Final Report

Effects of noise-mitigated offshore pile driving on harbour porpoise abundance in the German Bight 2014-2016 (Gescha 2)

Assessment of Noise Effects

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List of abbreviations

ABW: OWF Amrumbank West

AIC: Akaike Information Criterion (statistical value for comparison of different models)

ARMA: Auto-Regressive (AR) Moving-Average (MA) process

BBC: Big Bubble Curtain

BR: OWF Borkum Riffgrund 1

BU: OWF Butendiek

BW2: OWF Trianel Windpark Borkum Phase I (formerly Borkum West 2)

CPOD: Cetacean Porpoise Detector

DBBC: Double Big Bubble Curtain

DPH: Detection-Positive Hours

DPM: Detection-Positive Minutes

EEZ: Exclusive Economic Zone

G1: Gescha 1 dataset (original study: 2009-2013; re-analysed daily CPOD data: 2010-2013; re-analysed hourly CPOD data: 2011-2013)

G2: Gescha 2 dataset (2014-2016)

GAM: Generalised Additive Model

GAMM: Generalised Additive Mixed-effects Model

GEM: OWF Gemini

Gescha 1 study: "Effects of offshore pile driving on harbour porpoise abundance in the German Bight 2009-2013"

Gescha 2 study: "Effects of noise-mitigated offshore pile driving on harbour porpoise abundance in the German Bight 2014-2016"

GLM: Generalised Linear Model

GLMM: Generalised Linear Mixed-effects Model

GT1: OWF Global Tech 1

GW: OWFs Godewind 1 & 2

HiLo: Sequence of High- and Low-Energy Piling

HRW: Hour Relative to Piling Work

HSD: Hydro Sound Dampers

IHC: Integrated Monopile Installer (Company: IHC)

N1: OWF Nordsee One

NG: OWF Nordergründe

NMS: Noise Mitigation System

NSO: OWF Nordsee Ost

OSS: Offshore Sub-Station / Converter Platform / Transformer Station

OWF: Offshore Wind Farm

PAM: Passive Acoustic Monitoring

POD: Porpoise Detector

PTS: Permanent Threshold Shift

SB: OWF Sandbank

SEL: Sound Exposure Level

s.e.: Standard Error

SPL: Sound Peak Level

SST: Sea-Surface Temperature

SSTA: Sea-Surface-Temperature Anomaly

TTS: Temporary Threshold Shift

VM: OWF Veja Mate

WP: Work Package of the tender corresponding to Gescha 2

1 SUMMARY

This study (Gescha 2) analyses the impact of the construction of eleven offshore wind farms (OWFs) and offshore converter platforms (OSS) built in the German North Sea and adjacent Dutch waters in the period 2014-2016 on harbour porpoises (*Phocoena phocoena*). The study is a direct follow-up to the Gescha 1 project, which investigated the effects of pile driving of the first eight wind farms in the German Bight (2009-2013). For the present study, also a combined dataset from 2010 to 2016 could be considered, containing most Gescha 1 and all Gescha 2 data. The dataset combines porpoise monitoring data from passive acoustic monitoring using Porpoise Detectors (CPODs) and digital aerial survey data with measured data on noise levels in 750 m and 1500 m distance from the piling location as well as other piling characteristics. These data were analysed in order to describe the response of harbour porpoises to pile driving activities, most of which took place under operation of noise-mitigation systems with the aim to reduce disturbance effects on porpoises.

Prior to investigating piling effects on harbour porpoises, baseline analyses were conducted to identify the seasonal distribution of porpoises in different geographic subareas. Daily CPOD data and digital aerial survey data uncovered seasonal patterns with often higher densities in spring and summer, especially in the north-eastern part of the German Bight. Lowest porpoise abundance was found in the central part of the German Bight with deep waters, whereas higher densities were found in the more coastal subareas. Seasonal patterns differed from subarea to subarea. In the northern German Bight porpoises showed a pronounced summer peak, whereas in the eastern subarea animals also showed considerable activity in autumn. In overall, this resulted in highest porpoise densities and detections in summer within and next to the SAC Sylt Outer Reef. Another high-density area was identified near the SAC Borkum Reef Ground in the south-western German Bight and adjacent Dutch waters. Here, highest densities were found in late winter. These results are in line with previous findings and point towards a very stable occurrence of porpoises within the German Bight. Both CPOD and aerial survey datasets showed matching regional porpoise phenology trends, indicating a high degree of correlation between these completely independent datasets.

Noise measurements at 750 m and 1500 m distance from piling locations for all German wind farms constructed between 2014 and 2016 were combined with CPOD porpoise monitoring data. Analyses of noise levels revealed a high variability within each wind farm. However, both the variability of the sound values and the average noise level were significantly reduced with the noise-mitigated pile drivings of Gescha 2, and noise levels were mostly below the BSH's mandatory noise limit of 160 dB SEL_{05} at a distance of 750 m from a piling location. Pile driving carried out during the study period of Gescha 2 had on average 9 dB lower noise levels than those of Gescha 1, and had on average more than 15 dB lower noise levels than those measured during unmitigated piling, which can be attributed to a significant improvement in noise-mitigation systems in recent years. Still, some variability in the noise measurements remained, which may result from certain environmental factors affecting sound propagation, such as water depth, substrate, and wind speed. The present study shows that noise-mitigation systems used between 2014 and 2016 had improved considerably when compared to 2010-2013 and worked consistently well in the German Bight.

Establishing of the relationship of noise level to porpoise response is crucial for environmental impact assessment based on the noise prognosis for specific projects.

Since noise-mitigation technology became more efficient over the last years and noise levels were reduced significantly, the expectation was that the displacement range and duration for porpoises due to piling noise should have been reduced accordingly.

However, this was not the case. The effect range regarding porpoise detection rates based on all hourly CPOD data during mitigated pile driving from all projects within Gescha 2 was at 17 km (std. error range: 15-19 km), and the effect duration in close range lasted from 28 hours (lower s.e.: not available; upper s.e.: 22 hours) before until 48 hours (lower s.e.: 35 hours; upper s.e.: not available) after stop of pile driving. These values were similar to those obtained at Gescha 1, and thus no reduced displacement effect could be shown when comparing Gescha 2 to Gescha 1. Analyses of 12 digital aerial surveys, conducted during or up to 12 hours after stop of pile driving, showed an effect range of 11.4-19.5 km to piling sites and thus confirmed the effect range found by CPOD data.

We discuss this outcome with five explanatory approaches which might be relevant alone or in combination.

1. **Stereotypical escape distance** within a certain noise-level range: Results of the hourly CPOD data indicate that there is no correlation between noise level and displacement range below noise levels of 165 dB SEL_{05} at 750 m from piling locations. Below this value the effect range seemed not to be further reduced. This might be explained by animals maintaining a certain minimum escape distance independent of the respective noise level if it is below this value and within a certain intermediate range. Thus, animals may react stereotypically as soon as pile-driving noise exceeds a certain individually differing unknown threshold level that must be regarded in the context of a seasonally and site-specific different condition of animals. However, regarding piling-noise levels we only had access to the broadband SEL_{05} cut off at 20 kHz, and could not refer to noise levels being weighted according to the hearing spectrum of harbour porpoises; hence, we might not have dealt with the noise most relevant for porpoises.

2. **Increasing relative importance of the displacement effect of seal scarers** with better noise reduction: Based on theoretical considerations and on measured values at a distance of 750 m from piling sites, it can be assumed that seal scarer noise up to a distance of approximately 20 km is clearly better audible for harbour porpoises than pile-driving noise mitigated by well-functioning noise-mitigation systems. This cannot explain the far-reaching effect by its own because seal scarers were also used in projects where the response range was rather short. Thus, seal scarer effects cannot be the only explanation, but might have contributed to the fact that no improvement of effect range and duration from Gescha 1 to Gescha 2 was found.

3. **Other construction-related noise**, commencing already prior to the start of deterrence and driving a large part of the animals away from those noise sources: A reduction of detection rates before deterrence and pile driving was shown for all wind farms investigated during both Gescha studies. Thus, there has to be a reason why animals leave the area up

to 24 hours before the start of the seal scarer. However, displacement during pile driving is clearly stronger than the effect before piling, at least in the close range of a few kilometres. Since the animals' only sense of perceiving a disturbance over many kilometres is their hearing system, it is assumed that anthropogenic sounds associated with pile driving are the trigger for the reaction.

4. **Cumulative effects due to tight piling sequence**: Piling schedules became much tighter with latest OWFs. By this fact it cannot be completely excluded that the time between consecutive pilings was partly so short that animals did not have enough time to come back before the next piling started. Even though we tried to include several variables into our models to capture this possible phenomenon these were often thrown out during the model-selection process. By applying to the hourly CPOD dataset a model approach with a reduced dataset where at least a break of 72 hours occurred between two consecutive pilings, we tried to minimise the possible influence of tight piling sequences. Still, the displacement range was similar to the range for OWFs built in the period 2010-2013 when piling sequences were much less tight. However, the cumulative effect might not have been captured adequately by only three days of break between pilings.

5. **Habitat characteristics at different OWF areas:** Above all, there also exists a high variability of porpoise occurrence due to different small-scale habitat structures, which might have consequences on a seasonal and inter-annual time scale in the North Sea. A good example in this context is the patchy presence of sandeel and sand goby in and around the DanTysk and Sandbank project areas, which may have contributed to different displacement radii within these two areas. Hence, since the response of harbour porpoises to disturbance also depends on habitat use and habitat characteristics, the unexpectedly high effect range for Gescha 2 might partly be attributable to habitat differences between and among the Gescha 1 and 2 OFW projects.

When looking at long-term trends of daily harbour porpoise detection rates obtained by CPODs, spatial differences occurred among the investigated subareas. In the eastern and, less pronounced, the southern part of the German North Sea and adjacent Dutch waters, we found an increasing trend from 2010 to 2016, whereas porpoise detections remained relatively constant in the northern part, and decreased in the central part of the study area. The latter subarea, however, was less important for harbour porpoises, as it generally showed low porpoise detection rates. Regarding the entire study area, porpoise detection rates increased from 2010 to 2016. Hence, cumulative OWF construction activities in the German Bight apparently did not have any measurable negative effect on population level.

In conclusion, the future development of noise-reduction measures, with the aim of reducing the radius of disturbance of harbour porpoises, must be critically reviewed, as no improvement regarding piling effects on harbour porpoises was found. Nevertheless, despite of large disturbance radii no negative effect on population level was observed.

2 INTRODUCTION

The utilisation of offshore wind energy is developing rapidly in European waters, providing an alternative to fossil fuels and nuclear power. Especially in the German Bight of the North Sea this form of utilisation of alternative energy sources, which started with the construction of the offshore wind farm (OWF) alpha ventus in 2009, is largely expanding and aiming at a nominal capacity of 15 GW in 2030 in Germany (BSH 2015).

Up to now, turbine foundations for German offshore wind farms were predominantly driven into the sea floor by a noise-intensive piling procedure, bearing a potential threat for marine mammals relying on a sensitive underwater hearing system. It was shown that pile-driving noise negatively affects hearing of seals and cetaceans and disrupts the natural behaviour of these animals (MADSEN et al. 2006; HASTIE et al. 2015; RUSSELL et al. 2015).

Of special interest in this respect is the harbour porpoise (*Phocoena phocoena*), the only resident cetacean species known to regularly roam and reproduce in German waters (REID et al. 2003; SIEBERT et al. 2006), and listed as protected species in Annex IV of the Council Directive 92/43/EEC (EU 1992). Harbour porpoises are strongly dependent on echolocation for orientation, communication and foraging, and thus are particularly vulnerable to noise-intense anthropogenic offshore activities such as pile driving (MADSEN et al. 2006) and ship traffic (WISNIEWSKA et al. 2018).

Depending on its intensity, pile-driving noise can affect harbour porpoise behaviour, lead to temporary habitat loss, and even induce physical effects such as a temporary or permanent hearing damage. Such negative effects are to be reduced or prevented by a combination of deterrence measures prior to and a soft-start at the beginning of pile driving, as well as by active noise-mitigation systems (NMS). At some wind farms, a less noise-intense High Frequency Low Energy (HiLo) piling is conducted.

Since the early days of offshore wind energy utilisation in Germany, noise-mitigation systems have been developed. In 2011, along with the construction of the OWF "Trianel Windpark Borkum Phase I", a first research project started with the aim to test the effectiveness of a bubble curtain for noise reduction (BIOCONSULT SH et al. 2014). Since then, noise-mitigation technology became more and more efficient. Bubble curtains worked more consistently and were partly used in doubled or tripled versions, or in combination with other NMS like hydro-sound dampers (HSD), an IHC noise-mitigation screen, or a Kofferdam (the latter three systems were sometimes also used alone). While many of the pilings conducted from 2010 to 2013 did not meet the mandatory noise-protection criterion of the German Federal Maritime and Hydrographic Agency (BSH) of 160 dB SEL_{05} and 190 dB SPL at 750 m distance to the piling location (BSH 2013), those of 2014 to 2016 mostly did. A research project at “Trianel Windpark Borkum Phase I" showed that the response of harbour porpoises to pile driving was directly connected to sound exposure levels (SEL) (BIOCONSULT SH et al. 2014). The onset of behavioural reactions during pile driving (change in detection rates, density, or observable behaviour) was estimated to occur at noise levels between 140 and 152 dB re 1 µPa²s by different studies (BIOCONSULT SH & IFAÖ 2010, 2014; BRANDT et al. 2011; HAELTERS et al. 2012; DÄHNE et al. 2013; BIOCONSULT SH et al. 2014). During an experimental study of harbour porpoises in captivity, KASTELEIN et al. (2013) observed a significant increase in the jumping frequency of animals that were exposed to play-back pile-driving noise of 145 dB re 1 µPa²s; the lowest noise levels at which animals started to jump was at 136 dB re 1 µPa²s.

Development and application of noise mititgation has become an important aspect of offshore wind energy projects in Germany. While initial projects showed that noise levels can be reduced substantially, it is unclear whether further improvements of the efficiency would actually result in a further reduction of disturbance of harbour porpoises, and whether such a reduction is actually required to maintain a favourable conservation status of harbour porpoises in the German North Sea when further expanding offshore wind energy utilisation.

The first Gescha study on effects of pile driving on harbour porpoise regarding eight OWFs in the German Bight built in between 2009 and 2013 (here referred to as "Gescha 1") found disturbance radii of 14 km for mitigated, and 20-34 km for unmitigated pile driving (BIOCONSULT SH et al. 2016). Decreased porpoise detections and sighting rates during unmitigated piling events in up to 20 km and more around wind farm construction sites were also found by other authors (TOUGAARD et al. 2009; BRANDT et al. 2011; DÄHNE et al. 2013; NEHLS et al. 2016). Mitigated piling, on the other hand, led to a reduction of the disturbed area by 90 % at the OWF Trianel Windpark Borkum Phase I (NEHLS et al. 2016).

Recovery times lasted for up to two days after the end of piling within close vicinity of foundations without noise mitigation (TOUGAARD et al. 2009; BRANDT et al. 2011; BIOCONSULT SH & IFAÖ 2014). With mitigated and unmitigated pilings combined, the Gescha 1 study found an overall effect duration of 20 to 31 hours, whereas values for single OWFs ranged from 16 to 46 hours (BIOCONSULT SH et al. 2016). As to noise-level dependence of the response, the onset of behavioural reactions during pile driving (change in detection rates, density, or observable behaviour) was estimated to occur at noise levels between 136 and 152 dB re 1 μPa^2s by different studies (BIOCONSULT SH & IFAÖ 2010, 2014; BRANDT et al. 2011; HAELTERS et al. 2012; DÄHNE et al. 2013a; KASTELEIN et al. 2013; BIOCONSULT SH et al. 2014).

Besides short-term disturbance effects, pile driving – if conducted frequently – may also cause long-term effects on harbour porpoises. Not all animals might return to the piling locations after multiple piling events and are therefore deterred from a specific area. Or, because multiple disturbing effects may reduce fitness, consequences on population level may be suggested to occur over several years. However, drawing conclusions from non-lethal disturbance effects onto population-level consequences remains challenging (PIROTTA et al. 2018). Recently, model frameworks were developed that predict effects of pile driving on porpoises (KING et al. 2015; NABE-NIELSEN et al. 2018). In general, those models detected only minor effects of pile driving on porpoise populations. Nevertheless, each model has uncertainties, as they use either expert judgement, strongly simplified relationships and/or include informed assumptions (PIROTTA et al. 2018). Therefore, estimating population changes remains essential in order to detect actual population consequences and thereby to validate predictions from models.

Whereas Gescha 1 focused on the effects of all pilings (mitigated and unmitigated) and on cumulative effects of parallel pile driving at two or more OWFs, the present study (here always referred to as "Gescha 2") evaluates the small- and large-scale effects of mitigated pile driving in the German Bight during the years 2014 to 2016, as well as possible effects of deterrence devices and other noise sources during construction activities (e. g. boat traffic) on harbour porpoises. The main idea behind the Gescha 2 study is an assessment of the effects of OWF construction on harbour porpoises in general, as well as a more reliable assessment of the significance and necessity of noise mitigation in particular. For comparison reasons, Gescha 2 also considers most of the

Gescha 1 data (2010-2013). The entire dataset of seven years allows for first analyses on potential population changes of porpoises after intensive pile driving conducted during this period.

Besides further investigations of population-level consequences, the following questions will be addressed:

- Can we add more details on the spatio-temporal effects of noise-mitigated pile driving on harbour porpoises?
- What are the benefits of more efficient noise mitigation?
- Are the effects of pile driving constantly increasing with increasing noise levels?
- What is the effect of piling duration on porpoise detections?
- What is the contribution of deterrence measures and of other construction-related noise sources to porpoise disturbance around pile driving?
- What is the trend in porpoise detections at the long-term monitoring stations over the entire 7-year study period of both Gescha projects (2010-2016)?

During OWF construction in these years, extensive monitoring programs collected data on porpoise presence, which are combined here for a joint and cross-project analysis on the impact of pile driving on harbour porpoises in the southern North Sea over seven years (Gescha 1 and 2). From 2014 to 2016 (Gescha 2), ten offshore wind farms were built in the German part of the North Sea; the OWF Gemini in the Dutch North Sea was analysed here as well. Including offshore converter platforms (OSS), altogether nearly 750 piles were founded from 2014 to 2016. In German waters, noise mitigation during OWF construction is mandatory, hence an overwhelming number of these pilings was mitigated, rendering comparisons to unmitigated pile driving more difficult than within the Gescha 1 study. Since noise-mitigation technology became more efficient in recent years, it is a reasonable assumption that the effects of noise-mitigated pile driving on harbour porpoises should have been further reduced, compared to mitigated pilings of Gescha 1. Additionally, not only pile driving but also boat traffic and the usage of seal scarers have the potential to deter harbour porpoises from offshore construction sites, or to cause other adverse behavioural reactions. This aspect is considered in detail in the context of this study.

Two types of data were used in the present study, the one type consisting of detection rates from passive acoustic monitoring, the other type consisting of sightings from digital aerial surveys. Detailed information was gathered on deterrence and noise-mitigation measures, as well as other piling characteristics. All these metadata, together with manifold environmental variables, were merged with CPOD and aerial survey data. The obtained dataset was suitable for analyses of effects of mitigated pile driving on acoustic detection rates and densities of harbour porpoises in the study area, both at small and large spatio-temporal scales. Analytical issues arose with Gescha 2 due to tighter piling schedules of more recently built OWFs. Population-level effects were analysed, based on combined Gescha 1 and 2 data, in order to evaluate to what extent the harbour porpoise population of the German North Sea might have been affected on the long term by OWF construction activities in the period from 2010 to 2016.

3 GENERAL METHODS

The Gescha 2 study focusses on data collected from 2014 to 2016 (3 years) but also considers data collected from 2010 to 2013, which were subject of the Gescha 1 study. Eight offshore wind farms were entirely constructed in the period from 2014 to 2016 in the German North Sea with a total of 545 monopiles, one Suction Bucket Jacket, 24 piles for internal project platforms and two transformer platforms for electric grid connection offshore (see list below). In addition, pile driving in the year 2014 for the OWFs GT1 and NSO, where construction started before 2014, was included. The present study also takes into account pile driving for the Dutch wind farm Gemini, which is located directly at the German-Dutch border.

The research questions of Gescha 2 are analysed based on three different datasets for harbour porpoises:

- CPOD data collected during the environmental monitoring of OWFs during baseline, construction and operational phase, based on the methodology described in the StUK 4 (BSH 2013). Within this framework, long-term measurement series have been collected over a period of several years at fixed locations.
- CPOD data collected during pile driving in close vicinity to piling locations, following the procedure given by 'Nebenbestimmung 14' within the permission documents of the BSH for each OWF (also referred to as efficiency control). These data were collected from a few hours before to a few hours after the end of piling at fixed distances of 750 m and 1500 m to the construction site.
- Digital aerial flight data collected for environmental monitoring during baseline, construction and operational phase, based on three different techniques: HiDef, DAISI and APEM.

Besides porpoise data from CPODs and digital aerial surveys, a. o. the following explanatory data of different sources were used:

- Noise-level data were available for most of the piling events (except for OWF Gemini), consisting of direct measurements in 750 m and 1500 m distance to pile driving.
- Environmental data were extracted from various open sources and prepared to match the spatio-temporal resolution of CPOD data and aerial survey data on porpoise occurrence.

3.1 Research area, wind farm projects, and available data

The present study investigates pile-driving effects of construction works for eleven offshore wind farms (OWF) and two converter platforms (OSS) built in the German North Sea and adjacent Dutch waters between January 2014 and December 2016 (geographic positions in Figure 3.1), on harbour porpoises:

- OWFs: Amrumbank West (ABW; Cluster Helgoland), Borkum Riffgrund 1 (BR; Cluster UMBO), Butendiek (BU), Gemini (GEM; Dutch North Sea), Global Tech I (GT1), Godewind 1

& 2 (GW; Cluster UMBO), Nordergründe (NG), Nordsee Ost (NSO; Cluster Helgoland), Nordsee One (N1; Cluster UMBO), Sandbank (SB; Cluster Westlich Sylt), Veja Mate (VM).

- OSS: HelWin2, SylWin1.

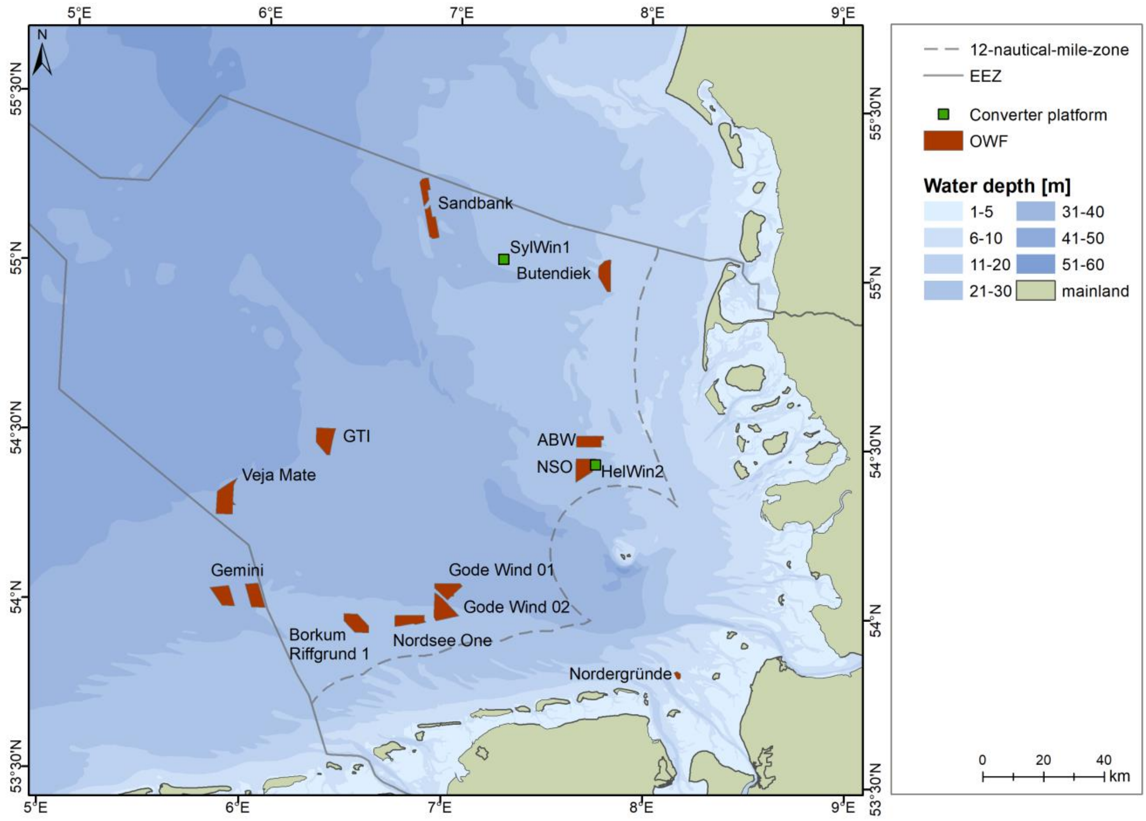


Figure 3.1 Map of the study area with all offshore wind farms (red) and converter platforms (green) for which at least some pilings were conducted between January 2014 and December 2016.

3.2 Pile driving

A piling event was defined as the time of continuous pile driving at one foundation with breaks of no more than three consecutive hours. After a break of more than three hours a new piling event started. Due to mainly using monopiles for the wind farms included to Gescha 2 (only NSO was constructed using jacket foundations), and due to the fact that a maximum duration for pile-driving work of three hours has been set by the BSH, the number of piling events for Gescha 2 only moderately exceeded the number of installed piles. A total of 770 piling events for 746 piles were considered for Gescha 2 (2014-2016). This was different from the data of the Gescha 1 study period where a lot more OWFs were constructed based on jacket or tripod foundations causing on average more piling events per foundation. Also, the piling process was more often interrupted by more than three hours with Gescha 1 pilings than with Gescha 2 pilings.

Table 3.1 Number of piles and piling events of the investigated OWFs and converter platforms (OSS) during the study period of Gescha 2 (2014-2016).

Project	Start of piling (including de-terrence)	End of piling	Number of OWF piles Total (+OSS)	Number of OWF piles 2014-2016 (+OSS)	Number of OWF piling events 2014-2016 (+OSS)
ABW	14.01.2014	17.03.2015	80+4	80+4	93+3
BR	21.01.2014	28.07.2014	77(78[1])+4	77	78
BU	31.03.2014	21.07.2014	80+4	80+4	80+3
GEM	01.07.2015	17.10.2015	150+4	150+4	151+9
GT1	05.10.2012	17.07.2014	80+4	4	4
GW	14.04.2015	13.09.2015	97+2	97+2	98+3
NG	03.05.2016	20.07.2016	18+1	18+1	20+1
NSO	24.10.2012	12.03.2014	48+4	8	8
N1	14.12.2015	07.05.2016	54+4	54+4	55+8
SB	06.07.2015	04.05.2016	72+1	72+1	74+1
VM	03.04.2016	05.09.2016	67+4	67+4	70+2
SylWin1	28.04.2014	09.05.2014	+9	+9	+5
HelWin2	20.04.2014	22.04.2014	+6	+6	+4
Sum			**824+51=875**	**707+39=746**	**731+39=770**

Pile driving within the wind farms occurred in varying numbers and sequences (Table 3.1). Whereas between 2014 and 2016 a total of 154 piles were installed for the OWF Gemini, only four piles were installed for Global Tech I. The latter and Nordsee Ost were the only two wind farms for which construction work had already started before the beginning of the study period, so that only a few pilings could be investigated for these wind farms within the framework of Gescha 2.

A timeline of pile-driving construction works that took place in the period from 2014 to 2016 for all OWFs as well as the OSS HelWin2 and SylWin1 is shown in Figure 3.2. Due to tighter pile-driving schedules, the overlap in construction times between the respective wind farms was less pronounced than in the dataset of Gescha 1. Therefore, cumulative effects of simultaneous pilings at different OWFs could not be investigated during the Gescha 2 project.

[1] Application of suction bucket for one pile.

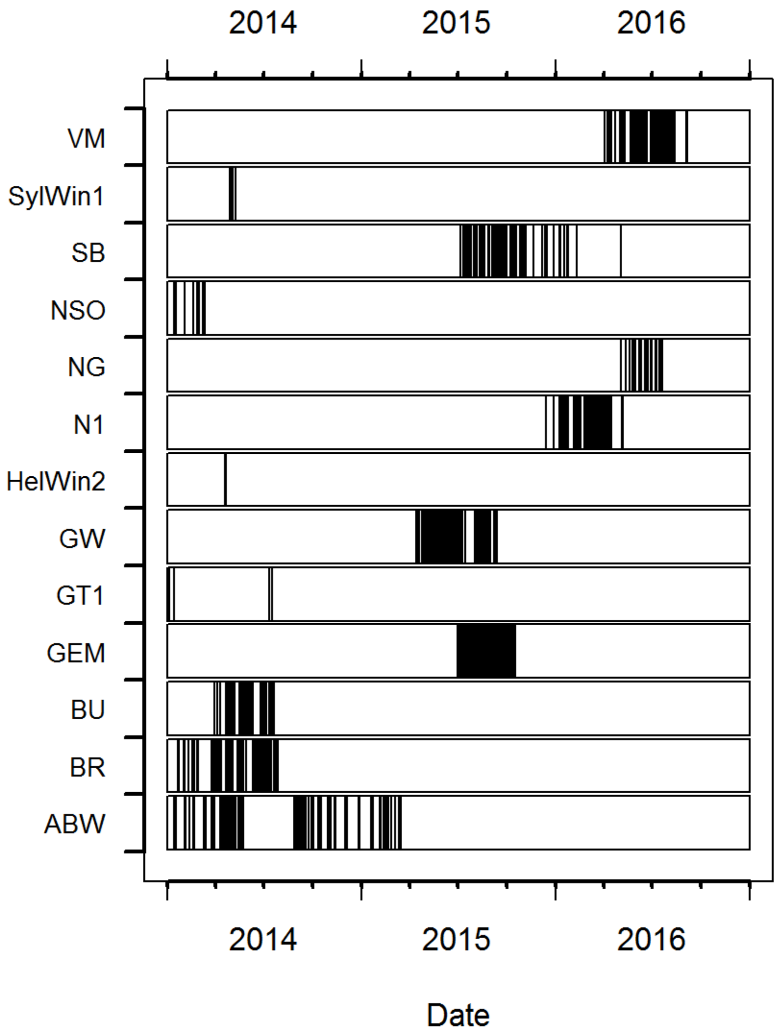


Figure 3.2 *Timeline of pilings conducted for the investigated OWFs and converter platforms in the period from January 2014 to December 2016.*

Even though piling events lasted up to 10.2 hours for projects using monopile foundations, the duration was mostly around two hours. Following, there was much less variation in piling duration among Gescha 2 OWFs than among Gescha 1 OWFs which to a greater deal used tripod and jacket foundations.

Previous studies showed that piling effects on porpoises can be detected for up to two days (e. g. TOUGAARD et al. 2009; BRANDT et al. 2011; BIOCONSULT SH & IFAÖ 2014), which is also supported by our Gescha 2 dataset (Figure 4.23). Therefore, for the small-scale CPOD analysis 48 hours between piling events have been regarded as the time span after which porpoise detections were not affected by previous pilings anymore.

Noise-mitigation characteristics varied among OWF projects. Of all 770 piling events, noise mitigation was applied during 589 piling events (76.5 %), whereas 181 piling events (23.5 %) remained unmitigated. The great majority of piling events without noise mitigation occurred at OWF Gemini in the Netherlands where noise mitigation was not required (N = 160). OWFs and OSS including 1-7 piling events without noise mitigation were ABW, BR, BU, GW, N1, SB, VM, and HelWin2. In the study period, exclusively mitigated pile driving took place at GT1, NG, NSO, and SylWin1 (Table 3.2).

Table 3.2 Number of foundations and piling events (+ OSS pilings) with and without noise mitigation per project and in total between 2014 and 2016; four piles had piling events both with and without noise mitigation (see footnotes 2 to 5).

Project	Foundations without noise mitigation (+OSS)	Foundations with noise mitigation (+OSS)	Piling events without noise mitigation (+OSS)	Piling events with noise mitigation (+OSS)
ABW	6[2)]+1	75[2)]+3	6+1	87+2
BR	5[3)]	73[3)]	5	73
BU	2	78+4	2	78+3
GEM	150+4	-	151+9	-
GT1	-	4	-	4
GW	1[4)]	97[4)]+2	1	97+3 345
NG	-	18+1	-	20+1
NSO	-	8	-	8
N1	2	52+4	2	53+8
SB	2	70+1	2	72+1
VM	1	66+4	1	69+2
SylWin1	-	+9	-	+5
HelWin2	+3[5)]	+4[5)]	+1	+3
Sum	**169+8=177**	**541+32=573**	**170+11=181**	**561+28=589**

With Gescha 1 a higher proportion and absolute number of attenuated piling events were available. In total, Gescha 1 comprised of 354 piling events attenuated by a NMS, and 220 piling events without any noise-mitigation system (BRANDT et al. 2016).

3.3 Noise measurements

The data of the mandatory sound measurements at 750 m and 1500 m distance from pile driving sites were used to evaluate small-scale and short-term effects of pile driving on harbour porpoises. The broadband Sound Exposure Level (SEL) served as a measure for the noise level of piling events. In contrast to other commonly used noise measurements, the SEL is not averaged over an *a priori* defined time interval. This is important as piling noise is inherently impulsive noise. Consequently, noise levels over time would strongly depend on the inter-pulse duration and not only on the noise level of single pulses.

[2] Pile ABW_A45: two piling events, one with and one without noise mitigation.

[3] Pile BR_H03: two piling events, one with and one without noise mitigation.

[4] Pile GW_H02: two piling events, one with and one without noise mitigation.

[5] Pile HelWin2_C2: two piling events, one with and one without noise mitigation.

The SEL is expressed in decibel units [dB re 1 µPa²s] and defined as:

$$SEL = 10\log\left(\frac{1}{T_0}\int_{T_1}^{T_2}\frac{p(t)^2}{p_0^2}dt\right)$$

T_1, T_2 Start time and end time (the noise event has to occur between start and end time);

T_0 Reference value for 1 sec;

p(t) Temporal variation of noise level;

p0 Reference noise level (underwater: 1 µPa).

For each piling impulse, a single SEL value was calculated. In order to describe a piling event, percentile levels are given, among them the median SEL_{50} (50 % of values are louder). Similarly, the SEL_{05} and SEL_{90} are defined as the noise levels exceeded by 5 %, or 90 % of all values, respectively. During this study, only the SEL_{05} was used for analyses.

Measured SEL_{05} values for all wind farm projects, both for Gescha 2 and Gescha 1 (for comparison), are shown in Figure 3.3. A marked difference exists between pilings under noise mitigation and without mitigation for all wind farm projects (except for GW where the only reference piling was less noise-intense than reference pilings of other OWFs). Furthermore, noise mitigation became more efficient during the last years. With Gescha 2 wind farms, the German noise protection criterion for marine mammals, demanding that 160 dB re 1 µPa²s should not be exceeded in 750 m distance to pilings, was mostly met for mitigated pilings (Figure 3.3). Nevertheless, some variation among the Gescha 2 projects was still visible, with pilings for ABW and BR being slightly louder than those for BU, GW and N1.

Since porpoises have the best hearing ability at frequencies around 130 kHz (e. g. KASTELEIN et al. 2010), whereas sound emissions from driving are dominated by low frequency sound (< 1 kHz), it is often argued that the hearing ability of the species must be taken into account for a better assessment of the effect of pile-driving noise on porpoises. In addition, bubble curtains used for noise mitigation with most wind farms predominantly filter out higher frequencies, leading to a further decrease in the noise perceived by harbour porpoises outside a bubble curtain. The leftover high-frequency noise would be the most interesting fraction with respect to effects on harbour porpoises. Therefore, it was originally intended to use a modified SEL_{05}, taking into account the hearing audiogram of harbour porpoises (NOAA 2016). However, it was difficult to adequately apply the so-called NOAA frequency weighting, because the frequency range of the hydrophone recorders used at 750 m and 1500 m was limited to 20 kHz. This is adequate for the system's primary purpose, i.e. the measurement of broadband noise levels of pile-driving noise (Betke, pers. comm.). However, it renders a frequency weighting according to the hearing ability of porpoises problematic, because only the lower part of the frequency spectrum audible by harbour porpoises was captured. Furthermore, the level controls of the recorder were set to the very high noise levels of pile driving. Therefore, the fainter background noise (e.g. ships) and seal scarer noise were hardly assessible. Following, it was not feasible to compute NOAA-weighted levels, and the broadband SEL_{05} was used instead which allowed a direct comparison with other studies like Gescha 1.

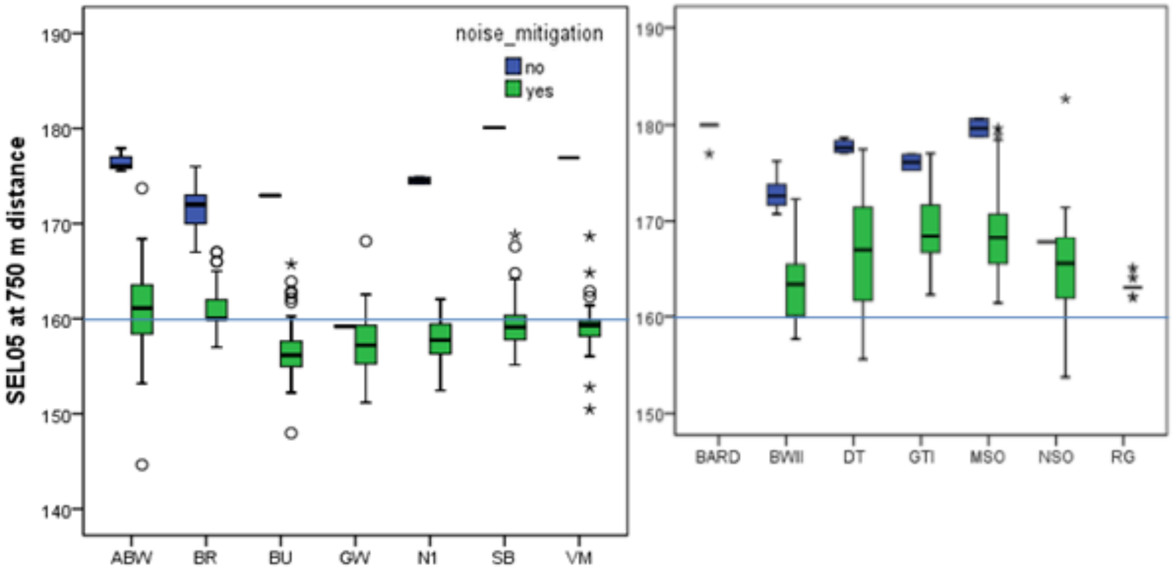


Figure 3.3 *Noise level SEL_{05} (dB) of piling events at 750 m distance for Gescha 2 OWF projects with mostly mitigated pile driving (left), and for Gescha 1 windfarms (right; from (BRANDT et al. 2018a); the blue line indicates the German noise protection criterion for marine mammals stating that 160 dB re 1 µPa²s should not be exceeded in 750 m distance to pilings; the bold black line within each box represents the median value, the boxes range from 25-% to 75-% quantiles, and whiskers indicate minimal and maximal values without outliers (outliers: asterisks).*

We based the assessment of possible effects of the seal scarer on theoretical propagation curves of unweighted and NOAA-weighted pile driving and seal scarer noise levels (Figure 3.4; provided by itap, Oldenburg). These indicate that the compartment of piling noise audible by harbour porpoises is about 40 dB lower than the broadband piling-noise level. By contrast, the audible compartment of seal scarer sound nearly equals its broadband noise level (Figure 3.4). In larger distances, the high-frequency seal scarer sound has a higher transmission loss than the low-frequency piling sound. But only at large distances the NOAA-weighted seal scarer and piling curves overlap. Yet, since these curves are only rough approximations where minor changes lead to a large change of the distance where both curves overlap, this overlap might well occur at a much narrower distance than the roughly estimated 20 km shown in Figure 3.4. Nevertheless, it remains evident that a dominant effect of a seal scarer can be quite far-reaching. As with all OWF projects in Gescha 1, also with all German projects in Gescha 2 seal scarers were used to deter porpoises from construction sites about 30 minutes before pile driving started. Table 3.3 lists the different deterrence devices that were used during Gescha 2.

Table 3.3 Deterrence device, emitted frequencies, noise mitigation system(s) used (see List of Abbreviations before Introduction), and foundation type installed for the Gescha 2 OWFs and OSS.

Project	Deterrence device	Frequency	Noise mitigation system(s)	Foundation type
ABW	LofiTech Seal scarer AirMar Seal scarer	14 kHz 10 kHz	BBC, DBBC, HSD, IHC	Monopile
BR	LofiTech Seal scarer	14 kHz	BBC (only for OSS), IHC	Monopile
BU	AirMar Seal scarer	10 kHz	BBC, IHC	Monopile
GEM	FaunaGuard	60-150 kHz	-	Monopile
GT1	LofiTech Seal scarer	14 kHz	BBC	Tripod
GW	LofiTech Seal scarer	14 kHz	BBC, IHC	Monopile
NG	LofiTech Seal scarer ACE Aquatech	14 kHz 10-20 kHz	BBC, DBBC	Monopile
NSO	LofiTech Seal scarer	14 kHz	BBC	Jacket
N1	AirMar Seal scarer	10 kHz	BBC, IHC	Monopile
SB	LofiTech Seal scarer	14 kHz	BBC, DBBC, HSD	Monopile
VM	LofiTech Seal scarer	14 kHz	DBBC, HSD, HiLo	Monopile
SylWin1	LofiTech Seal scarer	14 kHz	DBBC, Kofferdam	OSS
HelWin2	LofiTech Seal scarer	14 kHz	Kofferdam	OSS

Seal scarers are designed to scare marine mammals away from noise of potentially damaging quality. They emit loud pulses with a certain fundamental frequency (e. g. LofiTech: 14 kHz) and duration (LofiTech: around 0.55 s), with random pauses between the pulses (LofiTech: from <1 to 90 s) (Brandt et al. 2013a). As an alternative deterrence system, the FaunaGuard, which was only used at OWF Gemini, randomly emits sounds that are designed to fit specific requirements for the target species, here harbour porpoise. The different sounds are based on the hearing range and sensitivity of this species (frequency spectrum) and the reaction threshold levels, based on known literature and extensive behavioural response experiments. The frequency spectrum of the deterring sounds of the FaunaGuard have been designed to be within the functional hearing range of the target animals, and within the range of best hearing, so that the sensation level (number of dB above the hearing threshold for a particular frequency) is as high as possible, thus creating a deterring range that is as large as possible (van der Meij et al. 2015).

Another source of construction-related noise is the locally enhanced boat traffic from, towards, and around piling locations. Various behavioural reactions of harbour porpoises to ships are described in the literature (see chapter 4.1.3).

Finally, the marine environment produces a general background level of noise, e. g. by wave and sediment movements, so that noise levels of anthropogenic noise sources at some distance fall below the natural background level.

Originally, it was planned to directly relate these different underwater sound sources around the times of pile driving to the detection rates of harbour porpoises. Due to the settings of the hydrophones in 750 m and 1500 m, neither background sound (low sensitivity) nor high-frequency impulse sound (emphasis on main piling-noise frequencies) could be recorded adequately, so that such an analysis could not be performed.

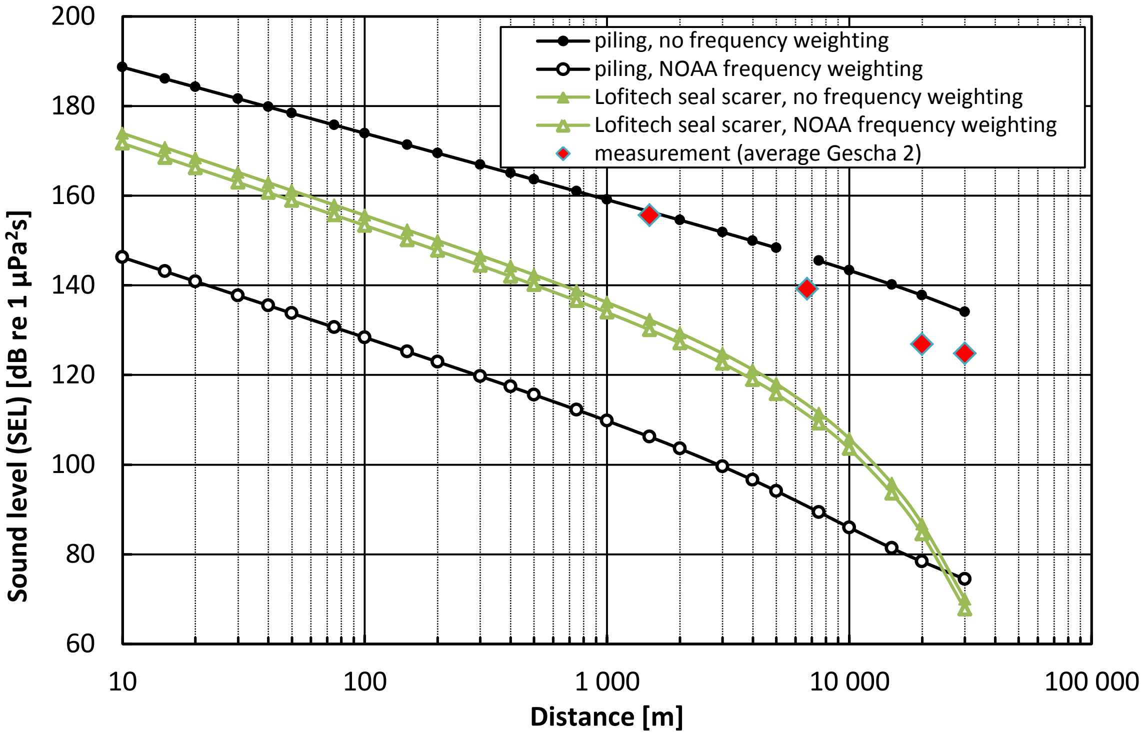


Figure 3.4 *Theoretical sound propagation curves (itap, Oldenburg) of the SEL (dB) of mitigated pile driving and seal scarer noise vs distance, with NOAA Hi-Cetacean frequency weighting, and without frequency weighting (= broadband); red symbols show three values measured at Gescha 2 wind farm projects, indicating that for broadband pile-driving sound the transmission loss is slightly higher than modelled at larger distances.*

3.4 Passive Acoustic Monitoring data using CPODs

Harbour porpoises use echolocation by means of short high-frequency click sounds which are emitted to communicate, assess surroundings, and track down prey (AKAMATSU et al. 2001; WISNIEWSKA et al. 2016). Passive Acoustic Monitoring (PAM) by Cetacean Porpoise Detectors (CPODs) makes use of this behaviour by registering the emitted clicks with hydrophones. Click sounds are emitted in frontal direction with a beam angle of 16.5° maximum (AU et al. 1999). In consequence, PODs are only able to detect porpoises if the animals (1) emit click sounds, (2) are within a range of about 300 m around the hydrophone, and (3) are facing towards the hydrophone. Registration probability is therefore strongly dependent on porpoise activity, distance and emission direction relative to the POD.

Harbour porpoises equipped with a hydrophone were shown to use their echolocation system almost continuously (AKAMATSU et al. 2007; WISNIEWSKA et al. 2016). Hence, echolocation is assumed to be the most important sensory perception, which by its constant use allows correlation between detection rates of PODs and porpoise density in a marine area. TOUGAARD et al. (2006) and KOSCHINSKI et al. (2003) were able to demonstrate a relationship between echolocation and time-congruent observations. TOUGAARD et al. (2006) published on decreasing detection rates (porpoise-positive minutes per day) with increasing distance to the hydrophone by distance-sampling theory (BUCKLAND et al. 2001). Their concept allowed computation of a relationship between POD detection rates and porpoise densities. Such a relationship was also found by KYHN et al. (2012). A significant correlation between densities obtained by aerial surveys and POD detection rates was furthermore observed by DIEDERICHS et al. (2002) and SIEBERT & RYE (2008). Thus, it is a valid assumption that POD detection rates are a rough measure of true harbour porpoise densities: the higher the detection rates, the more animals are present in the area.

CPODs are autonomous data loggers able to register high-frequency sound events. They consist of a plastic tube of 80 cm length with a hydrophone positioned inside at the one end. Directly attached to this are an amplifier and an electronic filter. The hydrophone works omnidirectional, registering all sound events ranging from 20 kHz to 160 kHz. For each click, the main frequency, frequency-response curve, sound duration and intensity (steps of 8 bit), as well as band width and envelope of the frequency spectrum are saved on an SD memory card (maximum 4 GB). A total of ten 1.5 Volt D batteries provide the device with energy for at least six weeks.

In overall, PODs provide the following important information on harbour porpoises:

- presence/absence of animals around a station;
- relative abundance (the higher the detection rate, the more animals were present at this position);
- assessment of diel and yearly (=phenology) activity cycles.

As we assume that detection rates are not much influenced by differences between single PODs, spatial and temporal dissimilarities between stations as well as temporal changes can be evaluated at different temporal resolutions. To achieve this goal, PODs were calibrated prior to their first deployment and regularly during the study period, which minimises errors caused by differences in POD sensitivity.

Generally, PAM is suitable for providing long-term datasets, thus giving rise to the possibility of integrating short-term fluctuations. However, the obtained data originate from a relatively small area since the detection range of PODs amounts to only about 300 metres. In contrast to aerial surveys, PAM provides continuous long-term, but spatially small-scale datasets. This is the reason why we used both PAM and aerial survey data to analyse porpoise responses to pile driving.

Data collection

In this study, data from three different POD-deployment schemes are used: continuous monitoring positions (POD stations with three PODs each), project-specific stationary PODs (single stationary PODs), and mobile PODs. Though deployment specifications differ slightly among locations or responsible companies, the general principle is always the same for the three schemes: a POD is located in the water column 5-10 m above the sea floor, it is held in position at the sea floor by a mooring system and kept in the water column by a buoy. Although the three POD-deployment schemes differ in design and settings, the same technical device, the CPOD (Cetacean POrpoise Detector; Chelonia Ltd., UK; Figure 3.6), was used.

- POD stations consist of three simultaneously deployed PODs in close vicinity to each other. They are located within a square of four marker buoys that indicate the location of the POD station and prevent ships from accidentally crossing this area, causing equipment loss. Simultaneous deployment of multiple PODs at one location accounts for an occasional loss or malfunction of single PODs. POD stations are serviced about every 1-2 months, when memory cards and batteries are exchanged and lost PODs replaced. In case of a noisy environment the memory cards data capacity might be exceeded. To avoid this, a maximum of 4,096 clicks/min was set as recording limit. If this number was reached, the POD stopped recording for the remaining seconds of that minute. Only data from one POD at a time were analysed per POD station, and it was always the POD with the most complete time series of recordings that was chosen.

- Single stationary PODs were deployed for specific wind farm projects. They consist of only one POD using a similar mooring system and the same POD settings as POD stations.

- Mobile PODs were deployed at close distance to a certain piling location (usually one at 750 m and one at 1500 m distance) with the aim to monitor the efficiency of deterrence measures. Each mobile POD is usually deployed only from a few hours before to a few hours after a specific piling event. For this type of monitoring, no scan limit was set due to short deployment times and for maximising detection probability during that time.

For the project Gescha 2, data from 21 POD stations and 30 single stationary PODs were used for analysis. Data from mobile PODs were used to check for possible small-scale differences between the times of seal scarer activation, pile driving and the few hours before and after pile driving in close vicinity of the piling location. Figure 3.5 shows the positions of POD stations and single stationary PODs.

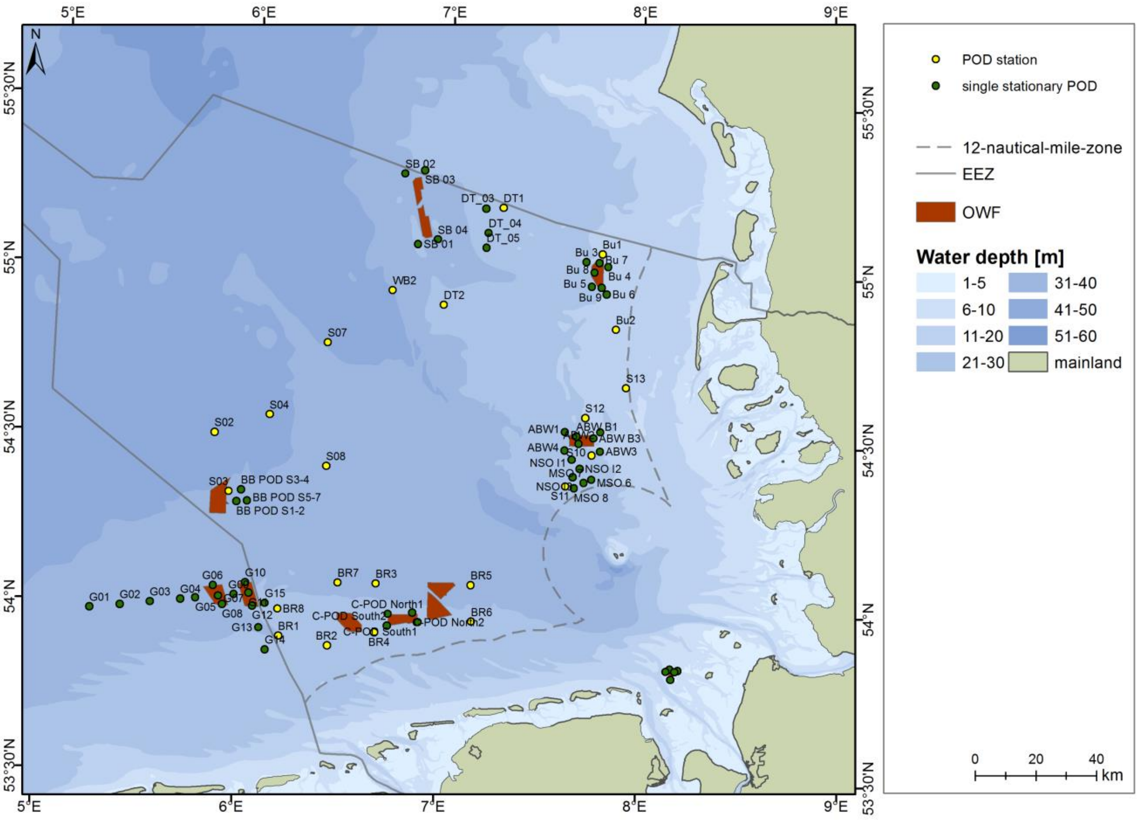


Figure 3.5 Stationary CPOD positions from which data are available for this study; yellow circles: CPOD stations; green circles: single stationary CPODs; red areas: offshore wind farms constructed between 2014 and 2016.

Figure 3.6 CPOD device (http://www.chelonia.co.uk/index.html).

All CPODs were calibrated to equal sensitivity threshold levels (± 3 dB) according to the main frequency of harbour porpoise click sounds (calibration at 125 kHz; best hearing ability of harbour porpoises at 100-140 kHz; KASTELEIN et al. 2002, 2015) by the manufacturer Chelonia Ltd.

Dealing with background noise

CPODs do not only register porpoise clicks but all tonal signals with impulse characteristics, i. e. signals that have a characteristic peak within the power spectrum of porpoise clicks. Thus, clicks can originate from other sources such as sonars, noise from sediment suspension, surface noise from waves, etc. Therefore, the quality of CPOD recordings has to be tested with respect to the effects that a noisy environment may have on the probability of recording porpoise clicks. Two problems emerge from high background noise:

1) In a noisy environment the memory card of a CPOD may quickly fill up. To prevent this, CPODs can be programmed to contain a recording limit per minute, which means that during one minute only a certain maximum number of clicks is registered. If this click limit within one minute is reached, the POD stops recording for the rest of that minute. This limits the amount of data that will maximally be stored per minute on the memory card and prevents the card from an overflow of data. If not controlled for, this issue would lead to an incorrect value for porpoise detection rates. The click limit for stationary PODs was set to be 4,096 clicks per minute; for most of the mobile PODs no scan limit was set, as these PODs were only deployed for a couple of days and the memory card was unlikely to be filled up during this short time interval.

2) Substantial noise also affects the performance of the detection algorithm of the CPOD.exe software, as porpoise clicks will be harder to distinguish from background noise when the latter is substantial, a phenomenon called masking. In consequence, the likelihood that the algorithm identifies porpoise clicks during the recorded time interval decreases with an increasing amount of background noise. This would result in an underestimation of porpoise activity if background noise is not controlled for.

We addressed these issues by visually exploring a) the relationship between porpoise detections and the number of minutes during an hour when the scan limit was reached, and b) between porpoise detections and the number of all clicks other than porpoise clicks that were recorded during that hour. Based on these relationships, data with more than 100,000 clicks per hour, and with more than 2 min per hour exceeding the scan limit, were excluded. This led to 14.8 % data exclusion for the hourly CPOD dataset. As for the daily CPOD dataset, 1.91 % of the data with a noise level of more than 5,160,000 clicks per day were excluded. Still a slight negative relationship between porpoise detection rates and all clicks recorded (*all_clx*) remained; therefore we included either the variable *all_clx* (all detected clicks: hourly POD data), or *corrected_all_clx* (all detected clicks, set to a threshold of $2.5*10^5$ clicks per day if *all_clx* were below that value: daily POD data) into each model to control for this effect.

3.5 Aerial survey data

Aerial surveys are a well-accepted method for obtaining distribution and abundance estimates of porpoises (e. g. HAMMOND et al. 2017) with the advantage of covering large areas in a relatively short time and with little disturbance to the animals. Within the Gescha 2 study, digital aerial survey data are used to: 1) identify an avoidance radius of porpoises to piling sites during or within a short time after piling, and 2) describe regional differences in harbour porpoise distribution which could explain the extent of possible wind farm-specific reactions to piling. To answer these questions, a small-scale gradient analysis on porpoise distribution in relation to piling events, as well as a large-scale distribution model was created. Both research questions and the respective methods are presented in detail in chapter 4.2.

