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Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea

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Abstract
The rapid increase in development of offshore wind energy in European waters has raised concern for the possible environmental impacts of wind farms. We studied whether harbour porpoise occurrence has been affected by the presence of the Dutch offshore wind farm Egmond aan Zee. This was done by studying acoustic activity of porpoises in the wind farm and in two reference areas using stationary acoustic monitoring (with T-PODs) prior to construction (baseline: June 2003 to June 2004) and during normal operation of the wind farm (operation: April 2007 to April 2009). The results show a strong seasonal pattern, with more activity recorded during winter months. There was also an overall increase in acoustic activity from baseline to operation, in line with a general increase in porpoise abundance in Dutch waters over the last decade. The acoustic activity was significantly higher inside the wind farm than in the reference areas, indicating that the occurrence of porpoises in this area increased as well. The reasons of this apparent preference for the wind farm area are not clear. Two possible causes are discussed: an increased food availability inside the wind farm (reef effect) and/or the absence of vessels in an otherwise heavily trafficked part of the North Sea (sheltering effect).

Keywords: passive acoustic monitoring, habitat use, T-POD, North Sea, offshore renewables

1. Introduction

Offshore wind energy is a rapidly expanding business in European waters, particularly in the North Sea. To be a sustainable alternative to fossil fuel and nuclear power, offshore wind farms will have to be large, thereby covering considerable marine habitat. Consequently, the environmental impact to the marine ecosystem could be significant (e.g. Hüppop *et al* 2006, Madsen *et al* 2006). Particular concerns have been raised for one key species, the harbour porpoise (*Phocoena phocoena*), which has been suggested to be negatively affected by noise pollution and habitat loss (e.g. Gilles *et al* 2009). Harbour porpoises are common in the North Sea, with a population estimated at about 250 000 individuals in 1994 and 2004 (Hammond *et al* 2002, SCANSII 2008). Although porpoises have been largely absent from Dutch waters in the last half of the 20th century (Smeenk 1987, Reijnders 1992) there has been a recent and well documented increase since the 1990s (Reijnders *et al* 1996, Camphuysen 2004).

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In 2002 the Dutch government permitted construction of the Offshore Wind Park Egmond aan Zee (OWEZ) as a demonstration project, with the aim of assessing technological and environmental challenges of offshore wind energy (NoordzeeWind 2008). Part of the evaluation of environmental impacts was a monitoring programme addressing effects of the wind farm on the local occurrence of harbour porpoises.

Previous studies from other offshore wind farms of similar dimensions have shown a reduction in harbour porpoise abundance during the construction of the wind farm (Carstensen *et al* 2006, Tougaard *et al* 2006b). In particular, the installation of steel monopile foundations by means of percussive pile driving represents a substantial impact on harbour porpoises in an area covering several hundred km^2 around the construction site (Tougaard *et al* 2009a, Brandt *et al* 2011). One study in the western Baltic (Nysted offshore wind farm) demonstrated a pronounced negative effect of construction on the local abundance of harbour porpoises (Carstensen *et al* 2006).

The operation of offshore wind farms is likely to present a smaller impact than construction, but throughout an extended period of time. Noise levels from operating turbines, as well as from shipping needed for surveillance and maintenance, are expected to be low and local, i.e. inside the wind farm and in the immediate vicinity of the wind farm (Madsen *et al* 2006, Tougaard *et al* 2009b). Nevertheless, at Nysted only a partial recovery of harbour porpoises two years into the operational period was recorded (Tougaard *et al* 2005), indicating that animals were displaced during construction and did not exploit this habitat to the same extent as they had done previously.

Potential positive effects of offshore wind farms have also been discussed and include an increase in biodiversity and possibly also biomass of prey species due to the addition of hard substrates (foundations and scour protection around foundations) to the otherwise monotonic sandy bottom (Petersen and Malm 2006). Often all or some types of fisheries are excluded from wind farms, which could lead to less disturbance of the bottom fauna (e.g. due to bottom trawling), a reduced mortality of fish and a reduced bycatch of porpoises (e.g. in set nets). Furthermore, the general exclusion of shipping activity, apart from maintenance and research in the park, might also play an important role, particularly in an area as heavily used by vessels as the southern North Sea.

2. Materials and methods

The occurrence of harbour porpoises in the Offshore Wind Park Egmond aan Zee and two reference areas was studied by stationary acoustic monitoring during a period prior to construction (June 2003 to June 2004, denoted baseline) and a similar period during normal operation of the wind farm two years after the construction was completed (April 2007 to April 2009, denoted operation).

The use of stationary acoustic monitoring was considered to be the most adequate method because free-swimming porpoises in the wild have been shown to vocalize almost constantly, rarely remaining silent for more than a minute at a time (Akamatsu *et al* 2005, 2007). This means that recorded acoustic activity can be expected to be a direct indicator of porpoise presence. Based on the inter-pulse interval, the maximum range at which free-swimming porpoises can detect an object is estimated to be about 100 m (Villadsgaard *et al* 2007). Thus, it can be safely assumed that porpoises swimming inside a wind farm will not detect the foundations most of the time. Stationary acoustics have been used successfully in other studies investigating behaviour, habitat use as well as the impact of human activities on porpoises (e.g. Carlström 2005, Carstensen *et al* 2006, Todd *et al* 2009). Furthermore, current studies (Kyhn 2010) indicate that acoustic activity of harbour porpoises is directly related to the local abundance of animals and in the future might even be used to estimate density (Tougaard 2008).

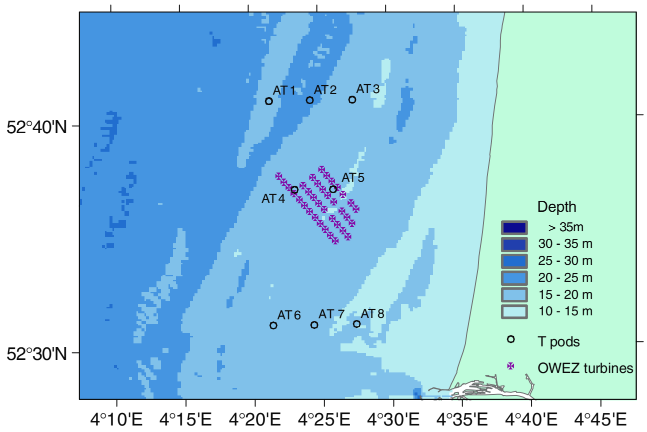

Figure 1. Offshore wind farm Egmond aan Zee with positions of the individual turbines and the eight monitoring stations (AT1–AT8).

