Assessment of the Effects of the Offshore Wind Farm Egmond aan Zee (OWEZ) for Harbour Porpoise (comparison T_0 and T_1)

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Note: Photo on front cover taken by Erwin Winter.

Executive summary

The aim of this study was to investigate if the Offshore Wind farm Egmond aan Zee (OWEZ) influenced the occurrence of harbour porpoises.
In order to evaluate the environmental impacts of OWEZ, porpoise occurrence in the area was monitored;

1) during a baseline (T_0) study 2003/2004 (Brasseur at al. 2004)
2) after the construction of the wind park (T_1) from 2007 to 2009.

The comparison between the T_0 and the T_1 was conducted to determine if and how harbour porpoises react to the presence of the wind park. This report describes the results and analyses of this comparison.

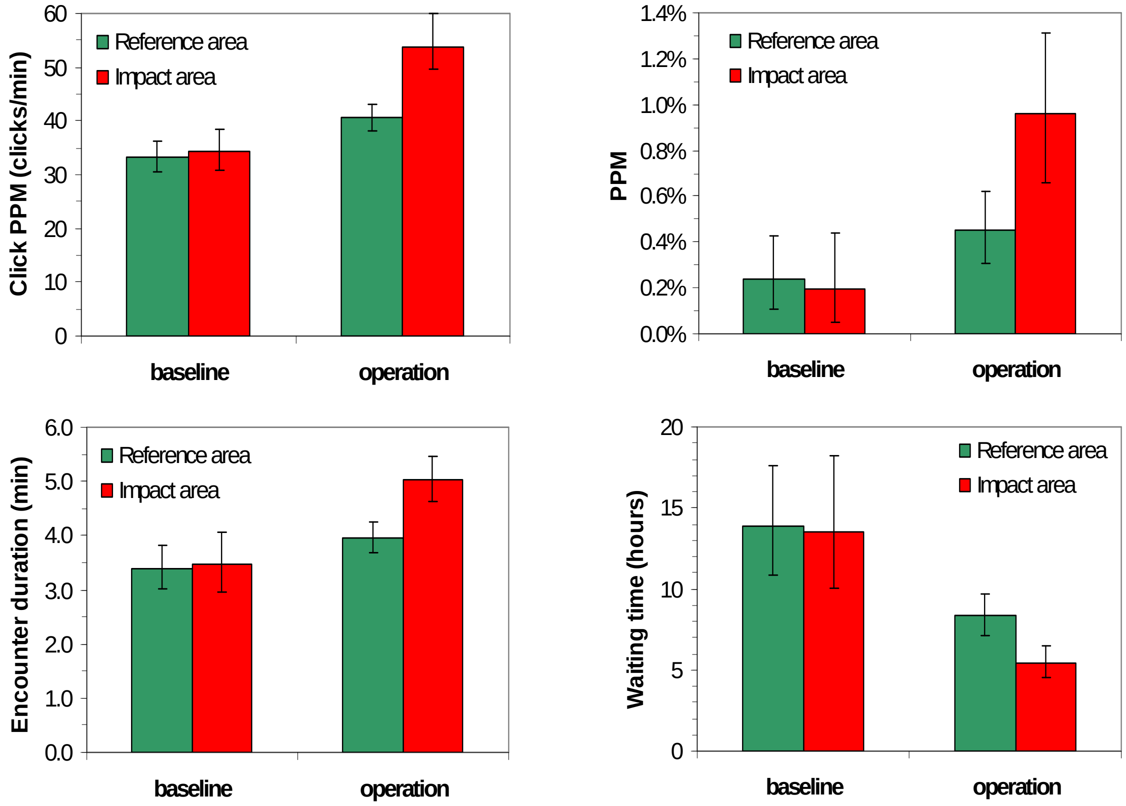
Harbour porpoise activity and presence was measured by acoustic monitoring of echolocation sounds with eight stationary acoustic porpoise detectors (T-PODs), which were permanently deployed and were operating on a 24 hour basis. Bi-monthly visual surveys were also carried out to investigate harbour porpoise occurrence. The results of the visual surveys showed that detection rates were highly weather dependent, in general very low and variable between surveys. The results from the T_0 study and a power analyses indicated that the most adequate method to investigate a potential effect of the wind park was through acoustic monitoring with T-PODs.

During both the T_0 and T_1study the T-PODs functioned very well and provided a wealth of data.. Four indicators of click activity (porpoise positive minutes, clicks per porpoise positive minutes, encounter duration and waiting time between encounters) were chosen for the analyses. These indicators can be related directly to porpoise occurrence and habitat use in the study area. To investigate a potential effect of the wind park a statistical Before-After Control-Impact (BACI) design was used. Here conditions in the wind farm (impact area, T_1) were compared to both the baseline conditions (T_0) and to conditions in the nearby reference area.

The acoustic results show a strong seasonal variation in harbour porpoise occurrence, with more recordings of animals in the autumn/winter/spring seasons compared to the summer months. This pattern was similar in both the T_0 and in the T_1 study.

There was a general increase in harbour porpoise occurrence from T_0 to T_1 for all T-POD stations. During T_0, the spatial distribution of porpoises did not differ significantly between the impact area (wind farm) and the two reference areas north and south of the wind farm.

The results of the BACI design showed that during the T_1 porpoises showed a significant change in distribution between the reference areas and the impact area. A higher number of porpoise occurrence was recorded within the wind park than outside. The cause behind the increase in abundance could not be determined, but may be linked to increased food availability due to the reef effect of the turbine foundations and the exclusion of fishery from the wind farm. The increase of harbour porpoise abundance inside the wind farm is in contrast to results from other offshore wind farms. This show that results from one wind farm are not necessarily transferable or valid for another wind farms located in a different area.



Mean values for combinations of area and period back-transformed to the original scale for combinations of the two areas and the two periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in sub-areas (Control N and S) and months have been accounted for by calculating marginal means.

Acknowledgement

The Offshore Wind farm Egmond aan Zee has a subsidy of the Ministry of Economic Affairs under the CO_2 Reduction Scheme of the Netherlands.

We would like to thank the crew of the Rijkswaterstaat owned vessel “Terschelling” for all the long hours they have spent on the deployment and recovery of the T-PODs, for their professional work under sometimes difficult conditions and the hospitality onboard the boat.

1 Introduction

1.1 Background of this study

Dutch government policy aims at realising sustainable energy production in The Netherlands. One possibility explored is offshore wind power. The government permitted the construction of Offshore Wind Park Egmond aan Zee (OWEZ) as a demonstration project, used for assessing both technological and environmental challenges in relation to operation. In order to evaluate environmental impacts from an offshore wind farm it is necessary to conduct a baseline or T_0 study, which provides a thorough description of the ecological reference situation, as well as, an impact study T_1, where the actual impact of the wind farm is assessed by comparison with the T_0 study.

Previous studies have shown a reduction in harbour porpoise abundance during the construction of other offshore wind farms (Carstensen et al. 2006, Tougaard et al. 2006b). In particular the installation of steel monopole foundations by means of percussive pile driving represents a substantial impact in an area covering several hundred km^2 around the construction site (Tougaard et al. 2009, Brandt et al. 2009). Operation of offshore wind farms probably presents a smaller impact, but throughout an extended period of time. Most significant negative impacts from an operating wind farm on harbour porpoises are likely to be underwater noise from the turbines and ship traffic related to service and maintenance (Madsen et al. 2006). Noise levels from operating turbines are expected to be low by any standard and effects, if any, are expected to be local, i.e. inside the wind farm and in the immediate vicinity of the wind farm (Tougaard et al. 2009). Potential positive effects have also been discussed and include a potential increase in potential prey (fish) in the wind park due to a reduction of fishing activities as well as the introduction of artificial hard substrate habitat.

Harbour porpoise activity and presence was measured by acoustic monitoring of echolocation sounds with eight acoustic porpoise detectors (T-PODs), permanently deployed and operating on a 24 hour basis. The comparison of the two study periods was done with a statistical BACI design, where conditions in the wind farm (impact area) is compared both to baseline conditions (T_0) and to conditions in nearby reference areas not affected by the wind farm.

1.2 Status of harbour porpoise in the Netherlands

The harbour porpoise (*Phocoena phocoena*) used to be a common animal in Dutch coastal waters. Until the 1950s it was not uncommon to encounter porpoises from the beach, in harbours, and even up rivers. Numbers observed started to decline in the second half of the century to such an extent that the porpoise became a rare visitor to the Dutch coast in the 1970s/1980s (van Deinse 1952, Reijnders 1992, Smeenk 1987). However, in the early 1990s, live sightings as well as dead strandings, started to increase and have continued to do so until present day (Camphuysen 1994, Reijnders et al. 1996, Witte et al. 1998).

2 Methods

2.1 Choice of methods

Different methods are available for monitoring the occurrence and habitat use of harbour porpoises.

When using visual surveys, e.g. using vessels or aircraft, only a proportion of the animals present can be recorded. Harbour porpoises spend most of the time under the water's surface, and are thus only visible to an observer for part of the time. Additionally sighting rates are dependent on a large number of parameters, such as weather conditions and observer expertise. Unless the general density is very high or the study area and the effort are very large, sighting rates will most likely be too low to have sufficient power to detect change. Also, the survey provides a snapshot of the distribution during a short time period (e.g. days, or even hours). As porpoises are highly mobile this can be problematic when surveying a small area. As the changes in distribution, even if small, will result in changes of sighting rates.

During the T_0 and T_1 study bird ship surveys were conducted that also collected information on marine mammals. In addition, during several surveys a towed hydrophone array was used to investigate if this method could provide sufficient data for the analyses of impacts.
The results from T_0 showed that both the towed hydrophone as well as the visual surveys where not adequate to investigate potential impacts of the OWEZ of porpoise presence and abundance. The detection as well as the sighting rate was generally too low to have sufficient power to detect changes in occurrence of porpoises.

T-PODs, stationary acoustic porpoise detectors, continuously register the presence of porpoises within the targeted areas (i.e. the wind farm site and two control sites). They collect continuous baseline data on the occurrence, and seasonal patterns of the animals. This method showed very powerful results during T_0 and has also proven successful in studies to monitor the effects of wind farms on harbour porpoise in Denmark (Tougaard et al. 2003). This method was therefore chosen as the primary method in the study presented here.

2.2 Site description

The study site is located in the North Sea, west of the province of North Holland (The Netherlands), where the offshore wind farm Egmond aan Zee (OWEZ) was constructed (*Figure 1*). OWEZ is located 8-18 km offshore with an approximately area of 40 km^2. There are 36 wind turbines with a hub height of 70 meters above median sea level (MSL), each with a nominal capacity of 3 MW. Construction began in April 2006 with all the turbines standing by August 2006 (pile driving period). The wind farm was commissioned on 1 January 2007.

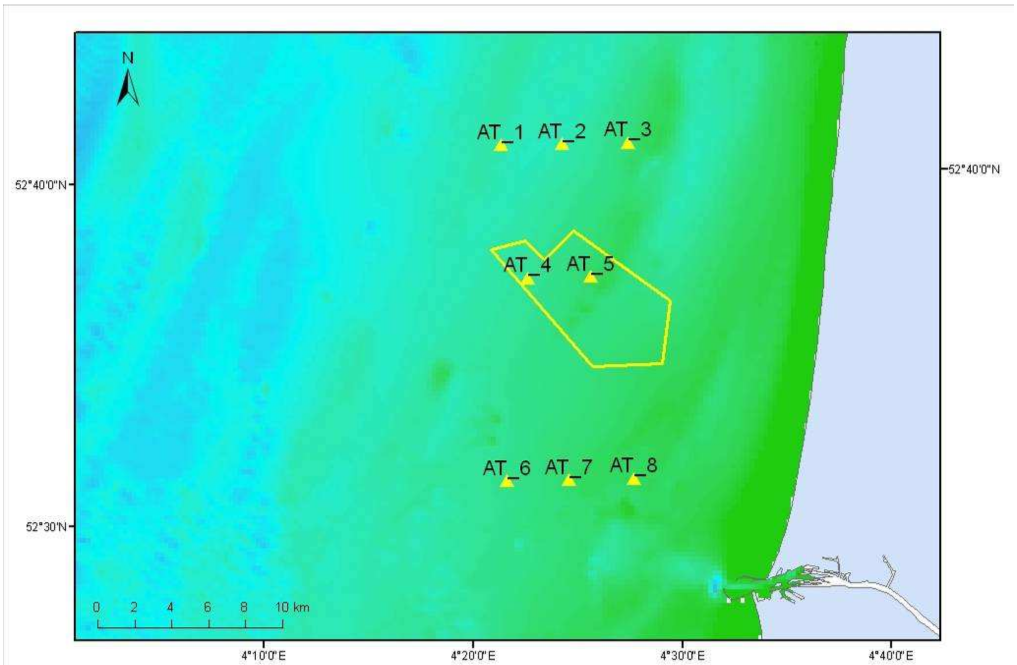


Figure 1. Positions of the 8 monitoring stations (AT1 –AT8), northwest of the harbour of IJmuiden (NL). The yellow line shows the outline of the OWEZ wind farm area. Geographic system: ED-50; Projection: UTM zone 31N.