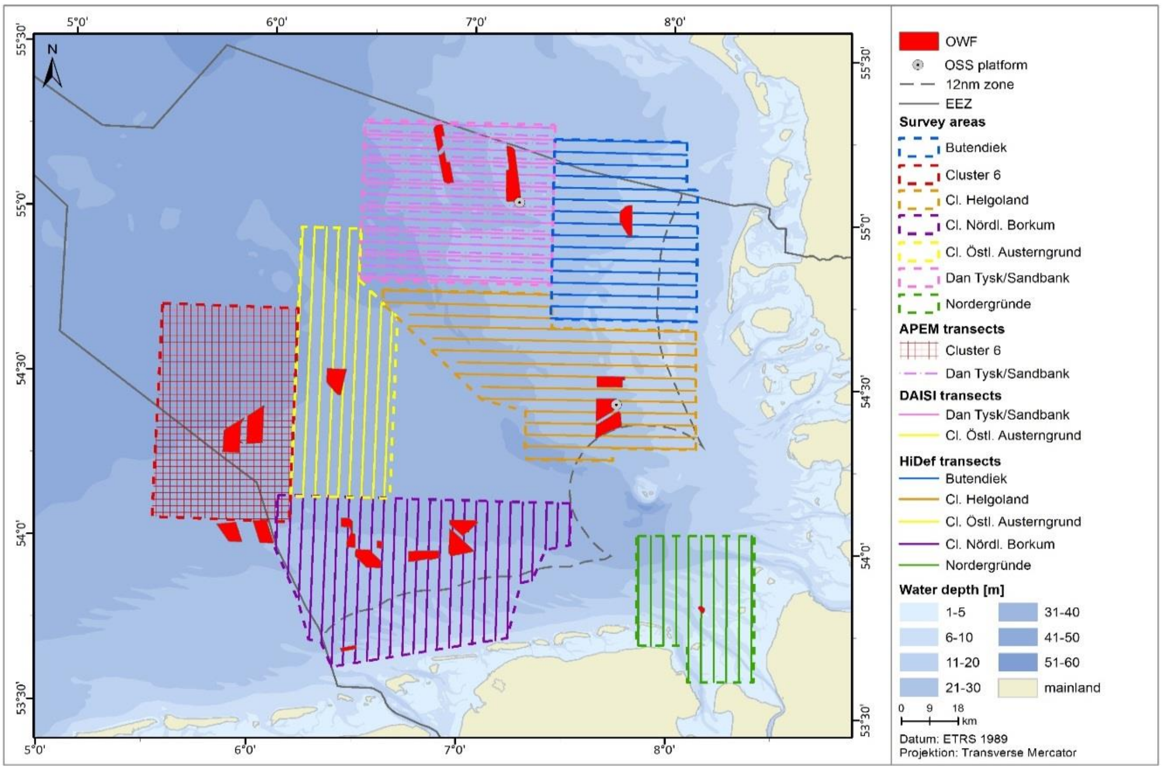


Figure 3.7 The seven aerial survey areas with the respective survey method for observing harbour porpoises using digital aerial surveys in the German Bight from 2014 to 2016.

Due to the large areas covered by flight surveys and the location of the wind farms which are often grouped together, a flight survey usually covers several wind farms. In 2014, with the change from conventional to digital recording technology, the survey design was adapted in line with BSH requirements so that the monitoring areas of so-called cluster studies (the combination of several OWFs together) are directly connected to each other and overlapping of survey areas is avoided. During the period of the present study seven survey areas were covered in the German Bight (Figure 3.7). Table 3.4 gives an overview of wind farms, the corresponding survey area and additional information on surveys. Generally, 8-10 surveys per year are required per survey area by the BSH, so some months might not be equally represented within the monitoring data. It is important to note, that in contrast to earlier observer-based surveys, digital aerial surveys are not conducted specifically for marine mammals. Hence, the surveys might not necessarily occur at the most favourable times for harbour porpoises but might rather have the phenology of a certain bird species in focus.

Table 3.4 *Aerial survey areas with respective wind farms, method of digital aerial survey, sampling month per year, and total number of surveys from 2014 to 2016. Wind farms constructed within the study period are in italics. ʹ = more than one survey took place in this month. * = both OWFs are not part of the management cluster, but are situated within the survey area of Cl. Nördlich Borkum.*

Survey area	Included wind farms	Method	2014 [month]	2015 [month]	2016 [month]	Surveys in total [n]
Butendiek	*Butendiek*	HiDef	3, 4‘, 5‘, 6, 7, 9, 12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	3, 4, 5‘‘, 6, 7, 8, 9‘, 12	30
Cl. Helgoland	*Amrumbank West*; *Nordsee Ost*; Meerwind Süd/Ost	HiDef	4‘, 5, 6, 7, 8, 10	2, 3, 4, 5, 6‘, 7, 8, 9, 10	1, 4‘, 5‘, 7, 8, 9‘, 11, 12	28
Cl. Nördlich Borkum	Riffgat*; alpha ventus*; Trianel; *Borkum Riffgrund 1*; *Nordsee One*; *Gode Wind 01*; *Gode Wind 02*	HiDef	2, 3, 4, 5, 6, 7, 8, 11	1, 3, 4, 5, 6, 7, 8, 9ʹ	2, 4, 5ʹ, 6, 7, 8, 9, 11	26
Cl. Östlich Austerngrund	*Global Tech I*	HiDef, DAISI	5, 7, 8, 10ʹ	3, 4, 5, 6, 8, 10	2, 3ʹ, 5, 6, 8, 9, 11, 12	20
Cluster 6	BARD offshore 1; *Veja Mate*	APEM	2, 3, 4, 7, 8, 9	2, 3, 4, 7, 8, 9, 10, 12	2, 3, 4, 5, 6, 7, 8, 9, 10	23
DanTysk/ Sandbank	DanTysk; *Sandbank*	DAISI, APEM	3, 4, 5, 7, 9, 10	3ʹ, 5ʹ, 6, 7ʹ, 8, 9ʹ, 11, 12	1, 2, 4, 5, 6, 7, 8, 9, 10, 11	28
Nordergründe	*Nordergründe*	HiDef	-	3, 4, 5, 8, 9, 10, 11, 12	1, 2, 3, 4, 5, 8, 9, 10, 11, 12	18

Another important factor regarding digital aerial surveys for Gescha 2 is the sampling method: three different observation systems were used within the study period from 2014 to 2016 in the German Bight (Table 3.4). The methodology and differences are discussed in section 3.5.1.

All surveys were part of the required environmental monitoring and restricted to favourable weather conditions as well as the pre-determined yearly flight schedule. Surveys were therefore not necessarily aligned with piling activity in the survey area, but at least sometimes occurred close to piling events (Figure 3.8). Depending on the area, between 4 % and 50 % of flight days took place within one week after a piling event (Table 3.5). It is important to note that flight days do not necessarily correspond to the number of surveys given in Table 3.4, because some areas require more than one day for a full survey. For the gradient analysis, a subset of digital aerial survey data was used that fully covers the surroundings of a construction site up to 25 km within 12 h after piling. Information on these surveys and a detailed description of methodology and conducted statistical analyses is given in chapter 4.2.1.

The bulk of surveys did not take place during or shortly after the end of a piling event (Table 3.5). Therefore, possible effects of piling cannot be detected at a temporal resolution as high as that of the analyses based on CPOD data. However, the digital aerial survey data supply large-scale distribution data of harbour porpoises, and cover large parts of the German Bight. Using a grid-based analysis and statistical modelling techniques, harbour porpoise distribution was correlated to environmental as well as anthropogenic properties in the area. This helps in distinguishing some of the driving factors of porpoise distribution in the study area and possible large-scale effects of anthropogenic disturbances. A similar study approach was followed within the Gescha 1 study. It is important to point out that no direct comparison of density values can be conducted between Gescha 1 and Gescha 2. Data used for Gescha 2 were collected by digital aerial surveys, whereas for Gescha 1 only observer-based surveys have been conducted. Even though both approaches provide density estimations, so far no peer-reviewed comparison between both approaches has been conducted with focus on marine mammals. Because it is beyond the scope of the present study, no comparative data were evaluated and therefore it was dispensed with a comparison of absolute densities on the basis of aircraft count data of both studies. Yet, the main conclusions of the studies will be discussed together in chapter 4.2.3. A detailed description of methods, including the specific treatment of environmental and anthropogenic factors, is given in chapter 4.2.1.

Table 3.5 Survey areas with total number of flight days from 2014 to 2016 and with number and percentage of flight days that took place 1, 3, or 7 days after piling in the survey area.

Survey area	Flight days with piling within 1 day prior to flight		Flight days with piling within 3 days prior to flight		Flight days with piling within 7 days prior to flight		Total flight days
Butendiek	4	13.3 %	5	16.7 %	8	26.7 %	30
Cl. Helgoland	4	14.3 %	5	17.9 %	7	25.0 %	28
Cl. Nördlich Borkum	11	42.3 %	12	46.2 %	13	50.0 %	26
Cl. Östlich Austerngrund	0	0 %	0	0 %	1	5.0 %	20
Cluster 6	14	22.2 %	19	30.2 %	19	30.2 %	63
DanTysk/ Sandbank	4	13.8 %	6	20.7 %	8	27.6 %	29
Nordergründe	0	0 %	1	4.0 %	1	4.0 %	25

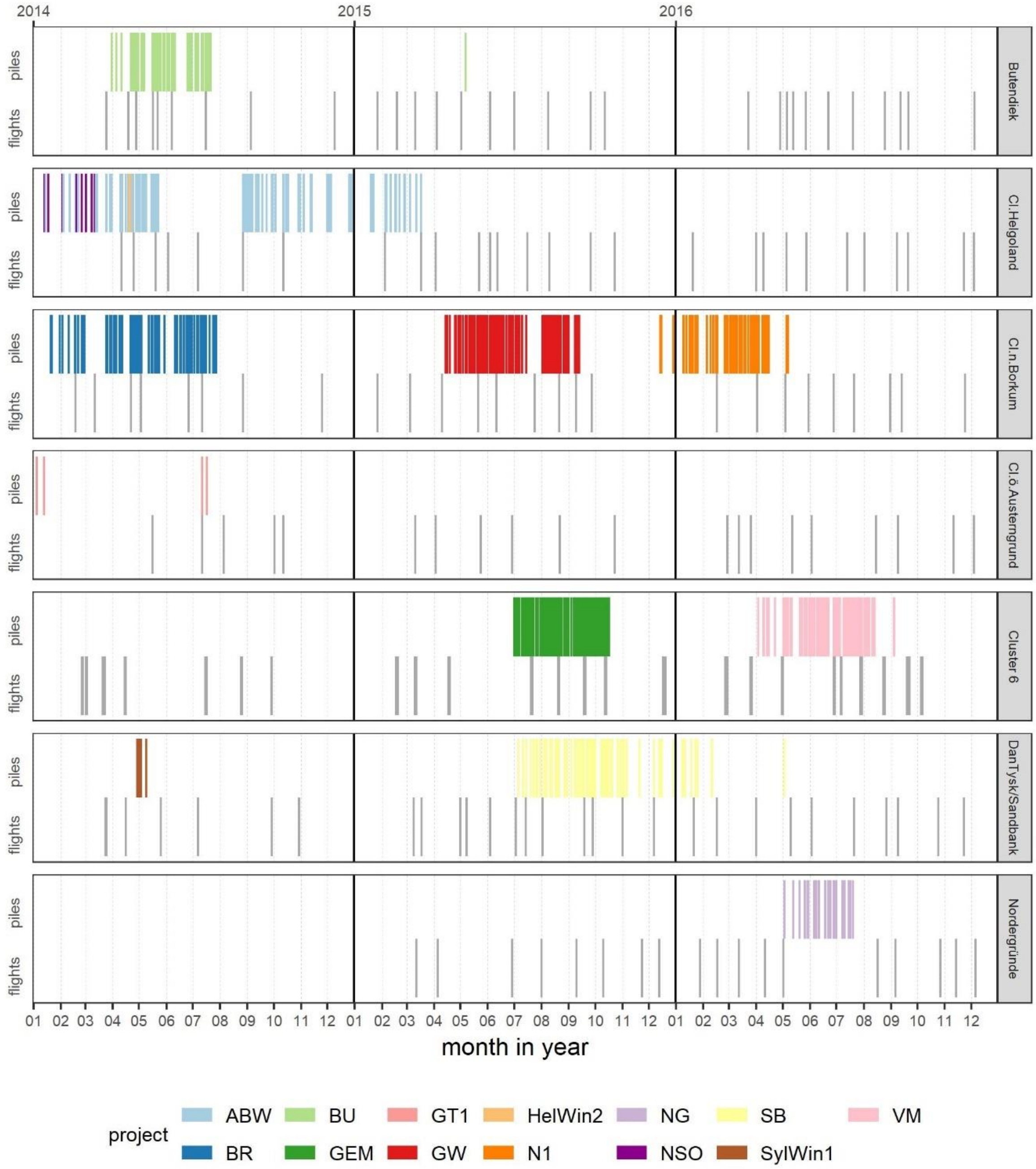


Figure 3.8 *Survey days (grey line) within the seven survey areas, and respective piling events (coloured line) in the area from 2014 to 2016.*

3.5.1 Different observation methods

Three different observation methods were used to survey porpoises via digital aerial surveys. Generally, the survey method stayed consistent per survey area, however in some areas, i. e. DanTysk/Sandbank and Cl. Östlich Austerngrund, more than one method was used. In the following, the three methods “APEM”, “DAISI” and “HiDef” are described. The namings originate from the company in charge or the camera system in use. One of the main differences between the methods is whether objects are recorded with still images or images taken from videos.

APEM

Cluster 6 was surveyed exclusively by the company APEM Ltd[6] (Figure 3.7). It includes narrow transect lines (ca. 1.6 km spacing) in north-south direction. The transect lines were close enough to each other to allow for forming of a grid. This is one of the main differences to the other two survey methods described below. APEM records objects, based on image analysis. Four cameras take images simultaneously and constantly. The four frames are merged into one image with the resolution of about 3 cm on the sea surface. Flight height was approximately 1300 ft (ca. 400 m) and speed at 120-130 knots. Species identification and quality control was done by IBL Umweltplanung GmbH up to January 2016. Thereafter, APEM Ltd continued with the image analysis. APEM also surveyed the DanTysk/Sandbank area in March and April 2014 with image analysis done by APEM Ltd. Here, the transect lines of the survey area were used rather than a grid. A detailed description of methods for APEM is given in the Appendix.

DAISI

The survey areas DanTysk/Sandbank and Cl. Östlich Austerngrund were covered by DAISI ("Digital Aerial Imagery System"; Figure 3.7). DAISI is developed by and belongs to IfAÖ GmbH[7] and uses a photo technique to record objects. The flight transects in the area DanTysk/Sandbank were east-west orientated, whereas transects in Cl. Östlich Austerngrund were north-south orientated. DanTysk/Sandbank was surveyed by APEM for two months in spring 2014, and Cl. Östlich Austerngrund was surveyed by HiDef in selected month (see Appendix). Transect lines in both survey areas were 3-4 km apart. DAISI consists of two cameras with a resolution of 2 cm on the sea surface at a flight height of 1400 ft (about 426 m). Plane speed was at 100-120 knots. Species identification and quality control was done by IfAÖ. A detailed method description for DAISI is given in the Appendix.

HiDef

The survey areas of Butendiek, Cl. Helgoland, Nordergründe and Cl. Nördlich Borkum were exclusively surveyed by BioConsult SH using HiDef video systems (Figure 3.7). Cl. Östlich Austerngrund was party surveyed by DAISI and HiDef. The survey areas included either north-south or east-west transects (Figure 3.7). Transects had a spacing of about 3-4 km. HiDef uses a high-resolution video camera system consisting of four independent cameras with a resolution of 2 cm on the sea surface. Flight height was approximately 1800 ft (549 m) and plane speed at about 120 knots. Depending on the survey area, species identification and quality control was done by BioConsult SH, IfAÖ, or IBL Umweltplanung. A detailed method description for HiDef is given in the Appendix.

[6] http://www.apemltd.co.uk/ (accessed 07.01.2019)

[7] http://www.ifaoe.de/en/services/ornithology/daisi.html (accessed 07.01.2019)

3.5.2 General data treatment

Despite the different methodology in obtaining aerial survey data, the image output was analysed in the same way. Effort and observation data of all digital aerial surveys in the German Bight from 01/01/2014 to 31/12/2016 were collected in a common database structure with information on the following features: trip data (i. e. cruise name, project, lab, datatype, flight date and time), basis data (position, position id, picture area analysed, date, time, sea state, picture quality), and observations (position, position id, observation, behaviour, activity, length, abiotic observation) (see Appendix). In a first step of data preparation, images with a quality of 2, covering land or tidelands and outliers for the variable "picture area analysed" were discarded (i. e. >0.3 km²). The remaining dataset consisted of 172 surveys and a total of 6,263,532 effort entries to be analysed. A list of surveys and details on the survey date, method and effort is given in the Appendix. Flights could only take place during favourable and safe flight conditions, hence sea state was at a maximum of 5, but generally well below. High glare was avoided by adjusting the camera position and flight time during the day. A vectorised grid with cells of 2 x 3 arc minutes (approx. 3.2 km by 3.7 km) was placed over the German Bight using QGIS version 2.18. For each analysed image, the area covered by the camera was given in km² and was referred to as "picture area analysed", which was taken as a proxy for effort in this study. All effort within a grid cell, i. e. the analysed image area that had coordinates within a grid cell, was summed for a specific time scale, e. g. seasonally (Figure 3.9), or monthly (see Appendix).

To correct for the probability to which some animals might not have been detected due to diving, all harbour porpoise sightings were corrected based on TEILMANN et al. (2013). Depending on month and time of day, porpoises spend a certain proportion of time at the surface, which can be corrected for, using: $y_{jk} = 42.7348 + 0 + month_j + time_k$. The proportion of time at the surface calculated after TEILMANN et al. (2013) and used as correction factor is given in the Appendix. No differentiation was made between adult and juvenile porpoises. The sum of all porpoises within a grid cell was calculated for a specific time unit (season or month). Harbour porpoise presence (as presence/absence) and density (Ind./km²) was calculated per grid cell by dividing the sum of porpoises with the corresponding effort. Seasons were described as meteorological seasons (winter: Dec-Feb; spring: Mar-May; summer: Jun-Aug; autumn: Sep-Nov).

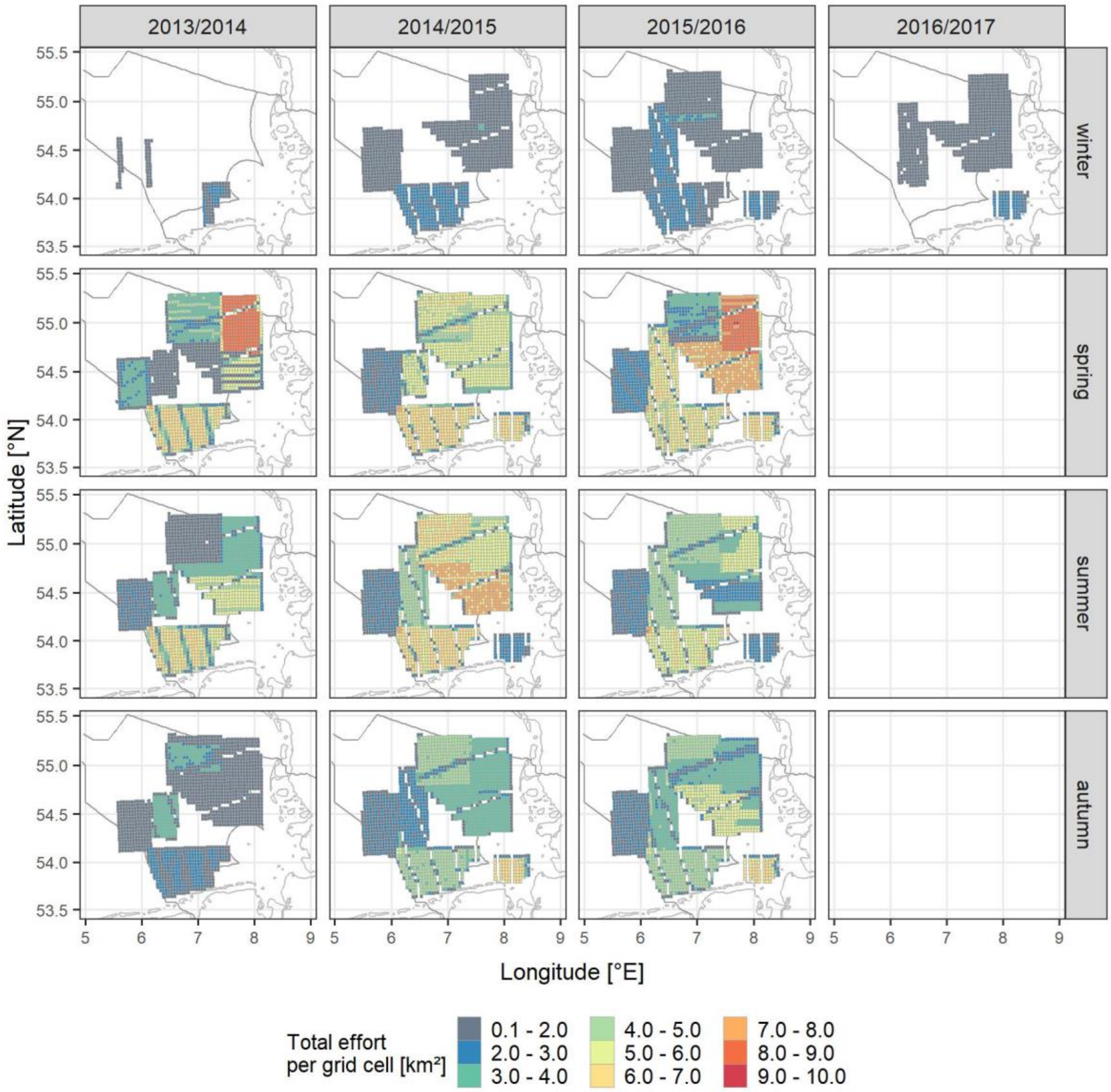


Figure 3.9 Flight effort as image area analysed [km²] per grid cell in the German Bight (2014-2016).

3.5.3 General harbour porpoise distribution and density

These data show porpoise distribution and densities for 2014-2016 and provide the background knowledge to understand analytical decisions regarding the large-scale model (see chapter 4.2.2).

The first aerial survey in the study area with digital recording took place on 18th February 2014 in Cl. Nördlich Borkum. Generally, fewer flights took place in autumn and winter, compared to spring and summer (Figure 3.9). A monthly overview of effort distribution as well as seasonal and monthly porpoise distribution in relation to offshore wind farms is given in the Appendix. Figure 3.10 shows the respective density distribution of porpoises per season and year. The distribution was similar over the study period. A comparison of distribution and density between regions and years must always include a respective comparison of effort intensity (e. g. Figure 3.9 and Figure 3.10), because some apparent difference between years may not reflect actual changes in distribution, but may be caused by unequal effort intensity (e. g. for Cl. Helgoland effort in spring 2016 was higher than usual and lower in summer 2016, causing lower abundances in summer 2016).

When all survey areas are pooled, the seasonal peak of porpoise densities occurred from May to July with 0.7-1.0 Ind./km² (Figure 3.11). Lowest densities (0.2 Ind./km²) were found from October to December. The seasonality for the pooled dataset is strongly influenced by the higher summer densities around and within the Sylt Outer Reef, i. e. the regions DanTysk/Sandbank, Butendiek and Cl. Helgoland (Figure 3.12). Also, the southern regions Cl. Nördlich Borkum and Nordergründe showed highest densities in summer, especially at Borkum Reef Ground (Figure 3.12). The western regions Cl. 6 and Cl. Östlich Austerngrund showed a slightly shifted seasonality with maximum densities in spring (Figure 3.12).

Due to methodological differences between Gescha 1 and Gescha 2, results of the two studies are not directly comparable. However, both studies show the same general seasonal density distribution of porpoises over the study area. The combination of the seven survey areas including three different observer methods showed a gradual transition of porpoise distribution patterns regarding the survey areas in the German Bight (Figure 3.12).

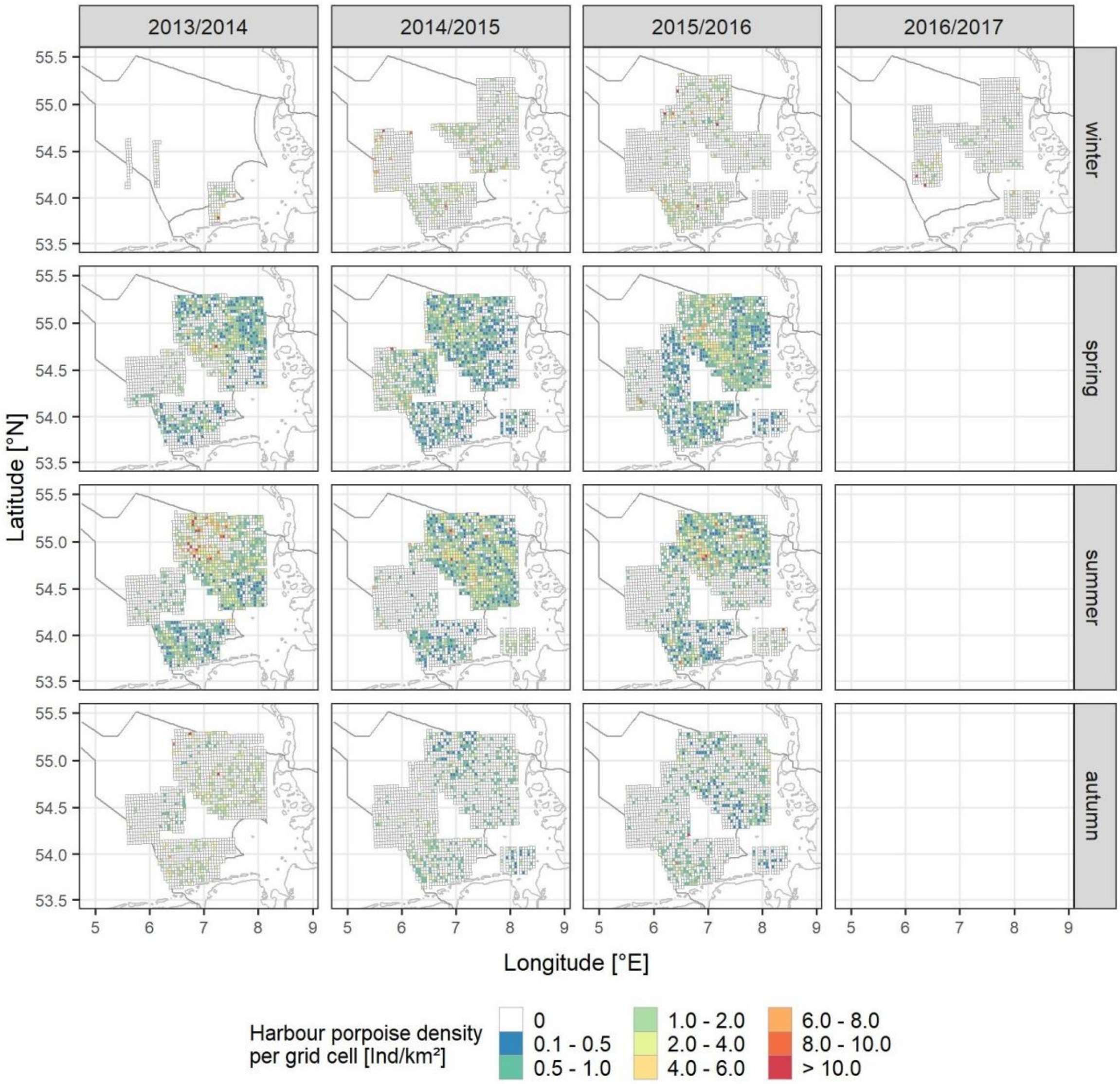


Figure 3.10 Seasonal porpoise densities [Ind./km²] per grid cell and year in the German Bight.

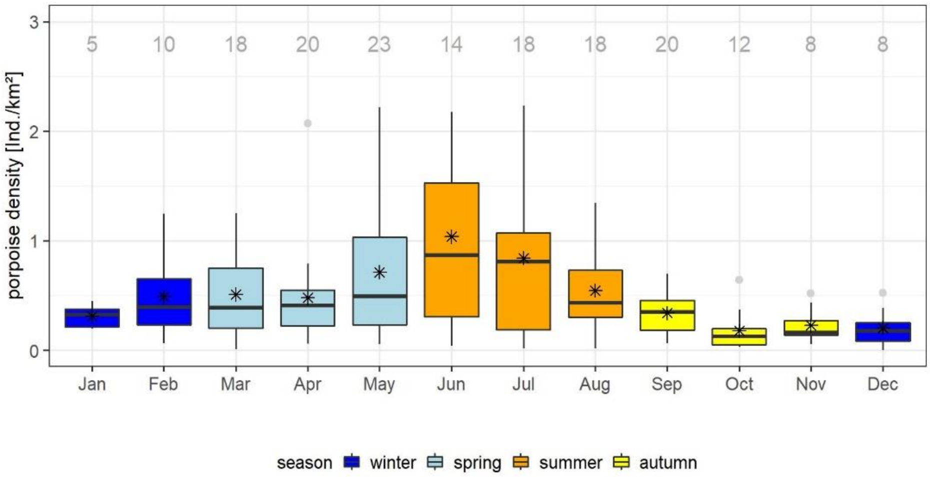


Figure 3.11 Monthly mean porpoise densities [Ind./km²], pooled over the entire study area and study period. Number of flights per month is given in grey.

Figure 3.12 Seasonal mean porpoise densities per grid cell [Ind./km²], pooled over the entire study period. Additionally, the nature reserves Borkum Reef Ground and Sylt Outer Reef are indicated (magenta lines).

3.6 Environmental parameters

The noise level at a certain distance from a construction site partly depends on the baseline source level (i. e. local background noise in addition to piling), but is also affected by other factors. For example, noise propagation in the water column a. o. depends on sediment, salinity, water depth, topography, sea state, and obstructions. These variables may partly affect the noise level in a frequency-specific way which, however, was beyond the scope of Gescha 2.

For most analyses, all environmental variables available for the whole study period of Gescha 2 were considered. These were day length, modelled densities of two groups of fish species living in sandy sediments (sandeels, sand gobies), sea-surface temperature, sea-surface-temperature anomaly, water depth, latitude and longitude, sea-bed sediment, wind speed and direction, current speed and direction, salinity, and phytoplankton. Information on the resolution and data source of these variables is given in Table 3.6.

Regarding models for comparisons with the Gescha 1 study and conducted on the hourly and daily CPOD datasets, the variables salinity, phytoplankton and the two current parameters were not considered since these were not available for the Gescha 1 dataset.

Table 3.6 Environmental variables: spatial and temporal resolution, depth/altitude, and data source (URL).

Parameter class	Variable name in models	Spatial resolution	Temporal resolution	Depth/ altitude	URL
bathymetry	*depth, slope*	~ 250 m	study time	-	http://portal.emodnet-hydrography.eu/
current	*surface_speed, surface_dir*	~ 7 km	1 hour	surface	http://www.myocean.eu/ (http://marine.copernicus.eu/)
phytoplankton	*phyto, Chl. a*	~ 7 km	1 day	surface	http://www.myocean.eu/ (http://marine.copernicus.eu/)
salinity	*sal*	~ 7 km	1 day	surface	http://www.myocean.eu/ (http://marine.copernicus.eu/)
seabed habitat	*sediment*	map	study time	seabed	https://www.emodnet-seabedhabitats.eu/
temperature	*SST*	~ 7 km	1 day	surface	http://www.myocean.eu/ (http://marine.copernicus.eu/)
temperature anomalies	*SST_anom*	0.25x0.25 degrees	1 day	surface	http://www.esrl.noaa.gov/psd/data/
wind	*wind_speed, wind_dir*	2.5x2.5 degrees	6 hours	10 m	http://www.esrl.noaa.gov/psd/data/
fish species of sandy sediments	*sandeel, sand goby, pr_at_pres, pr_am_pres, pr_hl_pres, pr_pm_pres*	catch localities	study time	-	http://ices.dk/marine-data/maps/Pages/ICES-FishMap.aspx

Data of two fish species groups (gobies/Sandgrundel and sandeels/Sandaal) were included. For sandeel species, densities of the three species Great sandeel (*Hyperoplus lanceolatus*), Lesser sandeel (*Ammodytes tobianus*) and Raitt's sandeel (*Ammodytes marinus*) were modelled; the same was done for the sand goby (*Pomatoschistus minutus*). Regarding these species, data were obtained from DATRAS, the online database of trawl surveys from ICES. In detail, CPUE (catch per unit effort in kg/h per haul and species) data were used which were collected during the NS-IBTS (North Sea international Bottom Trawl Survey) and BTS (Beam Trawl Survey) from 2010 to 2018 during summer months (from July to September). Fishing data per haul were extrapolated for the whole North Sea, using as predictors the bathymetry (extracted from EMODNET and rasterised at 115 m pixel resolution; emodnet.eu), slope (derived from bathymetry using the function *terrain* from the R package *raster;* HIJMANS 2016), seabed (extracted from EMODNET and rasterised at 115 m pixel resolution), and average SST and Chl a composites for the summer season 2010-2018 (at 2 km pixel resolution). All rasters where cropped to a common area and downgraded to the same pixel size (2 x 2 km). A model was then performed for each species using a Random Forest algorithm for classification. This resulted in maps showing the probability of occurrence by species or species group. In case of species groups, the probability of occurrence of all species of each group was averaged. Modelled densities of species groups are shown in Figure 3.13.

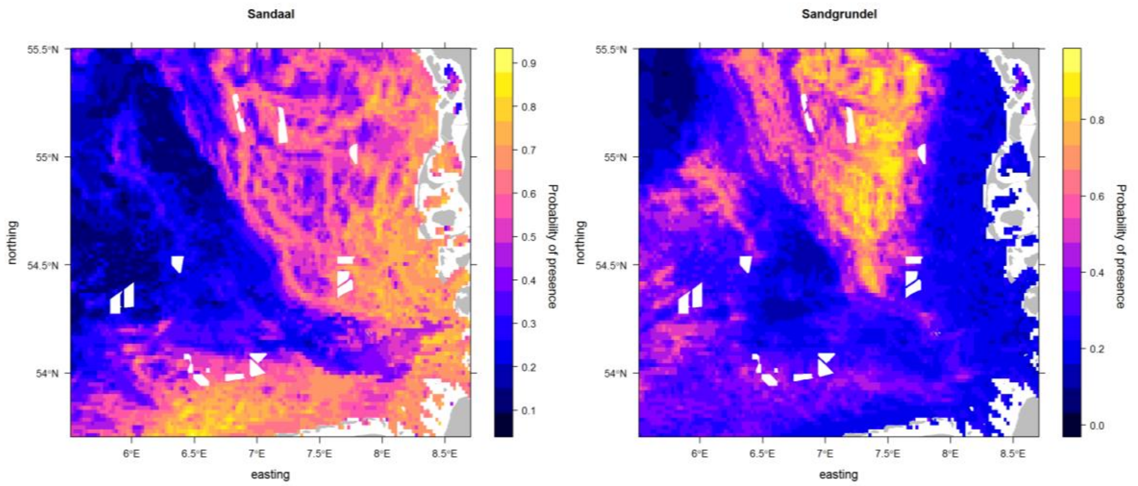


Figure 3.13 Distribution maps of three sandeel species (combined) and sand goby within the German Bight, calculated from data on fish catches downloaded from http://ices.dk/marine-data/maps/Pages/ICES-FishMap.aspx.

Regarding boat traffic, the variable *d_shippingLane* (distance to closest major shipping lane) was included as an explanatory covariate into the models built on hourly CPOD data. Baseline for this variable were not the shipping lanes as given in nautical charts, but those calculated from an average ship traffic density obtained by cumulative AIS signals of the year 2017 and downloaded from marinetraffic.com. Figure 3.14 shows the respective distance map used for the models on hourly CPOD data.

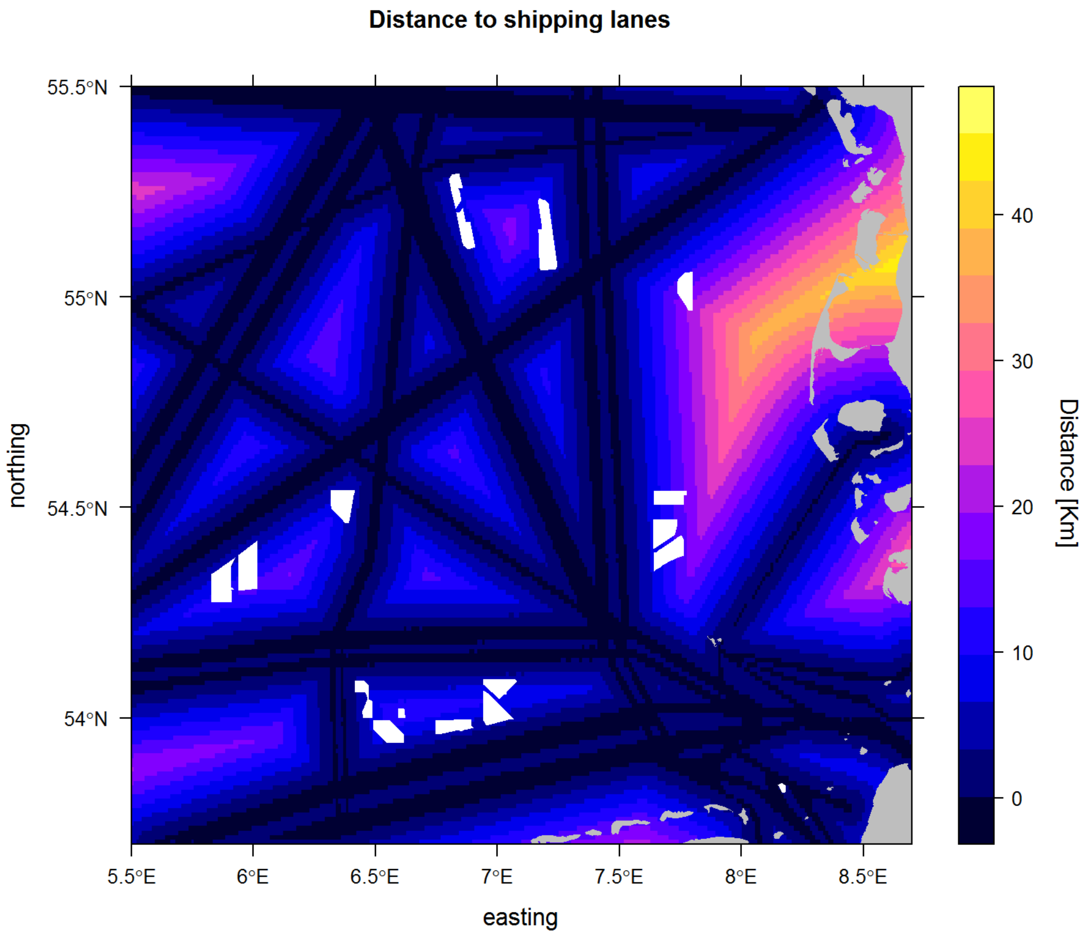


Figure 3.14 *Major shipping lanes as baseline for the variable d_shippingLane, calculated from cumulated AIS signals of the year 2017 (http://www.marinetraffic.com).*

For the analyses on aerial survey data, the AIS-signal dataset for ship traffic was aligned to the spatial grid as factorial variable (shipping as positive or negative). A cell with no AIS data was considered as “shipping negative”, whereas cells with AIS data were seen as “shipping positive”. The factor “shipping” was constant over time.

4 SPATIO-TEMPORAL AVOIDANCE BEHAVIOUR OF HARBOUR PORPOISES UNDER APPLICATION OF EFFICIENT NOISE MITIGATION SYSTEMS

A major aim of the project Gescha 2 was to evaluate the spatial and temporal response of harbour porpoise to mitigated piling noise. Did the improvement of NMS over the last years lead to a reduced effect range and duration during the construction process? Detailed questions arose from this, leading to specific work packages collected under WP 3. In this chapter, we address the following questions:

WP 3.1 (based on the analysis of hourly CPOD data)

- What is the spatial and temporal extent of porpoise response to pile driving?
- Can differences in response range, duration and strength be detected when compared to results found during Gescha 1 when noise mitigation systems were less efficient?
- Is the response range and strength regarding pile driving different from that regarding seal scarer and shipping or other construction-related noise?

WP 3.2 (based on digital aerial survey data):

- What is the spatial and temporal extent of porpoise response to pile driving?

WP 3.3 (based on the analysis of hourly CPOD data):

- Down to what piling noise levels can avoidance reactions of porpoises be detected?

WP 3.4 (based on the analysis of hourly and daily CPOD data):

- Can area-specific differences in habitat characteristics (such as prey availability, general background noise, distance to shipping lanes, etc.) lead to differences in the response of porpoises to piling noise among wind farms?

WP 3.5 (based on the analysis of hourly CPOD data):

- Does piling duration have an effect on the response range of porpoises and on the duration of such an effect after piling?

WP 3.6 (based on the analysis of hourly CPOD data):

- What are the contributions of construction-related boat traffic and other noise-intense activities within the vicinity of construction sites in causing porpoise reactions already before deterrence and piling starts?

Since WP 3.1, 3.3, 3.4, 3.5, and 3.6 are all based on hourly CPOD data, these are combined within a single chapter due to their overlapping methodology (chapter 4.1). Only WP 3.2 is based on aerial survey data, why it is dealt with in a separate section (chapter 4.2).

4.1 Hourly CPOD data

CPODs were used to record porpoise presence at positions irregularly spread over the study area. CPOD data on hourly resolution were suitable to answer questions on the effects of pile driving on porpoises on a temporally fine scale, namely the topics of WP 3.1, 3.3, 3.4, 3.5, and 3.6 (see previous section).

4.1.1 Methods

Originally, it was intended to repeat the methodology of the Gescha 1 project. However, this turned out to be not always feasible. Piling schedules became tighter and more efficient during recent years, which led to on average shorter breaks between piling events with Gescha 2 wind farm projects, compared to Gescha 1. Hours available before piling became less frequent, the same being true for hours more than a day after piling, since quite often a new piling started only a day or even less time after a previous one. This rendered Gescha 2 models less reliable regarding longer time-lags relative to piling time. We therefore decided to adapt our methodology to the dataset by pursuing two different approaches: On the one hand, the same modelling approach of Gescha 1 was used to answer the question of possible spatio-temporal effects of pile driving on harbour porpoises, including possible cumulative effects due to closely-sequenced pile driving. On the other hand, in a second approach the dataset was reduced to piling events for which sufficient uninfluenced reference times were available to assess pure pile-driving effects independently of possible cumulative effects:

1. Cl-type models: The old (Cl = classical) Gescha 1 approach was followed in principle, though we restricted the time frame to hours from 48 h before to 48 h after piling (instead of 120 h after piling in Gescha 1), and only looked at distances up to 40 km (instead of 60 km in Gescha 1) since at further distances habitat changes became more and more evident. This type of analysis allowed for the inclusion of all available piling events. By applying this approach, also possible cumulative effects of closely-sequenced pile driving were assessable and the whole dataset could be used. As the zero line in GAM plots of Cl-type models represents an average of the fitted values, the line is affected by piling effects and not a true zero-effect line. It is thus interpreted here as a minimum effect range whereas the true zero-effect range is slightly higher in most cases (other cases are indicated).

2. Reference-type models: A new approach was developed to analyse the effects of so-called 'ideal' piling events. With this approach, the pure effect of a piling event was analysed since enough time for the animals was left to come back after being disturbed by a previous piling. This was achieved by only including those piling events with long enough breaks before and afterwards, when it was assumed that a defined reference period at sufficient time before and after piling was without any effect due to pile driving. Thus, the

detection rates within the reference time (for each piling) could be compared to the detection rate in the time frame around piling. This approach had the advantage to partial out much of the effects of spatial and temporal heterogeneity, since the comparison was done within each combination of a piling event and a CPOD station. It came however at the cost of a smaller number of available piling events, because only those piling events with more than 72 h (= three days) timespan between consecutive pilings could be used. The approach thus reduced the overall dataset to between 2 % and 50 % of piling events for single OWFs, and 27 % of all Gescha 2 piling events (Table 4.1). Hence, the approach was only suitable for models of the complete dataset and those OWFs with sufficient data of more than 30 suitable piling events (ABW, BR, GW, SB). Since due to dataset restrictions the pre-piling reference period could earliest start at 48 h before piling (in that case lasting for 24 h; less hours if it starts later), and since the reference period was not allowed to overlap with the analysed period, the analysis time frame had to be restricted to hours from 24 h before to 48 h after piling, after which the post-piling reference period started.

Table 4.1 Number of Gescha 2 piling events (mitigated and unmitigated) available for analyses of CI-type and Reference-type models; red: insufficient number of piling events for meaningful Reference-type models.

OWF	ABW	BR	BU	GW	N1	SB	VM	GEM	Total
***N* for Reference-type models**	49	32	17	34	17	31	15	4	**199**
***N* for CI-type models (= all available piling events)**	96	78	83	101	63	75	72	160	**728**
Percentage of piling events for Reference type models [%]	51.0	41.0	20.5	33.7	27.0	41.3	20.8	2.5	**27.3**

Another difficulty arose from the fact that for some Gescha 2 wind farm projects only few CPOD data were available from distances below 5 km to piling locations. Since effects of pile driving on harbour porpoises are strongest at close range, the models for those wind farms produced unreliable results. Hence, only some OWFs were suitable for meaningful analyses for WP 3.4 which are presented here, whereas the model results for the other OWFs are shown in the Appendix.

We did not only run models with the Gescha 2 data, but also repeated some analyses of Gescha 1 data with the more restricted temporal and spatial frame of the Gescha 2 analyses, as well as with the new modelling approach. The Gescha 1 data were re-organised for this purpose and merged with some more environmental variables newly available for Gescha 2. Originally, analyses for Gescha 1 were conducted on a dataset including hourly CPOD data up to distances of 60 km to the piling location. For the present study, we cut the Gescha 1 dataset at 40 km distance to be comparable with Gescha 2 where too few data were available for larger distances. Gescha 1 data from 2009 and 2010 could not be included into re-analyses of hourly CPOD data because some parameters were only available from 2011 onwards. Furthermore, data from mobile CPODs, which to some extent were included to the original Gescha 1 project, were now completely omitted from the Gescha 1 dataset, since otherwise data could not be merged adequately. Finally, we computed overall models on the combined Gescha 1 & Gescha 2 dataset in order to have most reliable results regarding piling effects during the years 2011 to 2016.

Statistical analyses

Model types and parameters

Hourly CPOD data were extracted for analysing the effects of pile driving on porpoise detections according to WP 3.1, 3.3, 3.4, 3.5, and 3.6. For calculating distances between PODs and foundations, all three PODs from a POD station were assigned to a single geographic location. Short distances between the three POD devices of a POD station were negligible in the context of our analyses.

Detection rates were merged with piling- and noise-related variables (e. g. noise level, piling duration, distance to shipping lanes), environmental and geographical data (e. g. water depth, sandeel and sand goby densities, wind and current parameters), time-related information (e. g. hour of day, day of year), and POD information (POD station, position, and ID). Most of these were explanatory variables, except for POD station and ID which were included as factorial random effects. All variables considered for use within Generalised Additive Mixed-Effects Models (GAMM; in the following shortly referred to as GAM) are listed in Table 4.2.

Due to the inclusion of *Position* (i. e. POD station) as a random factor, static variables like *pos_lat_new* and *pos_long_new* did not improve the global model and were therefore not considered for further analyses.

Knowing from previous studies that piling effects (without noise mitigation) on porpoise detections partly occurred in more than 20 km distance, and in accordance to the Gescha 1 study, we decided to set a precautionary 40 km boundary around each wind farm for considering and assigning POD data to a wind farm. This was chosen in order to use a conservative limit in case that effects reach further, and to also capture distances at which no effect was assumed. Thus, all POD positions within a 40 km radius around a wind farm were included into the data subset specific for that wind farm. By this, single piling events were allowed to be as far as 60 km apart from a specific POD location, as OWF areas had a diameter of up to 20 km; but due to environmental heterogeneity we restricted the analysed datasets to distances of up to 40 km. The relative time of each full hour (example: 22:00:00 to 22:59:59 UTC) to the next piling event (hour relative to piling work: variable *A_HRW*) within that particular wind farm was determined by counting down from the start of deterrence and up from the end of piling. Each hour during which piling took place counted as hour 0 relative to piling work (hrw 0). Hours were only defined as being before a piling event (hrw-48 to hrw-1) if at least 48 h had passed since the end of the last piling event. If hours later than 48 h after a piling event were not assigned as being before the next piling event, incrementing of hours continued until hrw+72. All data outside this time frame were excluded from analyses.

Regarding analyses on the effects of specific piling events we excluded data that might have been confounded by the effects of other piling events in the vicinity. In detail, hourly data were excluded if piling took place in another wind farm within a 60 km radius around a POD position during that hour, or up to 24 h before. Furthermore, we excluded all hours when deterrence was active but no piling occurred (which sometimes happened before the start of pile driving; normally this would have been hrw-1). Based on the assignment of a specific hour at a specific location to a particular piling event, other piling variables (e. g. noise level, piling duration) were merged with the POD dataset.

The two modelling approaches used different response variables:

1. Cl-type models (the classical model type used in Gescha 1): In order to investigate short-term effects of all available piling events on porpoise activity at a small spatial scale, the response variable Detection Positive Hours per hour (*DPH*) was analysed as indicator for porpoise activity on an hourly basis (Table 4.2). *DPH* describes whether or not a porpoise click train was recorded and identified during a given hour, and is thus a binary variable (taking values 0 or 1). Here, all piling events within a time frame from hrw-48 to hrw+48 were analysed.

2. Reference-type models ('reference' in this case means that an unaffected reference period was selected for these models): For the assessment of the effects of those piling events with sufficient time-lags to previous and subsequent pilings, we used a new response variable *dDPH_ref*, based on raw *DPH* rates, as indicator for porpoise presence on an hourly basis (Table 4.2). Whereas *DPH* describes whether a porpoise click train was recorded and identified during a given hour, and is thus a binary variable, *dDPH_ref* can be regarded as the *DPH* value during the analysed period around pile driving in relation to the *DPH* value at a supposedly unaffected reference period (assumption here: the time >24 h before piling and the time >48 h after piling was not influenced by the construction process anymore).The variable is derived from *DPH* by the following mathematical procedure, taking into account porpoise detection rates during a reference period:

   DPH detection rates at the analysed hours hrw-24 (BU & VM: hrw-31, due to longer effects before piling) to hrw+48 were compared to mean *DPH* rates during a split reference period (*DPH_ref*). The reference time frames stretched from hrw-48 to hrw-25 (pre-piling), and from hrw+49 to hrw+72 (post-piling), when effects were assumed to be unlikely to occur, based on the results of the Gescha 1 project and raw data plots. *DPH_ref* was assessed for each combination of a piling event and a CPOD station, so that it was largely controlled for regional and phenological differences of detection rates by this approach. The reference period was used entirely if (a) previous piling event ended latest 96 full hours (48 + 48 h, as the time countdown for a new piling event started earliest 48 h after previous pile driving took place) before deterrence for the next piling started, and (b) the next piling phase started more than 72 h after a respective piling event. Otherwise, the reference period was truncated accordingly, or not available at all. In the latter case, no analysis of piling effects was possible for that particular piling event. The parameter *dDPH_ref* was calculated as follows for each combination of piling event and CPOD station:

$$dDPH\_ref = DPH - DPH\_ref$$

By this, negative *dDPH_ref* rates were tantamount to less detections and negative effects, and positive rates were equivalent to more detections during pile driving, compared to the reference period. No effect occurred if *dDPH_ref* rates ranged around zero.

Table 4.2 List of all variables considered for the GAM models on hourly POD data; asterisks: variable only available for the Gescha 2 dataset.

Variable	Type	Description
Response variables		
DPH	binary	Detection Positive Hours per hour (0 or 1); used for Cl-type models
dDPH_ref	continuous (-1 to 1)	*DPH* rate relative to an uninfluenced mean reference *DPH* rate at hours hrw-48 to hrw-25 and hrw+49 to hrw+72 (*DPH_ref*) at the same combination of piling event and CPOD (sub)station; In case of negative effects, *dDPH_ref* takes values below zero; used for Reference-type models
Piling- and noise-related variables		
SEL05_750	continuous	noise exposure level exceeded during 5 % of the piling period, measured in 750 m distance to construction site
noise_mitigation	factor (3 levels)	noise mitigation applied, not applied, or partially applied
A_HRW	integer	hour relative to piling (start of a piling event or deterrence), ranging from -48 to 120h; daytime hours with piling and/or deterrence are defined as hour 0
A_dist	continuous	distance to a piling event within the closest wind farm in metres
A_pilingduration	continuous	duration of a piling event within the closest wind farm in minutes
week.events	integer	number of piling events occurring during 7 days before a given piling event in a 40 km radius
d_shippingLane	continuous	distance to the next major shipping lane in km
all_clx	continuous	number of all clicks within an hour; these could originate from different noise sources: e. g. waves, sediment movement, ships, porpoises
Time-related variables		
DPHt	factor (2 levels)	*DPH* in previous hour; in Cl-type models to reduce autocorrelation
HH	circular integer	hour of the day
dayofyear	circular integer	day of the year
YYYY	factor	year
Environmental variables		
sediment	factor (5 levels)	levels of sea-bed sediment: 1: coarse sand with <20 % mud; 2: medium coarse sand with <20 % mud; 3: medium sand; 4: fine sand with < 20 % mud; 5: fine sand with 21-50 % mud
depth	continuous	water depth at a certain CPOD position
slope	continuous	variation of *depth* around a certain CPOD position
*sal**	continuous	salinity in ‰
wind_speed	continuous	wind speed in m/s
wind_dir	circular and continuous	wind direction in degree
*surface_speed_cur**	continuous	speed of surface currents in m/s

Variable	Type	Description
*surface_dir_cur**	circular and continuous	direction of surface currents in degree
*phyto**	continuous	modelled phytoplankton density
SST	continuous	sea-surface temperature
SST_anom	continuous	sea-surface-temperature anomaly
illimunatedFraction	continuous	moon phase (1: full moon; 0: new moon)
pr_hl_pres	continuous	density of sandeel *Hyperoplus lanceolatus*; modelled on ICES data starting from 2011
pr_at_pres	continuous	density of sandeel *Ammodytes tobianus*; dito
pr_am_pres	continuous	density of sandeel *Ammodytes marinus*; dito
pr_pm_pres	continuous	density of sand goby *Pomatoschistus minutus*; dito
sandaal	continuous	density of all sandeel species (N=3); dito
sandgrundel	continuous	density of all sand goby species (N=1); dito
POD-related variables		
Position	factor (as many levels as POD positions)	name of POD station: random effect
pod_id	factor (as many levels as used CPOD devices)	ID of POD device: random effect
pos_long_new	continuous	longitude of POD position
pos_lat_new	continuous	latitude of POD position

In order to keep the dataset consistent, piling data of four wind farms that did not use monopile foundations, were positioned in shallow waters, or did not use noise-mitigation systems were excluded from hourly POD-data analyses of the Gescha 2 dataset for global models:

- GEM: no NMS used;
- GT1: tripod foundations;
- NSO: jacket foundations;
- NG: shallower water depth than at the other OWFs and highly influenced by tide due to its proximity to shore inside the Wadden Sea.

OWF Gemini was only analysed on project scale (WP 3.4); it was furthermore not included into the sound-model dataset since noise-level data were available only for one out of 150 foundations of this OWF. OSS HelWin2 and SylWin1 were not analysed on project scale due to an insufficient number of pilings.

Collinearity

Inclusion of variables with strong collinearity into models should be avoided, as this may result in serious deterioration of the quality of the outcome and thus leads to unstable estimates. We examined collinearity of all numerical predictor variables (but not factors) in order to test which variables may not be used jointly in the final models. Variables with a correlation of r > 0.5 were not used together in the same model. Water depth (*depth*) and depth variation – which often meant inclination – of the sea floor (*slope*) were highly correlated with the three single sandeel species (*pr_hl_pres, pr_at_pres, pr_am_pres*), all sandeel species combined (*sandaal*), and longitude (*pos_long_new*); the same was true for *depth* and salinity (*sal*). Water depth (*depth*) and longitude (*pos_long_new*) were strongly correlated. Salinity (*sal*) was highly correlated with the sandeel species *Hyperoplus lanceolatus* (*pr_hl_pres*) and the grouped sandeels *(sandaal*). The sandeel species *Hyperoplus lanceolatus* (*pr_hl_pres*) was highly correlated with the other two sandeel species *Ammodytes tobianus* and *Ammodytes marinus* (*pr_at_pres, pr_am_pres*). Finally, the grouped sandeels (*sandaal*) and the single sandeel species (*pr_hl_pres, pr_at_pres, pr_am_pres*) were highly intercorrelated (Figure 4.1).

In consequence, we excluded salinity (*sal*). Then, *sandaal* and *sandgrundel* were mostly included instead of single species; however, in some cases the inclusion of a certain single species led to better model fits.

Temporal autocorrelation

Dealing with biological processes, we expected the input (environmental covariates) and output (residuals) time series of the statistical models to display temporal autocorrelation. Considering the model residuals, it was assumed that significant autocorrelation originated from the response variable, but not from the covariates.

For the CI-type models, we used a modified covariate (*DPHt*: *DPH* at t-1) acting as an autoregressive component of the first order (BESTLEY et al. 2010). This covariate was found to significantly reduce autocorrelation in the Gescha 1 study.

Since *DPHt* was not feasible with Reference-type models, another way to reduce autocorrelation was applied by deleting subsequent hours in the analysed datasets. This was done for the global Reference-type models of WP 3.1 and achieved by splitting each analysed dataset – except of those for the noise-level models only dealing with the piling hour hrw 0 – into three subsets, each consisting of data of every third hour (subset 1: daytime hours 0, 3, 6,…; subset 2: hours 1, 4, 7,…; subset 3: hours 2, 5, 8,…), so that principally no subsequent hours occurred in the subsets. There was one exception: the piling hour hrw 0 was always included, as it was of major interest.

