Harbour porpoise presence in the Dutch Borssele windfarms

Mid-Term report – March 2024

Client:
Rijkswaterstaat Water, Verkeer en Leefomgeving

Date:
22/04/2024

Clients Reference:
31167838

Our Reference:
WP1267_R5r1

Version:
Final

WATER PROOF Marine Consultancy & Services BV.

WAGENINGEN UNIVERSITY & RESEARCH

Title

Bruinvis Netwerk Borssele – Mid-Term report – March 2024

Client

Wozep, Rijkswaterstaat Water, Verkeer en Leefomgeving

Reference

31167838

Keywords

As built report, measurement stations Borssele, Noise Monitoring, PAM Monitoring, Harbour Porpoise, habitat, Borssele, Offshore Windfarm, OWF, North Sea.

Version	Date	Author	Review & Approval
R5r0 Draft	07/03/2024	M. Olivierse (WP) J.M. Ransijn (WMR) P.M. van Tol (WP) S.C.V Geelhoed (WMR) J.A. Brinkkemper (WP)	
R5r1	22/04/2024	M. Olivierse (WP) J.M. Ransijn (WMR) P.M. van Tol (WP) S.C.V Geelhoed (WMR) J.A. Brinkkemper (WP)	G van der Want (WP)

This study is financed by Rijkswaterstaat as part of WOZEP.

DUTCH GOVERNMENTAL OFFSHORE WIND ECOLOGICAL PROGRAMME

TABLE OF CONTENTS

1 SUMMARY

The swift expansion of offshore wind energy development in European waters has sparked concerns regarding their potential environmental impacts. We studied harbour porpoise (*Phocoena phocoena*) presence during the operational phase of Borssele wind farms located in the southern part of the Dutch EEZ. The passive acoustic monitoring network consists of cetacean click detectors at 14 locations in and outside the windfarms, co-located with broadband hydrophones at 4 locations.

Preliminary results indicate that ambient sound levels inside the windfarms are dominated by low-frequency sound emitted by the turbines, while ambient sound levels outside the windfarm are higher and deemed typical for an environment close to a shipping lane. Seasonality in harbour porpoise acoustic activity was observed, with higher detections with decaying sea surface temperature. This corresponds with previous studies at Dutch offshore wind farms and patterns in coastal sightings, aerial surveys, and strandings (i.e. higher porpoise density in winter and early spring). Porpoise acoustic activity increased during the night and around slack tide, possibly related with enhanced foraging opportunities.

Preliminary results also show a small but significant higher harbour porpoise acoustic activity near the monitoring stations inside the windfarm. The data that is collected in the next two years is expected to provide more insight, and reveal possible trends, of porpoise presence inside and outside the windfarm.

The monitoring network enables studying the soundscape in and around an offshore windfarm within a part of the North Sea with the highest shipping density, and the impact of an offshore windfarm on the presence and activity of harbour porpoises.

2 INTRODUCTION

2.1 Background

The Dutch government has set ambitious targets for the development of offshore wind energy, with a planned capacity of 21GW of offshore wind farms by 2030. The development of these various offshore wind farms has an impact on the marine ecosystem, which is being closely monitored by the Dutch government.

In 2016, the Ministry of Economic Affairs and Climate (EZK) commissioned Rijkswaterstaat (RWS) to carry out an integrated research program to reduce the knowledge gaps regarding the effects of offshore wind farms on the North Sea ecosystem. This *Wind op Zee Ecologisch Programma* (WOZEP) runs from 2016 to 2023 and the results of the studies that are carried out are used in the Ecology and Cumulation Framework (KEC) in which the cumulative effects of current and planned wind farms on protected species are determined.

The Borssele wind farms were built in 2019 and 2020, consisting of sites I +II and III+IV located on the Southern coast of the Netherlands (see Figure 2-1). Ørsted owns the wind farms of lots I+II and Blauwwind of the wind farms of lots III + IV. Since the summer of 2020, the Borssele wind farms supply electricity to the grid.

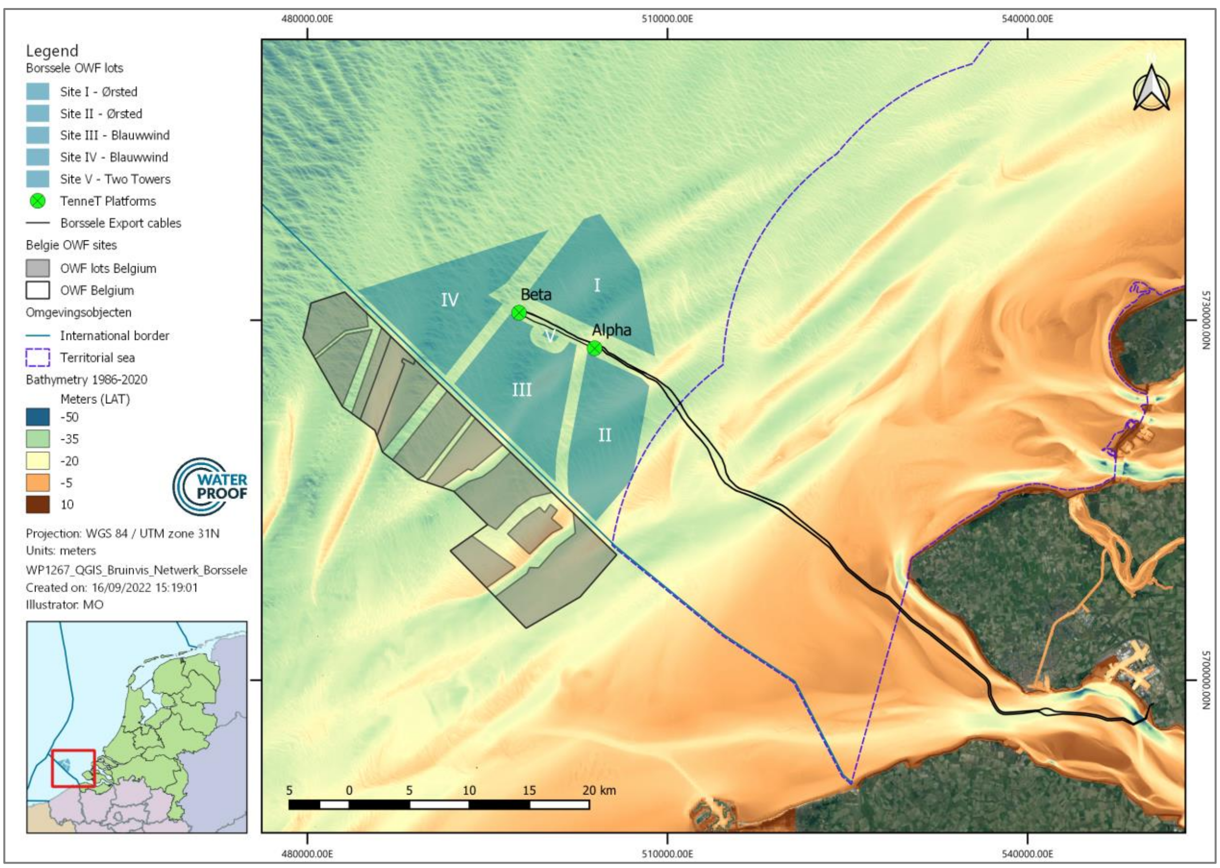


Figure 2-1 OWF Borssele, with lots I+II and lots III+IV installed by Ørsted and Blauwwind.

One of the current knowledge gaps for determining the effects of offshore wind farms on the ecology is the degree of change in habitat use of the wind farm areas by harbour porpoises. This requires insight into the presence and habitat use of harbour porpoises in and around operational wind farms.

2.2 RESEARCH QUESTIONS

In the action plan for the monitoring of harbour porpoises in the Borssele wind farms, the research question has been formulated as:

Do large-scale habitat changes due to the development of offshore wind farms in the North Sea have effects on harbour porpoises?

This question is further specified in seven sub-questions:

1) To what extend do harbour porpoises occur in the area of the Borssele operational wind farms and how does this differ from a reference area (i.e. open sea)?
2) Can any spatio-temporal variations of this occurrence be observed and if so what are these?
3) Can the spatio-temporal variations be linked to (sound produced by) activities within the wind park (like maintenance activity)?
4) Can variations in sound produced by harbour porpoises (like feeding buzzes) be observed and does this variation differ in time and space (within the park, and between the park and the open sea)?
5) Can the spatio-temporal variations in abundance and produced sound by harbour porpoises be explained (for example due to the presence or absence of a food source, due to external disturbance, or life cycle variations, habituation, etc.)?
6) Explain if the operational wind farm site of Borssele is (still?) a suitable (foraging) habitat for the harbour porpoise?
7) Can the results of this Borssele research project be translated to a broader perspective taken into account the foreseen Energy transition on the (Dutch) North Sea)?

3 DATA COLLECTION

In order to answer the research questions from chapter 2.2 data will be collection following two data streams.

Data stream 1 consist of the results from the Harbour Porpoise Network Borssele (Bruinvis Network Borssele) and will form the basis to fulfil the aim formulated above.

In addition (data stream 2), collaboration has been sought with current (research) initiatives that are carried out in the Borssele wind farm and in Belgium and available dataset from these initiatives are gathered. Results from this second data stream are considered as potentially valuable in adding ecological perspective to the findings of this project.

3.1 DATA STREAM 1 - HARBOUR PORPOISE NETWORK BORSSELE

3.1.1 HPNB layout

The aim of the Harbour Porpoise Network Borssele (HPNB) project is to gain insight into the presence and habitat use of harbour porpoises in and around the operational wind farm Borssele by setting up a large-scale PAM network.

The HPNB consists of 14 measuring stations, of which 6 stations are located outside the Borssele wind farm and 8 stations are located within the wind farm (Figure 3-1 and Table 3-1). All of these stations contain instruments to detect acoustic activity of harbour porpoises, four stations contain hydrophones to record ambient sound levels.

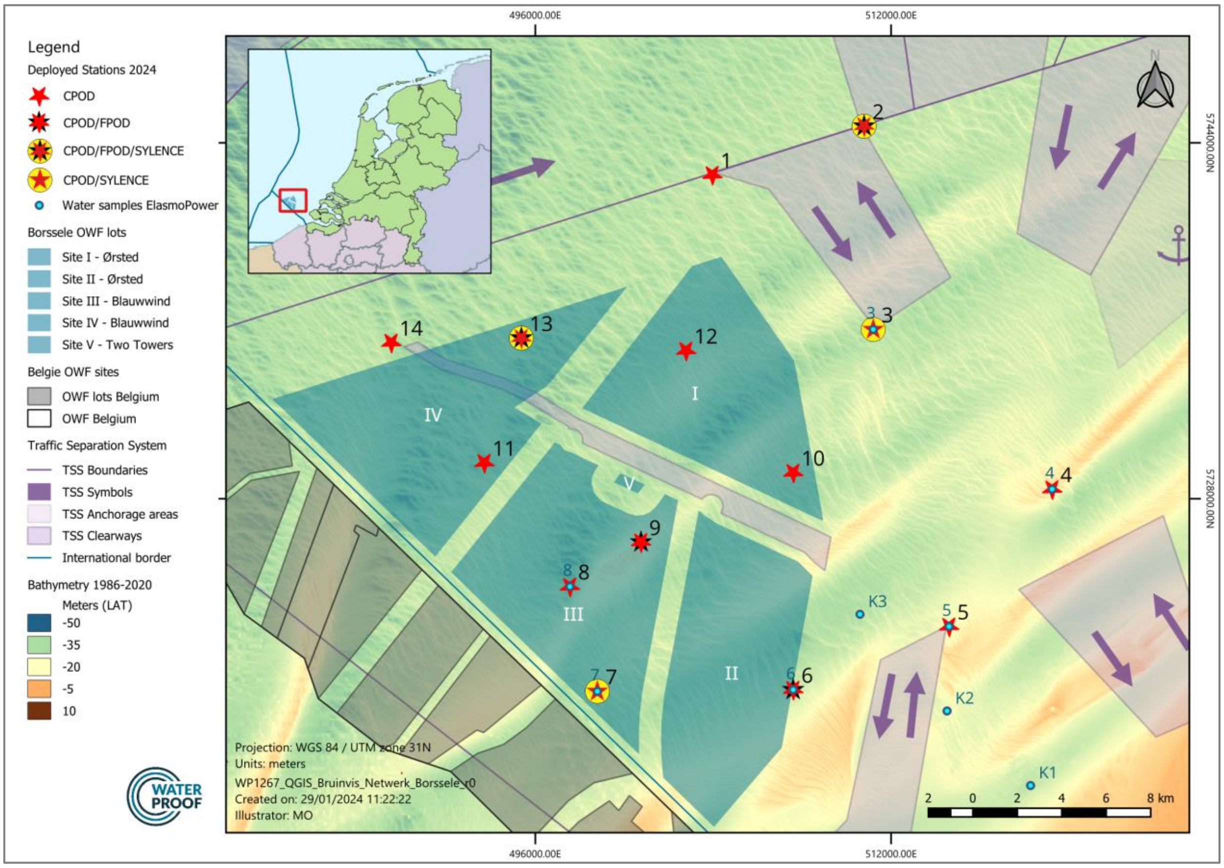


Figure 3-1 PAM station locations with CPODs (red stars), FPODs (black stars) and ambient sound recorders (yellow circles).

Table 3-1 PAM station coordinates in WGS84 UTM 31M.

					WGS84 UTM Zone 31N	
ID	**Instruments**	**Inside/ outside OWF**	**Area manager**	**Combined with existing RWS fairway marking buoy ID**	**X**	**Y**
1	CPOD	Outside	Coastguard	MW 1-SNW 4	503967.4	5742564.6
2	CPOD/FPOD/SYLENCE	Outside	Coastguard	MW 3	510792.1	5744751.2
3	CPOD/SYLENCE	Outside	GNA	SNW 2	511204.0	5735613.6
4	CPOD	Outside	GNA	S B Z	519250.4	5728428.7
5	CPOD	Outside	GNA	WP 5	514614.4	5722256.3
6	CPOD/FPOD	Inside	Ørsted		507600.1	5719411.2
7	CPOD/SYLENCE	Inside	Blauwwind		498792.4	5719340.0
8	CPOD	Inside	Blauwwind		497559.3	5724052.5
9	CPOD/FPOD/SYLENCE	Inside	Blauwwind		500755.6	5726048.9
10	CPOD	Inside	Ørsted		507604.6	5729173.3

					WGS84 UTM Zone 31N	
ID	**Instruments**	**Inside/ outside OWF**	**Area manager**	**Combined with existing RWS fairway marking buoy ID**	**X**	**Y**
11	CPOD	Inside	Blauwwind		493707.6	5729616.0
12	CPOD	Inside	Ørsted		502782.9	5734658.2
13	CPOD/FPOD/SYLENCE	Inside	Blauwwind		495374.5	5735223.4
14	CPOD	Outside	GNA	WFB 1	489524.4	5735018.5

3.1.2 Measurement equipment & setup

The equipment on the measurement stations consisted only of passive acoustic monitoring equipment, which means that these instruments do not emit sound, but only register sound from the environment. Harbour porpoise activity was registered based on the echolocation clicks these animals produce. These clicks were detected and stored using Chelonia CPOD and/or Chelonia FPOD instruments.

