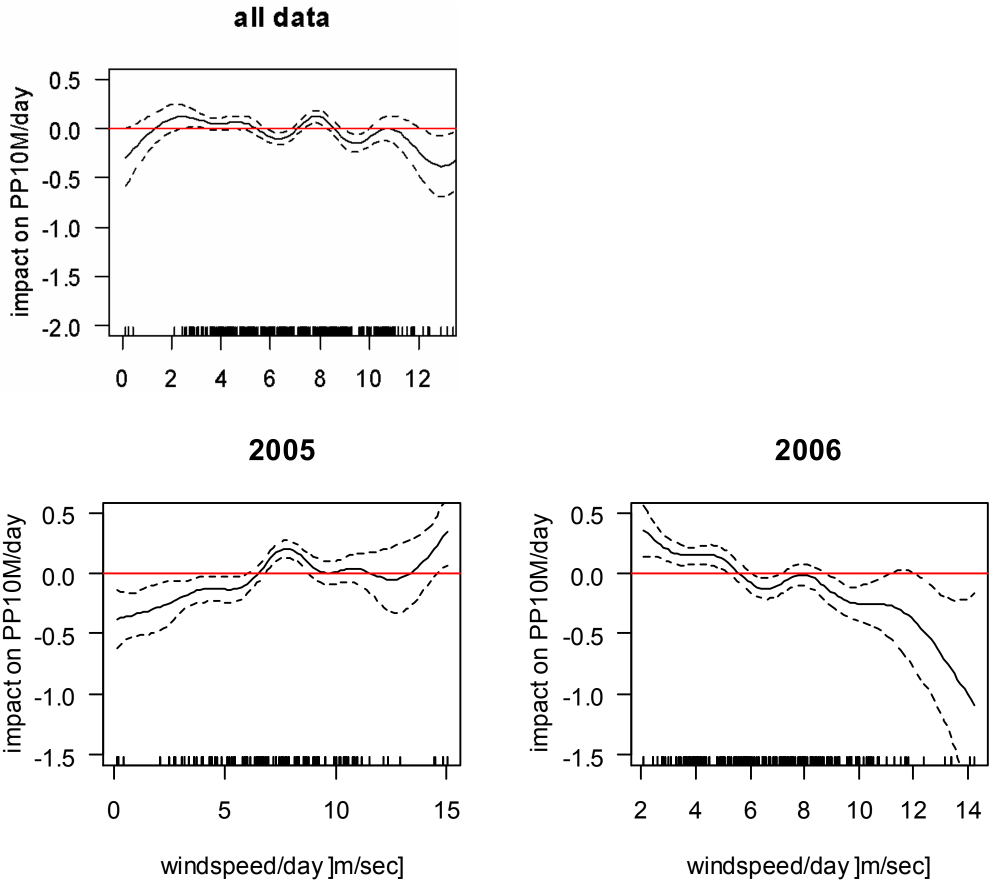


Fig. 2-48: GAM smoothing curves fitted to mean wind speed per day as an explanatory variable on PP10M/day. Above: all data, below: data separated by 2005 (left) and 2006 (right). Harbour porpoise density in the Horns Rev area is represented as a function of wind speed depicted for a GAM. Dashed lines represent 95 % confidence intervals around the main effects.

Dividing the data set into the years 2005 and 2006 a different picture for both years occurs (Fig. 2-48, below). Whereas in 2005 significant less recordings were made during wind speeds below 6 m/sec, this changed in 2006 to a converse picture: Below 5 m/sec more PP10M/day were recorded and with a continuous decrease less recordings were made during higher wind speeds.

The effect of wind speed on the presence of harbour porpoises dependent of the position of the T-PODs to the wind farm is shown in Fig. 2-49. In both cases the general number of recorded PP10M/day was very similar and no significant difference between the distance classes occurred (T-test: inside/outside: T=0.370, n=14, p=0.717; <200m/>900m: T. Only during low wind speed (below 6 m/sec) a slight difference with some more recordings outside the wind farm and > 900 m away from single turbines occurred. During lowest wind (< 2 m/sec) it changed to only very few recordings outside the wind farm and more than 900 away from the turbines. But due to very few data collected during very low wind speed no valuable information on the relation between very low wind speed and number of PP10M/day is available.

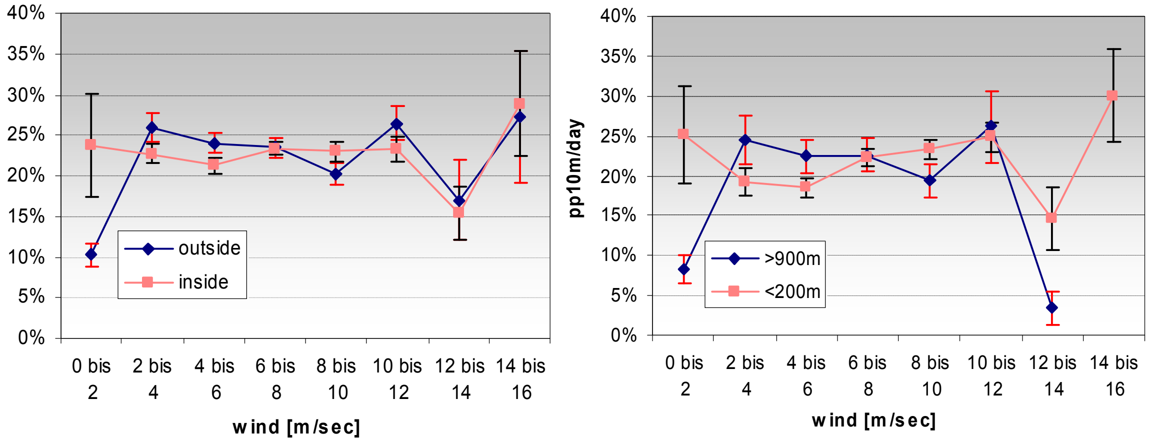


Fig. 2-49: Number of recorded PP10M/day during different daily wind speeds inside the wind farm compared to outside the wind farm (left) and close to a single turbine and more than 900 m away from a turbine (right). Error bars indicate standard error.

In the Horns Rev wind farm area no correlation of wind with the recordings of harbour porpoises is detectable for data inside or outside the wind farm (Spearman Rank, inside: R=0.029, n=920, p=0.192; outside: R= -0.048, n=695, p=0.102). For data of T-PODs close and far away to single turbines a significant correlation between wind speed and PP10M occurred only for T-PODs which were deployed close to single turbines. (Spearman Rank, <200 m: R=0.150, n=604, p<0.001; >900 m: R=-0.063, n=275, p=0.149).

In order to see if power production of the turbines effects the recordings of harbour porpoises, we proved first for an interaction of wind speed with power production by calculating a GAM. This interaction is highly significant (n=1,285, F=2.48, p<0.001). This is also supported by the correlation between wind and power production, calculating a Spearman Rank correlation (R=0.94, n=1,285, p<0.001). Power production data were only available for the year 2006 (Fig. 2-50). Similar to the effect of wind also for power production no differences between inside to outside the wind farm could be proved (T-test, inside/outside: T=-2.016, n=22, p=0.056). In contrast, a significant difference between PODs deployed < 200 m to next turbines to PODs deployed more than 900 m away occurred (T-test, <200m/>900m: T=-2.734, n=22, p=0.012). This most probably caused by the difference of recorded PP10M/day during higher power production between 1000 and 1800 kW. According to a Spearman Rank correlation power production has a significant effect on the recorded number PP10M both, inside and outside the wind farm (Spearman Rank, inside: R= -0.166, n=599, p<0.001, outside: R= -0.349, n=426, p<0.001). PODs close to single turbines show no correlation with turbine power production, whereas the results from PODs >900 m away are correlated with power production (Spearman Rank, <200m: R= -0.053, n=281, p=0.187; >900m: R= -0.303,n=175, p<0.001).

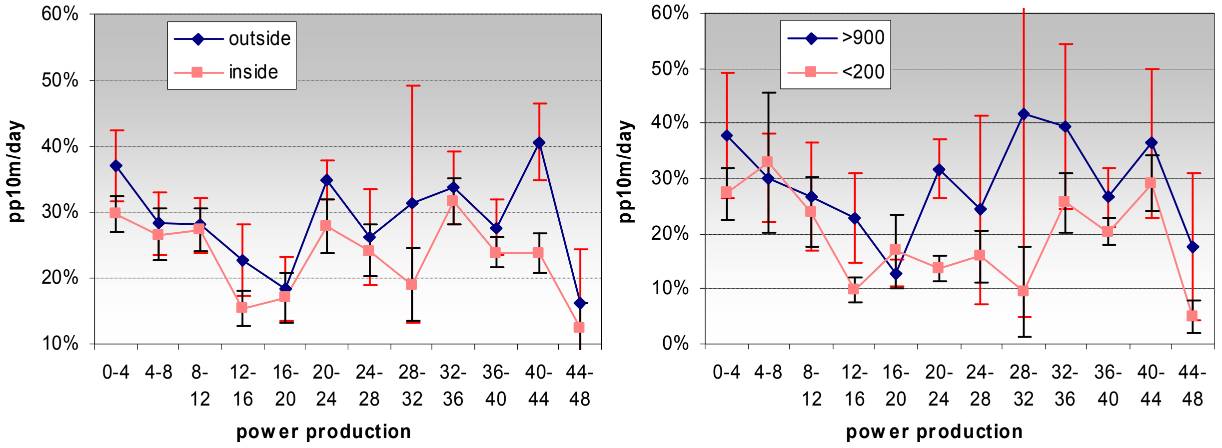


Fig. 2-50: Number of recorded PP10M/day during times with different power production inside the wind farm compared to outside the wind farm (left) and close to a single turbine and more than 900 m away from a turbine (right). Data only from 2006. X-Coordinate = kW x 50. Error bars indicate standard error.

Although wind and also power production show not a directed effect on the recorded number of PP10M/day, both parameter still have an effect. In order to avoid that wind effects the comparison from inside to outside the wind farm, we include wind as random factor in the models for the data analysis in the Horns Rev wind farm area.

Tab. 2-9: Results from a General Additive Model with different smoothing factors.

smoothing term	F	p
T-POD sensitivity	10.56	< 0.001***
windspeed	2.97	0.002 **
interaction (windspeed, power production)	2.48	<0.001***
season (month)	7.47	<0.001***
water temperature	7.58	<0.001***
interaction (season, water temperature)	9.17	<0.001***

With including further variables the explanatory power of the GAM increases: Next to wind and season (expressed by months), water temperature, the interaction of wind speed and power production of the turbines (which is highly correlated with each other (Spearman Rank: R=0.94, n=1,285, p<0.001) and the interaction of season with water temperature show a highly significant effect on the recorded PP10M/day (Tab. 2-9). Altogether 63 % of the deviance can be explained by these variables (R^2=0.58). Thus, these variables have to be included in order to test for effects caused by the wind farm or by single turbines of the wind farm.

2.6.3.4. Influence of the wind farm:

Spatial distribution pattern (Intra-row comparisons)

Comparing porpoise presence inside to outside the wind farm, we pooled the data from the two innermost T-PODs and plotted them against pooled data from the two T-PODs outside the wind farm (Fig. 2-51). According to the GLM, there is no difference in the distribution pattern between inside and outside the wind farm in both years (t=0.869, n=1,615, p=0.385). This picture is still present after randomising the effects of POD-sensitivity, wind, year, season, water temperature and the interactions of wind with power production and season with water temperature using a Generalized Linear Mixed Effect Model (LMER) and comparing both models with an ANOVA (Chi^2=0.273, df=1, p=0.60). Thus the presence of the wind farm has no effect on the occurrence of harbour porpoises.

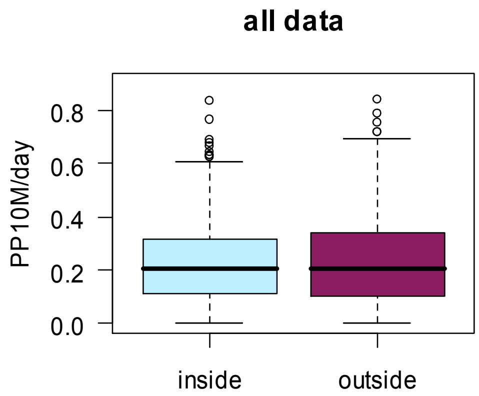


Fig. 2-51: Median PP10M/day outside and inside the Horns Rev wind farm area for all data pooled from 2005 and 2006 (n = 1,591).

Splitting the data set into the two years 2005 and 2006, there is still no difference in recorded echolocation signals between inside and outside the wind farm according to both, a GLM (2005: t=1.204,n=589, p=0.229; 2006: t=0.026, n=1,002, p=0.98) and to the ANOVA after using a LMER to randomise the effects of the above listed variables (2005: Chi^2=0.0871, df=1, p=0.7679; 2006: Chi^2=0.0871, df=1, p=0.7015, Fig. 2-52).