The study site is located in the North Sea, west of Egmond aan Zee in the province of North Holland (The Netherlands) (figure 1). The wind farm is located 10–18 km offshore and covers approximately 27 km^2 with a water depth of 15–19 m (NoordzeeWind 2008). The distance between the monopiles in the wind farm ranges from 0.6 to 1.1 km. The wind farm consists of 36 Vestas V90 wind turbines with a hub height of 70 m above sea level, each with a nominal capacity of 3 MW. Turbines are mounted on steel monopile foundations (4.6 m diameter), extending 30 m into the seabed which consists of hard sand (NoordzeeWind 2008). Scour protection consists of a filter layer with an armour layer of natural stones on top, the latter extending about 18 m from the monopile. Construction began in April 2006 and all turbines were installed by August 2006. The wind farm was commissioned for normal operation on 1 January 2007. About 10 km to the west of the Offshore Wind Park Egmond aan Zee, a second wind farm was built, the Princess Amalia Wind Farm. Construction at this site began in October 2006; the 60 turbines were installed by April 2007 and the wind farm has been fully operational since June 2008.

Eight stationary passive acoustic monitoring stations were established. Two stations were placed within the wind farm (at least 260 m away from the closest monopile) and a total of six stations were placed in two reference areas, designated Control N (three stations north of the wind farm) and Control S (three stations south of the wind farm) (figure 1). All stations were placed at least 1.8 km apart to ensure independence between stations in the recordings of harbour porpoises. Reference areas were placed approximately 10 km from the wind farm. This distance and location were chosen to cover similar overall biotic and abiotic environmental conditions as in the wind farm, yet outside the potential range of influence of the wind farm.

Stationary acoustic monitoring was done by means of T-POD porpoise detectors (Chelonia Inc., Cornwall, UK). The T-POD consists of a hydrophone, an amplifier, a number of band pass filters and a data logger that continuously logs echolocation click activity of porpoises. It processes the recorded signals in real-time and only logs time and duration of sounds that fulfil a set of acoustic criteria set by the user to match the specific characteristics of porpoise echolocation clicks. The T-POD operates with six separate sets of settings employed sequentially. During this study all channels had identical settings. The detection of porpoise signals is performed by comparing signal energy in a narrow band pass filter centred at 130 kHz with another narrow band pass filter centred at 90 kHz. Any signal, which has substantially more energy in the high filter relative to the low filter, is highly likely to be either a porpoise or a man-made sound (echosounder or boat sonar). Two versions of T-PODs were used in this study: version 3 (v3) and version 5 (v5). Both versions function according to the same general principles with the main difference that the v3 is equipped with 32 MB of memory whereas the capacity of the v5 is 128 MB. The T-PODs were powered by 12 or 15 alkaline D-cells batteries, respectively, which gives a maximum logging period of about 120 days. During operation v5 T-PODs were introduced and used interchangeably and on some occasions deployed together with v3 T-PODs to assess systematic differences in sensitivity between the two versions. Settings for T-PODs were: A filter: 130 kHz, B filter: 90 kHz, max. no. of clicks per scan: 160 min. click duration 30 μs. Specific settings for v3 were A/B ratio: 5, A filter integration time: short, B-filter integration time: long, sensitivity: 6. Specific settings for v5 were: Bandwidth: 5, gain control '+', Sensitivity: 10. V5 T-PODs were individually calibrated according to Kyhn *et al* (2008) and with one exception found to have comparable detection thresholds. The deviating T-POD was returned for repair before being used in the study.

The mooring used for the T-PODs was a scaled-up version of the moorings used in similar studies (see Dudzinski *et al* 2011) designed to withstand high currents, heavy shipping and beam trawling with heavy gear. The T-POD was deployed from a 380 kg anchor block at a height of approximately 2 m above the seabed (figure 2). It was connected to one (in the wind farm) or two (in the reference areas) additional anchor blocks of about 2000 and 4000 kg, each marked by a surface buoy (figure 2). The eight T-PODs were serviced at regular intervals and data was downloaded on to a PC.

The downloaded acoustic signals were compiled using Version 8.17 of the software 'tpod.exe' (supplied by the manufacturer of the T-PODs) to extract harbour porpoise echolocation clicks using an algorithm that filters out non-porpoise clicks. Porpoise click trains are recognizable by a gradual change of click intervals throughout a click sequence, whereas boat sonars and echosounders have highly regular repetition rates. The train filter used was 'cetacean-all' (for details on the filtering, see Kyhn *et al* 2008). Data were subsequently exported for statistical analysis as clicks per minute.

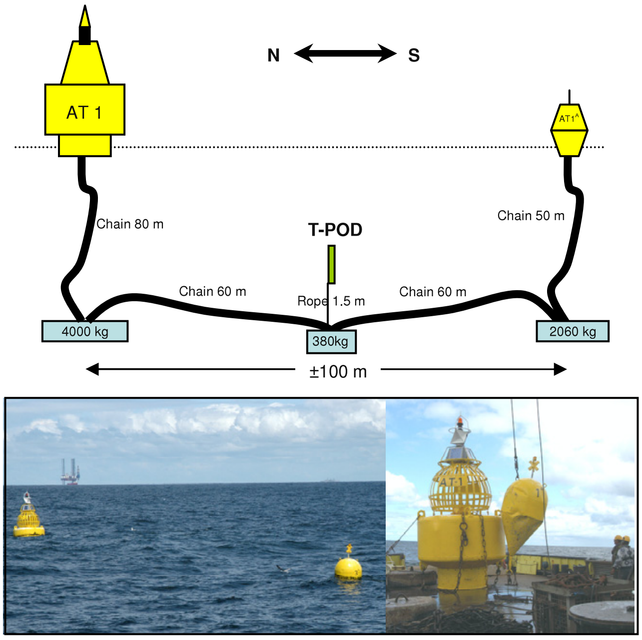

Figure 2. Schematic setup and photos of the T-POD mooring.