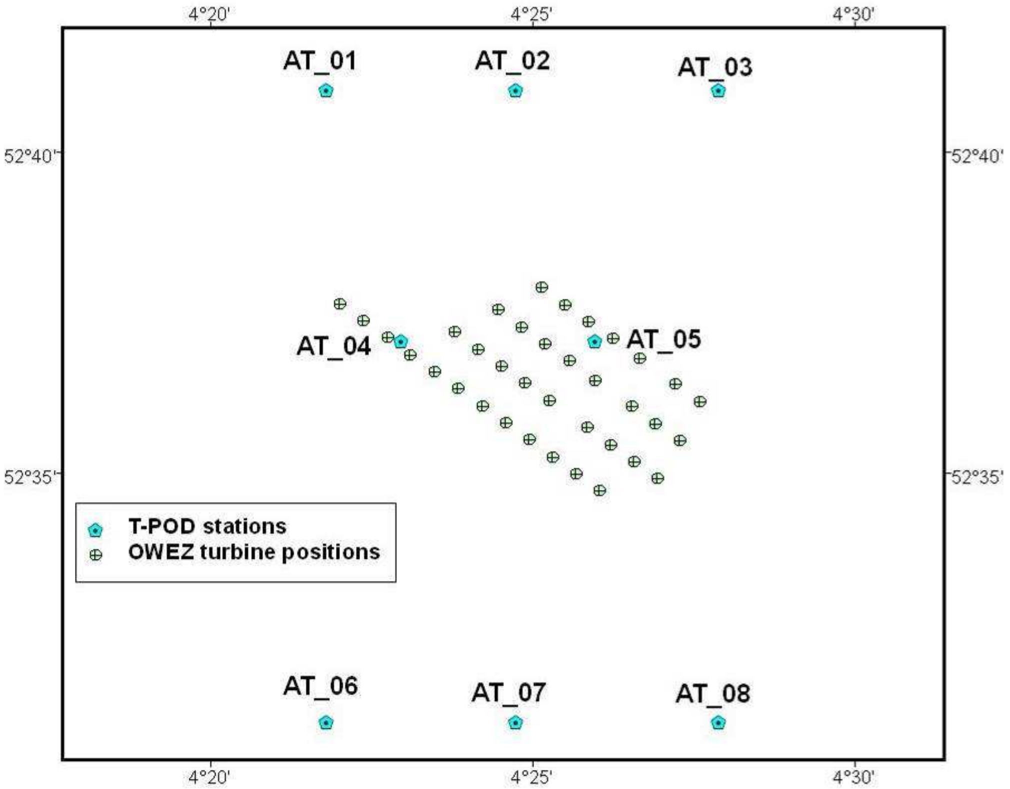


Figure 2: Positions of wind turbines of OWEZ

2.3 Acoustic monitoring (T-PODs)

The effect of Egmond aan Zee wind farm on harbour porpoises was studied by static acoustic monitoring. Static acoustic loggers (by means of T-PODs, see below) were deployed in a period prior to construction, denoted "baseline" or T_0 (June 2003 – May 2004) and a post-construction period, denoted "operation" or T_1 (June 2007 – April 2009). A total of 8 fixed stations were used for acoustic monitoring of harbour porpoises; three control stations north of the wind farm area, three control stations south of the wind farm and two stations within the wind farm area (Fig 1).

The positions of the T-POD stations were chosen on the following grounds:

- In the wind farm (OWEZ): T-PODs have to be placed at least 1 nautical mile or more apart from one another, to assure that T-POD can be considered independent and to avoid the situation of a porpoise being detected simultaneously by 2 neighbouring T-PODs. Maximum detection distance of T-PODs is around 500 m (Tougaard 2008). The two T-PODs positioned in the wind farm were AT4 and AT5.
- Outside the wind farm, based on experience obtained during wind farm studies in Denmark (Teilmann et al. 2002, Carstensen et al. 2006, Tougaard et al. 2006b, Teilmann et al. 2009) the T-PODs in the two reference areas were placed approximately 5-6 nautical miles from the wind farm. This distance should ensure that the reference area has the same biotic and abiotic factors as in the wind farm, but is outside the potential disturbance range of the wind park. The distance between the T-PODs in the reference areas was the same as for T-PODs inside the park.
- The choice for 3 T-PODs in two reference areas north and south of the wind park (respectively AT1 - AT3 and AT6 - AT8) and 2 in the park is based on the considerations that:
  a) only two T-PODs (with the required distance) fit in the park and
  b) because of the higher likelihood that T-PODs may disappear outside of the park
  c) the potential geographical effect north and south of the wind park could be investigated.

2.3.1 Technical description of T-PODS

The T-POD or POrpoise Detector is a small self-contained data-logger that logs echolocation clicks from harbour porpoises and other cetaceans. It is developed by Nick Tregenza (Chelonia, UK). 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 click-activity. It processes the recorded signals in real-time and only logs time and duration sounds fulfilling a number of acoustic criteria set by the user. These criteria relate to click-length (duration), frequency distribution and intensity, and are set to match the specific characteristics of echolocation-clicks. The T-POD operates with six separate and individually programmable channels. To maximise the chance to detect harbour porpoises during this study, all channels had identical settings (Table 1).

Table 1. T-POD filter settings used during deployments.

	Version 3	Version 5
A filter: frequency (kHz)	130	130
B filter: frequency (kHz)	90	92
Ratio: A/B	5	n.a.
A filter: Q (kHz) / integration time	short	n.a.
B filter: Q (kHz) / integration time	long	n.a.
Bandwidth	n.a.	5
Automatic gain control	n.a.	+
Sensitivity:	6	10
Max number of clicks / scan:	160	160
Minimum click duration: (µS)	30	30

Each of the six channels records sequentially for 9 seconds, with 6 seconds per minute assigned for change between channels. This gives an overall duty cycle of 90% (54 seconds per minute), 15% for individual channels (9 seconds per minute). In order to minimise 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 (time since deployment) is considerably less, due to drift in the T-PODs clock during deployment (up to a few minutes per month). This drift however, is only of concern when comparing records from two T-PODs deployed simultaneously. Clicks shorter than 30 µs and sounds longer than 2550 µs are discarded.

The T-POD relies on the highly stereotypical nature of porpoise sonar signals. These are unique in being very short (50-150 microseconds) and containing virtually no energy below 100 kHz. The main part of the energy is in a narrow band between 120-150 kHz, which makes the signals ideal for automatic detection. Most other sounds in the sea, with the important exception of echosounders and boat sonars, are characterised 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.

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 filter and is below 200 microseconds in duration is highly likely to be either a porpoise or a man-made sound (echosounder or boat sonar). Some spurious clicks of undetermined origin (such as background noise and cavitation sounds from high-speed propellers) may also be recorded. These, as well as boat sonars and echosounders are filtered out off-line in software, by analysing intervals between subsequent clicks. Porpoise click trains are recognisable by a gradual change of click intervals throughout a click sequence, whereas boat sonars and echosounders have highly regular repetition rates (almost constant click intervals). Clicks of other origins tend to occur at random, thus with highly irregular intervals.

No other cetacean regularly found in the North Sea uses sonar signals that can be confused with porpoise signals. Dolphins (with the exception of the genus *Cephalorhynchus*, which does not occur in the North Sea) use broadband sonar clicks, i.e. energy distributed over a wide frequency range, from below 20 kHz to above 200 kHz in some cases (Rasmussen et al. 2002). It is thus highly unlikely that they will trigger the T-POD when porpoise settings are used.

Figure 3: Standard T-POD (taken from www.chelonia.co.uk); the hydrophone is located at the top, the batteries are stored in the bottom part of the T-POD.

Comparison of T-POD recordings with simultaneous visual tracking of porpoises with theodolite show that the effective detection distance is between 100 and 200 meters (with a maximum detection of around 500m). Of 37 animals observed closer than 100 m from the T-POD, 81% were registered by the T-POD. Of 34 animals that came within 100-200 meters, of the T-POD, 31% were recorded by the T-POD (Tougaard 2008).

2.3.2 Field calibration of T-PODs

Two versions of T-PODs were used in this study: version 3 (v3) and version 5 (v5). The v3's were equipped with 32 MB RAM and the v5's with 128MB RAM and powered by 12 or 15 alkaline D-cells, respectively. This gives a maximum logging period of about 120 days.

To make sure that the eight T-PODs were working and provided similar results they were deployed simultaneously in a porpoise rich area in Denmark prior to the study in the OWEZ wind farm area. Results of this can be found in Brasseur et al. 2004.

Field calibrations were done at the begin of the T_0 study (Brasseur et al. 2004). Hydrographic data was collected in T_0 (Brasseur et al. 2004), but was found not to have an influence on the recording and thus this was not done in T_1. During the T_1 study new versions of T-PODs (v5) were used. To allow data analyses between the T_0 version (v3) and the T_1 version (v5) during the T_1 phase on a number of positions two different T-PODs were placed together on one position. This was done to calibrate the two different T-POD versions (v3 in the T_0 and v5 in the T_1). Deploying them together allowed a comparison of the data at a later stage, and thus allowed the two versions to be used interchangeably.

2.3.3 Mooring technique

The mooring used for the T-PODs in the Dutch coastal waters was designed using robust material. Where in other areas T-PODs are usually attached to small anchor blocks and small buoys, this study used very heavy equipment for anchoring the T-PODs due to the risk of collision with trawlers in the area. Approximately 15 tonnes of buoys, chain, and concrete is used for anchoring a single T-POD securely (Figure 4).

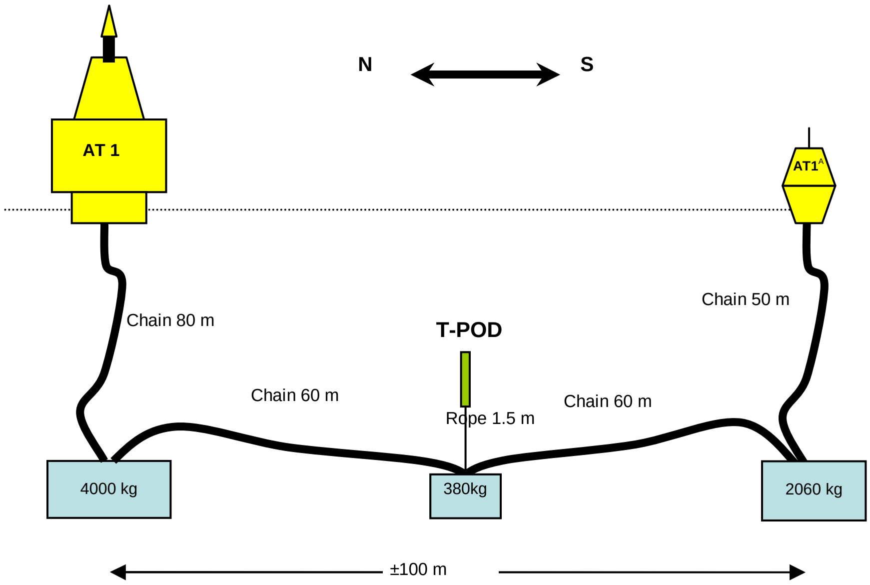


Figure 4. Schematic setup of the T-POD mooring. The large buoy is lighted at night.

Each T-POD was deployed between two large buoys, of which the larger was equipped with a yellow warning lantern. Furthermore, the experimental setup was proclaimed on VHF-radio regularly by the local authorities.

Figure 5. Set-up of the anchoring. View above water (photo Saskia Mulder, RIKZ)

2.3.4 Servicing of T-PODs

The eight T-PODs were regularly serviced. This included cleaning, downloading the data and changing the batteries and, when necessary replacing lost or broken T-PODs. Servicing periods were set in a way to ensure that batteries were changed before drained (about every 100 days) however, for several reasons of technical nature (see section 3.1.2) the actual time of recording was less than that.

Figure 6. Complete anchoring system on board the "Terschelling" (photo Saskia Mulder, RIKZ)

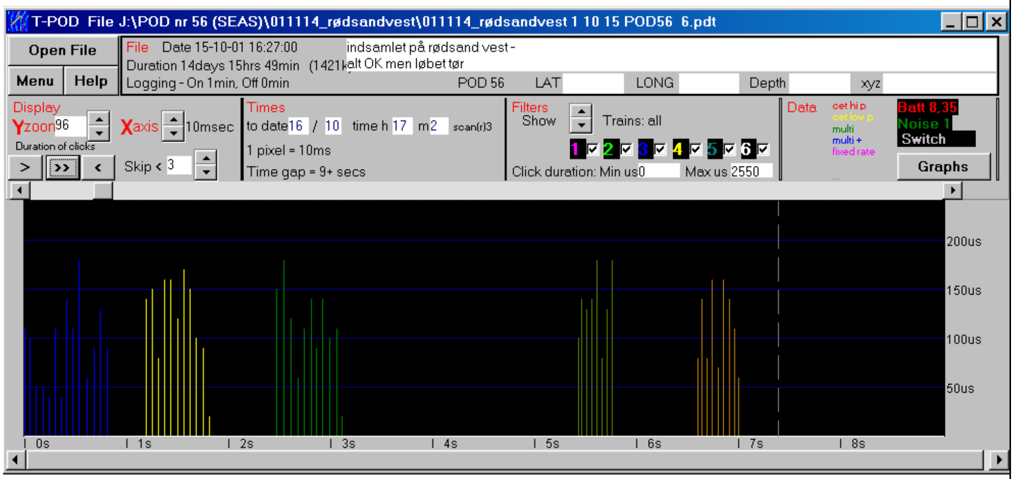
Figure 7: T-POD being attached to the anchoring system. The Kevlar line is reinforced with rubber tubing and a PVC foam float is attached at the top of the T-POD to increase the buoyancy.

Figure 8: T-POD about to be deployed at position AT_5 in the OWEZ

2.3.5 Analysis of T-POD data

Following recovery of the T-PODs, data logged were downloaded to a PC while still on board. Figure 8 shows an example of downloaded 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. Version 8.17 of the software "tpod.exe" was used to analyse all data collected from both T_0 and T_1. See (Kyhn et al. 2008) for details on the filtering. Data were exported in ASCII format for statistical analysis after filtering.