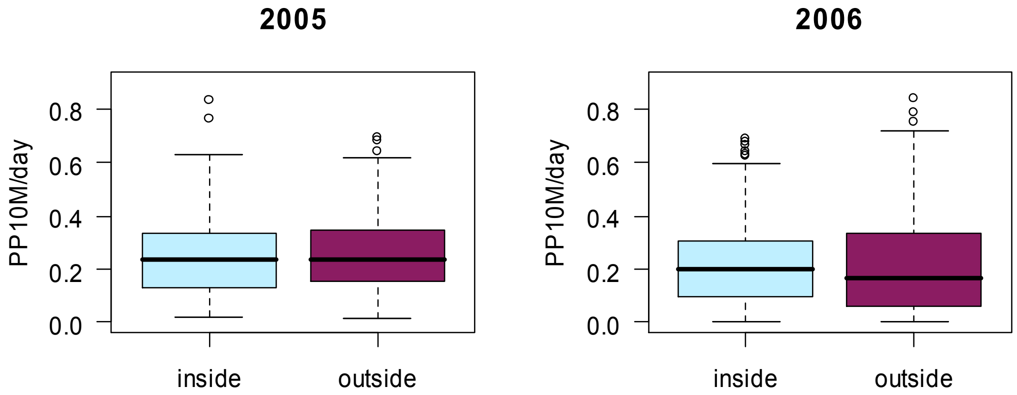


Fig. 2-52: Median PP10M/day outside and inside the Horns Rev wind farm area separated for the years 2005 (left, n = 589) and 2006 (right, n = 1,002).

Looking at the single rows a non-consistent picture is noticeable (Fig. 2-53). According to a GLM four experiments of ten show significantly more recorded porpoises inside the wind farm. In three experiments, more porpoise were recorded outside the wind farm and in three experiments no trend was detectable. This differences between inside and outside the wind farm disappears when the variables T-POD sensitivity, season, wind speed and water temperature are incorporated into a Generalised Mixed Effect Model. The ANOVA comparing model 1 with PP10M as fixed factor and model2 with the term ‘1’ as fixed factor shows no significant difference for any of the ten rows (Tab. 2-10).

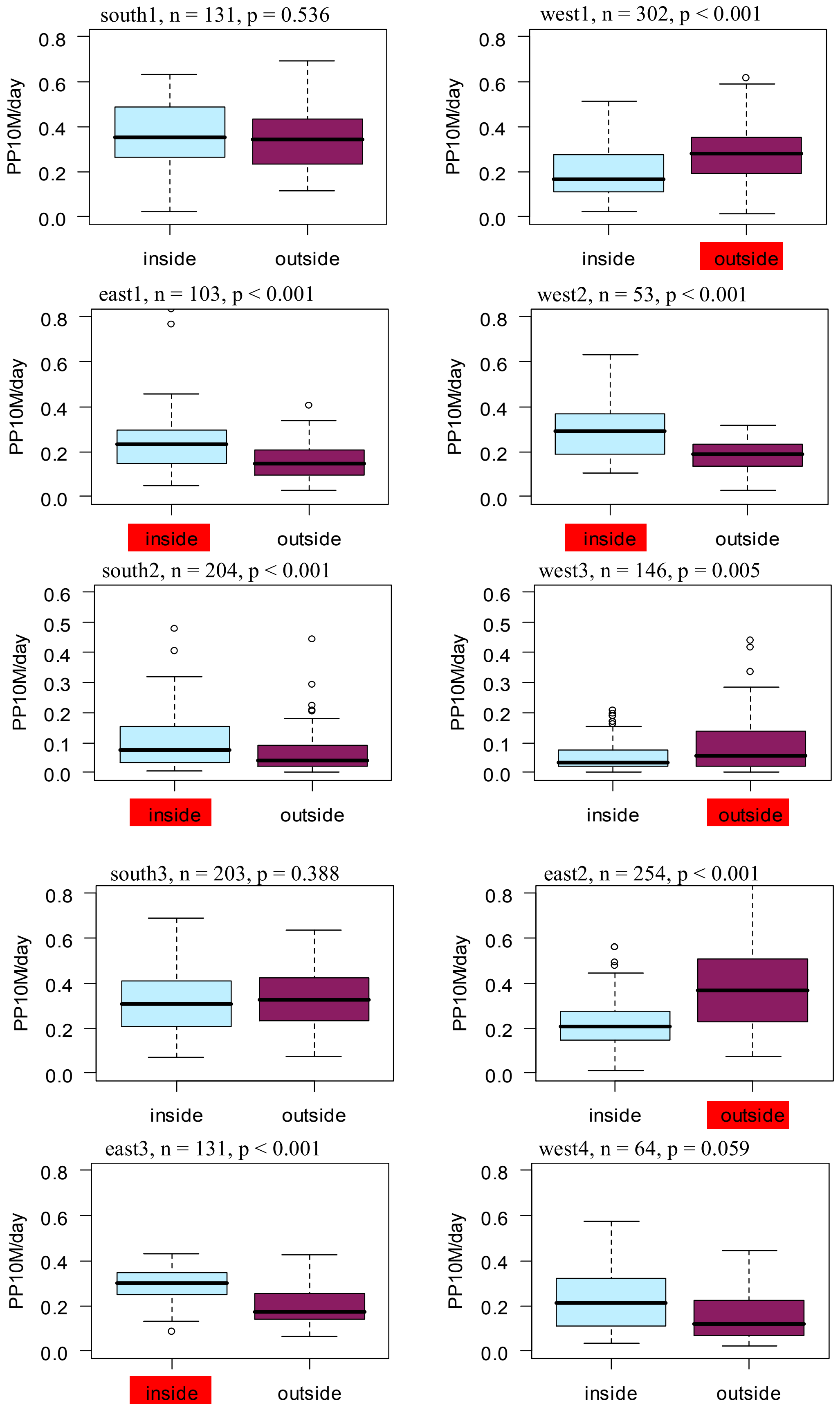


Fig. 2-53: Median PP10M/day outside and inside the Horns Rev wind farm area for 10 experiments. Two rows in a line were deployed during the same time. The wind farm site with significantly more recorded porpoises is marked by a red bar.

Tab. 2-10: Results of the ANOVA comparing the two Linear Mixed Effect Models with wind, season, sensitivity and water temperature as random factors for inside and outside the wind farm

experiment	Chi²	Df	n	p
south1	0.014	1	131	0.9058
west1	1.6095	1	302	0.2046
east1	0.8228	1	103	0.3644
west2	0.5537	1	53	0.4568
south2	0.8172	1	204	0.366
west3	0.5057	1	146	0.477
south3	3.1456	1	203	0.07613
east2	0.0323	1	254	0.8575
east3	1.0829	1	131	0.298
west4	0.283	1	64	0.5948

Some of the T-PODs inside the wind farm were deployed in between two turbines with a distance of more than 200 m to single turbines. In order to test for effects caused by single wind turbines, we grouped the data into two different classes with respect to their distance to the next turbine. T-PODs which were deployed closer than 200 m to the next turbine are able to record harbour porpoises, which swim in close vicinity to this turbine. Thus, the habitat these animals are swimming in is affected by the foundation of the turbine and the loose boulders around the foundation. If a T-POD is deployed more than 900 m away from the next turbine the seabed of the detection area is not influenced by wind turbine foundations. Additionally, to our present knowledge it is impossible for the animals to hear the turbine working in a distance of more than 900 m even with full capacity. Fig. 2-54 shows results for all data pooled in the groups below 200 m and beyond 900 m. According to both, GLM and LMER, no difference is detectable between the both distance groups (GLM: t=0.528, n=899, p=0.598; ANOVA: Chi^2=0.221, df=1, p=0.6383).

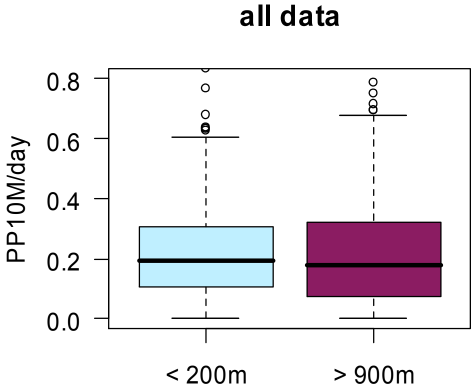


Fig. 2-54: Median PP10M/day close (< 200 m) and far away (> 900 m) to the next wind turbine in the Horns Rev wind farm area for all data pooled from 2005 and 2006 (n = 899).

This picture remains when the data set is divided into the 2005 and 2006 (Fig. 2-55). In both years, neither a difference occurred in the number of recorded PP10M per day between the T-PODs deployed close to a turbine and the devices deployed more than 900 m away according to a GLM (2005: t=0.388, n=422, p=0.698; 2006: t=1.832, n=455, p=0.068;), nor according to an ANOVA when calculating two LMERs to exclude the effects of sensitivity, seasonality, wind and water temperature (2005: ANOVA: Chi^2=0.0088, df=1, p=0.9254, 2006: ANOVA: Chi^2=0.2499, d=1, p=0.6172).

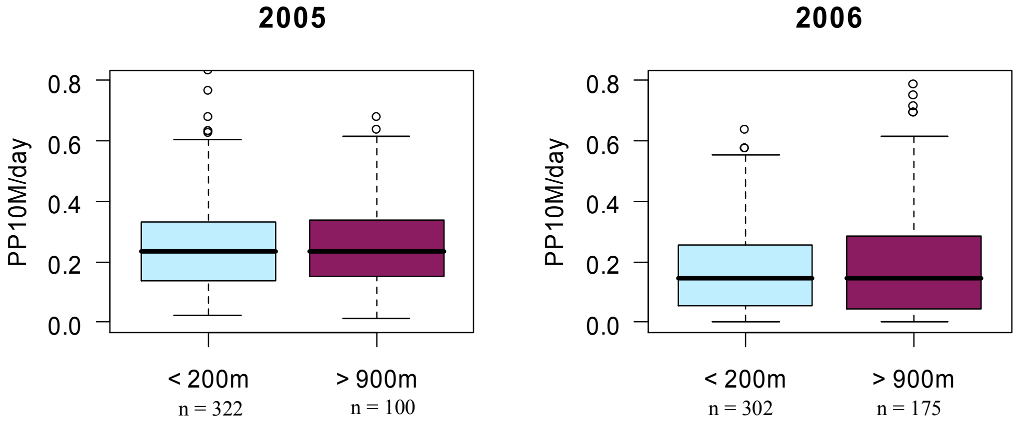


Fig. 2-55: Median PP10M/day close (< 200 m) and far away (> 900 m) to the next wind turbine in the Horns Rev wind farm area separated for the years 2005 (left, n = 422) and 2006 (right, n = 477).

When the data set is separated into ten rows (=experiments), in five experiments, no significant difference between the two distance groups could be detected: According to a GLM, in two rows significant more recordings were made at a distance of more than 900 m from the next turbine and in three experiments it was reverse with significant more recordings close to single turbines. In conclusion, we could neither demonstrate an avoidance nor an attraction of harbour porpoises at the Horns Rev wind farm. The few significant differences which occurred in single rows regarding the distance to single turbines were not consistent.

Inter-row comparisons

Similar to the Nysted wind farm also in the Horns Rev farm a more pronounced difference was detectable between the recordings of the two rows which were deployed at the same time (Fig. 2-56) than between inside and outside the wind farm.

According to a GLM, in three out of five comparisons one row recorded significantly more PP10M/day than the other (Tab. 2-11). In summer 2005 the difference was most obvious with nearly twofold more measured activity in row south1 compared to row west1. Only during this time period the difference between the two rows remains significant according to an ANOVA, comparing two LMER including the variables sensitivity, seasonality, wind and water temperature. Only during the last time period no difference could be detected.

Tab. 2-11: Results of the GLM statistics for the comparisons of PP10M/day of different rows during the same time.

Experiment No.	rows	n	t	p
time 1	south1/west1	551	-11.896	<0.0001***
time 2	east1/west2	199	1.932	0.0548
time 3	south2/west3	421	-1.659	0.0979
time 4	south3/east2	623	3.167	0.0016**
time 5	east3/west4	239	-1.993	0.0474*

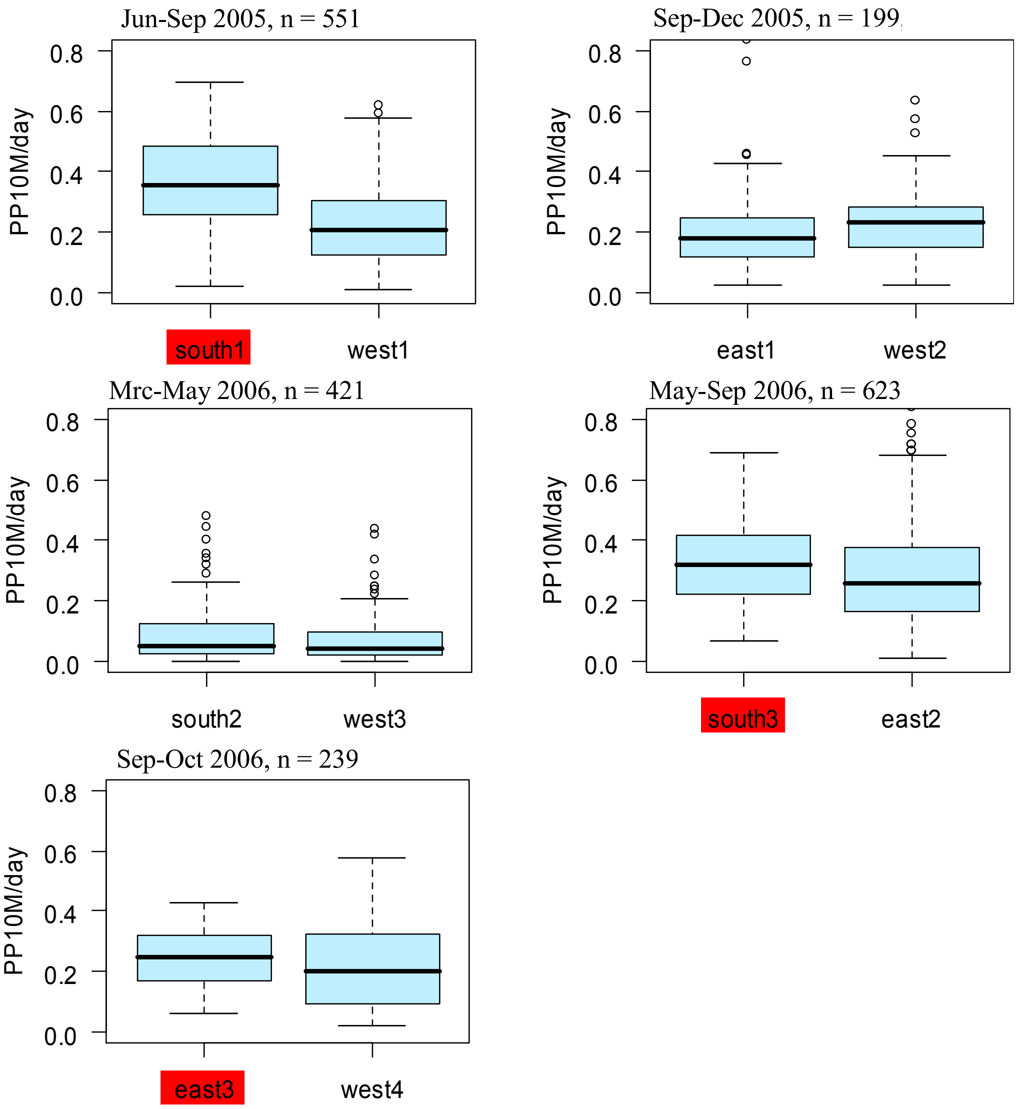


Fig. 2-56: PP10M/day in the Horns Rev wind farm area for two rows in five different time periods. All data from one row are pooled. The row with significantly more recorded porpoises according to a GLM is marked by a red bar.