In line with previous studies (e.g. Carstensen *et al* 2006) four indicators were extracted from the exported T-POD data. The recorded number of clicks per minute, denoted x_t, was aggregated into daily values of:

$$\text{PPM} = \text{porpoise positive minutes}$$
$$= \frac{\text{Number of minutes with clicks}}{\text{Total number of minutes}} = \frac{N\{x_t > 0\}}{N_{\text{total}}}$$
$$\text{Clicks per PPM} = \frac{1}{N\{x_t > 0\}} \sum_{x_t > 0} x_t.$$

PPM is expressed as a percentage and thus indicates the fraction of the day (out of 1440 min for a full day of recordings) wherein one or more porpoise click trains could be detected. Clicks per PPM indicates the daily average number of clicks in minutes where clicks were detected.

The series of clicks per minute, x_t was also converted into a point process in which x_t was considered a sequence of porpoise encounters within the T-POD range of detection, separated by silent periods without any clicks recorded (Carstensen *et al* 2006, Tougaard *et al* 2009a). All click trains separated by less than 10 min of silence were considered to belong to the same encounter. Two indicators were defined: (1) encounter duration = number of minutes between two silent periods, and (2) waiting time = number of minutes in a silent period >10 min. 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. Encounter duration and waiting

Table 1. Overview of factors.

Factor		Levels	Description
Area	Fixed	Impact; Control	Spatial variation between both control areas and impact area (wind farm)
Subarea(area)	Fixed	Control N; Control S; Impact	Spatial variation between the three areas
Station (area subarea)	Random	AT1–AT8	Station-specific variation (variation among stations) within each of the three areas
Period	Fixed	Baseline; operation	Difference between baseline and operation period
Year	Random	2003, 2004, 2007, 2008, 2009	Variation between years nested within the two periods baseline and operation
Month	Fixed	Jan–Dec	Seasonal variation by means of monthly values
Podtype	Fixed	v3; v5	Difference between v3 and v5 T-PODs
Podid	Random	20 Pod serial numbers	Random variation between individual T-PODs

time observations were assigned in time to the midpoint of the encounter or waiting time.

The difference between the two T-POD types (v3 and v5) was investigated by conducting a paired analysis of the two daily indicators (clicks per PPM and PPM) using only data from deployments days, where data was available for both types for an entire day at the same station. The indicators were then related by means of least squares regression. A few observations, one for clicks per PPM and three for PPM, were identified as outliers and excluded from the regression analysis. A similar comparative analysis could not be carried out for encounter duration and waiting time because observations of these indicators cannot be paired over time in the same manner as clicks per PPM and PPM, i.e. between the two T-POD types encounters and waiting times do not always match across time.

The four indicators were analysed according to a modified before–after control-impact (BACI) design (Green 1979) that included station-specific and seasonal variation. Variation in all four indicators was assumed to be potentially related to eight factors (five fixed and three random) and combinations thereof (table 1).

Four of the fixed factors (area, period, month as well as nested factor subarea(area)), and their seven interactions, describe the spatial–temporal variation in the echolocation activity, whereas podtype describes a potential monitoring bias from replacing v3 with 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 six factors in table 1) were disregarded in order to limit the model. Thus, variations in the echolocation indicators, after appropriate transformation, were assumed to be normal-distributed with a mean value described by the equation:

$$\begin{aligned}\mu_{ijklm} = {} & \text{area}_i + \text{subarea(area)}_{j(i)} + \text{period}_k + \text{area}_i \\ & \times \text{period}_k + \text{subarea(area)}_{j(i)} \times \text{period}_k + \text{month}_l \\ & + \text{area}_i \times \text{month}_l + \text{subarea(area)}_{j(i)} \times \text{month}_l \\ & + \text{period}_k \times \text{month}_l + \text{area}_i \times \text{period}_k \times \text{month}_l \\ & + \text{subarea(area)}_{j(i)} \times \text{period}_k \times \text{month}_l + \text{podtype}_m \qquad (1)\end{aligned}$$

where subscripts i, j, k, l and m indicate the various levels of area, subarea, period, month and podtype, respectively.

Random effects of the model included station (area subarea) and year (period) and their interactions with the fixed factors in (1) as well as pod id (podtype) that has a version-specific variance, i.e. captures a difference in magnitude of random variation between T-PODs for v3 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, the waiting time following a short 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 (e.g. 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 the data. PPM was transformed using an angular-transformation ($\arcsin\sqrt{y}$), the three other indicators were log-transformed. 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 log normal distribution. Applying the log-transformation thus implies that the additive factors as described in equation (1) are multiplicative on the original scale. This meant that, for example, the seasonal variation was described by monthly scaling means rather than by additive means.

The data comprised an unbalanced design, i.e. uneven number for the different combinations of the 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 the model does not take other effects into account. Typical responses of the different factors were instead calculated by marginal means (Searle *et al* 1980) where the variation in other factors was taken into account.

The statistical analyses were carried out within the framework of mixed linear models (McCullagh and Nelder 1989, Littell *et al* 1996) by means of PROC MIXED in the SAS system (SAS Institute 2003). 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. Only the final models, after eliminating all non-significant factors, are presented in the results.

The factor area$_i$ × period$_k$, also referred to as the BACI effect, describes a step-wise change (from baseline to operation) in the wind farm different from that in the control areas. A significant BACI effect implies that changes in activity in the wind farm area from baseline to operation differ from changes in the control area. In other words, any changes in the wind farm area from baseline to operation cannot alone be explained by general changes in the area but must be ascribed to the impact (i.e. the presence of the wind farm).

3. Results

There were a total of 5228 active station days (defined as one day of 24 h of T-POD monitoring data from one station). More than twice as many active station days were collected during the operation period ($n = 3507$) than during the baseline ($n = 1721$). The area Control S had the highest number of active station days ($n = 2081$), followed by Control N ($n = 1718$) and the wind farm area ($n = 1429$). The data was relatively evenly distributed across the eight positions ranging from 458 station days at AT1 to 838 station days at AT8. A total of 2565 station days were recorded with v3 T-PODs (49%) and 2663 station days were recorded with v5 T-PODs (51%), and of these 123 station days had simultaneous recordings on the two versions at the same position.

Periods of no recording were due to various logistical issues, such as loss of T-PODs, T-POD failure and memory limits of T-PODs. Several T-PODs were lost from their moorings but most were later found washed up on the coast. Useable data was downloaded up to the point of detachment from the mooring.