Figure 9. Screen snapshot from the T-POD.exe program. Five series of porpoise clicks can be seen as vertical bars. Time in seconds is shown on the X-axis, and the duration of each click is shown on the Y-axis.



2.3.5.1 Echolocation activity indicators

In line with previous studies (Carstensen et al. 2006, Tougaard et al. 2006a, Tougaard et al. 2006b, Teilmann et al. 2009), four indicators were extracted from the exported T-POD data, which had the fundamental unit of clicks per minute. This signal, denoted x_t, describes the recorded number of clicks per minute and consisted of many zero observations (no clicks). The click activity was aggregated into daily values of:

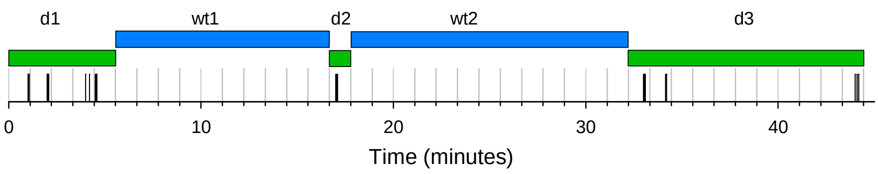
$$\text{PPM} = \text{Porpoise Positive Minutes} = \frac{\text{Number of minutes with clicks}}{\text{Total number of minutes}} = \frac{N\{x_t > 0\}}{N_{total}}$$

$$\text{Clicks per PPM} = \frac{1}{N\{x_t > 0\}} \sum_{x_t > 0} x_t$$

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

Another approach in analysis is to consider the recorded click as a point process, i.e. separate events occurring within the monitored time span. Therefore x_t was considered 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. In line with previous studies a silent period of 10 minutes was used to define two encounters as being separate from each other. Thus, two click recordings separated by a 9 minute silent period would still be part of the same encounter. A schematic example is shown in Figure 10.

Figure 10. Schematic illustration of encounter durations (green) and waiting times (blue) for a sequence of click trains.



Converting the constant frequency time series into a point process resulted in two new indicators for porpoise echolocation activity.

Encounter duration = Number of minutes between two silent periods

Waiting time = Number of minutes in a silent period >10 minutes

The definition of waiting time implies that it has a natural lower bound of 11 minutes, and that encounters potentially include 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 30th September at 12:14 and ending 1st October at 1:43 was associated with the mean time of 30th September 18:59 and categorised as a September observation.

2.3.5.2 Statistical design and model

First, differences between the two T-POD types (V3 and V5) were investigated in a paired analysis of the two daily indicators (click PPM and PPM) using only deployments days, where both types had been in operation for an entire day at the same position. As the T-PODs in some cases were started at different times and in all cases ended logging at different times of the day, only indicators from days with a complete dataset (24 hours) were used in the comparison. The indicators, derived from different types of T-PODs at the same station and date, were related by means of least squares regression to investigate if the two types of T-PODs produced comparable echolocation activity. A few observations, 1 for click PPM and 3 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 can not be paired over time in the same manner as click PPM and PPM, i.e. between the two T-POD types encounters and waiting times do not always match across time.

Second, the indicators were analysed according to a modified Before-After Control-Impact (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 (5 fixed and 3 random) and combinations thereof:

- *Area* (fixed factor with 2 levels: *impact* and *control*) describes the spatial variation between control areas and impact area (wind farm).
- *Subarea(area)* (fixed factor with 3 levels: *control N, control S* and *impact*) describes the spatial variation between the three areas. As this factor is nested within *area*, it describes differences between the two control areas *control N* and *control S*.
- *Station (area subarea)* (random factor with 8 levels: *AT1-AT8*) describes the station-specific variation (variation among stations) within each of the three areas.
- *Period* (fixed factor having 2 levels: T_0 and T_1) describes the difference between baseline and operation period.
- *Year(period)* (random factor with 5 levels: *2003, 2004, 2007, 2008, 2009*) describes the variation between years within the two periods T_0 and T_1.
- *Month* (fixed factor with 12 levels: *Jan-Dec*) describes the seasonal variation by means of monthly values.
- *Podtype* (fixed factor with 2 levels: *v3* and *v5*) describes the difference between v3 and v5 T-PODs.
- *Podid* (random factor with 20 levels: serial number of T-POD) describes the random variation between different T-PODs for v3 and v5 separately.

Four of the fixed factors (main factors *area*, *period*, *month* as well as nested factor *subarea(area)*), and their 7 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 6 factors in the list above) 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:

$$\begin{aligned}\mu_{ijklm} &= area_i + subarea(area)_{j(i)} + period_k + area_i \times period_k + subarea(area)_{j(i)} \times period_k \\ &+ month_l + area_i \times month_l + subarea(area)_{j(i)} \times month_l + period_k \times month_l \\ &+ area_i \times period_k \times month_l + subarea(area)_{j(i)} \times period_k \times month_l + podtype_m \end{aligned} \tag{1}$$

where subscripts *i, j, k, l* and *m* indicates 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 *podid(podtype)* that has a version-specific variance, i.e. captures a difference in magnitude of 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 time scale 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 (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. 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.

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

Indicator	Transformation	Distribution	Back-transformation
Clicks per PPM	Logarithmic – log(y)	Normal	$\exp(\mu+\sigma^2/2)$ [1]
PPM	Angular – $\sin^{-1}(\sqrt{y})$	Normal	Table 6 (Rohlf & Sokal 1981)
Encounter duration	Logarithmic – log(y)	Normal	$\exp(\mu+\sigma^2/2)$ [1]
Waiting time	Logarithmic – log(y-10)	Normal	$\exp(\mu+\sigma^2/2)$ +10[1]

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

Waiting times had a natural bound of 10 minutes imposed by the encounter definition, and we therefore subtracted 9 minutes 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 Eq. (1) were multiplicative on the original scale. This meant that e.g. the seasonal variation was described by monthly scaling means rather than by additive means. Variations in the four indicators were investigated within the framework of generalised linear mixed models (McCullagh & Nelder 1989), and the significance of the different factors in Eq. (1) was tested using F-test (type III SS) for the normal distribution (SAS Institute 2003).

The factor $area_i \times period_k$, also referred to as the BACI effect, describes a step-wise change (from T_0 to T_1) 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 T_0 to T_1 differ from changes in the control area. In other words any changes in the wind farm area from T_0 to T_1 cannot be explained alone by general changes in the area but must be ascribed to the impact (i.e. the presence of the wind farm).

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. Only the final models, after eliminating all non-significant factors, are presented in the results.

2.4 Ship based surveys

A detailed description of the visual surveys for birds can be found in Leopold et al. 2004 and 2009. An overview of all conducted surveys is given in table 3. All porpoise sightings were recorded. Ship groundspeed was kept at approximately 10 knots and this was constantly monitored by a portable GPS. The ships positions were logged every 5 minutes and mid-positions of individual 5 minutes calculated. Porpoises were counted in two (left and right, conditions permitting) or one (left or right) strips adjacent to the ship, following Tasker et al. (1984) and Camphuysen & Garthe (2001).

Table 3: Overview over all visual surveys conducted during T_0 and T1

Phase	**Survey work**	Phase	**Survey work**
T_0	September 23-27, 2002	T_1	April 9-11, 2007
T_0	October 21, 22, 24, 2002	T_1	June 27-29, 2007
T_0	April 07-11, 2003	T_1	August 19-22, 2007
T_0	May 19-23, 2003	T_1	September 24-27, 2007
T_0	June 23-27, 2003	T_1	November 20-24, 2007
T_0	August 11-15, 2003	T_1	January 14, 16-18, 2008
T_0	November 04-07, 2003	T_1	April 7-10, 2008
T_0	February 16-19, 2004	T_1	June 23-26, 2008
		T_1	August 11-14, 2008
		T_1	January 19-22, 2009
		T_1	April 6-9, 2009

2.5 Comparison of data derived from T-PODS and visual observations

Monitoring programs using T-PODs and survey programs are in some sense orthogonal investigations that supplement each other well and with almost no redundancy. Surveys thus have high spatial resolution, but poor temporal resolution, whereas the situation is exactly the opposite for T-PODs (low spatial and very high temporal resolution).

Because of the reasons described earlier (section 2.1) we did not perform direct quantitative comparisons of the results of the T-POD data with the survey data. We will describe some of the results from the ship surveys and compare the data qualitatively with the T-POD results, looking for similar trends during seasons.

3 Results

3.1 Effort

3.1.1 Monitoring effort

Monitoring effort in T_0 started in June 2003 and ended in May 2004. In T_1 first deployments were made in April 2007 and the last T-PODs were recovered in April 2009. Figure 11 gives an overview of the data collected at the different stations. An overview of all dates of T-POD exchange is given in Appendix 1.

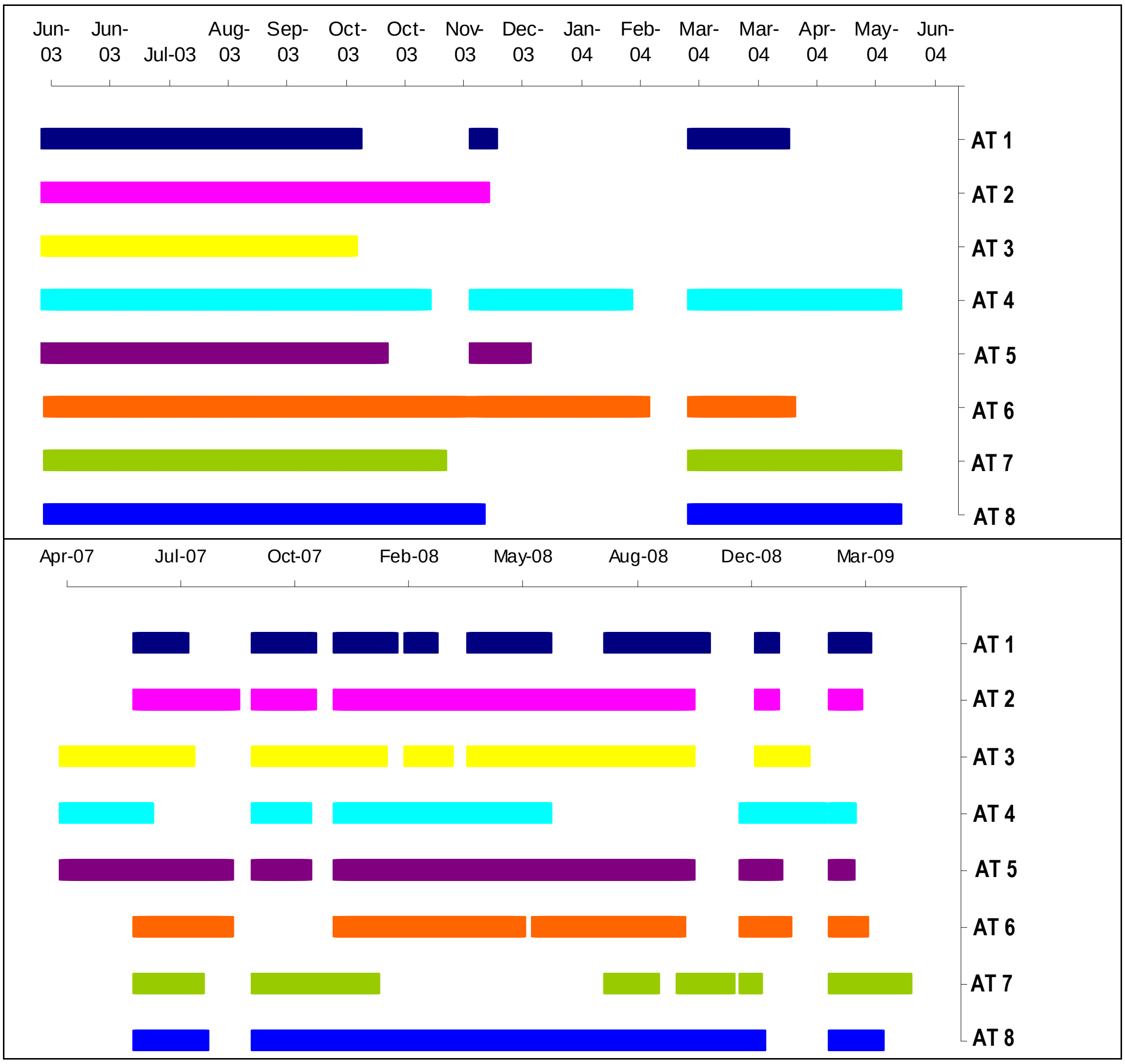


Figure 11. Monitoring effort at the stations AT1-AT8 during T_0 (A) and T_1 (B). During parts of T_1 two T-PODs of different versions were deployed simultaneously on some stations. Details can be found in appendix 1.

3.1.2 Logistical problems

Periods without data (Figure 11) were due to various logistical issues and included loss of T-PODs, T-POD failure and full memory of T-PODs. In the beginning of the study a number of T-PODs were lost from their anchoring system. Some of the loss could be ascribed to T-PODs being pushed to the ground for several days through strong currents in bad weather situations. While pushed horizontally onto the sea floor, the line connecting the T-POD to the weight was wearing through. When the design of the connecting line was changed to a rubber encased Kevlar cable and a float was added to the top of the T-PODs these losses stopped. Additionally, in at least two cases fishing operations were interacting directly with the anchoring system, partly damaging the buoys and/or ripping off the T-PODs from their anchor stone. Whenever losses of T-PODs occurred they were generally found within the next months and were retrieved by IMARES.