2.6.3.5. Diurnal rhythm

For the complete data set a 24-hour-rhythm in presence of harbour porpoises was assessed by a GAM on the basis of „porpoise positive minutes per hour during one day“. A clear daily rhythm with significant more activity than the average during the day and two significant activity minima, one at 2 AM and the other at 8 PM turned out in the offshore wind farm Horns Rev (Fig. 2-57).

When we split the data set into data from inside and outside the wind farm a different picture appears (Fig. 2-58). Outside the wind farm still significant more PPM/hour were measured during the day and also the two activity minima at 2 AM and 8 PM are still present. Inside the wind farm the picture changed: During the day light slightly less activity than the mean was measured and only one pronounced activity maximum at 5 am is noticeable.

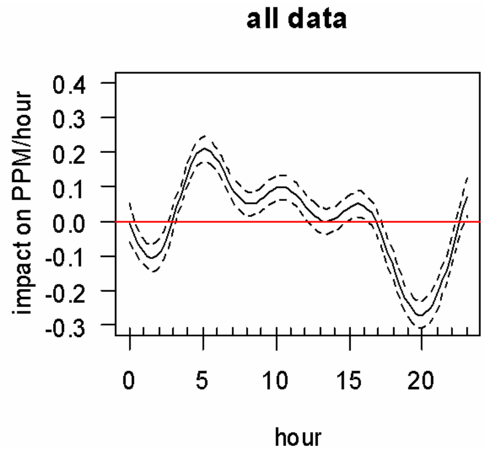


Fig. 2-57: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/day) on the basis of all data in the Horns Rev area. Dashed lines represent 95% confidence intervals around the main effects. Day time had a strong effect on presence of harbour porpoises.

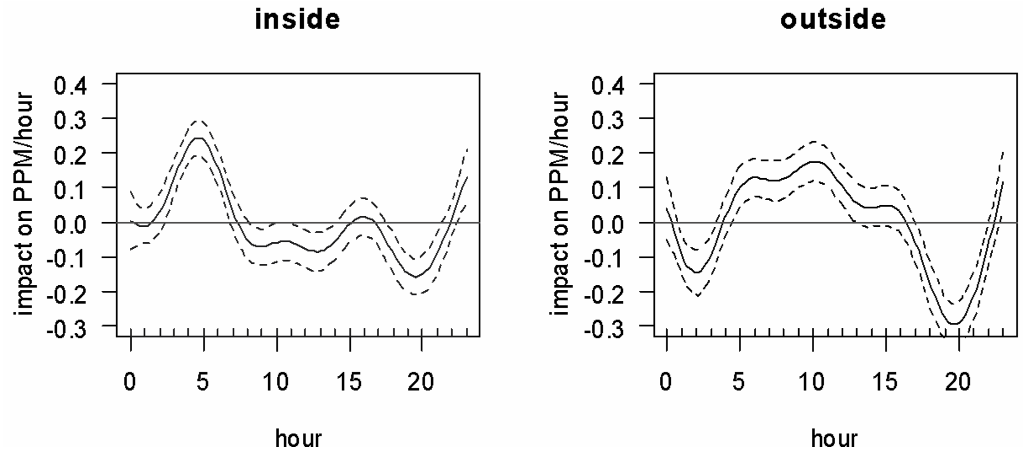


Fig. 2-58: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/day) inside (left) and outside (right) the Horns Rev wind farm. Dashed lines represent 95% confidence intervals around the main effects.

The different 24hour activity pattern between inside and outside the wind farm separated by the two years 2005 and 2006 show some differences between the two years (Fig. 2-59). In order to avoid the influence of different seasonal effects in both years, we only analysed data between July and October for each of both years. In 2005 the pattern is more different between the location of the T-PODs. Inside the wind farm area a very pronounced daily rhythm is detectable with high activity during the night and few activity during the day light phase between 7 AM and 8 PM. Also outside the wind farm higher activity was measured during the night but shorter and with a weak activity peak at 10 AM. The only clear activity minimum was at 6 PM.

One year later the pattern inside the wind farm changed from nocturnal activity to two activity peaks at 5 AM and at 4 PM and two activity minima at midnight and at 8 PM. In the same year outside the wind farm a clear pattern occurred which is completely converse to the pattern inside the wind farm in 2005: Low activity during the night and high activity during the day light phase from 4 AM to 5 PM.

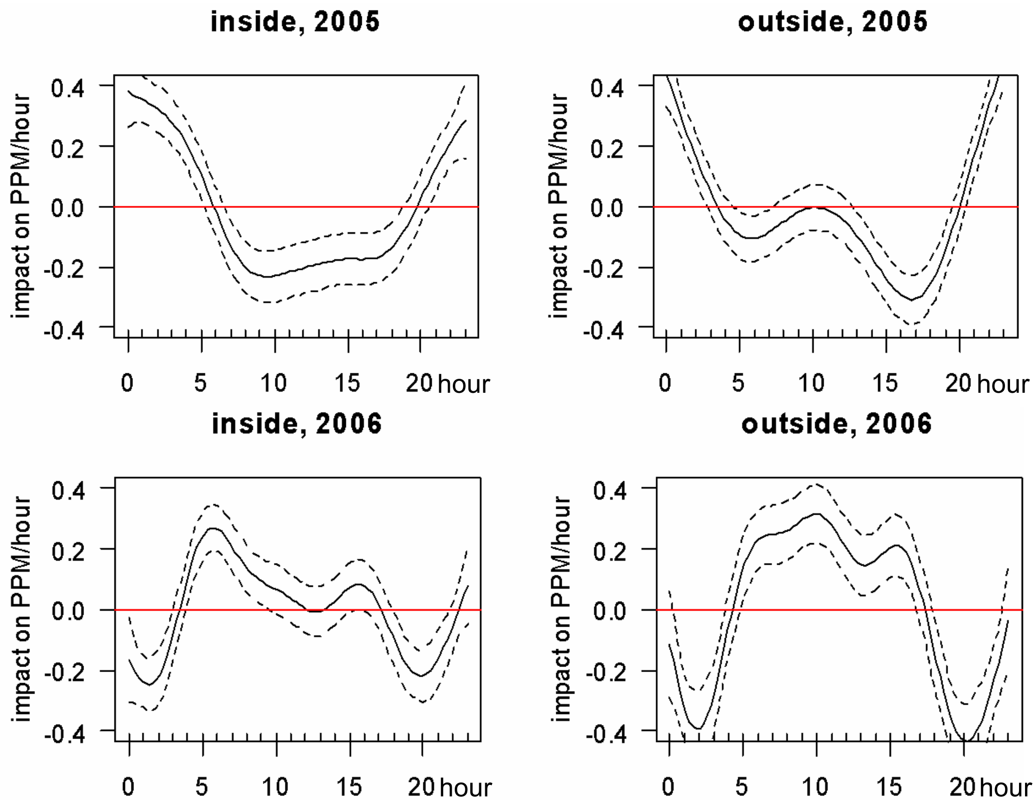


Fig. 2-59: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/hour) inside (left) and outside the Horns Rev wind farm (right) separated by the years 2005 (top) and 2006 (below). Only data between July and October were used. Dashed lines represent 95% confidence intervals around the main effects.

In order to look for differences in the daily activity pattern regarding the distance to single turbines the presence of the animals was assessed by a GAM with data from T-PODs deployed closer than 200 m to the next turbine and compared to the data from T-PODs deployed more than 900 m away from the next turbine (Fig. 2-60). Here, in 2005 a strong converse activity pattern occurred with high activity during the night close to single turbines and low activity during night far away from single turbines. During daylight it was converse with low activity close to the turbines and a pronounced activity peak at 10 AM away from the turbines. In 2006 the activity pattern between close and far away from turbines does not more differ very strong but still activity ups and downs are much more pronounced closer to wind mills (maximum at 5 AM and 5 PM, minimum at 1 AM, 9 AM and 9 PM). In a distance of more than 900 m to single turbines only for two hours around 8 PM the measured activity differed significantly from the mean.

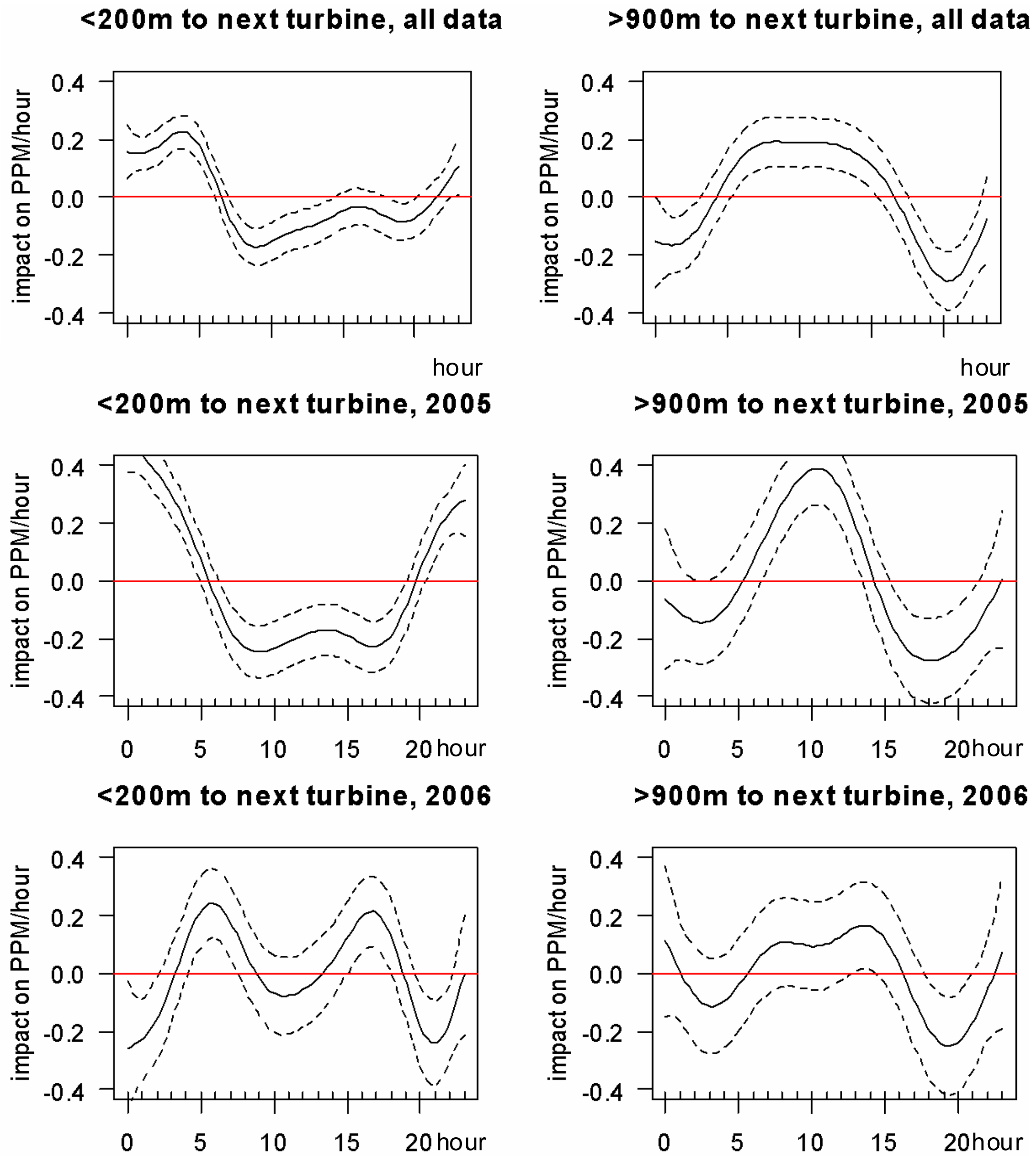


Fig. 2-60: GAM smoothing curves fitted to the 24 hours of a day on the presence of porpoises (ppm/hour) closer than 200 m to the next turbine (left) and more than 900 m away from the next turbine (right) separated by the complete data set (top), July to October 2005 (middle) and July to October 2006 (below) for the Horns Rev wind farm. Dashed lines represent 95% confidence intervals around the main effects.