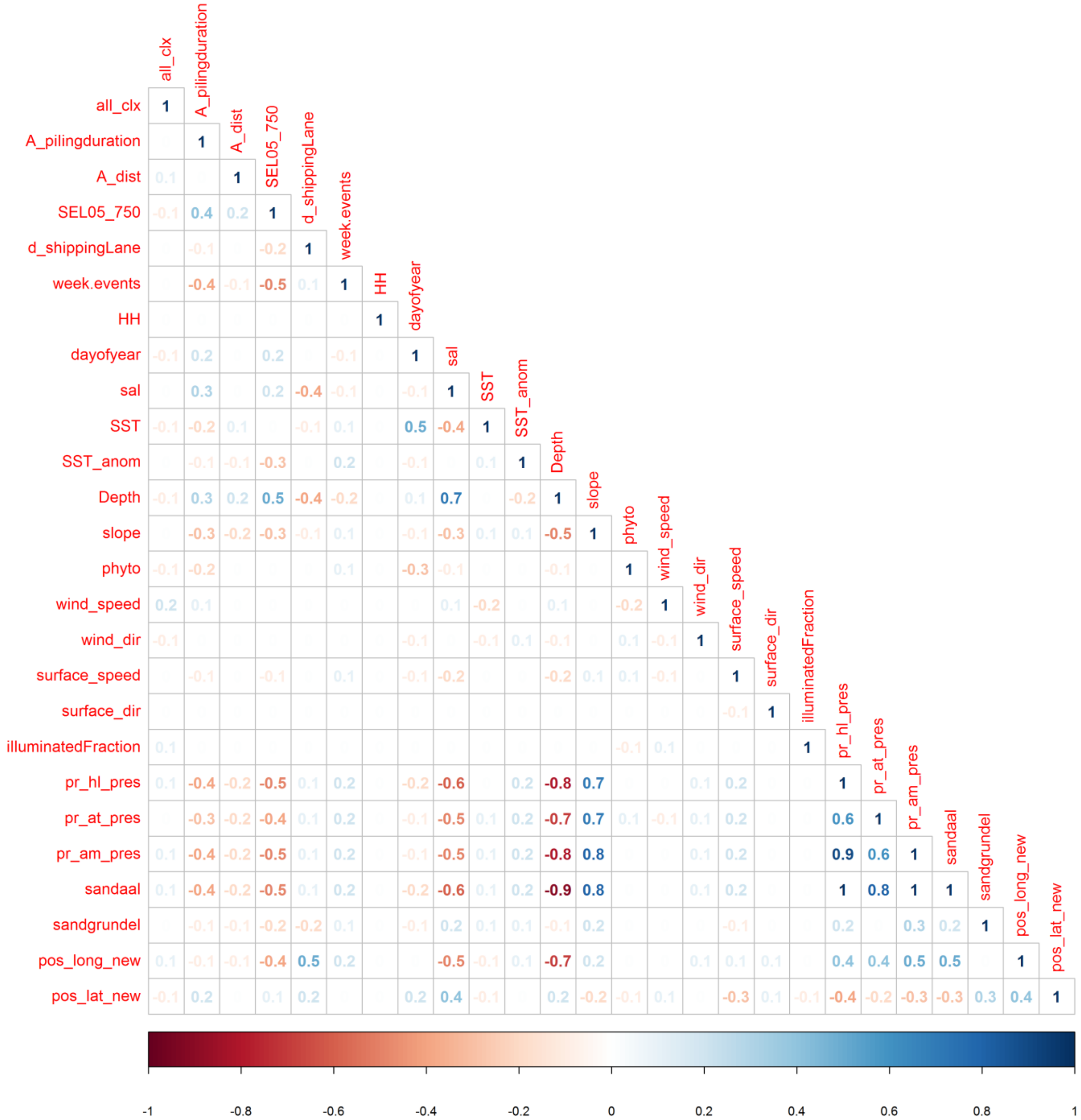


Figure 4.1 *Correlation structure of variables available for the hourly CPOD dataset ; range: 0 = no correlation, 1 and -1 = complete correlation; blue: positive correlation; red: negative correlation.*

For the Reference-type models of all other work packages with lower numbers of available data, we kept all daytime hours in the analyses in order to retain sufficient data and chose another way to reduce autocorrelation. For those and also for the global Reference-type models of WP 3.1, we corrected for autocorrelation of the first order by including a *rho* value into the *bam()* function for GAM modelling of large datasets (R package mgcv; Wood 2015) which was adequately chosen by the outcome of the function *start_value_rho()*.

Random effect selection

Preliminary analyses were conducted to compare the inclusion of several random effects in terms of model goodness-of-fit and model outputs based on AIC values. Based on the outcome of these analyses, we decided to include the name of the POD station (*Position*) and the ID of the POD device (*pod_id*) as random factors into GAM analyses. This procedure (a) corrected for effect differences due to geographical position and POD sensitivity, and (b) improved the deviance explained by the models and/or decreased the model AIC.

GAM model specifications

To facilitate model selection and deal with overfitting, a smooth modification technique (null-space penalisation) was implemented to allow smooths to be shrunk to zero as part of smoothness selection. Null-space penalisation constructs an extra penalty for each smooth which penalises the space of functions of zero wiggliness according to its existing penalties. If all the smoothing parameters for such a term tend to infinity then the term is penalised to zero and is effectively dropped from the model. The advantage of this approach is that it can be implemented automatically for any smooth by the *select* argument of the *bam()* function. To improve the reduction of overfitting, a *gamma* value of 1.4 was set within the *bam()* function, as recommended by WOOD (2015).

The obtained models can be regarded as a compromise between model accuracy and data availability. Global analyses of all available data in order to provide overall estimates on several different aspects of harbour porpoise avoidance behaviour during mitigated offshore pile driving were assumed to be reliable due to a broad database. However, for some specific aspects (e. g. avoidance radii in terms of distance, effects in terms of habitat characteristics) it was also necessary to consider each wind farm separately, which necessarily led to smaller datasets (especially with the new Reference-type models) with highly varying results. Ideally, separate models for each season and wind farm would have been computed to account for the specific conditions around certain wind farms which are likely to change the way porpoises respond to piling-noise emission. This, however, was not possible since the number of data rows became too low for meaningful analyses.

We conducted modelling with two types of grouped data:

1. We combined all data from all wind farms (each Gescha study alone and both studies combined) to investigate general patterns of wind farm construction effects, resulting in several models that specifically aimed at addressing the questions raised in the project tender. These models are called *global models* since they include the whole available dataset. Results of these models should be read as an average effect of all piling events in the German North Sea. The global models were conducted with Gescha 2 data from 2014 to 2016 alone, with combined Gescha 1 and Gescha 2 data from 2011 to 2016 (earlier data were excluded due to unavailability of some environmental variables), and finally the global models were applied to the Gescha 1 dataset alone (excluding data before 2011; see above) to be able to directly compare the results of Gescha 1 and Gescha 2 data according to the modified model approaches.

2. We ran *OWF-specific (project-specific) models* in order to look at project-specific differences which were likely to occur due to different natural patterns of porpoise occurrence and habitat characteristics at the OWF localities. These project-specific models were run separately for each wind farm and principally followed the specifications of the global model, though all Gescha 2 variables were included here (these were not available for

comparisons of the global models of the two project phase; see variables with asterisks in Table 4.2).

In total, 15 global models and 8 project-specific CI-type and Reference-type models were computed.

GAM model interpretation

Since CI-type models with *DPH* as dependent variable tended to be dependent on the distance range of included data, we also computed Reference-type models with *dDPH_ref* as dependent variable with the Gescha 2 dataset. The latter models were then also applied to the Gescha 1 dataset in order to get comparable results for both datasets. The new approach does not make use of the zero line of the CI-type models, being an average of all fitted values (on scale of the linear predictor) and thus being inherently affected by negative piling effects. Instead, Reference-type models are directly interpretable on the scale of the original response where a value of zero equals no effect. Since the new response variable inherently corrects for the effects of many covariates, the new approach rendered the models more stable. It was chosen here to show the contour line of a defined effect strength (percentage of reduction of *dDPH_ref*) instead of the zero-effect line of the response variable. We decided to use a contour line of a 20 % reduction of *dDPH_ref* (compared to the mean *DPH* value of the analysed dataset during the reference period, *DPH_ref*), which is shown in all plots of the Reference-type models. The 20 % reduction contour line seems suitable for interpretation, as it is robust enough to show clear effects. A 20 % reduction criterion was also used within Gescha 1 for non-parametric tests on piling effects relative to a baseline (BioConsult SH et al. 2016). The 0 % reduction line, which theoretically would have been desirable, is practically too much influenced by minor model fluctuations in larger distances and not robust. Confidence intervals could not be shown directly in the plots due to technical reasons, but the default model plots of the *gam.plot()* function give an indication of their approximate range (these are shown in the Appendix).

Table 4.3 gives an overview on the primary topics of the models, provides the names of the chapters where the results of a respective model are presented, and refers to the table number with model specifications. Models on unmitigated pilings alone are shown in the Appendix.

Table 4.3 Overview of the statistical models and analyses with respect to topic and work package, chapter with results, specifications, and information on the dataset with which the model was run (global and/or OWF-specific).

Model number / Analysis	Topic	Work package	Chapter	Global / OWF-specific	Table with model specifications
M3.1aG2	Effects of distance and time to piling; mitigated pilings; Gescha 2 data	3.1	4.1.2: WP 3.1	y/n	Table 4.4
M3.1aG1	Effects of distance and time to piling; mitigated pilings; Gescha 1 data	3.1	4.1.2: WP 3.1	y/n	Table 4.4
M3.1aG12	Effects of distance and time to piling; mitigated pilings; Gescha 1 and Gescha 2 data	3.1	4.1.2: WP 3.1	y/n	Table 4.4

Model number / Analysis	Topic	Work package	Chapter	Global / OWF-specific	Table with model specifications
M3.1a3G12	Effects of distance and time to piling; unmitigated pilings; Gescha 1 and Gescha 2 data	3.1	Appendix: WP 3.1	y/n	Appendix: Table A.2
M3.3a1G2	Effect range of piling noise level at piling hour (hrw 0); mitigated pilings; Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.4
M3.3a1G12	Effect range of piling noise level at piling hour (hrw 0); mitigated pilings; Gescha 1 and Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.4
M3.3b1G2	Effect duration of piling noise level at close range (0-10 km); mitigated pilings; Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.5
M3.3b1G12	Effect duration of piling noise level at close range (0-10 km); mitigated pilings; Gescha 1 and Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.5
M3.3a2G2	Effect range of piling noise level at piling hour (hrw 0); all pilings; Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.5
M3.3a2G12	Effect range of piling noise level at piling hour (hrw 0); all pilings; Gescha 1 and Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.5
M3.3a3G12	Effect range of piling noise level at piling hour (hrw 0); unmitigated pilings; Gescha 1 and Gescha 2 data	3.3	Appendix: WP 3.3	y/n	Appendix: Table A.2
M3.3b2G2	Effect duration of piling noise level at close range (0-10 km); all pilings; Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.6
M3.3b2G12	Effect duration of piling noise level at close range (0-10 km); all pilings; Gescha 1 and Gescha 2 data	3.3	4.1.2: WP 3.3	y/n	Table 4.6
M3.4a to M3.4h	Effects of distance and time to piling in accordance to habitat characteristics at wind farm areas; mitigated pilings (except for GEM)	3.4	4.1.2: WP 3.4	n/y	Table 4.6 Table 4.7
M3.5aG2	Effect range of piling duration shortly after piling hour (hrw 1-3); mitigated pilings; Gescha 2 data	3.5	4.1.2: WP 3.5	y/n	Table 4.8
M3.5aG12	Effect range of piling duration shortly after piling hour (hrw 1-3); mitigated pilings; Gescha 1 and Gescha 2 data	3.5	4.1.2: WP 3.5	y/n	Table 4.8
M3.5bG2	Effect duration of piling duration at close range (0-10 km); mitigated pilings; Gescha 2 data	3.5	4.1.2: WP 3.5	y/n	Table 4.8
M3.5bG12	Effect duration of piling duration at close range (0-10 km); mitigated pilings; Gescha 1 and Gescha 2 data	3.5	4.1.2: WP 3.5	y/n	Table 4.8
E3.6G12	Exploratory analysis of decrease of detection rates before piling events; Gescha 1 and Gescha 2 data	3.6	4.1.2: WP 3.6	y/y	-

*Table 4.4 Summary of specifications and results of the final models: 1st part. Inclusion and significance levels of each variable are indicated as follows: '-': variable not significant and therefore not included into the final model, except if it is a variable of primary interest, in which case 'ns' (not significant); other levels of significance: '***': p<0.001; '**': p<0.01; '*': p<0.05; if a certain sandeel species is significant, it is added as abbreviation ('am': Ammodytes marinus; 'hl': Hyperoplus lanceolatus); empty cell: variable not in the starting set of variables; '/': variable in starting set, but model stopped since a term had less unique combinations of covariates than maximum degrees of freedom; variable of primary interest within each model highlighted by grey cell.*

Work package	**3.1**						**3.3 (part 1)**			
Model number	**M3.1aG2**		**M3.1aG1**		**M3.1aG12**		**M3.3a1G2**		**M3.3a1G12**	
Model **Years** **Mitigation status** **Subset**	**global** **2014-16** **mitigated** **b**		**global** **2011-13** **mitigated** **c**		**global** **2011-16** **mitigated** **c**		**noise level** **2014-16** **mitigated** **0-40 km, hrw 0**		**noise level** **2011-16** **mitigated** **0-40 km, hrw 0**	
Model type	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**
Position (random factor)	***	***	***	***	***	***	***	-	***	**
pod_id (random factor)	***	***	***	***	***	***	***	**	***	***
DPHt (factor)	***		***		***		***		***	
YYYY (smooth)	***	***	***	***	***	***	***	**	-	***
dayofyear (cyclic smooth)	***	***	***	***	***	***	***	***	***	***
HH (cyclic smooth)	***	***	***	***	***	***	***	***	***	***
wind_speed (smooth)	***	***	***	***	***	***	**	-	***	***
wind_dir (cyclic smooth)	*	***	***	**	***	**	*	-	**	***
surface_speed (smooth)	***	***					-	**		
surface_dir (cyclic smooth)	***	-					-	-		
SST (smooth)	***	***	***	***	***	***	***	-	***	***
SST_anom (smooth)	***	***	***	***	***	***	-	-	***	***
all_clx (smooth)	***	***	***	***	***	***	***	***	***	***
depth (smooth)	-	-	***	-	**	-	-	-	***	***
slope (smooth)	***	-	**	-	***	-	-	-	-	-
phyto (smooth)	***	***					***	*		
illimunatedFraction*(smooth)*	***	***	***	***	***	***	*	-	***	***
sandaal (smooth)	*** *hl*	*** *hl*	-	-	** *hl*	*** *hl*	*	*** *hl*	-	-
sandgrundel (smooth)	-	-	***	-	***	-	***	-	***	-
A_pilingduration (smooth)	***	-	***	**	***	**	-	-	***	**
week.events (smooth)	***	***	***	-	***	***	*	***	-	***
d_shippingLane (smooth)	-	-	-	-	***	**	*	-	-	**
Interaction of ***A_HRW*** and ***A_dist*** (tensor)	***	***	***	***	***	***				
Interaction of ***A_dist*** and ***SEL05_750*** (tensor)							***	***	***	***
Deviance explained %	24.5	14.3	19.5	13.7	19.9	13.0	28.2	15.9	24.0	14.9
N hourly data	95,846	22,208	192,179	48,886	336,161	72,976	10,870	3,100	29,826	16,846
N piling events	493	160	333	206	826	366	401	127	704	350

Table 4.5 *Summary of specifications and results of the final models: 2nd part.*

Work package	**3.3 (part 2)**							
Model number	**M3.3b1G2**		**M3.3b1G12**		**M3.3a2G2**		**M3.3a2G12**	
Model **Years** **Mitigation status** **Subset**	**noise level** **2014-16** **mitigated** **0-10 km, hrw 0-48**		**noise level** **2011-16** **mitigated** **0-10 km, hrw 0-48**		**noise level** **2014-16** **all pilings** **0-40 km, hrw 0**		**noise level** **2011-16** **all pilings** **0-40 km, hrw 0**	
Model type	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**
Position (random factor)	**	-	***	***	***	-	***	***
pod_id (random factor)	**	***	***	***	***	**	***	***
DPHt (factor)	***		***		***		***	
YYYY (smooth)	-	-	***	-	***	***	-	***
dayofyear (cyclic smooth)	***	***	***	***	***	***	***	***
HH (cyclic smooth)	***	***	***	***	***	***	***	***
wind_speed (smooth)	***	***	***	***	**	-	***	***
wind_dir (cyclic smooth)	***	***	***	**	**	-	**	***
surface_speed (smooth)	-	**			-	**		
surface_dir (cyclic smooth)	-	*			-	-		
SST (smooth)	***	***	***	***	*	-	***	***
SST_anom (smooth)	***	-	***	**	*	-	***	***
all_clx (smooth)	***	***	***	***	***	***	***	***
depth (smooth)	-	***	***	***	-	-	***	***
slope (smooth)	*	*	***	**	*	-	-	-
phyto (smooth)	***	-			***	*		
illimunatedFraction *(smooth)*	**	-	***	***	**	-	***	***
sandaal (smooth)	**	-	-	** *am*	***	*** *hl*	-	-
sandgrundel (smooth)	-	-	**	***	***	-	***	-
A_pilingduration (smooth)	*	**	***	***	-	-	***	**
week.events (smooth)	**	***	***	***	*	***	-	***
d_shippingLane (smooth)	-	-	**	***	**	-	-	*
Interaction of ***A_dist*** and ***SEL05_750*** (tensor)					***	***	***	***
Interaction of ***A_HRW*** and ***SEL05_750*** (tensor)	***	***	***	***				
Deviance explained %	27.4	18.6	23.9	16.4	28.3	16.1	24.1	15.9
N hourly data	29,912	7,900	94,591	47,595	11,244	3,196	29,826	18,173
N piling events	353	110	676	336	416	131	746	341

Table 4.6 Summary of specifications and results of the final models: 3rd part.

Work package	3.3 (part 3)				3.4 (part 1)					
Model number	**M3.3b2G2**		**M3.3b2G12**		**M3.4a**		**M3.4b**		**M3.4c**	
Model Years Mitigation status Subset	**noise level 2014-16 all pilings 0-10 km, hrw 0-48**		**noise level 2011-16 all pilings 0-10 km, hrw 0-48**		**OWF-specific 2014-16 mitigated ABW**		**OWF-specific 2014-16 mitigated BR**		**OWF-specific 2014-16 mitigated BU**	
Model type	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**	**CI-type**	**Ref-type**
Position (random factor)	***	-	***	***	***	*	***	***	*	-
pod_id (random factor)	**	***	***	***	-	***	**	**	**	***
DPHt (factor)	***		***		***		***		***	
YYYY (smooth)	-	-	***	-						
dayofyear (cyclic smooth)	***	***	***	***	***	***	***	***	***	-
HH (cyclic smooth)	***	***	***	***	***	***	***	***	***	***
wind_speed (smooth)	***	***	***	***	***	***	***	**	**	-
wind_dir (cyclic smooth)	***	***	***	***	***	***	-	-	-	***
surface_speed (smooth)	-	**			***	***	***	***	***	***
surface_dir (cyclic smooth)	-	-			-	-	-	-	-	-
SST (smooth)	***	***	***	***	-	***	-	***	**	***
SST_anom (smooth)	***	-	***	***	***	***	-	***	-	***
all_clx (smooth)	***	***	***	***	***	***	***	***	***	***
depth (smooth)	-	***	***	**	***	-	/	/	/	/
slope (smooth)	*	*	***	*	***	***	/	/	/	/
phyto (smooth)	***	-			***	**	-	-	***	-
illimunatedFraction*(smooth)*	**	-	***	***	***	***	-	***	***	***
sandaal (smooth)	**	-	-	*	-	-	/	/	/	/
sandgrundel (smooth)	-	*	**	**	-	-	/	/	/	/
A_pilingduration (smooth)	-	**	***	***	-	**	-	**	-	***
week.events (smooth)	**	***	***	***	***	***	**	***	-	***
d_shippingLane (smooth)	-	*	**	*	-	-	/	/	/	/
Interaction of ***A_HRW*** and ***A_dist*** (tensor)					***	***	ns	**	***	**
Interaction of ***A_HRW*** and ***SEL05_750*** (tensor)		***		***						
Deviance explained %	27.6	18.2	23.9	15.8	27.2	18.8	27.5	20.6	29.4	24.0
N hourly data	31,085	8,228	94,591	56,450	17,236	10,899	11,241	5,180	9,056	3,433
N piling events	366	114	715	329	89	49	73	32	81	17

Table 4.7 Summary of specifications and results of the final models: 4th part.

Work package	3.4 (part 2)									
Model number	**M3.4d**		**M3.4e**		**M3.4f**		**M3.4g**		**M3.4h**	
Model **Years** **Mitigation status** **Subset**	**OWF-specific** **2014-16** **mitigated** **GW**		**OWF-specific** **2014-16** **mitigated** **N1**		**OWF-specific** **2014-16** **mitigated** **SB**		**OWF-specific** **2014-16** **mitigated** **VM**		**OWF-specific** **2014-16** **unmitigated** **GEM**	
Model type	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**	**Cl-type**	**Ref-type**
Position (random factor)	***	-	-	**	***	-	***	-	*	-
pod_id (random factor)	***	***	***	***	***	***	***	***	***	***
DPHt (factor)	***		***		***		***		***	
YYYY (smooth)										
dayofyear (cyclic smooth)	-	***	***	***	***	***	***	***	***	/
HH (cyclic smooth)	***	***	***	***	***	***	***	***	***	-
wind_speed (smooth)	***	**	***	-	-	***	***	-	***	-
wind_dir (cyclic smooth)	-	**	-	-	-	-	-	-	***	-
surface_speed (smooth)	-	-	**	***	***	***	-	-	-	-
surface_dir (cyclic smooth)	-	-	-	-	*	***	-	-	-	-
SST (smooth)	***	***	***	-	**	-	-	-	***	***
SST_anom (smooth)	**	**	***	***	-	-	-	-	***	***
all_clx (smooth)	***	***	***	***	***	***	***	***	***	***
depth (smooth)	/	/	-	***	-	-	/	/	-	/
slope (smooth)	/	/	*	-	-	-	/	/	-	/
phyto (smooth)	-	***	***	***	-	-	-	-	-	-
illimunatedFraction*(smooth)*	-	*	***	-	**	-	-	-	-	***
sandaal (smooth)	/	/	-	-	/	-	/	/	-	/
sandgrundel (smooth)	/	/	-	-	-	-	/	/	-	/
A_pilingduration (smooth)	-	***	-	-	***	***	***	***	-	/
week.events (smooth)	**	***	-	***	**	-	-	***	*	**
d_shippingLane (smooth)	/	/	-	-	**	-	/	/	***	/
Interaction of ***A_HRW*** and ***A_dist*** (tensor)	ns	**	***	ns	***	***	**	**	**	*
Deviance explained %	21.0	31.3	16.9	16.3	22.1	12.4	29.1	25.6	33.5	31.6
N hourly data	15,202	6,040	13,719	4,401	20,511	8,938	19,102	5,222	18,470	1,073
N piling events	100	34	61	17	73	31	71	15	160	4

Table 4.8 Summary of specifications and results of the final models: 5th part.

Work package	3.5							
Model number	M3.5aG2		M3.5aG12		M3.5bG2		M3.5bG12	
Model Years Mitigation status Subset	piling duration 2014-16 mitigated 0-40 km, hrw 1-3		piling duration 2011-16 mitigated 0-40 km, hrw 1-3		piling duration 2014-16 mitigated 0-10 km, hrw 0-48		piling duration 2011-16 mitigated 0-10 km, hrw 0-48	
Model type	Cl-type	Ref-type	Cl-type	Ref-type	Cl-type	Ref-type	Cl-type	Ref-type
Position (random factor)	***	-	***	*	-	-	***	***
pod_id (random factor)	***	**	***	***	***	***	***	***
DPHt (factor)	***		***		***		***	
YYYY (smooth)	-	***	-	-	-	-	-	***
dayofyear (cyclic smooth)	***	***	***	-	***	***	***	***
HH (cyclic smooth)	***	***	***	***	***	***	***	***
wind_speed (smooth)	***	-	***	**	***	***	***	***
wind_dir (cyclic smooth)	-	-	-	-	-	***	***	***
surface_speed (smooth)	-	*			-	***		
surface_dir (cyclic smooth)	-	-			-	*		
SST (smooth)	-	**	***	**	-	***	***	***
SST_anom (smooth)	-	-	-	*	***	-	***	***
all_clx (smooth)	***	***	***	***	***	***	***	***
depth (smooth)	-	-	**	-	-	***	***	-
slope (smooth)	-	-	-	-	-	*	-	**
phyto (smooth)	*	**			-	-		
illimunatedFraction *(smooth)*	**	-	**	-	***	-	***	***
sandaal (smooth)	*	* *hl*	-	-	-	-	-	-
sandgrundel (smooth)	*	-	*	-	-	-	*	-
week.events (smooth)	-	-	-	***	-	***	***	***
d_shippingLane (smooth)	-	-	-	-	-	-	-	-
SEL05_750 (smooth)	***	-	***	-	***	-	***	-
Interaction of ***A_pilingduration*** and ***A_dist*** (tensor)	*	***	***	***				
Interaction of ***A_pilingduration*** and ***A_HRW*** (tensor)					***	***	***	***
Deviance explained %	27.5	14.3	23.6	11.5	27.2	18.5	24.1	15.7
N hourly data	9,731	2,041	18,324	8,738	30,767	7,900	83,228	50,525
N piling events	484	126	779	333	432	110	736	319

4.1.2 Results

Evaluation of raw data

One important topic of Gescha 2 is the assessment of the overall effect range and duration of mitigated pile driving on harbour porpoise. Therefore, before any modelling approach was conducted, the available hourly CPOD dataset was inspected to uncover inconsistencies in the dataset, especially with respect to the four explanatory variables of main interest: *A_dist* (distance to piling), *A_HRW* (hour relative to piling), *SEL05_750* (noise level of the SEL_{05} in 750 m distance to piling), and *A_pilingduration* (duration of pile driving in minutes). The distribution of available hourly data varied considerably among the projects (i. e. offshore wind farms and transformer stations).

A_dist: Close-range data were crucial for meaningful analyses on piling effects, but such data were sparse or even missing for several projects (Figure 4.2: BR, GEM, GW, SylWin1). This was in contrast to the Gescha 1 study (Gescha 1 raw data plots with same axis-scale in the Appendix, emphasising the much higher number of available data for Gescha 1). The issue became a major restriction for analyses of piling effects of these four projects and was the main reason why model results for these projects were not reliable.

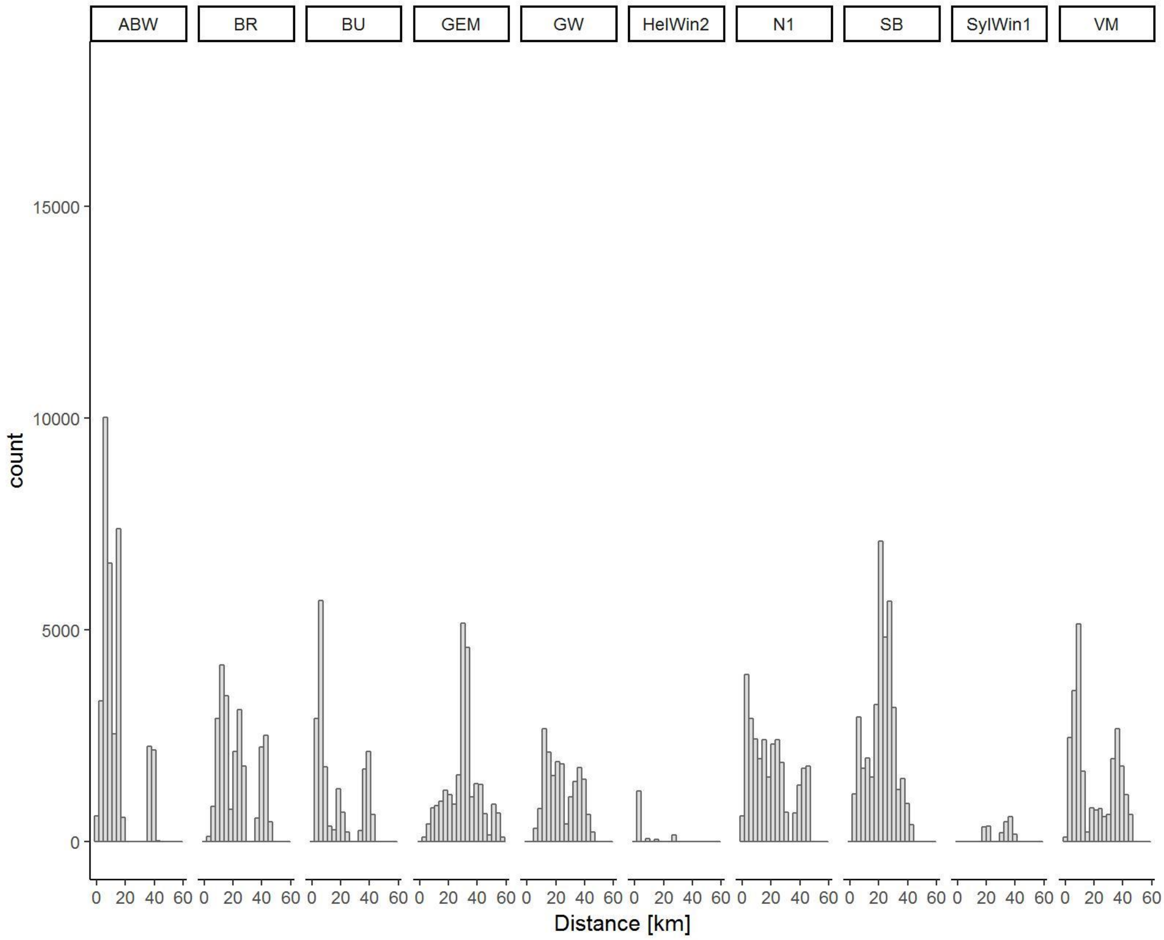


Figure 4.2 Gescha 2: Availability of hourly CPOD data for certain distance classes of the variable A_dist (CPOD distance to piling locations of the investigated OWFs and transformer platforms).

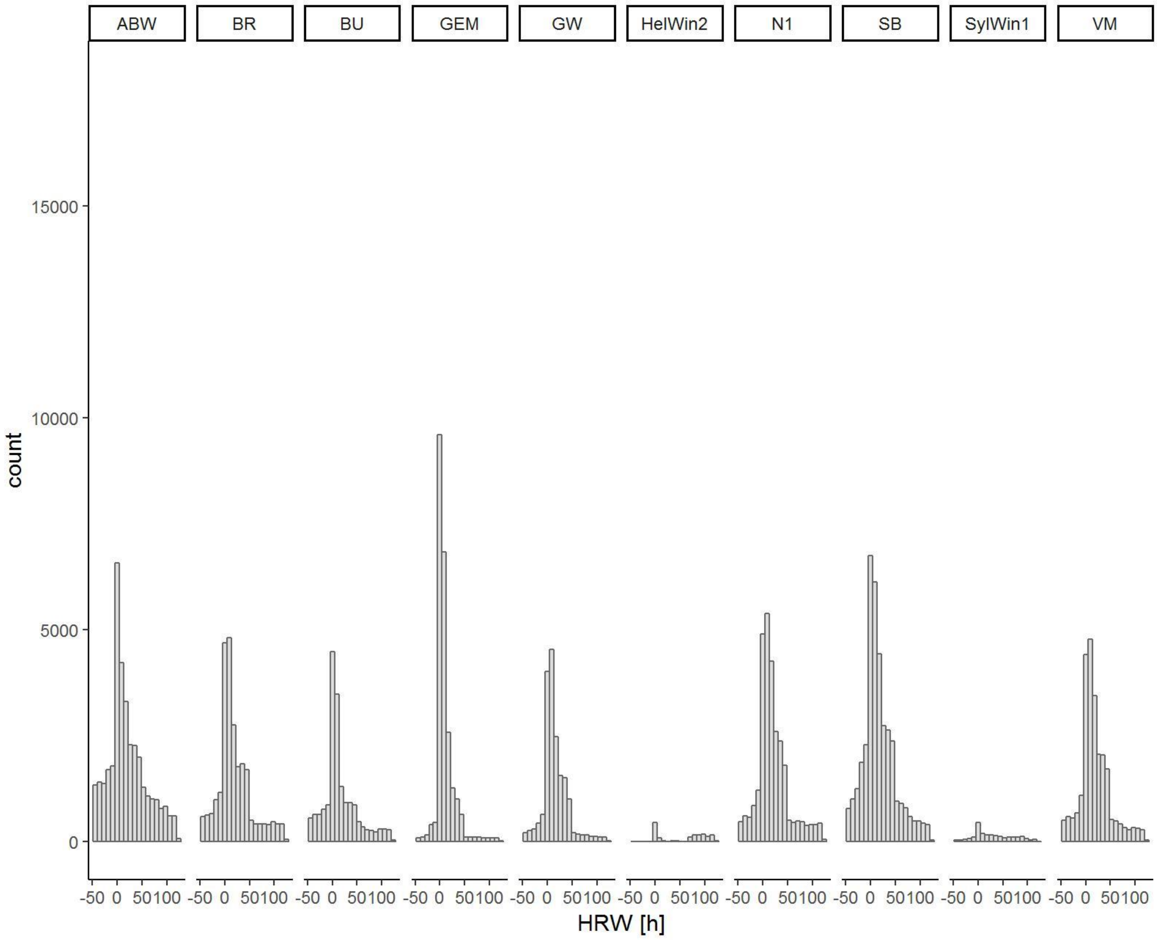


Figure 4.3 *Gescha 2: Availability of hourly CPOD data for the variable A_HRW (time relative to piling hour) at the investigated OWFs and transformer platforms.*

A_HRW: By far the most hourly CPOD data were available for hours with pile driving (hrw 0), since more than one hour in sequence could be assigned to hrw 0 if piling took place over several subsequent hours. This caused strong peaks at hrw 0 in Figure 4.3. The investigated transformer platforms (HelWin2, SylWin1), as well as two OWFs (GEM, GW), had only very few hourly data before piling and were therefore less suitable for Reference-type models. Often a steep decrease of the number of available data occurred from hrw+49 after piling onwards, which was caused by our method of assigning hours to a new piling event only after at least 48 h had passed since a previous piling event. Again, more hourly data were available for Gescha 1 than for Gescha 2 for both model types, both in general and with respect to hours before piling (see Appendix).

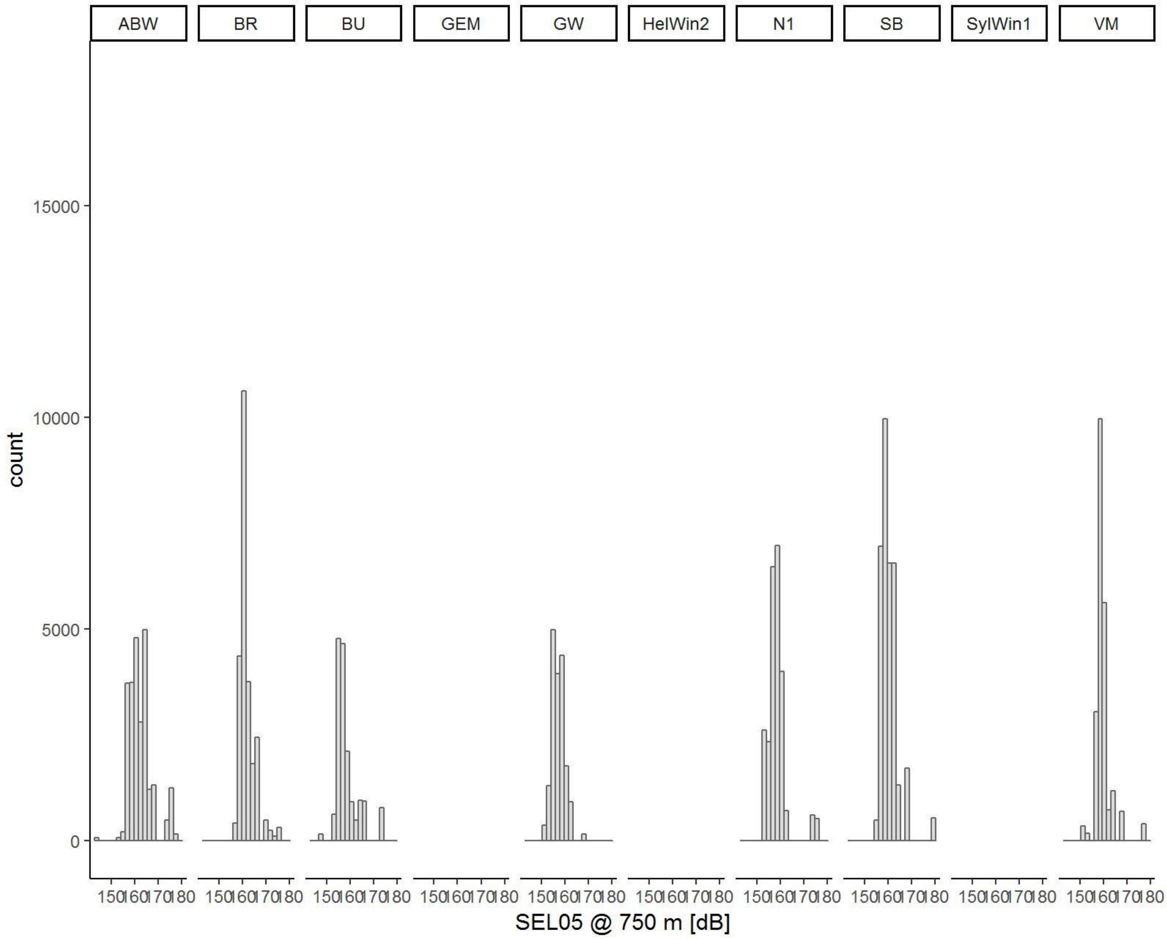


Figure 4.4 Gescha 2: Availability of hourly CPOD data for the variable SEL05_750 (noise level in dB of the SEL_{05} in 750 m distance) at the investigated OWFs and transformer platforms.

SEL05_750: Noise-level data were missing for OWF GEM and both transformer stations. Therefore, analyses on piling effects regarding different source noise levels could only be conducted on the data of seven OWFs. At Gescha 1, only data from six OWFs could be considered for such analyses, but in overall a much higher number of hourly data was available for Gescha 1 (see Appendix).

A_pilingduration: Piling events were on average shorter for Gescha 2 than for Gescha 1 projects. For Gescha 2, piling duration rarely exceeded 250 minutes (Figure 4.5), whereas for Gescha 1 piling events often lasted for 300 minutes and more (see Appendix). Therefore, analyses on the effects of piling duration were only meaningful when combining the Gescha 1 and Gescha 2 datasets. Gescha 2 data were strongly biased towards shorter piling durations and did not show enough variation over piling duration, given the data resolution of one hour in the response variable.

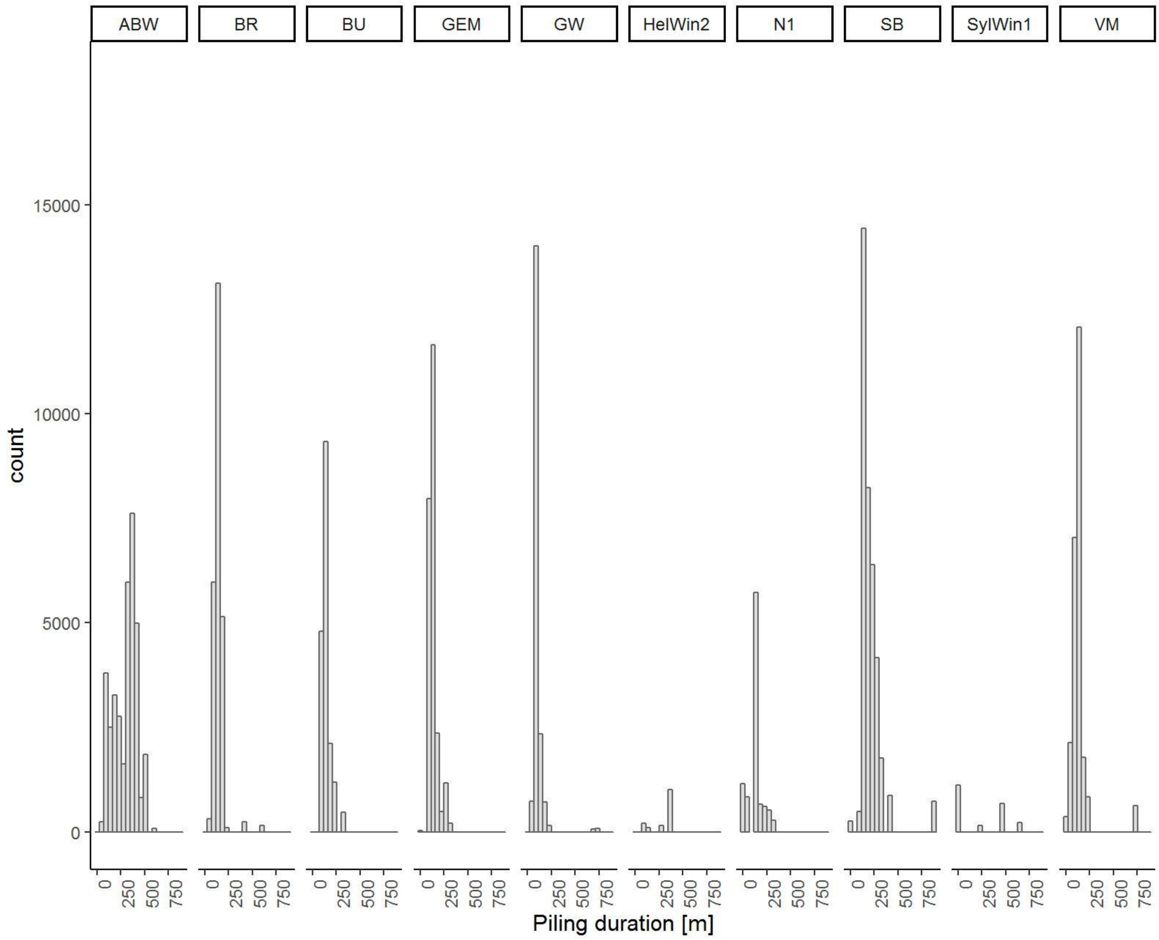


Figure 4.5 Gescha 2: Availability of hourly CPOD data for the variable A_pilingduration (duration of piling events in minutes) at the investigated OWFs and transformer platforms.

In summary, the database for Gescha 2 was smaller than for Gescha 1, which was caused by different reasons: First, the tighter sequence of pile driving for Gescha 2 with shorter breaks between pilings resulted in less hours before and after pile driving available for analyses. Second, less POD stations in a close range of up to 5 km around pile driving with the Gescha 2 dataset when compared to Gescha 1 reduced the dataset considerably.

WP 3.1 – Spatial and temporal extent of the effects of mitigated pile driving (CPOD data)

Topic of this work package is the assessment of the overall effect range and duration of mitigated pile driving in the years 2014-2016 alone (Gescha 2 data: model M3.1aG2), in combination with the effects of pile driving under first-generation noise mitigation systems (Gescha 1 and Gescha 2 data: 2011-2016; model M3.1aG12), and of mitigated pile driving from 2011 to 2013 alone (Gescha 1 data: model M3.1aG1) for comparability with Gescha 2 results under the same methodology. WP 3.1 deals with overall effect range and duration; differences of such effects regarding single OWFs are analysed in WP 3.4. Models on unmitigated pile driving alone are given in the Appendix.

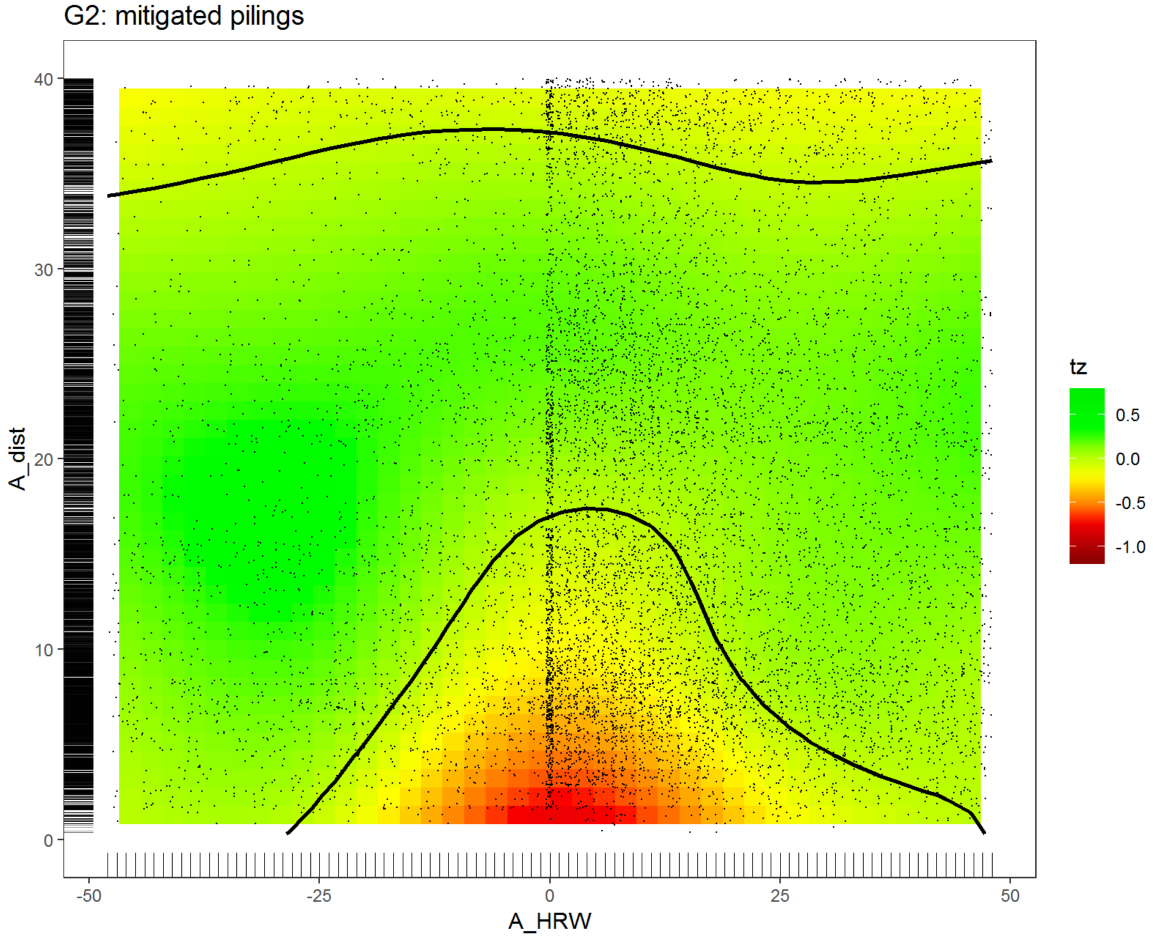


Figure 4.6 *Global Cl-type GAM M3.1aG2: Mitigated pile driving 2014-2016 (Gescha 2); DPH values on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.*

The Cl-type global GAM model M3.1aG2 on the overall effect range and duration of noise-mitigated pilings in the years 2014 to 2016 (Gescha 2) was computed with *DPH* as dependent variable (Figure 4.6). Besides the random factors (*Position, pod_id*), autocorrelation corrector (*DPHt*) and variables of main interest (the tensor product of *A_dist* and *A_HRW*), 16 covariates had a significant effect on the model outcome and stayed in the final model (Figure 4.6). If the zero line in GAM plots of Cl-type models is interpreted as a minimum effect range, effects of mitigated pile driving for Gescha 2 reached up to a distance of 17 km during hours of pile driving (hrw 0). Negative effects started 28 h before pile driving (for comparability with Gescha 1 and Gescha 1/Gescha 2 models: 22 h in 3 km distance) and continued until 48 h after piling (for comparability with Gescha 1 and Gescha 1/Gescha 2 models: 38 h in 3 km distance), the spatial range of effects being shorter to both ends of this period. The effect range of unmitigated pile driving was not investigated here due to a too low number of such events (except for OWF Gemini with over 150 unmitigated piling events, causing a strongly biased dataset in this respect, and being one reason why Gemini is analysed separately).

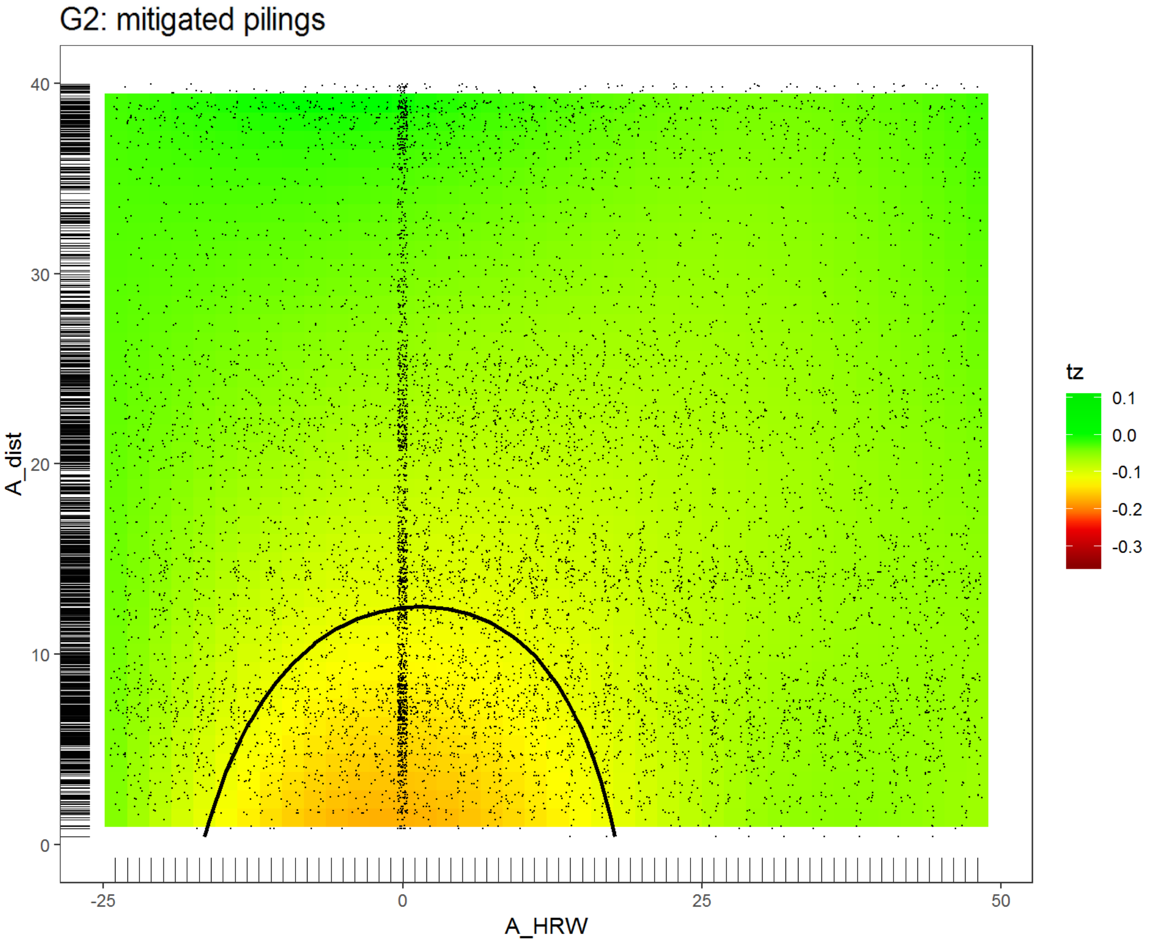


Figure 4.7 *Global Reference-type GAM M3.1aG2: Mitigated pile driving 2014-2016 (Gescha 2); dDPH_ref values on scale of the response where zero equals no effect (black contour line: 20 % reduction of dDPH_ref relative to reference level), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.*

The according Reference-type model produced an output that has to be interpreted differently to that of the Cl-type model, since it is based on different information and shows a contour line of a different type (Figure 4.7). Only ideal piling events, with breaks before and afterwards being sufficient to allow for reference periods, were analysed for this type of model, by this minimising cumulative piling effects which are supposed to occur mainly during tight piling sequences. The model outcome can directly be related to an assumedly unaffected reference level, in relation to which a 20 % reduction is shown in this and subsequent plots of Reference-type models (a zero-effect line is instable in such plots). The plot for the Gescha 2 dataset shows a 20 % reduction of the detection rate *dDPHref* (and thus also of *DPH*) in about 13 km distance from pilings at hrw 0 (Figure 4.7). As to the duration of the effect in close range to pile driving, a 20 % reduction of detection rates was exceeded between hrw-17 and hrw+18.

The same kind of models was computed for the Gescha 1 dataset (years 2011-2013). The best-fitted CI-type model indicates a minimum effect range of 15 km at hrw 0. Since the zero line bends up again at lowest distances, it is difficult to be interpreted in terms of the effect duration in less than 2 km distance to construction sites. In 3 km distance to pile driving, a reduction of *DPH* started latest at hrw-25 and lasted at least until hrw+30 (Figure 4.8). Besides the random factors (*Position, pod_id*), the autocorrelation corrector (*DPHt*) and the variables of main interest (the tensor product of *A_dist* and *A_HRW*), 14 covariates had a significant effect on the model outcome and stayed in the final model (Figure 4.6).

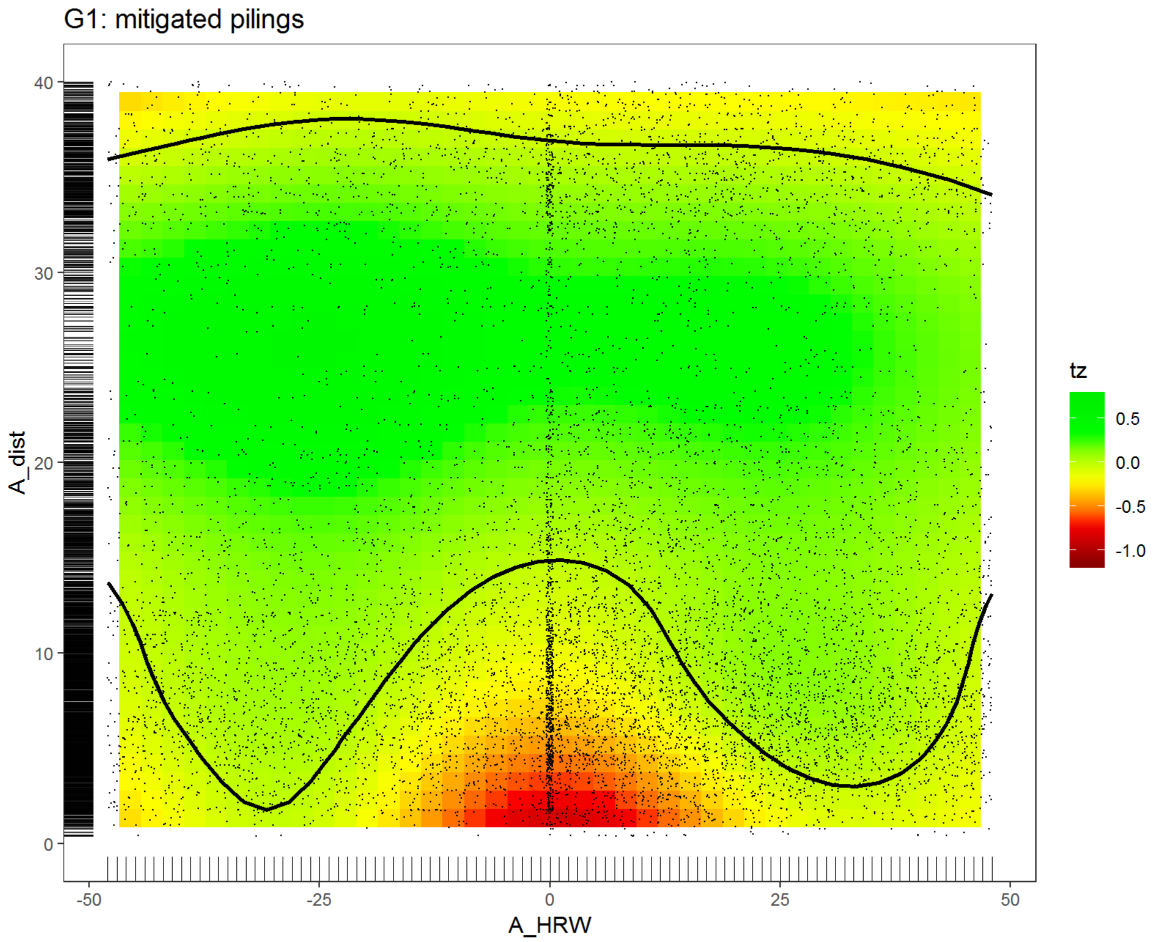


Figure 4.8 Global CI-type GAM M3.1aG1: Mitigated pile driving 2011-2013 (Gescha 1); DPH values on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.

The best-fitted Reference-type GAM for the Gescha 1 dataset shows a 20 % reduction of the detection rate *dDPHref* in about 11 km distance from pilings at hrw 0 (Figure 4.9). Regarding the duration of the effect in close range to pile driving, a 20 % reduction of *dDPHref* was exceeded between hrw-15 and hrw+15.

With the single Gescha 2 and Gescha 1 datasets, also directly comparable models with identical covariates (those of the best-fitted model of the overall Gescha 1 & Gescha 2 dataset) were computed. The outcome was similar to the best-fitted models and is shown in the Appendix.