Underwater ambient sound levels at stations 2, 3, 7 and 13 were recorded using a recorder-hydrophone combination. The instruments used were an Ocean Instrument SoundTrap ST300-HF and RTsys Sylence recorders with HTI 96-min hydrophones. These recorders recorded ambient sound levels with frequencies between 10 Hz and 20 kHz.

During the first deployment in September 2021, all standard instruments (CPODs and ambient sound recorders) were deployed at the measurement locations and serviced in the subsequent field visits.

In Augustus 2022, 4 Chelonia FPOD's were added to the network to be able to compare the measurements of these instruments with the conventional CPOD instruments. A further description of this data comparison study is provided in Appendix A.

Since Q4 2023 the older Ocean Instruments SoundTraps ST300-HF have been replaced by the newer RTsys SYLENCE-LP recorders.

The instruments were attached to a line between an anchor and subsurface float, this anchor was connected to a surface buoy using an anchor line or chain. The set-up of the measurement stations outside the Borssele wind farm is illustrated in Figure 3-2 and the set-up within the wind farm in Figure 3-3.

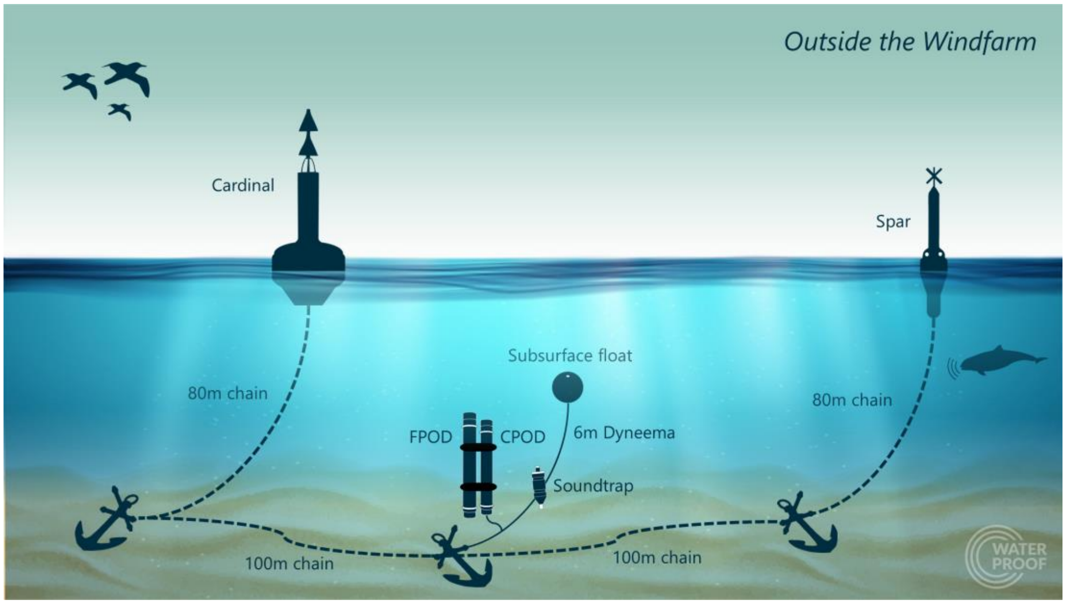


Figure 3-2 Mooring setup measurement stations outside the Borssele windfarm.

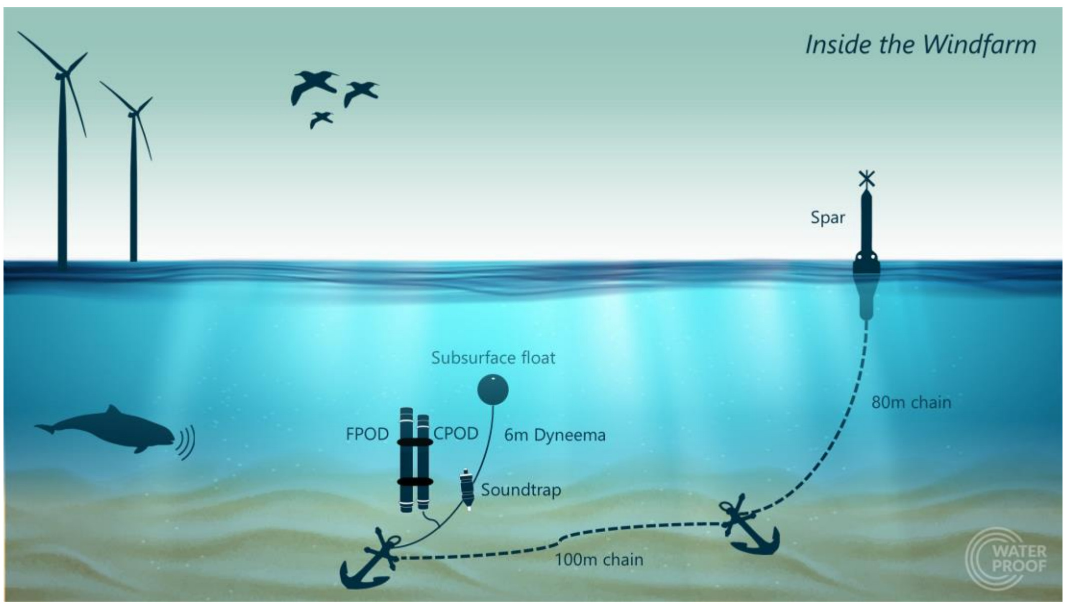


Figure 3-3 Mooring setup measurement stations inside the Borssele windfarm.

3.2 Data stream 2 - Collaboration with other (research) initiatives

To aid the analysis and interpretation of the acoustic monitoring data of harbour porpoises in the operational Borssele wind farms we have identified a few potentially suited data sources:

- PAM research in Belgian waters, future focused on continuous noise (RBINS);

Currently, the PURE WIND JPI Oceans project will "quantify key features of radiated noise from fixed and floating offshore wind farms, to increase understanding and simulate cumulative effect of clusters on radiated noise, helping to identify sensitive habitats in cross-basin soundscapes. From the biological perspective, the project will identify spatial and qualitative use of offshore wind by top predators (seals and harbour porpoise)" The project's study period (2023-2026) overlaps with the Borssele monitoring period., offering possibilities to combine analyses or compare results from the same timeframe.

- PAM network in Belgian waters, including setting up a public data portal (VLIZ);

The data on harbour porpoise activity that is collected within the windfarm Borssele is uploaded to the public data portal of VLIZ.

- PAM network MEP TenneT in relation to EMF's export cable (WaterProof/WMR).

Harbour porpoise presence was studied with a PAM network around the Borssele export cable between the Borssele wind farms and the Dutch mainland by WMR from 1 September 2021 until 21 October 2021 (Geelhoed et al., 2022), whilst simultaneous measurements by WaterProof provided information on EMF and underwater sound (Van der Neut & Brinkkemper, 2022). The acoustic activity of harbour porpoises was analyzed with a hurdle model that showed patterns in relationships between environmental variables and the acoustic activity of harbour porpoises. Taken these relationships into account, no clear relationship between EMF and the probability of acoustic activity of harbour porpoises was found. The results of this study can help in understanding spatial variability in harbour porpoise presence across the Dutch North Sea.

- High-definition aerial shots (Bureau Waardenburg);

Hi-Def aerial surveys are conducted monthly in the Borssele wind farm area by Waardenburg Ecology since February 2021 (Leemans et al., 2023). These data will be used as input for the development of an AI tool to identify and quantify harbour porpoises from the collected images. Although preliminary results show no differences in porpoise densities and distribution inside and outside the Borssele wind farms (Collier et al., 2022), the aerial data might be used to quantify effects of the Borssele wind farms on harbour porpoises. It should be noted, however, that aerial surveys might not be a very suitable method to quantify these, as Haelters et al. (2023) stated. They analysed regular aerial surveys of the Belgian part of the North Sea (BPNS), but could not shed any light on the effect of operational wind farms on the occurrence of harbour porpoises in Belgian waters.

- APELAFICO research, focusing on the effects of OWFs on the fish community (Univ. Leiden);

The APELAFICO research included the short-term deployment of bottom rigs that included both a CPOD and Fish echosounders. These deployments allow for the analyses of harbour porpoise presence in relation to the presence of prey species. The analyses of this study are still ongoing, but potentially provide insights that can be used to link spatial and temporal variability in harbour porpoise activity to prey species in the Borssele windfarm.

4 DATA ANALYSES DATA STREAM 1

4.1 DATA PROCESSING

4.1.1 CPOD data

After replacement of the SD cards, the data for each CPOD was separately downloaded as CP1 file using CPOD.exe (Chelonia ltd). In accordance with the WMR protocol, a quality check was performed. Per file was checked whether four standard times (noted in the field) correspond to the dates and times assigned to the CP1 file: CPOD on, CPOD in water, CPOD out of water, CPOD off. This check revealed a few discrepancies. These are probably due to the recording of local time instead of UTC.

Porpoise clicks were then extracted from the CP1-files and saved in so-called CP3-files using CPOD.exe.

Additionally, CPOD data were used to quantify foraging behaviour, specifically feeding buzzes (Berges et al., 2019).

All CPODs consistently recorded for nearly uninterrupted periods (Figure 4-1), averaging 473.6 deployment days (min = 192, max = 679 days). The duration was primarily constrained by the initial deployment and recovery dates of the CPOD. The completeness of the dataset is between 66% and 100% for the individual locations. The gap in the data that is seen across multiple recorders in the beginning of 2023 is due to a service interval being delayed due to weather conditions.

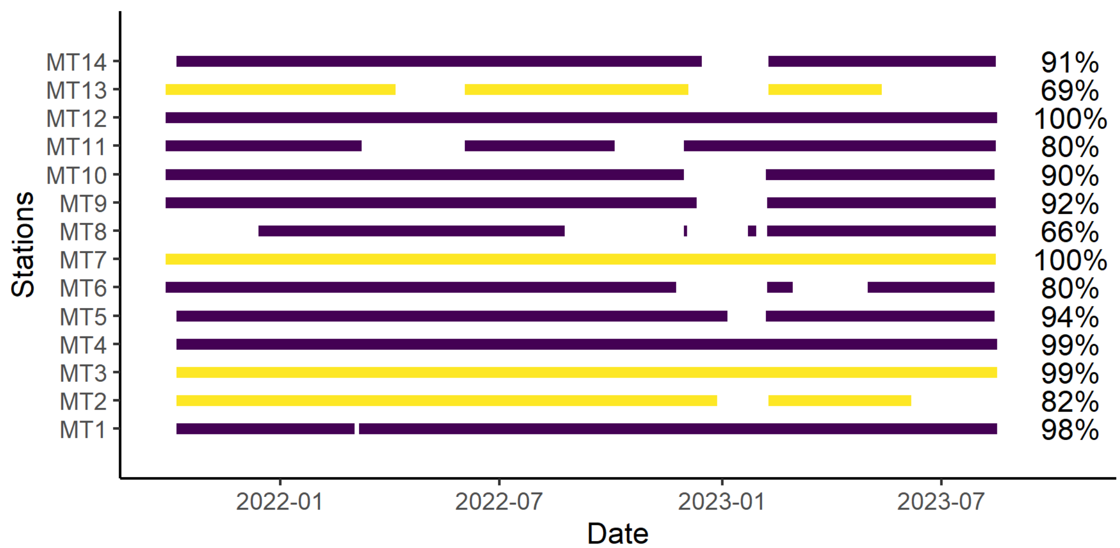


Figure 4-1. Periods with available data from CPODs and ambient sound recorders at different stations in and around the Borssele wind farms. Yellow bars represent stations at which both CPOD and ambient sound were recorded while purple bars only hold CPODs data. Percentage of total time period measured in days per station.

4.1.2 Ambient sound

In addition to a CPOD, Stations 2, 3, 7 and 13 were also equipped with a broadband hydrophone to collect ambient sound measurements. These measurements were either collected with an Ocean Instrument SoundTrap ST300-HF or with a RTsys Sylence with HTI 96-min hydrophone. Sound pressure levels were measured with at least 48k samples/s, which allowed to characterize the underwater sound up to decidecade (one-third-octave) band 13, with 20 kHz center frequency The instruments were set with a duty cycle and measured the first 5 minutes of every 15 minutes. This duty cycle was chosen to extend the recording time of the instruments, so the instruments could be exchanged less often, and it has been shown (in the JOMOPANS project) that this duty cycle is sufficient to characterize underwater ambient statics of sound levels in these type of environments.

The station equipped with the RTsys Sylence recorder are set to continuous measurements. This is possible since the battery life is not restricted for these instruments.

Ambient sound data at the four stations was successfully collected 91.4% of the time. A day is successful when data is collected for the whole day. At least 1 day of missing data is expected for each service round, as these days are discarded. This exclusion is necessary due to disturbances caused by the service vessel. The following conclusions can be drawn from the data availability (Figure 4-2):

- Stations 7 and 13 were first placed on 28/09/2021, stations 2 and 3 on 07/10/2021;
- The first gap in the data at station 3 was due to an empty battery as data was collected continuously instead of with the 5/15 minute duty cycle.
- Between mid-February 2023 and the end of April, no data is available from station 2. This is due to a connector failure, which prevents data from being downloaded from the instrument.
- Other gaps in the data at stations 3, 7 and 13 are caused by a system fault that causes the energy in the external battery packs to be used inefficiently.

Due in part to the random failure of the SoundTraps, the recorders were replaced by Sylence recorders from RTsys in combination with an HTI 96-min hydrophone. The hydrophone has a sensitivity of -170 dB re 1µPa and has a frequency response between 2Hz to 30 kHz. All SoundTraps have been replaced since the last service round (February 2024).