The picture of mean duration of the inter click interval distributed on a 24-hour day is shown in Fig. 2-61, using a GAM with the term “mean inter click interval per hour” as the explanation factor. For all tested situations a very similar picture showed up. Few activity was measured from midnight till 2 AM and a maximum was found around 5 AM. From 10 AM until 6 PM no pattern was observable and the interval does not differ from the mean. In the evening between 6 and 10 PM slightly smaller inter click intervals were measured.

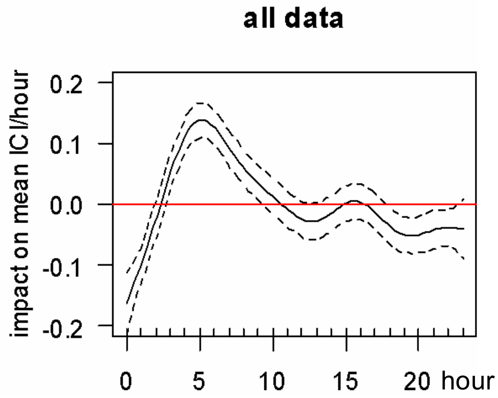


Fig. 2-61: GAM smoothing curves fitted to the 24 hours of a day on the performance of the click trains of harbour porpoises measured by mean inter click interval/hour inside the wind farm (left) and outside the wind farm (right). Dashed lines represent 95% confidence intervals around the main effects.

In order to check for differences between PODs deployed in close ranges to single turbines and PODs deployed at a distance of more than 900 away from single turbines, we split the data set into this two distance classes (Fig. 2-62). According to the complete data set, the curve is similar comparing both distance classes with shortest click intervals during night and longest during early morning. But only for the PODs closer than 200 m to single turbines the pattern differs significantly from the average with a distinct peak at 5 AM, when the inter click intervals were significantly longer than the average click interval. When the data set is split into both years and only data between July and October are analysed, in 2005 still the pattern between close to single turbines and far away is very similar: Small click intervals were measured during night (until 2 AM) and longer click intervals were measured during day (5 AM – 8 AM < 200 m and 5 AM – 1 PM > 900 m). In 2006 the picture is no longer persistent and the pattern differs clearly between the distance classes. At a distance > 900 m to the next turbine no pattern is observable beside a weak difference to the average between 8 PM and 11 PM with significant longer lick intervals. At a distance < 200 m to the next turbine one peak with significant longer click intervals occurred at 6 AM and a minimum at night between 9 and 11 PM.

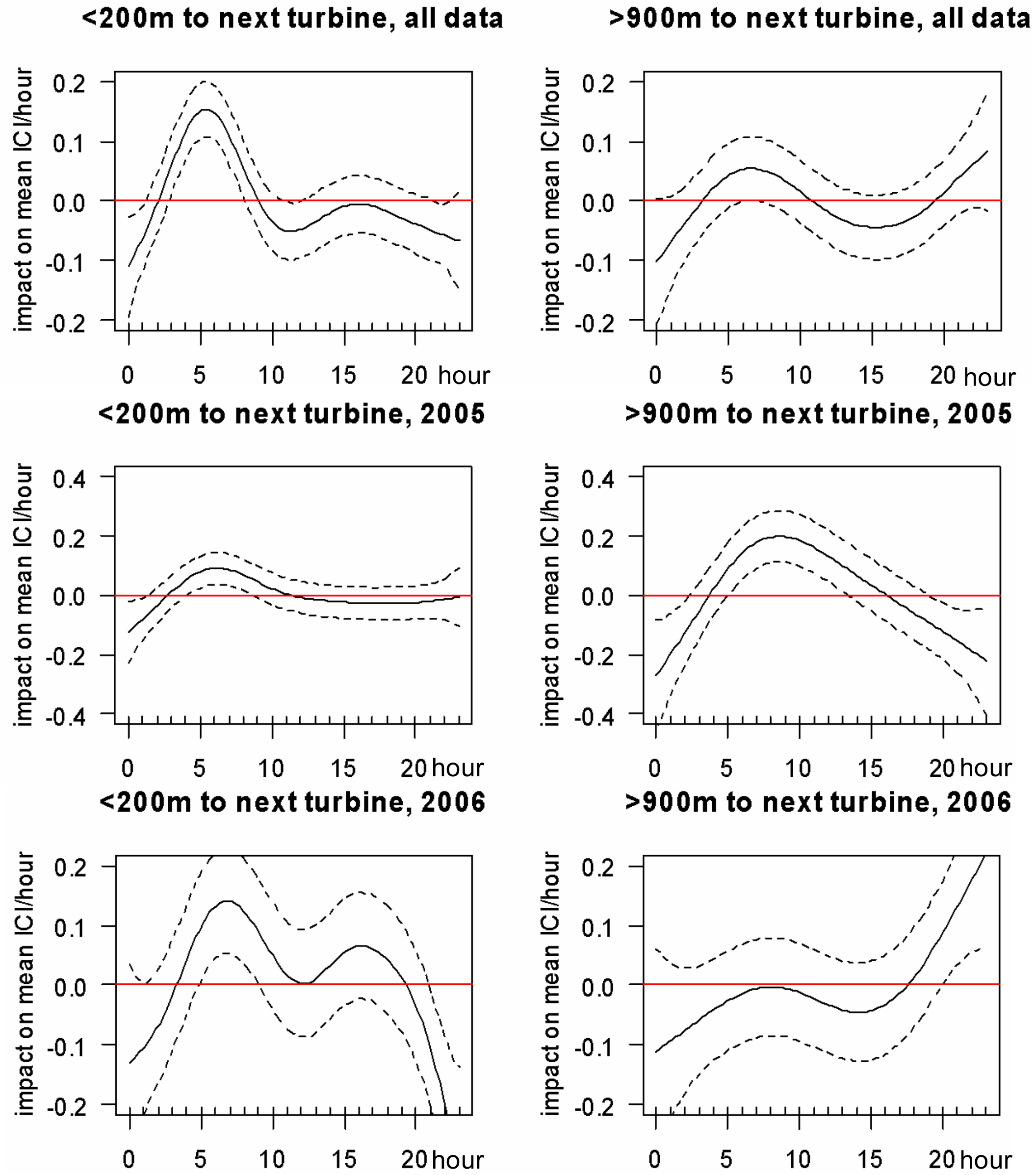


Fig. 2-62: GAM smoothing curves fitted to the 24 hours of a day on the performance of the click trains of harbour porpoises measured by mean inter click interval/hour closer than 200 m to the next turbine (left) and more than 900 m away from the next turbine (right) separated by the complete data set (top), July to October 2005 (middle) and July to October 2006 (below) in the Horns Rev wind farm. Dashed lines represent 95% confidence intervals around the main effects.

2.7. Discussion

Two years of acoustic recordings of harbour porpoise signals in very high spatial and temporal resolution provided a solid data base on the presence of these animals in the two offshore-windfarms Nysted in the Baltic and Horns Rev in the North Sea. In a first step we discuss the recorded occurrence of harbour porpoises in both areas without focussing on the effect of the wind farms, followed by specific discussion of the effects of the operating offshore wind farms.

2.7.1. T-PODs as a tool to study harbour porpoises

The T-POD was developed by Chelonia Limited (www.chelonia.co.uk) in 1999 in order to detect porpoises, dolphins and other toothed whales by recognising the trains of echo-location clicks the animals emit to detect their prey, orientate and interact. Since then the technique was enhanced and several studies on harbour porpoises were conducted on the basis of T-POD data (Cox et al. 2001, Cox & Read 2004, Carlström 2005, Carstensen et al. 2006, Leeney et al. 2007, Verfuß et al. 2007). In order to avoid that differences between different T-POD locations are caused only by differences in the sensitivity of the devices an important prerequisite is the standardisation of the sensitivity. For earlier versions of T-PODs differences in detection thresholds of more than 20 dB re 1µPa pp were described (Verfuß et al. 2004). In order to test the sensitivity between the T-PODs used in this study, an extensive calibration setup was conducted. The results proved the T-POD versions 4 and 5 as well developed devices, which achieved a high degree of standardisation and little variance in their sensitivity. Problems with noise recorded by the PODs during stormy weather led to some recording gaps in the North Sea but sufficient data could be obtained for each single experiment so that no comparison inside single rows had to be cancelled.

Test tank calibration proved that the version of T-PODs used in this study showed a much more stable sensitivity as the differences between the single devices did not exceed beyond 3 dB re 1µPa pp. However, differences caused by different sensitivities still exist. This is the first study to present a comparison of a detection threshold generated by test tank experiments and field calibration data based on a solid data base of more than 232 POD-days with more than 5,000 hours. Results show that with higher temporal resolution, a stronger correlation between test tank results and data collected in the field exists. This means that even small differences in sensitivity, expressed by differences in detection thresholds of less than 3 dB re 1µPa pp, caused differences in PPM, the smallest temporal parameter. For very large temporal parameters like PPD no correlation with detection thresholds could be shown. In order to find a good compromise between high temporal resolution and small differences caused by different sensitivities, we used the parameter PP10M. The remaining difference caused by the sensitivity of the T-PODs was set as a random factor when analysing the effect of the wind farm, so that we can exclude any blur caused by the method using T-PODs which are not working completely synchronised.

In conclusion, T-PODs are a unique and appropriate method to study the presence of harbour porpoises (and other cetaceans) at defined locations. A detection range of smaller than 300 m in diameter provides a high spatial resolution, which is needed to study the utilisation of specific habitats or responses to anthropogenic structures as turbine foundations. In combination with the nearly continuous recordings of porpoise clicks in areas of high densities as the two study areas, PODs deployed at different locations provide excellent datasets, which at present cannot be obtained by other methods and which are highly suitable to analyse spatial and temporal variation of habitat utilisation.

2.7.2. Seasonal and inter annual patterns in recordings of harbour porpoises

Nysted:

Between March and December harbour porpoises were recorded nearly every day (94 % of all recording days). Only in March, April and December more than 10 % of the POD-days provided no porpoise recordings. This characterised Nysted as an area where harbour porpoises are almost continuously present.

On average the animals were detected by T-PODs during seven hours per day but only for less than six minutes per hour.

The day to day pattern of PP10M/day confirmed a high variation between single days. Days with high PP10M/day were mostly followed by days with low activity. Given that 'porpoise positive time' is correlated with porpoise density (Tougaard 2006c), it can be concluded that the area is regularly visited by the animals but that the number of animals is low and the duration of stay within the area is rather short. Results from aerial surveys between 2002 and 2006 confirm that densities in the area around the Nysted wind farm range from zero to 1.2 animals per km² with a patchy distribution pattern (Gilles et al. 2007, Fig. 2-63).

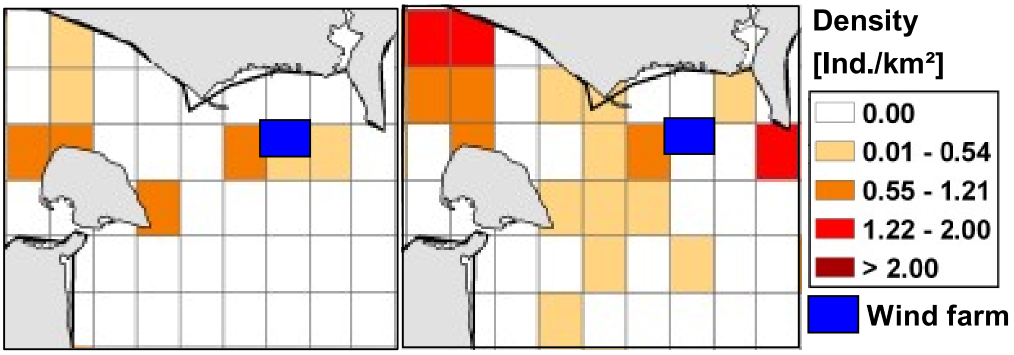


Fig. 2-63: Distribution of harbour porpoises around the Nysted offshore wind farm after aerial surveys between 2002 and 2006 in spring (March – May, left) and summer (June – Aug., right). From: Gilles et al. 2008.

Results from harbour porpoises, which were tracked by satellite telemetry showed similar results, and two areas of higher concentration were identified by a Kernel density estimation (Teilmann et al. 2008, Fig. 2-64, left). Thirteen tagged animals visited the area north of Fehmarn but only five of them stayed in the area more than two days and these only stayed for seven days on average. Therefore the authors suggest that the area is mainly used as an important corridor to the eastern part of the Baltic. The second area is the Kadet trench, which the tagged porpoises mostly used from September to December and in March. Both areas were designated as Special Areas of Conservation in the German part of the Baltic (Fig. 2-64, right) on basis of aerial surveys and static acoustic monitoring results (Verfuß et al. 2007). The offshore Wind farm Nysted is located in between these two areas. Our results fit well into this picture: The area of the Nysted wind farm is regularly visited by harbour porpoises but it is outside of areas with a high concentration of the animals. As suggested by Teilmann et al. (2008) the in average short stay of the animals in the area, which is also shown by our T-POD results, may result from a migration of animals between the Inner Danish Waters and the eastern parts of the Baltic.