3.1. Porpoise acoustic activity

Daily average clicks per PPM could be calculated for 3795 station days. Twenty-seven per cent of the deployment days were silent, most of these occurred between May and August. Encounter duration ($n = 22\,181$) and waiting time between encounters ($n = 22\,087$) were calculated from the data. The two control areas (Control N and S) each had approximately 6500 encounters and waiting times, whereas the impact area had almost 9000. The numbers of encounters and waiting times across the eight positions ranged from ∼1900 at AT1 to ∼4600 at AT5. There were more than twice as many encounters and waiting times during operation compared to baseline, partly explained by the longer deployment time. For the 2 periods and eight positions the relative variation in encounter duration (CV = 123–259%) and waiting time (138–369%) was larger than for the clicks per PPM but similar to PPM, however, there were also approximately four times as many observations during the operational versus the baseline phase. Both duration and waiting time distributions were strongly skewed to the right, supporting the log-transformation, with observations exceeding 1 h for encounter duration and 5 days for waiting time.

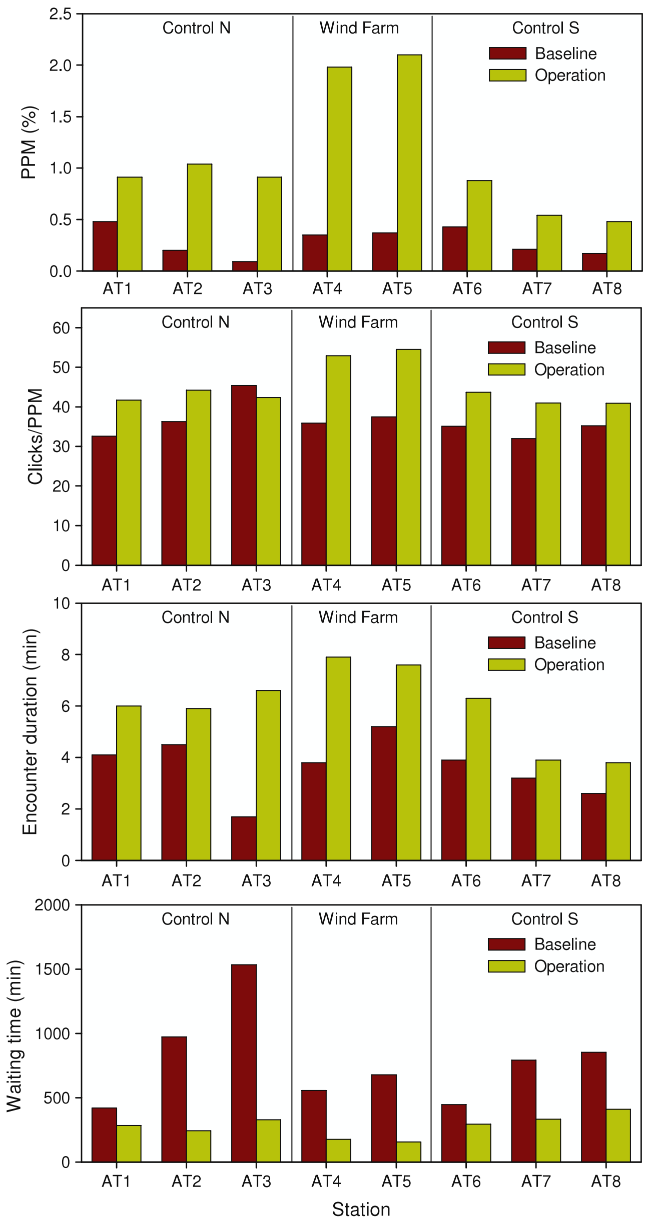

Figure 3. Station-specific averages of the four indicators. Stations within each area are ranked from west to east. PPM: porpoise positive minutes per day; Clicks/PPM: clicks per porpoise positive minute per day.

Encounters were on average 72% longer during operation than during the baseline period, whereas waiting times in the operation period were only 39% of those observed during the baseline. Marginal means for the four indicators at all stations are shown in figure 3.

3.2. Intercalibration

Combining the clicks per PPM and PPM indicators for the five positions for those days at which two T-PODs were deployed together resulted in 116 indicator values for clicks per PPM and PPM. There were significant correlations between the indicator values obtained with the two types of T-PODs, but the slopes of the intercalibration curves were not significantly different from

1, indicating that v3 and v5 recorded the same echolocation activity. The two versions were thus considered to be equally sensitive and no adjustment for the change from v3 to v5 was done.

In the model, T-POD specific variation was found to be non-significant for the four indicators, both as a systematic bias between v3 and v5 and as a difference in the variation between T-PODs for the two versions. Although v5 yielded slightly higher echolocation activity than v3 in the models, the bias was not significant relative to the large overall residual variation when the T-PODs were deployed in a natural environment. These results correspond to those obtained from the intercalibration of the two T-POD types on a reduced data set.

3.3. BACI analyses (effect of wind farm)

The model for spatial–temporal variation as well as T-POD specific variation (equation (1)) and an ARMA(1, 1) correlation structure was computed for the four indicators. Only 6 out of the 12 fixed effects in equation (1) could significantly explain variation in the echolocation indicators (table 2). All four indicators showed a significant increase in echolocation activity from baseline to the operation period (table 2): clicks per PPM increased from 33.8 clicks $\min^{-1}$ to 46.7 clicks $\min^{-1}$, PPM more than tripled from 0.22% to 0.68%, encounter duration increased from 3.4 to 4.5 min, and waiting times decreased from 13.7 to 6.7 h.

The significance of area × period indicates that echolocation activity in the impact area increased more than in the reference area (figure 4). Echolocation activity was similar in the two areas during the baseline period, but increased significantly more during the operation period in the impact area. The increase in the impact area relative to the reference areas was 28% for clicks per PPM, 160% for PPM, 24% for encounter duration and a 33% decrease in waiting time (figure 4).

Table 2. Significance testing of fixed effects in equation (1) for the four indicators after removing non-significant fixed and random effects.