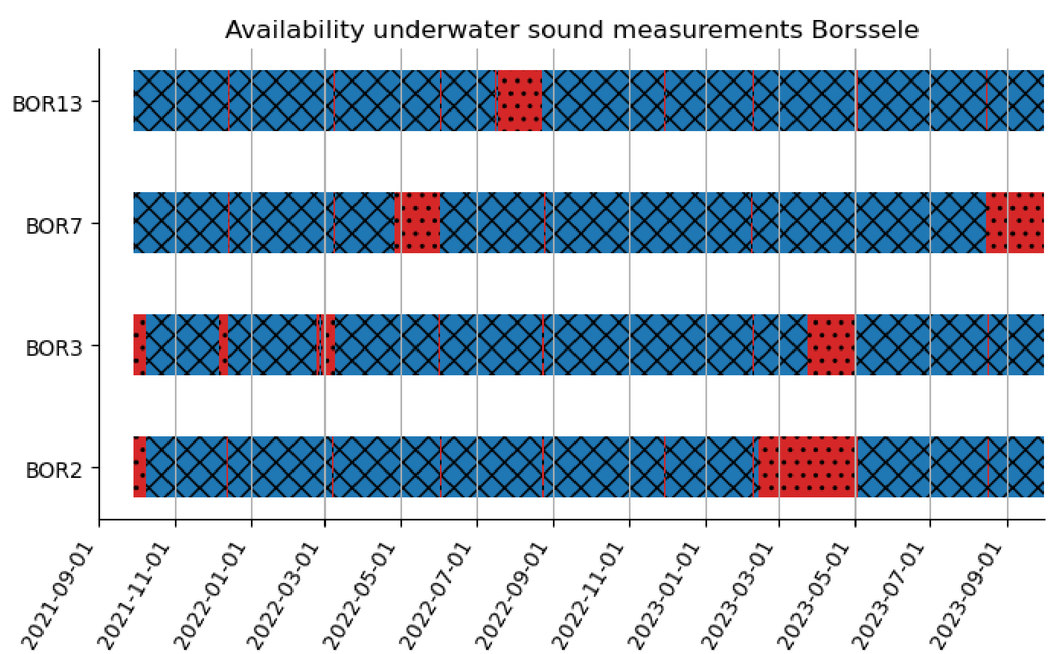


Figure 4-2 Successful (blue/crossed) processed ambient sound data collection and missing data (red/dotted), processed until week 33 2023.

The collected data was assessed for quality based on a visual and auditory check. The quality of the data was very comparable to the data collected in the construction phase of the wind farm.

Data quality control of the acoustic data was conducted in between deployments and focused on the identification of low-quality data and possible causes of reduced data quality.

Main interference in the measurements was caused by tidal flow. The movement of water around an object induces small pressure fluctuations, hydrophones are sensitive to these pressure fluctuations and these thus become part of the measured signal. In underwater acoustic measurements this phenomenon is referred to as flow noise. Flow can also cause movement in the mooring set-up, vibrations in the mooring line, and shackles and chains to emit sound. Vibrations were reduced as much as possible by attaching the acoustic recorder not directly to the mooring line. The required type of mooring set-up (for navigation safety), with the large cardinal buoys, did not allow for a fully silent set-up and the lower frequencies were thus contaminated during high flow velocities. The contribution of these tidal-influenced data to the broadband sound level was minimized by the application of a filter.

Recorded underwater noise values were processed by correcting raw voltages to sound pressure using the frequency response curves of the individual instruments that were attained through calibration in the anechoic basin of TNO. Sound pressure levels were analyzed for the entire measurement campaign and all measurement stations. Sound pressure levels were calculated in decidecade frequency bands between 20 Hz and 20 kHz for each second of data, following standards determined as part of the EU Interreg JOMOPANS project[1]. These levels were calculated by a summation of the amplitude of the Fourier transform over the frequency bins that lie within the decidecade bands. The frequency resolution of the Fourier transform in the low frequency bands was enhanced by zero-padding the one-second time series to four times the window length before performing the Fourier transform. The routines used for these analyses were benchmarked as part of the JOMOPANS project (2018-2021).

The frequency-weighted root-mean-square sound pressure level (or $L_{p,\ weighted}$) was calculated following the approach of Tougaard and Beedholm[2] (2019) for VHF and PCW mammal hearing groups. Temporal weighting was applied by using an integration time of 125 ms. The MATLAB routines that are delivered as supplementary data by Tougaard and Beedholm (2019) were used as the basis for the routines used here. The maximum value of $L_{p,\ weighted}$ was taken over each second of the recordings and then stored.

As mentioned above, it is possible to minimize the contribution of flow noise by applying a filter. One way to design such a filter is an approach by Van Geel et al.[3] (2020). If the tidal flow speed at the hydrophone is known during the measurement period, it is possible to calculate the Kendall correlation coefficient between the sound pressure level and the tidal flow speed. If this correlation is above a desired threshold, data points corresponding to the largest tidal flow speeds are excluded to recalculate the correlation coefficient. This process was repeated until the correlation coefficient drops below its

[1] Ward, J., Wang L., Robinson, S. and Harris, P., 2021. Standard for Data Processing of Measured Data. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS).

[2] Tougaard, J. and Beedholm, K., 2019. Practical implementation of auditory time and frequency weighting in marine bioacoustics. Applied Acoustics 145, 137-143.

[3] Van Geel, N. C. F., Merchant, N. D., Culloch, R. M., Edwards, E. W. J., Davies, I. M., O'Hara Murray, R. B., and Brookes, K. L., 2020. Exclusion of tidal influence on ambient sound measurements. J. Acoust. Soc. Am 148 (2), 701-712.

desired threshold, eliminating the data points that correspond most strongly to the tidal flow speed. Because flow noise was expected to manifest most strongly in low frequencies, this method was applied separately to each frequency band of the sound pressure level. One example of the result of this filter is shown in Figure 4-3. The filter was applied to each station separately, and the data from the stations were filtered per measurement day.

The following noise metrics were calculated and delivered in a database:

Continuous noise metrics (each second):

- Unweighted broadband sound pressure level, L_p, unfiltered
- Unweighted broadband sound pressure level, L_p, with application of tidal filter
- Weighted broadband sound pressure level, $L_{p,w(vhf)}$ and $L_{p,w(pcw)}$.

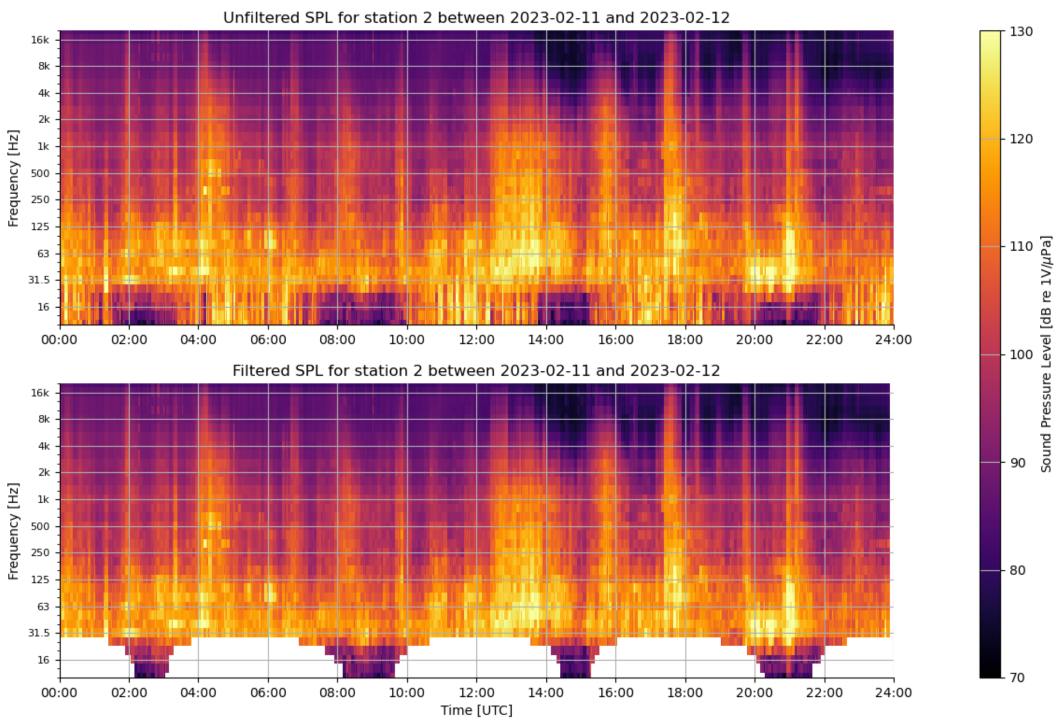


Figure 4-3 Sound pressure level of one day at station 2, with unfiltered data at the top, and filtered data at the bottom.

4.1.3 Environmental variables

Available environmental variables considered for the analysis are listed in Table 1. As some of these environmental variables were highly correlated, a selection was made to include time to high tide, wind speed, wind direction and sea surface temperature in the analysis. The selected variables ensured consistency with an analysis of the PAM data during the construction of the Borssele wind farms (de Jong et al., 2022). A part of the observations were missing for some variables (e.g. > 25% for sea surface temperature, >1% for wind speed, see Table 4-1). Following de Jong et al. (2022) these were predicted with a generalized additive model (GAM) framework for each environmental variable. Covariates included; month of the year, day of the month, and hour of the day and were included as low-rank thin-plate regression splines while year was included as a factor. Data analysis is described in detail in de Jong et al. (2022).

Table 4-1 Collected environmental data.

Environmental covariate		% missing observations	source
Tidal	flow magnitude (m/s)	0	Hydrodynamic model run for location 7 (WaterProof model)
	flow direction (°)	0	
	height (m)	0	
Wind	speed (m/s)	1.2	KNMI, Europlatform
	direction (°)	1.4	
Wave	period (seconds per hour)	0.2	RWS, Borssele Alpha
	direction (°)	3.2	
	significant height (m)	0.2	
Temperature	air (°C)	1.0	KNMI, Europlatform
	sea surface (°C)	25.2	

4.2 DATA ANALYSES

4.2.1 Ambient sound levels

To provide insight in differences in ambient sound levels between the four measurement locations, and the variability over the measurement period, sound level percentiles were calculated in decidecade frequency bands for each month of data.

4.2.2 Statistical analysis: presence of harbour porpoises

Porpoise presence was studied by looking at their acoustic activity expressed as porpoise-click positive minutes per hour (PPM/h). Both porpoise presence and the number of porpoise positive minutes were considered as response variables. For porpoise presence, porpoise clicks were transformed into a binary response variable (presence (PPM/h>0) or absence (PPM/h=0)). The probability of observing a presence or number of porpoise positive minutes in the modelling design is expected to be a non-linear function of the independent variables. Therefore, generalized additive mixed models (GAMMs) were fitted using the R package "mgcv". Porpoise presence was modelled with a binomial error structure and logit link function while the error distribution for the number of porpoise positive minutes per hour was assumed to best modelled with a Tweedie distribution. (i.e. according to a comparison with a negative binomial error distribution through Normal Q-Q plots and Residual vs Fitted plots).

The Tweedie distribution presents a versatile alternative to both the quasi-Poisson and negative binomial distributions when analyzing count data (particularly with a high proportion of zero) (Shono, 2008). The distribution is defined by three parameters; a mean (μ), dispersion (ϕ), and a power parameter (p). When the power parameter (p) falls between 1 and 2, the Tweedie distribution is referred to as the compound Poisson-gamma. It exhibits a point mass at zero and support on positive real numbers, characterized by

Poisson mixtures of gamma distributions. This form of the Tweedie distribution offers an elegant solution, effectively handling data with zeros uniformly. (Tweedie, 1984). A distinction was made between fixed and random effects.

Ambient sound covariate was either the unweighted SPL (L_p, 10Hz-20kHz) or the VHF-weighted SPL ($L_{p,w(vhf)}$, 10Hz-20kHz). As the ambient sound covariates are highly correlated, separate models were made.

L_p and $L_{p,w(vhf)}$ and most environmental covariates (i.e. windspeed, sea surface temperature, time to high tide) were included as penalized thin-plate regression splines. Hour was included as cyclic cubic regression splines (i.e. penalized cubic regression splines whose ends match). Shrinkage smoothers use an additional penalty that helps avoiding overfitting by allowing the smooth function to shrink beyond a linear function towards zero. CPOD_id was included as random effect to account for variability in different responses over which we want to generalize.

Year, and whether CPOD measurements were inside or outside the park were included as factors. Smoothing parameter selection was performed by restricted maximum likelihood (REML) (Wood, 2011).

To look at ambient sound the dataset was split in two, as ambient sound data was not recorded at all stations. The first dataset was the full dataset (14 locations) while the second dataset only consisted of the four stations that had both CPOD and ambient sound data.

We modelled the following relationships separately, resulting in six different models (Table 4-2):

- The relation between the presence and number of porpoise positive minutes per hour, without any ambient sound measurement which allowed taking all CPOD data into account.
- The relation between the presence and number of porpoise positive minutes per hour, and ambient sound without frequency-weighting the sound for the hearing of porpoises.
- The relation between the presence and number of porpoise positive minutes per hour, and ambient sound with the sound being frequency-weighted for the hearing of porpoises.

Table 4-2. Model definitions

Data set	% zero	Model name	Response	Model terms
		Base		$f1(Windspeed_i) + f2(Temperature_i) + f3(Tide_i) + f4(Hour) + Year + CPOD\ id + Inside\ park$
CPODs and soundtraps	93.9	Model 1	Porpoise presence (binomial)	Basic model + $f(SPL_{bb})$
		Model 2		Basic model + $f(SPL_{vhf})$
		Model 3	Number of porpoise positive minutes (tweedie)	Basic model + $f(SPL_{bb})$
		Model 4		Basic model + $f(SPL_{vhf})$
CPODs	76.1	Model 5	Porpoise presence (binomial)	Basic model
		Model 6	Number of porpoise positive minutes (tweedie)	

5 RESULTS – DATA STREAM 1

5.1 AMBIENT SOUND

The sound levels in decidecade frequency bands outside the windfarm are typical for an environment in close proximity to a shipping lane (Basan et al., 2024) with highest sound levels in the frequency bands with centre frequencies between 31 and 63 Hz. The sound level percentiles decrease with distance from the main shipping lane, compare station 2 to station 3.

The sound levels within the windfarm (station 7 and 13) are lower than outside the windfarm and are characterised by a wider peak between approximately 25 and 200 Hz. This wider peak represents sound emitted by wind turbines and the intensity of these levels scales with the wind speed (Brinkkemper et al., 2023).