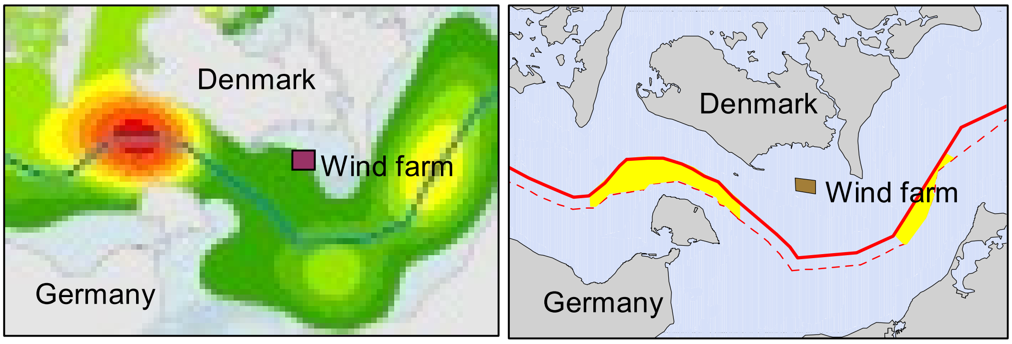


Fig. 2-64: Left: Kernel density estimation in 10% intervals based on 37 harbour porpoises tagged in the Inner Danish Waters area between 1997-2007. Red = high density, green low density. From Teilmann et al. 2008; right: Position of the two designated Special Areas of Conservation in German waters.

Horns Rev:

Similar to the Nysted area harbour porpoises were almost continuously present between March and December throughout the Horns Rev study area (98 % of all days recorded). On average the animals were detected during 14 hours per day by the T-PODs and for about six minutes per hour. This indicates that in the Horns Rev area more harbour porpoises are present than in the Nysted area. Aerial and ship based counts during the Environmental Impact studies for the Horns Rev 1 wind farm show that the area is characterised by high densities of harbour porpoises with more than one animal per square-kilometre (Tougaard et al. 2006a, Teilmann et al. 2008, Fig. 2-65, left). Aerial surveys in German North Sea waters confirm, that the area west of Schleswig-Holstein and close to the Danish border is part of a larger high density area with maximum numbers of more than three animals per square-kilometre during spring and summer months (Gilles et al. 2006, 2007, Fig. 2-65, right).

It can be assumed that the Horns Rev area is part of a larger high density area of harbour porpoises west of Schleswig-Holstein and Denmark. The longer stay in the area with 14 hours per day on average suggests, that the area is more intensively used by the animals than the Nysted area.

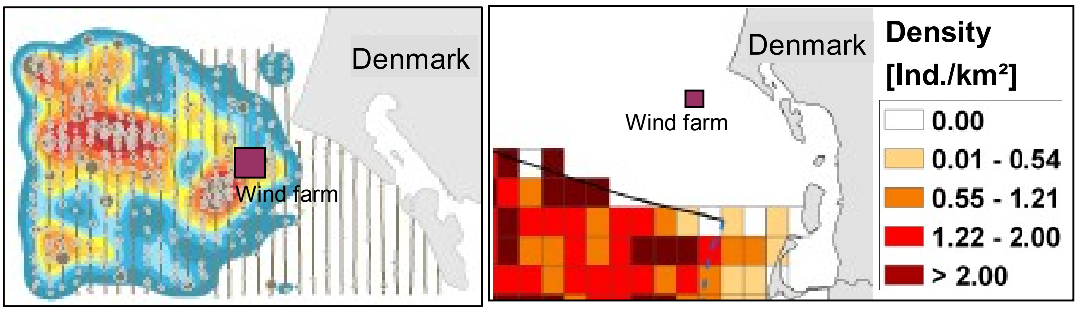


Fig. 2-65: Left: Kernel density map of harbour porpoise observations based on 33 aerial surveys conducted around Horns Rev from 1999 to 2005 covering the whole year. Red = high density, blue = low density. From Teilmann et al. 2008; right: Distribution of harbour porpoises in German waters after aerial surveys between 2002 and 2006 in summer (June – Aug.). From Gilles et al. 2007.

Seasonal variation in Nysted

During both years a pronounced seasonal effect is apparent with a peak during late summer to autumn. In both years the recorded activity decreased after October. No conclusions can be drawn about the winter months January and February, when no T-PODs were deployed. In March 2006 only 35 % of all POD-days recorded at least one harbour porpoise signal, which means that by far the lowest number of harbour porpoises was present in the Nysted area during early spring. T-POD data by Verfuß et al. (2004, 2007) showed a regular seasonal pattern in the German Baltic Sea over a period of six years in the same way as our data suggest. Harbour porpoises move east during early spring, with these movements peaking during summer/late summer. They move back to the west and the Danish Belt Sea during late autumn, and during this time a distinct gradient was observable with decreasing densities from west to east. Due to a very consistent pattern also described by Tougaard et al. (2006a) for the same area, it is very likely that the natural variation in the abundance of harbour porpoises in the Nysted area follows a seasonal pattern with few porpoises in winter, followed by an increase during April and a regular presence of the animals for the rest of the year with a peak in summer or late summer and a decrease after October. This seasonal pattern is also shown by Siebert et al. (2006) by more than ten years' data collection of incidental sightings and strandings in the German Baltic Sea, with a maximum of sightings and strandings in the summer months July to September along the German Baltic coast line.

The biological reason for this pattern is unknown, but it it is likely that prey availability plays a major role for movements of harbour porpoises. Koschinski (2002) reviewed historical reports on the distribution of harbour porpoises in the Baltic and showed, that until the mid-20th century, a migration of harbour porpoises between the North and Baltic Seas was believed to occur. In spring, the porpoises were thought to have followed movements of herring, passing through the Inner Danish Waters into the eastern Baltic Sea. In late autumn and winter, when the Baltic tended to freeze over in some years, the porpoises may have migrated back out of the Baltic Sea. Following the historical data, the area of the Nysted wind farm probably belongs to a corridor area, where the animals migrate from the Inner Danish Waters into the Baltic proper and back. Based on comparison of different T-POD locations distributed in the German Baltic, Meding (2005) also concluded that movements of harbour porpoises into the

Baltic proper occur during spring and back into the Danish Belt Sea during autumn. However, as our data show that the animals are continuously present in the Nysted area, it can be excluded that the area is only a seasonal transit-corridor between the Baltic proper and the Inner Danish Waters. Moreover, due to the daily recordings of short harbour porpoise click sequences it can be suggested, that next to a seasonal migration pattern, the area is also characterised by small scaled movements of the animals between different areas. During their small scaled movements around the area south of Lolland, harbour porpoises regularly (at least daily) visited or crossed the wind farm area. This hypothesis is supported by our T-POD data, which show a lot of short inconsistent porpoise contacts.

Inter-annual variation in Nysted

Our results show that the basic seasonal pattern with low densities in spring, high densities in summer and again decreasing densities in late autumn remains stable over both years, however, some variations occurred between the years. With a monthly mean of nearly 10 % PP10M/day two peaks were reached in 2005, one in July and the second in October, whereas in 2006 only one distinct peak appeared in July with a mean of 11 % PP10M/day. As only six months common in both years were studied in both years, no proper conclusions can be drawn. However, Verfuß et al. (2004, 2007) showed with T-POD data over a period of six years a very regular seasonal pattern in the German Baltic Sea, which confirms our observations. Whereas the mean density peaks remained at the same magnitude, the specific time of these peaks varied of up to two months. This inter-annual variation might be connected with prey availability, however, as long as no data on prey (fish) exist in a sufficient resolution to connect this to the harbour porpoise data, this remains a hypothesis.

Seasonal variation in Horns Rev

The daily pattern of PP10M showed regular changes of porpoise recordings from day to day although at some positions the recordings of harbour porpoises remained high for longer periods during summer. These findings indicate that the Horns Rev area is intensively used by the animals and therefore plays an important role during their annual cycle.

Similar to the Nysted area, we found a pronounced seasonal pattern, with lowest monthly means of 4-5 % PP10M/day recorded in March/April and maximum numbers in summer with monthly means of more than 30 % PP10M/day in July 2005 and again a decline of porpoise echolocation during winter. This pattern corresponds exactly to other results from T-POD studies conducted in the Horns Rev wind farm area (Tougaard et al. 2006a).

Diederichs et al. (2004), Grünkorn et al. (2004) and Gilles et al. (2006,2007) carried out studies on the distribution of harbour porpoises west of the island of Sylt, Germany, and all studies revealed a pronounced seasonal pattern with high densities recorded by aerial surveys, associated with high numbers of click recordings during early summer, and few sightings associated with a low number of acoustic recordings during winter. This consistent and pronounced seasonal variation in the area west of Denmark/Schleswig-Holstein is area specific. Other patterns in annual variation have been observed at other locations, such as in the Netherlands, where a converse pattern with a peak during winter and very low densities during summer was reported by Camphuysen (2004) and Brasseur et al. (2004). Where the animals move from the area west of Denmark/Schleswig-Holstein during winter and if a connection to the area west of the Netherlands exists, remains unknown.

Inter-annual variation in Horns Rev

As only six months common in both years were studied in both years, no proper statements can be concluded about inter-annual variation. The basic pattern in both years seems to be very similar with a distinct decrease in recorded PP10M/day in autumn after a peak during summer. The months, during which these peaks occurred, differed between both years. In 2005 two peaks occurred with monthly means of 28-29 % PP10M/day, the first in June and the second in September. Whereas in 2006 only one distinct peak with a monthly mean of 34 % PP10M/day was observed in July. Nothing is known about the variables that govern the occurrence of the animals in that area, but as stated by Tougaard et al. (2006a), it can be assumed that the animals move around in the area in response to movements or changes in prey availability, which is indirectly coupled with hydrographic factors. Gilles et al. (2006) showed changes in the mean summer density between 2 and 4 animals per square kilometre for the German Natura2000 area ‘Sylt Outer Reef’ for the years 2002 – 2005. This means that beside a basic seasonal pattern, changes in the numbers of animals can occur and peak number as well as the times when these peaks occur can change from year to year.

2.7.3. Small scale heterogeneity

The only significant difference regarding the recorded number of PP10M when including the factors season, sensitivity of the PODs and wind, was found between different T-POD-rows, which were deployed at the same time with a distance of a few kilometres to each other. This was apparent in both wind farms.

The observation, that the difference between two rows during the same time period is much more conspicuous than differences within rows shows a high spatial variance in use of a specific area by harbour porpoises. Snapshots of the distribution of harbour porpoises derived from aerial surveys show that the animals are often distributed in a very patchy pattern (Fig. 2-66). Especially in areas where higher concentrations of porpoises occur, sub-areas of some hundreds of square-kilometres with higher densities can be observed. Such a pattern is highly dynamic and often interpreted that governed by the distribution of prey (Santos & Pierce 2003). Again, the distribution of prey is often thought to follow special hydrographical features (Skov & Prins 2001).

The Horns Rev area is described as very dynamic regarding hydrographic factors (Tougaard et al. 2006a). The reef structure and the highly complex system of the mixing zone between estuarine water masses moving northwards from the rive Elbe and more saline North Sea water, leads to a high variability in factors that possibly govern the distribution of fish and also marine mammals. This complexity can lead to high heterogeneity in porpoise abundance on a spatial scale of a few kilometres as observed in this areas. Although the hydrographic system is not that complex in the Nysted area, the small scale distribution of harbour porpoises of a few square kilometres seems to be subjected to the presence of hydrographic features. Hydroacoustic surveys showed, that current boundaries play a major role in the distribution pattern of fish in the Nysted area. Fish aggregations were registered coincident with an observed current boundary within the wind farm area (Leonhard et al. 2006).

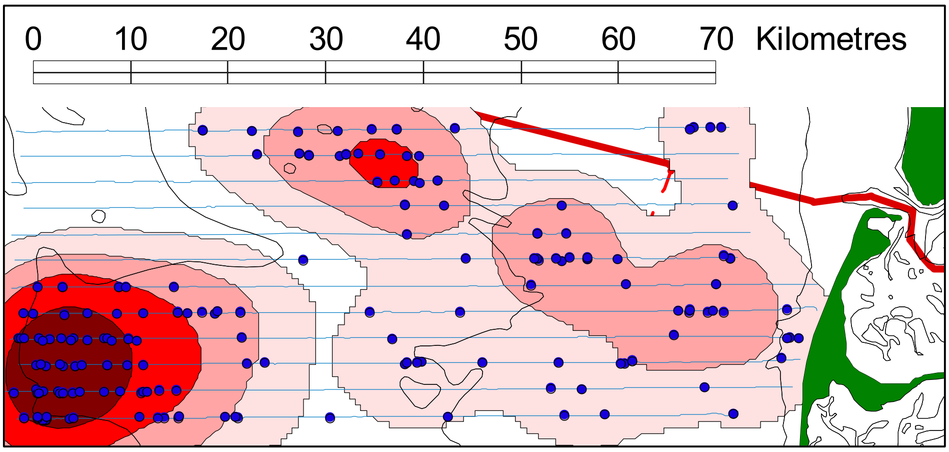


Fig. 2-66: Kernel distribution of 231 harbour porpoises counted on an aerial survey at June, 17th, 2003 west of Sylt, North Sea. Source: BioConsult SH. Kernel percentages: 95%, 85%, 70% and 40%.