A different source of data loss was battery loss. This was either occurring because batteries were drained faster than expected (e.g. colder weather), or because rough weather caused connections within the T-POD to loosen and stop the energy supply. Additionally, particularly during longer periods of storms, more acoustic signals were recorded by the T-PODs because of an increase in underwater noise. This caused the memory to fill up earlier than expected. To respond to this we increased the servicing trips during the winter months when weather permitting.

Even with some loss of recording time, the amount of data collected by the T-PODs was sufficient to detect changes in the occurrence of harbour porpoises in the study area with the desired statistical power (see Brasseur et al. 2004).

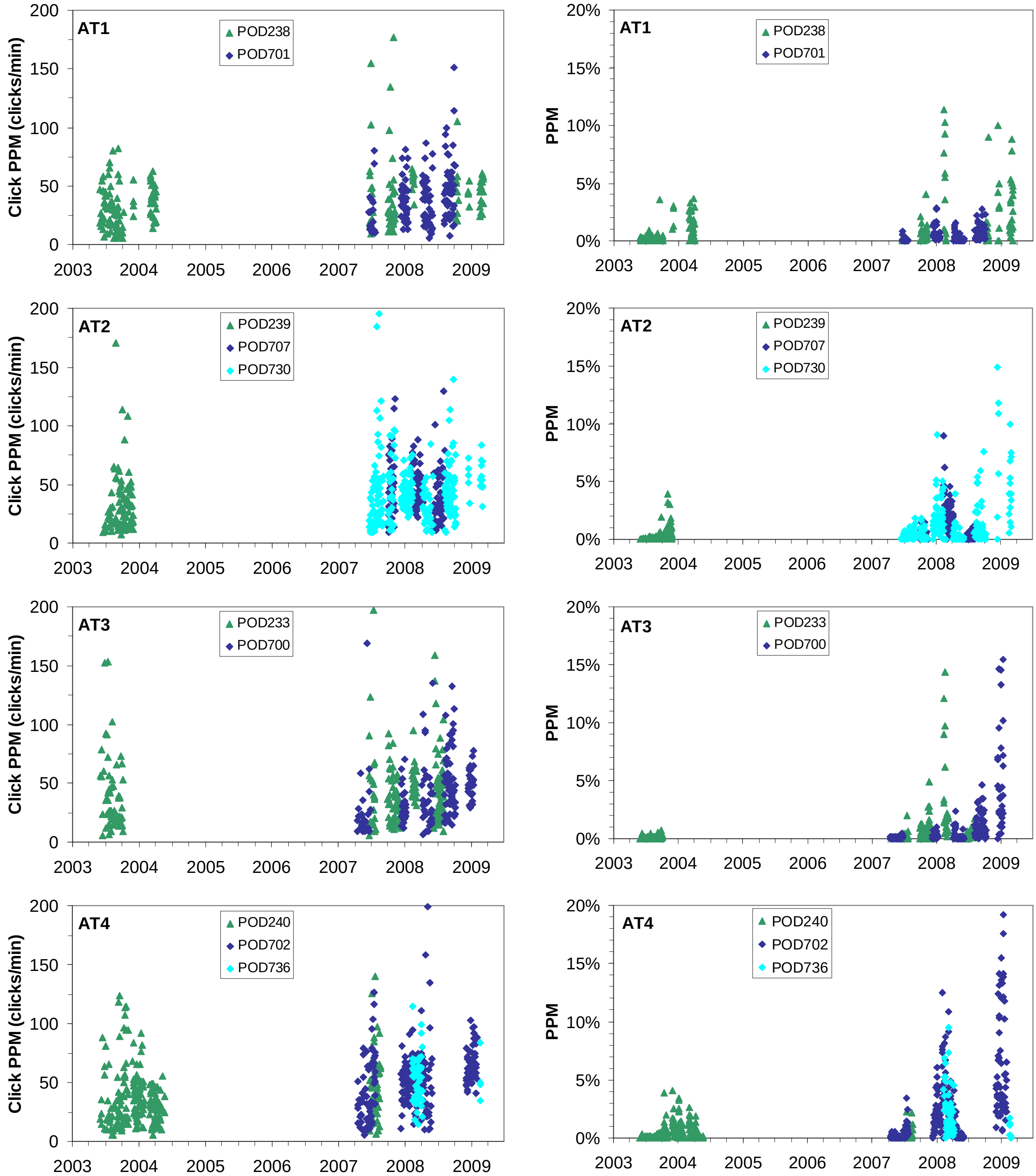
3.2 Stationary T-POD data

There was a total of 5228 active station days with T-POD monitoring data. One active station day is one day of data from one station. The maximal data that could have been collected was thus 8 x 365 station-days per year or about 8700 potential station days for the entire period. In reality, data for 60% of the potential station days were collected, with more than twice as many active station days during T_1 (n=3507) than during T_0 (n=1721). The area Control S had the highest number of active station days (n=2081), followed by Control N (n=1718). The wind farm area with its two stations had the least number of active station days (n=1429). The data was relatively evenly distributed across the 8 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 types at the same position.

3.2.1 Porpoise acoustic activity

Based on the number of clicks per minute the indicators PPM (porpoise positive minutes) and clicks per PPM were calculated (Figure 12, Table 4), as was the indicators encounter duration and inter-encounter waiting time (Figure 13, Table 5). Daily average clicks per PPM could be calculated for 3795 station-days daily values of e.g. number of days with click recordings. 27% of the deployment days were silent, most of these occurred between May and August. Temporal variations and variation between positions and PODs were relatively smaller for Click PPM compared to PPM (Table 4). For the two periods and the 8 positions the coefficients of variation varied between 45% and 119% for click PPM and between 141% and 268% for PPM.

Encounter duration (n=22181) and waiting time between encounters (n=22087) were calculated from the POD data (Figure 13, Table 5). The two control areas (Control N and S) each had about 6500 encounters and waiting times, whereas the impact area had almost 9000. The numbers of encounters and waiting times across the 8 positions ranged from ~1900 at AT1 to ~4600 at AT5 (Table 4). There were more than twice as many encounters and waiting times during operation compared to baseline, i.e. higher activity than could be accounted for simply by the larger number of stations days during operation (Table 5). For the 2 periods and 8 positions the relative variation in encounter duration (CV=123-259%) and waiting time (138-369%) was larger than for the click PPM but similar to PPM, however, there was also approximately four times as many observations. Both duration and waiting time distributions were strongly skewed to the right with observations exceeding 1 hour for encounter duration and 5 days for waiting time (Figure 13).


AT1
POD238
POD701
AT1
POD238
POD701
AT2
POD239
POD707
POD730
AT2
POD239
POD707
POD730
AT3
POD233
POD700
AT3
POD233
POD700
AT4
POD240
POD702
POD736
AT4
POD240
POD702
POD736
Click PPM (clicks/min)
PPM
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5%
10%
15%
20%

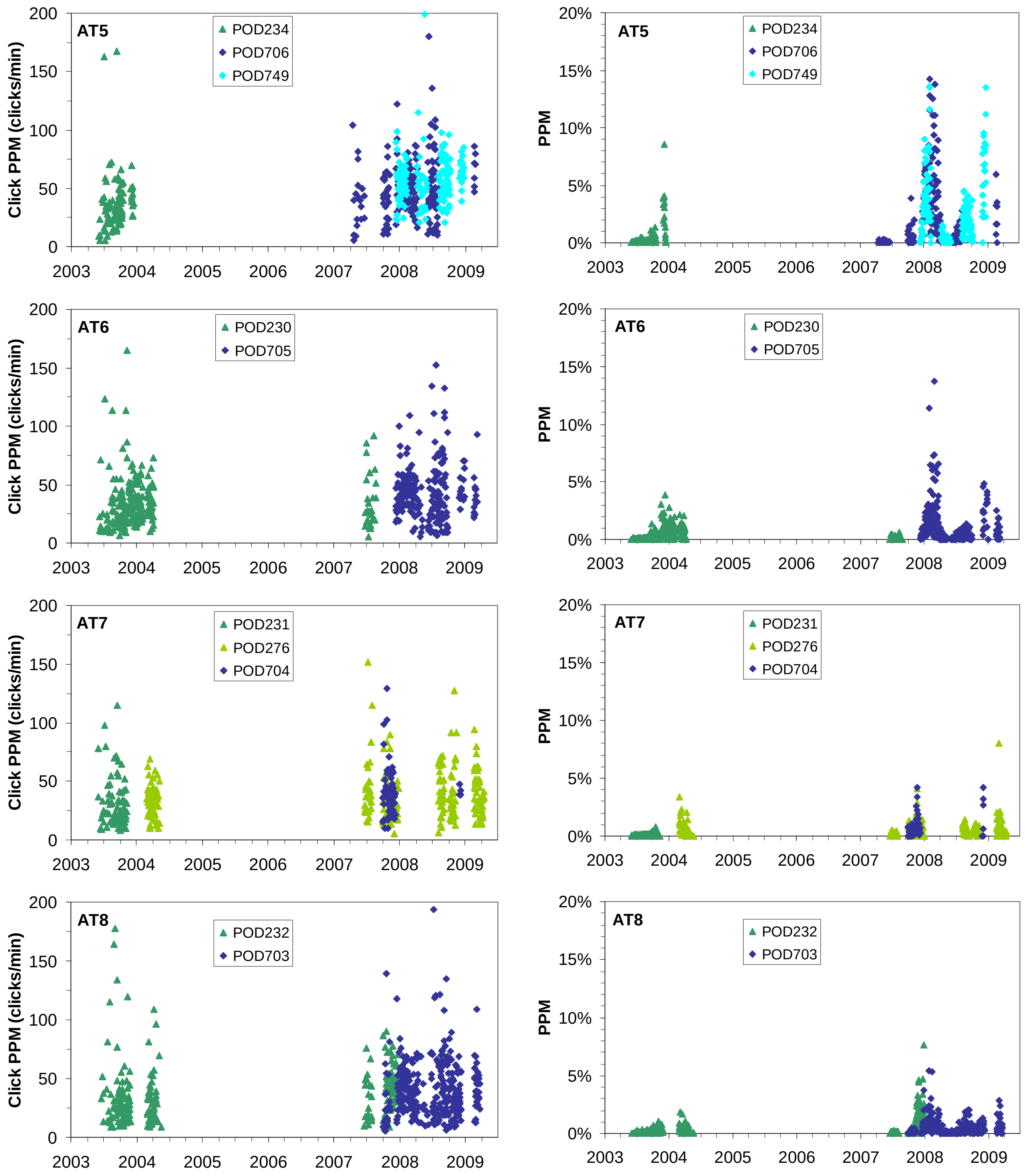
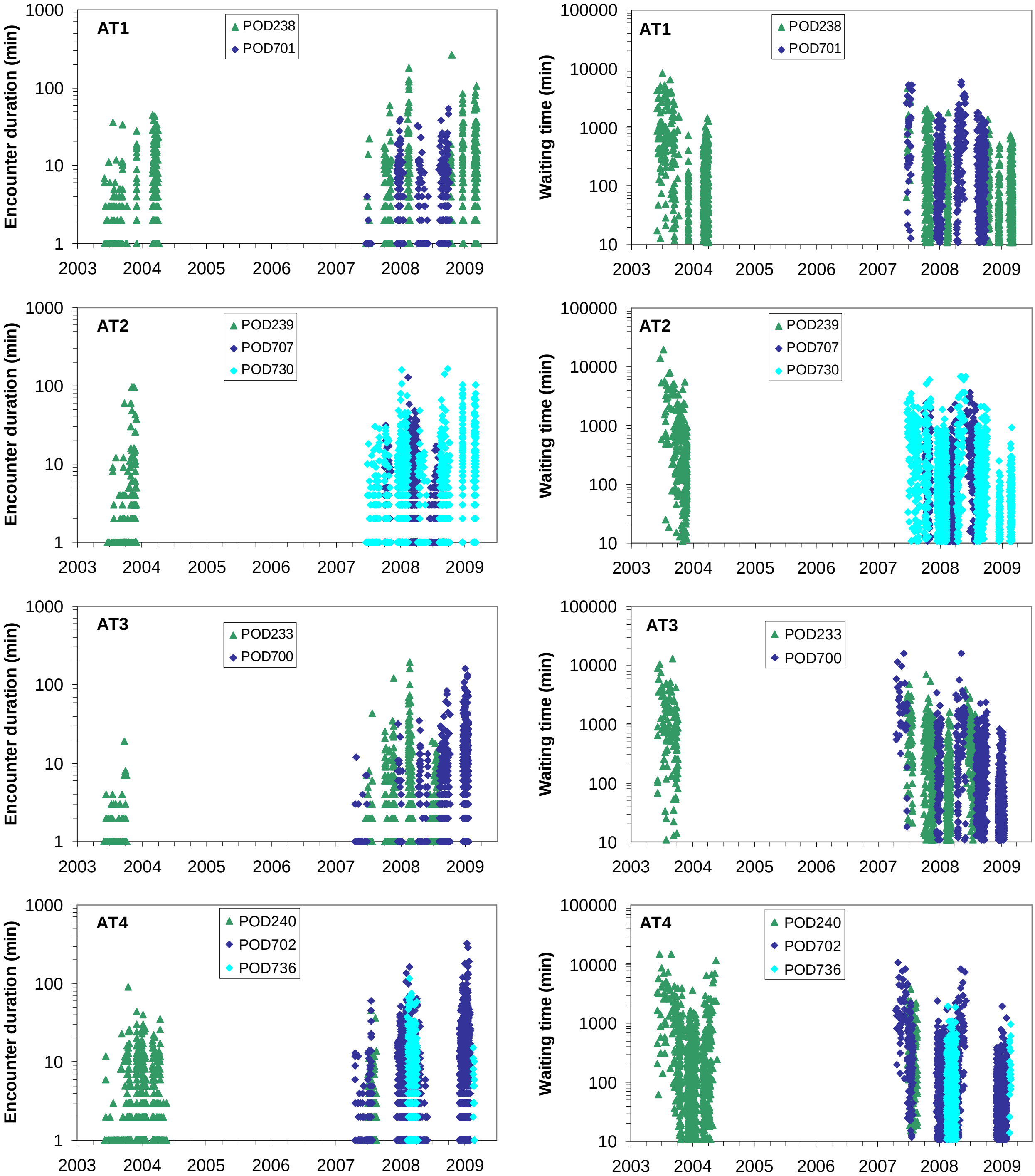


Figure 12: Click PPM (left panel) and PPM (right panel) extracted from T-POD data collected at Offshore Wind Park Egmond aan Zee during baseline (June 2003 – May 2004) and operation (June 2007 – March 2009). Different symbols and colours mark observations derived from different T-PODs (green triangles = V3, blue diamonds = V5). A few click PPM estimates (11 observations) and PPM estimates (4 observations) exceeded the plotting range (not shown).