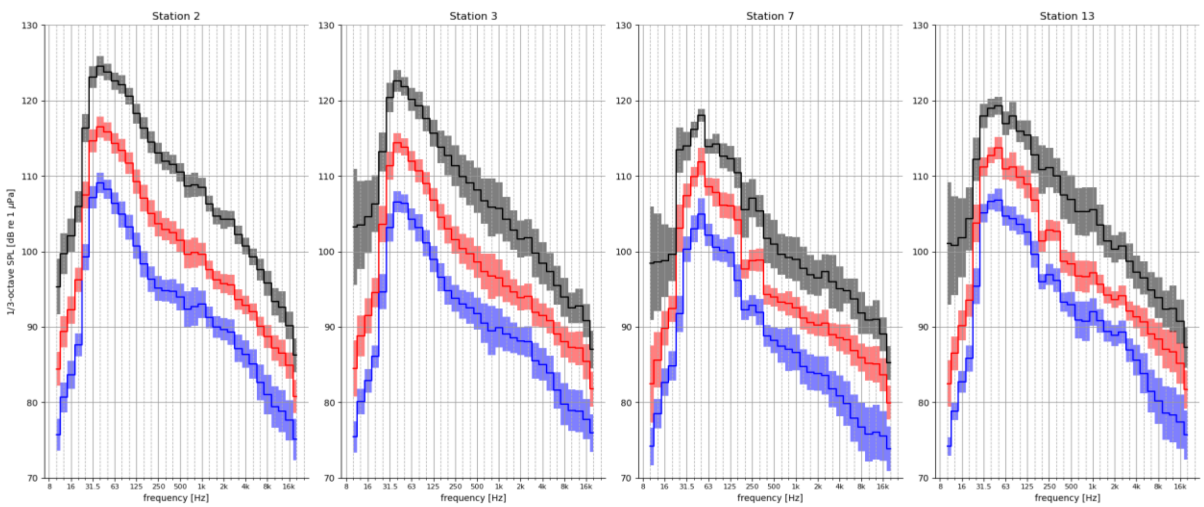


Figure 5-1. The 10th, 50th and 90th percentile of the sound pressure level (L_p) in decidecade frequency bands of the entire dataset. The shaded areas with the same color represent the standard deviation over the monthly percentiles.

5.2 PRESENCE OF HARBOUR PORPOISES

Acoustic activity of harbour porpoises was detected on all locations during the whole study period. Figure 5-2 illustrates the temporal pattern of porpoise click detections for the different locations. The acoustic activity differed not only per location, but showed strong day to day variation in presence and number of porpoise positive minutes per hour as well.

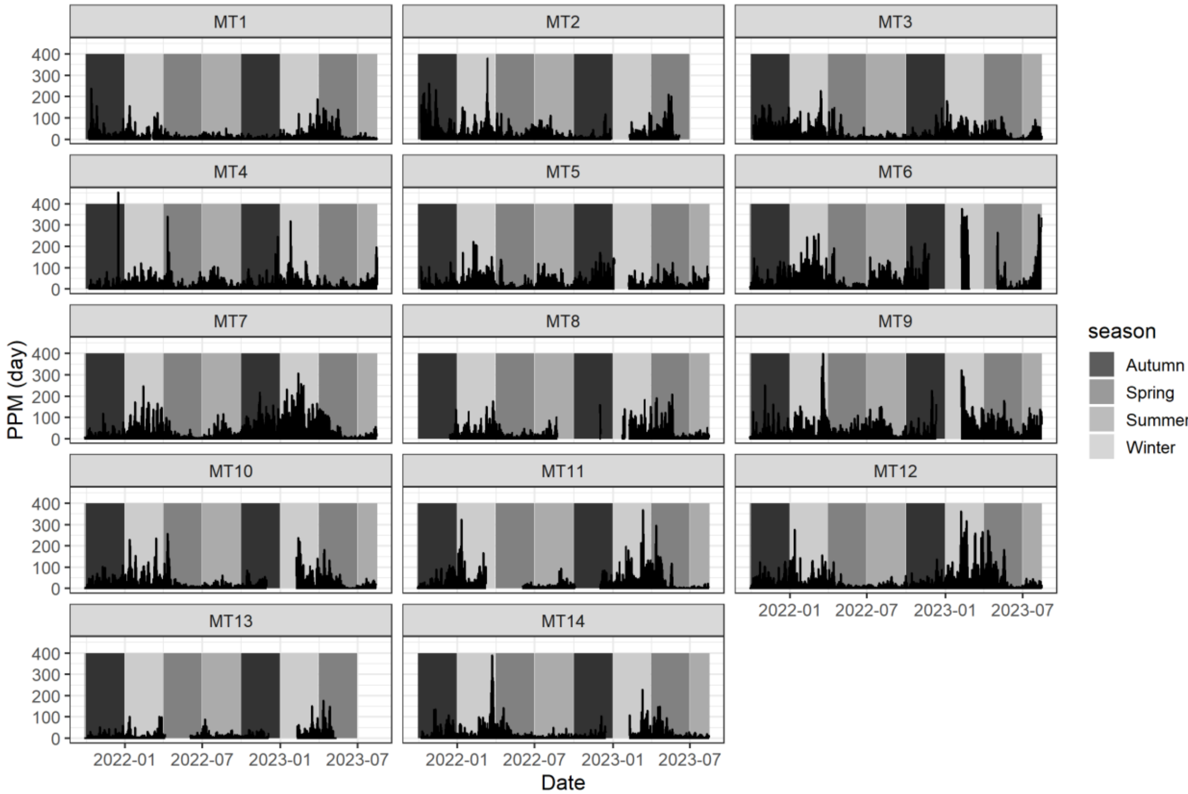


Figure 5-2 Porpoise acoustic activity in porpoise positive minutes per day (PPM/day) for the 14 CPOD locations.

The different models explained between 4.6% and 13.7% of the total observed variation in presence and number of porpoise positive minutes per hour (see Table 5-1). According to AIC and percentage deviance explained, $L_{p,w(vhf)}$ was a better predictor than L_p both for PPM presence (i.e. model 1 vs model 2) and number (i.e. model 3 vs model 4). The binomial models explained PPM presence better than the models using a tweedie distribution.

Table 5-1 For all models the AIC score, percentage deviance explained (% DE).

Dataset	Model	Response	AIC	%DE
CPODs and soundtraps	Model 1	Porpoise presence (binomial)	52437	7.5
	Model 2		52319	7.5
	Model 3	Number of porpoise positive minutes (tweedie)	149863	13.3
	Model 4		149662	13.7
CPODs	Model 5	Porpoise presence (binomial)	213896	4.6
	Model 6	Number of porpoise positive minutes (tweedie)	602932	9.4

Most covariates show a similar relationship with the response the probability of PPM/h>0 in the different models. The results of the binomial model using data from all locations (Figure 5-3) and from the four locations with sound measurements (see Figure 5-4) are shown. The other results can be found in Appendix C.

- The probability of PPM decreased with increasing temperature;
- The probability of PPM decreased with increasing wind speed;
- The probability of PPM was lower with increasing $L_{p,w(vhf)}$;
- The probability of PPM showed a strong diel pattern, it was lower during the day and higher during the night;
- The probability of PPM showed a tidal pattern, with peaks around 3 hrs before and 2-3 hrs after high tide.

Whether porpoise acoustic detections differed between the Borssele wind farms and the surrounding North Sea waters is shown in the lower panel of (Figure 5-3 and Figure 5-4). When the full dataset was used a statistically significant higher probability of PPM within the wind farms was predicted although with a small effect size. Whereas the subset of four sound-measurement locations predicted a statistically non-significant lower probability of PPM within the wind farms.

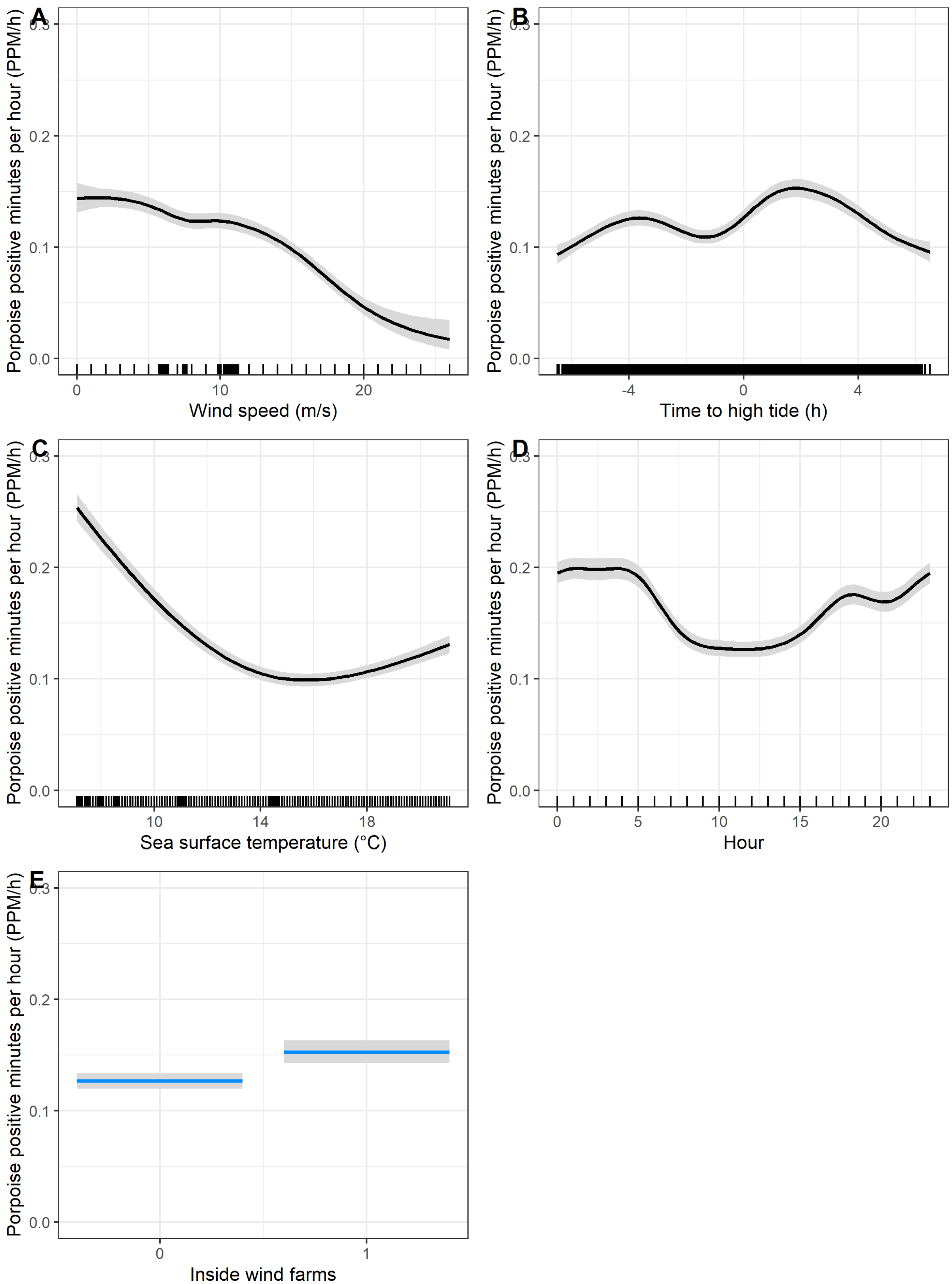


Figure 5-3 Model 5 predicted patterns in the probability of porpoise presence in relation to environmental factors and presence inside or outside Borssele wind farms based on data from all locations

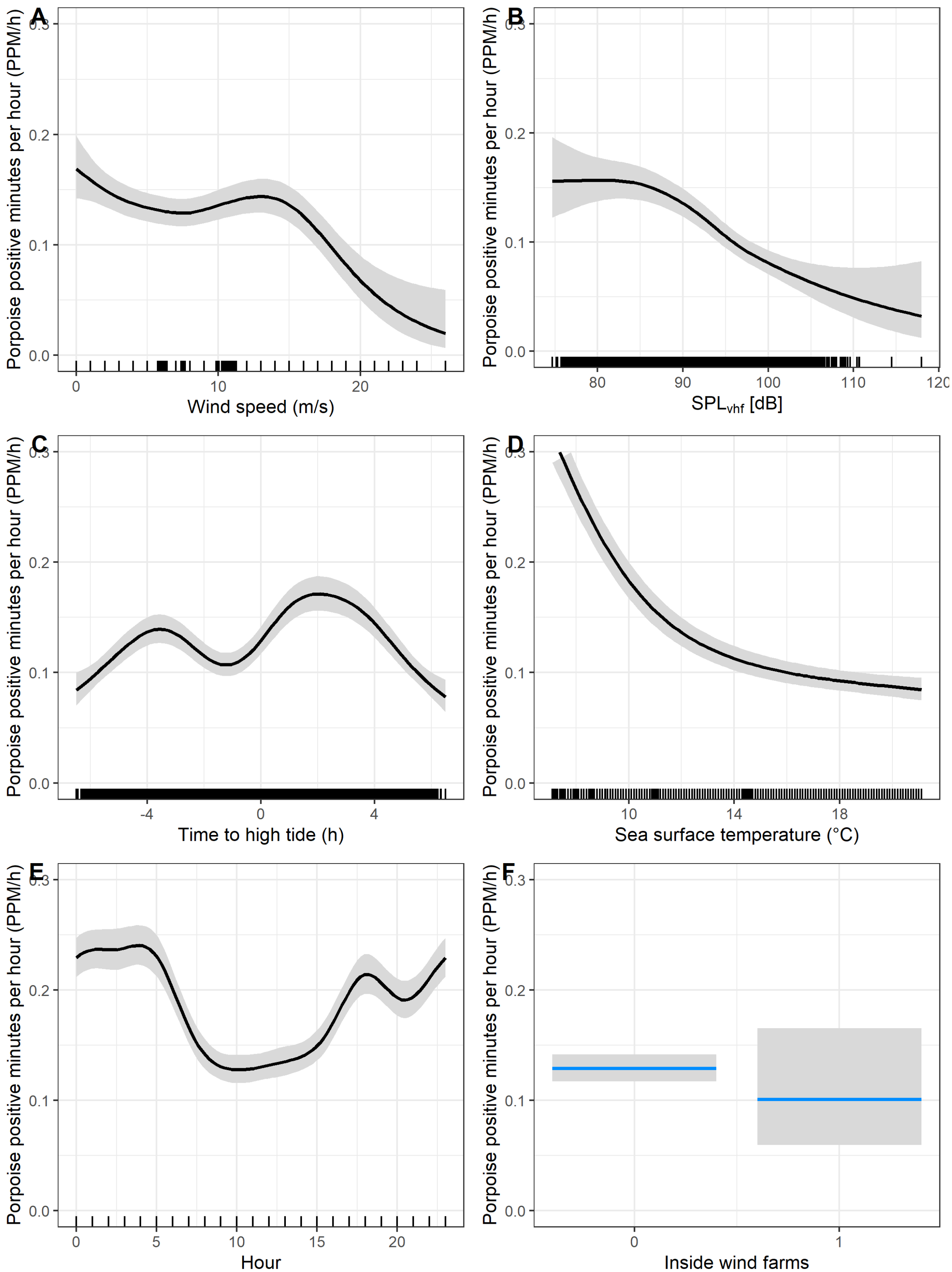


Figure 5-4. Model 2 predicted patterns in the probability of porpoise presence in relation to environmental factors and presence inside or outside Borssele wind farms based on data from four locations

6 DISCUSSION

This Mid Term report provides the ecological interpretation of the PAM data in relation to the research question "*Do large-scale habitat changes due to the development of offshore wind farms in the North Sea have effects on harbour porpoises?*" and the seven sub-questions.