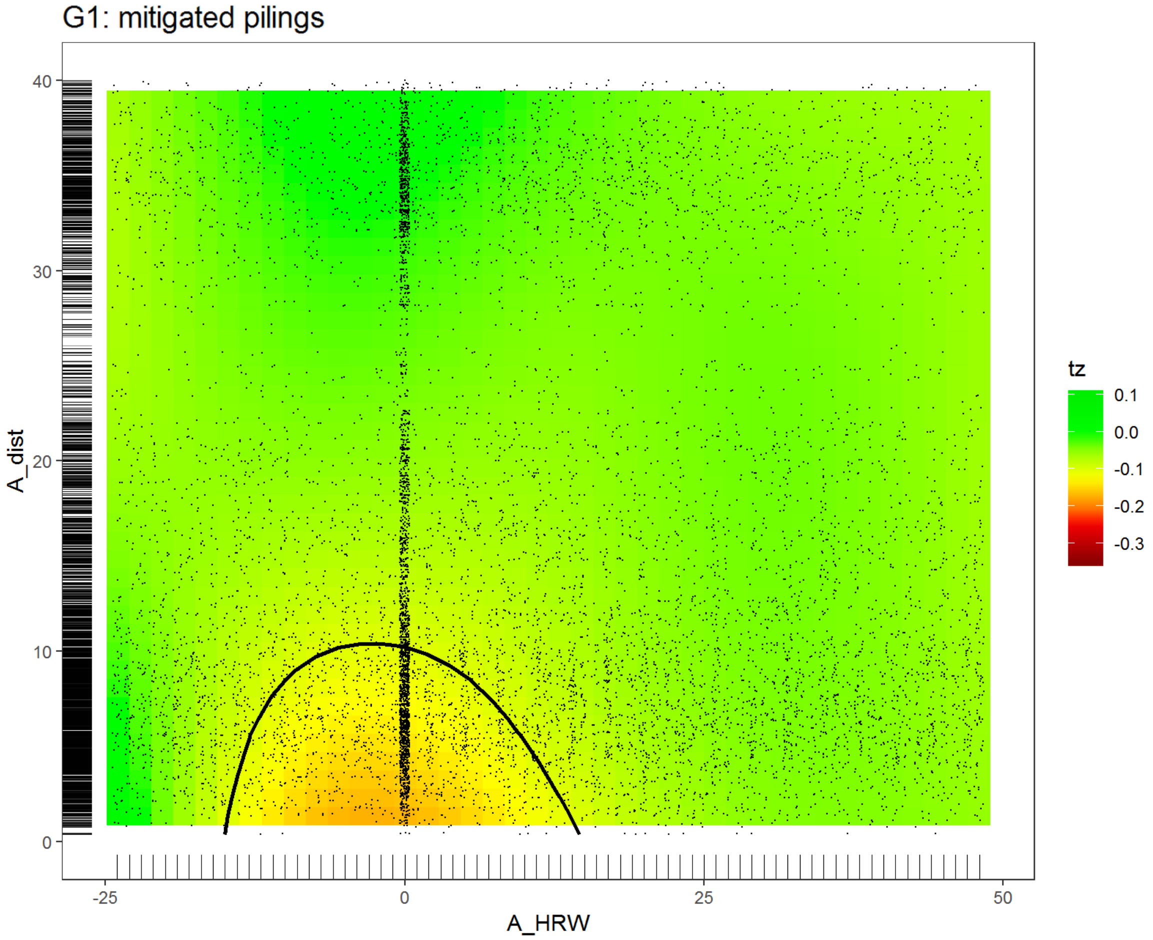


Figure 4.9 *Global Reference-type GAM M3.1aG1: Mitigated pile driving 2011-2013 (Gescha 1); dDPH_ref values on scale of the response where zero equals no effect (black contour line: 20 % reduction of dDPH_ref relative to reference level), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.*

When combining Gescha 1 & Gescha 2 data (GAMs M3.1aG12; years 2011-2016), the CI-type model (Figure 4.10) shows that effects of mitigated pile driving reached up to a minimum effect distance of 15 km during hours of pile driving (hrw 0). The onset of effects in close distance to construction sites was at least 28 h before pile driving (22 h at 3 km distance). Since the zero line bends up again after piling at lowest distances, it is difficult to be interpreted in terms of the effect duration after piling in less than 2 km distance to construction sites. In 3 km distance to pile driving, a reduction of *DPH* rates lasted until hrw+28.

The Reference-type GAM for the overall dataset shows a 20 % reduction of the detection rate *dDPHref* (and thus also of *DPH*) in about 11 km distance from mitigated pilings at hrw 0 (Figure 4.11). In the vicinity of construction sites, a 20 % reduction of detection rates was exceeded between hrw-19 and hrw+19.

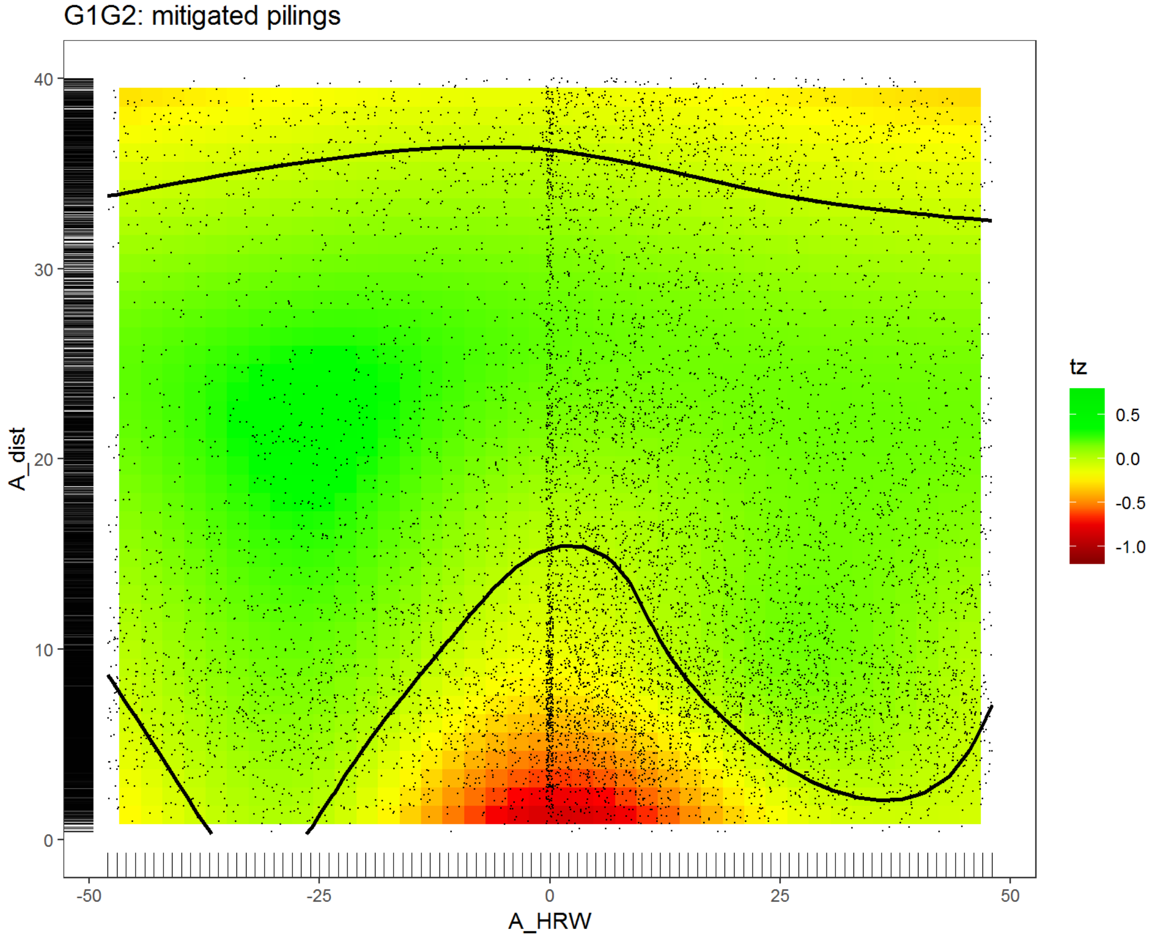


Figure 4.10 Global CI-type GAM M3.1aG12: Mitigated pile driving 2011-2016 (Gescha 1 & 2); DPH values on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.

Even though noise-mitigation measures became more efficient during recent years, no reduction of effect ranges was found for mitigated Gescha 2 pilings, compared to Gescha 1 pile driving. A summary of all effect ranges and durations with approximate standard error ranges (taken from standard GAM plots in the Appendix) is given in Table 4.9.

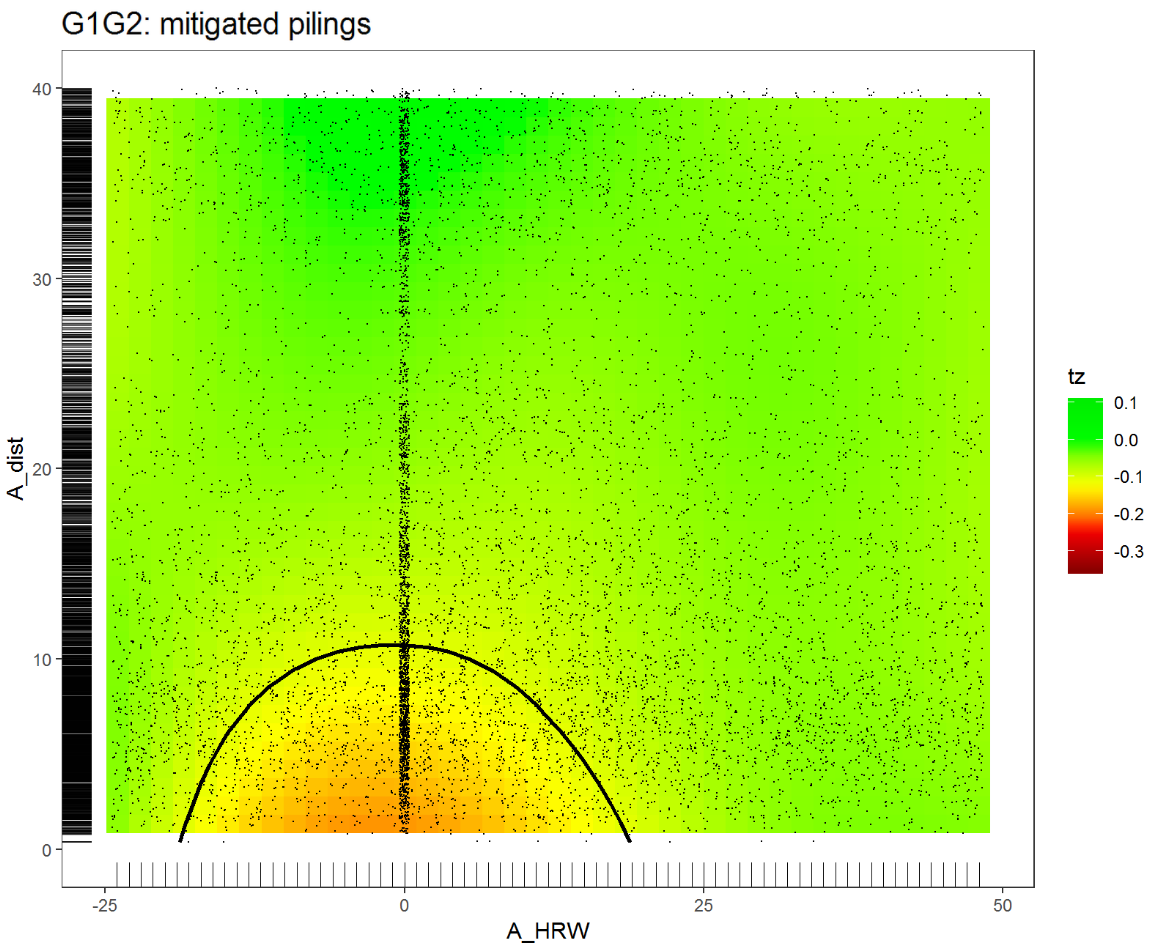


Figure 4.11 *Global Reference-type GAM M3.1aG12: Mitigated pile driving 2011-2016 (Gescha 1 & 2); dDPH_ref values on scale of the response where zero equals no effect (black contour line: 20 % reduction of dDPH_ref relative to reference level), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.*

Table 4.9 *Summary of effect ranges and durations for the Gescha 2, Gescha 1, and the Gescha 1 & 2 dataset of mitigated pilings under both model types (with approximate range after standard errors obtained by default GAM plots in the Appendix; ∞: no finite lower or upper standard error).*

Study	Cl-type: Min. effect range at hrw0	Cl-type: Min. effect duration before piling (0 km; if not available: *3 km*)	Cl-type: Min. effect duration after piling (0 km; if not available: *3 km*)	Cl-type: Min. effect duration before piling (3 km)	Cl-type: Min. effect duration after piling (3 km)	Ref-type: 20 % reduction at hrw0	Ref-type: 20 % reduction before piling (0 km)	Ref-type: 20 % reduction after piling (0 km)
G2	17 (15-19) km	28 (∞-22) h	48 (35-∞) h	22 (19-25) h	38 (29-∞) h	13 (11-15) km	17 (15-19) h	18 (15-21) h
G1	15 (14-16) km	*25 (22-28) h (3 km)*	*30 (25-∞) h (3 km)*	25 (22-28) h	30 (25-∞) h	11 (10-12) km	15 (14-16) h	15 (13-17) h
G1G2	15 (14-16) km	28 (∞-24) h	*28 (25-33) h (3 km)*	22 (20-24) h	28 (25-33) h	11 (10-12) km	19 (18-20) h	19 (17-21) h

Also models on unmitigated pile driving were computed, but these only for the combined Gescha 1 & 2 dataset, since insufficient unmitigated piling events were available for each of the projects alone, especially regarding the Reference-type model. Results and plots are given in the Appendix document (Figures A.19 to A.22; Tables A.1 and A.2). The global CI-type model shows a zero line (average of fitted values) that is open-ended with respect to distance (only the lower s.e. was assessible: 22 km). This might have been caused by spatial heterogeneity, as we found lower detection rates also in large distances many hours before piling (Figure A.19). It caused the zero line to be lifted outwards as it represented the mean of the fitted values. The piling effect reached further than for mitigated pilings, but interestingly the onset of effects started later (unmitigated: from hrw-16 [s.e.: hrw-14 to hrw-19]; mitigated: from hrw-28 [s.e.: hrw-∞ to hrw-24]) and ended earlier (unmitigated: until hrw+23 [s.e.: hrw+20 to hrw+26]; mitigated: until hrw+28 [s.e.: hrw+25 to hrw+33]). The difference before pile driving might have been due to the additional effects of vessels carrying noise-mitigation equipment; however, it was not found with the following Reference-type model. The difference after pile driving cannot be sufficiently explained, as we found the opposite trend with the following Reference-type model.

Also the global Reference-type model showed that effects of unmitigated pilings are farther-reaching than those of mitigated pile driving (unmitigated: 26 km [s.e.: 22-30 km]; mitigated: 11 km [s.e.: 10-12 km]). With the Reference-type model, a 20 % reduction of *dDPH_ref* relative to reference level occurred at a similar time before piling (around hrw-18; Figure A.21 of the Appendix), but an effect of at least 20 % reduced *dDPH_ref* lasted much longer after piling (unmitigated: hrw+28 [s.e.: hrw+24 to hrw+34]; mitigated: hrw+19 [s.e.: hrw+17 to hrw+21]). The difference after pile driving might be due to the longer timespan it took porpoises to return from farther distance; however, the opposite trend was found with the CI-type model. At the hours of pile driving, the effect at close range was much stronger for unmitigated pilings (dark-red colour in Figure A.21 of the Appendix) than for mitigated pilings (bright-orange colour in Figure 4.11).

WP 3.3 – Effect of piling-noise level

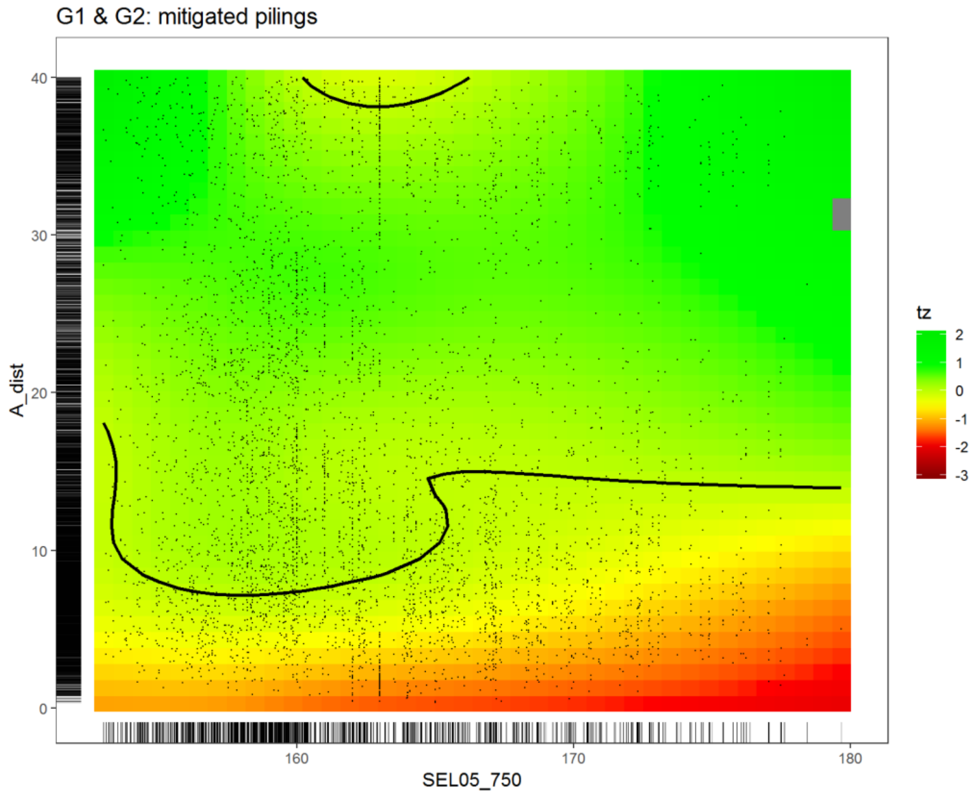
Topic of this work package is the analysis of the possible effects of different noise levels of pile driving on porpoise detection rates. In contrast to the Gescha 1 study, noise levels for Gescha 2 were not calculated for certain POD distances to piling via sound propagation curves. Instead, measured noise levels at 750 m distance were taken. In order to be able to combine data of both projects, the new methodology was applied to the combined Gescha 1 & 2 dataset (2011-2016; model suffix part "G12") since a sufficient number of unmitigated pilings was available only when including the Gescha 1 dataset. Results for the Gescha 2 dataset alone and of unmitigated pilings the Gescha 1 & 2 dataset are given in the Appendix. Two types of analysis were conducted:

1. Short time range (time of pile driving: hrw 0): Models of the effect range (*A_dist*) of mitigated pile driving against noise level SEL_{05} in 750 m distance (*SEL05_750*) (model suffix part "a").

2. Close distance range (0-10 km distance to piling): Models of the effect duration (*A_HRW*) of mitigated pile driving against noise level SEL_{05} in 750 m distance (*SEL05_750*) (model suffix part "b"). Only hours from piling onwards were considered (hrw0 to hrw+48) since piling-noise effects could not occur before pile driving.

Analyses were carried out with all pilings (in order to have a sufficient noise-level range; model suffix part "2"), and with data of mitigated pilings only (model suffix part "1"), resulting in eight different forms of analysis, for each of which Cl-type and Reference-type models were computed.

As to the effect distance during piling hours (hrw 0), both model types revealed that below noise levels of roughly 165 dB no further decrease of the deterrence range of harbour porpoises occurred. This might have been a reason why improved noise reduction of pilings, which led to noise levels below 160 dB SEL_{05} in 750 m distance caused no improvement with respect to reduced detection rates (Figure 4.12 & Figure 4.13). This was especially true for stronger effects (orange and red parts in the figures). From ca. 165 dB upwards, a continuous increase of effect strength with increasing noise levels became apparent. The upbending parts of the curves towards lowest noise levels are difficult to explain and may be due to a few aberrant piling events which, even though being conducted at lowest noise levels, caused rather strong effects, so that the model accuracy deteriorated to the curve ends (see s.e. contours of default plots in the Appendix). As for louder pilings of 175 dB with sufficient break times before and afterwards (Reference-type models; Figure 4.13), a 20 % decrease of detection rates was found in 15 km distance with mitigated pilings, and in 20 km distance with all pilings. If loud enough, unmitigated pilings had apparently stronger effects than mitigated pilings. By contrast, at 165 dB no difference was found anymore (20 % decrease of detection rates in 12 km distance). However, this pattern could only be found to a minor extent with the Cl-type models, which included more piling events than the Reference-type models. With Cl-type models, the minimum zero-effect line ranged around 14 km distance for mitigated pilings of 175 dB, and around 16 km distance for all pilings of 175 dB (Figure 4.12). Regarding the effect duration in up to 10 km distance, longer-lasting and stronger effects occurred with louder piling events. Even though this was equally true for both Cl-type models (mitigated vs all piling events; Figure 4.14), with the Reference-type models the positive correlation of effect duration to noise level was less expressed with mitigated pilings alone, when compared to all piling events (Figure 4.15). Models on unmitigated pile driving are presented in the Appendix.



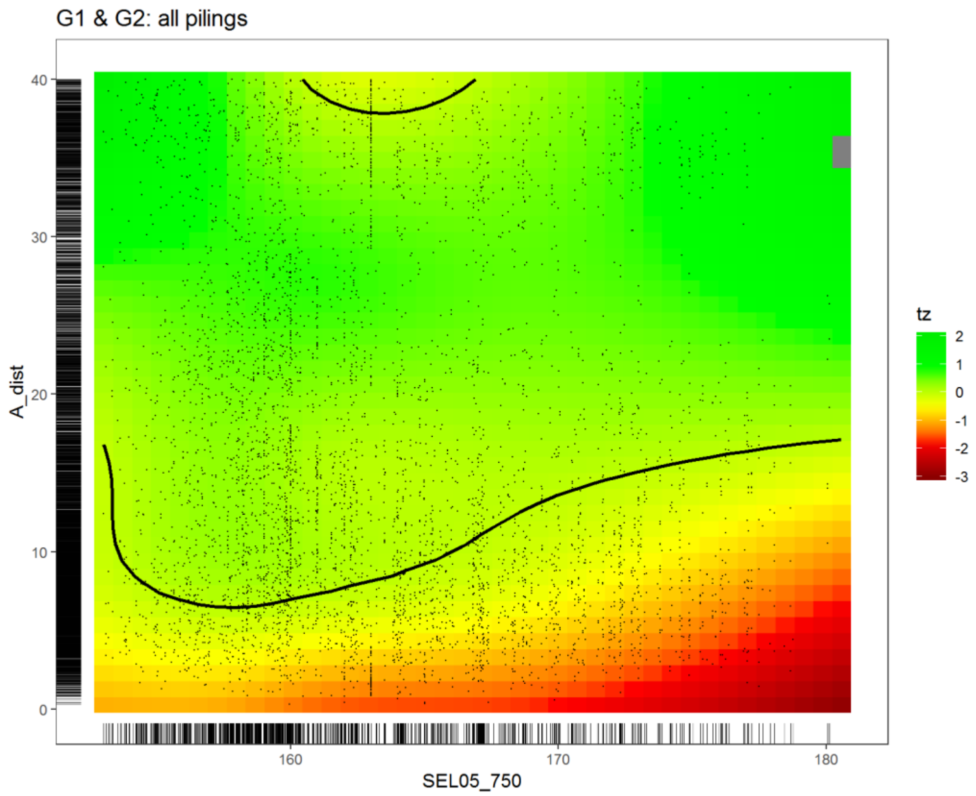
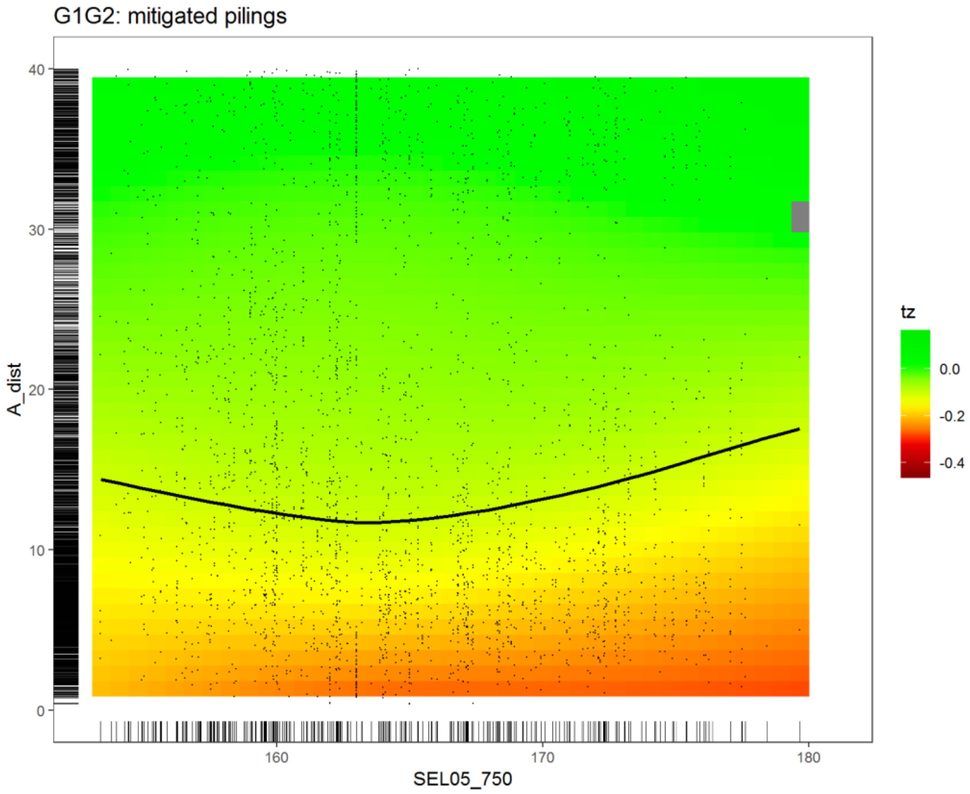


Figure 4.12 CI-type noise-level GAMs M3.3a1G12 & M3.3a2G12: mitigated pile driving (top) and all pilings (bottom) 2011-2016 (Gescha 1 & 2); DPH values at piling hour (hrw 0) on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on the interaction of the variables SEL05_750 (noise level of SEL_{05} in 750 m distance) and A_dist (distance to piling); black dots: data.



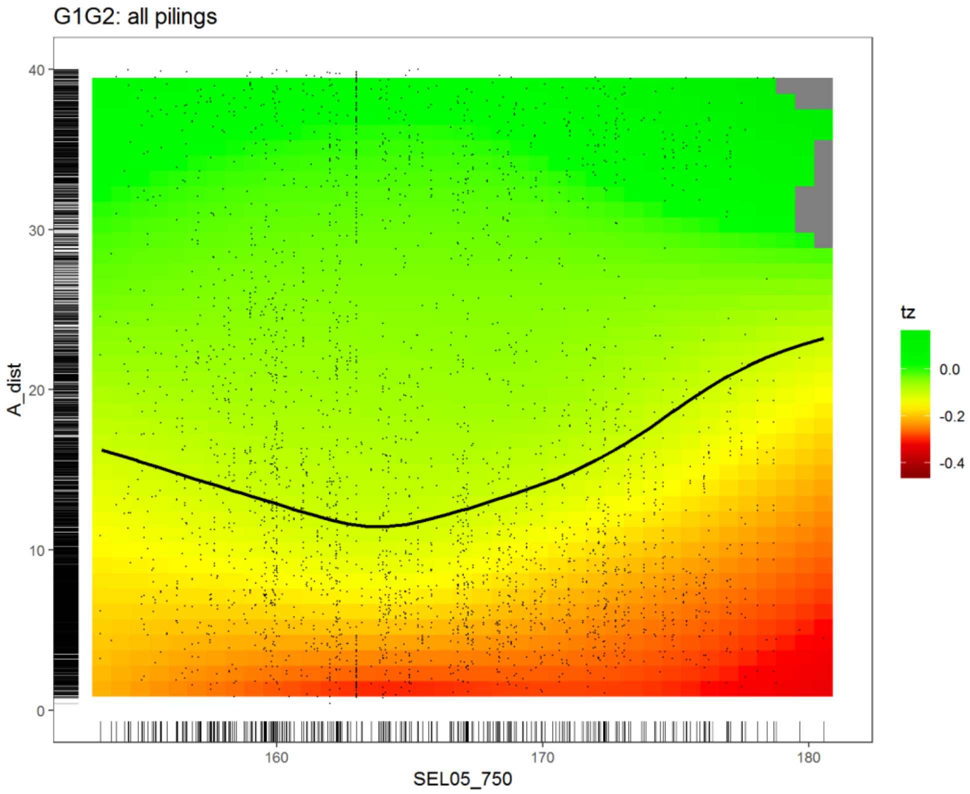
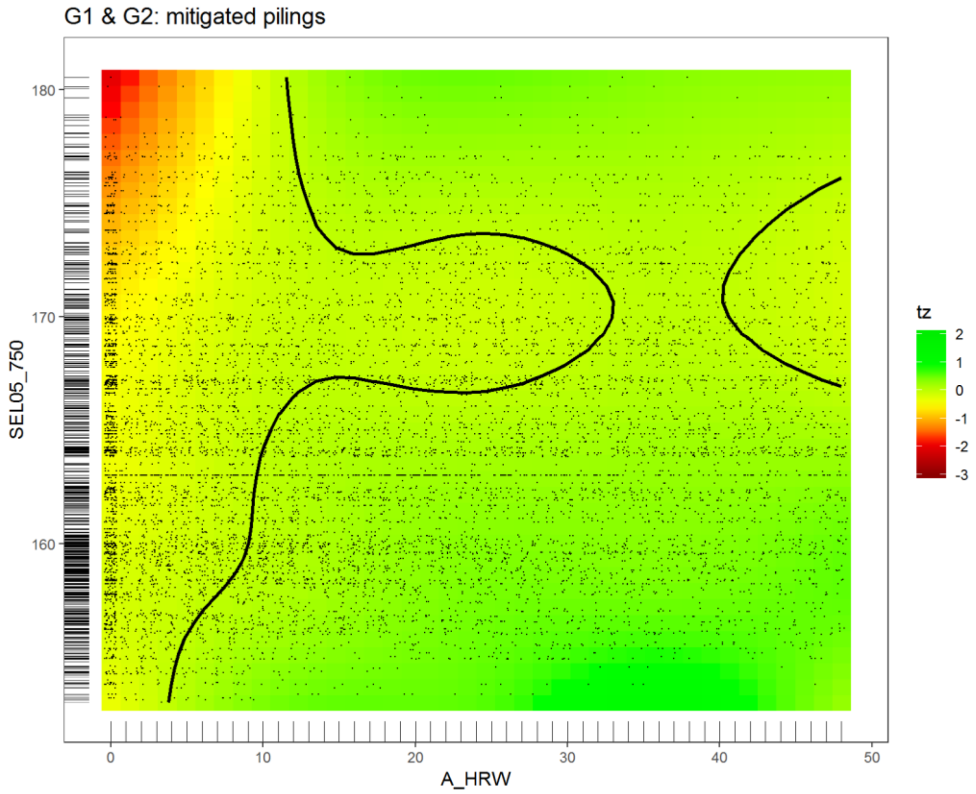


Figure 4.13 Reference-type noise-level GAMs M3.3a1G12 & M3.3a2G12: mitigated pile driving (top) and all pilings (bottom) 2011-2016 (Gescha 1 & 2); dDPH_ref values at piling hour (hrw 0) on scale of the response where zero equals no effect (black contour line: 20 % reduction of dDPH_ref relative to reference level), modelled on the interaction of the variables SEL05_750 (noise level of SEL_{05} in 750 m distance) and A_dist (distance to piling); black dots: data.



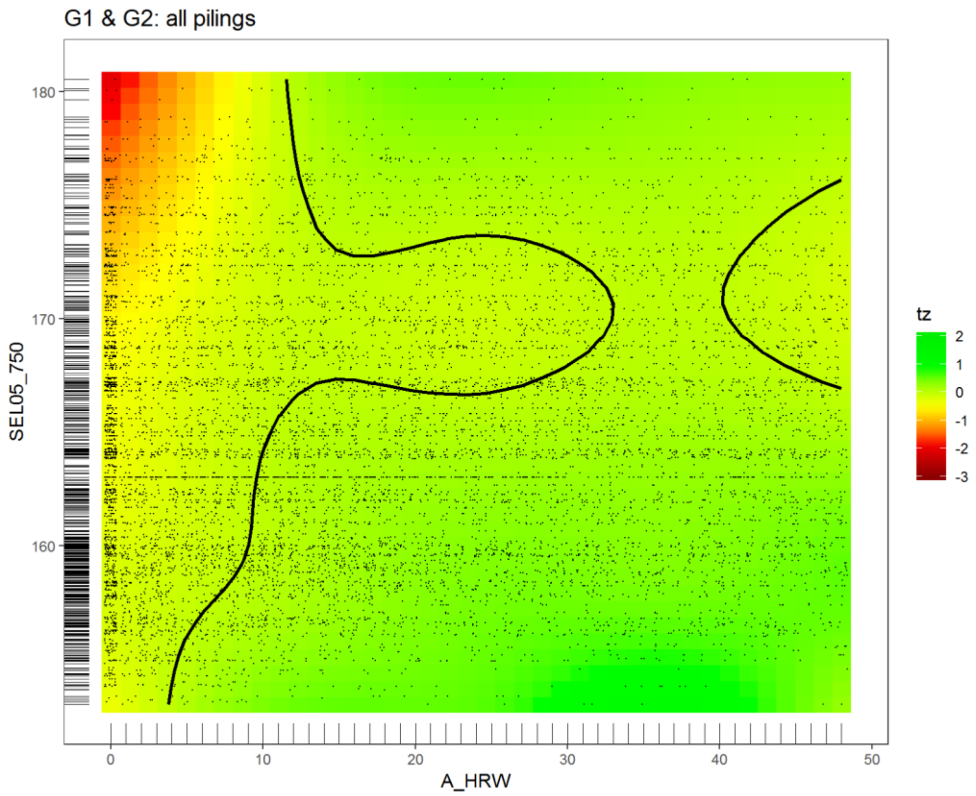
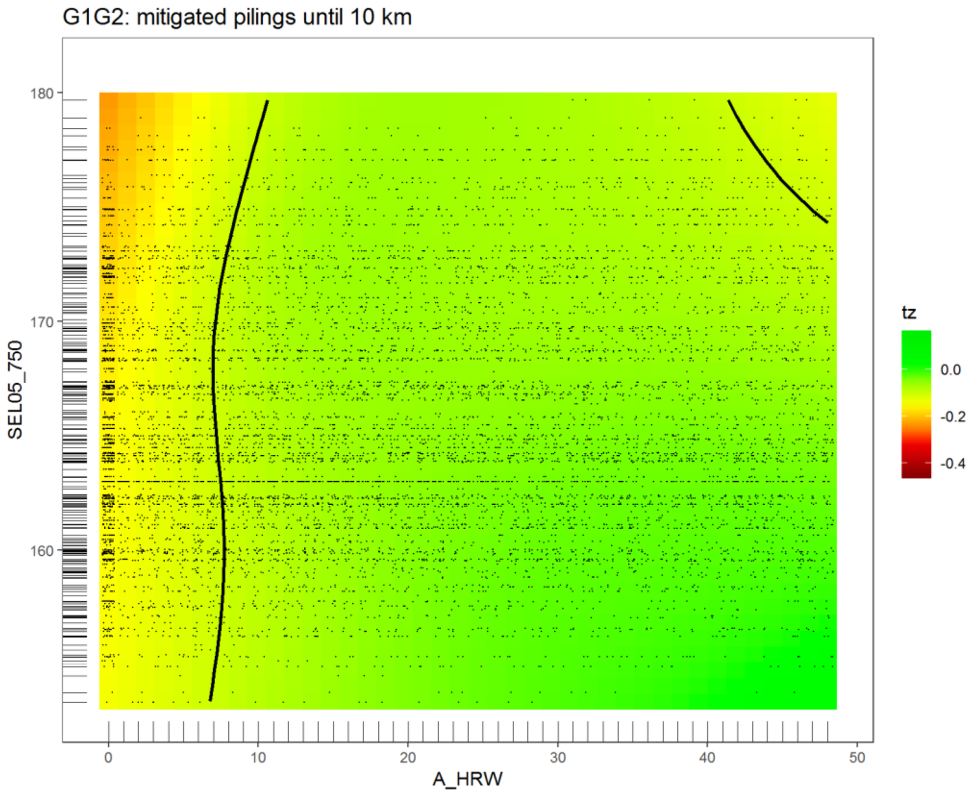


Figure 4.14 Cl-type noise-level GAMs M3.3b1G12 & M3.3b2G12: mitigated pile driving (top) and all pilings (bottom) 2011-2016 (Gescha 1 & 2); DPH values in close range (0-10 km) on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on the interaction of the variables SEL05_750 (noise level of SEL_{05} in 750 m distance) and A_HRW (hour relative to piling); black dots: data.



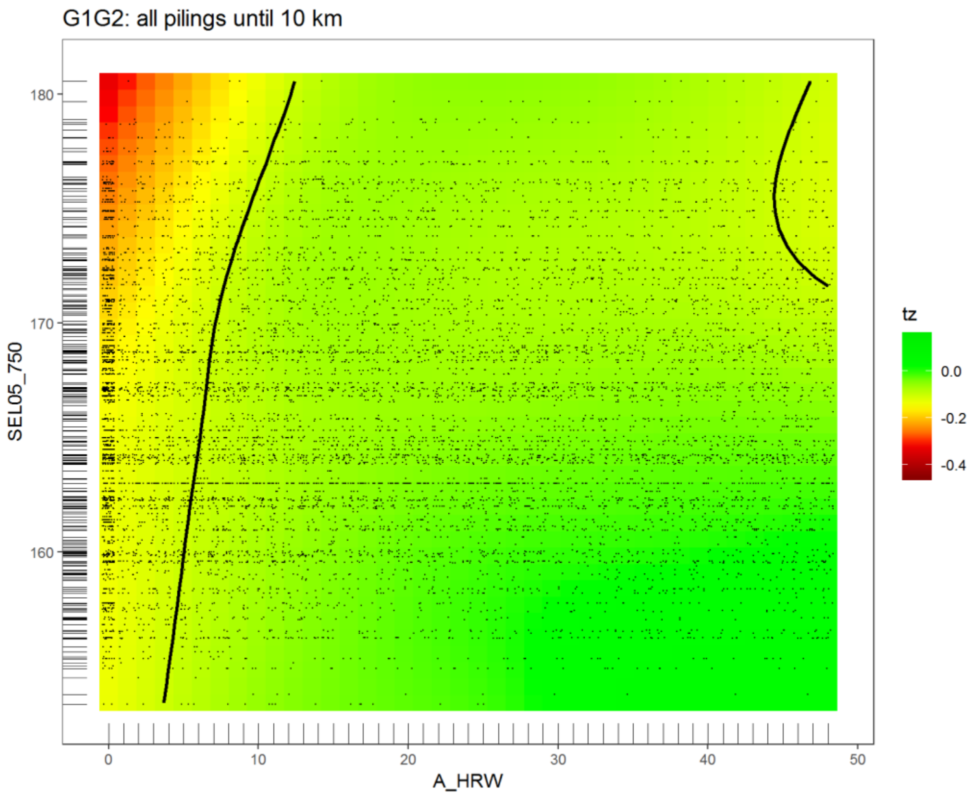


Figure 4.15 *Reference-type noise-level GAMs M3.3b1G12 & M3.3b2G12: mitigated pile driving (top) and all pilings (bottom) 2011-2016 (Gescha 1 & 2); dDPH_ref values in close range (0-10 km) on scale of the response where zero equals no effect (black contour lines: 20 % reduction of dDPH_ref relative to reference level), modelled on the interaction of the variables SEL05_750 (noise level of SEL_{05} in 750 m distance) and A_HRW (hour relative to piling); black dots: data.*

WP 3.4 – Differences of effect ranges among offshore wind farms

This work package addresses the question whether OWF-specific differences in habitat characteristics led to differences in response ranges of single offshore wind farms built in the period from 2014 to 2016, by this complementing WP 3.1 which deals with the overall effects of all wind farms combined. The North Sea is not a homogeneous habitat. Locations of wind farm projects differ as to prey availability, general background noise, distance to major shipping lanes, water depth, surface sediment structure, and other factors that might affect the response range of porpoises to pile driving. However, most of these variables were included as explanatory variables in the above models. Nevertheless, the question arises whether the consideration of these factors in the modelling process is sufficient to adequately capture the influence of these factors, or whether an area-specific analysis provides more meaningful results.

Table 4.10 Summary of effect ranges and durations for the OWFs of the Gescha 2 study (2014-2016) suitable for analyses of one or both model types (with approximate range of standard errors obtained by default gam plots in the Appendix; ∞: no finite lower or upper standard error).

OWF	Cl-type: Min. effect range at hrw0	Cl-type: Min. effect duration before piling (0 km)	Cl-type: Min. effect duration after piling (0 km)	Cl-type: Min. effect duration before piling (3 km)	Cl-type: Min. effect duration after piling (3 km)	Ref-type: 20 % reduction at hrw0	Ref-type: 20 % reduction before piling (3 km)	Ref-type: 20 % reduction after piling (3 km)
ABW	11 (10-12) km	>48 h[8]	43 (34-∞) h	46 (∞-34) h	44 (35-∞) h	7 (5-9) km	9 (5-13) h	14 (9-19) h
BU	13 (11-14) km	22 (19-28) h	41 (29-∞) h	22 (19-28) h	32 (25-∞) h	not avail.	not avail.	not avail.
N1	12 (10-15) km	44 (∞-33) h	36 (27-47) h	37 (27-∞) h	34 (27-41) h	not avail.	not avail.	not avail.
SB	25 (24-26) km	30 (24-40) h	32 (27-37) h	28 (23-37) h	31 (26-35) h	13 (11-15) km	14 (11-17) h	16 (11-21) h
VM	>13 km, no upper limit visible	18 (15-21) h	25 (22-28) h	18 (15-21) h	24 (21-27) h	not avail.	not avail.	not avail.
GEM[9]	13 (11-17 km[10]	not avail.	not avail.	not avail.	5 (3-6) h	not avail.	not avail.	not avail.

Not all OWFs built during the period covered by Gescha 2 were suitable for analyses regarding one or both model types. With four wind farms (BU, N1, VM, GEM), less than 30 piling events were left for Reference-type models (Table 4.1) due to very short time periods between consecu-

[8] Low detection rates in large distances lifted up the zero line for ABW, so here 48 h is not the minimum effect duration, but the true value is probably lower. The raw data plot indicates a decline from 24 h before piling.

[9] Only unmitigated pilings at GEM; mitigated pilings at all other OWFs.

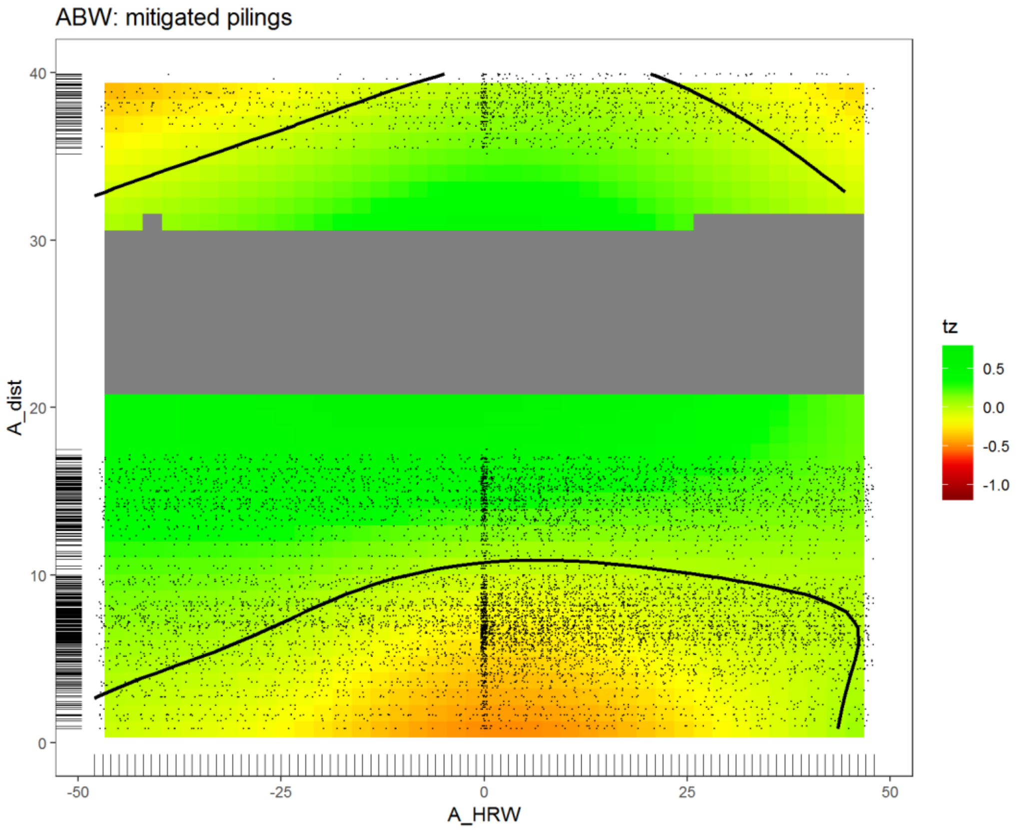
[10] The same is true for GEM. Low detection rates in large distances lifted up the zero line, so that 13 km distance is not a minimum value here.

tive pilings. Then, three OWFs (BR, GW, GEM) had no close-range data and hence offered no possibilities for analyses with both model types. Model plots of those OWFs and GAM plots with all covariates are shown in the Appendix. Six OWFs were suitable for analyses by Cl-type models and two OWFs (ABW, SB) available for Reference-type models (Figure 4.16 to Figure 4.19; Table 4.10).

With Cl-type models including all mitigated pilings, the minimum effect range span from 11 km (ABW), over 13 km (BU, N1), to 25 km for SB. The effect range at VM was not extractable from the plot (Figure 4.18), but seemed to exceed 13 km distance during pile driving. At a distance of 3 km from construction sites, negative effects started between 18 h (VM) and 46 h (ABW) before pile driving, with intermediate values for BU (22 h), SB (28 h) and N1 (37 h). After pile driving, negative effects lasted for at least 24 h (VM), and up to 44 h (ABW); BU, N1 and SB again showed intermediate values (31-34 h). Approximate standard error ranges, taken from default plots of the *gam.plot()* function which are shown in the Appendix, are provided in Table 4.10.

Since only hours around pile driving were considered in the models, the interpretation of area-specific differences is restricted to such periods (Cl-type models: hours hrw-48 to hrw+48 ; Reference-type models: hrw-24 to hrw+48).

As for the Cl-type models, some covariates were significant with all OWFs that were suitable for analysis. Besides the tensor product of *A_HRW* and *A_dist*, these were *dayofyear*, *HH*, and *all_clx*. Among the other variables, *wind_speed* and *surface_speed* were often significant. This might have been due to technical reasons since both variables have the potential to affect background noise and thus the probability to detect porpoise clicks.



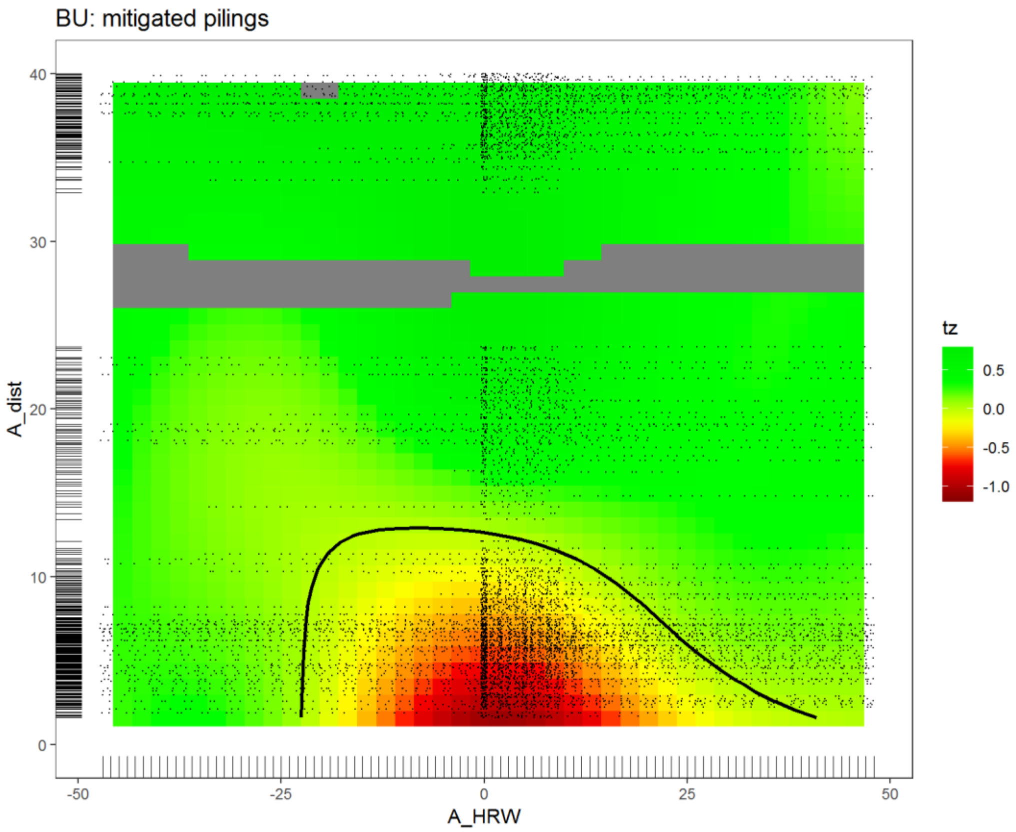


Figure 4.16 CI-type GAMs M3.4a & M3.4c for OWFs ABW & BU: Mitigated pile driving 2014-2016; DPH values on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on interaction of variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.

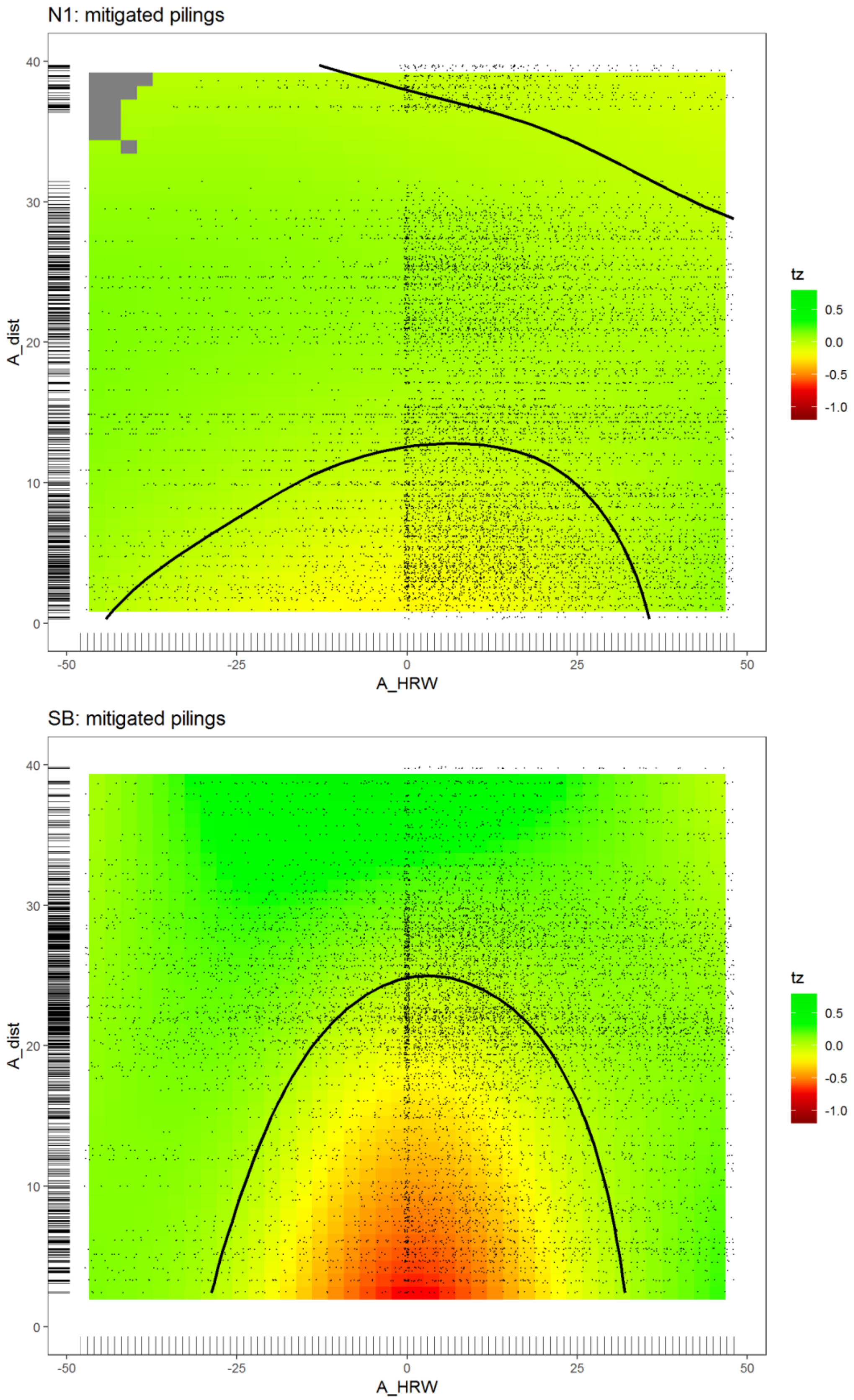


Figure 4.17 *Cl-type GAMs M3.4e & M3.4f for OWFs N1 & SB: Mitigated pile driving 2014-2016; DPH values on scale of the linear predictor where zero equals the average of all fitted values (black lines: 0), modelled on interaction of variables dist (distance) and A_HRW (hour relative to piling); black dots: data.*

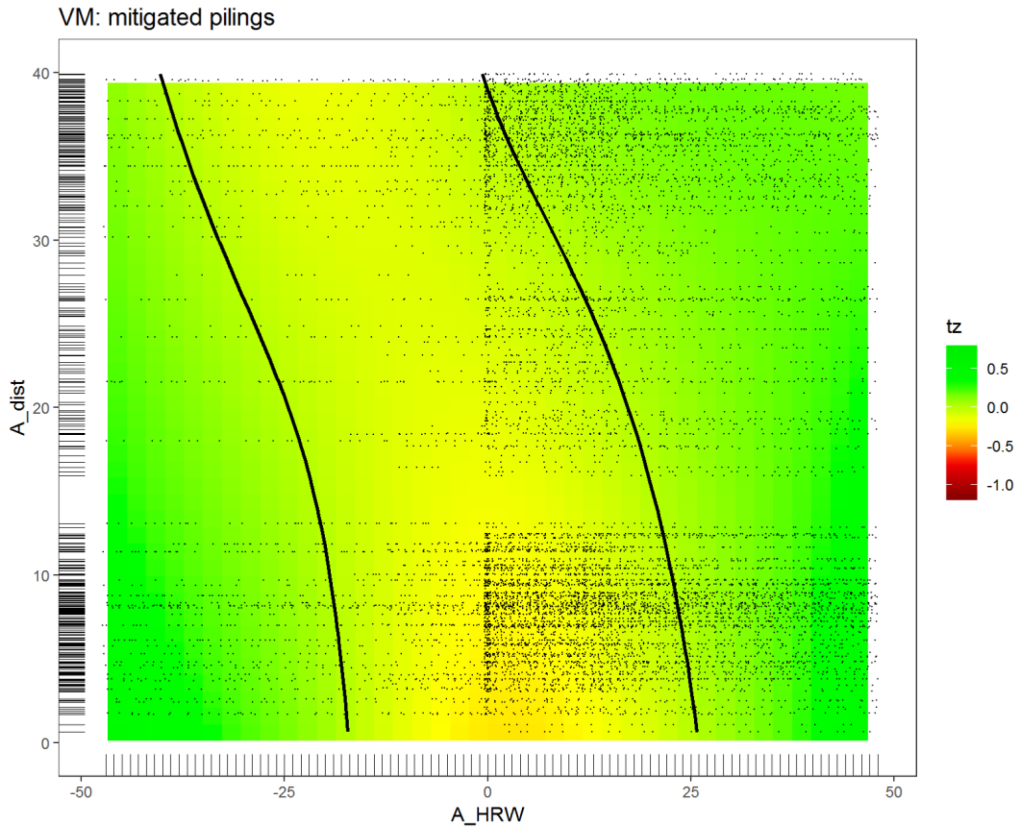


Figure 4.18 Cl-type GAM M3.4g for OWF VM (mitigated pile driving 2014-2016): DPH values on scale of the linear predictor where zero equals the average of all fitted values (dotted lines: std. error), modelled on interaction of variables dist (distance) and A_HRW (hour relative to piling); black dots: data.

As for the Reference-type models, the effects of certain covariates, especially the area-specific ones, were likely to have been partialled out by the approach. This explains why *Position, depth, slope, sandaal* and *sandgrundel* are not significant anymore with most OWFs. Therefore, this model type was more suitable to detect OWF-specific differences regarding pure construction effects. However, only two OWFs were suitable for this model type: ABW and SB. More covariates were significant with ABW than with SB. This was probably due to the construction effects dominating the effects of other covariates for SB. Effects for SB reached much farther and were stronger than for ABW (Figure 4.19; plots are on the same colour scale). For SB, detection rates were reduced by 20 % in 13 km, for ABW the respective distance was only about 7 km. Confidence intervals could not be shown directly in these plots, but the default model plots of the *gam.plot* function give an indication of their approximate range (see Appendix).

Comparing the plots of both model types for ABW and SB, the detected effects seemed to be stronger with the Cl-type models. However, the plots show different types of contour lines (average of the linear predictor vs 20 % reduction line), and it has to be kept in mind that the Reference-type models were based on ideal pilings with sufficient break times around to allow all animals to come back. Cumulative effects are assumed to be smaller with such pilings. On the other hand, Cl-type models included all pilings, also those in tight sequences, and this might have led to cumulative effects causing a farther-reaching and longer-lasting deterrence of harbour porpoises.