2.7.4. Effect of the wind farm

The main aim of this study was the investigation of possible responses of harbour porpoises to offshore wind farms. Negative responses might be induced by underwater noise emitted from the turbines which could disturb the animals or mask their echolocation calls. On the other hand, an attraction to the wind farms might occur, if the reef effects of the foundations provided an enhanced food source. The main finding of the investigation was that harbour porpoises frequently roam in both wind farms studied, and that their daily presence is similar to the surrounding. Any effect, positive or negative, is thus small, and it is obvious, that the wind farm areas do not have a marked specific function in harbour porpoise habitat utilisation.

Offshore wind turbines produce a relatively constant “humming” underwater noise with highest energy at low frequencies, which are not audible to harbour porpoises. Noise emissions within the range of audibility reach 90 to 100 dB at a distance of 100 m, which is already close to background levels at moderate windspeeds (Nehls et al. 2008). Aversive responses of harbour porpoises have been induced by transient sounds at received noise levels around 100 dB, however, responses to continuous sounds occur at higher levels (Nehls et al. 2008). Richardson et al. (1995) report avoidance reactions of marine mammals exposed to continuous sounds above 120 dB and conclude that marine mammals would avoid areas with continuous levels above 140 dB. Other studies reported behavioural responses to higher continuous noise levels, but little is known about the onset so far. Operating offshore wind turbines emit noise of this strength only at frequencies, which are not audible to harbour porpoises. It thus can be assumed that noise emissions from wind turbines in the audible range are unlikely to cause aversive responses even at close distance (Madsen et al. 2006).

Reef effect

The foundations of offshore turbines soon become heavily overgrown by benthic animals, with blue mussels and amphipods being the most numerous species (Leonhard & Petersen 2005). The foundations thus form a local enrichment of benthic biomass, however, as it is restricted to secondary production it is not clear, whether it increases biomass on a larger level as the total wind farm area. However, the foundations form hotspots with a high biomass, which is available to higher trophic levels as fish and consequently marine mammals. Such reef effects have been shown for a variety of offshore installations. As outlined above, differences in porpoise recordings at our PODs in relation to the distance to the nearest turbine were small and did not show any systematic trend. However, at Nysted it became apparent, that PODs moored close to the turbines showed higher harbour porpoises recordings at night as compared to the more distant PODs, indicating, that porpoises were approaching the turbines more frequently at night. This behaviour might well indicate an attraction of harbour porpoises to increased abundance of night-active fish species utilising the rich food source at the foundations. The effect is not too pronounced and was not observed in Horns Rev. Regarding the wide spacing of the turbines, total biomass enrichment is apparently low on the level of the total wind farm area. However, it is remarkable, that such behaviours can be detected, as it indicates a response of harbour porpoises to offshore foundations, which might become more pronounced as the number of wind farms increases.

Influence of wind

In Horns Rev a significant effect of wind on the recording of PP10M/day was found. However, this effect was neither correlated with wind speed (at least not equally correlated in the years 2005 and 2006) nor was the effect different between the two distance groups of T-PODs (inside/outside and <200m/>900m). The number of recorded harbour porpoises was also not correlated with power production. These results fit well with our hypothesis, that noise production of operating turbines is too low to cause aversive responses of harbour porpoises. The non-directional effect of wind on the recordings of harbour porpoises is weak, as only 2 % of the data can be explained by this factor. Thus, the factor wind (and hence also power production of the turbines) was included into a Linear mixed effect model as an explanatory factor, in order to exclude its influence on the comparison between different T-POD locations.

In the Nysted area the factor wind plays a different role. Though noise production of operating turbines is considered to be too low to cause aversive responses of harbour porpoises, in Nysted the results showed a negative correlation of porpoise recordings and wind speed. The effect is distinct with more recordings during days with low wind speed and only few recordings during days with high wind speed. There is no difference in this effect between T-PODs deployed inside and outside the wind farm or between T-PODs deployed close to and more than 700 m away from single turbines. The correlation of recordings of harbour porpoises with wind speed in the Nysted wind farm area is independent from season and hence might indicate that porpoises avoid the vicinity of operating turbines. However, noise emitted by the turbines is weak compared to the hearing threshold of harbour porpoises and only has energy at very low frequencies and the actual power output has little impact on the noise emissions (ISD et al. 2007). Therefore the noise should not be audible for the animals at a distance of more than 100 m away from the turbine, so that it should be impossible to see any reaction of the animals at a distance of more than 700 m based on the noise emitted by the turbine (see also Madsen et al. 2006). If the observed negative correlation of porpoise presence with wind speed was caused by the operation of wind turbines, one should thus find a difference in this effect when comparing T-PODs inside and outside the wind farm. As this was not the case the influence of wind is probably unrelated to the operation of wind farms.

There was no difference in harbour porpoise presence between the week, when no turbines in the Nysted area were operated, and the weeks before that. It is therefore highly unlikely that noise emissions from operating turbines disturbed harbour porpoises.

The negative correlation of porpoise recordings and wind speed might be a methodological problem, as we faced some problems with noise (especially in the Horns Rev area) caused by moving sand at times with high wind speed. This means that during times with high wind speed, noise from waves and moving sediments increase, which reduce the detection distance of the T-PODs and make it difficult for the algorithm to detect true porpoise signals. However, if this was the case, this phenomenon should also be recognisable in other areas like Horns Rev. As this was not the case, we cannot conclude, that the correlation in Nysted is caused by the method of T-PODs. At present, we have to assert, that in Nysted wind (and hence power production of the turbines) plays a significant role for the recording of harbour porpoises, independent from the position of the T-PODs. As the effect is still present in a distance of more than 700 m away from the turbines, this effect is probably not induced by the wind farm.

Influence of T-POD positions

In Horns Rev no effect of the wind farm could be detected according to the number of PP10M inside and outside the wind farm or between T-PODs at close distance to single turbines and T-PODs more than 900 m away. Independent of other variables like wind, turbine power production, season, T-POD specific sensitivity and water temperature, which clearly effect the recordings from harbour porpoises, some differences occurred when zooming into single experiments, but neither was an effect stable over different experiments nor was the effect apparent when including the above mentioned parameters. Hence for the Horns Rev area our data suggest that the wind farm has no influence on the presence of harbour porpoises. Neither an attraction nor an avoidance of the wind farm area or the vicinity of the turbines is detectable in the presence of the animals.

In the Nysted area also no effect could be seen when comparing T-POD data from inside the wind farm with outside the wind farm. However, a slight difference was apparent when comparing the results from PODs close to single turbines to PODs more than 700 m away from the turbines. Then, in both years more recordings were made at a greater distance to the turbines. This picture still remained, when zooming into the 10 single experiments. 5 out of 10 experiments showed the effect, that more than 700 m away from single turbines more PP10M/day were recorded than close to single turbines. Only at one experiment it was converse. This negative effect in the vicinity of the turbines on the recordings of harbour porpoises is only apparent when no other variables are included into the comparison. After the inclusion of such variables no significant difference between the different distances from the turbines can be shown. The effect is therefore probably weak and no strong conclusions can be drawn. If there are any impacts of the operating turbines on the distribution of harbour porpoises, this effects are related to the close vicinity of the turbines as no effect can be seen by comparing T-PODs outside with inside the wind farm. Thus, the effect is probably on a much smaller spatial scale than on the here investigated scale of a few hundred metres, which is given by the detection radius of a T-POD. On the larger scale of a few kilometres, the effect of hydrography, bottom structure and other possible impact factors appear stronger and show differences between areas, which are only separated by a few kilometres from each other, independent from the influence of the wind farm.

Independent of the weak effect of less recordings close to single turbines, the results obtained in the Nysted area cannot answer the question why significantly fewer than expected harbour porpoises had returned to the area after the construction of the wind farm, even in the second year of operating. This effect was shown by the comparison of the wind farm area with a reference area approximately 10 km away from the wind farm by Tougaard et al. (2006b). Our study shows that this effect does not exist across the outer edge of the wind farm. No gradient in porpoise abundance can be seen by comparing the results from inside to outside the wind farm.

2.7.5. Diurnal rhythm

Based on observations of Akamatsu et al. (2006) we assume that harbour porpoises echolocate almost constantly and that their echolocation ability is independent of visibility conditions. Hence, the proportion of click sequences distributed over the 24 hours of a day can give us some indications about the animals presence in the detection radius of the T-PODs. Because their echolocation beam is very narrow (Au et al.1999), the detection probability of harbour porpoises will increase the longer the animals stay in the vicinity of the T-PODs. Therefore, the more an animal moves around inside the detection radius of a POD the higher the detection probability. Thus, it can be assumed that the recordings of a small scaled temporal parameter like PPM during a day gives some details on the behaviour of the animals. It is known from tagged harbour porpoises, that they show a seasonal dependent 24-hour cycle in their dive behaviour (Teilmann et al. 2000).

The diurnal rhythms in recorded PPM/hour show a distinct significant pattern in both wind farms.

In Nysted the diurnal pattern basically follows a clear day-night rhythm with a lot of recordings during the night and only few recordings during the day light phase between 5 AM and 7 PM. This pattern is very pronounced inside the wind farm as well as close to single turbines. Only in 2006 exactly the same pattern is found more than 700 m away from the turbines. In 2005 outside the wind farm and more than 700 m away from the turbines the daily pattern changed to regular ups and downs without showing a clear day-night rhythm. In 2006 the daily pattern showed outside the wind farm next to the basic pattern a significant peak in recordings during day at 2 PM.

Inherent diurnal rhythms in cetaceans have been proved to be highly different and dynamic. For example, the taxon Tursiops is more active at daytime (Mc Cormick 1969), whereas Hawaiian Spinner Dolphins are inactive during daytime hours and increase prey capture activities at night (Norris & Dohl 1980). Carlström (2005) showed with the help of T-PODs a higher echolocation activity of harbour porpoises at night in Scottish waters. Meding (2005) confirmed this diurnal rhythm for harbour porpoises in the Baltic Sea.

The biological reason behind a diurnal rhythm may be caused by behaviour of prey species. Harbour porpoises prey upon the predominating fish species of suitable size in the area. As both bottom fish (flatfish) and pelagic species (e. g. herring) exhibit considerable differences in their diurnal activity rhythms and, in consequence, in their availability as prey for harbour porpoises, the timing of foraging is expected to be highly dynamic in porpoises. Especially the vertical distribution of fish within the water column is known to differ with respect to the hour of the day (for herring: Blaxter & Parrish 1965).

Although Leonhard et al. (2006) report from hydroacoustic fish surveys in the Nysted offshore wind farm that no general and unambiguous regional effect could be demonstrated in the distribution pattern of pelagic and semi pelagic fish communities when comparing impact and reference areas, they nevertheless found in one out of two samples a significantly higher density of small fish (less than 10 cm in length) during darkness inside the wind farm area while the opposite, a higher density during daylight, was found outside the wind farm. The greater amount of small fish in the wind farm area might reflect semi pelagic fish species like sand gobies and small Atlantic cod, which displays nocturnal dispersion behaviour. Nocturnal dispersion behaviour, as demonstrated in other studies of demersal or semi pelagic fish species hiding around hard structures during day and dispersing throughout the water column at night, are only hydroacousticly detectable at night (Soldal et al., 2002). As this study was conducted in 2005 in the Nysted wind farm, these findings fit the results of our T-POD study in 2005 well. As long as prey species are hidden in sediment or between stones enclosing the turbine foundations, harbour porpoises do not search for this food source or they search for food by using a special feeding behaviour, the so called ‘bottom grubbing’ (Lockyrer et al. 2001). During this behaviour the animals scan the sea bottom by swimming in a vertical position with the mouth close to the bottom. Due to the narrow echolocation beam it is very likely that only few click sequences can be recorded by the T-POD, which were deployed approximately 2 m above the sea bed.

In contrast it is more likely that harbour porpoise clicks can be recorded by the T-PODs when they are feeding in the water column on pelagic fish. Because harbour porpoises use short click intervals during investigation of close objects and especially during prey capture (Busnel & Dziedzic 1967, Koschinski et al. in press), it is suggested that times with small click intervals correspond with a higher feeding behaviour. Hence, possible feeding behaviour was investigated by comparing the mean click interval of each click train during the 24 hours of a day. Due to a similar day-night pattern of mean click intervals with smaller intervals during night and longer intervals during day in 2005, it seems that harbour porpoises use the food source of pelagic fish during night and show less feeding behaviour during daylight, independent of the position of the wind farm.

For the Nysted wind farm area we can conclude that in 2005 a clear day-night-rhythm with higher porpoise activity during the night existed, that was induced by the foundations of the turbines. This might be due to higher fish density in the water column during night. Outside the wind farm and also far away from single turbines in 2005 no clear difference was found between day and night, which is in line with observation by Tougaard et al. (2006b), who showed no daily pattern in harbour porpoise click activity for the reference area during the baseline and operational phase.

In 2006 the pattern changed outside the wind farm and far away from single turbines. Now, no clear difference between both distance groups occurred. In all cases most recordings were made during the night and only few recordings during the day. Because no studies on fish abundance were carried out in 2006 in the Nysted wind farm, nothing can be stated about the fish distribution in that area in 2006. Due to a complete change of the daily pattern of the mean click interval close to single turbines to a converse pattern with longer intervals during night and smallest intervals during day, a change in behaviour of harbour porpoises in the vicinity of the turbines may have occurred. More than 700 m away smallest intervals were still recorded during the night. Following the interpretation for the year 2005, this might indicate a change in the local fish community around the turbine foundations and hence a change in feeding activity of harbour porpoises during the day.