The potential impact of the Borssele operational windfarm was studied using the acoustic activity of harbour porpoises, quantified as positive porpoise minutes, as indicator of porpoise presence. Although the models explained a relatively low percentage of deviance (see Table 3, min = 4.6%, max = 13.7%), which is not unusual in these type of studies (de Jong et al., 2022; Holdman et al., 2019), there was enough power to detect statically significant differences in the acoustic presence of harbour porpoises and the covariates considered.

Variation among CPODs was statistically significant since CPOD-device related variation should be minimized as a result of calibrating of the used equipment, the result indicates small-scale spatial fluctuations in porpoise acoustic activity. Wind speed was included in the model to correct for the deficiency of CPODs to detect clicks for higher wind speeds.

We found a seasonal pattern with higher detections of harbour porpoise positive minutes with decreasing sea surface temperature (Figure 5-3), that is similar to previously found seasonality in porpoise echolocation within other Dutch offshore wind farms (Geelhoed et al., 2018; Scheidat et al., 2011; Van Polanen Petel et al., 2012). In Dutch coastal waters harbour porpoises are present year-round but display marked seasonal patterns with highest detection in winter in coastal sightings (Camphuysen, 2011), aerial surveys (Geelhoed et al., 2013), and strandings (IJsseldijk et al., 2021).

Temporal patterns were demonstrated in the Borssele data on a more detailed level as well. Time of the day (hours) and time in relation to tide showed relationships with the presence of harbour porpoises. Consistent with other studies (Schaffeld et al., 2016; Todd et al., 2016), the results revealed a strong diel pattern with highest click detections during the night (Figure 5-3). Furthermore, our results support previous studies that porpoise presence varied with tidal cycle (Figure 5-3) which might reflect enhanced foraging opportunities (Benjamins et al., 2016, 2016; Zamon, 2001). Local variations in topography and tides may exert diverse effects at different sites.

Furthermore, in a study that deployed sound and movement recording tags (DTAGs) observed higher buzz rates in the night performing primarily pelagic dives (Wisniewska et al., 2016). This could be related to prey species being more accessible by vertically migration, schooling patterns, and/or reduced swimming speed (Cardinale et al., 2003; Didrikas & Hansson, 2009). However, a study on captive porpoises suggested that diel patterns in acoustic activity was influenced by vocalization behaviour rather than prey activity (Osiecka et al., 2020).

The impact of ambient sound on porpoise acoustic activity, as found in the results, aligns with a previous study in the Borssele wind farms during the construction phase (de Jong et al., 2022). They also found a decaying linear relationship between $L_{p,w(vhf)}$ and porpoise presence (Figure 4b), but a less clear relationship with L_p (Appendix model 1 figure 4b).

The anticipated noise levels from operational turbines, as well as from shipping required for surveillance and maintenance purposes, are expected to be minimal and localized. High levels of shipping noise reduces harbour porpoise acoustic activity which could lead to fewer prey capture attempts (Wisniewska et al., 2018).

Finally, our study shows a difference in acoustic activity of harbour porpoises inside and outside the Borssele wind farms. Using the whole dataset we found a statistical significant higher acoustic activity within the wind farms, whereas the subset of four locations showed a statistically non-significant lower acoustic activity inside the wind farms. Note, however, that the effect of the wind farm is relatively small in comparison with the other covariates. Furthermore, as no pre-construction data were recorded it is impossible to evaluate if porpoise acoustic activity has returned to baseline levels, or if the difference between the wind farms and surroundings reflect the baseline levels. Aerial surveys did not yield support for differences between densities and abundance of harbour porpoises inside and outside the Borssele wind farms (Collier et al., 2022). Acoustic activity of porpoises within the operational Prinses Amalia wind farm and a control area outside the wind farm did not differ either (Van Polanen Petel et al., 2012). Danish studies in Horns Rev I, the first studied offshore wind farm in European waters, and Nysted in the Baltic Sea showed no or a negative effect of operational wind farms on the occurrence of harbour porpoises (Blew et al., 2006; Tougaard et al., 2006). The few conducted PAM studies in other operational wind farms (e.g. Dähne et al., 2014; Teilmann & Carstensen, 2012) support that effects are probably dependent and restricted to local conditions.

Our results could tentatively provide additional support, although correlations are weak, that marine mammals could be attracted to offshore structures after construction (Clausen et al., 2021; Fernandez-Betelu et al., 2022; Russell et al., 2014; Scheidat et al., 2011). There they may utilize feeding grounds or may be attracted due to limited fishing and vessel operations. The submerged parts of man-made structures (i.e. offshore wind farms, oil and gas platforms) can create artificial reefs and alter ecosystem structure and functioning (Degraer et al., 2020; Wilhelmsson et al., 2006). These structures are colonised by epifaunal (fauna that lives attached to a substrate) communities, consequently altering fish abundance and diversity. However, whether reefs produce or attract fish has been topic of ongoing debate and is species specific (Bohnsack, 1989; Lima et al., 2019; Pickering & Whitmarsh, 1997)·. Whether these 'reef-effects' compensate the loss of the fish diversity and abundance present before the construction of a wind farm has not been quantified yet. Consequently, the effect of wind farm induced changes in fish communities on the presence and foraging efficiency of harbour porpoises cannot be quantified either.

The Borssele windfarm is relatively new, and it is uncertain to what extent artificial reefs have fully established. The formation time of artificial reefs at offshore wind farms varies due to factors like materials, environmental conditions, and specific design, impacting the speed of marine organism colonization (McLean et al., 2022). Whether there is an impact of artificial reefs on fish diversity and abundance is not solely driven by changed feeding grounds but also depends on the provision of shelter from predation or water movements. Furthermore, fish could utilize them for spatial orientation (Pickering & Whitmarsh, 1997).

7 CONCLUSIONS

To conclude, the preliminary answers for the research questions are summarized below.

1. To what extend do harbour porpoises occur in the area of the Borssele operational wind farms and how does this differ from a reference area (i.e. open sea)?

Harbour porpoises occur in the operational Borssele wind farms; acoustic activity is measured on all CPOD-locations within and outside the wind farms. Analysis of the full dataset predicted a statistically significant higher probability of acoustic activity within the Borssele wind farms, whereas the subset of four sound-measurement locations predicted a statistically non-significant lower probability of acoustic activity within the wind farms.

2. Can any spatio-temporal variations of this occurrence be observed and if so, what are these?

The models showed spatio-temporal variations in the acoustic activity of harbour porpoises that were related to the environmental parameters temperature, wind speed, Sound Pressure Level, time of the day and time to high tide as found in previous PAM studies.

3. Can the spatio-temporal variations be linked to (sound produced by) activities within the wind park (like maintenance activity)?

The models predicted a decrease in the probability of PPM with increasing $SPL_{VHF.}$ Further analyses are needed to provide a satisfactory answer to this question.

4. Can variations in sound produced by harbour porpoises (like feeding buzzes) be observed and does this variation differ in time and space (within the park, and between the park and the open sea)?

Feeding buzzes are currently analysed, preliminary results are expected to be included in the final version of the mid-term report.

5. Can the spatio-temporal variations in abundance and produced sound by harbour porpoises be explained (for example due to the presence or absence of a food source, due to external disturbance, or life cycle variations, habituation, etc.)?

Collected data may be sufficient to partially answer the question. Whether or not habituation occurs can be distilled from a comparison over the years between harbour porpoise activity inside and outside the windfarms.

Data on external factors such as food supply and disruption (by ships) are largely lacking and are collected to a limited extent within the Borssele project. However, data is available (besides the data from the SoundTraps that measure the underwater noise at a number of locations as a measure of disturbance). For example, WaterProof collects additional AIS data; these can be used to quantify ship movements. The APELAFICO collects information about the presence of fish and porpoises.

6. Explain if the operational windfarm site of Borssele is (still?) a suitable (foraging) habitat for the harbour porpoise?

Harbour porpoises are present at all monitoring locations, and their acoustic activity is very similar inside and outside the windfarm. Further analyses are needed to provide a more detailed answer to this question. The data can answer whether harbour porpoise activity differs inside and outside the windfarm (questions 1 and 2), but this is only a proxy for the suitability of the Borssele windfarms. Variation in foraging activity (question 4) can be demonstrated and is currently being analysed. The results of this analysis will be included in the final report of this project.

7. Can the results of this Borssele research project be translated to a broader perspective taken into account the foreseen Energy transition on the (Dutch) North Sea)?

The Borssele research project provides very valuable data on the presence and activity of harbour porpoises and the soundscape, in and around an operational OWF. The collected data is expected to provide more detail on the spatio-temporal variation in the occurrence of harbour porpoises and possibly also to quantify relationships with environmental variables in this part of the Dutch North Sea. The final report of this study will include an extensive discussion how the results can be translated into a broader perspective taken into account the foreseen energy transition.

8 COLLABORATION

In order to make efficient use of the available vessel time of the Rijksrederij and to achieve as much synergy as possible between projects, the possibility is offered, for other projects to sail along during the quarterly maintenance trips and work on board the ship at the Borssele OWF. Up till now, three research projects have made use of the offered shipping time:

- Elasmopower – Monitoring program to collect eDNA samples on top off the OWF export cables and inside the Borssele OWF
- Bird observations by WMR
- Harbour porpoise observations by Waardenburg Ecology.

8.1 ELASMOPOWER

"ElasmoPower is looking at the effects of electromagnetic fields from undersea power lines on rays and sharks in the North Sea. The research includes laboratory experiments with embryos and adults. We also want to see if there is a difference between the species and relative quantities of rays and sharks inside a wind farm, outside it and on a cable. For this we use eDNA, for which we filter fragments of skin or feces from the water. We survey 9 sample points quarterly for two years.

Ship time is not only expensive, but there is a lot of arrangement involved. By using WOZEP's porpoise survey sample sites, we save time and resources. This allows us to conduct more research within our budget. Hopefully, after the analysis, we will be able to state our conclusions with more certainty. In addition, the collaboration also allows us to match our results with the results from the porpoise survey. After all, you can look at rays and sharks, as well as porpoises, from the same water sample."

Quote: *Annemiek Herman, PhD candidate ElasmoPower 27/02/2024*

8.2 BIRD OBSERVATIONS BY WMR

"In 2020 & 2021 Wageningen Marine Research (WMR) together with partner organizations in The Netherlands, Belgium and Germany has been working with Rijkswaterstaat (RWS) to develop a method to use Artificial Intelligence to analyse digital images collected during aerial survey on the North Sea. RWS has been collecting these images in and around Borssele OWF. The project visits to the PAM network represented as an unique opportunity to collect additional 'ground truthing data' on seabirds present in the wind park to be used in the analyses for the AI image recognition in the future.

A secondary reason for this survey in December 2021 & March 2022 has been the increased numbers of dead Razorbills & Guillemots that were found on the beaches of The Netherlands in the past months. Ship survey work (in areas that are not often monitored by ship) provide an opportunity to get an insight into the current 'bird situation at sea'."

Source: *Risk Assessment Method Statement, Wageningen Marine Research 20/01/2022*.

8.3 HARBOUR PORPOISE OBSERVATIONS BY WAARDENBURG ECOLOGY

"The aim of the work is to carry out observations of harbour porpoises inside the Borssele OWF. For these purposes, the WE-crew will conduct visual observations from a location on the vessel with good overview of the sea surface. The precise location will not interfere with any other activities on board of the vessel and as such will be determined in consultation with the project leader of WaterProof BV and crewmembers of the vessel.

At location, the WE-crew will scan the sea surface both visually as well as with binoculars. If a harbour porpoise if sighted, the observer will try to take pictures of the animal with the photo camera and subsequently records the observation on paper.

The work is carried out during a three-day trip from 1-3 May 2023. The vessel will leave from Vlissingen harbour and will return to port every afternoon/evening. During these days the WE-crew will start the work upon entering BSW and end the work upon leaving the wind farm. Hence, the duration of the work depends on the duration of the regular maintenance activities. No additional time is required."

Source: *Harbour porpoise observations in offshore wind farm Borssele - Work Method Statement, Waardenburg Ecology 21/04/2023*

9 DATA DELIVERY

Data is collected and stored in four different datasets; raw underwater noise, processed underwater noise, raw harbour porpoise activity and processed harbour porpoise activity.

The raw collected data for both underwater noise as well as harbour porpoise activity are available upon request at WaterProof and/or WMR and a back-up of this data will be delivered to RWS. The metadata is stored within this dataset.

The underwater noise data is processed, analysed and stored based on international standards (ISO:17025) and following guidelines developed during the Interreg JOMOPANS project. Processed data is stored in hdf5-files and will be uploaded to the ICES data repository.

The harbour porpoise activity is processed to detective positive minutes. The processed data in the form of comma-separated files to a data repository (e.g. VLIZ/LifeWatch).

10 REFERENCES

Benjamins, S., Dale, A., Van Geel, N., & Wilson, B. (2016). Riding the tide: Use of a moving tidal-stream habitat by harbour porpoises. *Marine Ecology Progress Series*, *549*, 275–288. https://doi.org/10.3354/meps11677

Blew, J., Hoffmann, M., Nehls, G., & Hennig, V. (2006). *Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark Part I: Birds*.

Bohnsack, J. A. (1989). Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bulletin of Marine Science*, *44*(2), 631–636.

Brinkkemper, J.A., Van Tol, P.M., Snoek, R.C. & Kinneging, N., 2023. Underwater sound in an operational OWF. Presentation at the 7th Conference on Wind Energy and Wildlife, Šibenik, Croatia.

Camphuysen, K. C. (2011). Recent trends and spatial patterns in nearshore sightings of harbour porpoises (Phocoena phocoena) in the Netherlands (Southern Bight, North Sea). *Lutra*, *54*, 39–47.