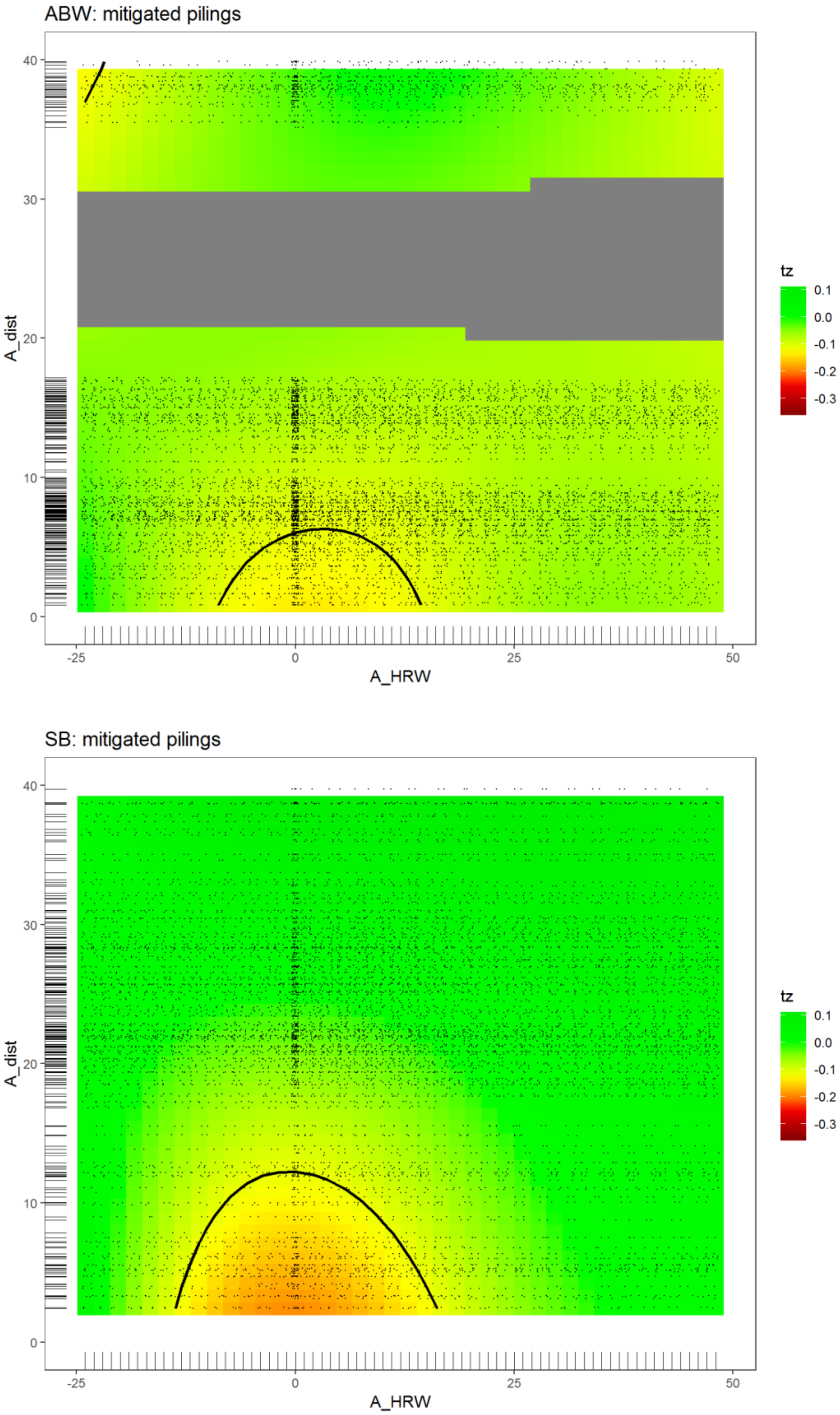


Figure 4.19 Reference-type GAMs M3.4a & M3.4f for OWFs ABW & SB: Mitigated pile driving 2014-2016; dDPH_ref values on scale of the response where zero equals no effect (black contour line: 20 % reduction of dDPH_ref relative to reference level), modelled on the interaction of the variables A_dist (distance) and A_HRW (hour relative to piling); black dots: data.

OWF Gemini

Since the OWF Gemini (GEM) was the only Gescha 2 project that used no NMS at all, this wind farm is looked at in more detail. Additionally, the response of porpoises to pile driving for this wind farm was used as a major reference regarding impacts of unmitigated piling on harbour porpoises for the DEPONS individual-based modelling approach (VAN BEEST et al. 2015; NABE-NIELSEN et al. 2018). As a result, there is great interest in comparing the data of this wind farm to the results of the German projects accompanied by noise mitigation measures. However, at this OWF only few CPOD data were available during the hours before piling, such that the dataset with 4 out of 160 piling events was too small for the Reference-type model (see Appendix). Furthermore, neither noise levels nor CPOD data in a close distance below 2 km were available for GEM.

Due to these constraints, we reduced the dataset to the hours during and after piling (hrw 0 to hrw+48), and only computed CI-type models. The best-fitting model (Table 4.7) indicated that negative effects lasted until about 5 h after piling and ranged up to about 13 km during pile driving (Figure 4.20). Spatial heterogeneity might have led to an unexpected reduction of detection rates in larger distances and at later times, but this was probably not caused by pile driving. When comparing the effect duration after pile driving at GEM to those of the other investigated OWFs, 5-10 h was by far the lowest value (Table 4.10), even though a response range of 13 km (as found by this study) was within the range of most of the Gescha 2 OWFs (except for Sandbank).

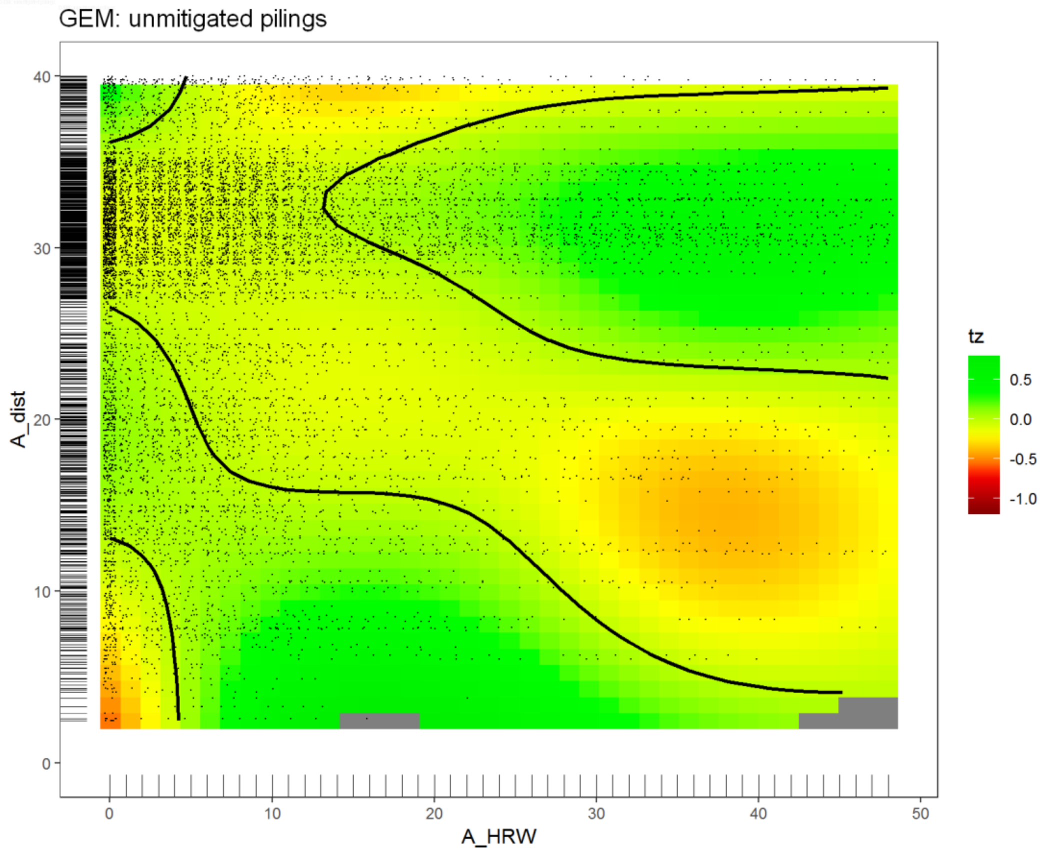


Figure 4.20 CI-type GAM M3.4h for OWF GEM (unmitigated pile driving 2014-2016): DPH values on scale of the linear predictor where zero equals the average of all fitted values (indicated by the black line), modelled on interaction of variables dist (distance) and A_HRW (hour relative to piling); black dots: data.

WP 3.5 – Effect of piling duration

Topic of this work package is the assessment of the effect of piling duration on the response range of porpoises and the duration of such an effect after pile driving. A difficulty occurred with the Gescha 2 dataset, as it turned out that most piling events lasted less than three hours and therefore only low variability was available in the dataset to adequately investigate the effect of pile-driving duration. Only at OWF Amrumbank West the time range of piling events was longer, causing an unbalanced dataset. The informative value of the results from the Gescha 2 dataset alone would have been rather low. The results gained a higher informative value by combining Gescha 1 & 2 data since a larger range of piling durations was available then. We therefore decided to perform these models only on the combined dataset (2011-2016; model suffix part "G12"). Results for the Gescha 2 dataset alone are given in the Appendix. Two types of analysis were conducted:

1. Short time range (time shortly after pile driving: hrw 1-3): Models of the effect distance range according to the duration of mitigated pile driving.

2. Close distance range (0-10 km distance to piling): Models of the effect duration and strength according to the duration of mitigated pile driving. Only hours from piling onwards were considered (hrw 0 to hrw+48) since effects of piling duration could not occur before piling.

Cl-type and Reference-type GAMs were computed in each case. Pilings of more than 600 minutes duration were considered as outliers and excluded from analysis.

Regarding the effects of piling duration on the response range and duration, the Cl-type model revealed that after longer pilings stronger negative effects were found at short distance, but that at about 12 km distance from piling locations the effects were equal over all piling durations (Figure 4.21; upper panel). The latter was also true for the Reference-type model, but that model did not show stronger effects of longer piling durations at short distances (Figure 4.22; upper panel). Thus, stronger effects of longer pilings at short distances were only found with the Cl-type model including all mitigated pilings, where cumulative effects were more likely to occur.

The effect duration in up to 10 km around construction sites, on the other hand, was independent of piling duration, according to both the Cl-type and Reference-type model (Figure 4.21 & Figure 4.22; lower panels).

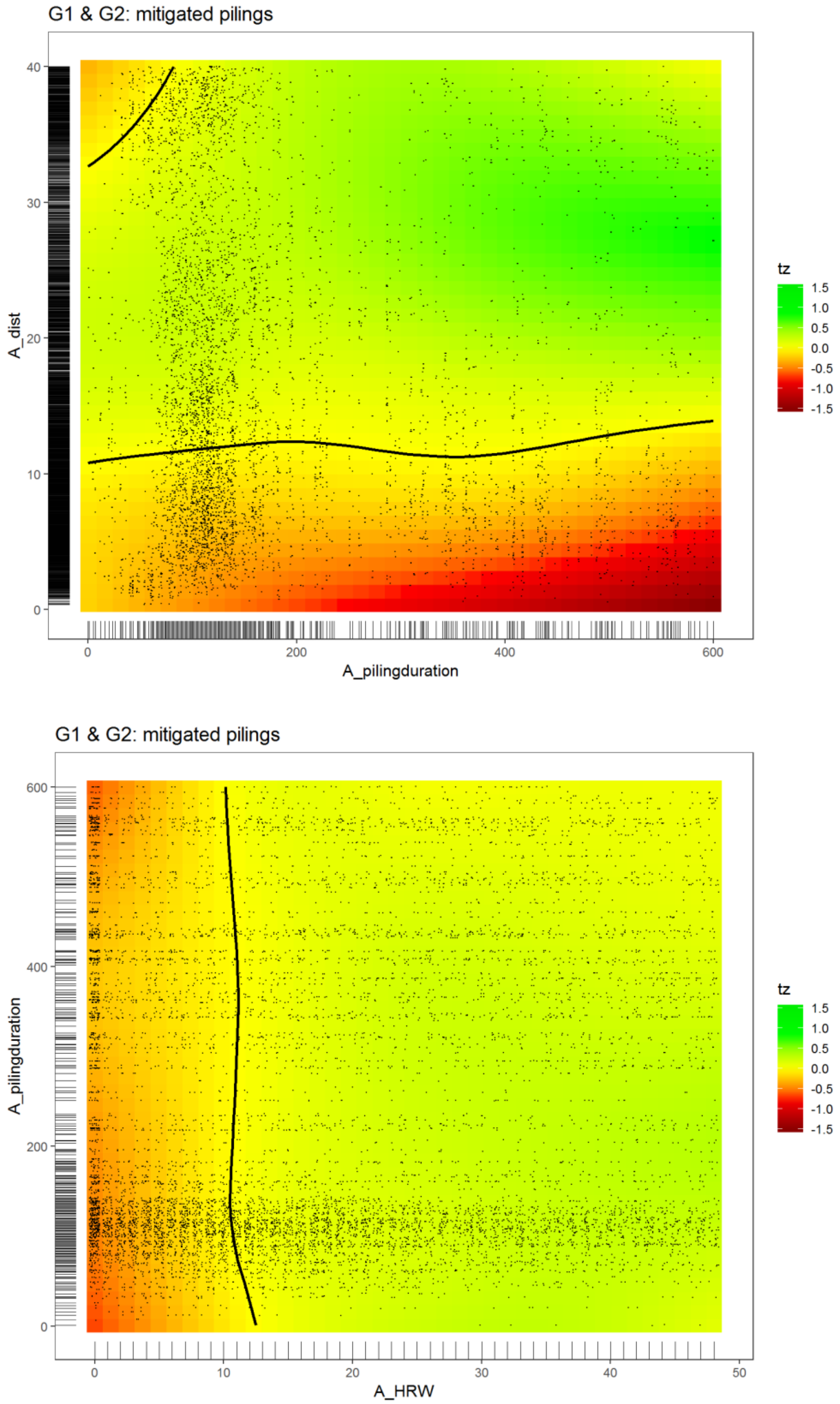


Figure 4.21 Cl-type piling-duration GAMs M3.5aG12 & M3.5bG12: Mitigated pile driving 2011-2016 (Gescha 1 & 2); top: DPH values shortly after piling (hrw 1-3), modelled on the interaction of the variables A_pilingduration (piling duration in min) and A_dist (distance to piling); bottom: DPH values in close range (0-10 km), modelled on the interaction of the variables A_pilingduration (piling duration in min) and A_HRW (hour relative to piling); DPH values on scale of the linear predictor where zero equals the average of all fitted values (indicated by black line); black dots: data.

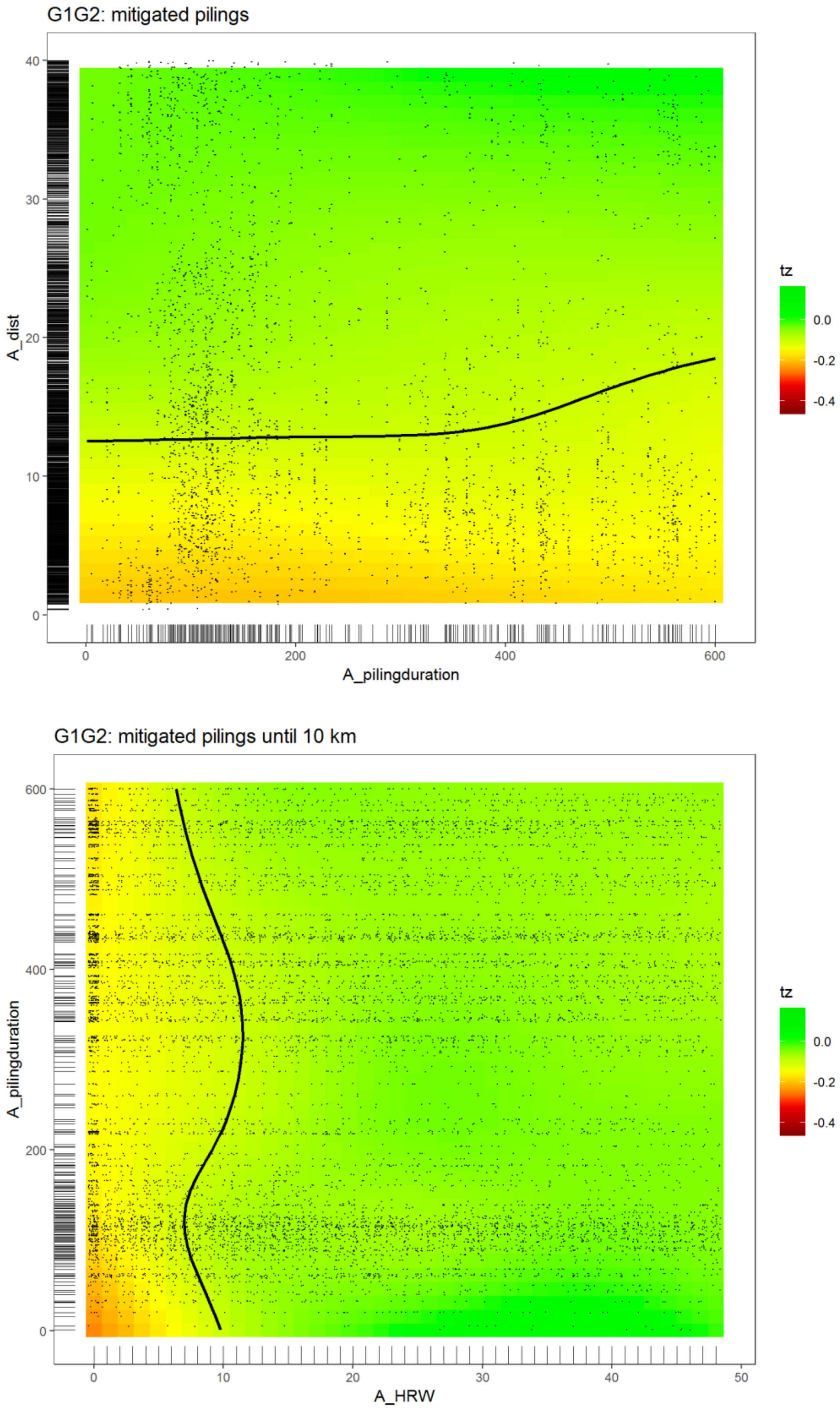


Figure 4.22 Reference-type piling-duration GAMs M3.5aG12 & M3.5bG12: Mitigated pile driving 2011-2016 (Gescha 1 & 2); top: dDPH_ref values shortly after piling (hrw 1-3), modelled on the interaction of the variables A_pilingduration (piling duration in min) and A_dist (distance to piling); bottom: dDPH_ref values in close range (0-10 km), modelled on the interaction of the variables A_pilingduration (piling duration in min) and A_HRW (hour relative to piling); black contour line: 20 % reduction of dDPH_ref relative to reference level; black dots: data.

WP 3.6 – Effects of construction-related noise from sources other than piling and deterrence

Topic of this work package is the assessment of the potential contribution of construction-related boat traffic and other noise-intense activities within the vicinity of the construction sites in causing porpoise avoidance reactions. Did harbour porpoise detection rates decrease already before the start of pile driving?

Boat activities in the vicinity of construction sites were not registered in detail during wind farm monitoring programmes. Hence, the potential effect of construction-related boat traffic could only be answered by inspecting the raw data and performing an indirect analysis regarding a potential decrease of detection rates at defined time classes (or phases) relative to the pile driving process. The time class when a possible decrease of detection rates due to pile driving or seal scarer activity could be excluded (as there was no pile-driving or seal scarer activity) was named "Traffic" (as construction-related traffic was the most probable explanation for any response of the animals here) and comprised the hours from hrw-3 to hrw-1 during which no piling and deterrence-device effects could have occurred. A regular decrease of detection rates of harbour porpoises during this period could be related to anthropogenic activities (mainly boat traffic) in the vicinity of piling locations.

When comparing the effects of the time class "Traffic" to those of "Baseline" (hrw-48 to hrw-24), "Piling" (hrw 0: combined effects of deterrence and piling), and "Reference after piling" (hrw+49 to hrw+120), "Traffic" shows intermediate detection rates that were lower than those of "Baseline" and "Reference after piling", but higher than those of "Piling". This was true both for the Gescha 1 and the Gescha 2 dataset, which were also remarkably consistent with respect to the absolute effect size (Table 4.11; Figure 4.23). Within both projects, the differences between the mean *DPH* rates were highly significant for all pairwise comparisons (after a significant Kruskal-Wallis test, pairwise Wilcoxon tests were conducted with correction for multiple testing by the False Discovery Rate, FDR, after BENJAMINI & HOCHBERG 1995). Unexpectedly, this was also true for a comparison of "Baseline" with "Reference after piling", but since the absolute effect difference was rather small here (Gescha 1: 0.46 vs 0.50; Gescha 2: 0.54 vs 0.51), the significance was partly attributable to the especially high *N* for this pairwise comparison, causing the strongest discriminative power of all pairwise comparisons.

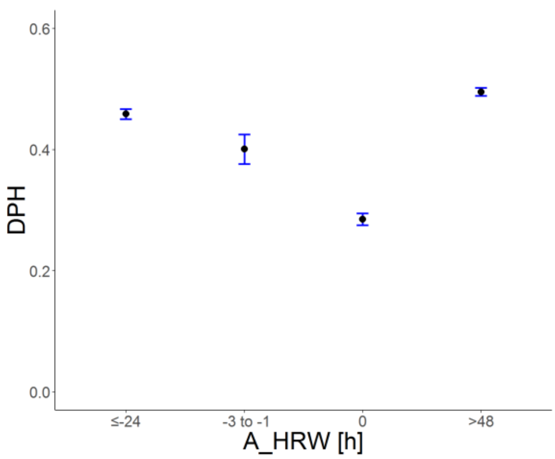
For the Gescha 2 dataset, the decrease in detection rates during the three hours before piling and during piling was strongest in up to 15 km from construction sites, then decreasing with increasing distance, and not being detectable anymore beyond 25 km distance from pilings (Table 4.12; Figure 4.24). There still might have been a delayed effect in 20-25 km distance which, however, became less visible in 15-20 km distance. Effect ranges were slightly different for the Gescha 1 dataset. Here, the decrease in detection rates in both phases (before and during piling) was strongest in short distances of up to 5 km, then decreasing until up to 15 km distance from construction sites, beyond which distance no effects were visible anymore in the raw-data plots (Table 4.12; Figure 4.25).

Table 4.11 *Gescha 1 and 2: Mean DPH rates (with std. deviation, std. error, confidence interval) in up to 10 km distance over four time classes: Baseline (Reference time: hrw-48 to hrw-24); Traffic (red; times of boat-traffic and other noise sources before piling: hrw-3 to hrw-1); Piling (deterrence and piling time: hrw 0); Reference after piling (times with detection rates likely to be unaffected by the previous piling: hrw+49 to hrw+120); results are visualised in Figure 4.23.*

Project	Phase	*A_HRW*	*N*	*DPH* mean	sd	se	ci
G1	**Baseline**	-48 to -24	13,703	**0.46**	0.498	0.004	0.008
	Traffic	-3 to -1	1,542	**0.40**	0.490	0.012	0.024
	Piling	0	8,043	**0.29**	0.451	0.005	0.010
	Reference after piling	+49 to +120	23,389	**0.50**	0.500	0.003	0.006
G2	**Baseline**	-48 to -24	4,864	**0.54**	0.498	0.007	0.014
	Traffic	-3 to -1	714	**0.41**	0.492	0.018	0.036
	Piling	0	5,052	**0.32**	0.465	0.007	0.013
	Reference after piling	+49 to +120	8,732	**0.51**	0.500	0.005	0.010

Table 4.12 *Gescha 1 and 2: Mean DPH rates for six distance classes over three time classes: Baseline (Reference time: hrw-48 to hrw-24); Traffic (times of boat-traffic and other noise sources before piling: hrw-3 to hrw-1); Piling (deterrence and piling time: hrw 0); hourly raw data used for this table are plotted in Figure 4.24 and Figure 4.25.*

Project	Phase	*A_HRW*	0 - 5 km	5 - 10 km	10 - 15 km	15 -20 km	20 - 25 km	>25 km
G1	**Baseline**	-48 to -24	0.45	0.46	0.54	0.53	0.61	0.52
	Traffic	-3 to -1	0.36	0.41	0.45	0.48	0.58	0.48
	Piling	0	0.2	0.33	0.43	0.49	0.55	0.48
G2	**Baseline**	-48 to -24	0.52	0.56	0.58	0.55	0.63	0.54
	Traffic	-3 to -1	0.38	0.44	0.46	0.49	0.56	0.5
	Piling	0	0.24	0.35	0.37	0.46	0.51	0.51



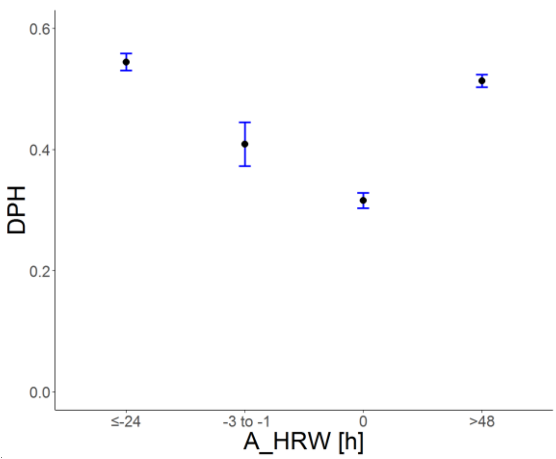


Figure 4.23 *Gescha 1 (left) and 2 (right): Mean DPH rates (with 95 %-confidence intervals) in up to 10 km distance over four time classes: from left to right: Baseline (hrw-48 to hrw-24); Traffic (hrw-3 to hrw-1); Piling (hrw 0); Reference after piling (hrw+49 to hrw+120).*

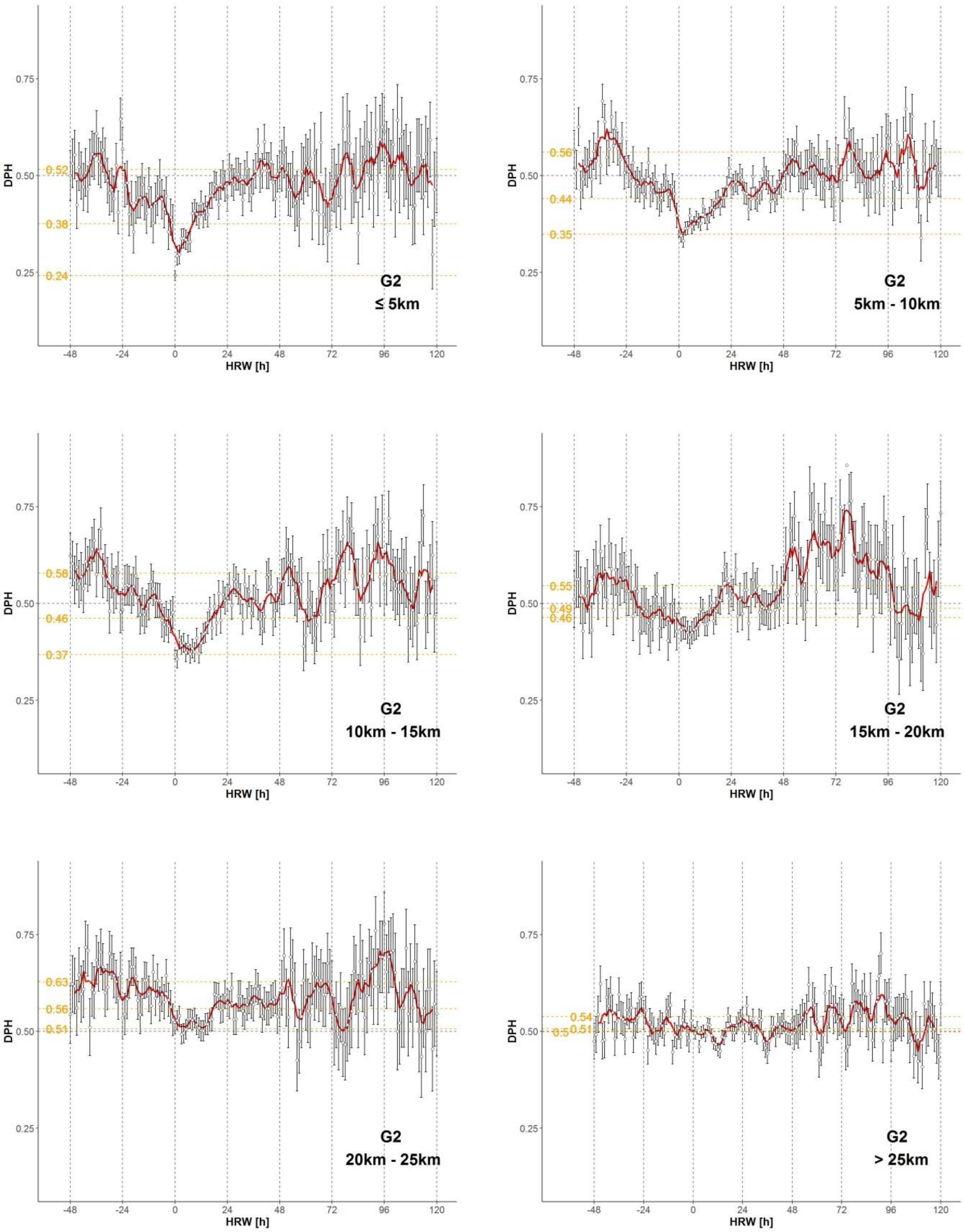


Figure 4.24 Gescha 2: DPH raw data (with std. errors) along time axis for six distance classes; hour zero (hrw 0) denotes piling hour(s); yellow dotted lines show the following average DPH values: upper: Baseline (hrw-48 to hrw-24); middle: Traffic (hrw-3 to hrw-1); lower: Piling (hrw 0).

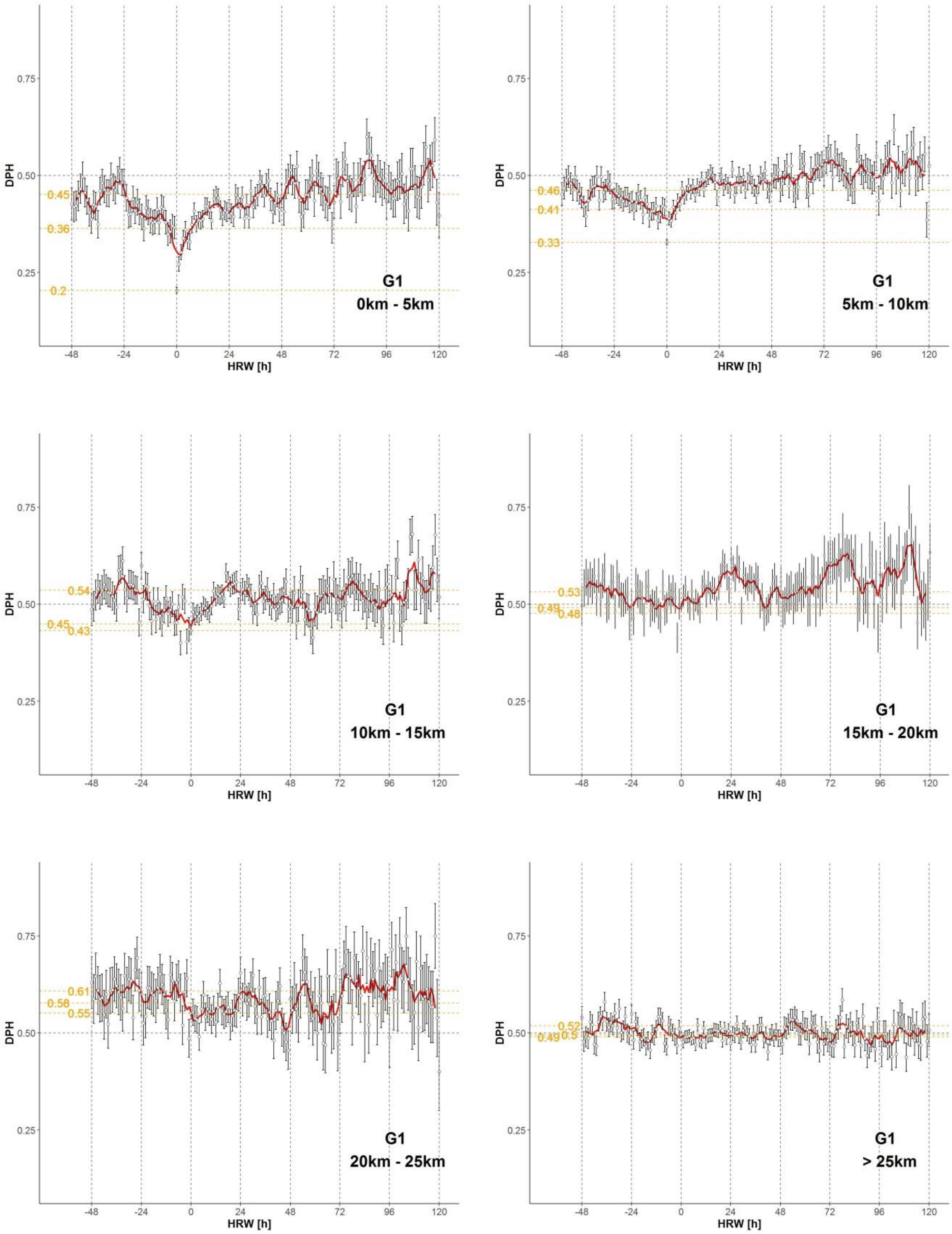


Figure 4.25 *Gescha 1: DPH raw data (with std. errors) along time axis for six distance classes; hour zero (hrw 0) denotes piling hour(s); yellow dotted lines show the following average DPH values: upper: Baseline (hrw-48 to hrw-24); middle: Traffic (hrw-3 to hrw-1); lower: Piling (hrw 0).*

Table 4.13 Gescha 2: OWFs with mitigated pilings: Mean DPH rates in up to 10 km distance from construction sites for three time classes: Baseline (Reference time: hrw-48 to variable end); Traffic (times of boat-traffic and other noise sources before piling: variable start, until hrw-1); Piling (deterrence and piling time: hrw 0). The last hour of the Baseline ("Baseline end") and the first hour assigned to Traffic ("Traffic start") were chosen for each wind farm individually according curves in the raw data plots (Figure 4.27 to Figure 4.29).

Phase	ABW	BR	BU	N1	SB	VM
Baseline	0.51	0.56	0.49	0.7	0.58	0.51
Traffic	0.36	0.59	0.34	0.6	0.49	0.28
Piling	0.37	0.41	0.16	0.54	0.35	0.17
Baseline end	hrw-24	hrw-24	hrw-12	hrw-7	hrw-20	hrw-22
Traffic start	hrw-3	hrw-3	hrw-3	hrw-2	hrw-2	hrw-3

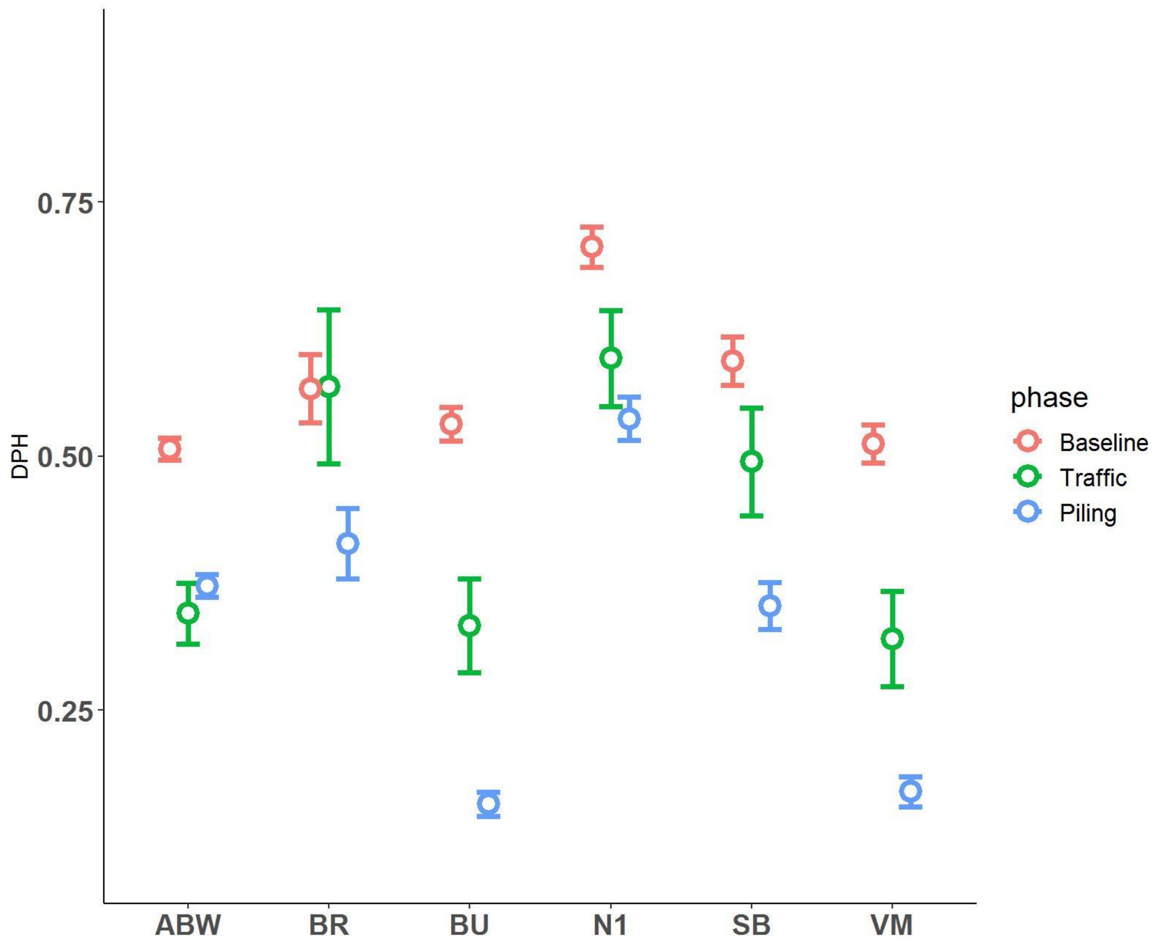
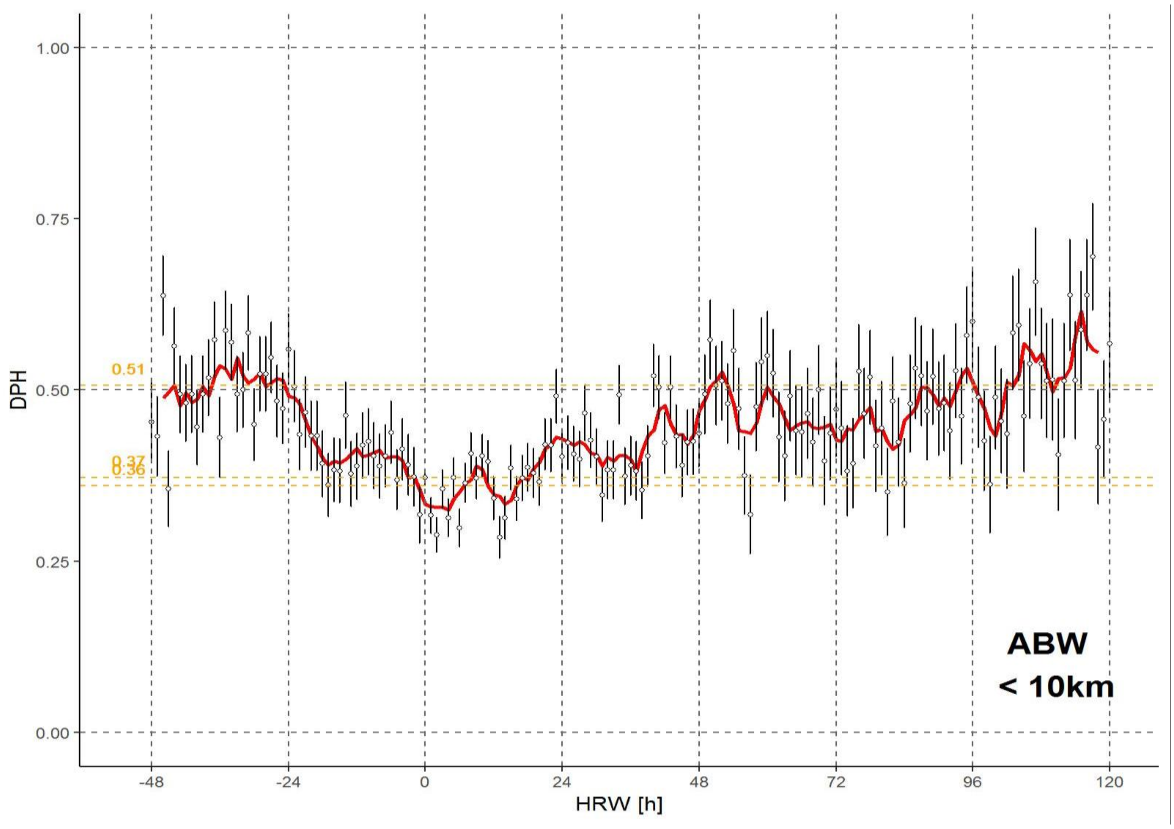


Figure 4.26 Gescha 2: OWFs with mitigated pilings: Mean DPH rates (with std. error bars) in up to 10 km distance from construction sites for three time classes (see Table 4.13).



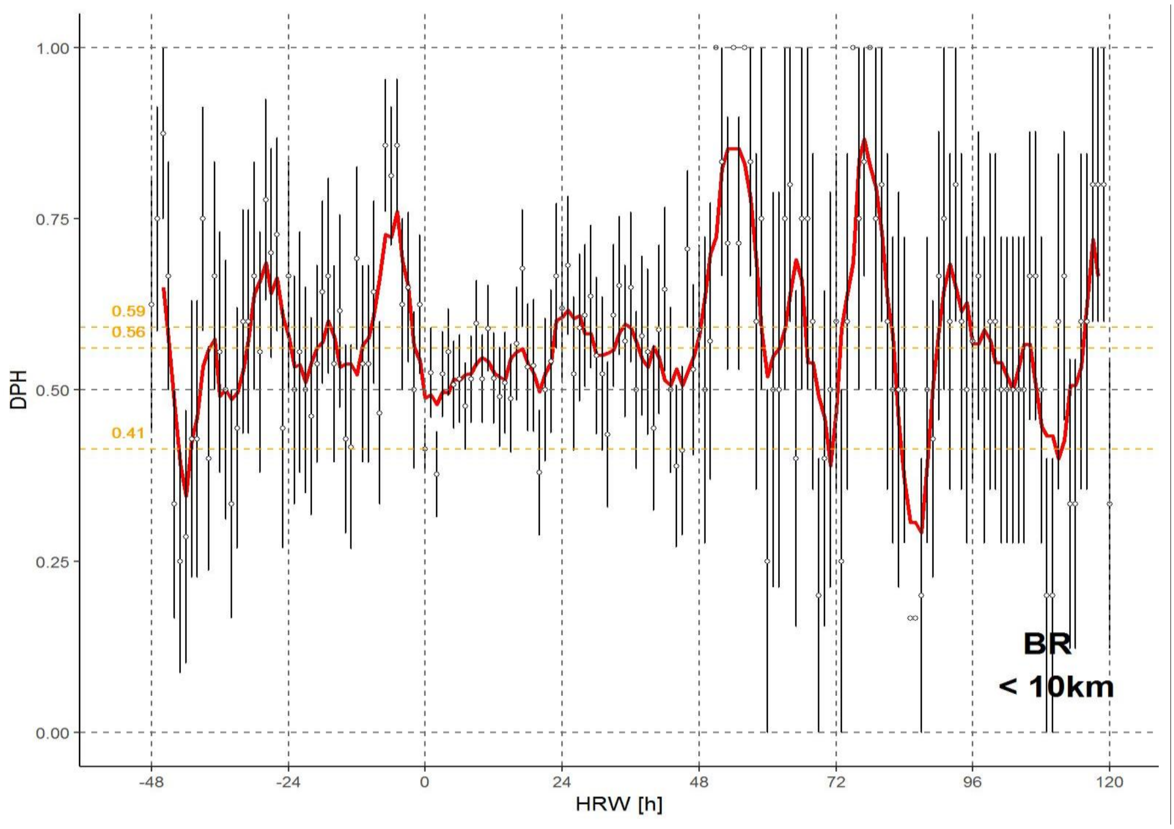


Figure 4.27 Gescha 2: DPH raw data (with std. errors) along time axis for OWFs ABW and BR; hour zero (hrw 0) denotes piling hour(s); yellow dotted lines show the following average DPH values: upper: Baseline (hrw-48 to hrw-24); middle: Traffic (hrw-3 to hrw-1); lower: Piling (hrw 0).

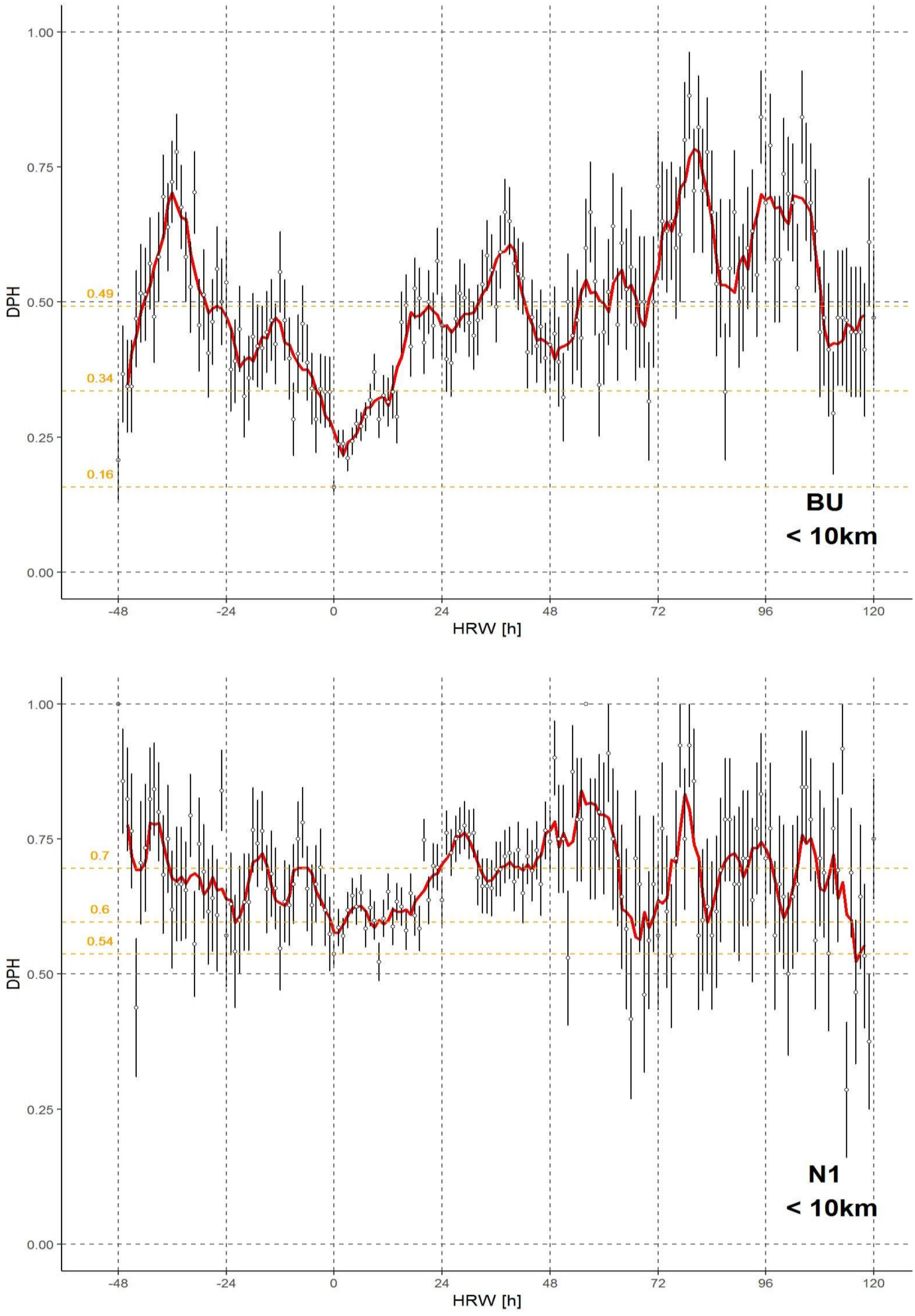
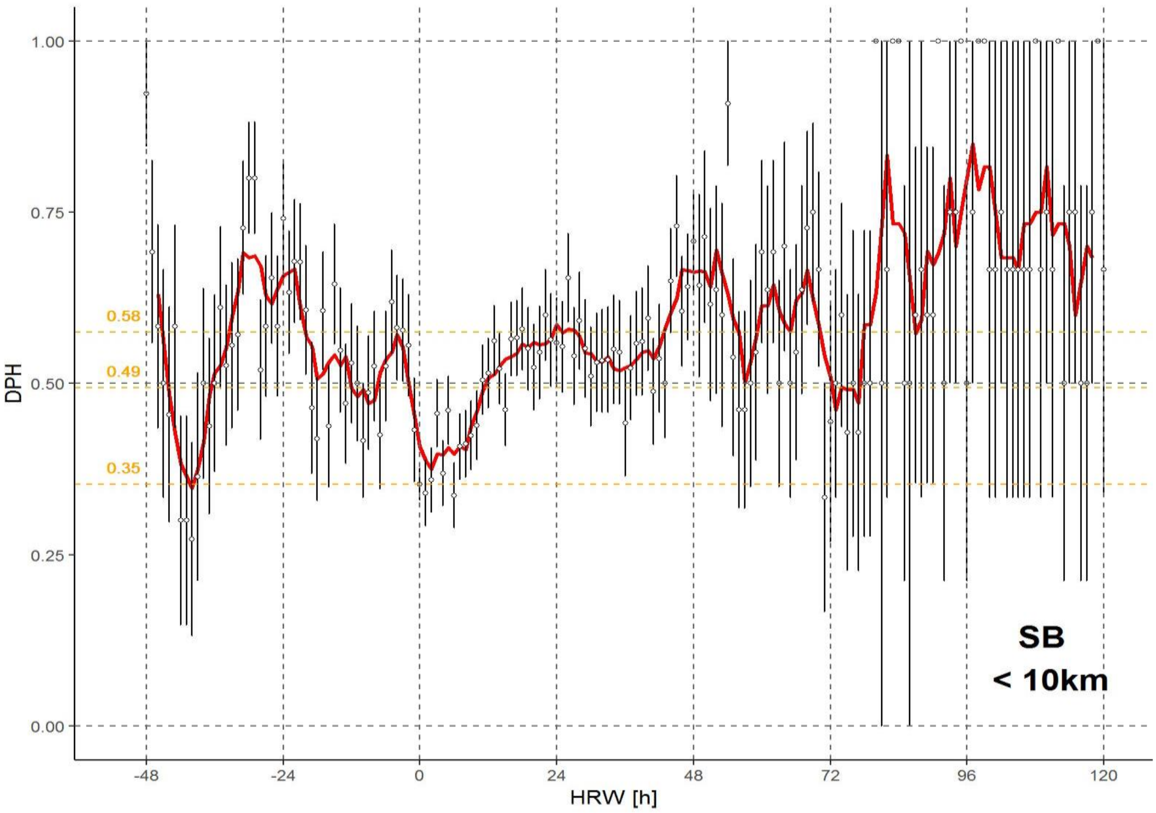


Figure 4.28 Gescha 2: DPH raw data (with std. errors) along time axis for OWFs BU and N1; hour zero (hrw 0) denotes piling hour(s); yellow dotted lines show the following average DPH values: upper: Baseline (hrw-48 to hrw-24); middle: Traffic (hrw-3 to hrw-1); lower: Piling (hrw 0).



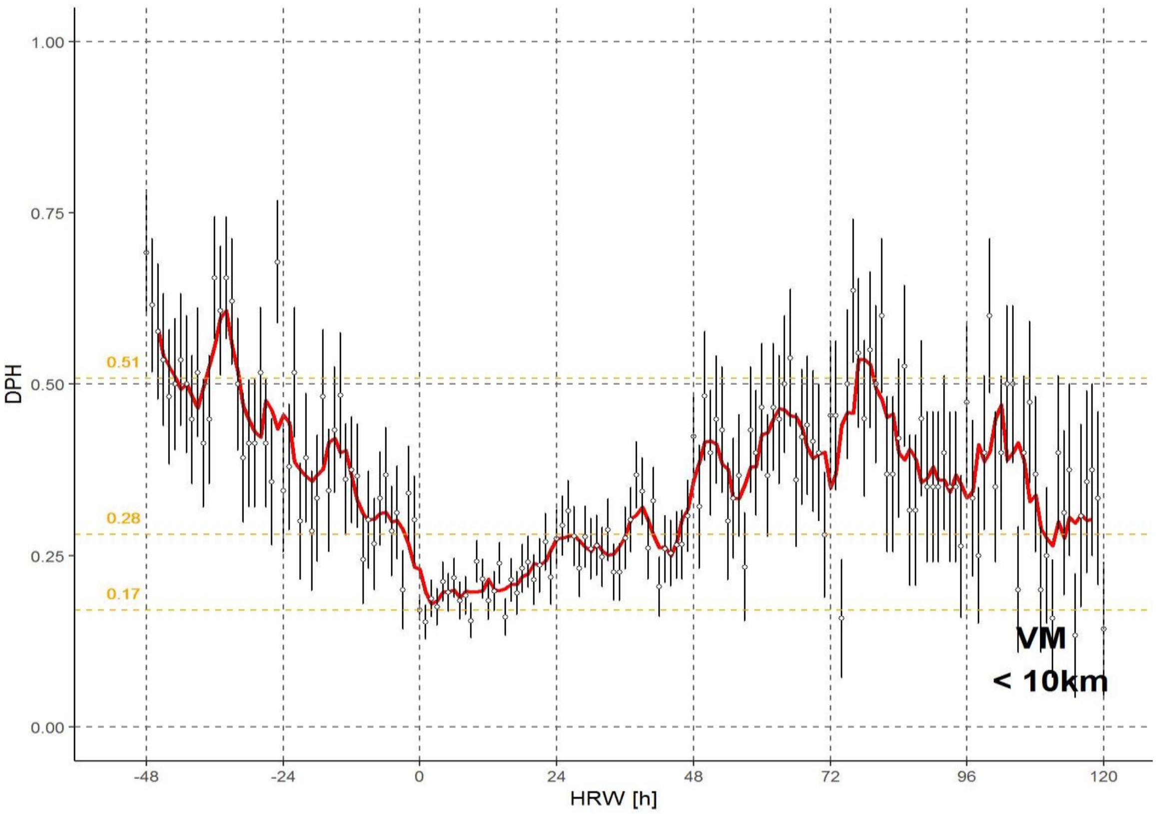


Figure 4.29 Gescha 2: DPH raw data (with std. errors) along time axis for OWFs SB and VM; hour zero (hrw 0) denotes piling hour(s); yellow dotted lines show the following average DPH values: upper: Baseline (hrw-48 to hrw-24); middle: Traffic (hrw-3 to hrw-1); lower: Piling (hrw 0).

4.1.3 Discussion

Harbour porpoises respond to construction activities at offshore wind farms by moving away from areas with high noise levels (BRANDT et al. 2011; HAELTERS et al. 2012; DÄHNE et al. 2013; BIOCONSULT SH 2014; BRANDT et al. 2016, 2018a; KASTELEIN et al. 2018). However, not all animals react in the same manner. Even though many porpoises swim away from the vicinity of pilings to outer regions (BRANDT et al. 2018a), still some animals stay within a close range to construction sites (BIOCONSULT SH et al. 2016). The proportion of porpoises that swim away greatly depends on their distance to the construction site and the received noise level (both are closely inter-connected; BIOCONSULT SH et al. 2014), on deterrence measures, boat traffic and other noise-intense activities at the locality. Regarding pile-driving noise, the onset of behavioural reactions during pile driving (change in detection rates, density, or observable behaviour) was estimated to occur at noise levels from 140 dB up to 152 dB re 1 µPa²s SEL by different studies (BIOCONSULT SH & IFAÖ 2010, 2014; BRANDT et al. 2011; HAELTERS et al. 2012; DÄHNE et al. 2013; BIOCONSULT SH et al. 2014). On the other hand, the particular attractiveness of a certain site, or an individual's decision (e. g. depending on fitness; VAN BEEST et al. 2018) might affect whether or not an animal will leave a noise-intense area. Therefore, a uniform response of harbour porpoises to pile driving or other construction-related activities across different OWFs was not to be expected. Yet, a statistical response was assessable by the large hourly CPOD dataset. CPODs are valuable instruments for the assessment of porpoise response patterns, as they allow for continuous monitoring of selected localities on a fine-scale temporal resolution. The flaws and merits of this method were described in detail in the previous report (BIOCONSULT SH et al. 2016).

In WP 3, the small-scale effect range and short-term effect duration of pile driving on harbour porpoises was investigated. It was also looked at the role of the noise-level of piling, of other noise sources associated with construction activities, and at OWF-specific differences in response patterns. Here the results obtained by analyses on the hourly CPOD dataset are discussed.

Different studies showed a deterrence of harbour porpoises of 20 km and more from construction sites during unmitigated pile driving (TOUGAARD et al. 2009: >20 km; BRANDT et al. 2011: 18 km; HAELTERS et al. 2012, 2015a: 20-22 km; DÄHNE et al. 2013a: 20 km; BIOCONSULT SH 2014: 17 km (tripods); NEHLS et al. 2016: 15 km; ROSE et al. 2016: 20-25 km). Based on the results of LUCKE et al. (2009), noise-mitigation measures to protect harbour porpoises from injury (TTS/PTS) were stipulated with the start of the expansion of the offshore wind industry in Germany. This circumstance was a driving factor for the development of NMS leading to improvement over the years. Research projects on first noise-reduction technologies were able to show that these led to a reduced area of noise impact (NEHLS et al. 2016). On this basis, the so-called noise-protection concept of the BMU was developed in 2013, which stipulates noise-protection measures in order to prevent injuries and to establish a (reduced) disturbance range (BMU 2013). Despite legal requirements, the effectiveness of noise-mitigation systems has not yet been reviewed. The present study is therefore an important step to compare the technical success of noise mitigation during the foundation of offshore wind farms with focus on the key species harbour porpoise. Main topic of Gescha 2 is the question whether technical improvements in noise protection led to an expected reduction of harbour porpoise displacement during pile driving.

From 2014 to 2016, the period under review of the Gescha 2 study, pile driving for German offshore wind farms in the North Sea was mostly conducted under the operation of one or a combination of several noise-mitigation procedures (BBC, DBBC, HSD, IHC, HiLo, Kofferdam; Table 3.3) (KOSCHINSKI & LÜDEMANN 2013). Only very few unmitigated reference pilings took place during that period. A major difference to Gescha 1 was that in these projects most of the systems were still under development and reached a 9 dB lesser noise reduction than the Gescha 2 projects. Hence, the expectation was that due to considerably improved NMS the disturbance range and duration of harbour porpoises should have been reduced accordingly, which however was not the case.