Table 4: Statistics of the two daily indicators monitored in the baseline and operation periods at Offshore Wind Park Egmond aan Zee. Number of days with PPM is equal to the number of deployment days, whereas number of days with click PPM can be less due to days without any click recordings (missing value of click PPM).

Period	Area	Posi-tion	Click PPM (clicks/minute)					PPM (%)				
			N	Min	Median	Mean	Max	N	Min	Median	Mean	Max
Baseline	Control N	AT1	105	5.6	31.7	32.6	82	151	0	0.14	0.48	3.7
		AT2	95	7.8	26.7	36.3	261	183	0	0.07	0.20	3.9
		AT3	67	5.6	26.7	45.4	370	127	0	0.07	0.09	0.8
	Impact	AT4	197	5.6	31.1	35.9	123	304	0	0.07	0.35	4.0
		AT5	87	5.6	33.9	37.5	168	159	0	0.07	0.37	8.5
	Control S	AT6	195	6.1	31.9	35.1	165	287	0	0.14	0.43	3.8
		AT7	138	7.8	29.7	32.0	115	247	0	0.07	0.21	3.4
		AT8	139	8.9	26.7	35.2	278	263	0	0.07	0.17	1.9
Operation	Control N	AT1	259	5.6	39.1	41.7	177	307	0	0.28	0.91	11.4
		AT2	414	8.9	40.9	44.2	196	498	0	0.42	1.04	14.9
		AT3	350	5.6	37.9	42.4	253	452	0	0.21	0.91	15.5
	Impact	AT4	390	5.6	52.4	52.9	499	465	0	0.76	1.98	24.5
		AT5	408	5.6	52.9	54.5	228	501	0	0.97	2.10	25.1
	Control S	AT6	269	5.6	40.4	43.7	262	375	0	0.21	0.88	20.5
		AT7	267	5.6	36.5	41.0	320	334	0	0.35	0.54	8.1
		AT8	415	5.6	37.7	40.9	193	575	0	0.21	0.48	7.6

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. This increase in porpoise activity can be due to an overall change in presence and behaviour between T_1 and T_0, the shift from V3 to V5 T-PODs and changes in the months of monitoring between the two periods. Spatial differences were also apparent from the observations (Figure 13, Table 5), but due to seasonal variation combined with differences in the months covered by the monitoring and the employment of two different T-POD versions during the operation period the statistics given in Table 5 cannot be compared without resolving all the different sources of variation. These different sources of variation are partitioned out in the statistical analysis of the encounter statistics.


AT1
POD238
POD701
Encounter duration (min)
Waiting time (min)
AT2
POD239
POD707
POD730
AT3
POD233
POD700
AT4
POD240
POD702
POD736
1
10
100
1000
10000
100000
2003
2004
2005
2006
2007
2008
2009

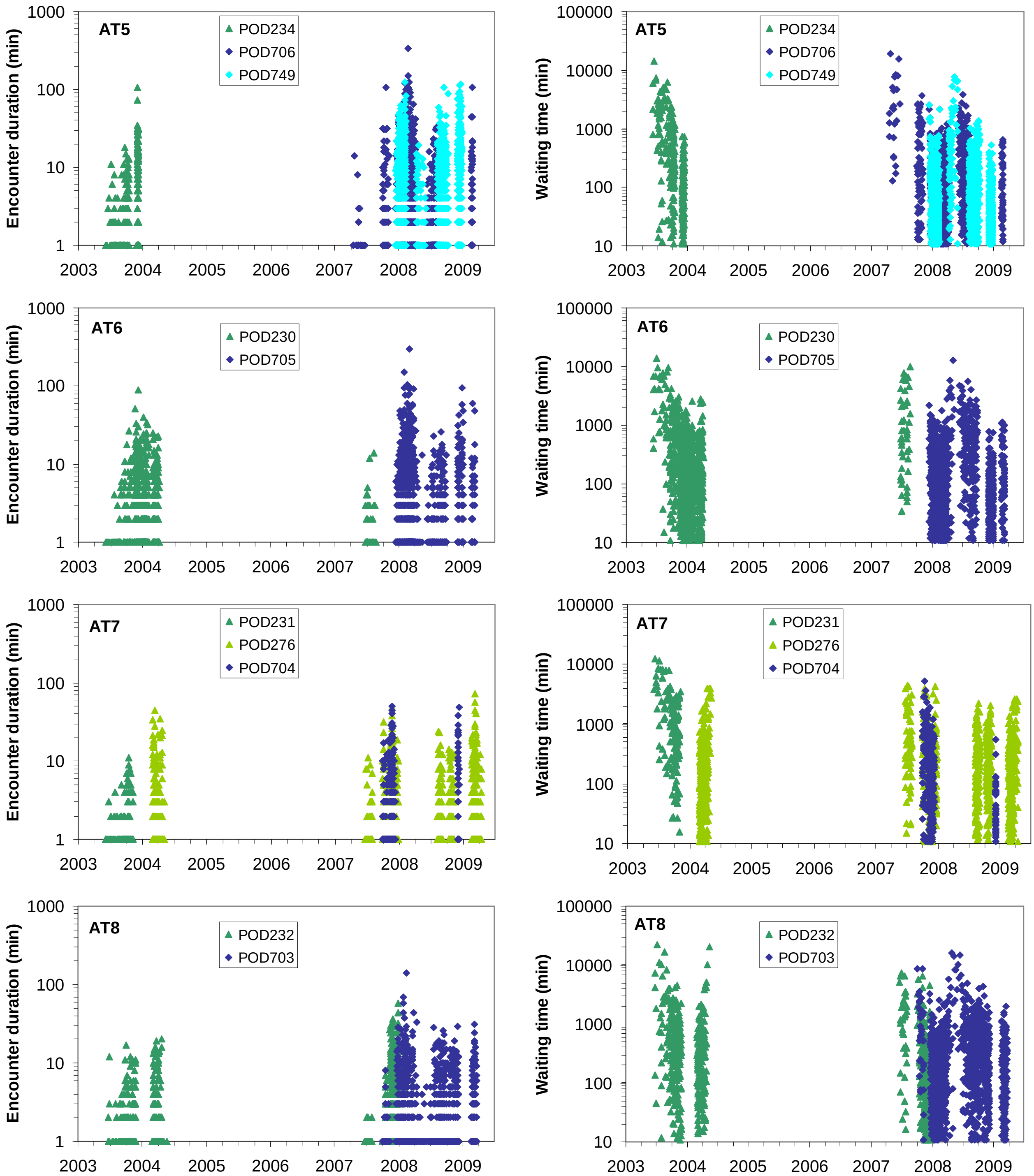


Figure 13: Encounter duration (left panel) and waiting time (right panel) extracted from T-POD data collected at Offshore Wind Park Egmond aan Zee during baseline (June 2003 – May 2004) and operation (June 2007 – March 2009). Different symbols mark observations derived from different T-PODs (green triangles = V3, blue diamonds = V5). Note the log-scale on the y-axis.

Table 5: Statistics of encounters and waiting times monitored in the baseline and operation periods at Offshore Wind Park Egmond aan Zee.

Period	Area	Position	Encounter duration (minutes) N	Min	Median	Mean	Max	Waiting time (minutes) N	Min	Median	Mean	Max
Baseline	Control N	AT1	496	1	1	4.1	45	492	11	101	420	8510
		AT2	242	1	1	4.5	97	241	11	354	972	19290
	Impact	AT3	116	1	1	1.7	19	115	11	794	1534	13212
		AT4	750	1	1	3.8	91	746	11	146	557	14968
		AT5	312	1	1	5.2	108	310	11	156	678	14635
	Control S	AT6	879	1	1	3.9	88	876	11	152	446	14132
		AT7	408	1	1	3.2	44	406	11	238	793	12258
		AT8	403	1	1	2.6	20	401	11	299	853	22068
Operation	Control N	AT1	1416	1	1	6.0	264	1404	11	100	285	6057
		AT2	2686	1	1	5.9	166	2676	11	80	243	6946
	Impact	AT3	1845	1	1	6.6	193	1834	11	84	329	16105
		AT4	3496	1	3	7.9	329	3487	11	55	176	10597
		AT5	4274	1	3	7.6	332	4264	11	49	155	19148
	Control S	AT6	1624	1	1	6.3	299	1615	11	76	294	13058
		AT7	1301	1	1	3.9	72	1292	11	136	333	5281
		AT8	1933	1	1	3.8	142	1928	11	133	409	15812

3.2.1.1 Seasonal variation

There was a distinctive seasonal pattern for PPM in both the baseline period and operation period, but there appeared to be no seasonal pattern for clicks per PPM (Figure 14). Clicks per PPM was on average 28% higher during operation than during the baseline period, whereas PPM was almost 4 times higher during operation. This increase could be due to the same reasons as mention in the previous section. Spatial differences were also apparent from the observations (Figure 12, Table 4), but due to seasonal variation combined with differences in the months covered by the monitoring and the employment of two different T-POD version during the operation period the statistics, given in Table 4, cannot be compared without resolving all the different sources of variation. These different sources of variation will be partitioned out in the statistical analysis of the daily indicator observations.

The baseline and operation periods had similar and distinctive seasonal patterns for encounter duration and waiting times (Figure 15). Encounters were shorter and waiting times longer in the summer months, whereas in winter, encounters were longer and waiting times shorter. This seasonal pattern corresponds to the observed pattern for PPM (Figure 14).

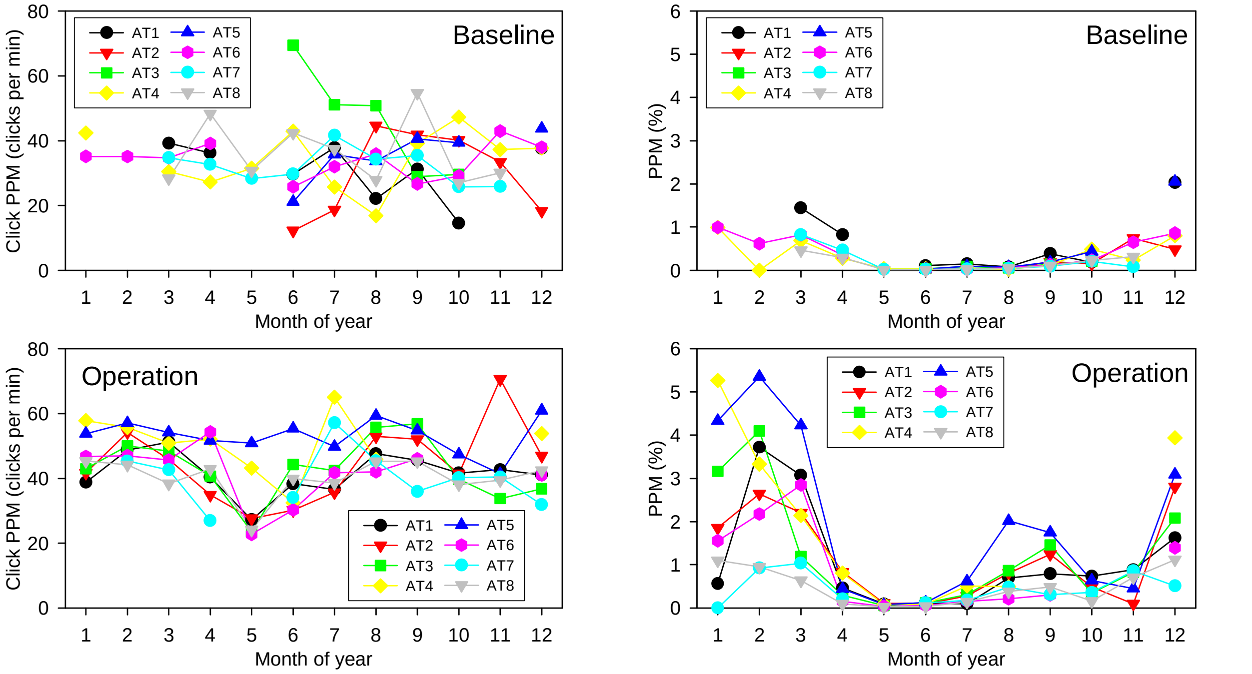


Figure 14: Monthly averages of Click PPM (left panel) and PPM (right panel) for the 8 stations during baseline and operation periods. The two stations in the impact area (AT4 and AT5) are red coloured, whereas area Control N and Control S are dark and light green, respectively.