Cardinale, M., Casini, M., Arrhenius, F., & Håkansson, N. (2003). Diel spatial distribution and feeding activity of herring (Clupea harengus) and sprat (Sprattus sprattus) in the Baltic Sea. *Aquatic Living Resources*, *16*(3), 283–292. https://doi.org/10.1016/S0990-7440(03)00007-X

Clausen, K. T., Teilmann, J., Wisniewska, D. M., Balle, J. D., Delefosse, M., & van Beest, F. M. (2021). Echolocation activity of harbour porpoises, Phocoena phocoena, shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms. *Ecological Solutions and Evidence*, *2*(1), 1–12. https://doi.org/10.1002/2688-8319.12055

Clausen, K. T., Tougaard, J., Carstensen, J., Delefosse, M., & Teilmann, J. (2019). Noise affects porpoise click detections–the magnitude of the effect depends on logger type and detection filter settings. *Bioacoustics*, *28*(5), 443–458. https://doi.org/10.1080/09524622.2018.1477071

Collier, M. P., Middelveld, R. P., Van Bemmelen, R. S. A., Weiß, F., Irwin, C. G., & Fijn, R. C. (2022). *High-definition bird and marine mammal aerial survey image collection in Borssele*. www.waardenburg.eco

Dähne, M., Peschko, V., Gilles, A., Lucke, K., Adler, S., Ronnenberg, K., & Siebert, U. (2014). Marine mammals and windfarms: Effects of alpha ventus on harbour porpoises. In *Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, Results and Perspectives* (Vol. 9783658024628, pp. 133–149). Springer Fachmedien. https://doi.org/10.1007/978-3-658-02462-8_13

de Jong, C. A. F., Lam, F. P. A., von Benda-Beckmann, A. M., Oud, T. S., Geelhoed, S. C. V., Vallina, T., Wilkes, T., Brinkkemper, J. A., & Snoek, R. C. (2022). *Analysis of the effects on harbour porpoises from the underwater sound during the construction of the Borssele and Gemini offshore wind farms*. www.tno.nl

Degraer, S., Carey, D. A., Coolen, J. W. P., Hutchison, Z. L., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore wind farm artificial reefs affect ecosystem structure and functioning. *Oceanography Society*, *33*(4), 48–57. https://doi.org/10.2307/26965749

Didrikas, T., & Hansson, S. (2009). Effects of light intensity on activity and pelagic dispersion of fish: studies with a seabed-mounted echosounder. *ICES Journal of Marine Science*, *66*(2), 388–395. https://academic.oup.com/icesjms/article/66/2/388/593972

Fernandez-Betelu, O., Graham, I. M., & Thompson, P. M. (2022). Reef effect of offshore structures on the occurrence and foraging activity of harbour porpoises. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.980388

Geelhoed, S. C. V., Friedrich, E., Joost, M., Machiels, M. A. M., & Stöber, N. (2018). *Gemini T-c: aerial surveys and passive acoustic monitoring of harbour porpoises 2015*. https://doi.org/10.18174/410635

Geelhoed, S. C. V., Scheidat, M., van Bemmelen, R. S. A., & Aarts, G. (2013). Abundance of harbour porpoises (Phocoena phocoena) on the Dutch Continental Shelf, aerial surveys in July 2010-March 2011. *Lutra*, *56*(1), 45–57.

Geelhoed, S. C. V., Verdaat, H., & Wilkes, T. (2022). Effect of electromagnetic fields generated by Borssele export cables on harbour porpoise acoustic actvity. (Wageningen Marine Research report; No. C067/22). Wageningen Marine Research. https://doi.org/10.18174/579669

Holdman, A. K., Haxel, J. H., Klinck, H., & Torres, L. G. (2019). Acoustic monitoring reveals the times and tides of harbor porpoise (Phocoena phocoena) distribution off central Oregon, U.S.A. *Marine Mammal Science*, *35*(1), 164–186. https://doi.org/10.1111/mms.12537

IJsseldijk, L. L., Camphuysen, K. C. J., Keijl, G. O., Troost, G., & Aarts, G. (2021). Predicting Harbor Porpoise Strandings Based on Near-Shore Sightings Indicates Elevated Temporal Mortality Rates. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.668038

Leemans, J.J., R.C. Fijn & J. Kwakkel, 2023. Observations of harbour porpoise in offshore wind farms. Report 23-073. Waardenburg Ecology, Culemborg.

Lima, J. S., Zalmon, I. R., & Love, M. (2019). Overview and trends of ecological and socioeconomic research on artificial reefs. In *Marine Environmental Research* (Vol. 145, pp. 81–96). Elsevier Ltd. https://doi.org/10.1016/j.marenvres.2019.01.010

McLean, D. L., Ferreira, L. C., Benthuysen, J. A., Miller, K. J., Schläppy, M. L., Ajemian, M. J., Berry, O., Birchenough, S. N. R., Bond, T., Boschetti, F., Bull, A. S., Claisse, J. T., Condie, S. A., Consoli, P., Coolen, J. W. P., Elliott, M., Fortune, I. S., Fowler, A. M., Gillanders, B. M., … Thums, M. (2022). Influence of offshore oil and gas structures on seascape ecological connectivity. In *Global Change Biology* (Vol. 28, Issue 11, pp. 3515–3536). John Wiley and Sons Inc. https://doi.org/10.1111/gcb.16134

Osiecka, A. N., Jones, O., & Wahlberg, M. (2020). The diel pattern in harbour porpoise clicking behaviour is not a response to prey activity. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-71957-0

Pickering, H., & Whitmarsh, D. (1997). Artificial reefs and fisheries exploitation: a review of the "attraction versus production" debate, the influence of design and its significance for policy. In *Fisheries Research* (Vol. 31).

Russell, D. J. F., Brasseur, S. M. J. M., Thompson, D., Hastie, G. D., Janik, V. M., Aarts, G., McClintock, B. T., Moss, S. E. W., & McConnell, B. (2014). Marine mammals trace anthropogenic structures at sea. *Current Biology*, *24*(14), R638–R639. https://doi.org/10.1101/cshperspect.a002774

Schaffeld, T., Bräger, S., Gallus, A., Dähne, M., Krügel, K., Herrmann, A., Jabbusch, M., Ruf, T., Verfuß, U. K., Benke, H., & Koblitz, J. C. (2016). Diel and seasonal patterns in acoustic presence and foraging behaviour of free-ranging harbour porpoises. *Marine Ecology Progress Series*, *547*, 257–272. https://doi.org/10.3354/meps11627

Scheidat, M., Tougaard, J., Brasseur, S., Carstensen, J., Van Polanen Petel, T., Teilmann, J., & Reijnders, P. (2011). Harbour porpoises (Phocoena phocoena) and wind farms: A case study in the Dutch North Sea. *Environmental Research Letters*, *6*(2). https://doi.org/10.1088/1748-9326/6/2/025102

Shono, H. (2008). Application of the Tweedie distribution to zero-catch data in CPUE analysis. *Fisheries Research*, *93*(1–2), 154–162. https://doi.org/10.1016/j.fishres.2008.03.006

Teilmann, J., & Carstensen, J. (2012). Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic - Evidence of slow recovery. *Environmental Research Letters*, *7*(4). https://doi.org/10.1088/1748-9326/7/4/045101

Todd, V. L. G., Warley, J. C., & Todd, I. B. (2016). Meals on wheels? A decade of megafaunal visual and acoustic observations from offshore Oil & Gas rigs and platforms in the North and Irish Seas. *PLoS ONE*, *11*(4). https://doi.org/10.1371/journal.pone.0153320

Tougaard, J., Carstensen, J., Bech, N. I., & Teilmann, J. (2006). *Final report on the effect of Nysted Offshore Wind Farm on harbour porpoises Technical report to Energi E2 A/S*. www.nystedhavmoellepark.dk.

Tweedie, M. C. K. (1984). An index which distinguishes between some important exponential families. *Statistics: Applications and New Directions*, 579–604.

Van der Neut, R. & Brinkkemper, J., 2022. EMF and Sound monitoring around the Borssele export cable. Environmental measurements to study effects on harbour porpoise presence. WaterProof Marine Consultancy & Services BV. Report WP1268_R2r0.

Van Polanen Petel, T., Geelhoed, S., & Meesters, E. (2012). *Harbour porpoise occurrence in relation to the Prinses Amaliawindpark*.

Wilhelmsson, D., Malm, T., & Öhman, M. C. (2006). The influence of offshore windpower on demersal fish. *ICES Journal of Marine Science*, *63*(5), 775–784. https://doi.org/10.1016/j.icesjms.2006.02.001

Wisniewska, D. M., Johnson, M., Teilmann, J., Rojano-Doñate, L., Shearer, J., Sveegaard, S., Miller, L. A. A., Siebert, U., & Madsen, P. T. T. (2016). Ultra-high foraging rates of harbor porpoises make them vulnerable to anthropogenic disturbance. *Current Biology*, *26*(11), 1441–1446. https://doi.org/10.1016/j.cub.2016.03.069

Wisniewska, D. M., Johnson, M., Teilmann, J., Siebert, U., Galatius, A., Dietz, R., & Madsen, P. T. (2018). High rates of vessel noise disrupt foraging in wild harbour porpoises (Phocoena phocoena). *Proceedings of the Royal Society B: Biological Sciences*, *285*(1872). https://doi.org/10.1098/rspb.2017.2314

Zamon, J. E. (2001). Seal predation on salmon and forage fish schools as a function of tidal currents in the San Juan Islands, Washington, USA. *Fisheries Oceanography*, *10*(4), 353–366. https://doi.org/10.1046/j.1365-2419.2001.00180.x

APPENDIX A – HARBOUR PORPOISE TRACKING STATION

INTRODUCTION

The main instruments used for monitoring in the Bruinvis Netwerk Borssele project are the conventional porpoise detectors and hydrophones. The advantage of using conventional instruments is that the results are directly comparable with previous studies. The BNB project, however, also included a contribution in developing and testing new monitoring methods. Studying the feasibility to develop a hydrophone array to detect, locate and track harbour porpoises is one example.

Conventional porpoise click detectors, such as the CPODs and FPODs used in this study, provide information on the acoustic activity of harbour porpoises in an area, and can be used to study spatial and temporal variability in porpoise presence and foraging behaviour. The data collected with these instruments do, however, not provide more detailed information on small-scale movements of porpoises. With the application of hydrophone arrays, the location of individual harbour porpoises can be tracked in time, providing data to study harbour porpoise behaviour in much detail.

Tracking of harbour porpoises by means of triangulation of hydrophones is complicated, due to the short duration of the echolocation clicks that porpoises use and the narrow beam in which the sound pulse is transmitted. To track harbour porpoises, individual clicks must be detected by multiple hydrophones simultaneously. Also, the sampling frequency of the instruments used should be sufficiently high to record the clicks, implicating the need of extensive battery and storage capacity for the recording stations.

Here, an inventory and some first tests are described toward the development of an offshore deployable Harbour Porpoise Tracking Station (HPTS).

EQUIPMENT INVENTORY

An inventory of suitable equipment for the development of the harbour porpoise tracking stations was executed. In the first place, it was concluded that there need to be three hydrophone arrays deployed simultaneously in each others vicinity to accurately track harbour porpoises, as is illustrated in Figure 0-1.

Several manufacturers were contacted and enquiries were made for different solutions. However due to the extremely large storage capacity needed, it was concluded that no turn-key solution / equipment was available that could be used directly for the application of the HPTS.

Based on this inventory, our main acoustic supplier RTsys was contacted to discuss a custom solution for the development of the HPTS. Together with RTsys, we designed a setup that can sample continuously for approximately 44 days on 4 synchronized channels, sampling at 512 kHz, needed for triangulation.

Since it was concluded that at minimum three stations are needed for accurately tracking of the harbour porpoises, the costs are higher than can be fitted within the budget of this project. As discussed with Rijkswaterstaat, a proposal was made for the additional costs to acquire and further develop the HPTS based on the custom equipment offered by RTsys.

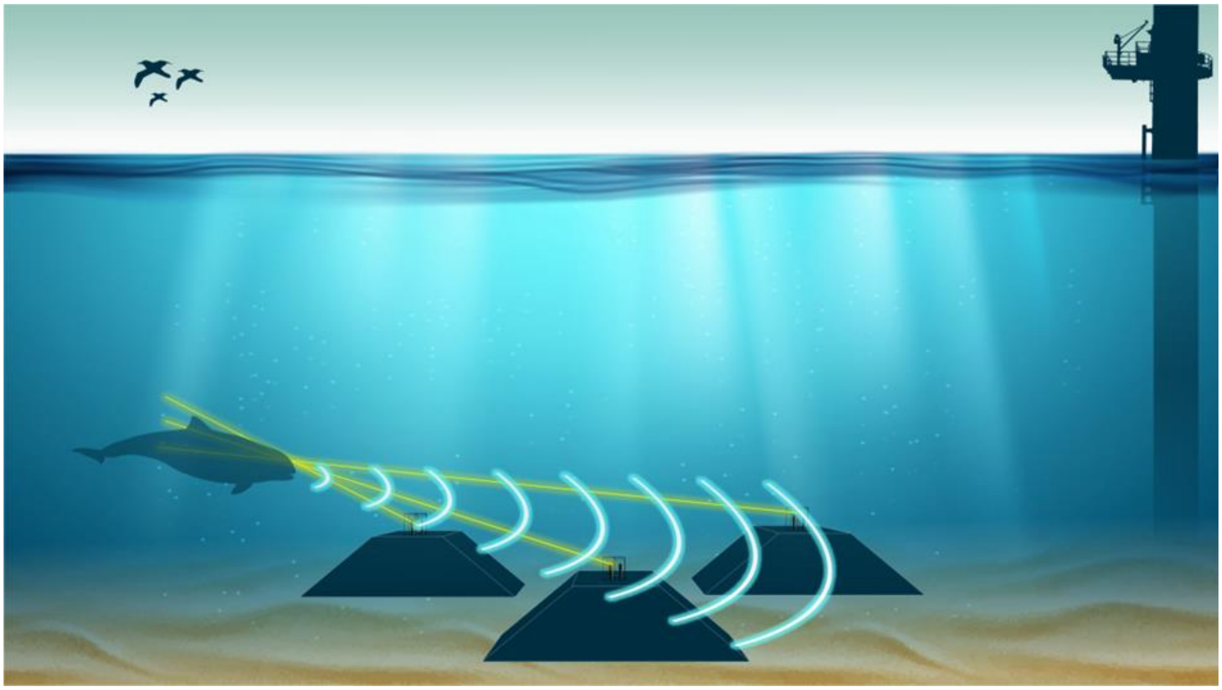


Figure 0-1 Setup of Harbour Porpoise Tracking Station, consisting of three separate hydrophone arrays.

PILOT TEST

Prior to acquiring the HPTS system that can record in the required high frequency, we developed a test-setup to work on the tracking algorithms. This test-setup is shown in Figure 0-2 and has been deployed in coastal waters in July 2022 for making test recordings.

During this campaign, two recording sessions were conducted in coastal waters (Voordelta) with a depth of approx. 5m. The station orientation was aligned with a compass to know the direction of the sources. Subsequently, controlled noises were made in a range of several meters in various directions around the station. Sounds were produced in six horizontal directions and additionally directly above the station. Also, the vessel used for deployment has sailed a circle around the station to generate a dataset that can be used for the development of the tracking algorithms.

The data has been successfully recorded and stored on the WaterProof data server.

Figure 0-2 HPTS test station, with four hydrophones for triangulation.

PRIMARY RESULTS

Data was collected by the RTsys Resea recorder with 4 Colmar high-frequency hydrophones and with a sampling rate of 312.5 kHz. The raw data from the time that the controlled noise was made near the station is shown in Figure 0-3. The eight distinct pulses have a high signal-to-noise ratio on all channels. This means that the same signal could be identified on different channels and the time lag could be used to calculate the source location. The localization was based only on the time differences between the channels in the raw data signal, so the absolute pressure values are not relevant.