	Click PPM			PPM		
Fixed effects	DFs	F	P	DFs	F	P
Area	1, 138.6	22.0	<0.0001			n.s.[a]
Subarea(area)			n.s	1, 13.0	16.2	0.0014
Period	1, 21.8	38.5	<0.0001	1, 31.8	12.1	0.0015
Area × period	1, 139.9	13.9	0.0003	1, 12.6	6.9	0.0213
Month	11, 17.2	4.1	0.0046	11, 21.0	8.4	<0.0001
Area × month			n.s.	11, 110.4	2.7	0.0037
	Encounter duration			**Waiting time**		
Fixed effects	DFs	F	P	DFs	F	P
Area	1, 164.6	8.41	0.0042	1, 150.9	7.8	0.0059
Subarea(area)	1, 157.1	11.07	0.0011	1, 142.2	39.0	<0.0001
Period	1, 37.8	15.03	0.0004	1, 22.4	9.1	0.0062
Area × period	1, 167.5	5.93	0.0159	1, 152.4	5.6	0.0195
Month	11, 23.1	6.15	0.0001	1, 20.5	9.9	<0.0001
Area × month			n.s.			n.s.

[a] Results for non-significant tests not included.

For baseline and operation period combined, there was a significant difference in clicks per PPM between the reference area (36.7 clicks $\min^{-1}$) and the impact area (43.0 clicks $\min^{-1}$), but no difference between the reference areas Control N and Control S. For PPM the difference between reference area (0.34%) and impact area (0.51%) was not significant, but between Control N (0.50%) and Control S (0.20%) it was significant. The mean encounter duration for the reference area (3.7 min) was significantly lower than in the impact area (4.2 min), and for the two reference areas Control N had a significantly higher encounter duration (3.9 min)

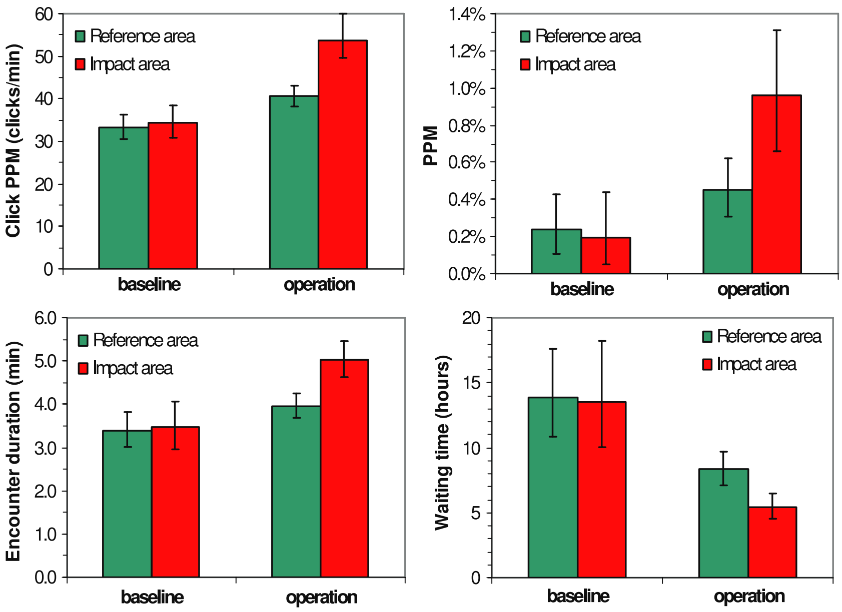

Figure 4. Mean values for combinations of T-POD data within reference and impact areas and period back-transformed to the original scale for comparisons of the two areas and the two periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in subareas (Control N and S) and months have been accounted for by calculating marginal means.

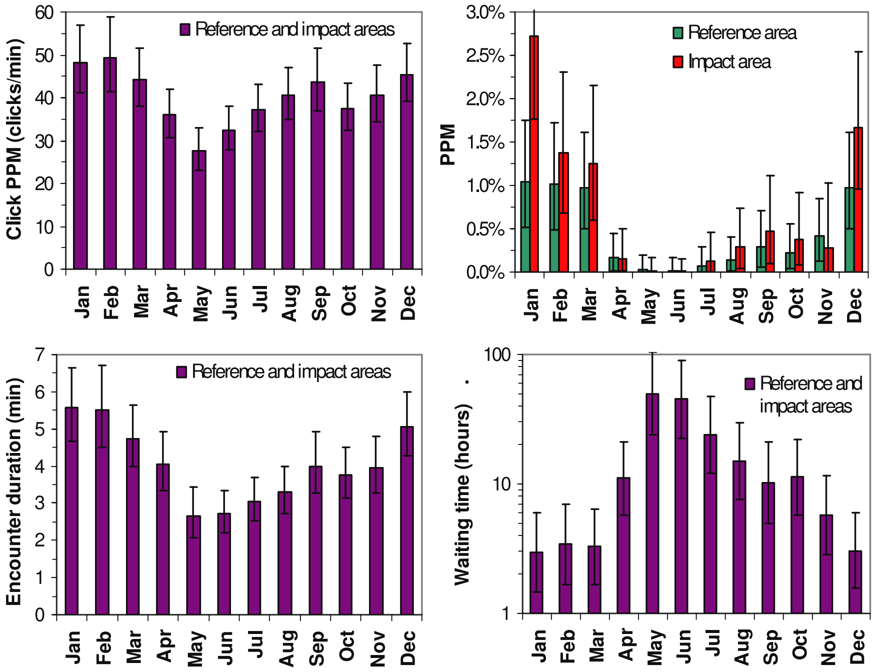

Figure 5. Monthly means for the four indicators after back-transformation for baseline and operation period combined. Error bars show 95% confidence limits of the mean values. Variations caused by differences in area, subarea and period have been accounted for by calculating marginal means. Only PPM showed significantly different seasonal variation in the two areas and is thus plotted separately.

than Control S (3.4 min). The mean waiting time in the reference area (10.7 h) was significantly higher than in the impact area (8.6 h), but there was also a significant difference between Control N (8.6 h) and Control S (13.4 h). Overall, all four indicators showed that the impact area had the highest echolocation activity together with Control N (at almost the same level), whereas Control S had the lowest activity level.