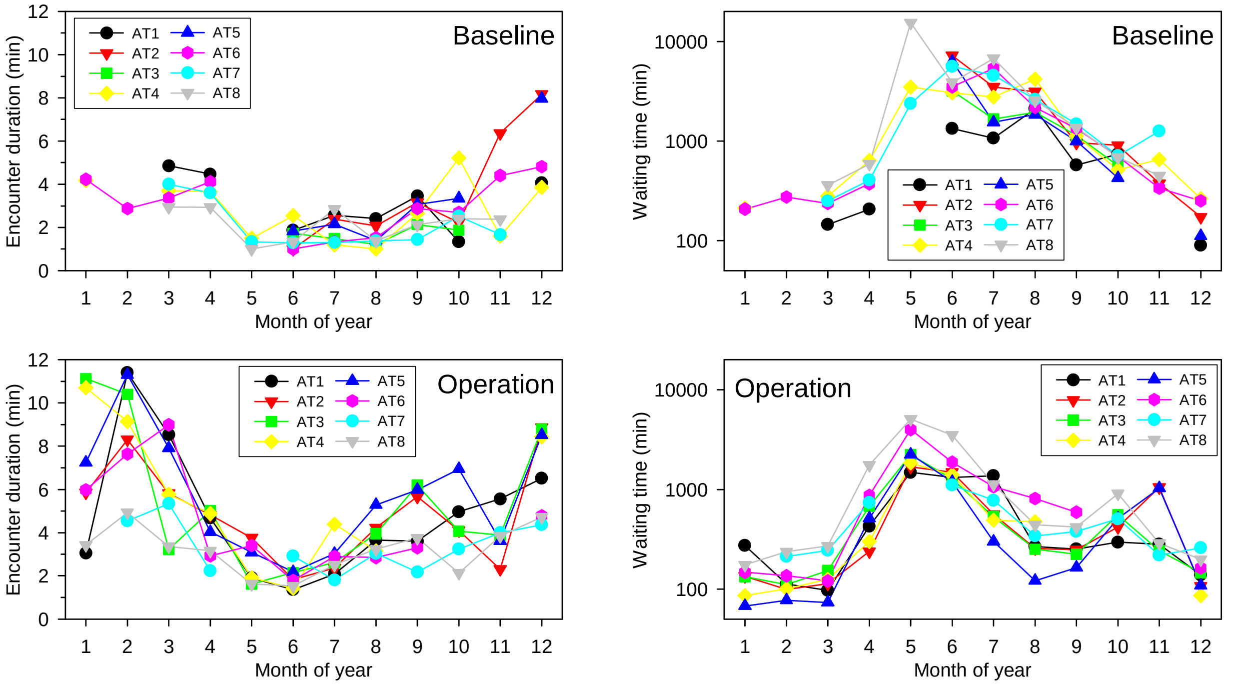


Figure 15: Monthly averages of encounter duration (left panel) and waiting time (right panel) for the 8 stations during baseline and operation periods. The two stations in the impact area (AT4 and AT5) are red coloured, whereas area Control N and Control S are dark and light green, respectively.

3.2.2 Differences across stations

Figure 16 shows the station-specific means for the four variables, separated into T_0 and T_1. Common to all stations is an increase in acoustic activity from T_0 to T_1, seen as an increase in mean PPM, clicks per PPM and encounter duration and a decrease in waiting time between encounters. Two other general effects are obvious. First, the increase in acoustic activity in the wind farm area (AT4 and AT5) appears greater than that in the control areas (AT1-AT3 and AT6-AT8). Secondly, the apparent east-west gradient in activity during T_0, with most activity at the off-shore stations (AT1 and AT6), is absent during the T_1.

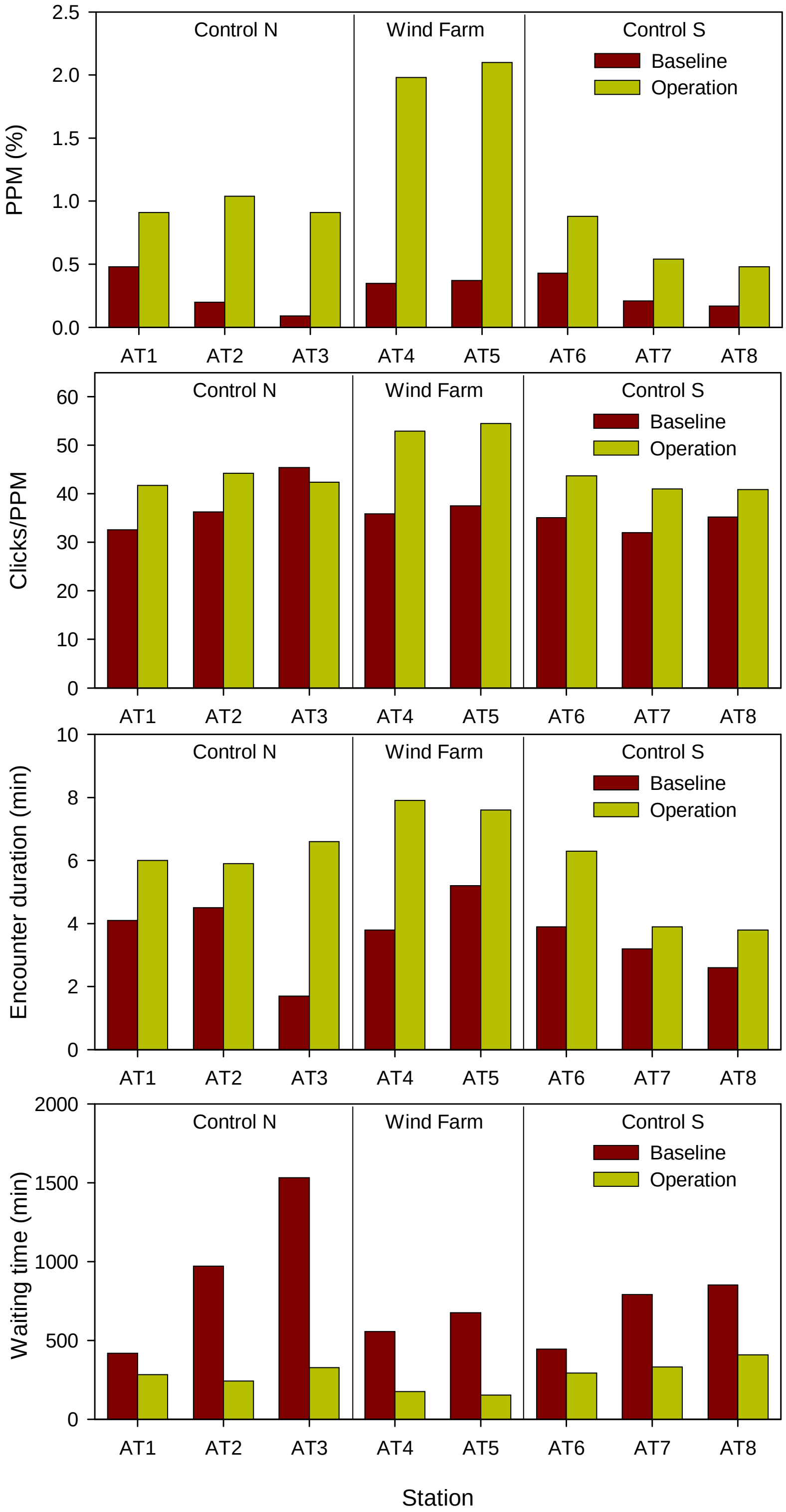


Figure 16. Station-specific averages of the four indicators. Stations within each area are ranked from west to east. PPM – Porpoise positive minutes per day; Click PPM – Click per porpoise positive minute per day

3.2.3 Intercalibration V3 vs. V5

On five positions (AT1, AT3, AT4, AT7 and AT8) two T-PODs of different types were deployed simultaneously for periods during T_1. The two different types of T-PODs (V3 and V5) could thus be intercalibrated by comparing their daily indicators. One click PPM observation (499 clicks/min) obtained with a V3 T-POD was obviously extremely high (cf. Figure 12) and much higher than what was obtained with the concurrent V5 T-POD (20.6 clicks/min). Similarly, during 3 days within a week (December 2007 at AT8) high PPM was recorded with the V3 T-POD (>2.5%) and more moderate PPM (~0.5%), similar to the overall level for the period as a whole, were recorded with the V5 T-POD. These observations were considered outliers and excluded from the regression analysis.

Combining the clicks per PPM and PPM indicators by their days of monitoring for the 5 positions with two T-PODs deployed 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 suggesting that V3 and V5 recorded the same echolocation activity (Figure 20).

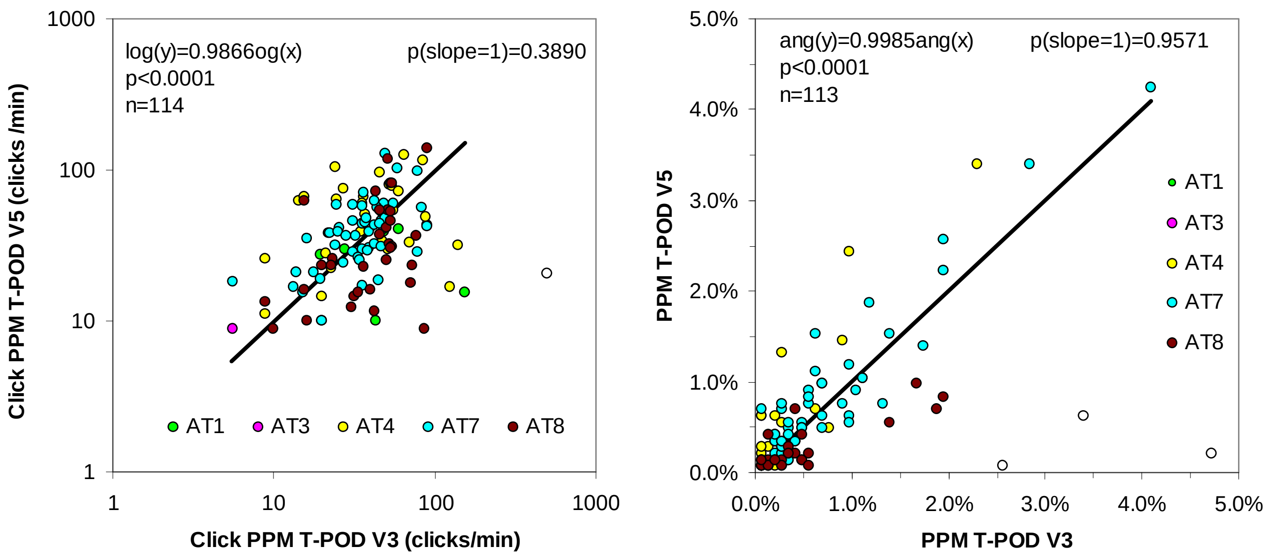


Figure 17: Intercalibration of V3 and V5 T-PODs by means of the daily indicators, clicks per PPM and PPM. Regressions were carried out on transformed variables (logarithmic transformation for Click PPM and angular transformation for PPM) but are shown using the back-transformations. One observation of clicks per PPM and three observations of PPM were excluded from the regressions as outliers (shown by open symbols).

3.2.4 BACI analyses (effect of wind farm)

The model for spatial-temporal variation as well as T-POD specific variation (Eq. 1) and an ARMA(1,1) correlation structure was computed for the 4 indicators. Only 6 out of the 12 fixed effects in Eq. (1) could significantly explain variation in the echolocation indicators (Table 6). For none of the four indicators the T-POD specific variation was found significant, neither as a systematic bias between V3 and V5 nor 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 (Section 3.2.3). In other words, the differences found from T_0 to T_1 are not caused by the change from V3 to V5 T-PODs (see also further discussion below).

Two random factors were consistently significant for all four indicators: *month×year(period)* describes changes in the seasonal pattern between years for the two periods and *station×month×year(area subarea period)* describes that this random season pattern varies significantly also at the station level. In addition, the random factor *station×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 click 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.

Table 6: Significance testing of fixed effects in Eq. (1) for the four indicators after removing non-significant fixed and random effects.

Fixed effects	Click PPM			PPM		
	DFs	F	P	DFs	F	P
area	1, 138.6	22.0	<0.0001			n.s.[1)]
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
Fixed effects	**Encounter duration**			**Waiting time**		
	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.

1) Results for non-significant tests not included.

For clicks per PPM there was a significant difference between the reference area (36.7 clicks/min) and the impact area (43.0 clicks/min), but there was 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 so was the difference between Control N (0.50%) and Control S (0.20%). 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) 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.

All four indicators also showed a significant increase in echolocation activity from baseline to operation period: clicks per PPM increased from 33.8 clicks/min to 46.7 clicks/min, PPM more than tripled from 0.22% to 0.68%, encounter duration increased from 3.4 minutes to 4.5 minutes, and waiting times decreased from 13.7 hours to 6.7 hours. However, the significance of *area*×*period* suggested that echolocation activity in the impact area increased more than in the reference area (Figure 18). Echolocation activity was similar in the two areas during the baseline, 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 times.