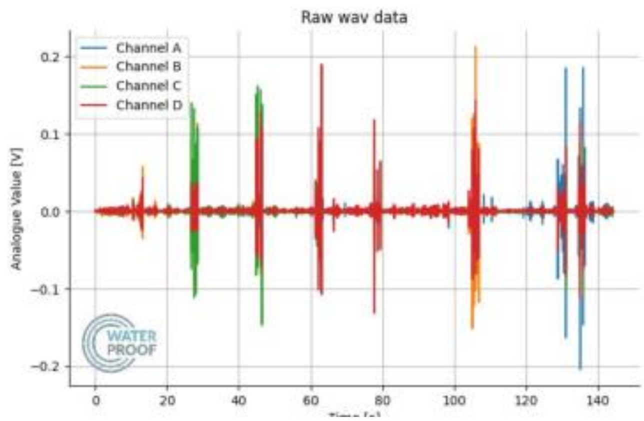


Figure 0-3 Raw data signal recorded by the four hydrophone channels.

To calculate the source location, a local reference frame was used. Hydrophones B, C, and D were positioned on a 2D plane, forming an equilateral triangle with a 75 cm distance between each hydrophone. Hydrophone A was situated at the center of this equilateral triangle, at a height of 61 cm. Hydrophone B was located North, and hydrophones C and D were positioned clockwise.

First, each individual peak was detected in 1 channel, in this case channel A. A total of 8 peaks were found, corresponding with the number of events that were emitted during the test. A peak detection algorithm was used to find the peaks in the audio signal. Based on the timing of the peaks found in the first channel, peaks were also found on the other channels at about the same time, Figure 0-4.

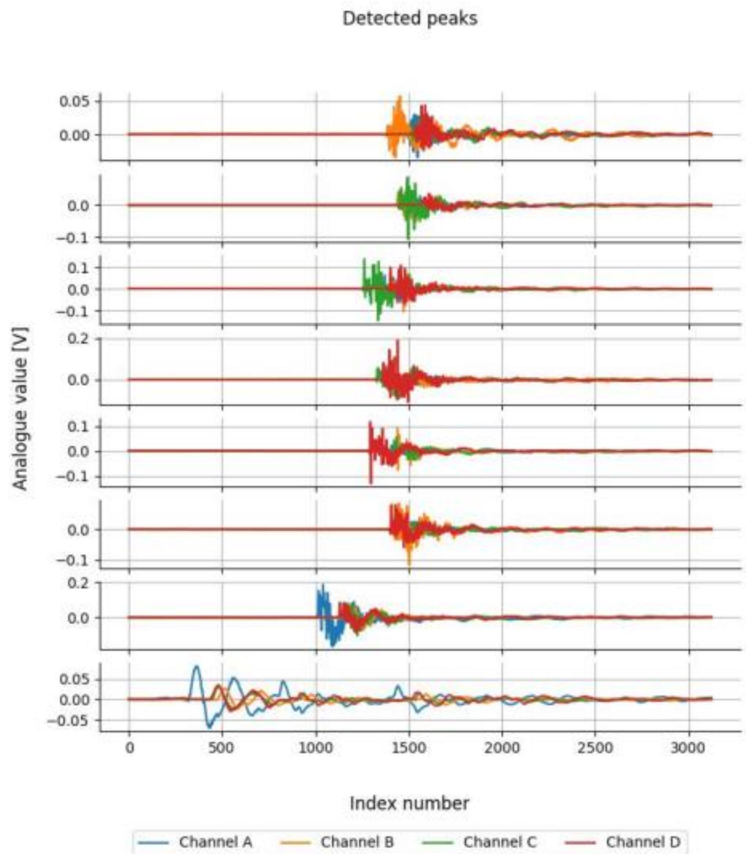


Figure 0-4 The detected peaks in the four channels.

As can be seen in Figure 0-4, there are time differences between the arrival of the sound events at the different channels. For example, the last two source locations were approximately above the hydrophone array. It can be seen that the signal was first recorded on channel A (which was above the other three channels) and later on the other channels. Based on this figure alone, it can be said that the source was located above the frame.

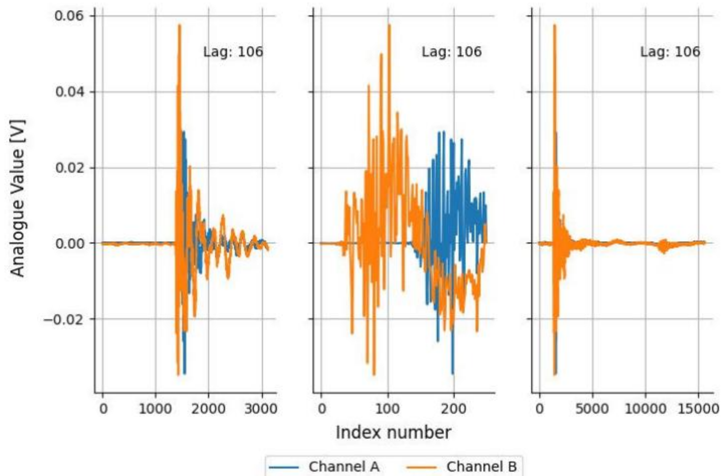
After finding the different peaks, the time delay was determined. The audio was sampled at a fixed sampling rate. Because of the fixed sampling rate, the calculated time delay is an integer. Therefore, the sampling rate is also a measure of the resolution of the calculated time delay in seconds.

The calculation of the time delay is shown below.

$$\Delta t = \frac{argmax\ (F\{x(t)\}(F\{y(t)\})^{*}\ ) - N + 1}{f_s}$$

Where $F(\dot{})$ is the Fourier Transform, $(\dot{})^{*}$ is the conjugate, f_s is the sampling frequency and N is the length of the signal. The x and y signals should have the same length.

In this case, the calculated time delay did not depend on the length of the signal used. The reason for this may be the high signal-to-noise ratio in these signals. Exactly the same time delay was calculated using the entire peak, part of the peak, and the peak including the signal after the peak.



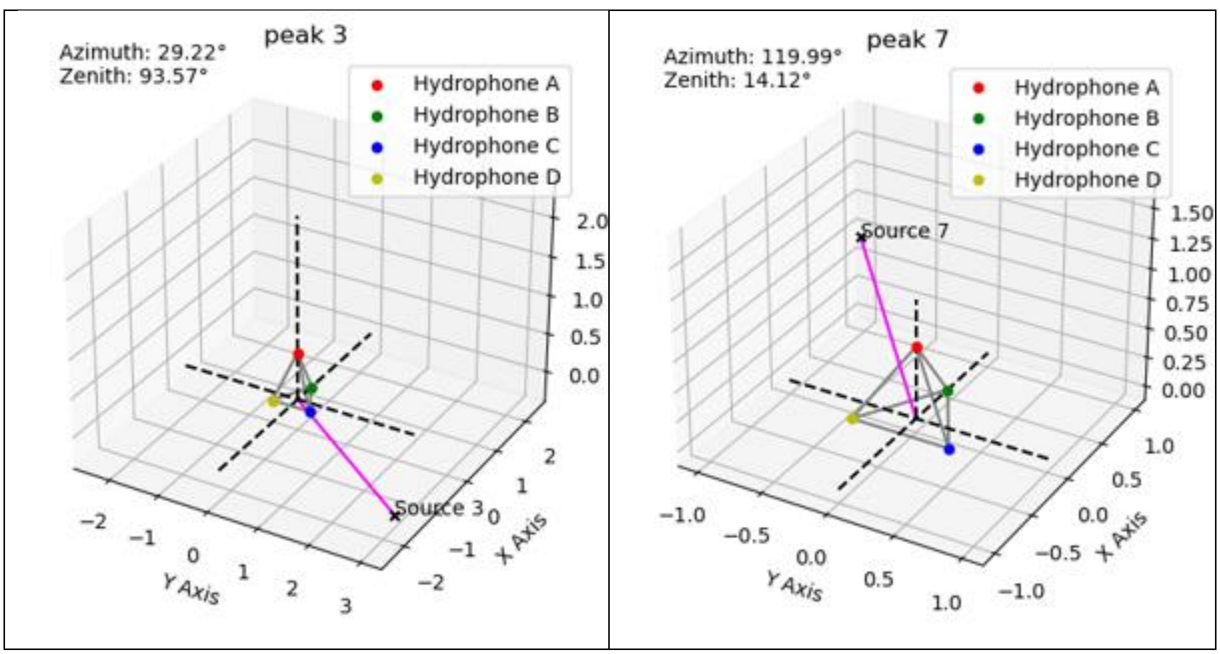
The source location was calculated based on the time differences. The system of equations was solved based on the distances between the hydrophones and the distance to the source.

$$D_h = \sqrt{(x_h - x_s)^2 + (y_h - y_s)^2}$$

Where D_h is the distance between the source and hydrophone h. The time lag was determined by;

$$\Delta t_{h1,h2} = \frac{(D_{h1} - D_{h2})}{c_w}$$

Where c_w is the speed of water, and $h1$ and $h2$ are two hydrophones. In total there are 6 unique hydrophone combinations. Based on this method the location of the source was calculated, two examples are provided in the figure below.



DISCUSSION

The test marks the start of the development of the HPTS (Harbour Porpoise Tracking Station). The provided test case delivers information about the timing accuracy of the recorder, the impact of time delay resolution and sample rate, and the capability to measure on multiple channels simultaneously.

Several aspects need consideration for a fully functional HPTS. As mentioned above, a dedicated recorder will be developed to measure at a higher sample rate. Harbour porpoise clicks fall within 120 and 150 kHz. RTsys systems do not measure up to the Nyquist frequency, but rather at $\frac{2}{5}^{th}$ of the sample rate due to an implemented anti-alias filter. The proposed system will thus need to measure at with a sampling frequency of at least 384 kHz on four channels simultaneously.

Harbour porpoise clicks are highly directional, making the frame used in the test case unsuitable for detecting individual clicks on multiple hydrophones simultaneously. The distance between the hydrophones should thus be reduced. This means that the 4 hydrophones are approximately on a wave plane from the source, i.e. the sound wave is local linear near the hydrophones. Based on the linearization approximation of the sound wave, azimuth and zenith angles can be determined, though not the exact source location. The source in the test case was relatively close to the station, but when the source is further away, the sound wave will be better described as a local (linear) plane.

Based on the observations above, one hydrophone array with four hydrophones is not enough to locate a source. One station, consisting of a recorder and four hydrophones, can measure azimuth and zenith angles (or 3D bearing). Three stations are needed to combine the three 3D bearings into a source location.

Using three hydrophones in an equilateral triangle configuration minimizes the error propagation due to timing resolution effects. This setup ensures that the angle between any two hydrophones and a random source location is constrained between 60 and 120 degrees relative to the hydrophone-baseline. Error propagation from time delay errors is minimal when the source is perpendicular to two hydrophones and increasing non-linearly as the source aligns more with the two hydrophones. The measurement model, based on the hydrophone geometry and source location, makes it possible to predict the effect of source location relative to the hydrophone baselines on the final azimuth accuracy.

FUTURE STEPS

A new recorder is currently being developed in collaboration with RTsys to be able to measure with a sufficiently high sample rate on four channels simultaneously. Due to the large amount of data needs to be collected, both the batteries and the memory of the recorder require special attention.

In addition to a localization system, i.e. the HPTS with three different recorders and frames, a solution with a single frame is also considered. While a solo array cannot compute 3D locations, it offers the potential to determine the swimming direction based on azimuth and zenith angles. This will improve the understanding of harbour porpoise avoidance behaviour around sound sources.

In addition to harbour porpoise localization, several other sound sources are present in acoustic data. By modifying the existing method, it is possible to detect other pulse sources, such as pile driving activities. Localization of continuous sources, such as vessels, presents a more complicated challenge due to the complexity in determining time delays. Both the HTPS for 3D localization and the directional arrays promise interesting datasets with valuable information on harbour porpoise behaviour.

APPENDIX B

Table xx. Statistical significance of smooth term in all models…

model_name	variable_name	p-value	
Model 5	Wind speed	<0.01	****
	Time to high tide	<0.01	****
	Sea surface temperature	<0.01	****
	Hour	<0.01	****
	Inside wind farms	<0.01	****
	year	<0.01	****
	CPOD id	<0.01	****
Model 6	Wind speed	<0.01	****
	Time to high tide	<0.01	****
	Sea surface temperature	<0.01	****
	Hour	<0.01	****
	Inside wind farms	<0.01	****
	year	<0.01	****
	CPOD id	<0.01	****
Model 1	SPLbb	<0.01	****
	Wind speed	<0.01	****
	Time to high tide	<0.01	****
	Sea surface temperature	<0.01	****
	Hour	<0.01	****
	Inside wind farms	**0.15**	**ns**
	year	<0.01	****
	CPOD id	<0.01	**
Model 3	SPLbb	<0.01	****
	Wind speed	<0.01	****

	Time to high tide	<0.01	****
	Sea surface temperature	<0.01	****
	Hour	<0.01	****
	Inside wind farms	**0.15**	**ns**
	year	<0.01	****
	CPOD id	<0.01	****
Model 2	SPLvhf	<0.01	****
	Wind speed	<0.01	****
	Time to high tide	<0.01	****
	Sea surface temperature	<0.01	****
	Hour	<0.01	****
	Inside wind farms	**0.16**	**ns**
	year	<0.01	****
	CPOD id	<0.01	****
Model 4	SPLvhf	<0.01	****
	Wind speed	<0.01	****
	Time to high tide	<0.01	****
	Sea surface temperature	<0.01	****
	Hour	<0.01	****
	Inside wind farms	**0.15**	**ns**
	year	<0.01	****
	CPOD id	<0.01	****