In Horns Rev a very similar pattern to Nysted was observed. When comparing daily cycles with respect to the position of the PODs, inside or outside the wind farm, no differences in the basic trend was observable. However, a clear change between both study years exist: Whereas in 2005 more recordings were made during night, it was converse in 2006 with more recordings during day.

During the year 2005 the picture changed completely when zooming into the data of PODs deployed more than 900 m away from single turbines. Again, this pattern, obviously caused by the turbine foundation, is thought to be connected with different activity of the animals. From the Northeast Atlantic it is known that harbour porpoises tend to feed primarily on few main species like sandeels in Scottish waters (Santos & Pierce 2003). Sandeels also play a major role in the fish community in the Horns Rev area (Jensen et al. 2004). Diederichs et al. (2004) showed a daily activity pattern of harbour porpoises in an area 30 km west of Sylt, which was constant over the period of three years with highest activity measured during days and lowest activity during night. This pattern was discussed with the distribution of sandeels, which show a distinct diurnal pattern with being buried in the sand during night and swimming around during daylight (Winslade 1974).

Hence, the daily rhythm in the Horns Rev area far away from the turbines with a maximum in measured porpoise activity during night can also be caused by prey, which are distributed in the water column only during day like the sandeel. Due to the fact that this pattern was most distinct at a distance of more than 900 m away from the turbines (2005) or outside the wind farm (2006), it may show that also in Horns Rev the turbines govern the behaviour of harbour porpoises in their vicinity due to a different fish community in the habitat of the foundation. Schools of whiting and Atlantic cod associated with the turbine foundations were observed at Horns Rev Offshore Wind Farm (Leonhard and Petersen, 2004).

As the diurnal cycle of the mean duration of the click interval show no clear pattern, except for a weak maximum in the morning for most cases, no additional information on different feeding behaviour can be obtained. A Diploma thesis prepared during this project could show, that for two investigated T-PODs in 2005 outside the wind farm in Horns Rev a strong diurnal rhythm occurred according to the click trains with smallest click interval below 10 ms (Thiele 2006). This click trains occurred more often during night, which suggest high feeding activity during night within the detection radius of the T-PODs.

2.7.6. Conclusions

This study was carried out in order to investigate whether the operation of wind farms in Horns Rev and Nysted has an effect on the behaviour of harbour porpoises. In this context we asked the following specific questions:

Are there differences in the presence, echolocation activity and behaviour of harbour porpoises between inside and outside the wind farm or close to a single turbine compared to far away from a single turbine (up to 1.5 km away)? Are potential differences related to wind speed and therefore to the performance and noise emission of the turbines?

During this study no differences could be detected in harbour porpoise presence between inside and outside the wind farm in both areas Nysted and Horns Rev.

In Horns Rev there were also no difference between T-PODs at different distances to single turbines. Here, the wind farm does not seem to influence the presence of harbour porpoises at all.

In the Nysted area a weak effect was detectable according to the distance of the T-PODs to single turbines with more recordings more than 700 m away from turbines compared to T-PODs closer than 150 m to single turbines. This effect was only apparent when no additional variables, that could also affect harbour porpoise activity, were included. Wind was negatively correlated with the number of recorded PP10M/day in Nysted only. As this correlation was independent from the distance of the T-PODs to single turbines, it is unlikely that the wind farm itself and in particular the performance and noise emission of the turbines was the reason for this correlation.

The only effect of the turbines on harbour porpoises that was observed in both wind farms was an effect on the 24-hour cycle of harbour porpoise recordings. Especially in 2005 a pronounced diurnal rhythm with most recordings during the night occurred at T-PODs deployed close to single turbines in both wind farms. At the same time the diurnal pattern at T-PODs deployed more than 900 m away from single turbines showed a converse pattern with a maximum of porpoise recordings during the daylight in Horns Rev. In Nysted at the same time more than 700 m away from single turbines no clear pattern between day and night could be found. In 2006 this diurnal pattern changed in both areas and the differences between the distance groups was no longer very pronounced.

We discussed these differences in the diurnal cycle of harbour porpoise activity with regard to differences in the fish community close to single turbines, which has been demonstrated by several other studies.

From our results it can be concluded, that operating offshore wind farms are regularly incorporated into harbour porpoises habitats and do not induce significant aversive responses of these protected animals.

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2.9. References

Akamatsu, T., Y. Hatakeyama, T. Kojima & H. Soeda 1992: The rate with which a harbour porpoise uses echolocation at night. In: J. Thomas [ed.]: Marine mammal sensory systems. Plenum Press, New York, pp. 299-315.

Akamatsu, T., J. Teilmann, Miller, L.A., Tougaard, J., Dietz, R., Wang, D., Wang, K., Siebert, U. and Y. Naito. 2007: Comparison of echolocation behaviour between coastal and riverine porpoises. Deep-Sea Res. 54: 290-297.

Amundin, M. 1991: Sound Production in Odontocetes with Emphasis on the Harbour Porpoise *Phocoena phocoena*. Ph.D. thesis Department of Zoology, Division of Functional Morphology, University of Stockholm.

Au, W.W.L. 1993: Sonar of dolphins. Springer, New York.

Au, W.W.L., R.A. Kastelein, T. Rippe & N.M. Schooneman 1999: Transmission beam pattern and echolocation signals of a harbor porpoise *(Phocoena phocoena*). J. Acoust. Soc. Am.106: 3699–3705.

Bach, S., J. Teilmann & O.D. Henriksen 2000: VVM-redegørelse for havmølleparker ved Rødsand. Teknisk rapport vedrørende marsvin.

Benke, H., U. Siebert, et al. 1998: The current status of harbour porpoises (*Phocoena phocoena*) in german waters. Arch. Fish. Mar. Res. 46: 97-123.

Benke, H., U. Verfuß, S. Kotzian, A. Kilian, C. Honnef, I. Baresel & R. Kinzelbach 2003: Untersuchungen zur Nutzung ausgewählter Gebiete der Deutschen und Polnischen Ostsee durch Schweinswale mit Hilfe akustischer Methoden. FKZ-Nr.: 901 86 020. Bundesministerium für Umwelt. F+E-Vorhaben. 2. Zwischenbericht.

Benke, H. and C. Honnef 2006: Erfassung von Schweinswalen in der deutschen AWZ der Ostsee mittels Porpoise Detektoren. Stralsund, Deutsches Meeresmuseum. BfN: 34.

Blaxter, J. H. S. and B. B. Parrish 1965: The importance of Light in Shoaling, Avoidance of Nets and Vertical Migration by Herring. J. Cons. perm. int. Explor. Mer 30(1): 40-57.

BioConsult SH & GfN 2002: Environmental Impact Assessment Butendiek. Report to Offshore-Bürger-Windpark-Butendiek GmbH & Co KG, Husum.

Brasseur, S., P. Reijnders, Damsgaard Henriksen, O., Carstensen, C., Tougaard, J., Teilmann, J., Leopold, M., Camphuysen, K. and J. Gordon. 2004: Baseline data on the harbour porpoise, Phocoena phocoena, in relation to the intended wind farm site NSW, in the Netherlands, Alterra: 80.

BSH 2007:. Standard – Untersuchung der Auswirkungen von Offshore-Windanlagen auf die Meeresumwelt (StUK 3) BSH-Nr. 7003. Bundesamt für Seeschifffahrt und Hydrographie (BSH). Hamburg and Rostock, Germany. p. 1-58.

Busnel, R.G. & A. Dziedzic 1967: Resultats metrologiques experimentaux de l'echolocation chez le *Phocoena phocoena* et leur comparison avec ceux de certaines chauves-souris. In: R. G. Busnel [ed.]: Animal Sonar Systems - Biology and Bionics. Laboratoire de Physiologie Acoustique, Jouy-en-Josas, pp. 307-335.

Camphuysen, C. J. 2004: The return of the harbour porpoise (*Phocoena phocoena*) in Dutch coastel waters. Lutra 47(2): 113-122.

Carlström, J. 2005: Diel variation in echolocation behaviour of wild harbour porpoises. Marine Mammal Science 21(1): 1-12.

Carstensen J, Henriksen OD & Tielmann J 2006: Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echo-location activity using porpoise detectors (T-PODs). Marine Ecology Press Series, 321: 295-308.

Cox TM and Read AJ 2004: Echolocation behaviour of harbour porpoises *Phocoena phocoena* around chemically enhanced gill nets. Marine Ecology Progress Series 279: 275-282.

Cox TM, Read AJ, Solow A and Tregenza NJC 2001: Will harbour porpoises (*Phocoena phocoena*) habituate to pingers? Journal of Cetacean Research and Management 3(1): 81-86.

Crawley, M.J. 2002: Statistical Computing – An introduction to data analysis using S-plus. Wiley & Sons, London, pp. 761.

Dähne, M., Verfuß U.K., Diederichs, A., Meding, A. and H. Benke 2006. T-POD test tank calibration and field calibration. ECS Newsletter no. 46 – Special isssue - Proceedings of the workshop STATIC ACOUSTIC MONITORING OF CETACEANS held at the 20th annual meeting of the European Cetacean Society, Gdynia, Poland, 2 April 2006. p. 34-36.

Diederichs, A., T. Grünkorn & G. Nehls 2002: Erprobung von Klickdetektoren zur Erfassung von Schweinswalen im Sommer und Herbst 2002 im Seegebiet westlich von Sylt. Status report to Offshore-Bürger-Windpark-Butendiek GmbH & Co KG, Husum.

Diederichs, A., T. Grünkorn & G. Nehls 2004: Einsatz von Klickdetektoren zur Erfassung von Schweinswalen im Seegebiet westlich von Sylt. Final report to Offshore-Bürger-Windpark-Butendiek GmbH & Co KG, Husum.

Erbe, C. 2002: Underwater noise of whale-watching boats and potential effects on killer whales (Orcinus orca), based on an acoustic impact model." Mar. Mammal Sc. 18(2): 394-418.

Faraway, J.J. 2006: Extending the linear Model with R. Chapman & Hall, London, pp. 301.

Gilles, A., Risch, D., Scheidat, M., Siebert, U. 2006. Erfassung von Meeressäugetieren und Seevögeln in der deutschen AWZ von Nord- und Ostsee (EMSON). Teilvorhaben: Erfassung von Meeressäugetieren. Endbericht für das Bundesamt für Naturschutz. F+E Vorhaben FKZ: 802 85 250, 92 pp.

Gilles, A., H. Herr, K. Lehnert, M. Scheidat, K. Kaschner, J. Sundermeyer, U. Westerberg, U. Siebert. 2007: Erfassung der Dichte und Verteilungsmuster von Schweinswalen (*Phocoena phocoena*) in der deutschen Nord- und Ostsee. In: Forschungsverbund MINOSplus- Weiterführende Arbeiten an Seevögeln und Meeressäugern zur Bewertung von Offshore – Windkraftanlagen. Teilvorhaben 2.

Grünkorn, T., A. Diederich, et al. 2004: Linientransektzählungen mit Flugzeug und Schiff westlich von Sylt, BioConsult SH: 44.

Fisher, F. H. and Simmons, V. P. 1977: Sound absorption in sea water. J. Acoust. Soc. Am. 62, 558-564.

Fisher, P. & N. Tregenza 2003: An assessment of the effect of a tidal power generator on porpoise habitat use and an evaluation of the acoustic methods employed, August – October 2003. Report to the Highlands and Islands enterprise, Shetland Islands Council, The Croen Estate & The Engineering Business Ltd.

Hammond P.S., H. Benke, P. Berggren , A. Collet , M.P. Heide-Jørgensen, S. Heimlich-Boran, M.F. Leopold & N. Øien 1995: The distribution and abundance of harbour porpoises and other small cetaceans in the North Sea and adjacent waters. LIFE 92–2/UK/027 final report to the European Commission. European Community, Brussels.

Hammond, P.S., P. Berggren, H. Benke, D.L. Borchers D. L., Collet, A., Heide- Jørgensen, M. P., Heimlich, S., Hiby, A. R., Leopold, M. F., Øien, N. 2002: Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters. J. Appl. Ecol. 39: 361–376.

Hammond,P.S. 2007. Small Cetaceans in the European Atlantic and North Sea (SCANS-II). In: LIFE04NAT/GB/000245. Final Report. St Andrews, UK. pp 1-52.

Hastie, T., Tibshirani, R., Friedman, J. 2001. The Elements of Statistical Learning. Springer New York.

Henriksen, O.D., J. Teilmann & J. Carstensen 2003: Effects of the Nysted Offshore Wind Farm construction on harbour porpoises. 2002 annual status report for the acoustic T-POD monitoring programme. Ministry of the Environment.

Jensen, H., P. S. Kristensen, E. Hoffmann. 2004: Sandeels in the wind farm area at Horns Reef. Final report to Report to ELSAM August 2004.

Johnston, D.W., A.J. Westgate & A.J. Read 2005: Effects on fine-scale oceanographic features on the distribution and movements of harbour porpoises *Phocoena phocoena* in the Bay of Fundy. Mar. Ecol. Prog. Ser. 295: 279-293.

Kastelein, R.A., N.M. Schooneman, W.W.L. Au, W.C. Verboom, & N. Vaughan 1997: The ability of a harbour porpoise (*Phocoena phocoena*) to discriminate between objects buried in the sand. In: A.J. Read, P.R. Wiepkema & P.E. Nachtigal [eds.]: The biology of the harbour porpoise. De Spil Publishers, Woerden pp. 329–342.