3.4. Temporal variation

All four indicators were characterized by a significant seasonal variation that was common to both the reference and impact area, except for PPM (table 2). Echolocation activity was generally high during the winter months and low during the summer months (figure 5). Mean clicks per PPM varied from 28 clicks min^{-1} in May to 46 clicks min^{-1} in February. The seasonal pattern for PPM was not common to the reference and impact area. Most of the year PPM was highest in the impact area, but in the low echolocation activity months (April, May and June) as well as November more clicks were recorded in the reference area relative to the impact area. Overall, for the two areas combined PPM varied from 0.01% in June to 1.78% in January. Encounter duration displayed a pattern quite similar to clicks per PPM ranging from 2.7 min in May to 5.6 min in January. Waiting times had the reverse pattern with the shortest median waiting times in January (2.9 h) and the longest waiting times in May (49.8 h), i.e. more than two days between encounters.

Two random factors were consistently significant for all four indicators. The factor month $\times$ year (period) describes changes in the seasonal pattern between years for the two periods and station $\times$ month $\times$ year (area subarea period) describes that this random seasonal pattern also varies significantly at the station level. In addition, the random factor station $\times$ year (area subarea period) describing random shifts across stations from year to year in the two periods, was significant for PPM only. Finally, for all indicators the correlation structure of the residuals (cf ARMA(1, 1) dependency) was significant, although for clicks per PPM and PPM the correlation structure of the residuals could be reduced to an AR (1) process. The significant autocorrelation suggests that porpoise echolocation activity follows smaller scale temporal variations (order of days) in addition to the overall seasonal pattern, i.e. consecutive days have similar echolocation activity.

4. Discussion

T-POD monitoring demonstrated a substantial increase in acoustic activity from baseline to operation at all stations (significant factor period) indicating an increase in the number of porpoises occurring in the area as a whole. This is in line with conclusions from a number of other studies that indicate a general increase in harbour porpoise abundance in Dutch waters over the last two decades (Hammond *et al* 2002, SCANSII 2008). For Dutch waters, some quantitative information on coastal abundance is provided by systematic ‘seawatching’ counts carried out by the Dutch Seabird Group. Although initiated for birds, data on the presence of marine mammals has also been collected since its initiation in 1972. It is clear from the data that the relative abundance of harbour porpoises observed has increased substantially since the mid-1990s (Camphuysen 2004).

We observed a strong and significant seasonal pattern in porpoise echolocation activity (all four indicators) during both the baseline and operation study period. Most acoustic detections were recorded in the winter months (December to March) with very few recorded during early summer (almost no detections in May and June). Camphuysen (2004) describes a seasonal pattern of harbour porpoise occurrence along the Dutch coast with most animals observed between February and April. A similar pattern has been described for the Borkum Reef Ground, close to the Dutch–German border, where the highest densities of porpoises are observed during spring (Gilles *et al* 2009). This pattern of high densities in winter and spring differs distinctly from areas further north, such as the German Bight and at Horns Reef, where the highest densities are observed in the summer months (Scheidat *et al* 2004, Siebert *et al* 2006, Tougaard *et al* 2006b).

The results of this study showed a pronounced and significant increase in harbour porpoise acoustic activity inside the operating wind farm, compared to the baseline conditions before construction began. This was far more than the general increase which was apparent in the control areas from baseline to operation. The fact that when comparing baseline to operation no significant changes were found between the northern and the southern reference areas, or in seasonality patterns between areas (factors subarea(area) × period and area × period × month, respectively) suggests that the effect is genuinely linked to the presence of the wind farm, as it cannot be explained by either a general north–south change in distribution of porpoises or a local change in the seasonality pattern within the wind farm.

We do not know what caused the local change in habitat use of porpoises in reaction to the wind farm. At least two possibilities, or a combination thereof, are conceivable: (1) an increase in food (reef effect) and/or (2) an avoidance of disturbance (sheltering effect). A number of studies have shown that the introduction of hard substrates (turbine foundations and scour protection) changes the species composition of the otherwise homogeneous sandy bottom (Petersen and Malm 2006, Leonhard and Pedersen 2006) and is likely followed by an increase in production, as sessile organisms can gain access to the more productive upper layers of the water column. The fish communities could also change due to a reduction or exclusion of fishery activities in the wind farm. Dutch waters are under intense fishing pressure, in particular heavy beam trawling for sole and other flat fish (Rijnsdorp *et al* 1998). For the Offshore Wind Farm Egmond aan Zee all vessel traffic is prohibited in the farm as well as in a marginal 500 m buffer zone (with the exception of vessels on behalf of the authorities, maintenance and research vessels working in the wind farm). This effectively means that no fishing takes place in the wind farm. A reduction of fishing activity will lead to less disturbance to the bottom fauna as well as an overall reduced mortality of fish. Two studies have investigated the fish community and the pelagic fish occurrence in the Egmond aan Zee wind farm before and after construction. They observed that species richness as well as relative abundance increased overall from the baseline to the operation study. For some species, such as sole, whiting and striped mullet, a significant increase in the wind farm was found during the summer (ter Hofstede 2008). A study of pelagic fish along the Dutch coast could not find a clear and direct effect of the wind farm, probably due to the highly dynamic pelagic fish community (Ybema *et al* 2009). Although harbour porpoises are considered opportunistic feeders with a wide range of prey species, in the North Atlantic they mainly feed on small shoaling fishes from both demersal and pelagic habitats (Santos and Pierce 2003). It remains to be demonstrated that the observed changes in the fish community actually lead to higher abundance of preferred prey of porpoises and thus improved conditions for porpoises as well.

A sheltering effect, by exclusion of most ship traffic from the wind farm and the buffer zone is also a conceivable explanation for the observed increase in porpoises. The south-eastern part of the North Sea, along the coasts of Belgium and the Netherlands, is among the busiest waterways in the world. It is utilized by fishery, tourist and military vessels, several ferry lines, as well as cargo ships moving to and from major continental ports such as Rotterdam and Hamburg. Herr *et al* (2005) have shown a negative correlation between harbour porpoise occurrence and vessel traffic. It is therefore possible that porpoises find wind farms attractive because the conditions outside the farm are more unfavourable. Between the two study periods in Egmond aan Zee, a second wind farm, Princess Amalia Wind Park, was built at a distance of about 10 km from the wind farm Egmond aan Zee. Installation of the wind turbines (i.e. pile driving) was finished by April 2007, thus a direct effect of construction noise on porpoise abundance in Egmond aan Zee is unlikely. However, it is conceivable that the continued construction activities in Princess Amalia Wind Park also impacted the distribution of porpoises in Egmond aan Zee in some way.