Considering hourly CPOD data, the response range and duration of effects were similar to Gescha 1. Newly developed Reference-type models (based on a dataset reduced to a subset of piling events that were at least three days apart from others, thus being less susceptible to possible cumulative effects) showed that during hours of pile driving (hrw 0) porpoise detection rates were reduced by 20 % in 13 km (s.e.: 11-15 km) distance from Gescha 2 construction sites (Table 4.9). The respective distance for Gescha 1 pilings (only 2011-2013 available for comparisons on hourly CPOD data) was 11 km (s.e.: 10-12 km). With Cl-type models (the classical model type also used in the Gescha 1 study, based on a dataset with all mitigated piling events), the minimum effect range was 17 km (s.e.: 15-19 km) with Gescha 2 data, and 15 km (s.e.: 14-16 km) with Gescha 1 data. The duration of effects was similar as well: According to the Reference-type models, detection rates were reduced by 20 % about 17 hours (s.e.: 15-19 hours) before and 18 hours (s.e.: 15-21 hours) after Gescha 2 pilings, and 15 hours (s.e.: 14-16 hours) before and 15 hours (s.e.: 13-17 hours) after Gescha 1 pilings. Even though according to Cl-type models the minimum effect duration before piling in 3 km distance (0 km not available with Gescha 1 models) was similar (22 hours [s.e.: 19-25 hours] for Gescha 2; 25 hours [s.e.: 22-28 hours] for Gescha 1), the minimum effect duration after pile driving was slightly higher for Gescha 2 (38 hours [s.e.: 29-∞ hours; no finite upper s.e.] in 3 km distance) than for Gescha 1 (30 hours [s.e.: 25-∞ hours; no finite upper s.e.]).

What could have caused the unexpected result of a still similar effect range and duration, even though pilings for Gescha 2 took place under improved noise mitigation? In the following, we present some possible explanations regarding processes that might have acted alone or in combination:

1. A minimum response distance of harbour porpoises to noise may exist: Within a certain range of intermediate piling-noise levels sufficient to cause a response, a relevant number of animals might express a stereotypical response behaviour and swim away at least to a certain minimum distance irrespective of the source-noise level. This kind of response of harbour porpoises to pile driving is included into the DEPONS model approach (VAN BEEST et al. 2018). DEPONS also takes into account that the initial noise level at which a reaction occurs may depend on the physical condition of the animal: Weaker animals are less likely to change their behaviour and withstand negative effects longer (VAN BEEST et al. 2018). Only for higher piling-noise levels a positive correlation with response distance would exist, so that improvement of NMS would only show desirable results if piling noise would be reduced from high sound levels where the effect range is correlated with sound levels to intermediate levels where the stereotypical response occurs, or if noise levels are reduced below the noise-level range for a stereotypical response. The hypothesis is supported by our model results. For pilings not prone to cumulative effects we found a sound level of around 165 dB of the SEL_{05} at 750 m distance below which the response range during hours of piling did not further decrease (Figure 4.13). The model outcome indicates that the range of the displacement effect does

not change at sound levels below 165 dB. This might be explained by animals maintaining a certain minimum escape distance independent of the respective noise level if it is below this value and within a certain intermediate range. Thus, animals may react stereotypically as soon as pile-driving noise exceeds a certain individually differing unknown threshold level that has to be regarded in the context of a seasonally and site-specific different condition of animals. In contrast, the hypothesis is not supported by studies which were able to show continuously decreasing effect ranges below 165 dB (BRANDT et al. 2011, BIOCONSULT SH 2014, NEHLS et al. 2016, ROSE et al. 2016). However, regarding piling-noise levels we only had access to the broadband SEL_{05} cut off at 20 kHz and could not refer to noise levels being weighted according to the hearing spectrum of harbour porpoises; hence, we might not have dealt with the noise relevant for porpoises.

2. Seal scarer noise may cause a stereotypical aversive response similar to the reaction to moderate piling noise, triggering the animals to swim away to a minimum escape distance that might well be above 2 km (effects up to 7.5 km shown by BRANDT et al. 2013b). Effect ranges found during most Gescha 2 projects might thus reflect a porpoise response to the seal scarer rather than to piling noise, and even though noise-mitigated piling would otherwise have caused shorter effect ranges, this may have been masked by a relatively stronger and farther-reaching avoidance reaction to seal scarer noise (seal scarers were applied during all Gescha 2 OFW projects, except for Gemini where another type of harassment device, the FaunaGuard, was used). Although the broadband noise level of a seal scarer is not as loud as piling, it emits noise at a much higher frequency spectrum where porpoise hearing is more sensitive (KASTELEIN et al. 2002). Accordingly, porpoise detections were already found to decrease if the seal scarer noise exceeded a broadband level of 119 dB SEL (BRANDT et al. 2013a), but only if piling noise levels exceeded 143 dB SEL (BRANDT et al. 2018a). When modelling the sound propagation of frequency-weighted noise levels (following weighting methods proposed by the U.S DEPT. OF COMMER., NOAA 2016, using a weighting function approximately inverse to the harbour porpoise audiogram) we found indications that even in up to 20 km distance weighted noise levels for the seal scarer were above those of piling noise (Figure 3.4), which would theoretically allow for strong effects of a seal scarer on harbour porpoises and support our hypothisis. To further test the hypothesis it would be crucial to study effects of noise-mitigated piling without confounding effects of the seal scarer. In further support, we showed that in 1.5 km distance to construction sites the effects of a seal scarer were at least as strong as piling effects (Figure 5.2). Hence, even though no direct measurements of seal scarer noise were available, its effects on porpoises in 1500 m distance at exactly the time when the seal scarer started, compared to the effects when piling started, were available. They were the same for the Gescha 2 dataset. However, seal scarers were also used at OWFs DanTysk and Sandbank. Both projects are located approximately 15 km apart from each other in a similar area. Whereas DanTysk was piled in 2013 with NMS under development and noise levels averaged at 167 dB SEL_{05} in 750 m, Sandbank was constructed in 2015 with a well-functioning NMS reaching average noise levels of 159 dB SEL_{05} in 750 m. Both projects used the seal scarer as standard methodology. At DanTysk, the response range was 6 km during pile driving, whereas based on the same approach the response range for Sandbank was 25 km. Thus, seal scarer effects cannot be the only explanation, but still might have contributed to the fact that no improvement of effect range and duration from Gescha 1 to Gescha 2 was found.

3. Shipping and other construction-related noise may elicit a response of porpoises already some hours before deterrence and piling occurs when arriving at site and preparing for construction works, but also during and after piling when boat-traffic effects may add to piling effects. In this respect, possible positive effects of improved NMS with Gescha 2 OWFs might have been masked by the operation of service and construction vessels in the area. DYNDO et al. (2015) showed that even low levels of high-frequency noise of boat engines resulted in potential avoidance behaviour of harbour porpoises in more than 1000 m distance. Hence, a minimal escape distance of porpoises to boat noise irrespective of the noise level (as presented in explanations A and B for pile driving and the seal scarer) might be relevant for ships as well. BARLOW (1988) directly observed avoidance behaviour of these animals from board of a vessel. And during a study of WISNIEWSKA et al. (2018), using telemetry in the Baltic Sea, one harbour porpoise showed responses to a fast-approaching ferryboat by altered diving and echolocation behaviour from 7 km distance downwards (however, it remained unclear why the same animal did not respond to a similarly noisy boat signal shortly before). Shipping noise might drive porpoises to swim away before piling starts. For those animals leaving the area already before the beginning of pile driving, a further improvement of noise-mitigation technology would be to no avail and hence would show no effect. A reduction of detection rates before deterrence and piling was shown for most Gescha 1 and 2 wind farms (Gescha 2: Figure 4.26; Gescha 1: BIOCONSULT SH et al. 2016), so it can safely be assumed that negative effects of boat noise and other noise sources exist. With the Gescha 2 dataset, a decline of detection rates before piling and deterrence was found in up to 15 km distance (Figure 4.24). The exact reason why the effect range was so large remains unknown so far. The finding might partly be related to calmer weather conditions during piling, which allowed noise from anthropogenic activities at the construction site to propagate farther due to increased reflection at the sea surface and less effective noise mitigation by fewer air bubbles in the water (HEINIS et al. 2015; BIOCONSULT SH et al. 2016). Several noise sources may be of importance in this respect, of which some have the potential to be very noise-intense:

    a. All larger ships at the construction site use their sonar system constantly, and thus are producing continuous high-frequency noise. Porpoises are known to respond to such noise (KASTELEIN et al. 2017).

    b. Boat traffic to and from construction sites leads to farther-reaching anisotropic effects, best detected when a CPOD is close to the boat routes. By using sonars and thrusters, these ships produce noise of various qualities and frequencies.

    c. If a jackup barge is operating, lowering of the legs by gearwheels may produce a loud and scratching noise (Bellmann, oral comm.). Even though response distances of more than 10 km to normal vessel noise by high-frequency cetaceans like harbour porpoises are not described so far, the scratching noise of jackup barges might have the potential to scare animals farther away.

    d. If no jackup barge is used, the construction vessel has to be held in position in another way. Smaller boats carry anchors with long chains in order to fix the construction vessel at the piling site, a procedure that may take a few hours. The thrusters of these boats emit rumbling noise at various frequencies, whereas lowering the anchor chains produces clattering noise.

e. Sometimes pre-blows are conducted with the bubble curtains in order to blow sand out of the hose. These pre-blows and the compressors may cause noise at various frequencies in the surrounding of construction sites some hours before noise mitigation officially starts.

4. Cumulative effects of subsequent pilings on harbour porpoises are more likely to have occurred with Gescha 2 than with Gescha 1 wind farms, as intervals between piling operations were shorter with newer OWFs. Such cumulative effects could have outweighed the benefits of improved noise mitigation. However, Reference-type models on effect range and duration, which were less affected by cumulative piling effects, showed differences between Gescha 1 and 2 that were similar to those found by CI-type models. Likewise, Gescha 1 found no indication for cumulative piling effects (BioConsult SH et al. 2016). On the other hand, longer pilings within the combined Gescha 1 & 2 dataset had stronger effects at short distances with the CI-type model on the whole dataset (where cumulative effects were more likely to occur as all mitigated pilings were included), but not with the Reference-type model on the dataset reduced to more segregated pilings (thus with a lower probability of cumulative effects being included). We conclude from these findings that within a close range around construction sites the effects of longer piling duration may be more severe if such piling takes place within a tight construction schedule.

5. OFW projects differed in terms of habitat characteristics. Since the response of harbour porpoises to disturbance also depends on habitat use and habitat characteristics, the unexpectedly high effect range found by Gescha 2 might be due to habitat differences outweighing the positive effects of improved noise mitigation. But also the heterogeneous quality of the data available for analysis might have been relevant. Among the OWFs suitable for analysis, the largest minimum effect range during pile driving was found at OWF Sandbank (25 km; Table 4.10); only half of that range was found at Amrumbank West, Butendiek and Nordsee One (12-13 km). The extraordinarily high effect range at Sandbank might be explainable by particularities of that area which is presumably rich in the seasonally preferred but patchily distributed prey of sandeels (fat-rich fish preferred by adult porpoises and especially important for lactating females) and sand gobies (due to their small size preferred by juvenile porpoises) (Leopold 2015). The densities of these fish species, which were highest in that area, turned out to be a significant explanatory variable in global models on hourly CPOD and aerial survey data. Hence, the area around Sandbank is obviously a preferred one for harbour porpoises in spring and summer (see seasonal aerial survey analysis: chapter 4.2). Yet, we found a strong difference in response ranges between Sandbank and DanTysk, the latter OWF being studied within Gescha 1 (Brandt et al. 2016). DanTysk is located closely to Sandbank, and porpoises therefore should have shown a similar response pattern as found at Sandbank. However, this was not the case. At DanTysk, a response of porpoises during pile driving was found in only up to 5-10 km distance, even though the noise levels during pile driving were on average 167 dB SEL_{05} and thus clearly above the values for Sandbank (159 dB SEL_{05}). It might have been relevant here that pilings took place from February to December for DanTysk, and from July to February for Sandbank, so that seasonally differing behaviour and abundance of porpoises, associated to the behaviour and availability of sandeels or other fish, might somehow have affected the effect range of pile driving. Concluding, even in relatively similar areas in terms of harbour porpoise presence and phenology the response of these animals to construction

noise can be quite different, a fact possibly being related to specific habitat and prey-distribution characteristics that overlay the effects of anthropogenic noise. Highly variable spatio-temporal patterns of porpoises were found to indicate a great flexibility of these animals in variable environments (ZEIN et al. 2019).

All these points seem to be reasonable explanations for the more or less unchanged effect range and duration from Gescha 1 to Gescha 2. On the other hand, it is known from different studies that disturbance of porpoises by impulsive sound is clearly related to the noise level: The higher the noise level the stronger the displacement effect (BIOCONSULT SH et al. 2016; DÄHNE et al. 2017; TOUGAARD & DÄHNE 2017). Thus, noise mitigation should reduce effect ranges, which was e. g. shown by a study of DÄHNE et al. (2017) who found that habitat loss was reduced by 75 % when pile driving for the OWF DanTysk was mitigated by bubble curtains. Similarly, at the OWF Trianel Windpark Borkum Phase I (BW2), noise-mitigated piling with the effective noise-mitigation system BBC2 led to a reduction of the disturbed area by even 91.5 % (effect range 7 km) compared to unmitigated piling (effect range 25 km), whereas the less effective system BBC1 only led to a reduction of the disturbed area by 56.4 % (effect range 16 km) (NEHLS et al. 2016; ROSE et al. 2016). At BW2, a difference of only 4 dB in piling-noise levels between a BBC1 and BBC2 (164.8 vs 160.4 dB) caused a strong difference in the effect range. Principally, the situation was analogous to the improvement of noise-mitigation technology from Gescha 1 to Gescha 2, which, however, resulted in no reduction of effect ranges. We were not able to resolve this contradiction but presented possible explanations for the Gescha 2 outcome.

A clear spatial gradient in effect duration was found, with shorter-lasting effects at greater distances. This is in line with results of other studies (BRANDT et al. 2011; BIOCONSULT SH 2014). On the other hand, TOUGAARD et al. (2009) could not demonstarte this for the OWF Horns Rev 1, which may have been caused by a limited dataset.

As to the effects of piling duration on the response range and duration, the CI-type model on the combined Gescha 1 & 2 dataset revealed that shortly after longer pilings stronger negative effects were found at short distances, but that at about 12 km distance from piling locations the effects were equal over all piling durations. The latter was also true for the Reference-type model, but that model did not show stronger effects with longer piling durations at short distances. Thus, the stronger effects of longer pilings at short distances became visible only with the whole dataset, where cumulative effects were more likely to occur as all mitigated pilings were included (CI-type model), but not with the dataset reduced to pilings with sufficient break times around them, thus with a low probability of cumulative effects (Reference-type model). Supposedly, within a close range around construction sites the effects of longer piling duration may be more severe if such piling takes place within a tight construction schedule. On the other hand, in up to 10 km around construction sites the effect duration was independent of piling duration, according to both model types. In contrast to this, farther-reaching effects of longer pilings were found at the OWF alpha ventus (BIOCONSULT SH 2014), but this result could also have been due to different types of piles that were used at that OWF.

As shown above, the OWFs investigated for Gescha 2 differed considerably regarding range and duration of the modelled piling effects on harbour porpoises. This was not only due to habitat characteristics, but at least partly addressable to the heterogeneous quality of the data available for analysis. For some wind farms, no or only few close-range data existed because the positioning of CPODs was unfavourable, and for some OWFs data from before pile driving were scarce due to tight construction schedules. Thus, only a reduced number of OWFs was suitable for analysis. Furthermore, the effect range and duration only seemed to be part of the story. For example, when comparing Butendiek and Nordsee One by the CI-type models, the effect strength at close distance was much higher for Butendiek than for Nordsee One, even though the effect range was the same for both OWFs (Figure 4.16 & Figure 4.17). Partly, this might have been due to the fact that more close-range data were available for Butendiek than for Nordsee One, so that close-range effects at Nordsee One might have been stronger than actually shown by the model. In any way, not only the effect range but also the effect strength at a certain distance has to be taken into account when evaluating piling effects.

Among the OWFs, a special focus was on Gemini due to the fact that all pilings were unmitigated. Additionally, the response of porpoises to pile driving for this wind farm was used as a major reference regarding impacts of unmitigated piling on harbour porpoises for the DEPONS individual-based modelling approach (VAN BEEST et al. 2015; NABE-NIELSEN et al. 2018), causing a great interest in comparing the data of this wind farm to the results of the German projects accompanied by noise mitigation measures. Our modelled range (13 km [s.e.: 11-17 km]) and duration (5 hours [s.e.: 3-6 hours]) of piling effects is more or less in line with CPOD results of NABE-NIELSEN et al. (2018) (deterrence range: 9 km; effect duration: 5 hours within close range), and GEELHOED et al. (2018a) (effect range: 10-20 km; effect duration: 6-10 hours in up to 10 km distance). When comparing the effect duration found at Gemini with effect durations found at the Gescha 2 OWFs with noise-mitigated pile driving and the operation of a seal scarer, 5 hours was by far the lowest value. The modelled response range of 13 km was within the range of most Gescha 2 OWFs (except for Sandbank), which is interesting since pile driving for Gemini was unmitigated and a larger effect range and duration would have been expected (however, piling-noise levels were not assessed at Gemini). One difference between Gemini and the other investigated OWFs was the usage of the seal scarer at the latter, whereas at Gemini a FaunaGuard was used. The FaunaGuard is especially designed to disturb porpoises but it is operated at lower noise levels (VAN DER MEIJ et al. 2015). GEELHOED et al. (2018a) found no negative effects of the FaunaGuard on the acoustic activity of harbour porpoises at Gemini. Still, the peculiarities of the construction process at Gemini (e.g. no ships carrying noise-mitigation technology), compared to that of most other OWFs in the North Sea, as well as the farther-reaching effects of unmitigated pile driving at most other OWFs (TOUGAARD et al. 2009; BRANDT et al. 2011; HAELTERS et al. 2012, 2015; DEGRAER et al. 2013; DÄHNE et al. 2013; NEHLS et al. 2016; ROSE et al. 2016) renders Gemini less suitable to be representative for the majority of OWFs in the North Sea in population models. Instead, it would be desirable to base population models on a variety of wind farms.

The Gescha 2 project was based on a relatively large dataset originating from standard monitoring activities during the construction of a number of North Sea wind farms and transformer substations. Even though the standard procedure delivered a large hourly CPOD dataset, the data were quite heterogeneous. Regarding the results, the future development of noise-reduction measures, with the aim of reducing the radius of disturbance of harbour porpoises, must be critically reviewed, as no improvement regarding piling effects on harbour porpoises was found under current construction procedures. The large avoidance distance of harbour porpoises to pile driving might have resulted from a combination of the aspects discussed above: stereotypical escape distance over a larger intermediate noise-level range; stereotypical escape distance for the noise of seal scarers; ship and other construction-related noise that already prior to the start of deterrence drives out a large amount of animals; cumulative effects due to fast piling sequences. But above all, a high seasonal and inter-annual variability of harbour porpoise occurrence in the North Sea area due to habitat characteristics might have masked construction-related effects and could have governed heterogeneous results. Experimental approaches with a higher number of CPODs at crucial locations, as well as the inclusion of AIS data for the assessment of the effects of boat traffic, would broaden our knowledge of basic processes and greatly improve the outcomes of statistical models on OWF-construction-related effects in future.

4.2 Aerial survey data

WP 3.2 – Spatial extent of the effect of mitigated pile driving (aerial survey data)

The following chapter describes the spatio-temporal reactions of harbour porpoises to pile driving based on digital aerial survey data. Aerial survey data cover a wider geographical area than spatially-restricted CPOD data. However, aerial survey data only provide temporal snapshots of harbour porpoise density, as surveys are usually conducted not more than once per month. Surveys were not planned according to a piling schedule, and thus the majority of surveys did not occur within a week of piling (Table 3.5). Answering questions related to pile-driving events was therefore a statistical challenge that we met by performing a gradient analysis and various large-scale GAM models.

First, a gradient analysis was performed to describe the spatial extent of an avoidance reaction to piling within a short time-lag of up to 12 h from piling. Second, a large-scale analysis was conducted based on GAMs to describe porpoise distribution in relation to piling. All analyses address WP 3.2. which aims at the assessment of the spatial and temporal extent of porpoise avoidance behaviour to pile driving based on digital aerial survey data.

4.2.1 Methods

Gradient analysis

Data preparation

Based on the results of previous studies (e. g. BIOCONSULT SH et al. 2016; BRANDT et al. 2018), a duration of up to 12 h to a piling event was included as time-lag for the gradient analysis. Because the deterrence measures prior to piling intend to dispel porpoises out of the construction area, it is difficult to separate the effect of deterrence and piling disturbance to the animals. Therefore, the logged times of seal scarer activation were taken as the start of a piling event (disturbance), and all aerial surveys covering a construction site within 12 h relative to the start of disturbance were considered in this gradient analysis. Not all surveys were conducted within one day, some surveys even covered several days (see chapter 3.5). Only the transect lines flown within those 12 h were considered. From 2014 to 2016, 28 out of 172 surveys met the time-lag criteria. However, among these only 12 covered the construction area sufficiently in all cardinal directions. The study range was reduced to a 25 km radius around piling sites, so that the full circle included flight effort and was not influenced by the edges of the survey area. The selected surveys came from the survey areas Butendiek, Cl. Nördl. Borkum and Cl. Helgoland, and were all conducted by HiDef. The considered piling events belonged to the projects Butendiek, Borkum Riffgrund 1, Gode Wind, Nordsee 1, and Amrumbank West. Table 4.14 shows the metadata of the respective surveys and piling events. In the subsequent analysis, data from those 12 surveys were pooled and not differentiated by location or piling event. All 12 piling events were noise mitigated. Maps of all harbour porpoise sightings during these surveys are shown in the Appendix.

Table 4.14 Metadata of flights and respective piling events used within the gradient analysis. Time-lag to piling event defined as the time difference in hours (rounded) from the moment of seal scarer start to crossing the piling site by plane.

Area	Survey and date	Flight time	Pile	Piling time	Piling duration [min]	Sel_{05} at 750m	Time lag to piling event [h]
Butendiek	Zone03_M04_S02_14 28.04.2014	13:10 – 17:02	BU56	09:04 – 11:42	105	155	4
	Zone03_M05_S01_14 17.05.2014	11:52 – 15:33	BU69	09:28 – 12:10	123	157	2
	Zone03_M05_S02_14 22.05.2014	12:26 – 16:27	BU61	02:19 – 05:49	152	157	10
	Zone03_M06_S01_14 07.06.2014	12:57 – 16:40	BU14	05:00 – 07:25	104	154	8
Cl. Nördlich Borkum	Zone02_M05_S01_14 03.05.2014	07:10 – 14:25	L02	07:10 – 10:47	171	161	<1
	Zone02_M07_S01_14 12.07.2014	08:41 – 15:54	M08	07:35 – 10:15	111	160	1
	Zone02_M08_S01_15 21.08.2015	07:35 – 14:02	S02	02:54 – 04:52	89	161	7
	Zone02_M09_S01_15 09.09.2015	08:56 – 16:36	L09	05:54 – 07:44	82	159	7
	Zone02_M04_S01_16 02.04.2016	07:22 – 14:45	N41	07:00 – 08:55	76	157	3
Cluster Helgoland	Zone01_M05_S01_14 20.05.2014	12:23 – 17:11	A21	08:45 – 16:03	405	-	4
	Zone01_M08_S01_14 27.08.2014	13:54 – 17:09	A65	14:24 – 16:05	65	153	<1
	Zone01_M10_S01_14 12.10.2014	08:49 – 15:29	A32	03:00 – 11:48	493	165	9

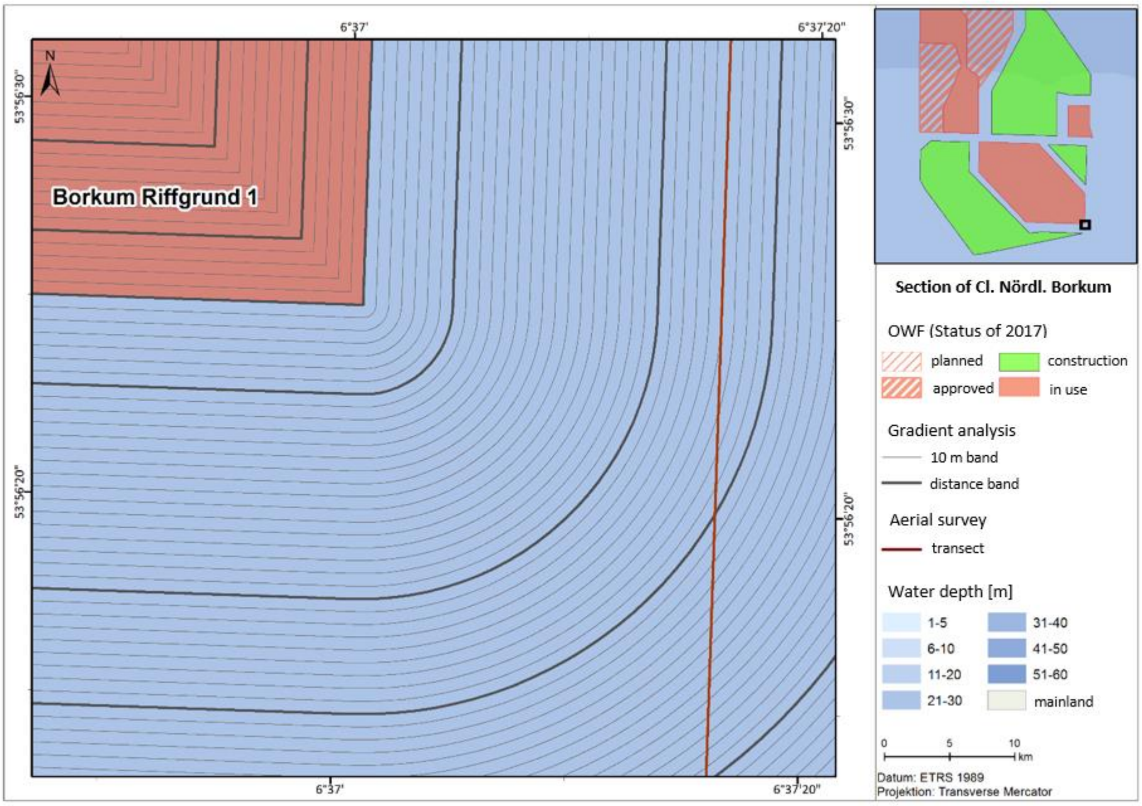


Figure 4.30 Example of the combination of 10 m bands to form distance bands inside and outside of a wind farm. Here shown for the OWF Borkum Riffgrund 1 within Cl. Nördl. Borkum.

Statistical analyses

Statistical analyses focused on the non-parametric comparison of porpoise abundance in relation to distance to the piling site, as well as on GAM modelling of the abundance in response to distance to the construction site.

A 10 m wide circle (hereafter referred to as 10 m band) was projected around each piling location (Figure 4.30). For non-parametric comparisons, distance classes were defined for every 2.5 km distance from the piling site, and all 10 m distance bands were merged within the respective distance class. The sightings were corrected by effort. For this approach, each distance class had a different effort, but since sightings/km were calculated it was already corrected for the effort. The last distance class of 22.5-25 km was taken as reference class without disturbance caused by piling. Using a Wilcoxon signed rank test, harbour porpoise sightings within a distance class were compared to the reference class (significance level of $\alpha = 0.05$). Additionally, the percentage distribution of porpoise sightings/km over all ten distance classes was calculated.

Data preparation for the GAM was different. Here, 10 m bands were combined to form a so-called distance band with similar effort. Each of these distance bands contained an effort of 25 transect-km (±10 %). Distance bands can vary in width, as with increasing distance from the piling site fewer 10 m bands are required to reach 25 km of effort since more and more transect lines cross the 10 m bands. Even though the width of the distance bands varied, the effort per distance band was fixed at 25 transect-km, hence number of porpoises per distance band can be compared directly.

The GAM was used to define an effect range of piling. It contained a regression analysis for non-linear interactions, and a negative binomial distribution including five nodes was chosen (KEELE 2008; ZUUR 2009). It was calculated using the function *gam()* from the R package mgcv. The response variable was the sum of porpoises per distance band. The explanatory variable "distance to the piling site" was defined as the midpoint of each distance band. The model was calculated, smoothed and presented with a 95 % confidence interval. The mean effect range was calculated, based on the lower confidence interval of the model smooth at the point of maximum abundance (plateau phase) (Figure 4.31). Additionally, the distance range where 50 % of the maximum number of animals occurred was calculated (Figure 4.31).

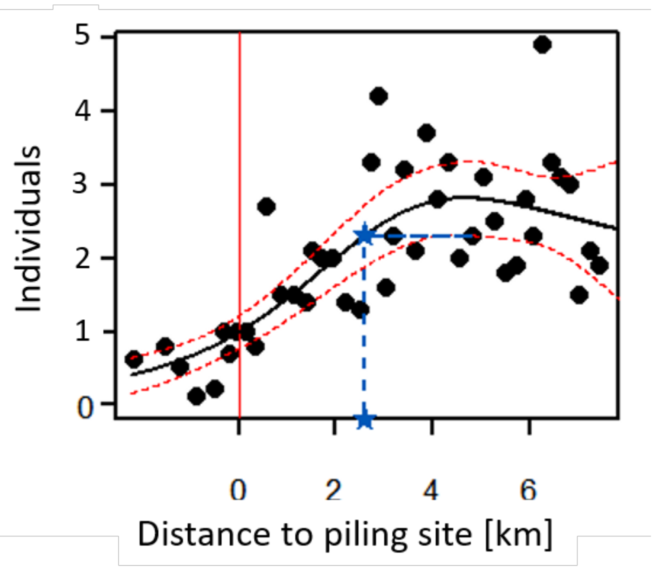


Figure 4.31 *Example of the presentation and interpretation of the gradient analysis. The intersection of the lower confidence interval at the plateau phase with the model smooth and the respective nadir define the mean effect range (blue asterisk). The distance where 50 % of the maximum number of animals occurred is indicated by a red vertical line.*

Methods of the large-scale analysis

The large-scale distribution model was based on a grid laid over the German Bight (see chapter 3.5). All porpoise densities were merged by month and grid cell. If multiple surveys occurred in a month within a grid cell, the mean density of those surveys was taken to obtain only one density value per month. A set of models was created to explain the variance in porpoise presence and absence based on a set of explanatory variables. These explanatory variables were combined into three groups to ease the understanding of model construction and selection: basic variables, environmental variables and human-induced disturbance ("anthropogenic") variables (Table 4.15). The data origin of environmental variables is given in chapter 3.6. Due to heterogeneity of habitats and phenology in the German Bight, three subareas within the German Bight were set: "Northeast", "South" and "West" (Figure 4.32). The subareas were formed solely by grouping neighbouring survey areas and do not represent the clusters applied with CPOD data in chapter 6.1.4. Subarea "Northeast" consists of the survey areas DanTysk/Sandbank, Butendiek and Cl. Helgoland, "South" consist of the areas Cl. Nördlich Borkum and Nordergründe, and "West" consists of Cluster 6 and Cl. Östlich Austerngrund.

Models were built for each subarea individually, and one model was based on the entire digital aerial dataset (hereafter referred to as "holistic model"). Hence, a total of four models were built to describe the presence and absence of porpoises. The following sections describe the definition of explanatory variables, as well as model construction and variable selection.

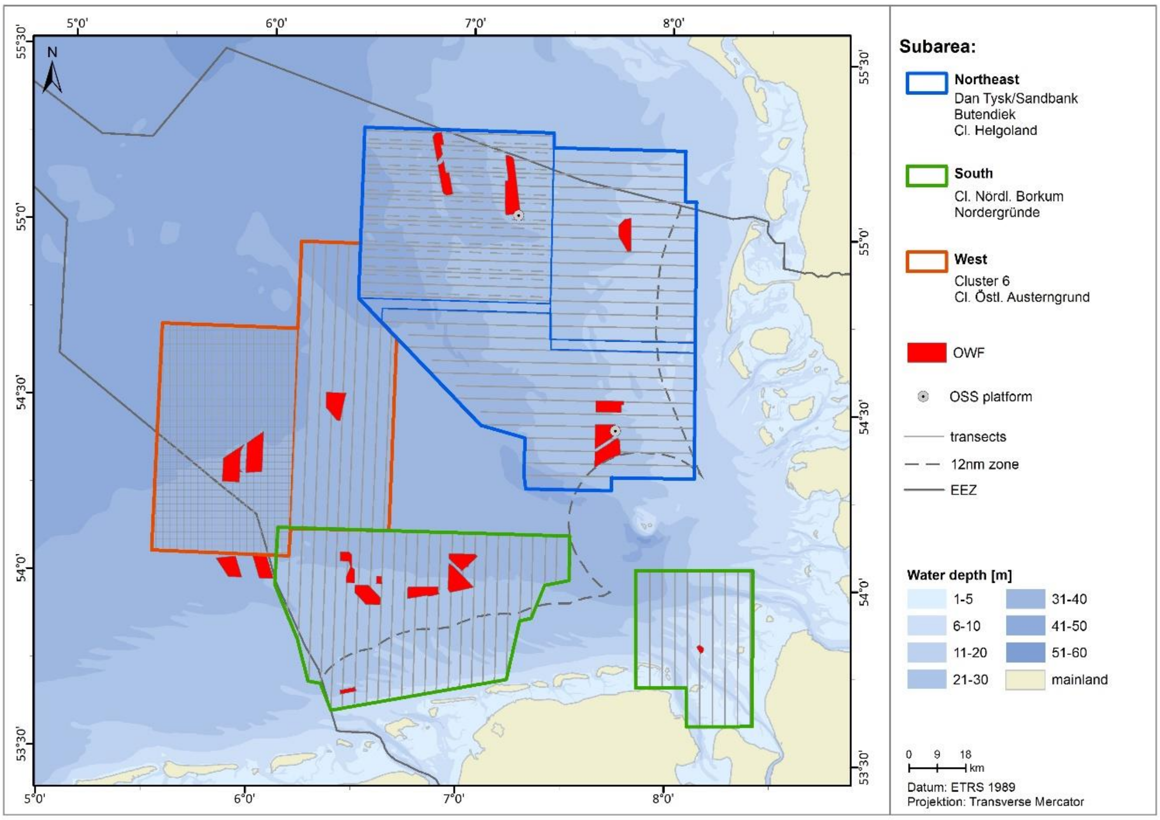


Figure 4.32 Three subareas "Northeast", "South" and "West" in the German Bight, grouped by the different survey areas.

Basic variables

Spatial and temporal variables were used in every model to describe the general spatial and temporal variance. The central grid-cell coordinates, the survey area (Figure 3.7) and the subarea were included to describe spatial variance. Temporal variables were survey month (continuous and factorial), survey year, season and season by year. Additionally, survey method, i. e. APEM, DAISI or HiDef, was used as explanatory variable; however, due to the usage of different methods in the survey areas, survey method was often interchangeable with survey area.

Environmental variables

Environmental variables consisted of a set of oceanographic and biological variables. Their data source is described in chapter 3.6. Water depth and sediment structure were constant variables over time. Further oceanographic variables were sea-surface temperature (SST), sea-surface-temperature anomaly (SSTA), salinity, current speed, and wind speed. For each of these variables, the arithmetic mean of the three days prior to the flight survey was taken as a monthly value per grid cell. Biological variables were used as a proxy for prey availability for porpoises. Satellite measurements of Chlorophyll a concentration (Chl. a) were used as a proxy for phytoplankton abundance. Phytoplankton, here described by Chl. a, is at the bottom of the food chain, followed by zooplankton, fish and harbour porpoise. We therefore included Chl. a as a proxy for prey availability for porpoises into our models. However, the food chain reaction from Chl. a to prey for porpoises requires time; that is why we included the arithmetic mean of the previous seven days to survey flight by grid cell as value into the model. The probability of sandeel occurrence (*Ammodytes marinus, Ammodytes tobianus and Hyperoplus lanceolatus*), as well as sand goby (*Pomatoschistus minutus*) occurrence was calculated by grid cell, referring to the same data as described in chapter 3.6. The mean probability of the occurrence of fish species living in sandy sediments, not differentiating between sandeels and sand gobies, was considered as an additional more specific proxy for prey distribution. All three fish variables were considered constant over time. Monthly SST, salinity and Chl. a data, as well as the mean probability of fish occurrence in the study area are shown in the Appendix.

Anthropogenic variables

The AIS-signal dataset for ship traffic, referred to in chapters 3.6, was aligned to the spatial grid as factorial variable (shipping as positive or negative). A cell with no AIS data was considered as "shipping negative", whereas cells with AIS data were seen as "shipping positive" (see Appendix). The factor "shipping" was constant over time. The second anthropogenic variable was the presence of a wind farm in the cell. Information of wind farm position and wind farm border, including a 500 m buffer as a safety zone around the OWFs provided by the GeoSeaPortal by BSH, were transferred to the grid cells. If no wind farm border cut the cell, the value "no wind farm" was given; if the cell was cut by a wind farm border, the value "construction" or "wind farm present" was given. The phase "construction" defines the period from the piling date of the first foundation to the piling date of the last foundation. After this period, the wind farm was considered present. All wind farms constructed before 2014 were considered present throughout the study.

Piling variables were aligned to the grid, based on two criteria: distance and time. All piling events that occurred within 7, 3, or 1 days before the aerial surveys were considered for cells within a 40 km radius around piling locations. The number of piling events was summarised for the three time periods (1, 3, and 7 days), as well as the sum of all piling minutes and the sum of all piling energy. Furthermore, the distance and time-lag to the most recent piling within 7 days prior to the survey were calculated. The information whether the most recent piling event was noise-mitigated or not was added as a factorial variable. An additional factorial variables provided the information whether there was at least one piling event within 7, 3, or 1 day prior to the survey, or not.

Spatial-grid modification

Chapter 3.5 gives an overview of effort and porpoise distribution on the 2 x 3 arc minutes grid (Figure 3.9 and Figure 3.10). However, in the process of model selection, we discovered a strong spatial autocorrelation among grid cells when using the small grid. It was not possible to account for the spatial autocorrelation within the models, and consequently model results became unreliable. To overcome issues of spatial autocorrelation, four neighbouring cells were merged to create a larger grid cell, resulting in larger grid dimensions. The new size of the grid cells was 7.43 x 7.43 km (Figure 4.33). The arithmetic mean of four cells was calculated for each numerical variable, and categorical variables were unified. In case two contradictory levels occurred (e. g. "wind farm within the cell" and "no wind farm in the neighbouring cell") a precautionary decision was taken, e. g. in the above case a wind farm was considered in the larger cell, or, as another example, if piling occurred within the previous day in one cell but not in the neighbouring cell piling was still considered for the new cell.

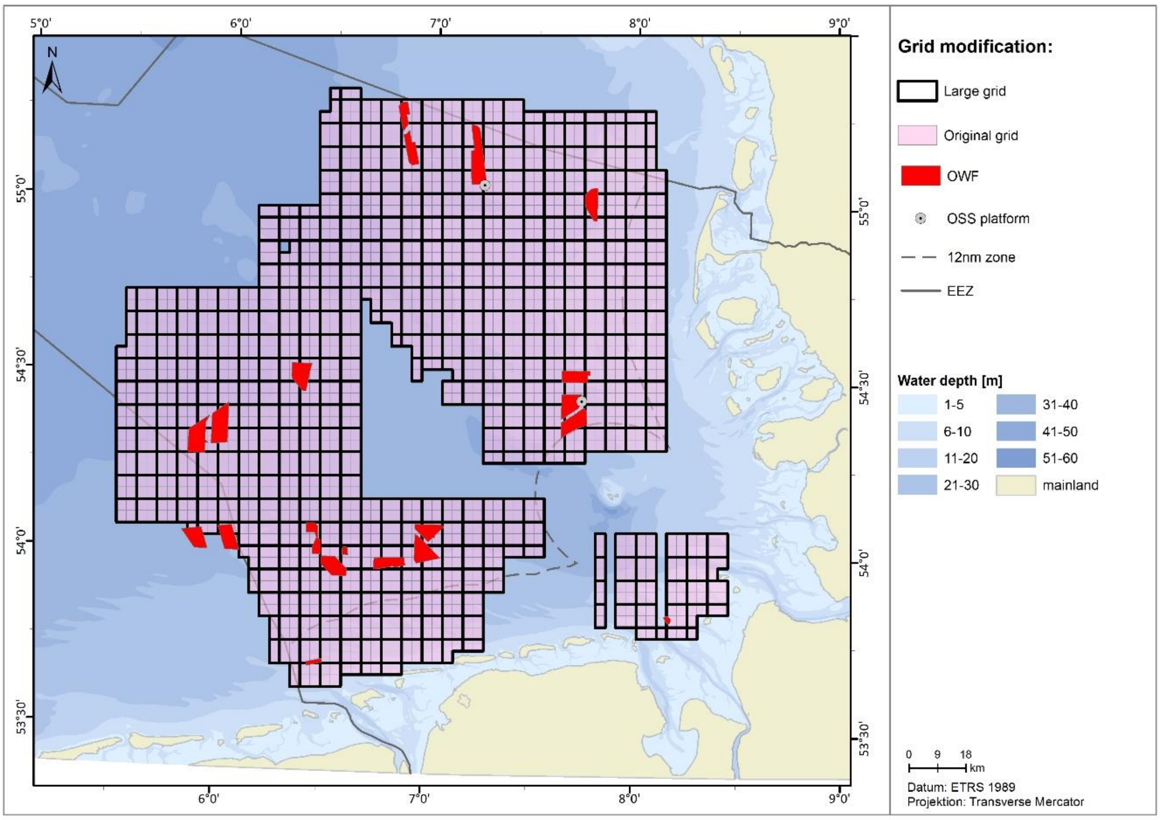


Figure 4.33 Spatial-grid modification from smaller to larger grid dimensions to avoid spatial autocorrelation within the statistical analyses.

Statistical analyses

Datasets by subarea differed in size, i. e. the complete dataset was n = 10,484, the "Northeast" dataset n = 5,401, the "South" dataset n = 2,714, and the "West" n = 2,369. Model selection and parameter testing on collinearity was done individually per dataset (see Figure 4.34 for the complete dataset and the Appendix for subarea datasets). As in Gescha 1 and in other peer-reviewed literature (e. g. Gilles et al. 2016), Generalised Additive Models (GAMs) were compiled using the function *bam()*, suitable for large datasets, of the package mgcv (Wood 2015). A binomial distribution was used for the logistic regression of presence and absence. For non-factorial parameters the default thin-plate regression splines were used. Cyclic parameters were included with the default cyclic cubic regression splines. Model selection followed a stepwise addition and exclusion of uncorrelated variables, based on AIC. If the p value of a variable was smaller than 0.1, it was checked whether exclusion resulted in a model with a lower AIC than the model including this variable, and the simpler model was consequently preferred. The year was included into all models to identify annual variance. Furthermore, all models contained a three-dimensional tensor product of space (coordinates) and time (month) to adjust for spatial and temporal variance. All statistical analyses were done with R version 3.5.2 (R CORE TEAM 2018).

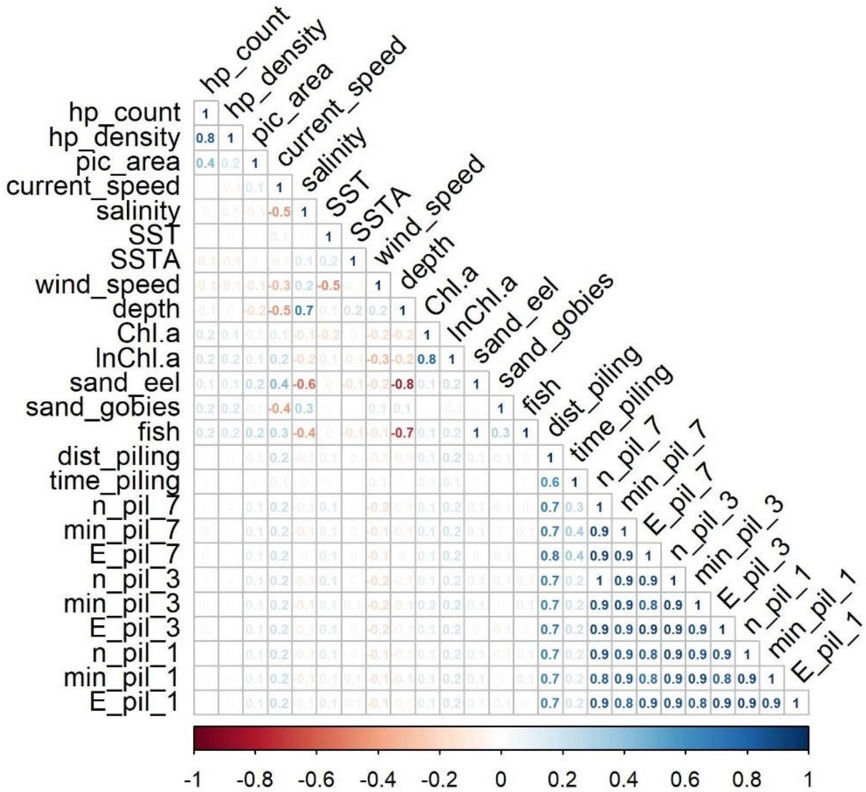


Figure 4.34 Correlation between explanatory variables for the complete dataset. Variables are explained in Table 4.15.

Table 4.15 List of all variables associated per grid cell.

	Variables	Type	Unit	Description
basic variables	grid cell ID	factor	categorical	unique grid cell ID
	longitude	continuous	UTM32 WGS84	central grid x coordinate
	latitude	continuous	UTM32 WGS84	central grid y coordinate
	month	continuous	digit	survey month numeric (from 1 to 12)
	month	factor	12 levels	factorial survey month
	unique month	factor	35 levels	unique month per year (one factor level per month and year)

	Variables	Type	Unit	Description
	season	factor	4 levels	meteorological seasons
	season by year	factor	13 levels	meteorological season by year (one factor level per season and year)
	year	factor	3 levels	survey year (2014, 2015, 2016)
	pic area analysed	continuous	km²	sum of all picture area analysed within a month
	area	factor	7 levels	survey areas
	subarea	factor	3 levels	survey areas combined to subareas
	method	factor	4 levels	observer method with levels APEM, DAISI and HiDef or, if more than one method was used in overlapping areas, "twodiff"
environmental variables	mean current speed	continuous	m/s	mean current speed of previous 3 days to flight
	mean salinity	continuous	PSU	mean salinity of previous 3 days to flight
	mean SST	continuous	°C	mean SST of previous 3 days to flight
	mean SSTA	continuous	°C	mean SSTA of previous 3 days to flight
	mean wind speed	continuous	m/s	mean wind speed of previous 3 days to flight
	mean depth	continuous	m	mean water depth; constant over time
	substrate	factor	5 levels	category of the seabed; constant over time

	Variables	Type	Unit	Description
	mean Chl. a	continuous	mg/m³	mean Chl. a concentration of previous 7 days to flight
	ln Chl. a	continuous	mg/m³	logarithm of mean Chl. a concentration
	mean sandeel probability	continuous	digit	mean sandeel probability; constant over time
	mean sand goby probability	continuous	digit	mean sand goby probability; constant over time
	mean fish probability	continuous	digit	mean of mean sandeel and mean sand goby probability
anthropogenic variables	shipping	factor	2 levels	shipping within grid cell (yes or no)
	OWF presence	factor	3 levels	no OWF present, OWF under construction or OWF present
	distance to piling	continuous	m	distance from cell centre to the most recent piling event within 40 km
	time since piling	continuous	min	time passed from most recent piling event within 40 km to flight
	mitigation of piling	factor	2 levels	was the most recent piling event noise mitigated (yes or no)
	piling_7	factor	2 levels	any piling events within 40 km within 7 days to flight (yes or no)
	n piling events_7	continuous	count	sum of all piling events within 40 km in the previous 7 days to flight
	sum piling minutes_7	continuous	min	sum of all piling minutes within 40 km in the previous 7 days to flight

	Variables	Type	Unit	Description
	sum piling energy_7	continuous	kJ	sum of all energy applied in all piling events within 40 km in the previous 7 days to flight
	piling_3	factor	2 levels	any piling events within 40 km within 3 days to flight (yes or no)
	n piling events_3	continuous	count	sum of all piling events within 40 km in the previ-ous 3 days to flight
	sum piling minutes_3	continuous	min	sum of all piling minutes within 40 km in the previ-ous 3 days to flight
	sum piling energy_3	continuous	kJ	sum of all energy applied in all piling events within 40 km in the previous 3 days to flight
	piling_1	factor	2 levels	any piling events within 40 km within 1 day to flight (yes or no)
	n piling events_1	continuous	count	sum of all piling events within 40 km in the previ-ous day to flight
	sum piling minutes_1	continuous	min	sum of all piling minutes within 40 km in the previ-ous day to flight
	sum piling energy_1	continuous	kJ	sum of all energy applied in all piling events within 40 km in the previous day to flight

4.2.2 Results

First, the results of the gradient analysis are shown. Here, aerial survey data were reduced to 25 km around a construction site and given a temporal limit of 12 h to the start of deterrence measures. Thus, results represent a spatially and temporally limited analysis of pile-driving effects on harbour porpoises. Secondly, large-scale effects of pile driving were investigated based on GAMs for the subareas as well as the entire study area.

Gradient analysis

This type of analysis was carried out to estimate the effects of pile driving events on the spatial distribution of harbour porpoises around piling sites within 12 h to pile driving.

Porpoise sighting rates increased continuously with increasing distance to the construction site up to the distance class of 12.5-15 km (Figure 4.35). Up to the class of 7.5-10 km the mean sighting rate was significantly lower compared to the distance class of 22.5-25 km (Wilcoxon signed rank test, p < 0.05). The other distance classes were not significantly different from the reference class.

Sighting numbers per distance band with equal effort also increased with distance to piling location (Figure 4.36). Based on the GAM results, distances of 11.4-19.5 km to piling sites were identified as the effect range, with a mean effect distance of 14.4 km (Figure 4.36). Below 14.4 km, porpoise numbers were lower than expected, whereas at more than 14.4 km distance porpoise numbers were close to the projected mean abundance. At 7.4 km, porpoise abundance was 50 % of the projected mean abundance (range 5.9-9.1 km). Figure 4.37 shows the actual porpoise distribution per survey within 25 km to the piling site. The estimated effect radii of 7 km (50 % threshold) and 14 km (mean effect distance) are indicated within each map.

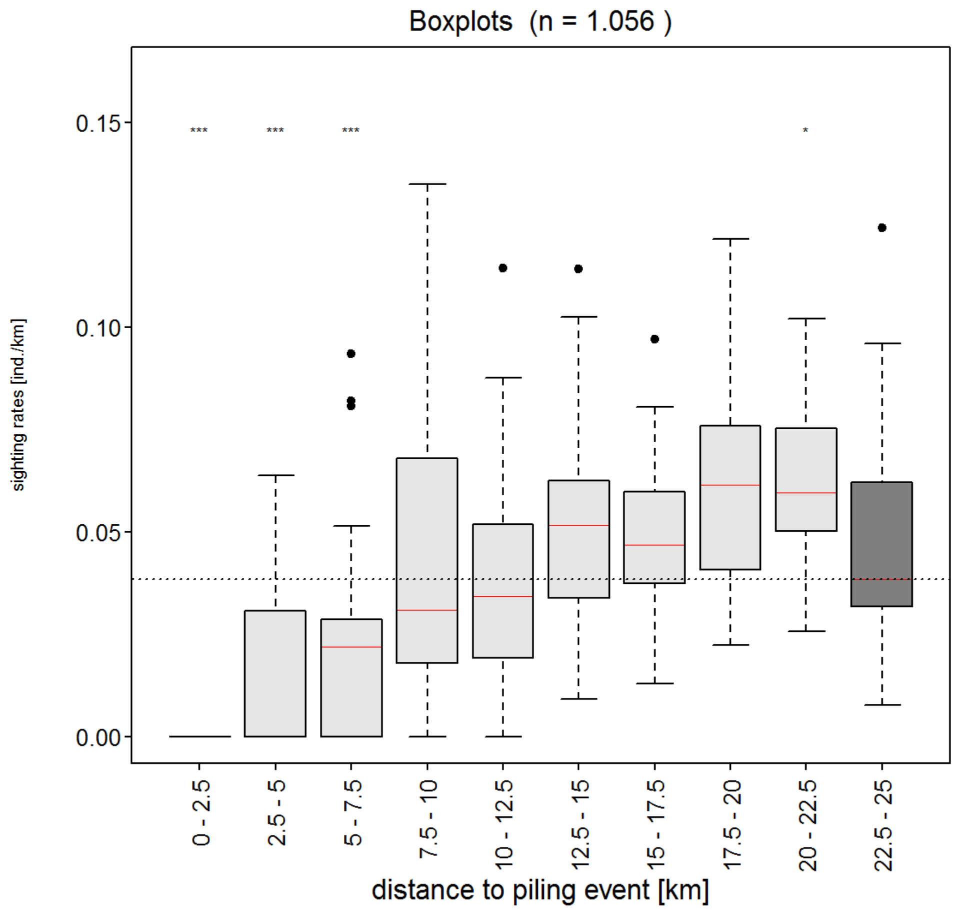


Figure 4.35 *Porpoise sighting rates [ind./km] by distance class to the piling site. The distance class of 22.5-25 km (in dark grey) was taken as reference class. Significantly different distance classes to the reference class are indicated by * (*** shows p < 0.05; * shows p < 0.1).*

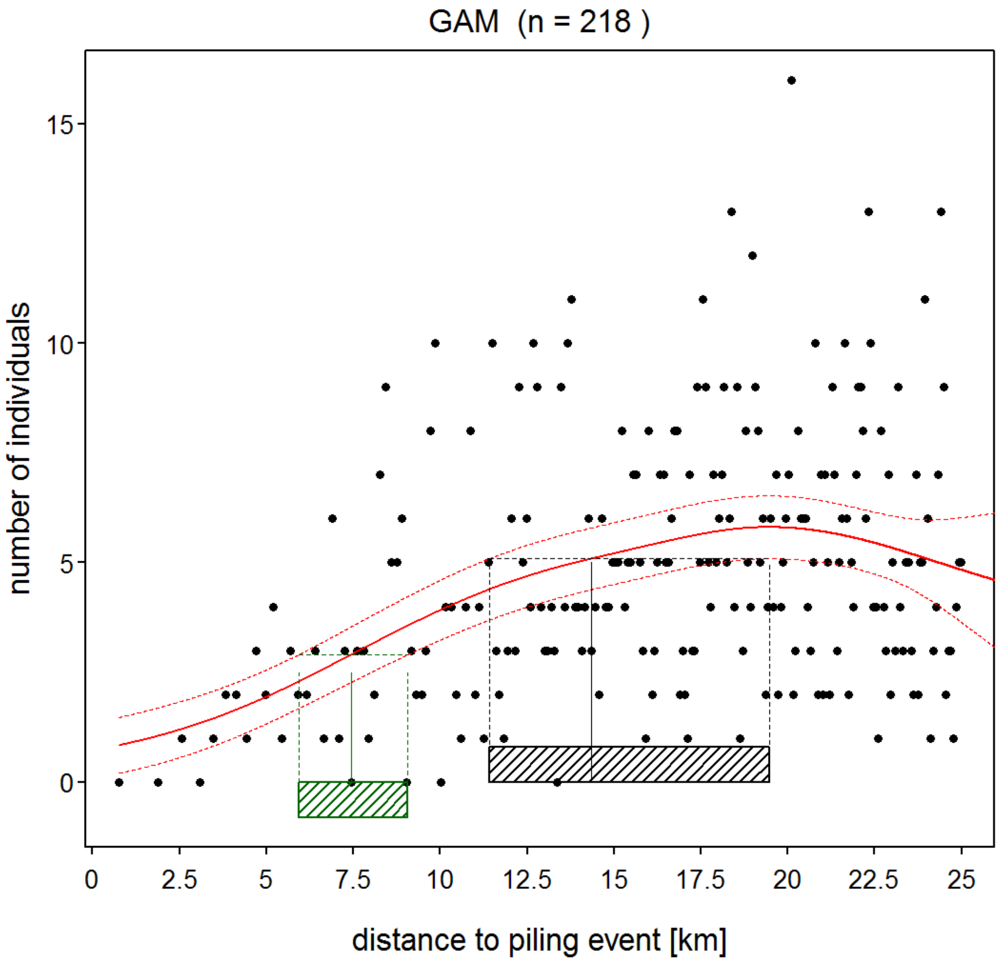


Figure 4.36 *Modelled number of porpoises (red line) by distance to the piling site with respective confidence interval (red, broken line). Distance where plateau of projected mean individual number is reached is indicated by the black striped box, with calculated avoidance distance of 14.4 km. Distance where 50 % of projected mean individual number is reached is indicated by green striped box, with calculated 50 % avoidance distance of 7.4 km.*

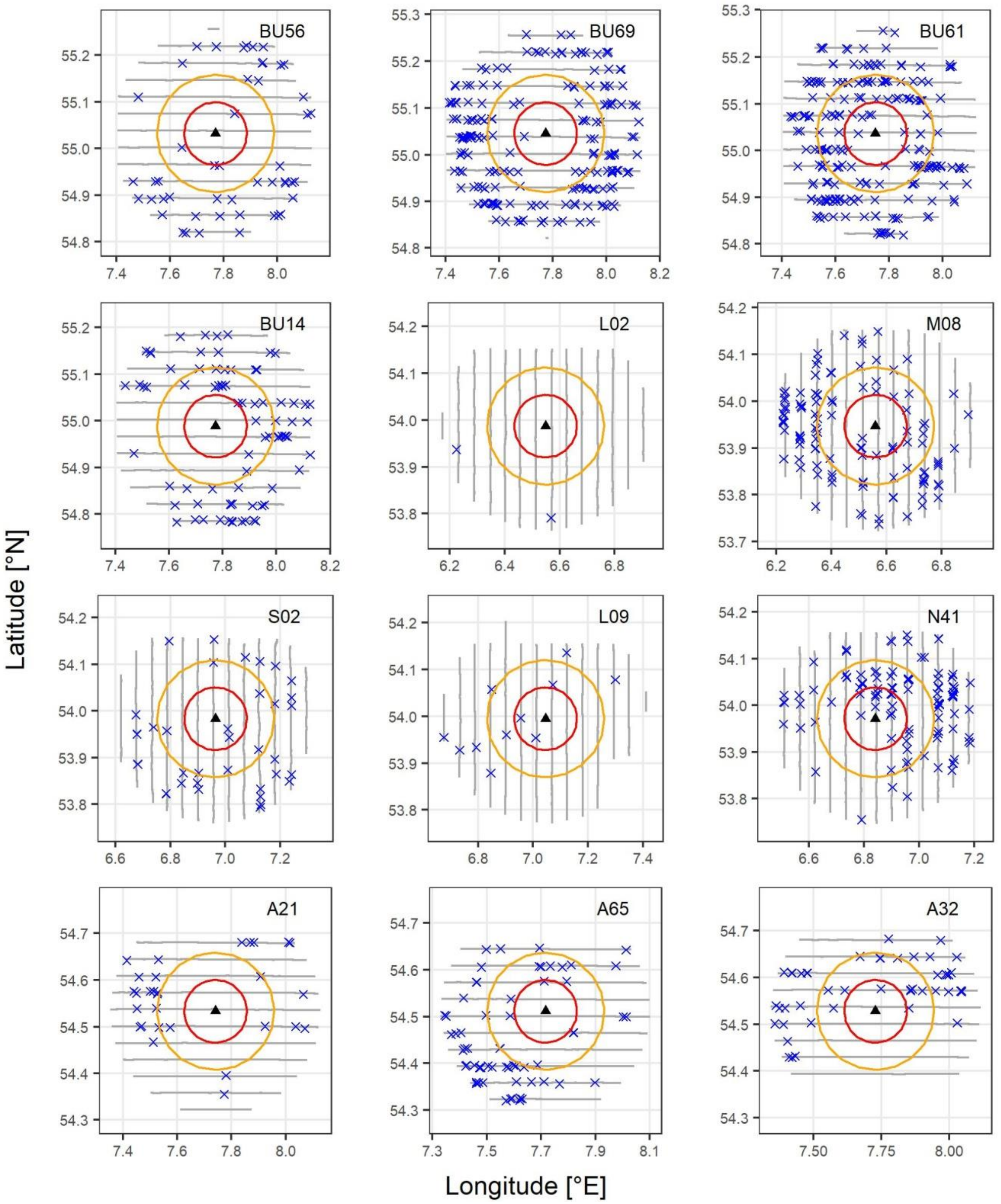


Figure 4.37 Porpoise sightings (blue cross) observed from digital aerial surveys within 12 h to piling. Flight effort (grey line) within 25 km to the piling site (black triangle) are shown. Red circles show an avoidance radius of 7 km to the piling site, while yellow circles show an avoidance radius of 14 km. Number within each figure: pile number c. f. Table 4.14.