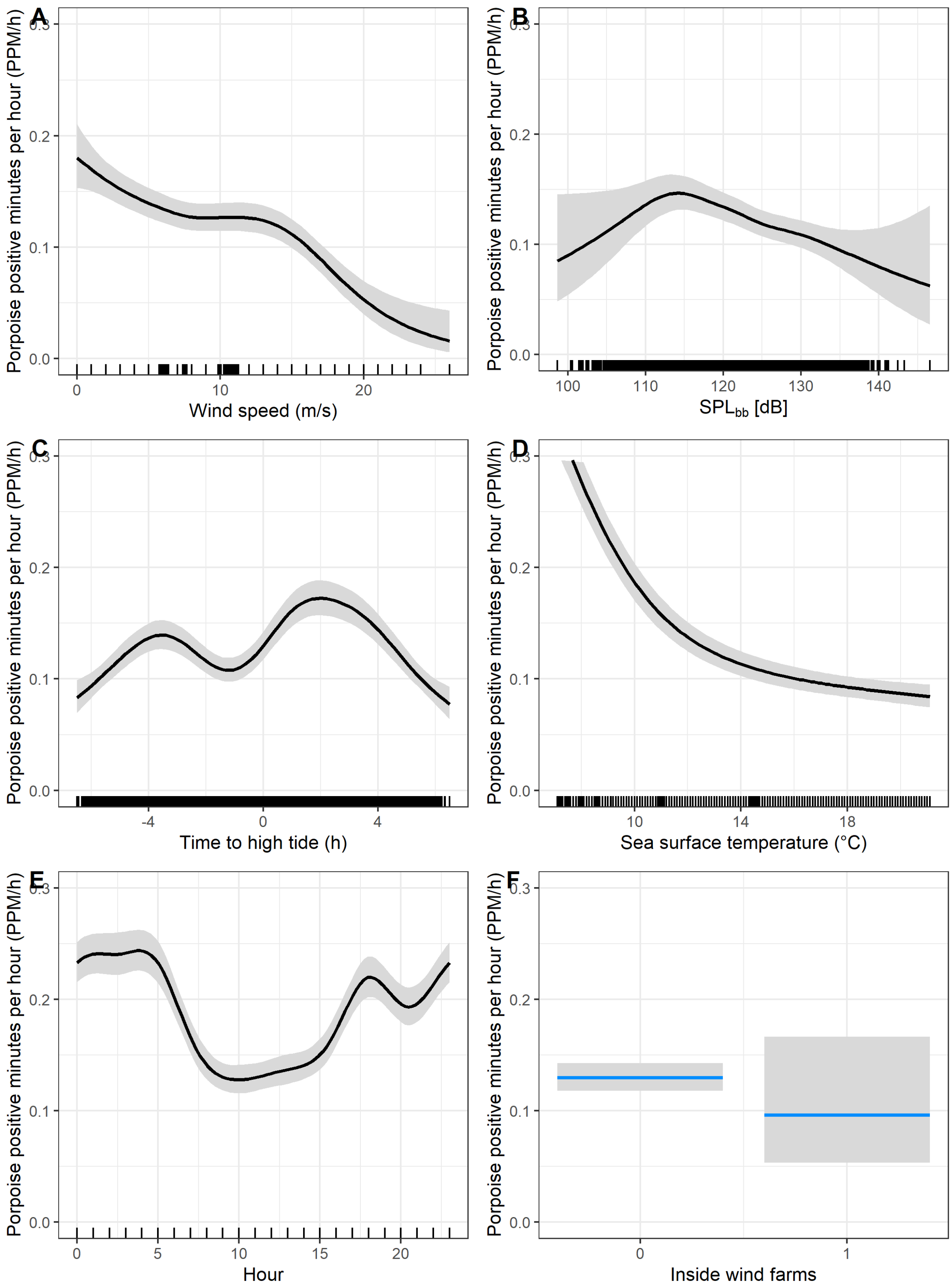


Figure 0-1 Model 1 predicted patterns in the probability of porpoise presence in relation to environmental factors and presence inside or outside Borssele wind farms based on data from all locations

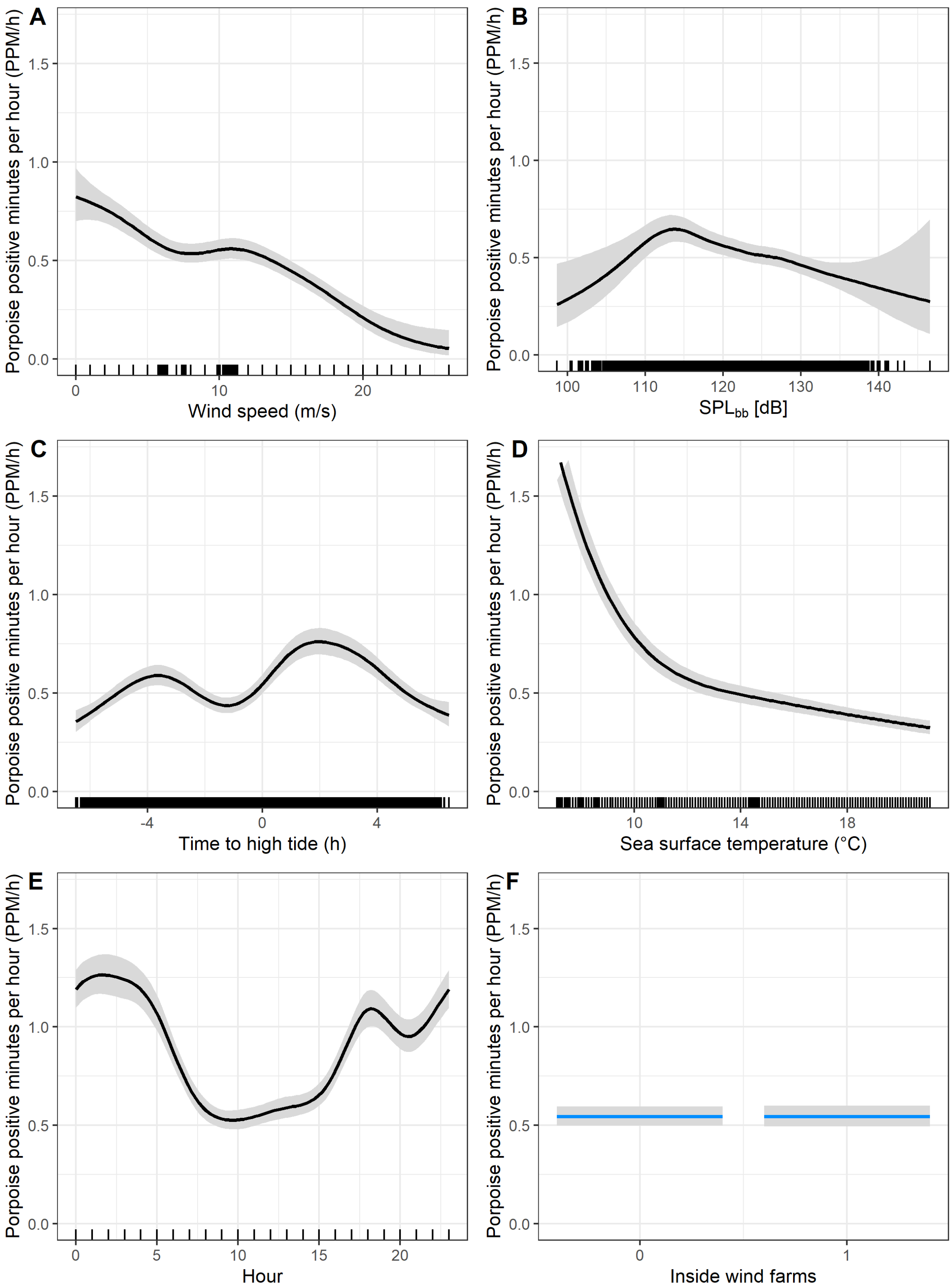


Figure 0-2 Model 3 predicted patterns in the probability of porpoise presence in in relation to environmental factors and presence inside or outside Borssele wind farms based on data from all locations

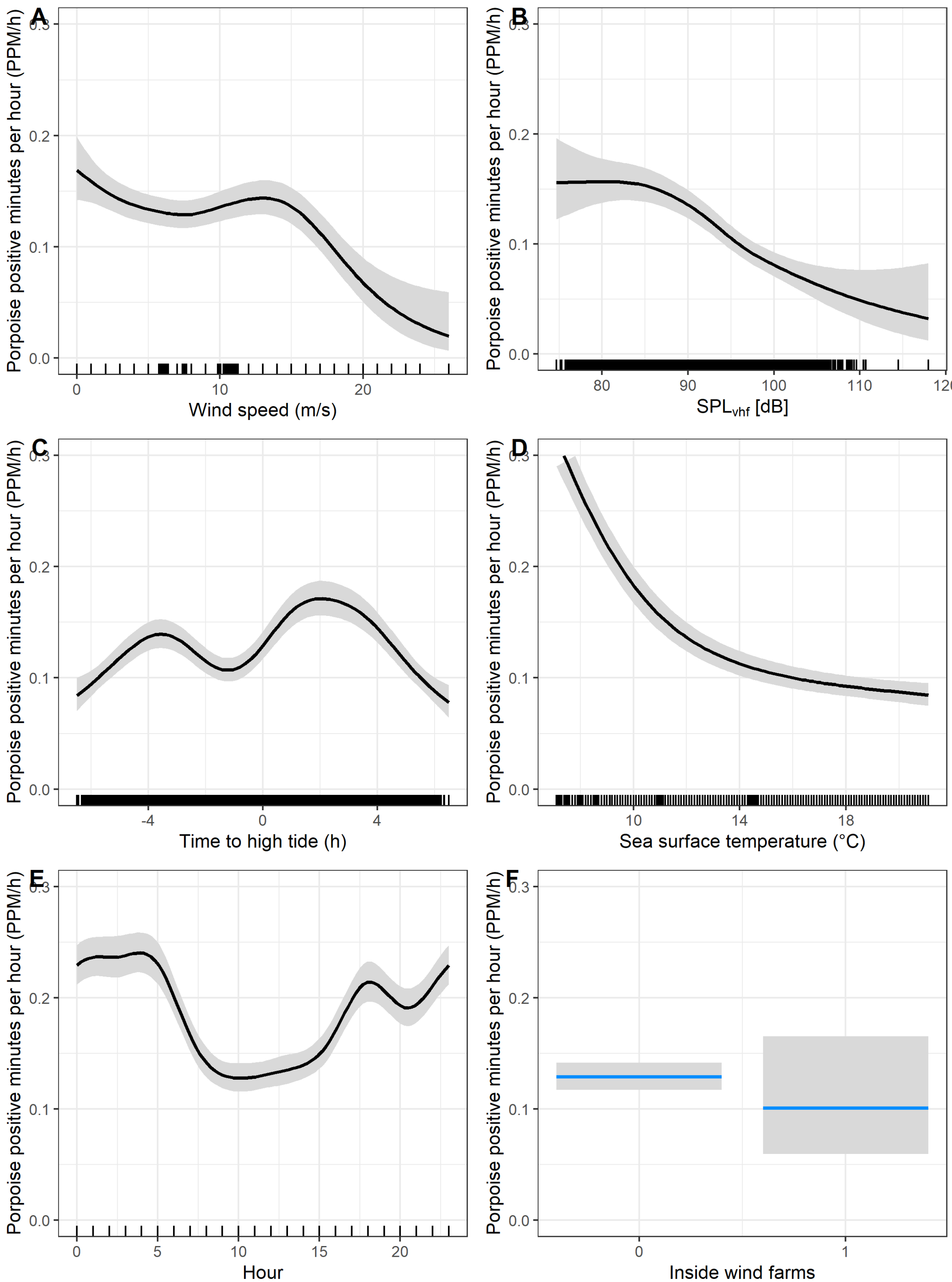


Figure 0-3 Model 4 predicted patterns in the probability of porpoise presence in in relation to environmental factors and presence inside or outside Borssele wind farms based on data from all locations

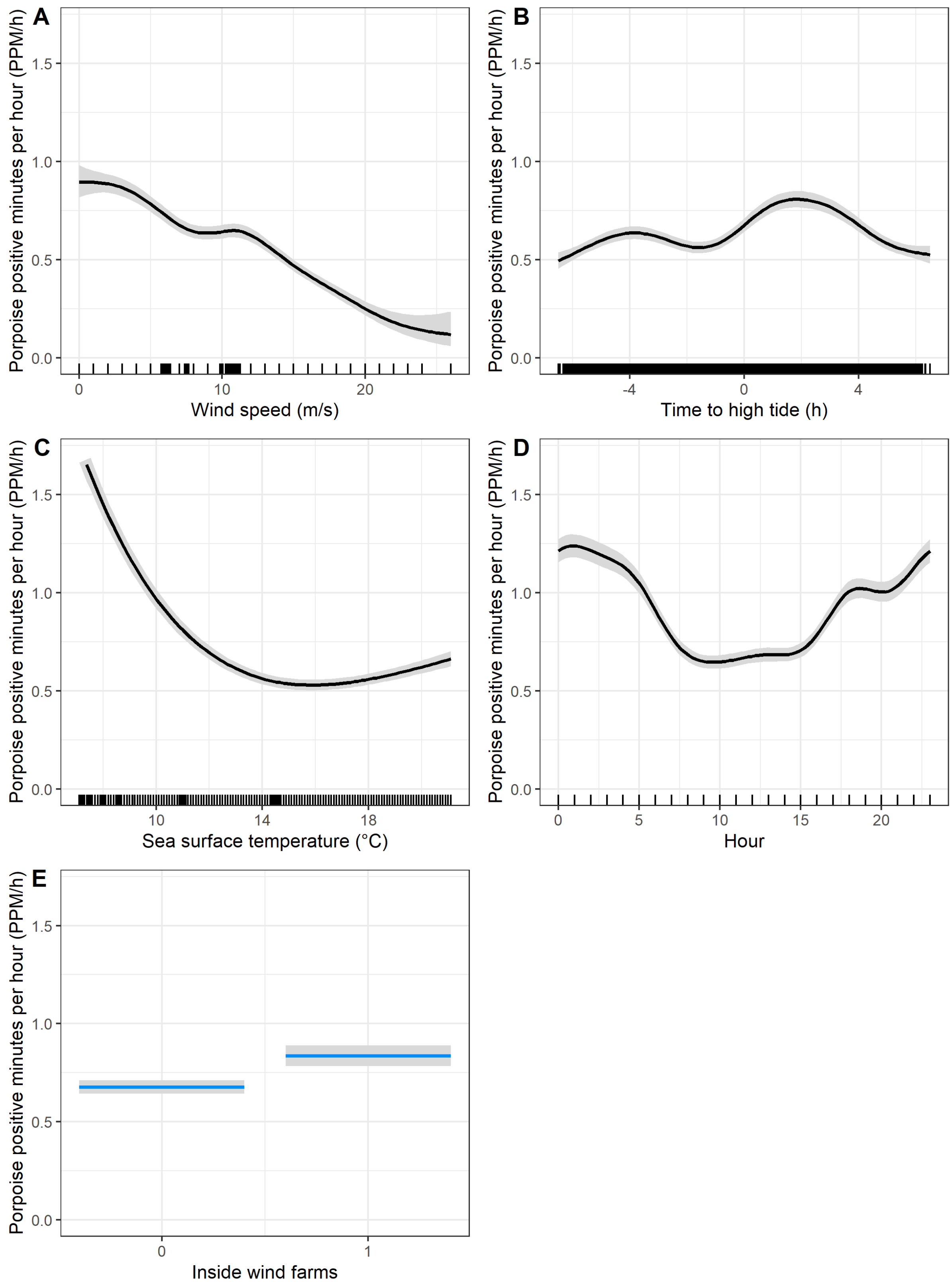


Figure 0-4 Model 6 predicted patterns in the probability of porpoise presence in in relation to environmental factors and presence inside or outside Borssele wind farms based on data from all locations