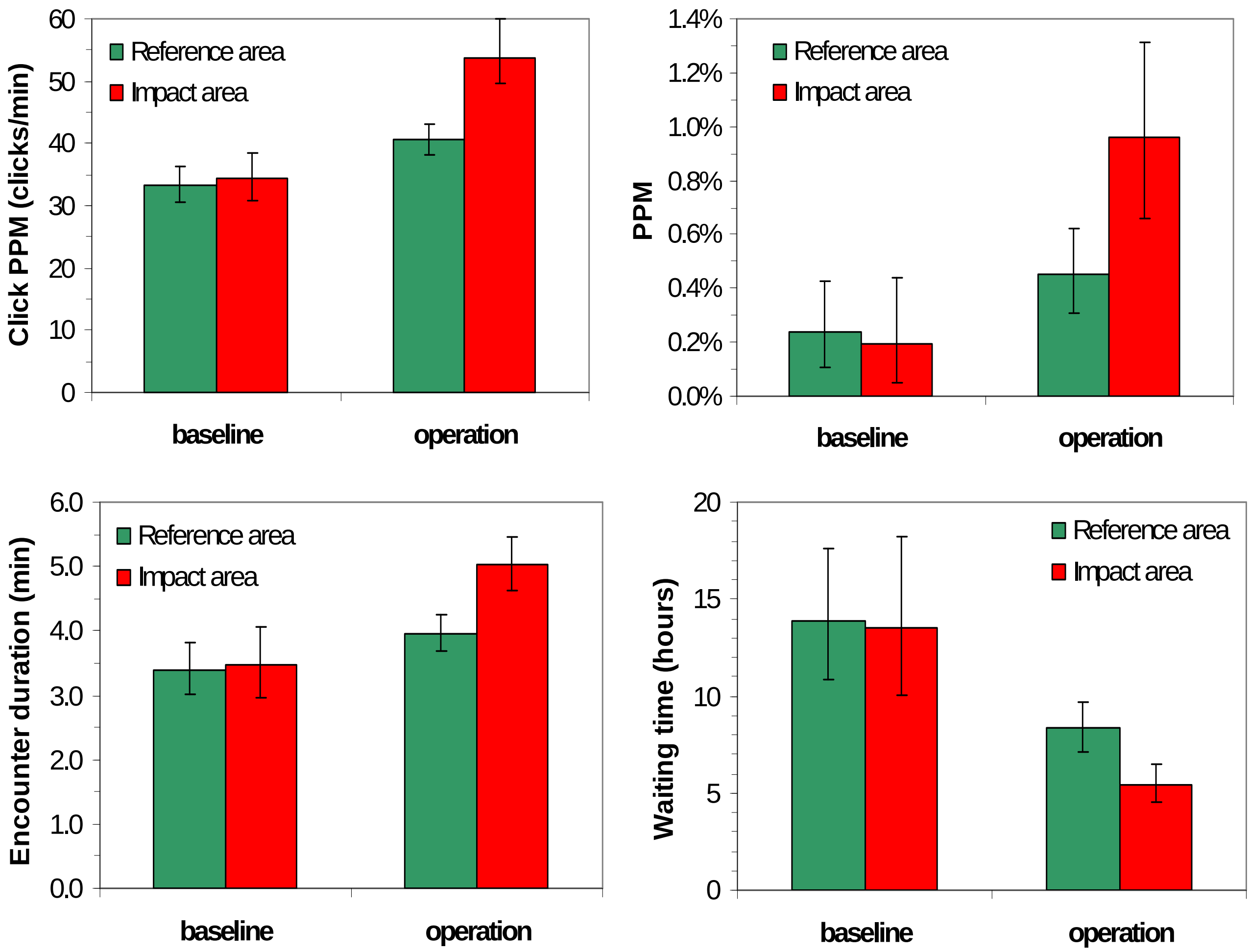


Figure 18: Mean values for combinations of T-POD data within reference and impact areas and period back-transformed to the original scale for comparisons of the two areas and the two periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in sub-areas (Control N and S) and months have been accounted for by calculating marginal means.

All four indicators were characterized by a significant seasonal variation that was common to both the reference and impact area, except for PPM (Table 6). Echolocation activity was generally high during the winter months and low during the summer months (*Figure 19*). Mean clicks per PPM varied from 28 clicks/min in May to 46 clicks/min 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 recording 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 minutes in May to 5.6 minutes in January. Waiting times had the reverse pattern with the shortest 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.

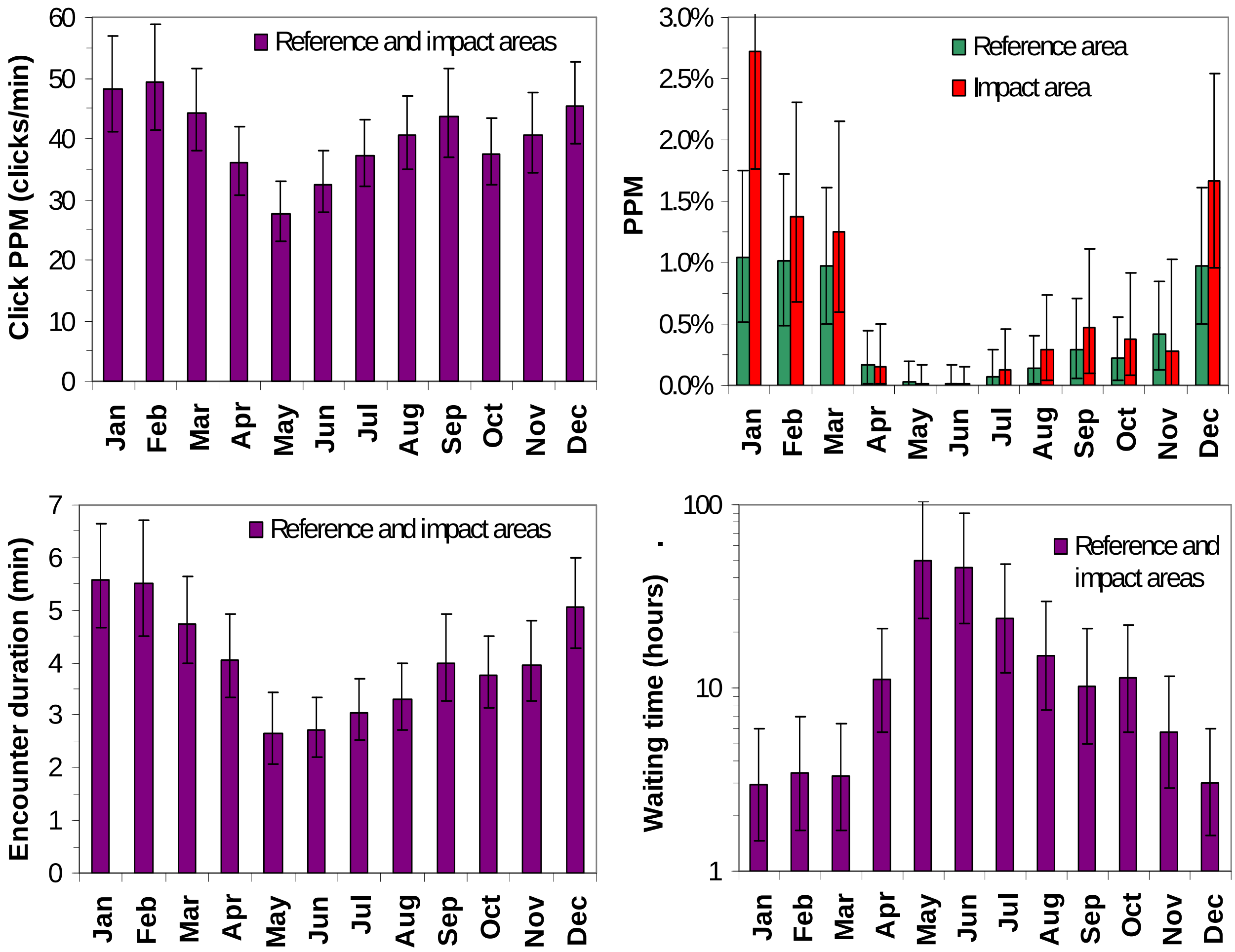


Figure 19: Monthly means for the four indicators after back-transformation. Error bars show 95% confidence limits of the mean values. Variations caused by differences in area, sub-area and period have been accounted for by calculating marginal means. Only PPM showed significantly different seasonal variation in the two areas and are thus plotted separately.

3.2.5 Intercalibration V3 vs. V5

On five positions (AT1, AT3, AT4, AT7 and AT8) two T-PODs of different types were deployed simultaneously for periods during T_1. The two different types of T-PODs (V3 and

V5) could thus be intercalibrated by comparing their daily indicators. The indicators derived from different types of T-PODs at the same station were related by means of least squares regression to investigate if the two types of T-PODs produced comparable echolocation activity. As the T-PODs in some cases were started at different times and in all cases ended logging at different times of the day, only indicators from days with a complete dataset (24 hours) were included. This test is stronger than the test employed in the BACI model (Eq. 1), because the daily indicators from the two different T-POD types are paired such that short-term temporal variation (day-to-day variation) is accounted for.

Combining the Clicks per PPM and PPM indicators by their days of monitoring for the 5 positions with two T-PODs deployed 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 (Figure 20).

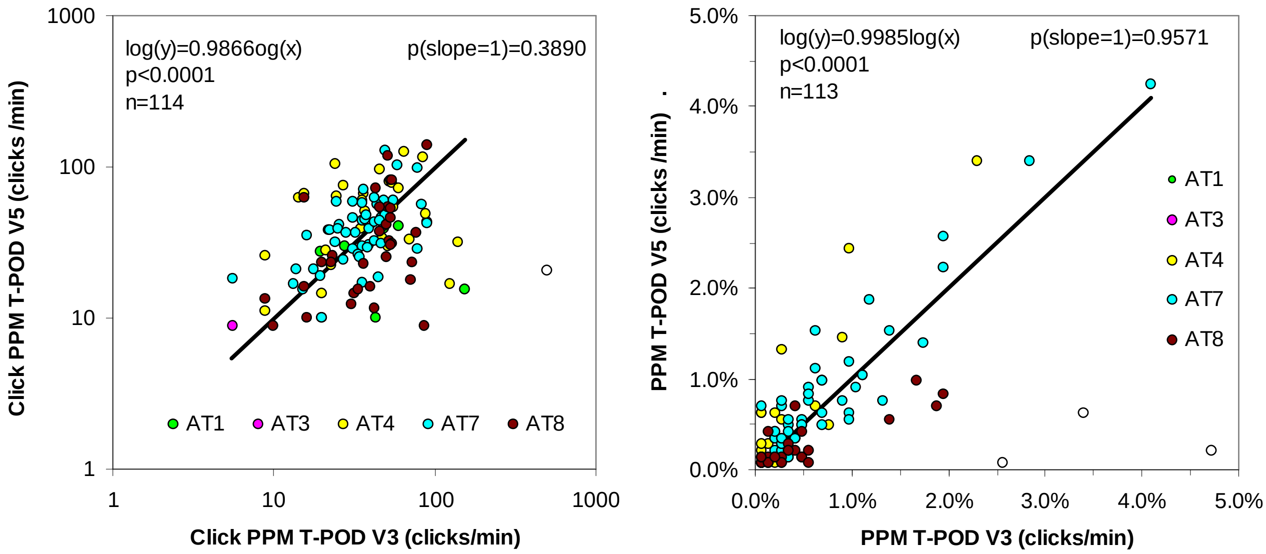


Figure 20: Intercalibration of V3 and V5 T-PODs by means of the daily indicators, clicks per PPM and PPM. Regressions were carried out on transformed variables (see Materials and methods) but are shown using the back-transformations. One observation of clicks per PPM and three observations of PPM were excluded from the regressions as outliers (shown by open symbols).

3.3 Ship based surveys

In total eight surveys were conducted during the T_0 phase and 12 during the T_1 phase. Table 6 gives an overview of all dates on which surveys were conducted. The average density of porpoises (animals per km², not corrected for animals missed on or away from the trackline) was calculated for each survey and plotted in figure 20 for the survey month. Both the period 2002 to 2004 and 2007 to 2009 show a seasonal pattern of porpoise density in the study area with highest densities in the winter months. Sighting rate within the perimeter of OWEZ were too rare to make a useful impact-control comparison.

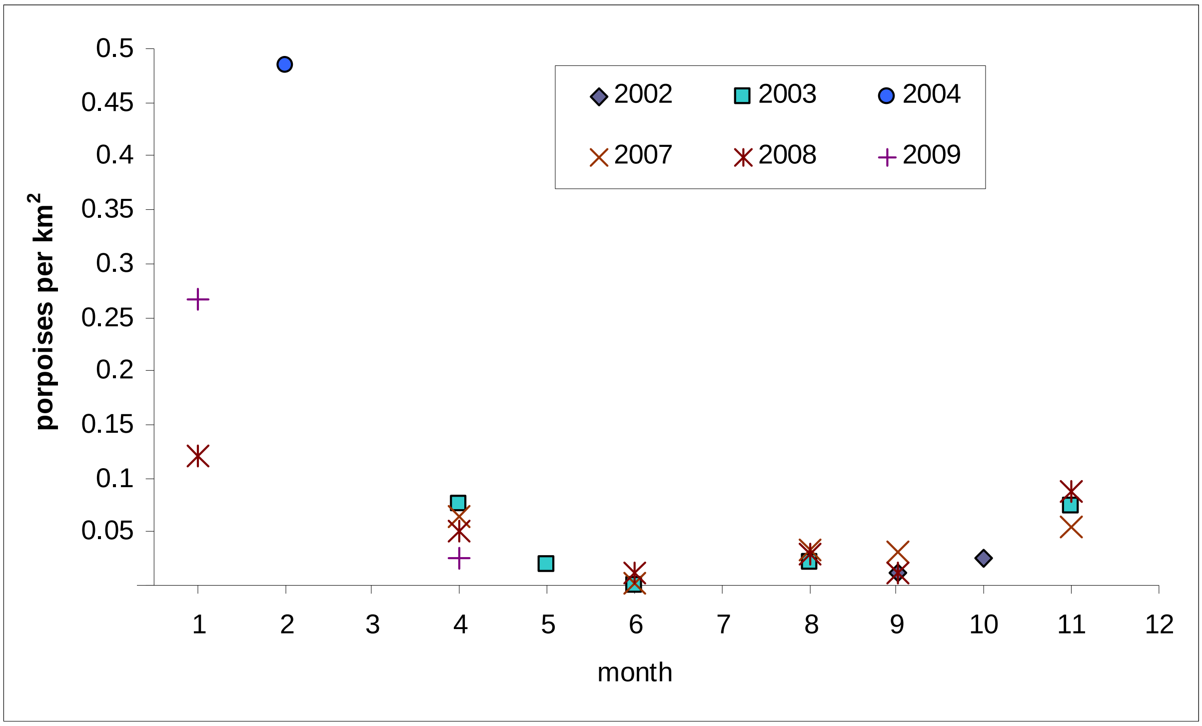


Figure 21. Mean harbour porpoise density (animals per km², not corrected for animals missed by the observers) estimated from the visual boat surveys. Densities are averaged for a week's survey effort per symbol, combining all sightings in a survey area of approximately 900 km², around and including the OWEZ site (Leopold et al. 2004).