The observed increased porpoise acoustic activity in the Egmond aan Zee wind farm is in contrast to findings from other wind farm studies of comparable size (both regarding the number and size of turbines). In the Danish offshore wind farm Nysted, located in the Western Baltic close to the Darss Sill, a strong negative effect of construction was observed on the occurrence of harbour porpoises in the wind farm area and adjacent reference area (Carstensen *et al* 2006). This negative effect extended into the operation period, where porpoise activity within the wind farm was still reduced two years after construction, whilst it had returned to baseline levels in the reference area (Tougaard *et al* 2006a). The cause behind the reduction has not been identified and it is currently unknown whether porpoise activity has re-established to baseline levels in the wind farm. However, it is important to note that there are many differences between the general ecology of the two locations where Nysted wind farm and offshore wind farm Egmond aan Zee are located. Offshore wind farm Egmond aan Zee is located in the open North Sea in an area dominated by hydrographical frontal systems created by the efflux from large rivers, most notably the Rhine. Nysted is located in near-brackish waters with a bottom substrate of bare sand and sand overlaid with mud. It displays a lower overall biodiversity of marine species as well as a lower overall density of harbour porpoises. There is also a difference in terms of wind farm construction, with Nysted wind turbines consisting of concrete caisson foundations, whereas Horns Rev 1, a wind farm located on Horns Reef at the northern border of the German Bight, and offshore wind farm Egmond aan Zee have monopile foundations. It is thus not immediately evident whether the different effects of the two wind farms on harbour porpoises can be attributed to differences in the parks per se (e.g. differences in turbine types or foundation or even a memory effect relating to differences in disturbance during construction) or whether general ecological differences between the two areas causes harbour porpoises to respond differently to the presence of the wind farm.

At Horns Rev 1 a pronounced effect of construction was observed but with complete recovery to baseline levels during the first year after the wind farm was put into regular operation (Tougaard *et al* 2006b). The Horns Rev 1 is similar to offshore wind farm Egmond aan Zee in respect to its location in the open North Sea and the occurring riverine frontal systems. However, the Horns Reef area is hydrographically much more complex due to the presence of a long shallow reef which acts as a strong damping barrier to the tidal current. Thus, as with Nysted, it is not immediately evident whether the different effects of the wind farms (no effect at Horns Rev 1, positive effect at offshore wind farm Egmond aan Zee) are due to differences between the areas or the wind farms themselves. This conclusion is of great importance in planning future wind farms as it stresses the fact that results from one wind farm are not necessarily transferable to other wind farms located in different areas.

Monitoring was not undertaken during construction of the offshore wind farm Egmond aan Zee and it is thus not possible to comment on the effects on porpoises during this period. However, the installation of steel monopile foundations by means of percussive piling has been shown to affect porpoise behaviour at distances of at least 20–30 km from the piling site and for durations of up to 24 h (Brandt *et al* 2011, Tougaard *et al* 2009a). As monopile size and installation procedure used in offshore Wind Farm Egmond aan Zee was comparable to the wind farms at Horns Reef it can be expected that harbour porpoises were affected in a similar way during construction. The present data (operation) show that the effect year (period) was not significant and no difference could be seen between the three post-construction monitoring years (2007–2009). This implies that either there was little long-lasting construction effect on harbour porpoise distribution (which is unlikely considering the results from Horns Reef), or that recovery after construction occurred fairly quickly.

In summary, the results of this study show that the acoustic activity of harbour porpoises, and thereby the number of animals, increased in the wind farm area during our study period. This observed effect of the wind farm is most likely a net effect, i.e. positive factors (such as increased food availability and/or shelter) outweigh any negative factors (primarily underwater noise from turbines and service ships). These results should be generalized with caution and not be uncritically transferred to other wind farms in other habitats as the balance between positive and negative factors may be different under different conditions.

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References

Akamatsu T, Teilmann J, Miller L A, Tougaard J, Dietz R, Wang D, Wang K, Siebert U and Naito Y 2007 Comparison of echolocation behaviour between coastal and riverine porpoises *Deep-Sea Res.* II **54** 290–7

Akamatsu T, Wang D, Wang X and Naito Y 2005 Biosonar behaviour of free-ranging porpoises *Proc. R. Soc.* B **272** 797–801

Brandt M J, Diederichs A, Betke K and Nehls G 2011 Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea *Mar. Ecol. Prog. Ser.* **421** 205–16

Camphuysen K C J 2004 The return of the harbour porpoise (*Phocoena phocoena*) in Dutch coastal waters *Lutra* **47** 113–22

Carlström J 2005 Diel variation in echolocation of wild harbour porpoises *Mar. Mammal Sci.* **21** 1–12

Carstensen J, Henriksen O D and Teilmann J 2006 Impacts on harbour porpoises from offshore wind farm construction: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs) *Mar. Ecol. Prog. Ser.* **321** 295–308

Chatfield C 1984 *The Analysis of Time Series—An Introduction* 3rd edn (London: Chapman and Hall)

Dudzinski K M, Brown S J, Lammers M, Lucke K, Mann D A, Simard P, Wall C A, Rasmussen M H, Tougaard J and Eriksen N 2011 Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow- and deep-water applications *J. Acoust. Soc. Am.* **129** 436–48

Gilles A, Scheidat M and Siebert U 2009 Seasonal distribution of harbour porpoises and possible interference of offshore wind farms in the German North Sea *Mar. Ecol. Prog. Ser.* **383** 295–307

Green R H 1979 *Sampling Design and Statistical Methods for Environmental Biologists* (New York: Wiley)

Hammond P S, Berggren P, Benke H, Borchers D L, Collet A, Heide-Jørgensen M-P, Heimlich S, Hiby A R, Leopold M F and Øien N 2002 Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters *J. Appl. Ecol.* **39** 361–76

Herr H, Gilles A, Scheidat M and Siebert U 2005 Distribution of harbour porpoise (*Phocoena phocoena*) in the German North Sea in relation to density of sea traffic *Working Paper AC12/Doc.8(P) Presented to ASCOBANS (Brest)* (available at http://www.service-board.de/ascobans_neu/files/8_NS_HP_Distr.pdf, accessed 30 March 2011)