Large-scale models

Four large-scale GAMs were calculated with porpoise presence/absence as response variable, based on the entire aerial survey dataset (holistic model), as well as on data subsets defined as subareas "Northeast", "South" and "West". Subareas were set up due to regional differences in porpoise phenology and density; thus, subareas were characterised by different expressions of the explanatory variables. All four models included a tensor product of the geographical coordinates (x, y) by unique month to correct for spatial autocorrelation and spatial variance in the models. Furthermore, all models included a correction for effort, described by a smooth for sum of image area analysed.

Holistic model

The variables included in the best model for the holistic model were subarea, year and wind farm presence, as well as the explanatory variables Chl. a separated by season, SST separated by month, and fish presence (Table 4.16). The model explained 32 % of the deviance. No annual variance was found (Figure 4.38). Inclusion of ship traffic or specific piling variables (e. g. piling duration or piling events) did not improve the model for porpoise presence/absence over the entire area. However, it was important to include wind farm presence as a factor. The model found a significant difference in the factor “construction phase” to the factors “wind farm present” and “no wind farm present”. The factor “construction phase” defined the period between the first and last piling event of a wind farm for the cells neighbouring the wind farm. The model predicted a lower probability of porpoise presence during the construction phase, compared to the other two factors of wind farm presence and absence (Figure 4.38). Including the variable subarea into the holistic model resulted in a higher explanatory power than including variables for survey area or observer method.

Figure 4.39 shows the general seasonal probability of porpoise presence as determined by the model with the complete dataset. In the north-eastern subarea, the model fitted a high and widely distributed probability of porpoise presence in spring and summer. In the southern subarea, the probability of porpoise presence was modelled as being high during winter and summer. For the western area, the model showed a higher probability of porpoise presence in spring compared to the other seasons. The modelled probability of porpoise presence corresponded well with the actual density distribution (compare with Figure 4.40).

Table 4.16 Model parameter and GAM results for the holistic model on porpoise presence/absence.

Variable	Regression technique	Df / Edf	Chi²	p value
OWF presence	factor	2	20.864	< 0.000
year	factor	2	0.138	0.933
subarea	factor	2	42.653	< 0.000
te(x,y, unique month)	3-D tensor spline	299.505	1158.782	< 0.000
Chl.a – winter	thin plate smooth	1	1.463	0.227
Chl.a – spring	thin plate smooth	2.386	13.170	0.003
Chl.a – summer	thin plate smooth	1.130	2.077	0.205
Chl.a – autumn	thin plate smooth	3.584	8.624	0.069
SST by month	thin plate smooth	14.894	48.354	< 0.000
fish probability	thin plate smooth	3.074	17.968	0.001
total picture area analysed	thin plate smooth	6.560	529.981	< 0.000

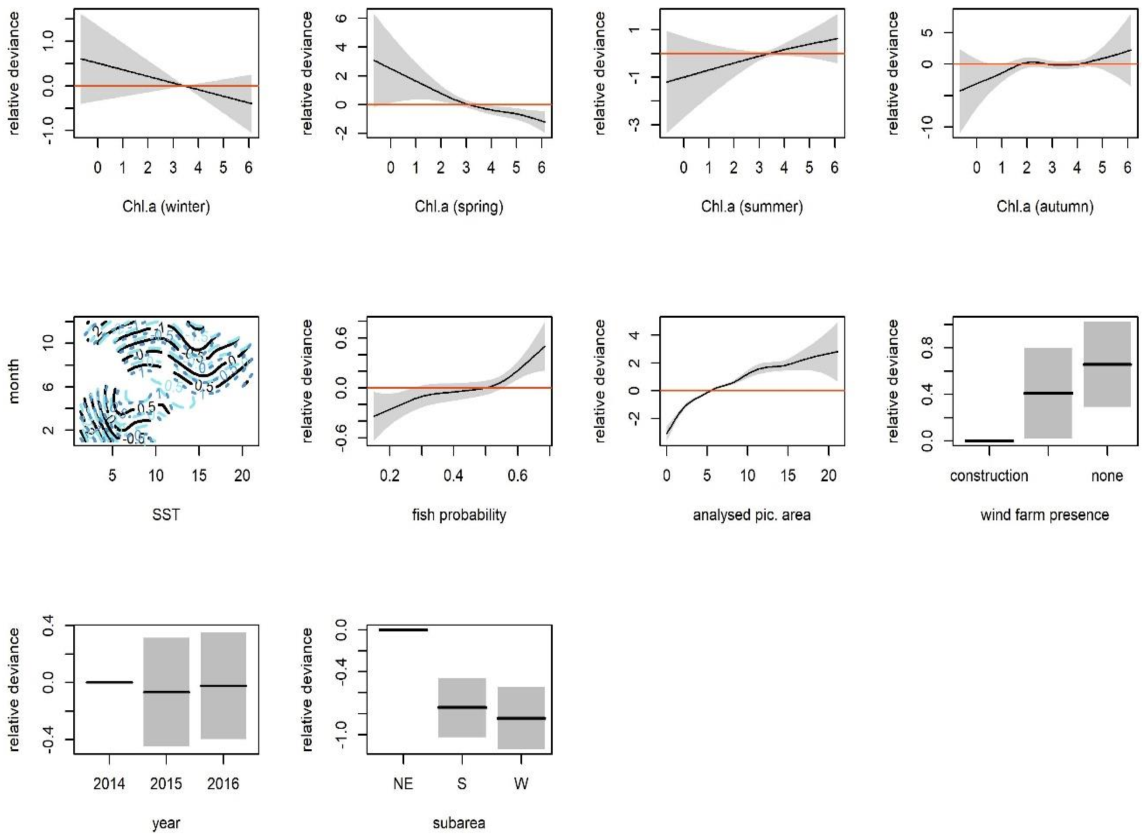


Figure 4.38 Smoothed model parameters for the holistic GAM model of porpoise presence/absence.

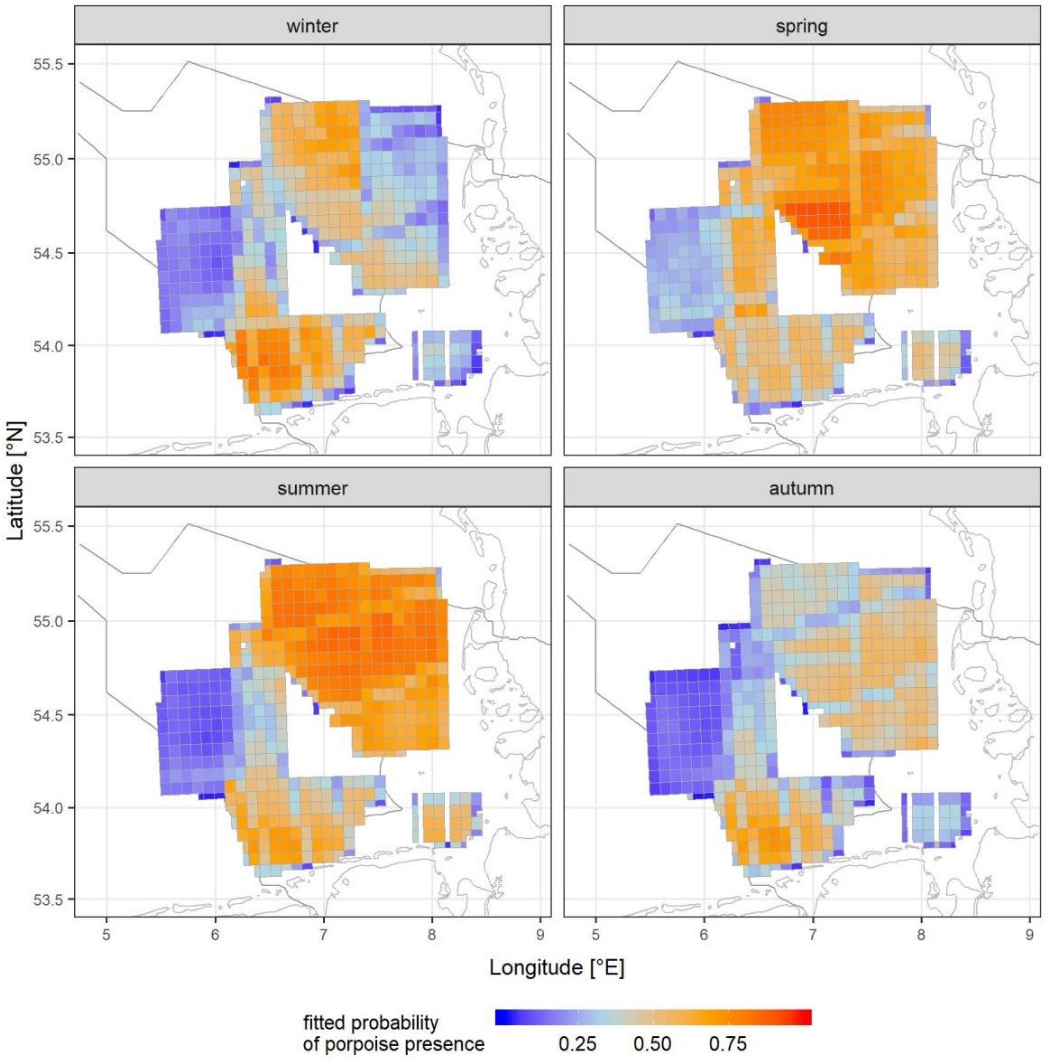


Figure 4.39 Fitted probability of porpoise presence for the full dataset containing all survey areas.

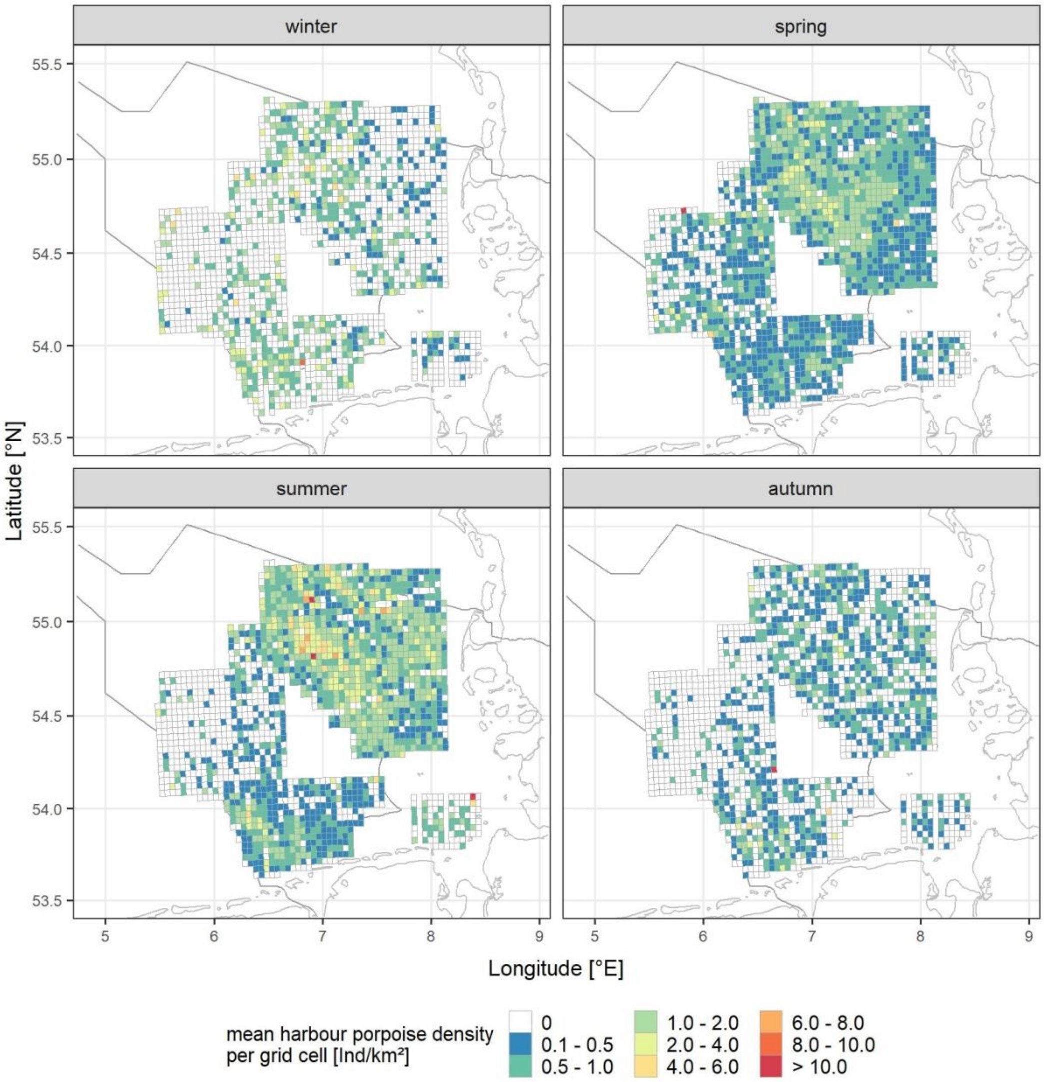


Figure 4.40 Actual seasonal porpoise densities and distribution for the entire survey area from 2014 to 2016.

"Northeast" model

The "Northeast" model included some variables differing from the holistic model. The following variables were significant in the "Northeast" model: a correction for observer method, month (as continuous variable), year (as factor), salinity, fish presence, and presence of wind farms (Table 4.17). The model explained 34.3% of the deviance. The "Northeast" subarea contained an east-west gradient, from the mainland to more open waters, with increasing salinity (see Appendix). Especially the western area of the Sylt Outer Reef overlapped with higher salinity values and high predicted fish probability (sandeel and sand goby) (see Appendix). The factor "month" captured the peak of porpoise presence in June and the general high presence in summer (Figure 4.41).

Anthropogenic variables were not selected as explanatory factors within the model, meaning that shipping or piling specific variables did not improve the model. The "construction phase" was significantly different to wind farm presence/absence, predicting a significantly lower porpoise probability. There was no significant difference, however, between wind farm presence and absence. During the study period, three OWFs were constructed within the "Northeast" subarea: OWF Amrumbank West, OWF Butendiek and OWF Sandbank.

In the "Northeast" subarea, three observer methods were applied (APEM, DAISI and HiDef). While the inclusion of the observer method improved the model (and was therefore included as an explanatory variable), the APEM method contributed only 2.5 % (135 of 5401 data points) to the sample size, representing two flights in spring 2014. These two months were also responsible for a significantly higher presence of porpoises in 2014, compared to 2016, within the model. This yearly variance did not remain significant if the dataset was reduced by these months (see Appendix). Therefore, not too much weight should be put on any yearly trend in presence and absence based on the model results for the "Northeast".

Porpoise presence was shown by the models to be lower in winter, especially within the survey area of Butendiek, which is due to the lower survey effort in this region in winter (compare Figure 4.40 with Figure 4.42). This represents a model artefact rather than an actual discontinuity of porpoise distribution along the border of survey areas. The model included the variable "total picture area analysed" (i. e. effort), which was lower in this area during winter and hence predicted a lower porpoise probability. The model confirmed a higher spring and summer presence of porpoises around the western edge of the Sylt Outer Reef and a generally less dense distribution in autumn (Figure 4.42).

Table 4.17 Model parameter and GAM results for the "Northeast" model on porpoise presence/absence.

Variable	Regression technique	Df / Edf	Chi²	p-value
OWF presence	factor	2	5.120	0.078
year	factor	2	5.353	0.069
observer method	factor	3	14.825	0.002
te(x,y, unique month)	3-D tensor spline	255.393	716.46	< 0.000
salinity	thin plate smooth	3.412	21.51	< 0.000
fish probability	thin plate smooth	1	25.58	< 0.000
month	cyclic smooth	4.257	97.90	< 0.000
total picture area analysed	thin plate smooth	4.170	246.88	< 0.000

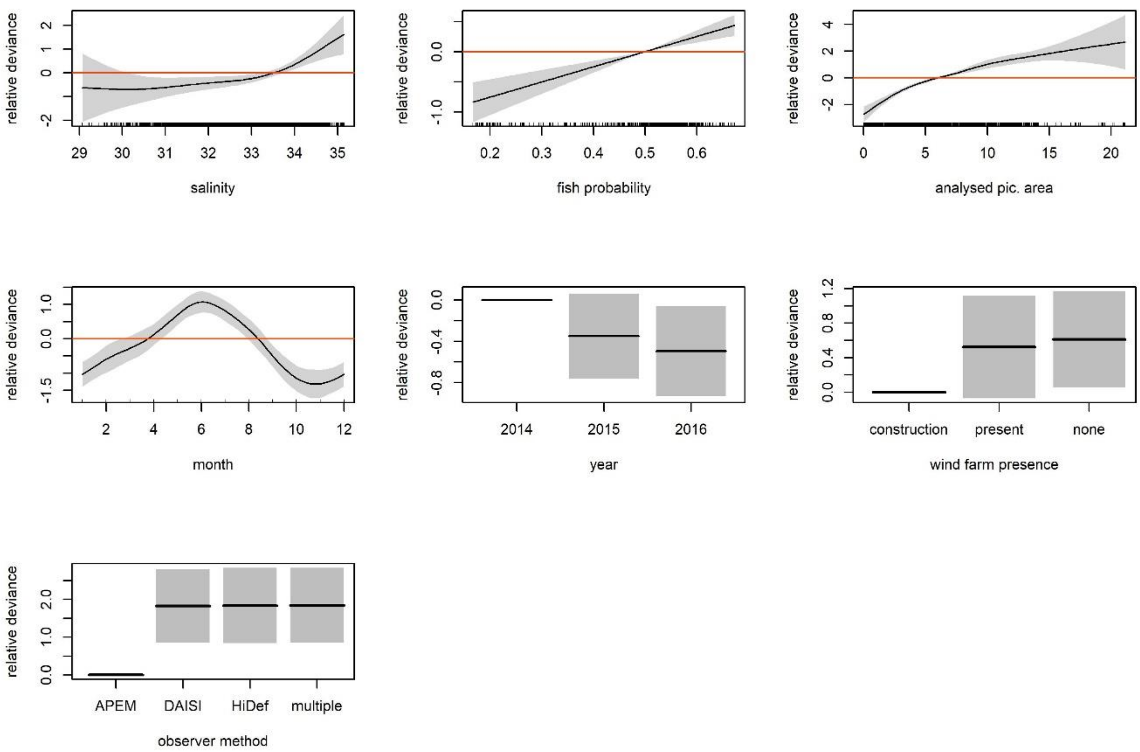


Figure 4.41 Smoothed model parameters for the "Northeast" GAM model of porpoise presence/absence.

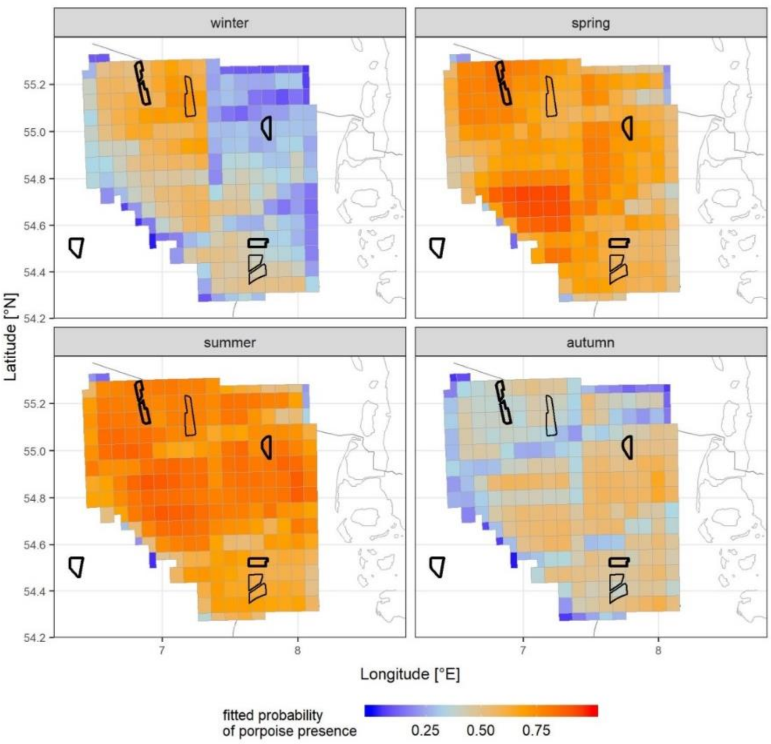


Figure 4.42 Fitted probability of porpoise presence for the "Northeast". Existing wind farms prior to 2014 are indicated by a thin black outline, while wind farms constructed within the study period are indicated in bold.

“South” model

For the “South” model, the best explanatory variables were Chl. a concentration separated by season, SST separated by month, as well as salinity and presence of wind farms (Table 4.18). The model explained 28.2 % of the deviance. Year was not a significant factor for the “South” model (Figure 4.43). Fish presence, which was selected in the other models as a constant factor by time, was not selected in the final model here. However, Chl. a concentration in summer proved to be a good explanation for porpoise presence. Porpoises were especially widely distributed and present in the summer months in this subarea. In this study, the “South” included the survey area of Nordergründe, which is very close to the mainland and under the influence of river runoff and tidal mixing (see Appendix). Hence, salinity proved to be a significant explanatory variable to account for the diverse oceanographic features in the area (Table 4.18).

As in the other subareas, no anthropogenic variables besides wind farm presence were significant in the model. The subarea “South” was the area where most wind farms were constructed within the study period, in particular the OWFs Borkum Riffgrund 1, Nordsee One, Gode Wind and Nordergründe, as well as OWF Gemini, which is close to the border of the “South” subarea. The model predicted the lowest probability of porpoises for the construction phase (Figure 4.43). The difference to the factor “wind farm present” was not significant, but still the probability of porpoise presence for a wind farm was higher than for the construction phase. The probability of porpoise presence was highest when no wind farm was present. This was driven mainly by the overlap of the subarea “South” with the nature reserve Borkum Reef Ground without any wind farm but with high porpoise abundance. The model fitted a higher probability of porpoises in the western part of the subarea “South”, corresponding to Borkum Reef Ground (Figure 4.44). The higher abundance of porpoises in the survey area of Nordergründe during summer was well represented in the model (Figure 4.44).

Table 4.18 Model parameter and GAM results for the “South” model on porpoise presence/absence.

Variable	Regression technique	Df / Edf	Chi^2	p-value
OWF presence	factor	2	8.297	0.016
year	factor	2	3.082	0.214
te(x,y, unique month)	3-D tensor spline	149.394	407.639	< 0.000
Chl.a – winter	thin plate smooth	1	0.186	0.666
Chl.a – spring	thin plate smooth	1	0.110	0.741
Chl.a – summer	thin plate smooth	1	4.744	0.029
Chl.a – autumn	thin plate smooth	3.266	7.581	0.159
SST by month	thin plate smooth	2.000	7.987	0.018
salinity	thin plate smooth	2.048	6.954	0.046
total picture area analysed	thin plate smooth	4.677	153.058	< 0.000

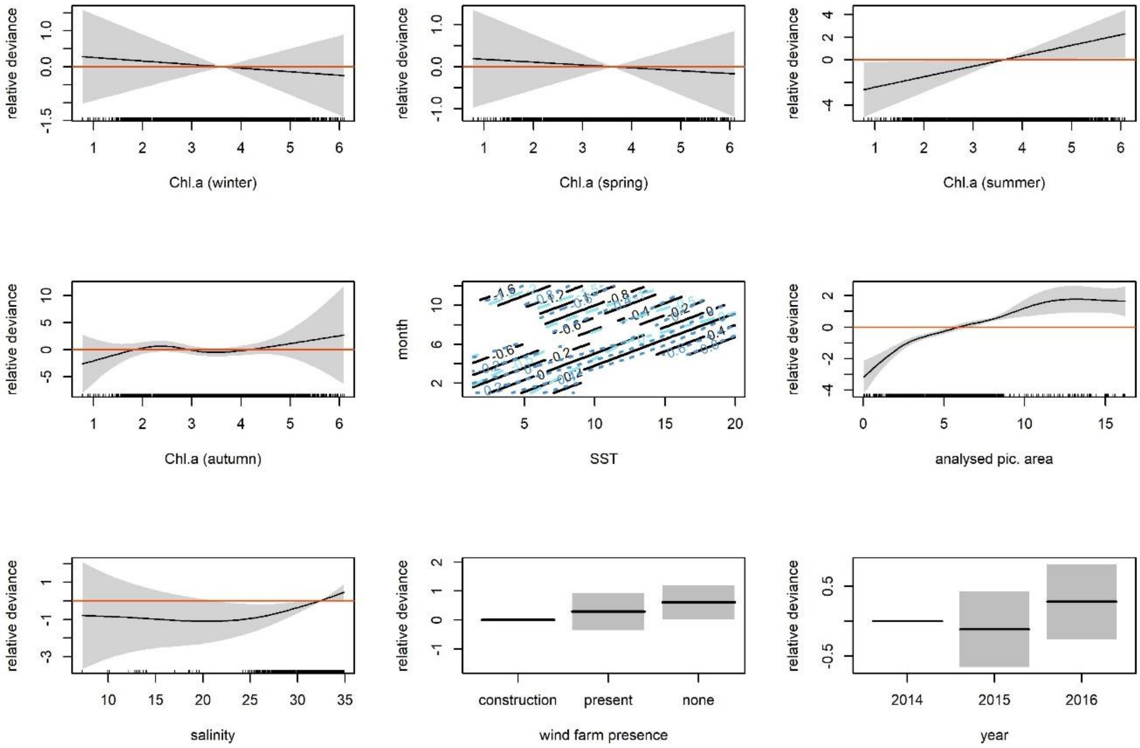


Figure 4.43 Smoothed model parameters for the "South" GAM model of porpoise presence/absence.

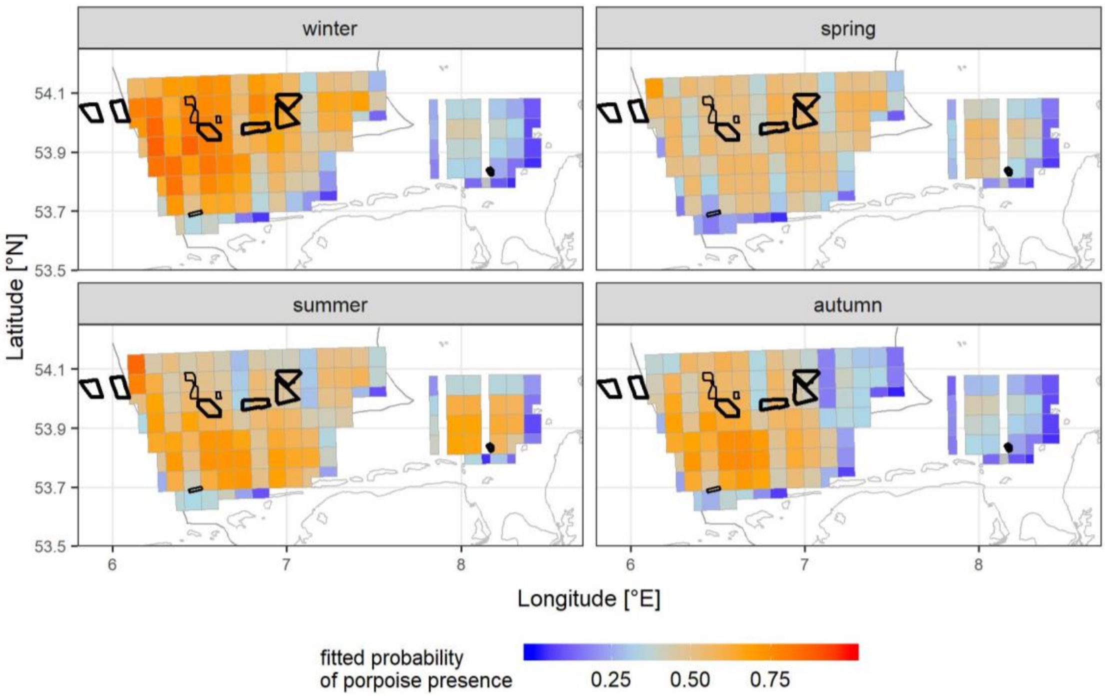


Figure 4.44 Fitted probability of porpoise presence for the "South". Existing wind farms prior to 2014 are indicated by a thin black outline, while wind farms constructed within the study period are indicated in bold.

"West" model

The best model for the subarea "West" contained the variables survey area, fish probability, and SST separated by month (Table 4.19). Year was not a significant factor in the model (Figure 4.45). The model explained 30.4 % of the deviance. The subarea "West" contains a gradient in water depth, going from 30 m to about 45 m from south to north. Fish probability was constant over time and strongly correlated with water depth (see Appendix). In the southern part of the "West", adjacent to the subarea "South", waters are less deep and fish probability is higher. Especially in spring, porpoises were abundant in this part of the subarea (Figure 4.40). The model accounted for this feature with the significant explanatory factor of fish probability, which also included a partial depth effect. Additionally, SST separated by month was included to represent oceanographic characteristics in the area.

During the study period, only few wind farms were constructed within the "West": OWF Global Tech I contributed with four piling events to the dataset; OWF Gemini was built at the border; and the construction of OWF Veja Mate was the only one with several mitigated pilings in the subarea. Hence, together with the naturally low presence of porpoises in the area, it was stochastically more difficult to model effects of wind farm construction in the "West", compared to the other subareas, and consequently wind farm construction was not significant for this model.

Like the "Northeast" subarea, the "West" consisted of several survey areas which were surveyed with different observer methods. It was necessary to account for the different survey areas within the model, yet the difference in survey effort became apparent in the model fit (Figure 4.46). Survey area was a better explanation than observer method in the model selection. The subarea "West" is generally an area with lower porpoise densities (Figure 4.40) and the model consistently fitted the probability of porpoise presence as being low, with higher probabilities in winter and spring.

Table 4.19 Model parameter and GAM results for the "West" model on porpoise presence/absence.

Variable	Regression technique	Df / Edf	Chi^2	p-value
area	factor	5	16.145	0.006
year	factor	2	6.423	0.040
te(x,y, unique month)	3-D tensor spline	11.953	257.727	< 0.000
SST by month	thin plate smooth	6.181	28.594	< 0.000
fish probability	thin plate smooth	1.210	4.466	0.046
total picture area analysed	thin plate smooth	3.343	72.839	< 0.000

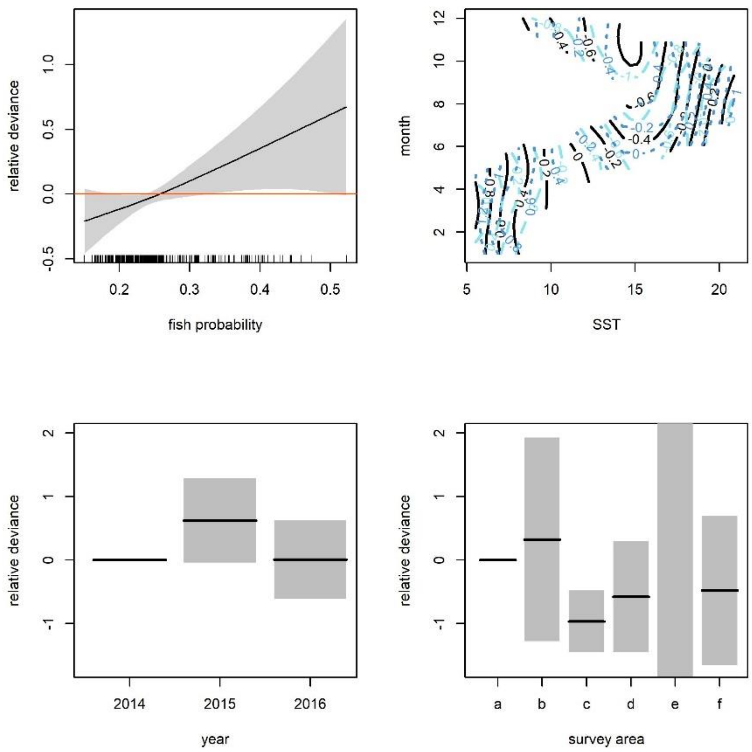


Figure 4.45 *Smoothed model parameters for the “West” GAM model of porpoise presence/absence Suvery areas are coded as: a = Cl. Östl. Austerngrund, b = Overlap of Cl. Helgoland and Cl. Östl. Austerngrund, c = Cluster 6, d = Overlap of Cluster 6 and Cl. Östl. Austerngrund, e = Overlap of Cluster 6, Cl. Östl. Austerngrund and Cl. Nördl. Borkum, and f = Overlap of Cluster 6 and Cl. Nördl. Borkum. Only one grid cell referred to survey area “e”, hence modelled deviance was calculated out of the plotting range, but lower and upper confidence interval were at -358.3 and 333.4 and mean was at -12.5.*

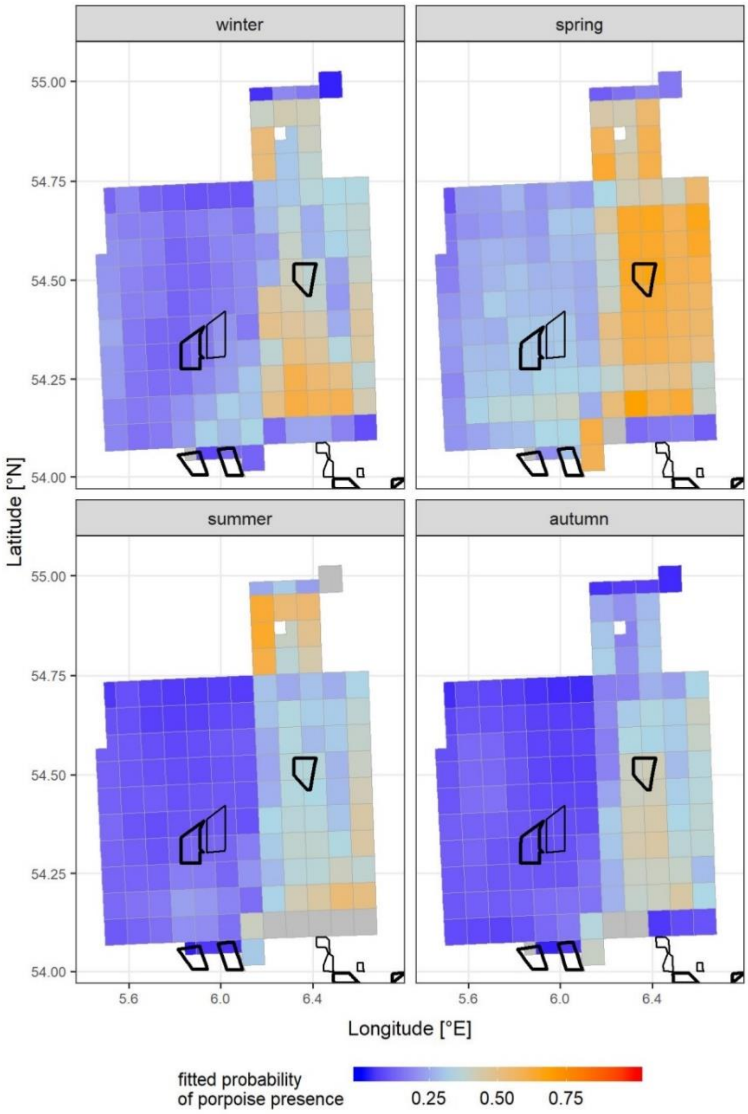


Figure 4.46 *Fitted probability of porpoise presence for the "West". Existing wind farms prior to 2014 are indicated by a thin black outline, while wind farms constructed within the study period are indicated in bold.*

4.2.3 Discussion

This chapter answers the question of WP 3.2. on the spatio-temporal reactions of porpoises to piling noise by means of digital aerial survey data. The aim was to evaluate whether the conclusions of chapter 4.1.3 based on CPOD data were supported by a different type of data. The advantage of aerial surveys to cover large areas was used to full capacity by combining seven survey areas to one large dataset over a large part of the German Bight. A disadvantage of aerial survey data is the short temporal coverage within the survey area. Aerial survey data provide only a snapshot in time with 8-10 surveys per year and region, when the timing of surveys was not synchronised between survey areas and not planned according to piling events. Hence, the CPOD dataset has a better temporal than spatial resolution, whereas for the aerial dataset it is vice versa. As the majority of surveys (74.2 %) did not take place within a week to piling, it was statistically challenging to analyse porpoise distribution with respect to piling noise based on aerial data. Still, two kinds of analysis were possible: 1) gradient analysis focussing on local and immediate effects of piling noise on porpoises; 2) large-scale GAMs assessing regional peculiarities of effects.

Gradient analysis was based on a data subset, containing only those surveys that took place within 12 h to a piling event and sufficiently covering the surrounding of the explicit piling event. Even though the dataset was reduced from 172 to 12 surveys, i. e. 7 % of the dataset, data came from three different survey areas and five different wind farm projects. This spatial and project-specific diversity in the dataset allowed for a generalisation of the conclusions of this analysis on the effect range due to piling noise in the German Bight. The non-parametric comparison showed significantly less porpoise sightings up to 7.5 km from the piling site, compared to the mean sighting rate. The consecutive GAM analysis showed that up to 7.4 km 50 % of the mean sightings occurred. The GAM results showed an effect range of 11.4-19.5 km, with a mean effect range of 14.4 km. In other words, up to 14.4 km from the piling site, porpoise sightings were below the expected average sighting rate.

Effect ranges based on aerial survey data given in the literature range from 13 km to 22 km (HAELTERS et al. 2012, 2015; DEGRAER et al. 2013; DÄHNE et al. 2013). Gescha 1 found reduced porpoise densities up to 19 km during pilling, then becoming more evenly distributed with passing time. Densities remained low up to 27 h after piling in near distances of 0-6 km to the construction site (BIOCONSULT SH et al. 2016). The methodology of Gescha 1 did not allow for comparison of noise levels between the two Gescha studies, but the 12 piling events of this study were generally below or at the 160 dB threshold at 750 m, and all piling events were noise mitigated. The above-mentioned studies in the literature, as well as Gescha 1 and Gescha 2, refer to aerial data, but with different analytical approaches. Yet, the identified effect ranges are very similar. Gescha 1 and Gescha 2 presented strong spatial reactions of porpoises to piling events up to 7 km away, and effect ranges reaching as far as 20 km. Even though the temporal resolution of the data does not allow a direct conclusion on piling noise itself, this analysis showed a strong and far-reaching avoidance radius of porpoises to the construction site caused by the entire piling event (i. e. shipping and other construction activities, deterrence measures, piling). Hence, the absence of porpoises detected by aerial surveys support the very low porpoise detections with CPODs presented in chapter 4.1, and both analytical approaches show far-reaching immediate spatial reactions of porpoises to piling events.

Whereas the gradient analysis uncovered a local spatial reaction of porpoises to piling, the large-scale GAMs should ideally show regional distribution patterns explained by piling activities. Unfortunately, the grid-based large-scale analysis suffered from strong spatial autocorrelation, which required the subdivision of the study area into the subareas “Northeast”, “South” and “West”, the modification of the spatial grid, as well as a correction for spatial autocorrelation in the GAMs. These modifications came at the cost of masking local and immediate reactions of porpoises to piling. Nevertheless, the large-scale GAMs identified a significant negative effect of the wind farm construction phase on the probability of porpoise presence. This effect was prominent for the “Northeast” and the “South”, which contributed to a significant overall effect of wind farm construction in the model, based on the entire aerial survey dataset. Hence, on a large spatial and temporal scale – as the construction phase often covers several weeks – an effect of piling was shown with aerial survey data. Yet, the complexity of the data structure requires a closer look at the methodological approach before any anthropogenic influence on porpoise distribution can be discussed.

During the study period of Gescha 1, all aerial surveys were observer flights, which facilitated the combination of survey areas into subareas. Whereas the analysis of observer-based flight data required accounting for identification skills of the observer, we now need to consider three digital observer methods (i. e. APEM, DAISI and HiDef). The methods have been compared with special focus on bird identification, highlighting differences in bird densities, but less pronounced differences in porpoise identification (MENDEL et al. 2016). Gescha 2 is the first study that combines data of these digital observer methods for the German Bight into one large dataset. Monthly survey effort was unevenly distributed over the years, creating temporal and spatial gaps in the dataset for the entire study area. These gaps were survey-area-specific (see Appendix). Apart from two exceptions (Cl. Östl. Austerngrund and DanTysk/Sandbank), all areas were surveyed with a unique method, which makes it statistically difficult to differentiate between the factors “method” and “area”. Within the GAMs for the subareas, it was necessary to correct for either method or area, while in the holistic model the factor “subarea” provided the best model fit. This may indicate that regional habitat characteristics are a stronger factor than the survey method. Figure 4.40 shows that all data of the survey areas combined produced a good picture of the seasonal porpoise distribution without sharp borders between survey areas, supporting the feasibility of combining digital aerial datasets, but also highlighting the need to correct for these regional and methodical differences in the models.

Various attempts have been presented in the literature to link porpoise distribution to environmental conditions. SST and Chl. a were important variables to explain porpoise distribution in the eastern and western Atlantic (COX et al. 2017; WINGFIELD et al. 2017), whereas especially around the UK porpoises preferred waters with certain current and tidal conditions and moderate depths (EMBLING et al. 2010; JONES et al. 2014; WAGGITT et al. 2017). In Danish waters, salinity was a good explanatory variable for porpoise distribution (EDRÉN et al. 2010). Gescha 1 referred to “depth” as explanatory variable for porpoise distribution. For Gescha 2, the environmentals SST, Chl. a, fish presence and salinity were selected as best explanatory variables regarding aerial survey data. However, it must be noted that environmental variables were often strongly inter-correlated; therefore, variables like current and depth were not selected in our models. Especially in the North Sea, the distinct depth gradient creates specific salinity and current gradients (see Appendix). The variable selection in the final GAMs therefore does not imply that other variables do not influence porpoise distribution rather than that habitat is described by a combination of oceanographic characteristics that can be represented by a set of exemplary variables.

With the temporal and spatial resolution of the analysed grid data (i. e. 7.5 km x 7.5 km cells with monthly values), environmental variables together with a spatial variance (3D tensor spline product of coordinates by unique month) described the probability of porpoise presence in the GAMs, while detailed piling variables (e. g. distance to piling, sum of piling energy) or shipping lanes were not selected. Several studies have shown impacts of vessel noise on porpoise behaviour on a small scale of a few hundred metres (e. g. HERMANNSEN et al. 2014; DYNDO et al. 2015; WISNIEWSKA et al. 2018). Thus, the absence of an effect of shipping within the presence/absence models cannot be generalised to shipping having no impact on porpoises. Individual reactions of animals to the actual passing of ships cannot be picked up with this analytical approach. Yet, the disturbance effect of wind farm construction, from first to last piling, significantly lowered the probability of porpoise presence in the near surroundings, i. e. the neighbouring grid cells, of the wind farm under construction. The analysis of CPOD data showed that porpoise detections decreased well before, during and after a piling event (chapter 4.1). It is not possible to separate the effects of actual piling activity, increased ship traffic, or high frequency of piling events during the construction phase; however, the variable “construction phase” summarises these effects in the GAMs for aerial survey data.

Spatial reaction of porpoises due to disturbance by pile driving, summarised as low porpoise probability during the construction phase, was shown on an interregional scale for the German Bight based on GAM analysis with aerial survey data. The gradient analysis further defined the effect range of about 14 km to a finer spatial resolution and linked to single piling events. Both analytical approaches support the findings on porpoise reactions to piling based on CPOD data (chapter 4.1), but focus rather on spatial than on temporal reactions. Figure 4.47 shows that CPOD data are a good representation for porpoise presence, and high detection rates overlap with high porpoise density areas. The seasonal distribution pattern found in this study is in accordance with the literature for the German Bight (GILLES et al. 2009, 2011, 2016a). With the power of combining seven survey areas to one large study area, while acknowledging the drawbacks in temporal resolution and analytical difficulties, aerial survey data supported the conclusions from CPOD data and our knowledge on disturbance of harbour porpoises by pile driving in general.

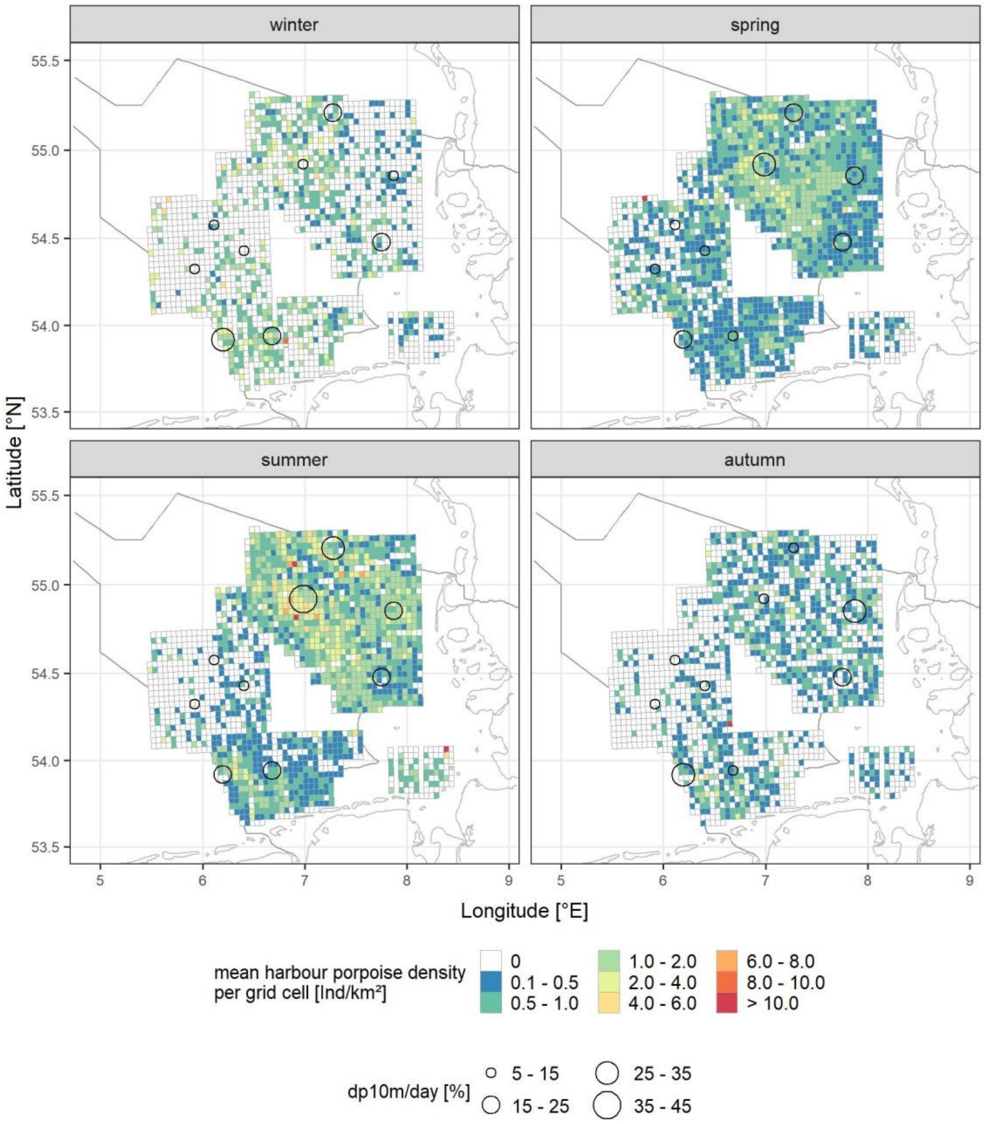


Figure 4.47 *Actual seasonal porpoise densities for the entire survey overlapping with CPOD detection rates. Circles indicate the corresponding average porpoise activity at the CPOD stations BR1, BR4, BU2, DT1, DT2, S3, S4, S8 and S10. Both datasets are pooled over the study period from 2014 to 2016.*

5 EFFICIENCY OF DETERRENCE MEASURES

WP 4.1 – Efficiency of deterrence measures (data of mobile CPODs)

Before pile driving, marine mammals must be scared away to protect them from physiological damages from piling noise. Therefore, two deterrence devices were applied before each piling event (except for OWF Gemini where a FaunaGuard was used): the pinger and the seal scarer.

Pingers, originally developed to scare animals away from gill nets (COX et al. 2001; CULIK et al. 2001; CARLSTRÖM et al. 2009), emit a randomised structure of acoustic signals between 20 kHz and 120 kHz. Noise levels range from 130 to 150 dB (e. g. for Banana Pingers by Fishtek marine) which, in connection with the higher frequency, means that the range of the displacement effect of pingers is only a few hundred metres.

Seal scarers were developed to scare seals away from fish farms. They use irregular and random burst signals with frequencies between 13.5 kHz and 15 kHz, with noise levels of >160 dB@10m (e. g. Lofitech seal scarer; Table 3.3).

The lower frequency, in connection with the high noise levels, leads to a much larger area affected by a seal scarer compared to a pinger (JOHNSTON 2002; OLESIUK et al. 2002). Effects of seal scarers on porpoises were found in distances of up to 7.5 km (BRANDT et al. 2013a).

In order to deter porpoises from the close vicinity of the construction site and to protect them from construction noise, 40 minutes before piling the pinger is activated. 10 minutes later, the seal scarer is activated to ensure a displacement from porpoises in a radius of about 750 m to the construction site. To reduce the risk of a permanent threshold shift (PTS), which describes physical damage of the hearing capability of the animals, the piling noise is required not to exceed 160 dB within 750 m to the piling site (BSH 2013).

The efficiency of the deterrence, the so called efficiency control, has to be monitored by two randomly deployed CPODS (BSH 2013): one in a distance of 750 m, the other one in a distance of 1500 m to the piling site. As those CPODs are relocated for each piling location, they are called "mobile" CPODs. These devices are normally deployed up to a few hours before each piling event and recovered some minutes to hours after piling. They therefore only record porpoise vocalisations in close vicinity to the piling site during the piling phase itself, the deterrence phase, and a relatively short phase before and after piling.

In this chapter we analysed data from mobile CPODs deployed for the efficiency controls to answer the question whether deterrence measures are adequate to displace harbour porpoises sufficiently from the vicinity of piling (corresponds to "WP 4: Efficiency of deterrence measures" of the tender). Additionally, we compare displacement effects during deterrence and piling. For the analyses, we chose the seal scarer phase as representative for the deterrence phase, since seal scarer effects are supposed to be more pronounced than the effects of pingers.

5.1 Methods

5.1.1 Dataset preparation

This section is based on the mobile CPOD data used for the efficiency control during piling. CPODs were placed at distances of 750 m and 1500 m to the construction site and collected data from deployment, usually a few hours before the start of the deterrence (“before” phase) until the recovery, usually a few hours after pile driving has stopped (“after” phase). Since there are no binding specifications of how much time before and after disturbance data needs to be collected, the recording periods depend on the installation schedule and are specific to the project and piling event. The reason is, that device handling is limited to vessels, which are mostly integrated in construction logistics. Data were available for the following projects: Amrumbank West, Butendiek, Global Tech 1, Nordsee One, Nordergründe, Sandbank and Veja Mate. A graphical overview of porpoise detections for each project used in the analysis is given in the Appendix. Mobile CPOD data of the other projects within Gescha 2 were not available for this analysis.

The dataset of piling events (Table 3.3) was aligned with the CPOD recordings. For a better separation of phase effects and to avoid any overlap of phases, a 10 min gap between one phase to the next was cut out of the dataset (Figure 5.1). Instead of shortening the already shorter “seal scarer” phase, the 10 min prior to seal scarer activation were cut out of the “before” phase. Respectively, the 10 min gap was taken out of the “after” phase instead of the “piling phase”. In order to receive comparable recording time periods between piling events, the recording time in the “before” and “after” phase was limited to a maximum of 3 h. If the recording time was less than 3 h, the total available recording time was analysed. In any case 20 minutes of the dataset after deployment and before collection of the equipment was discarded, to rule out disturbance effects caused by the service ship. The seal scarer activation and deactivation times were reported within the provided noise mitigation protocols from the respective OWF project. No other information on seal scarer activity (e.g. acoustic detection on hydrophone logs) was available. Hence activation and deactivation times of seal scarer were extracted from the protocols and used to define the deterrence phase. It was assumed, that seal scarers worked properly once they were activated. Piling start and end times were taken from log files from the installation ship. If piling started within the duration of deterrence, the start time of piling was still considered as piling start, but at the same time implied the end of deterrence. Especially in such cases, the 10 min gap was important to separate the overlapping phases. The logged piling end was considered as beginning of the “after” phase.

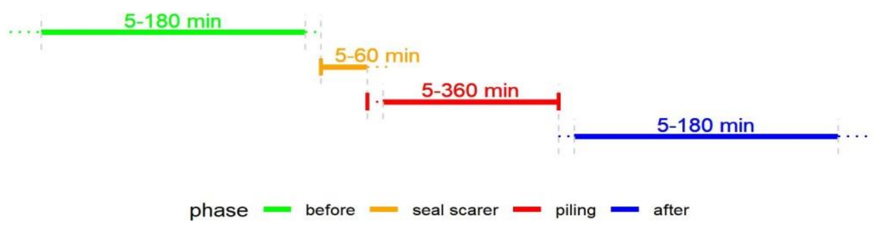


Figure 5.1 Definition of phases before piling (“before”), during seal scarer deterrence (“seal scarer”), piling activity (“piling”) and after piling (“after”). All phases were separated by 10 min (grey, dotted line). “Before” and “after” phase was taken up to a duration of 180 min. Piling might have started within the seal scarer phase (yellow); then, piling start implied the end of deterrence.

Some of the piling events had unusually long or short phases, e. g. a very long piling phase due to technical difficulties, or very short piling phase because of re-piling. Hence, piling events were excluded if they did not meet the following criteria: 1. “seal scarer” phase of 5-60 min, and 2. “piling” phase of 5-360 min. If recordings, however, ended within the “piling” phase due to CPOD malfunction, or the “before” phase was shorter than 5 min (due short recording times and the above described cutting process), these phases were excluded from the analysis, but the piling event itself with the remaining complete phases was still considered in the analysis. The dataset for the two distances might differ because of CPOD failure at one distance but not at the other for the same piling event.

For all phases of a piling event, two response parameters were calculated. The first parameter, detection-positive minutes per minute of phase (dpm/min), was used to get an overview of porpoise detection by phase in respect to phase duration, e. g. 0.2 dpm/min equal to 36 minutes with porpoise detections within 180 min phase duration. The second parameter, detection-positive block per 10 min of phase, was only used within the linear mixed model (see below). Here, a binary sequence was created for each phase, by splitting phase duration into 10 min blocks starting from the phase start until the phase end. Respectively, the last 10 min block might have been shorter than 10 min. A block with at least one porpoise detection was given the value 1, while a 10 min block without porpoise detection was given the value 0. Often a detection minute was followed by consecutive detection minutes (see Appendix). Hence, the binary aspect helped to structure the zero-inflated dataset via keeping the zeros and considering a sequence of detections, which might correspond to the same animal as one detection irrespective of the number of detections.

5.1.2 Statistical analysis

First, boxplots were used to visualise porpoise detections by phase and distance. Data were pooled from all projects. Then, the binary data of 10 min blocks with and without porpoise presence were analysed using a Generalized Linear Mixed-Effects Model (GLMM). A GLMM considers both fixed effects as well as random effects. The function *glmmPQL* within the package MASS was used within the statistical software R (version 3.5.2; R CORE TEAM 2018). The GLMM was conducted to explain the presence or absence (1 or 0) of porpoises within a 10 min block of a phase and the fixed factors of “phase” (before, seal scarer, piling and after) and “project” (ABW, BU, N1, NG, SB, VM). A random effect was included, based on piling event. Acting on the assumption that porpoises are more likely to be detected in a 10 min block when they were already present during the previous 10 min, a correlation was included into the model that considers the presence or absence of porpoises within the previous six 10 min blocks (i. e. previous hour), irrespective of the phase. Therefore, the model takes into account if porpoises were present before deterrence and piling, it is more likely that porpoises will be detected in another phase, and equally, if no porpoises were present during a phase, it is less likely that animals will be detected later-on. The model was fitted according to the penalised quasi-likelihood.