4 Discussion

The data collected before and after construction of the Offshore Wind Park Egmond aan Zee constitutes a large and well balanced dataset for evaluation of the effects of the wind farm on harbour porpoises. The statistical analysis of the results included 8 explanatory variables and a number of interactions among these variables. Conclusions based on the results are divided into those relating to 1) methodological considerations, 2) changes in occurrence between years and months as well as 3) the effects of the wind farm.

4.1 Methodological considerations

The OWEZ site is located 8 – 18 km off the coast. Because of the expected exposure to strong currents and conflict with potential fishing operations the anchoring system of the T-PODs was carefully considered. Unfortunately, even with heavy weights and large buoys some T-PODs were temporarily lost and as a consequence data loss occurred. Even so large amounts of continuous data over long time periods were collected.

The analyses showed that changing T-POD type from v3 to v5 had no affect on the results and thus, both versions could be used interchangeably. Similarly the differences between individual T-PODs (POD-ID) was not significant in the model.

4.2 Porpoise occurrence

The results of T-POD monitoring demonstrated a substantial general increase in acoustic activity from T_0 to T_1 (significant factor *period*). The higher occurrence in the study area 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, SCANS II 2008). For Dutch waters, some quantitative information on coastal abundance is provided by the systematic "seawatching" counts carried out by the Dutch Seabird Group. Although initiated for birds, data on presence of marine mammals has also been collected since its establishment in 1972. It is clear from the data that the number of harbour porpoises observed has increased dramatically since the mid 1990s. The reasons for the increase remain unclear. Possible explanations include changes in prey availability in the southern North Sea (Camphuysen 2004).

4.3 Seasonality

The T-POD results show a strong and significant seasonal pattern in porpoise echolocation activity for all four indicators. Most acoustic detections are recorded in the winter months (December to March) and very few during early summer (almost no detections in May and June). A similar pattern was observed throughout the boat survey by Leopold et al. (2004, 2009). Camphuysen (2004) described a seasonal pattern of harbour porpoise occurrence along the Dutch coast with most animals observed between February and April. The seasonal trend is in general the same between the baseline and impact study period. This pattern differs from areas further north such as the German Bight and at Horns Reef, where the highest densities are observed in the summer months (Siebert et al. 2006, Tougaard et al. 2006b).

4.4 Effect of construction

Monitoring was not undertaken during construction of the wind farm and it is thus not possible to comment on the effects on porpoises during this period. However, from other studies of offshore wind farms, in particular the construction of Horns Rev 1 and Horns Rev 2 (Horns Reef) it is evident that construction activities can have a negative effect on the presence of porpoises. In particular 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 hours after the installation of each monopile (Tougaard et al. 2009, Brandt et al. 2009). As monopile size and installation procedure used in OWEZ is comparable to the wind farms at Horns Reef it would be expected that harbour porpoises would be affected in a similar way during monopile installations in OWEZ. The present data (T_1) show that the effect *year(period)* was not significant and no difference could be seen between the three monitoring years (2007 to 2009). This implies that either there was little construction effect on harbour porpoise distribution (which is unlikely considering the data from Horns Rev), or that recovery after construction took place fairly quickly thereafter.

Of interest is the construction of Prinses Amalia Wind Park. That wind farm consists of 60 wind turbines on monopile foundations, just like in OWEZ. The construction of the wind farm occurred between October 2006 and April 2008. Given the close vicinity of the wind farm to OWEZ (approx. 9 km), it is likely that harbour porpoises recorded in OWEZ during that time frame were negatively affected by the construction of the wind farm. A more detailed analysis of this possible effect was beyond the scope of this study.

4.5 Effect of operation on presence of harbour porpoises

The BACI analysis demonstrated a positive effect of the wind farm on porpoise acoustic activity (factor *area×period*), or expressed more clearly: there was more acoustic activity in the wind farm area after the establishment of the wind farm, even when taking into account that there was a significant general increase in acoustic activity at all stations from the baseline period to the operational period (see below). Thus, if higher acoustic activity is interpreted as higher abundance of porpoises, then relatively more porpoises are found in the wind farm area compared to the two reference areas. Such close correlation between abundance and acoustic activity, as monitored by static acoustic monitoring, remains to be established. However, studies where acoustic activity of free-swimming porpoises in the wild were equipped with acoustic dataloggers demonstrates that porpoises are vocalising almost constantly (Akamatsu et al. 2005, 2007). These data showed that porpoises rarely remained silent for more than one minute at a time, meaning that even though animals may be more vocal during certain behaviours (such as foraging) than others, these differences are expected to have little influence on the statistics porpoise positive minutes (PPM), encounter duration and inter-encounter waiting time.

The fact that no significant differential 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 seasonality pattern within the wind farm area.

The local change in habitat use with an increase in porpoises in the wind park relative to adjacent areas indicates that there is a reason for animals to change their distribution locally. Conceivable reasons for the observed increase in porpoise occurrence could be an avoidance of disturbance that is occurring outside the wind park (e.g. increased shipping) or an attraction to the characteristics of the park (e.g. more fish). The most likely reason for an increased occurrence of porpoises is that the wind park provides an increase in prey occurrence. It can be hypothesized that exclusion of fishery from the wind farm area and the introduction of hard substrate to the otherwise homogeneous sand bottom will increase both biodiversity and biomass. It is well known that such hard substrates will attract sessile organisms that in turn attract fish and invertebrate species otherwise not commonly found on sandy bottoms (Petersen & Malm 2006, Leonhard & Pedersen 2006), some of which may provide a beneficial addition to the food resources available to porpoises.

As the two T-POD stations were located close to the eastern and western edges of the wind farm, respectively, one could raise concern that the increase observed is not due to more animals *inside* the wind farm, but rather caused by animals outside the wind farm. Such edge-effects have been discussed example migrating birds (e.g. Bruderer and Liechti 1998, van Dobben 1953, Meyer et al. 2000). The higher acoustic activity recorded by the T-PODs inside the wind farm would then be due to recordings of higher than normal concentrations of porpoises moving up and down along the outer edges of the wind farm and thus be indicative of an *avoidance* of the turbines. However, this scenario is unlikely, given that the T-PODs have maximal detection ranges of 3-500 m and drastically reduced detection probabilities beyond 100-150 m (Tougaard, 2008). As the T-PODs are locate more than 150 m inside the wind farm, the absence of detections near the T-POD (where detection probability is high) should be counterbalanced by an increased abundance of porpoises at the very edge of the detection range of the T-POD, and only along a fraction of the perimeter of the area of detection (the part that reaches outside the wind farm). This would require unrealistically high numbers of porpoises to be present immediately outside the wind farm. Thus, because of the low spatial resolution of the T-PODs, it is very unlikely that the increased acoustic activity recorded inside the wind farm can be explained by even a very steep gradient in porpoise abundance perpendicular to the edge of the wind farm.

The finding that harbour porpoises may be attracted to the wind farm is in contrast to findings from other wind farm studies of comparable size (both regarding turbine numbers and size). In the Danish offshore wind farm Nysted, located in the Western Baltic close to the Darss-sill usually defining the border to the Baltic Proper, a strong negative effect of construction was observed on abundance 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 was still reduced 2 years after construction within the wind farm, 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. However, it is important to note that there are many differences between the general ecology of the two locations where Nysted wind farm and OWEZ are located. OWEZ 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, whereas Nysted is located in near-brackish waters with lower biodiversity and lower overall density of harbour porpoises. There is also a difference in the wind park construction itself with Nysted wind mills consisting of concrete caisson foundations and Horns Rev and OWEZ of monopole foundations. It is thus not immediately evident whether the different effect 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 whether general ecological differences between the two areas causes harbour porpoises to respond differently to the presence of a wind farm.

At the second Danish offshore wind farm "Horns Rev 1", located on Horns Reef at the northern border of the German Bight, also a pronounced effect of construction was seen 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 Reef area is more similar to the OWEZ, than to the Nysted area, with sandy bottom, is in the open North Sea and is dominated by riverine frontal systems. However, Horns Reef is hydrographically much more complex than OWEZ due to the presence of the long shallow reef which acts as a strong damping barrier to the tidal current. Thus, as with the Nysted Offshore Wind Farm, it is not immediately evident whether the different effects of the wind farms (no effect at Horns Rev, positive effect at Egmond aan Zee) are due to differences between the areas or the wind farms. This conclusion is of great importance in planning future wind farms as it stresses the point that results from one wind farm are not necessarily transferable or valid for another wind farms located in a different area.

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Appendix 1

Overview of deployment of T-PODs

Position	Depth (m)	3-4/06/03	26/08/03	02/12/03		04/03/04		25-26/05/04
		Dep	Serviced	Rec?	Dep	Rec?	Dep	Final Rec
AT1 (CTD 488)	20	238	238	238			238	238
AT2	21	239	239	239			@	NA
AT3	17	233	233	^	233	233		233
AT4	18	240	240	240		240		240
AT5 (CTD 489)	18	234	234	234		234		234
AT6	20	230	230	230		230		230
AT7	19	231	231	*			276	276
AT8	18	232	232	#			232	232

^ TPOD found on Dutch coast on 11/10/03.
* TPOD found at Hondsboschse zeeweering on 20/11/03.
# missing, but TPOD found on 10/12/03.
@ TPOD found on Texel on 08/01/04.

Position	17/04/07	21/06/07		02/10/07		13/12/07		13/02/08		09/04/08	
	Dep	Rec	Dep	Rec	Dep	Rec	Dep	Rec	Dep	Rec	Dep
AT1	701	701	701+238	701+238	238	238	701	701	238	238	701
AT2	707*	707	707+730	#	707+730	#	730	730	707	707	730
AT3	700	700	700+233	700+233	233	233	700	700	233	233	700
AT4	702	702	702+240	702+240	240	#	702	702	702+736	702+736	702
AT5	706	706	234	#	706	706	706+749	706+749	706	706	749
AT6	705	705	705+230	705+230	230	230	705+230	705+230	705	705	705
AT7	704	704	276	276	704+276	704+276	276	276	704	704	276
AT8	703	703	232	232	232+703	#	703	703	703	703	703

* TPOD not functioning on 17/4/07 therefore deployed in May
# found to be missing

Position	05/06/08		07/08/08		09/10/08		03/12/08		16/12/08		19/02/09		14/04/09	15/04/09	16/04/09
	Rec	Dep	Rec	Dep	Rec	Dep	Rec	Dep	Rec	Dep	Rec	Dep	Final Rec	Final Rec	Final Rec
AT1	701	238	238	701	701	238	238	^	NA	238	238	238	238	-	-
AT2	730	707	707	730	730	707	^	^	#	730	730	730	730	-	-
AT3	700	233	233	700	700	233	^	^	233	70	700	233	233	-	-
AT4	702	736	736	702	702	700	#	702	NA	NA	702	736	-	736	-
AT5	749	706	706	749	749	706	#	749	NA	NA	749	706	-	706	-
AT6	705	705	705	705	705	705	705	705	NA	NA	705	705	-	-	705
AT7	276	704	704	276	276	276	276	704	NA	NA	704	276	-	-	276
AT8	703	703	703	703	703	703	703	703	NA	NA	703	703	-	-	703

found to be missing
^ not deployed/recovered due to weather conditions
NA not applicable due to already having been recovered and deployed on the 3/12/08
- final recovery took three days (14^{th}-16^{th} of April 09)

TPOD	History
238	lost after 10/12/03, found 08/01/04
239	lost after 02/12/03
233	found on Dutch coast 11/10/03 sent for repairs
240	lost after 2/10/07
234	lost after 21/06/07
230	no longer used after 13/02/08 due to crack on the outside (water and mud found inside - memory chip okay, but TPOD could not be repaired)
231	found on Hodsboschse zeeweering, damaged and sent for repair. Not used here after
276	all good
232	lost after 26/08/03, found on texel stripped but working, Sent for repair, deployed at next opportunity. Lost after 2/10/07
701	communication error after 9/10/08 therefore no longer used
707	lost after 21/6/07 and recovered before 2/10/07, missing after 9/10/08
700	all good
730	lost after 21/6/07 and recovered before 2/10/07, lost after 2/10/07 and recovered before 13/12/07
702	all good
706	lost after 9/10/06 and recovered in November in Scheveningen
70	all good
704	all good
703	lost after 2/10/07 and recovered before 13/12/07
749	all good