Kastelein, R. A., Au, W. W. L., Rippe, T. and Schooneman, N. M. (1999). Target detection by an echolocating harbour porpoise (Phocoena phocoena). J. Acoust. Soc. Am. 105, 2493-2498.

Kinze, C. C., T. Jenssen, et al. 2003: Blickpunkt Wale in Dänemark 2000-2002." Biologiske Skrifter(2): 47.

Koschinski, S. 2000: Current knowledge on Harbour Porpoises (*Phocoena phocoena*) in the Baltic Sea. Ophelia 55 (3): 167-197.

Koschinski, S. & B. M. Culik. 2001. Reaktionen von Schweinswalen (Phocoena phocoena) und Seehunden (Phoca vitulina) auf Betriebsgeräusche einer simulierten 2 MW Offshore-Windenergieanlage. Unveröffentlichtes Gutachten.

Koschinski, S. 2002. Current knowledge on harbour porpoises *Phocena phocena* in the

Baltic Sea. Ophelia 55: 167-197.

Koschinski, S., B. M. Culik, O. D. Henriksen, N. Tregenza, G. Ellis, C. Jansen & G. Kathe. 2003. Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Mar Ecol Prog Ser, Vol. 265: 263-273.

Koschinski, S., Diederichs, A. & A. Amundin 2008: Click train patterns of free-ranging harbour porpoises acquired via T-POD may be useful as indicators of their behaviour. J. Cetacean Res. Manage. In press.

Krause, G. R. R. 1988: Fronten in der Deutschen Bucht." Einblicke 7: 24-28.

Leeney, R. H., S. Berrow, McGrath D, O'Brien J, Cosgrove R and Godley BJ. 2007: Effects of pingers on the behaviour of bottlenose dolphins. J. Mar. Biol. Ass. U.K. 87: 129-133.

Leonhard, S.B. & J. Pedersen, 2005. Hard bottom substrate monitoring. Horns Rev Offshore Wind Farm. Annual status report 2004. Bio/consult. Report commissioned by Elsam Engineering: 1-79.

Leonhard, S.B., C.B. Hvidt, M. Klaustrup & J. Pedersen 2006: Hydroacoustic monitoring of fish communities at offshore wind turbine foundations, Nysted Offshore Wind Farm at Rødsand. Annual Report 2005 for Energy E2 A/S.

Lockyer, C., Amundin, M., Desportes, G., Goodson, A. D. & Larsen 2001: F. The tail of EPIC - Elimination of harbour porpoise incidental catches. Project DG XIV 97/0006. Final report, 1-249. 2001.

Madsen, P.T., M. Wahlberg, J. Tougaard, K. Lucke & P.L. Tyack 2006: Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. Mar. Ecol. Prog. Ser. 309: 279-295.

Meding, A. 2005: Untersuchungen zur Habitatnutzung von Schweinswalen (*Phocoena phocoena*) in ausgewählten Gebieten der Ostsee mit Hilfe akustischer Methoden. Diplomarbeit, Ernst-Moritz-Arndt-Universität Greifswald.

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

McCormick J. G. 1969: Relationship of sleep, respiration, and anesthesia in the porpoise. Proc Natl Acad Sci USA 1969;62:697–703.

Nehls, G. K. Betke, K. Lüdemann & S. Koschinski 2008: Sources of underwater noise and their implications on marine wildlife - with special emphasis on the North Sea and the Baltic Sea. Report to Federal Environmental Agency, Berlin.

Norris, K. S. and T. P. Dohl. 1980. Behavior of the Hawaiian spinner dolphin, *Stenella longirostris*. Fish. Bull. 77:821-849.

Petersen, J. K. & T. Malm 2006: Offshore Windmill Farms: Threars to or Possibilities for the Marine Environment. Ambio 35(2): 75-80.

Richardson, W.J., C.R. Greene, C.I. Malme & D.H. Thompson 1995: Marine Mammals and Noise. Academic Press, San Diego, California.

Rye, J. H., H. Charwat, C. Rocholl, M. Hesse, M. Linnenschmidt, R. Mundry, K. Kaschner, H. Herr, J. Sundermeyer, S. Adler, L. Lehnert, U. Siebert. 2007: Einsatz und Vergleich visueller und akustischer Erfassungsmethoden zur Beurteilung von Schweinswalvorkommen. In: Forschungsverbund MINOSplus- Weiterführende Arbeiten an Seevögeln und Meeressäugern zur Bewertung von Offshore – Windkraftanlagen, Teilvorhaben 4.

Santos, M. B. and G. J. Pierce 2003: The diet of harbour porpoise (*Phocoena phocoena*) in the northeast Atlantic. Oceanography and Marine Biology: an Annual Review 41: 355-390.

Scheidat, M., K.-H. Kock & U. Siebert 2003: Summer distribution of harbour porpoise (*Phocoena phocoena*) in the German North and Baltic Sea. Working paper presented to ASCOBANS. Bonn.

Scheidat, M., A. Gilles & U. Siebert 2004: Erfassung der Dichte und Verteilungsmuster von Schweinswalen (*Phocoena phocoena*) in der deutschen Nord- und Ostsee. In: A. Kellermann et al. 2004: Marine Warmblüter in Nord und Ostsee: Grundlagen zur Bewertung von Windkraftanlagen im Offshore-Bereich. Verbundvorhaben MINOS Teilprojekt 2. Band 1.

Schevill, W.E., W.A. Watkins & C. Ray 1969: Click structure in the porpoise, *Phocoena phocoena*. Journal of Mammalogy 50: 721-728.

Schulze, G. 1996. Die Schweinswale. Magdeburg. Neue Brehm Bücherei. 188 pp.

Siebert, U., A. Gilles, et al. 2006: A decade of harbour porpoise occurence in German waters - Analysis of aerial surveys, incidental sightings and strandings. Journ. Sea Res. 56: 65-80.

Skov, H. & E. Prins 2001: The impact of estuarine fronts on the dispersal of piscivorous birds in the German Bight. Mar. Ecol. Prog. Ser. 214: 279-287.

Soldal, A.V.; Svelling, S.; Jørgensen, T.; Løkkeborg, S. 2002. Rigs-to reefs in the North Sea: Hydroacoustic quantification of fish in the vicinity of a ”Semi-Cold” platform. ICES journal og marine Science, 59; s281-s287.

Sonntag, R.P., H. Benke, A.R. Hiby, R. Lick & D. Adelung 1999: Identification of the first harbour porpoise (*Phocoena phocoena*) calving ground in the North Sea. J. Sea Res. 41: 225–232.

Teilmann, J., O.D. Henriksen & J. Carstensen 2001: Status report of the pilot project: Porpoise detectors (PODs) as a tool to study potential effects of offshore wind farm on harbour porpoise at Rødsand. Report for SEAS.

Teilmann, J., L.A. Miller, T. Kirketerp, R.A. Kastelein, P.T. Madsen, B.K. Nielsen & W.W.L. Au 2002: Characteristics of echolocation signals used by a harbor porpoise *(Phocoena phocoen*a) in a target detection experiment. Aquat. Mamm. 28: 275-284.

Teilmann, J., O.D. Henriksen, J. Carstensen & H. Skov 2002: Monitoring effects of offshore wind farms on harbour porpoises using PODs (porpoise detectors). Technical report to SEAS Wind Energy Center and Tech-wise A/S.

Teilmann, J., 2003: Influence of sea state on densitiy estimates of harbour porpoises (*Phocoena phocoena*). J. Cetacean Res. Manage. 50: 85-92.

Teilmann, J., R. Dietz, F. Larsen, G. Desportes, B.M. Geertsen, L.W. Andersen, P. Aastrup, J.R. Hansen & L. Buholzer 2004: Satellitsporing af marsvin i danske og tilstødende farvande. Danmarks Miljø-undersøgelser. Faglig rapport fra DMU nr. 484.

Teilmann, J., S. Sveegaard, Dietz, R., Petersen, I.K., Berggren, P. and G. Desportes. 2008: High density areas for harbour porpoises in Danish waters. Aarhus, Denmark, National Environmental Research Institute: 45.

Thiele, A. 2006: Erfassung der Aktivität von Schweinswalen (Phocoena phocoena) in zwei ausgesuchten Gebieten der Nord- und Ostsee mit Hilfe akustischer Methoden. Diplomarbeit, Universität Hamburg, 88pp.

Tougaard, J., J. Carstensen, O.D. Henriksen, J. Teilmann & J.R. Hansen 2004: Horns Reef - Effects of the Horns Reef Wind Farm. Annual Status Report 2003 to Elsam Engineering A/S NERI. Technical Report Final version June 2004.

Tougaard, J., J. Carstensen, M.S. Wisz, J. Teilmann, N.I. Bech, H.Skov & O.D. Henriksen 2005: Harbour Porpoises on Horns Reef – Effects of the Horns Reef Wind Farm. Annual status report 2004 to Elsam Engineering A/S. NERI Technical Report NERI July 2005, Roskilde.

Tougaard, J., Carstensen, J., Bech, N. I., & Teilmann, J. 2006a: Final report on the effect of Nysted Offshore Wind Farm on harbour porpoises. Annual report to EnergiE2 A/S. Ministry of the Environment, Roskilde, Denmark, NERI.

Tougaard, J.; Carstensen, J.; Bech, N. I. & Teilmann, J. 2006b. Final report on the effect of Nysted offshore wind farm on harbour porpoises - Annual Report 2005. Technical report to Energi E2 A/S. Ministry of the Environment, Roskilde, Denmark. NERI.

Tougaard, J., Rosager Poulsen, L., Amundin, M., Larsen, F., Rye, J., and Teilmann, J. 2006c: Detection function of T-PODs and estimation of porpoise densities. ECS NEWSLETTER NO. 46 - SPECIAL ISSUE - Proceedings of the workshop STATIC ACOUSTIC MONITORING OF CETACEANS Held at the 20th Annual Meeting of the European Cetacean Society, Gdynia, Poland, 2 April 2006. European Cetacean Society. 14 pp.

Urick, R. J. 1967: Principles of underwater sound for engineers. McGraw Hill, New York.

Verboom, W.C. & R.A. Kastelein 1995: Acoustic signals by harbour porpoises (*Phocoena phocoena*). In: P.E. Nachtigal, J. Lien, W.W.L. Au & A.J. Read [eds.]: Harbour porpoises - laboratory studies to reduce bycatch. De Spil Publishers, Woerden, pp. 1-39.

Verboom, W.C. & R.A. Kastelein 1997: Structure of harbour porpoise (*Phocoena phocoena*) click train signals. In: A. J. Read, P.R. Wiepkema & P.E. Nachtigal [eds.]: The biology of the harbour porpoise. De Spil Publishers, Woerden, pp. 343-362.

Verfuß, U.K. & H.-U. Schnitzler 2002: Untersuchungen zum Echoortungsverhalten der Schweinswale (*Phocoena phocoena*) als Grundlage für Schutzmaßnahmen. Report to the Federal Agency for Nature Protection, Bonn. FKZ-Nr.: 898 86 021. Eberhard Karls Universität Tübingen.

Verfuß, U.K., C. Honnef & H. Benke 2004: Untersuchung zur Raumnutzung durch Schweinswale in der Nord- und Ostsee mit Hilfe akustischer Methoden (PODs). In: A. Kellermann et al. 2004 : Marine Warmblüter in Nord und Ostsee: Grundlagen zur Bewertung von Windkraftanlagen im Offshore-Bereich. Verbundvorhaben MINOS, Teilprojekt 3. Band 1.

Verfuß, U.K., L.A. Miller & H.-U. Schnitzler 2005: Spatial orientation in echolocating harbour porpoises (*Phocoena phocoena*). J. Exp. Biol. 208: 3385-3394.

Verfuß, U. K., C. G. Honnef, et al. 2007: Geographical and seasonal variation of harbour porpoise (Phocoena phocoena) presence in the German Baltic Sea revealed by passive acoustic monitoring. J. Mar. Biol. Ass. U.K. 87: Seite 165-176.}

Verfuß, U. K.; Dähne, M.; Meding, A.; Honnef, C. G.; Jabbusch, M.; Adler, S.; Mundry, R.; Hansen Rye, J.; Charwat, H. & Benke H. 2007: Untersuchungen zur Raumnutzung durch Schweinswale in der Nord- und Ostsee mit Hilfe akustischer Methoden (PODs). In: Forschungsverbund MINOSplus- Weiterführende Arbeiten an Seevögeln und Meeressäugern zur Bewertung von Offshore – Windkraftanlagen, Teilvorhaben 3.

Villadsgaard, A., M. Wahlberg & J. Tougaard 2007: Echolocation signals of wild harbour porpoises, *Phocoena phocoena*. The Journal of Experimental Biology 210, 56-64.

Wahlberg, M. and H. Westerberg 2005: Hearing in fish and their reaction to sounds from offshore wind farms. MEPS 288: 295-309.

Winslade, P. 1974: Behavioural studies on the lesser sandeel Ammodytes marinus (Raitt) I. The effect of food availability on activity and the role of olfaction in food detection.

Wood, S.N. 2006: Generalized Additive Models: An Introduction with R. Chapman and Hall/CRC, London.

Wood, S.N. 2004: Stable and efficient multiple smoothing parameter estimation for generalized additive models.Journal of the American Statistical Association. 99:673-686.