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

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

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

1. Introduction

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

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

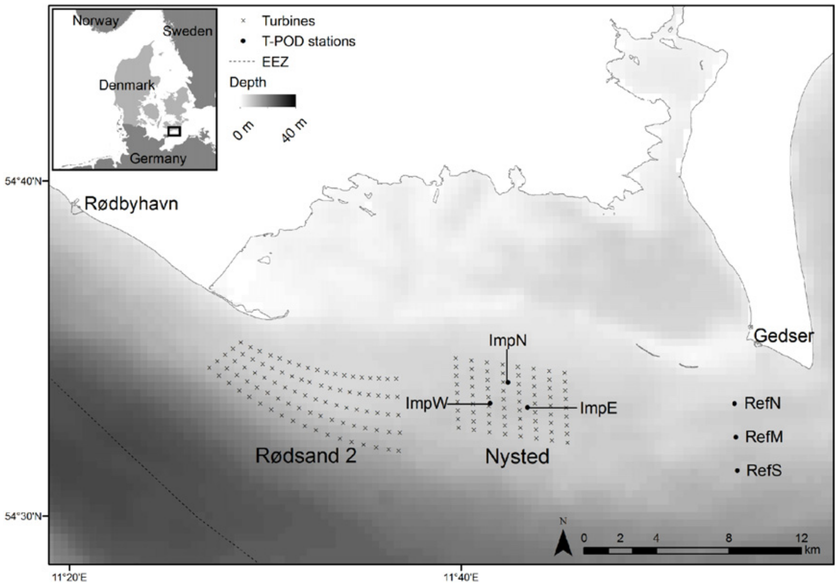

Figure 1. Study area with Nysted and Rødsand 2 Offshore Wind Farm. Wind turbines are shown with an 'X' and T-POD monitoring stations with solid circles. Three stations (ImpW, ImpN and ImpE) are located inside the wind farm and three stations (RefN, RefM and RefS) are located in a reference area about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

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

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

2. Material and methods

2.1. Study area

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

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

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

2.2. Acoustic monitoring

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

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

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

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

2.3. Data collection

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

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

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

[a] Value depend on calibration.

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

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

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

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

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

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

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

2.4. Porpoise activity indicators from T-POD signals

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

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

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

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

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

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

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

2.5. Statistical analysis

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3. Results

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

4. Seasonal patterns

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

4.1. Long term assessment

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

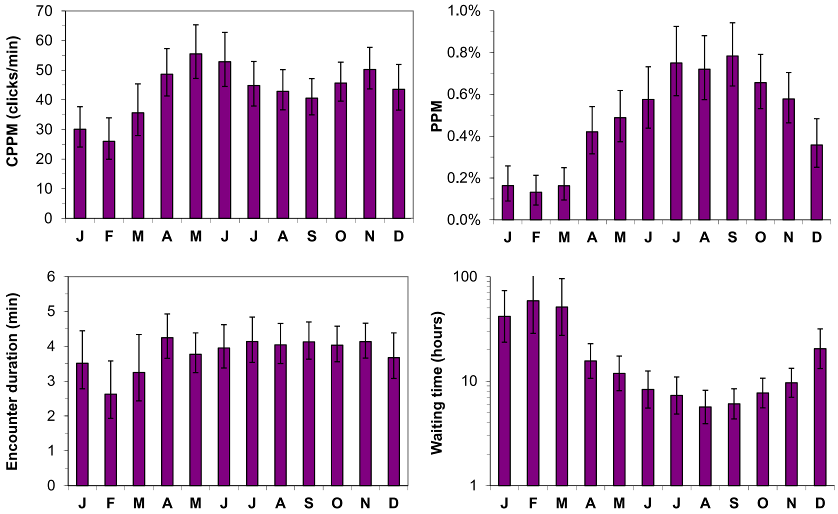

Figure 2. Monthly means at Nysted reference and impact areas combined showing the four indicators after back-transformation. Error bars show 95% confidence limits of the mean values. The covariation with other factors in equation (2) has been accounted for by calculating marginal means.

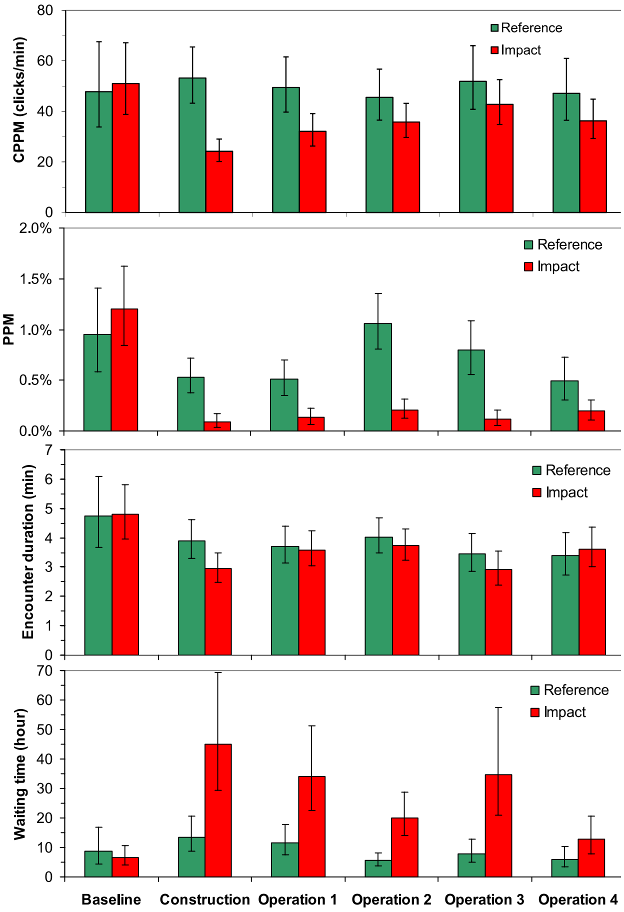

Figure 3. Mean values for the four indicators back-transformed to the original scale for combinations of the two areas and the six periods (baseline Nov 2001–Jun 2002, construction Jul 2002–Nov 2003, operation 1 Dec 2003–Dec 2004, operation 2 Jan–Dec 2005, operation 3 Sep 2008–Feb 2009 and operation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

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

5. Discussion

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

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

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

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

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

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

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

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

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

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

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

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