Hüppop O, Dierschke J, Exo K-M, Fredrich E and Hill R 2006 Bird migration studies and potential collision risk with offshore wind turbines *Ibis* **148** 90–109

Kyhn L A 2010 Passive acoustic monitoring of toothed whales, with implications for mitigation, monitoring and biology *PhD Thesis* Aarhus University (available at www2.dmu.dk/Pub/phd_lak.pdf)

Kyhn L A, Tougaard J, Teilmann J, Wahlberg M, Jørgensen P B and Bech N I 2008 Harbour porpoise (*Phocoena phocoena*) static acoustic monitoring: laboratory detection thresholds of T-PODs are reflected in field sensitivity *J. Mar. Biol. Ass. UK* **88** 1085–91

Leonhard S B and Pedersen J 2006 Benthic communities at Horns Rev before, during and after construction of Horns Rev Offshore Wind Farm *Final report to Vattenfall A/S.Bio/Consult A/S (Aarhus)* (available at www.vattenfall.dk/da/file/benthic-communities-at-horns_7841598.pdf)

Littell R C, Milliken G A, Stroup W W and Wolfinger R D 1996 *SAS System for Mixed Models* (Cary, NC: SAS Institute)

Madsen P T, Wahlberg M, Tougaard J, Lucke K and Tyack P L 2006 Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs *Mar. Ecol. Prog. Ser.* **309** 279–95

McCullagh P and Nelder J A 1989 *Generalized Linear Models* (Boca Raton, FL: Chapman and Hall/CRC Press)

NoordzeeWind 2008 Offshore Windfarm Egmond aan Zee *General Report, Document No OWEZ_R_141_20080215* (available at www.noordzeewind.nl)

Petersen J K and Malm T 2006 Offshore windmill farms: threats to or possibilities for the marine environment *Ambio* **35** 75–80

Reijnders P J H 1992 Harbour porpoises *Phocoena phocoena* in the North Sea: numerical responses to changes in environmental conditions *Neth. J. Aquat. Ecol.* **26** 75–86

Reijnders P J H, Leopold M F, Camphuysen C J, Heessen H J L and Kastelein R A 1996 The Status of the Harbour Porpoise *Phocoena phocoena*, in Dutch Waters and the State of Related research in the Netherlands: an overview *46th Report of the International Whaling Commission* (Cambridge: International Whaling Commission) pp 607–11

Rijnsdorp A D, Buys A M, Storbeck F and Visser E G 1998 Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms *ICES J. Mar. Sci.* **55** 403–19

Santos M B and Pierce G J 2003 The diet of harbour porpoise (*Phocoena phocoena*) in the Northeast Atlantic *Oceanogr. Mar. Biol.: Annu. Rev.* **41** 355–90

SAS Institute 2003 *SAS/STAT User's Guide, Version 8.2* (Cary, NC: SAS Instititute)

SCANSII (Small cetaceans in the European Atlantic and North Sea (SCANS II)) 2008 *Final Report to the European Commission under project LIFE04NAT/GB/000245* (available from SMRU, Gatty Marine Laboratory, University of St Andrews, St Andrews, Fife KY16 8LB, UK)

Scheidat M, Kock K H and Siebert U 2004 Summer distribution of harbour porpoises (*Phocoena phocoena*) in the German North Sea and Baltic Sea *J. Cetacean. Res. Manage.* **6** 251–7

Searle S R, Speed F M and Milliken G A 1980 Populations marginal means in the linear model: an alternative to least squares means *Am. Stat.* **34** 216–21

Siebert U, Gilles A, Lucke K, Ludwig M, Benke H, Kock K-H and Scheidat M 2006 A decade of harbour porpoise occurrence in German waters—analyses of aerial surveys, incidental sightings and strandings *J. Sea Res.* **56** 65–80

Smeenk C 1987 The harbour porpoise *Phocoena phocoena* (L., 1758) in The Netherlands: stranding records and decline *Lutra* **30** 77–90

ter Hofstede R 2008 Effects of a wind farm on the local fish community. A comparative study of field sampling data collected before and after the construction of the Offshore Wind farm Egmond aan Zee (OWEZ) *IMARES Report C057/08* (available at http://edepot.wur.nl/143730)

Todd V L G, Pearse W D, Tregenza N C, Lepper P A and Todd I B 2009 Diel echolocation activity of harbour porpoises (*Phocoena phocoena*) around North Sea offshore gas installations *ICES J. Mar. Sci.* **66** 734–45

Tougaard J 2008 Radial distance sampling with passive acoustics: the prospect of estimating absolute densities of cetaceans from static acoustic datalogger data *J. Acoust. Soc. Am.* **123** 3100

Tougaard J, Carstensen J, Bech N I and Teilmann J 2006a Final report on the effect of Nysted Offshore Wind Farm on harbour porpoises *Annual Report to EnergiE2* (Roskilde: NERI)

Tougaard J, Carstensen J, Teilmann J and Bech N I 2005 Effects of the Nysted Offshore Wind Farm on Harbour Porpoises *Annual Status Report for the T-POD Monitoring Program* (Roskilde: NERI)

Tougaard J, Carstensen J, Wisz M S, Teilmann J, Bech N I and Skov H 2006b Harbour porpoises on Horns Reef in relation to construction and operation of Horns Rev Offshore Wind Farm *Technical Report to Elsam Engineering A/S* (Roskilde: NERI)

Tougaard J, Carstensen J, Teilmann J, Skov H and Rasmussen P 2009a Pile Driving Zone of responsiveness extends beyond 20 km for Harbour Porpoises (*Phocoena phocoena*, (L.)) *J. Acoust. Soc. Am.* **126** 11–4

Tougaard J, Henriksen O D and Miller L A 2009b Underwater noise from three offshore wind turbines: estimation of impact zones for harbor porpoises and harbor seals *J. Acoust. Soc. Am.* **125** 3766–73

Villadsgaard A, Wahlberg M and Tougaard J 2007 Echolocation signals of wild harbour porpoises, *Phocoena phocoena J. Exp. Biol.* **210** 56–64

Ybema M S, Gloe D and Hille Ris Lambers R 2009 OWEZ-pelagic fish, progress report and progression after T1 *IMARES Wageningen UR: 1-33* (available at http://www.noordzeewind.nl/files/Common/Data/OWEZ_R_264_T1_20091110_pelagic_fish.pdf)