Significant differences between phases were tested following a multiple comparison of means based on Tukey Contrasts (function *glht* of the package multcomp). Significance was defined as a p-value <= 0.05. The different odds ratios of registering a porpoise detection were calculated for each phase and compared to each other. Odds ratios were extracted from the *glht* results output.

Odds compare the probability of detecting a porpoise with the probability of not detecting a porpoise. A value < 1 indicates that the probability of not detecting a porpoise is higher than detecting the animals. This analysis does not present the actual probability of detection, but the results present a comparison of odds between phases. Phase and odds comparisons were based on the full dataset and did not differentiate between single projects.

5.2 Results

Detection-positive minutes/minute (dpm/min) at 750 m were close to zero during all phases (Figure 5.2). This indicated, that only very few porpoises were present at this distance to the construction site during piling events. At 1500 m all phases showed higher dpm/min values with the exception of the “seal scarer” phase (Figure 5.2). Table 5.1 gives the respective mean dpm/min values with standard deviation. Because of the small variance to zero in all phases, it was not possible to fit a GLMM to the data of 750 m, so the following results include only data collected at 1500 m distance. No further analysis for the CPOD dataset at 750 m was feasible.

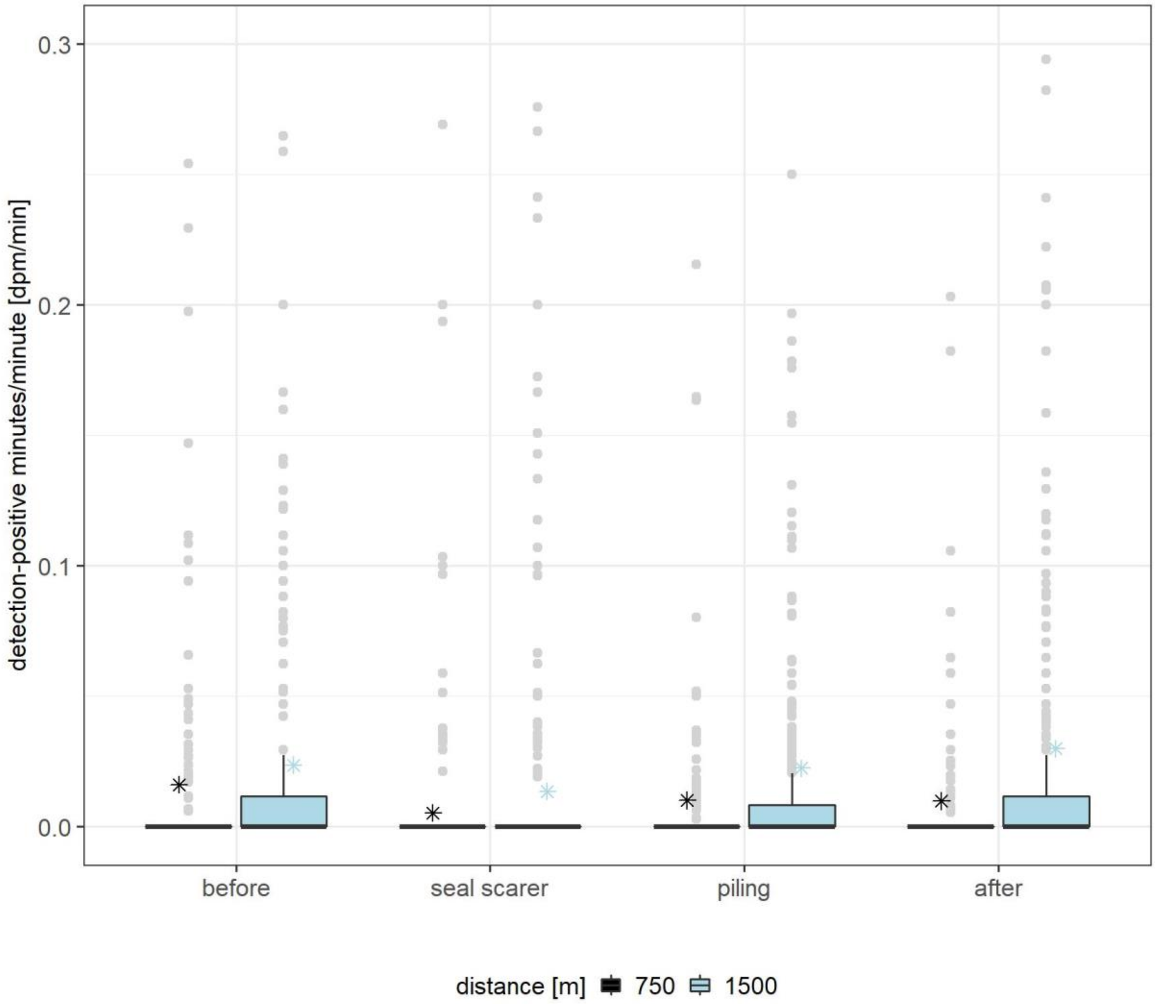


Figure 5.2 *Detection-positive minutes per minute (dpm/min) for the four phases of a piling event and at a distance of 750 m (black) and 1500 m (blue) to the construction site. Outlier values are displayed in grey. Outliers > 0.3 have been excluded to facilitate depiction. Mean values are indicated by a coloured asterisk.*

Table 5.1 *Mean detection-positive minutes/minute (ø dpm/min) with standard deviation (SD) for the four phases of a piling event and by distance to the construction site for all projects pooled.*

Distance	Before phase (ø dpm/min ±SD)	Seal scarer phase (ø dpm/min ±SD)	Piling phase (ø dpm/min ±SD)	After phase (ø dpm/min ±SD)
750 m	0.0087 ±0.0296	0.0055 ±0.0307	0.0047 ±0.0200	0.0050 ±0.0205
1500 m	0.0231 ±0.0725	0.0169 ±0.0654	0.0157 ±0.0502	0.0242 ±0.0582

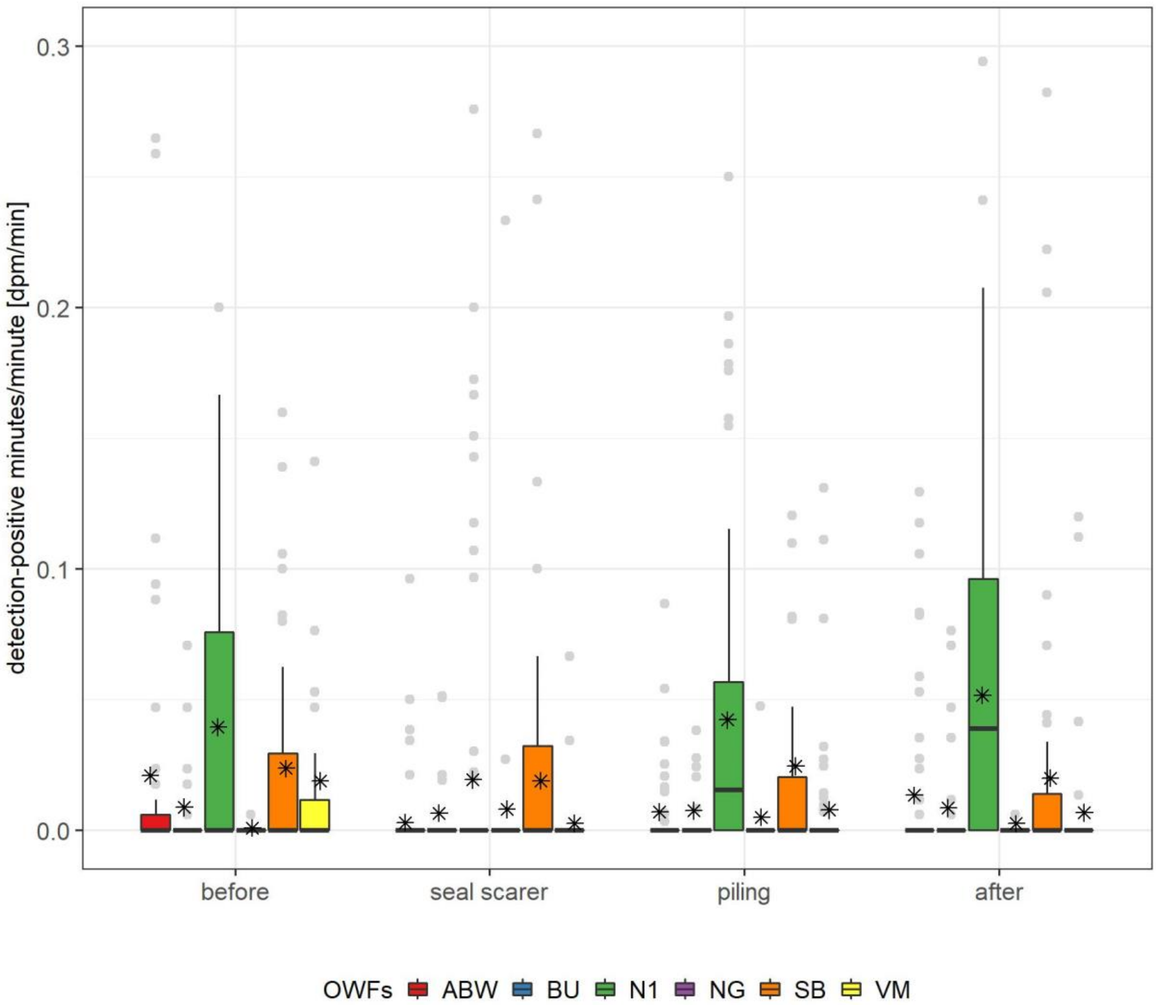


Figure 5.3 *Boxplot of detection-positive minutes per minute (dpm/min) for the four phases of a piling event at 1500 m by project. Outlier values are indicated in grey. Outliers > 0.3 have been excluded to facilitate perceptibility. Mean values are indicated by an asterisk (black).*

Table 5.2 Mean detection-positive minutes/minute (ø dpm/min) with standard deviation (SD) at 1500 m for the four phases of a piling event and per project.

Project	Before phase (ø dpm/min ±SD)	Seal scarer phase (ø dpm/min ±SD)	Piling phase (ø dpm/min ±SD)	After phase (ø dpm/min ±SD)
ABW	0.0205 ±0.0586	0.0036 ±0.0146	0.0045 ±0.0141	0.0124 ±0.0309
BU	0.0045 ±0.0134	0.0031 ±0.0112	0.0026 ±0.0081	0.0059 ±0.0170
N1	0.0709 ±0.1303	0.0500 ±0.1219	0.0563 ±0.1042	0.0741 ±0.0940
NG	0.0003 ±0.0014	0.0145 ±0.0550	0.0026 ±0.0112	0.0004 ±0.0016
SB	0.0377 ±0.1055	0.0316 ±0.0801	0.0160 ±0.0275	0.0215 ±0.0557
VM	0.0107 ±0.0239	0.0021 ±0.0102	0.0075 ±0.0238	0.0080 ±0.0276

The dataset collected at 1500 m consisted of 302 piling events which corresponded to the projects as follows: 67 to ABW, 46 to BU, 52 to N1, 18 to NG, 55 to SB and 64 to VM. The distribution of phase durations is given in the Appendix. At 1500 m and for all phases, project specific differences in dpm/min were apparent (Figure 5.3), ranging from close to zero up to 0.074 dpm/min at N1 during the “after phase” (Table 5.2). Therefore, “project” was added as a fixed factor within the GLMM to explain porpoise presence in a phase. Table 5.3 gives the model statistics for the fixed factors in the GLMM. The model statistics showed a negative slope for the “seal scarer” as well as the “piling” phase, and a less steep but still negative slope for the “after” phase. This indicates, that porpoise presence decreased from the “before” phase during all following phases, but strongest during the “seal scarer” and “piling” phase. It is not possible to calculate a typical R^2 value in GLMM as a measure of the goodness of the fit like in ordinary linear models due to the iteration processes in model fitting. Hence, the most important explanatory power of a GLMM is the effect size, i. e. the slope of the GLMM shown as value in Table 5.3.

The “seal scarer” phase and the “piling” phase were significantly different to the “before” phase, but not significantly different to each other (Figure 5.4). The following phases differed significantly in porpoise detections: 1. fewer detections during the “seal scarer” phase compared to “before”; 2. fewer detections during the “piling” phase compared to “before”; and 3. more detections in the “after” phase than during piling. The presence of porpoise detections 3 h prior to disturbance was not significantly different to the detections up to 3 h after disturbance. The respective statistical results are presented in the Appendix.

Table 5.3 Model statistics for the fixed factors "phase" and "project" within the GLMM. Significant fixed effects are indicated in bold (p < 0.05).

Effect	Value	Std. error	DF	P-value
intercept	**-3.365552**	**0.1974662**	**13248**	**0.0000**
seal scarer phase	**-0.443116**	**0.1490012**	**13248**	**0.0029**
piling phase	**-0.528131**	**0.1203697**	**13248**	**0.0000**
after phase	-0.209687	0.1183967	13248	0.0766
BU	-0.459376	0.3104033	296	0.1400
N1	**1.927948**	**0.2570858**	**296**	**0.0000**
NG	**-1.229244**	**0.5634757**	**296**	**0.0299**
SB	**0.928995**	**0.2634046**	**296**	**0.0005**
VM	0.050292	0.2763883	296	0.8557

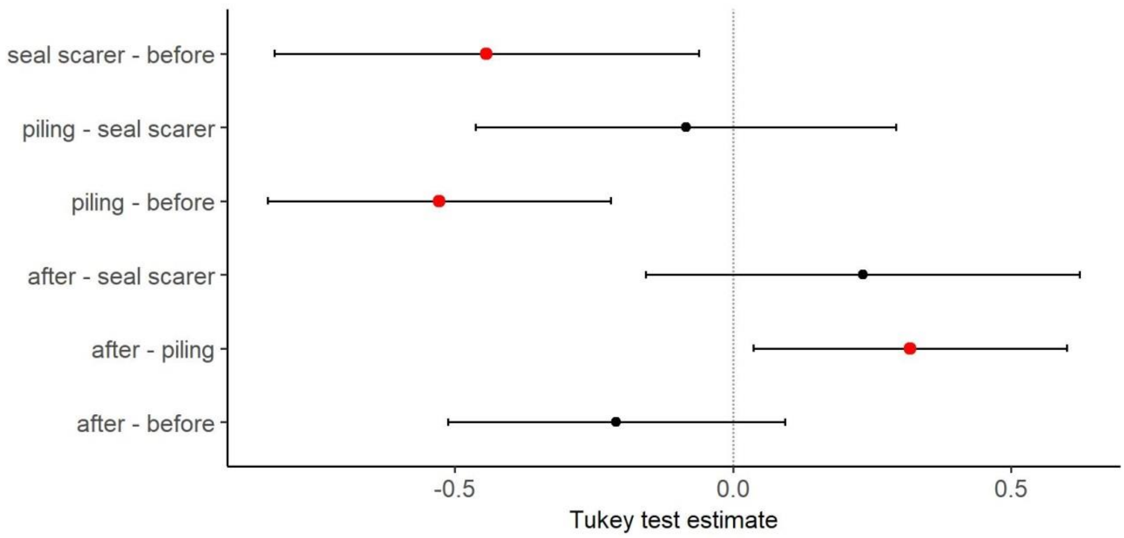


Figure 5.4 Simultaneous test-statistics for Tukey's all-pairwise comparison of phases. Significant different phases are indicated in red (p < 0.05). Values < 0 indicate less porpoise detections in the first to the second phase, while values > 0 indicate more detections in the first compared to the second phase.

It must be noted, that the values given do not represent the actual odds of detecting porpoises in a phase, but how much the odds differ from each other. Significantly different odds ratios were found for: 1. “seal scarer” to “before”; 2. “piling” to “before”; and 3. “after” to “piling” (Figure 5.5). With reference to Figure 5.5 the probability of detecting porpoises during the “seal scarer” phase was 64 % of the detection probability during the “before” phase, i. e. a reduction of 36 % from the “before” to “seal scarer” phase. Likewise, the probability of detecting porpoises during piling was 59 % of the detection probability during the “before” phase, i. e. a reduction of 41 % from “before” to “piling”. The probability of detection during the “after” phase was 137 % compared to the detection probability during piling. This equals a 37 % higher detection probability after the disturbance. The probability of detecting porpoises during the “seal scarer” phase was not significantly different to the probability of detecting porpoises during piling (93 %). Even though the probability of detecting porpoises after piling was lower compared to the “before” phase, the reduction of 19 % was not significant. The respective statistical results are presented in the Appendix.

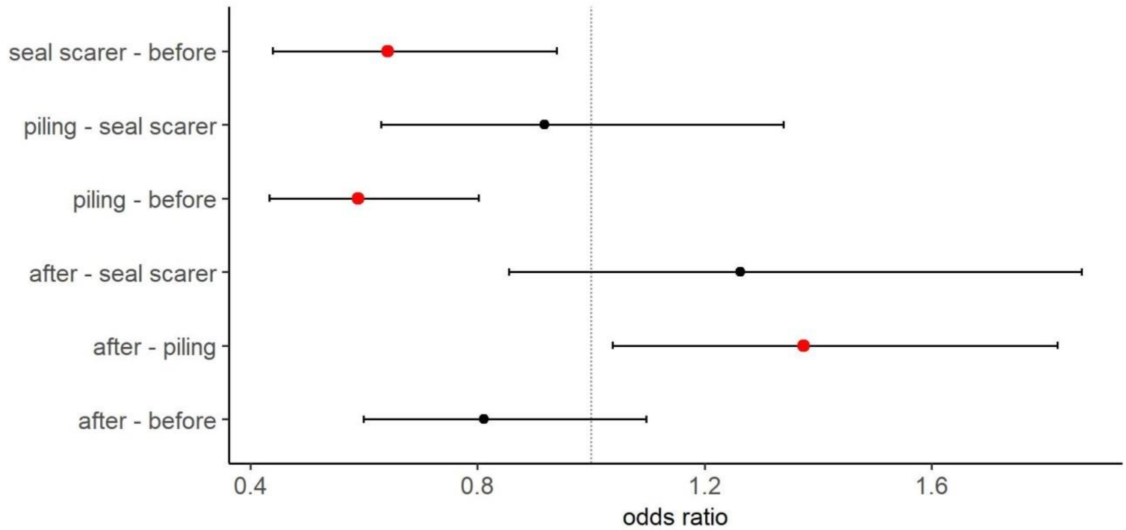


Figure 5.5 Comparison of the odds ratio between phases. Significant different phases are indicated in red ($p < 0.05$). Values < 1 indicate a smaller odd of detecting porpoises in the first phase compared to the second phase, while values > 1 indicate a higher odds ratio of the first compared to the second phase.

5.3 Discussion

Studies like BRANDT et al. (2012), HAELTERS et al. (2015), and BIOCONSULT SH et al. (2016) (among others) showed that fewer porpoise detections in relation to piling activities are not due to a change in vocal behaviour of porpoises, but are caused by animals avoiding the wider area of disturbance. CPODs can only record clicks directed towards the hydrophone within a range of a few 100 metres. Nevertheless, due to the positive relation between number of detections and abundance of porpoises, CPODs are a valid measurement of porpoise presence and relative abundance in close vicinity of the monitoring location. Seal scarers and other deterrence devices are applied to displace the animals from a potentially harmful area, the surrounding of a pile driving event. To meet this purpose the devices have a high degree of efficiency at close range but should not have an effect far beyond the area in which the animals do not suffer any physical damage. This ensures that animals can be displaced from the potentially harmful area but avoids too much additional stress on the animal due to temporary habitat loss. From Brandt et al. (2013b) it is known that seal scarer can lead to displacements of porpoises up to distances of 7.5 km.

Since all piling events used within this analysis were carried out with activated noise mitigation the sound exposure level at 1500 m was below the given German noise threshold of 160 dB (SEL_{05} at 750 m) (Figure 5.6). Each project belongs to a different management cluster (i. e., Cluster Helgoland, Butendiek, Cluster Nördlich Borkum, Nordergründe, DanTysk/Sandbank and Cluster 6) and porpoise abundance could differ by project due to different distribution of the animals within the German Bight. These differences are accounted for in this analysis by integrating "project" as fixed explaining factor into the GLMM. While the other chapters of this study describe the far-reaching disturbance effect and project specific differences, the strength of this analysis is to generalise seal scarer disturbance effects during wind farm construction.

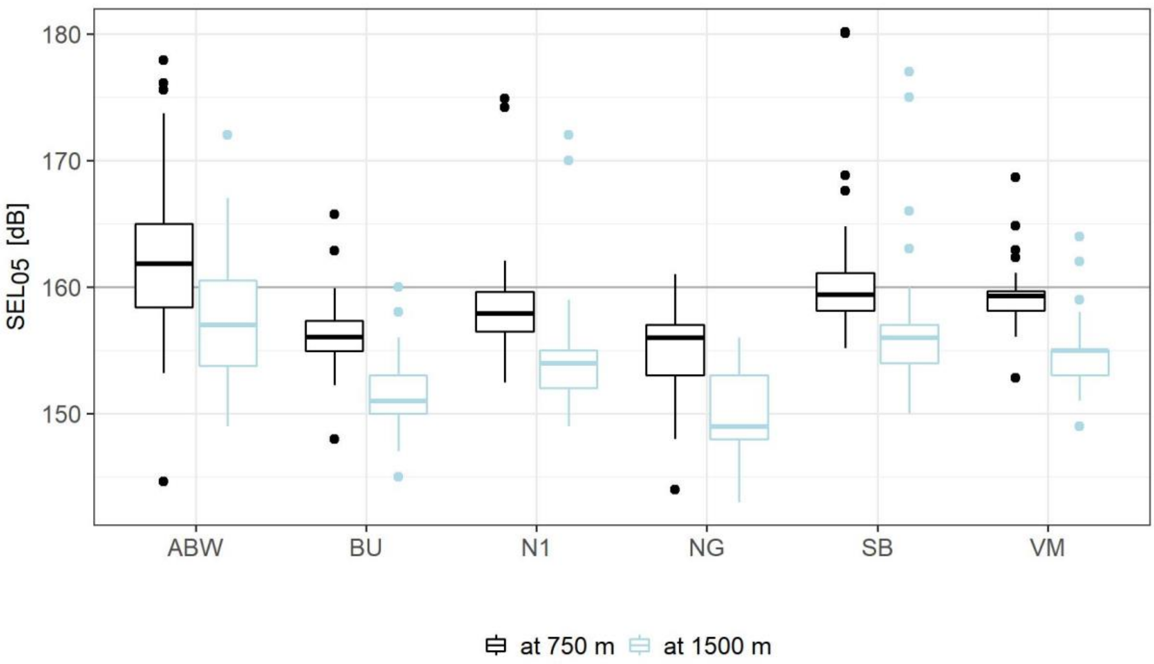


Figure 5.6 *SEL_{05} at 750 m (black) and 1500 m (light blue) distance to the construction site. The legal threshold of 160 dB re 1 µPa^2s at 750 m is indicated by a grey line.*

In all phases, before, during and after a piling event, porpoises avoided the near surroundings of the construction site (Figure 5.2). The topic of this chapter was to investigate the deterrence impact on harbour porpoises from the vicinity of piling events. Based on the available dataset on seal scarer activation and deactivation times, we assume that all deployed and activated seal scarers were working correctly. So we assume that seal scarer were well functioning within the defined deterrence phase. Porpoise deterrence from the vicinity of piling events was especially noticeable from the CPOD dataset at 750 m where the porpoise detection rate was close to zero during all phases. It has to be emphasised that even before the activation of the scaring devices at 750 m distance considerably fewer detections occurred than at a distance of 1500 m to the construction site. This is in line with outcomes from Gescha 1 that already before the start of seal scarer activity porpoises seem to leave the vicinity of the piling location up to distances of several kilometres (BIOCONSULT SH et al. 2016). Similarily, Chapter 4.1 showed that porpoise detection already decreased before deterrence and piling. Bases on the data limitation in close vicinity to the piling site, we defined the 3 h prior to deterrence as a baseline period. Even if the first 20 min were excluded from the dataset to minimise disturbance effects during CPOD deployment, the 3 h before a piling event do not represent a quiet, undisturbed baseline. Here, additionally an unintended displacement effect seems to have occurred, which probably was caused by preparations around the construction site such as increased shipping intensity.

Several studies have already presented a deterrence effect by the seal scarer on harbour porpoises (e. g. BRANDT et al. 2012, 2013a; DÄHNE et al. 2017a; MIKKELSEN et al. 2017). These studies found a far-reaching deterrence effect up to several km from the piling site. In an experimental setup without piling disturbance BRANDT et al. (2013a) found strong deterrence effects at 750 m and at farther distances. DÄHNE et al. (2017a), without looking at close distances up to 1500 m, detected the largest decrease in porpoise activity at 1.5-3 km during the seal scarer phase for the construction of DanTysk. Even though methodological differences hinder a detailed comparison between this study and the literature, we found a strong deterrence effect of seal scarer activity and piling at 750 m and 1500 m distance to the piling site as well.

In the "before" phase, porpoise detection rates were already low (see Chapter 4.1 and Figure 5.2) and then further decreased during seal scarer activity and piling. Although a 10 min buffer was used to ease the separation of effects by avoiding phase overlap, no significant difference between the effect of the seal scarer and the effect of piling was shown. The effect size was similar for both phases. The odds of detection decreased to 58-64 % of the odds "before" (Figure 5.5). Seal scarer frequencies are well within the hearing window of porpoises. This implies a general disturbance effect on the animals, but individual behaviour may still differ. Here, as in other studies (e. g. BRANDT et al. 2013a; DÄHNE et al. 2017a; MIKKELSEN et al. 2017)), seal scarer activity did not deter all porpoises, but deterrence was close to 100 % at 750 m distance and still strong at 1500 m. A clear overall and general disturbance effect on porpoise abundance during piling events was found. At 1500 m to the piling site, noise mitigated piling activity did not have a significantly larger effect on porpoise detection rates than seal scarer deterrence.

In conclusion, mobile CPODs provided useful data to detect short-term and close-range effects on porpoise activity during piling events. No analysis could be done for data collected at 750 m, because in the periods before, but especially during seal scarer activity and piling, porpoise activity was close to zero. Even though seal scarer efficiency was not 100 %, only very few animals could have been at risk of potentially suffering from TTS/PTS due to the general compliance of the noise level threshold at 750 m. This is especially so since CPODs detect porpoises in a radius of up to 300 m, which means that recorded porpoises can be in distances of 1000 m from the construction site. At 1500 m, seal scarer activity and piling caused a drop in porpoise detection from an already low baseline prior to the piling event. Not all animals were deterred from the area farther away than 1500 m, or animals already return to the area during the "piling" phase after being deterred farther away, but in any case, at this distance the noise level was below the legal threshold. By analysing 302 piling events within the German Bight between 2014 and 2016, a marked deterrence effect of at least 1500 m was found before the start of a piling event. Seal scarer activity was effective in deterring porpoises at least 1500 m away from the construction site. This displacement lasted at least up to 3 h after piling stopped.

6 POPULATION-LEVEL EFFECTS OF PILING NOISE ON PORPOISES

WP 5.1 – Population-level effects of pile driving

In contrast to the hourly dataset, the reduced temporal resolution of the daily POD dataset is well suited to estimate “long term trends” of harbour porpoise detections. In this chapter, we therefore focus on the development of harbour porpoise detections in the German Bight over the study periods of Gescha 1 and Gescha 2 (2010 to 2016).

6.1 Methods

6.1.1 Daily POD data

Since we analyse the combined dataset from both the first (Gescha 1: 2010-2013) and the second report phase (Gescha 2: 2014-2016), data preparation was the same in both projects to ensure comparable results and a consistent dataset.

The general principle of POD deployment is covered in detail in chapter 3.4. Data from two different stationary POD deployment designs, POD stations and single stationary PODs, were used to record porpoise clicks. For single stationary PODs only one POD is deployed at a monitoring position, whereas for POD stations three PODs are deployed simultaneously. Multiple PODs monitoring simultaneously at one location can compensate occasional loss or malfunction of devices. To remove the resulting but unwanted redundancy from our dataset, only the POD with the longest time series of data was chosen. Gaps in the data series were filled with available data from another POD at the same station.

Data from mobile PODs were excluded, as they normally only cover the time of piling and a short period before and afterwards. Therefore, the entire recording phase is strongly influenced by pile driving activity or related construction work masking population trends which would be the focus of this chapter. These data are evaluated in chapter 5.

Data for the nearshore wind farm Nordergründe was collected between April and December 2016 (one single POD continuously until December and further PODs until July 2016). PODs were deployed in shallow waters and click recordings are heavily influenced by other noise sources with a similar click characteristic such as noise emission from sand in suspension or crustaceans. As data for this wind farm was collected only during a short time period and had different characteristics compared to all other POD locations, data from these stations were discarded from further analyses.

Excluding Nordergründe, there were data from 130 other stationary POD locations (see Figure 6.1).

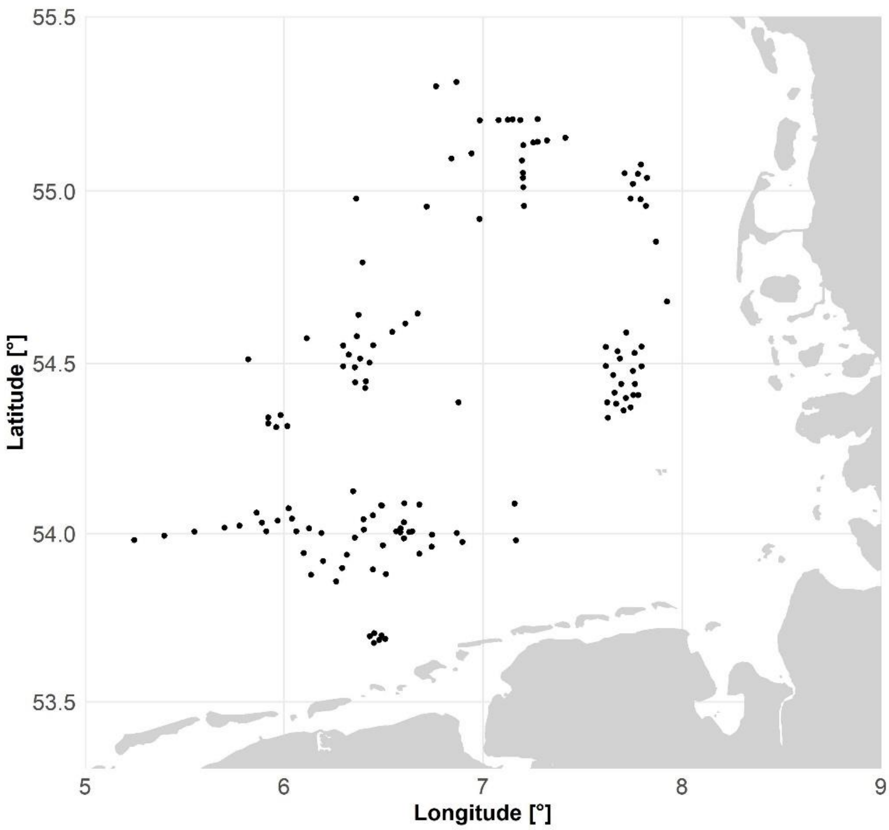


Figure 6.1 Position of single PODs and POD stations used for analyses of daily POD data from 2010 to 2016.

PODs record all kinds of noise within a specific frequency band and with a certain click or rather impulsive characteristic. Besides porpoises, noise fulfilling such criteria can originate from environmental noise like crustaceans and sediment movement as well as from human activities or the mooring of the POD. All clicks recorded are summed up by time in the variable "all clicks". Later, those clicks are assigned to their most likely sonic source, porpoise, sonar or environmental noise, by evaluating the specific click characteristics and temporal sequence of clicks. Furthermore, a category (doubtful, low, medium or high) for the quality of the sonic source identification is given.

Only porpoise click data classified as medium or high were used for creating the response variable detection positive 10 minutes (dp10m) per day. The detection rate dp10m per day is determined by assigning every one of the 144 possible 10-minutes blocks per day a 1 or a 0 (porpoise present yes or no) leading to a maximum value of 144 dp10m/day. It is therefore crucial to avoid any bias caused by diurnal activity patterns of porpoises, and therefore only complete days with 144 of the 10-minutes blocks of data were used. Days when PODs had not recorded the entire day (e. g. because of deployment or recovery) were discarded because not only was the covered time per day shorter than on other days but also the porpoise activity was influenced by the vessel and service work at the POD position.

During Gescha 1, the variable "all clicks" was identified as an important explanatory variable due to its strong correlation with the number of porpoise detections. This is also the case in the current study (see also chapter 4.1). For stationary CPODs, a limit was set for the number of clicks that can be detected per minute. This click limit was set at 4,096 clicks per minute. The maximum number of recorded clicks per day should therefore not exceed 5,859,360 total clicks per day (4,096*60 minutes*24 hours). If this limit was exceeded by more than 1 %, it indicated deviating settings (no click limit resulted in a maximum 23 million total clicks: less than 0.1 % of the data) and those data were excluded. Figure 6.2 illustrates the relationship between all clicks and the number of detected porpoises for the daily dataset. The variable “all clicks” includes both clicks of porpoises as well as environmental or anthropogenic noise. Therefore, two different effects act on the relationship “number of all clicks” and “number of porpoises detected”: 1) If no clicks were detected there was also no detection of porpoise clicks, and 2) if too much environmental noise was recorded it became more difficult to identify porpoise clicks as they were masked by noise or because porpoises could not be detected if they were present after the click limit was reached. As we only wanted to correct for the technical limitations, the number of all clicks was set to a minimum value of $2.5*10^5$ clicks per day. This was applied to 53.13 % of the data. If the number of all clicks became too large, the technical limitations noticeably influenced the detected porpoise activity. If the click limit was reached in every minute of a day, the maximum number of clicks would be 5,898,240 clicks per day. In this study, we applied the same limit as in the preceding study: All data with a noise level of more than 5,160,000 clicks per day (right vertical line Figure 6.2) were excluded. This criterion fit 1.91 % of all data. Therefore, from the remaining 98.09 % of data 53.13 % showed no technical influence of environmental noise on porpoise detections, whereas in 44.95 % of data, an effect of environmental noise on porpoise detections is visible but was considered acceptable for further analyses.

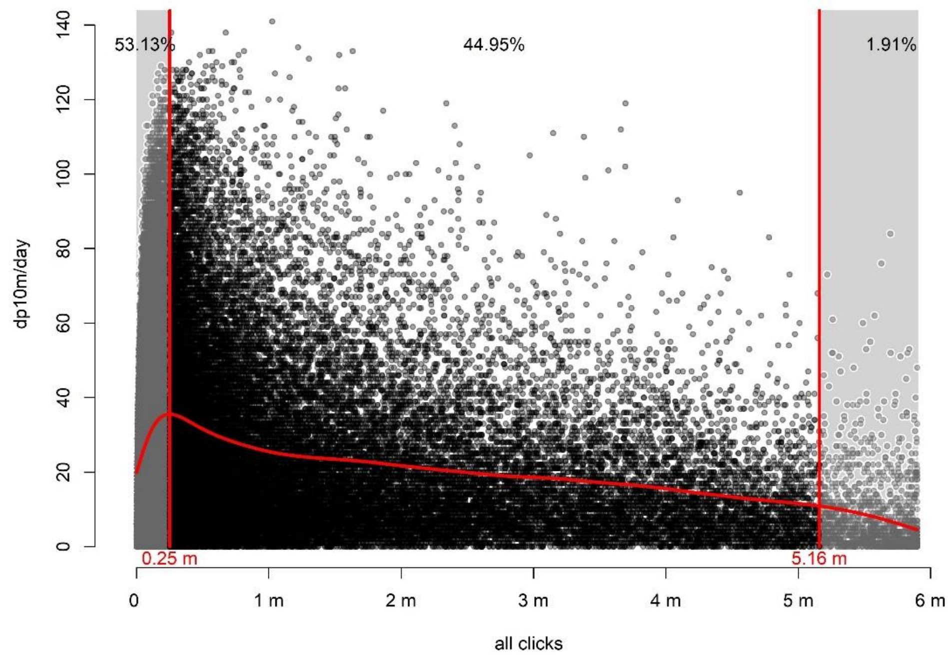


Figure 6.2 Detection positive ten minutes per day in relation to the total number of clicks detected. The red line visualises a smoothed spline fitted to the data whose characteristic were used to determine the limit with maximal porpoise detection rate (left vertical red line) and the limit above which data shall be discarded (right vertical red line) in the future. For details of data treatment below and above red lines see text.

6.1.2 Piling data

Every pile-driving event that occurred in the German Bight in the study period 2010 to 2016 was considered in our analyses. General processing of pile driving data is described in chapter 3.2. Our study covers almost the entire construction phase of wind turbines in the German Bight from its very beginnings until 2016. Only the OWF alpha ventus, comprising twelve wind turbines, was erected in 2009 before this study starts. Even though porpoise data from Nordergründe was excluded, piling events were included. Additional to piling in the German EEZ, the construction of the two Gemini wind farms in the Dutch North Sea were also included, as the eastern parts of these wind farms lie in close proximity to the German border. Data from Danish wind farm construction was not available for this study. However, the wind farms Horns Rev 1 and Horns Rev 2, which at ca. 36 km and ca. 41 km are closest to the German border, were already built in 2002 and 2008/2009 before our study started. Construction for Horns Rev 3 started in 2017 and therefore were within the time range of our study data neither.

A piling event was only defined as a single piling event if continuous piling activities took place with breaks of less than three hours. So, there can be multiple piling events at a single piling location even if the foundation was a monopile. Additionally, for tripods, jackets or platforms, three or more fundaments had to be installed at one geographic location. Therefore, the number of piling events exceeded the number of piling locations. In this study, we analysed 1,350 piling events from 1,160 locations (wind turbine foundations or OSS stations) in 18 wind farms.

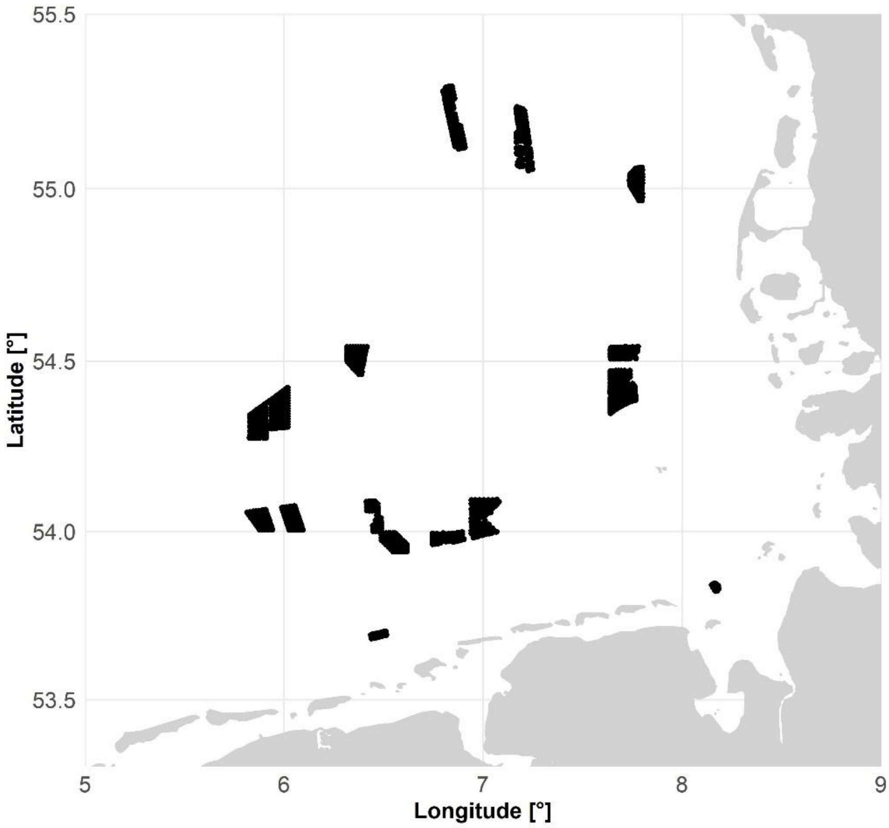


Figure 6.3 Position of piling locations in the German Bight and adjacent Dutch waters (2010 to 2016). Piling events in Nordergründe were also considered for calculating distances to piling locations.

POD data were considered to be influenced by pile driving if a piling event ended on the same day within a radius of 20 km. To determine this, distances from each piling location to each POD location were calculated (Figure 6.4) for piling days. Out of 50,638 POD days where monitoring occurred during piling days, 7,695 (15.2 %) lay within a radius of 20 km to the piling location. The radius of 20 km was chosen based on the results from analysis of the hourly data (chapter 4.1).

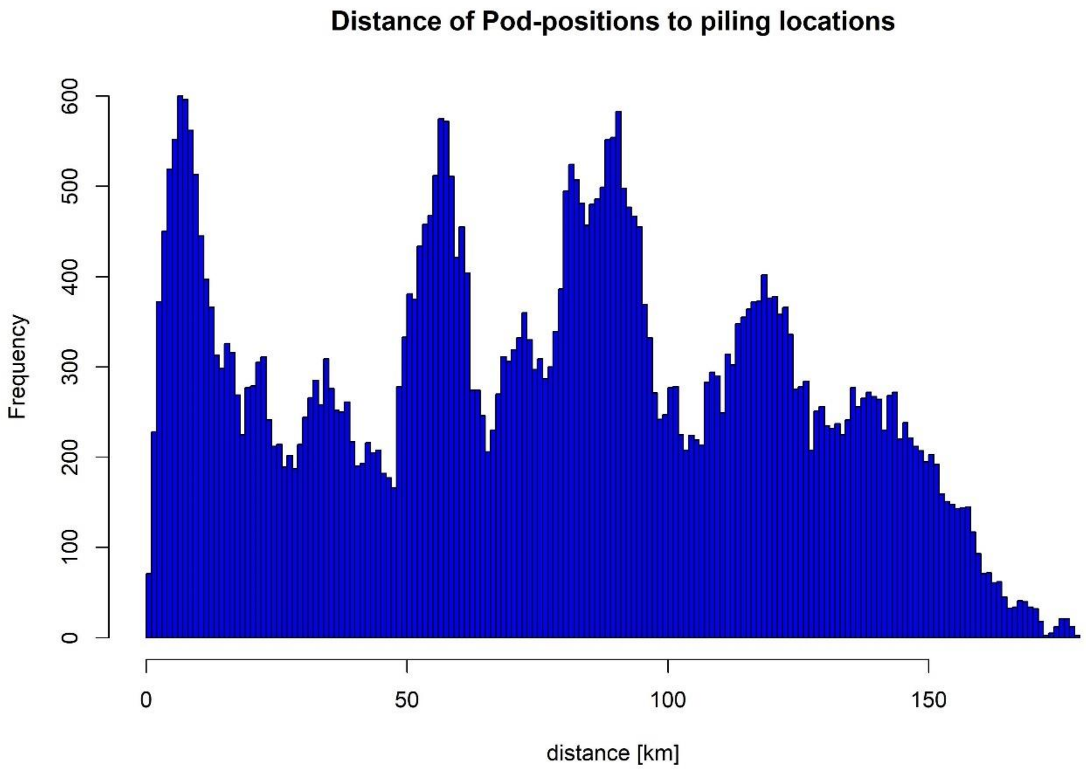


Figure 6.4 Distance from piling location to each POD location.

6.1.3 Environmental variables

We used two types of environmental variables: temporally static explanatory variables (at least approximately over the time period of our study) and temporally variable explanatory variables. A condition for the final choice of variables was that they had to be available for the whole period from 2010 until 2016. We chose the static variables geographic position (Longitude and Latitude), water depth, sediment type and, new to Gescha 2, the distance to shipping lanes and estimated sandeel density, an important prey of harbour porpoises (see Chapter 4.1.3, p. 90). As temporally variable explanatory variables we decided on wind speed and sea surface temperature anomalies (SSTA). The acquisition of environmental variables is described in chapter 3.6.

6.1.4 Subarea

Porpoises migrate and are not equally distributed within the German Bight, which might be due to different habitat characteristics. To consider these habitat characteristics and related differences in porpoise detections we clustered POD positions. The resulting clusters, called subareas in subsequent chapters (but not to be confounded with subareas of chapter 4.2), were then used for stratification of modelling. To cluster stationary monitoring positions, we chose temporally invariable explanatory variables – or variables that can be considered almost static over the period of our study. We assume that these variables are important habitat characteristics from the perspective of a harbour porpoise: latitude and longitude (geographic position), water depth, sediment type, distance to shipping lanes and estimated density of sandeel species. For sandeel species, the modelled density of the three species Great sandeel (*Hyperoplus lanceolatus*), Lesser sandeel (*Ammodytes tobianus*) and Raitt's sandeel (*Ammodytes marinus*) were modelled (see chapter 3.6) and summed up. We assume these variables to be directly or indirectly important for porpoises and to influence the attractiveness of an area for these animals. This is not because porpoises differentiate between different sediment types per se, but different sediment types are indications for the availability of different food types (CALLAWAY et al. 2002). Geographic position is related to several other environmental factors such as day length, water temperature, distance to coast etc.

We used the clustering algorithm *pam* (R library cluster: MAECHLER et al. 2018), a partition clustering method which clusters the data around k medoids. Since we not only have continuous data but also ordinal data (sediment) we used the *daisy* function (R library cluster: MAECHLER et al. 2018) to calculate the dissimilarity matrix between monitoring positions. In this step we weighed geographic position double, meaning that we gave geographic position as much weight as the other four variables together. The underlying assumption is that two monitoring points which are close neighbours geographically are twice as likely to be similar in harbour porpoise habitat usage, even if either are environmentally more similar to geographically more distant locations. The number of k clusters, meaning the final number of subareas, was chosen by visually comparing results.

6.1.5 Models

To model our data, we used the function *gamm* with a quasi-corrected poisson error distribution to account for overdispersion, from the package mgcv (R library mgcv: WOOD 2011; WOOD et al. 2016; WOOD 2004). The advantage of the *gamm* function was the possibility of correcting for temporal autocorrelation with an Auto-Regressive Moving Average (ARMA) process implemented in the function corARMA. The most parsimonious orders of p (AR term) and q (MA term) were estimated using the function *auto.arima* from R library forecast (HYNDMAN et al. 2018). Adequate orders were then chosen on this estimation and their suitability in accounting for autocorrelation in the models evaluated by sight using the *acf* and *pacf* functions of R package stats (R CORE TEAM 2018).

Different models were designed to answer specific questions examining different aspects of "long-term" trends. The validation of comparable models or models of different complexity was primarily based on the lowest AIC value but also on good explanatory power (high values of adjusted r^2). The robustness of model results was validated by comparing key results of several related models. Model validation was done by plotting the fitted values against the normalised residuals of the LME part of the GAMM model (which holds the residuals corrected by random effects) and by plotting each of the explanatory variables against the normalised residuals. If the distribution was considered homogeneous then the respective model does not violate assumptions and is therefore valid.

Most models include the variable *day of year*. For this variable every day gets assigned an integer value starting with 1 on 1st January and ending with 365 (or 366 for the leap years 2012 and 2016) on 31st December (Table 6.1).

Table 6.1 Variable day of year. For the leap years 2012 and 2016 numbers are written in grey.

season	month	day of year			
		min		max	
winter	January	1		31	
	February	32		59	60
spring	March	60	61	90	91
	April	91	92	120	121
	May	121	122	151	152
summer	June	152	153	181	182
	July	182	183	212	213
	August	213	214	243	244
autumn	September	244	245	273	274
	October	274	275	304	305
	November	305	306	334	335
winter	December	335	336	365	366

Single-station models

To separate seasonal from stochastic effects and get a first insight into the data and long-term trends, we conducted single-station models. Each model was calculated on a subset of data from a single monitoring position. In total, we analysed 12 POD stations, three from each subarea based on the length of the data series.

As key explanatory variables, we decided on year as a factor, day of year as a cyclic smooth to capture seasonal phenology, and piling (boolean variable: piling within 20 km radius from POD station) to take the influence of pile-driving activities into account. POD ID nested in station was included as a random factor.

Subarea models (magnitude and phenology)

For evaluating the development of harbour porpoise activity within the respective subareas, we analysed each subarea separately. Hereby we focused on two different aspects of development: 1) possible changes of the magnitude of harbour porpoise detections over the years, and 2) possible changes in yearly phenology. Key explanatory variables for analysing changes in magnitude were year as a factor, and for analysing change in phenology both season and year as factor.

German Bight model

Setting into context developments in the different subareas required calculating a model on the whole dataset. As key explanatory variables we therefore chose a combined factor variable of season and subarea.

Habituation models

To approach the question of possible habituation or sensitisation of harbour porpoises to pile driving induced short-term disturbance, we formulated one model for each subarea. As key explanatory variable we created a factor combining year and piling.

6.2 Results

6.2.1 Subarea clustering

The optimal number of clusters was decided to be four, which resulted in four subareas augmenting the subareas presented in Gescha 1 (see Figure 6.5). Subarea 1 is located in the eastern part of the German Bight and includes the wind farm area north of Heligoland and most CPODs for Butendiek. Subarea 2 is located in the south-western part of the German Bight and adjacent Dutch Waters. The westernmost CPOD in the Dutch Sea forms subarea 3 together with CPODs in the central German Bight. Subarea 4 is located in the Northern German Bight. Hereby, subarea 1 corresponds to the MSO/NSO area from Gescha 1, subarea 2 corresponds to the BW2 area, subarea 3 corresponds to the BARD area and subarea 4 corresponds to the DanTysk area. The classification of subarea is used as a factor in one model as well as in a model where the dataset was split in four subsets with one model built for each subarea independently.

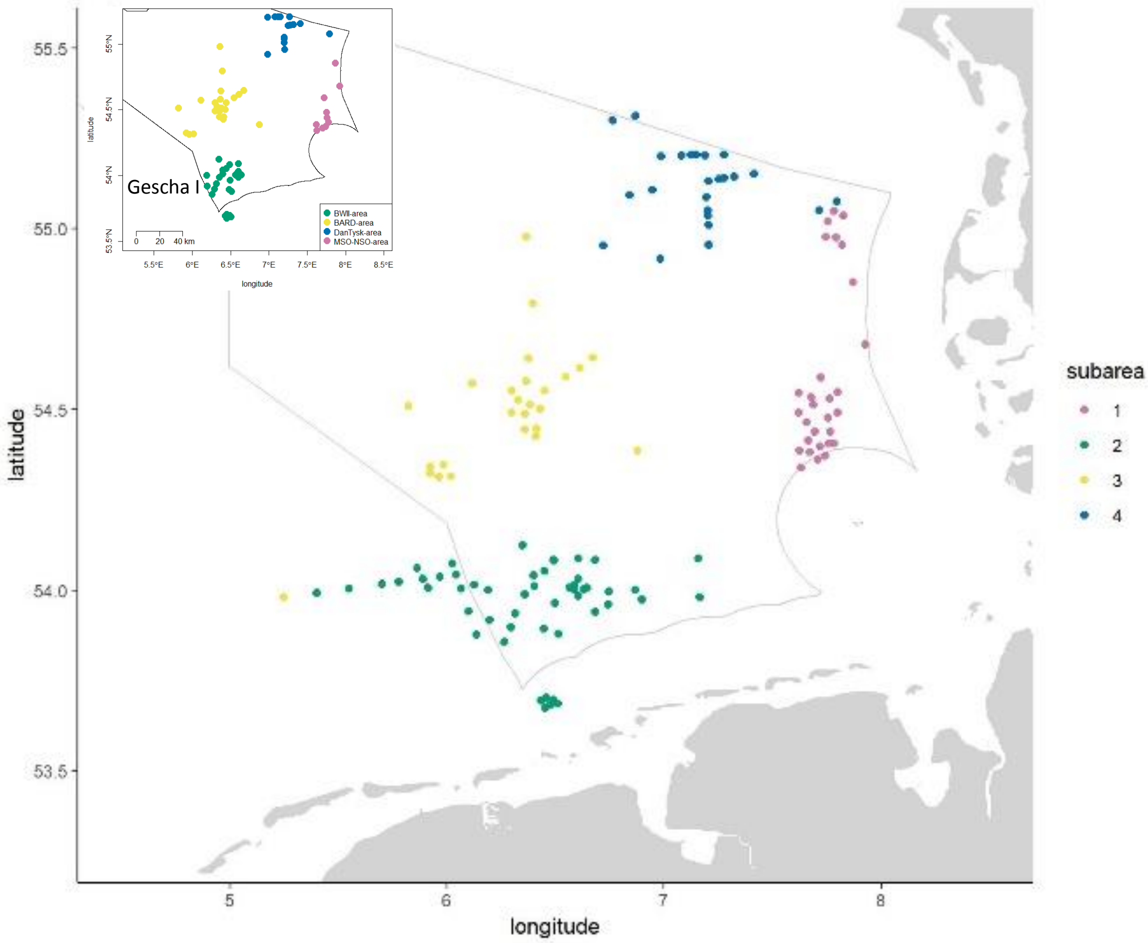


Figure 6.5 *Subarea classification of stationary CPOD positions for the Gescha 1 project (2010-2013 upper left corner), and re-clustered for the entire study period (2010-2016).*

6.2.2 Single-station models

Single-station models were meant as case studies for several POD monitoring positions enabling the separation of seasonal and stochastic effects from trends over several years. We thus performed trend analyses for 12 monitoring positions. From each subarea, the three monitoring positions with the longest collection of data were chosen. The analysed POD stations are listed in Table 6.2.

The longest timespan was recorded at the station S8 in the subarea 3 with a total of 2,452 recording days. Stations in subarea 2 had a recording phase of 1,824 and 1,277 days for MEG1 and BR 1, respectively. Station S3/S3 (new) had 2,274 recording days – far more than MEG1 and especially BR 1– but was not selected as it is positioned in subarea 3 where stations S8 and S4 had more recording days. Raw data plots for all single stations are shown in the Appendix.

Table 6.2 POD stations with the longest recording period for each subarea.

POD-station	subarea	number of monitoring days
S10	1 (east)	2192
BU2	1 (east)	1992
S13	1 (east)	1839
MEG1	2 (southwest)	1824
BR1	2 (southwest)	1277
BR2	2 (southwest)	1222
S8	3 (central)	2452
S4	3 (central)	2357
S3/S3 new	3 (central)	2274
BU1	4 (north)	1939
DT2	4 (north)	1925
DT1	4 (north)	1895

Model selection for single stations was carried out as described in chapter 6.1.5. The variables year, SSTA, all clicks (refers to the variable modified click variable with the minimum value of $2.30*10^5$ clicks see chapter 6.1.1), wind speed, and piling were chosen as relevant parameters (Table 6.3). The factor piling considers whether a piling event took place at a distance of 20 km to the POD station. The distance of 20 km was chosen based on results from detailed analyses on the hourly dataset (chapter 4.1). This factor did not apply for DT2, since there were no wind farms built at this distance.

Table 6.3 *Parameters used in single station models. Significance codes: '***' p<0.001, '**' p<0.01, '*' p<0.05, '.' p<0.1, 'n.s.' p≥0.1. Terms for which no significance estimates were available are assigned by 'n.a.', and terms not included in the model are assigned by '-'.*

variable	type in model	purpose	subarea 1			subarea 2			subarea 3			subarea 4		
			S10	BU2	S13	MEG 1	BR1	BR2	S8	S4	S3	DT1	DT2	BU1
dp10m	response		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
day of year	cyclic smooth	seasonal pattern	**	***	***	***	***	***	***	***	***	***	***	***
year	factor	changes over time	**	***	***	n.s.	n.s.	**	***	***	***	***	**	***
SSTA	smooth	effect of temperature anomalies	.	n.s.	.	n.s.	*	n.s.	.	n.s.	**	n.s.	n.s.	n.s.
all clicks	smooth	correct for technical biases	***	***	***	***	***	***	***	***	***	***	***	***
wind speed	smooth	effect of wind speed	***	**	***	***	***	***	***	***	***	***	n.s.	***
piling	factor	effect of piling in a radius of 20 km	**	n.s.	*	.	n.s.	n.s.	***	n.s.	***	n.s.	-	***
POD ID	random factor	sensitivity differences between PODs	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
error distribution	quasi-Poisson		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

variable	type in model	purpose	subarea 1			subarea 2			subarea 3			subarea 4		
			S10	BU2	S13	MEG 1	BR1	BR2	S8	S4	S3	DT1	DT2	BU1
temporal autocor-relation	ARMA on day (p=1, q=0)	correct for temporal de-pendence be-tween consecu-tive days	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
AIC		goodness of model fit	3452.493	2913.556	2554.173	1666.652	1550.97	1114.741	4116.714	4131.379	4407.325	2808.034	2387.408	3132.238
r-squared adjusted		coefficient of determination	0.121741	0.3492156	0.4376022	0.2017998	0.2981741	0.5977515	0.3587945	0.3493678	0.3893883	0.3079939	0.6038991	0.3142726
number of data records		sample size	2192	1994	1839	1824	1277	1222	2452	2357	2274	1895	1925	1939

Environmental variables, all clicks and piling influence

The variable all clicks, correcting for potential masking of porpoise clicks by noise, was highly significant for all station models. In all models except for DT2, the effect of wind speed was significant (Table 6.3).

SSTA, anomaly from the expected sea surface temperature, was only significant in the models for BR1, and S3 showed no significant effect for any of the other stations. A non-directional trend was visible for SSTA in the models for stations S10, S13 and S8. At BR1, the acoustic porpoise activity was lowest with about average or slightly increased sea-surface temperature (Figure 6.10). At S3, porpoise activity increased with unusually high sea-surface temperatures (Figure 6.14).

For approximately half of the monitoring positions piling in a distance of up to 20 km leads to lower porpoise activity than what is found on days without piling (Figure 6.6 to Figure 6.17). For five – S10, S13, S8, S3 and BU1 – of the twelve stations this effect was significant, for six stations not significant, and for DT2 no piling event took place within a radius of 20 km (Table 6.3).

The five stations with a significant effect of piling were usually closer to wind farms than the other stations.

Subarea 1 (eastern German Bight)

In subarea 1, S10 and S13 recorded data from 2010 to 2016 (and ongoing) (Figure 6.6 and Figure 6.8), whereas BU2 was recording data from 2011 to 2016 (and ongoing) (Figure 6.7). All three stations showed detection peaks in autumn (October/November) and minima in late winter (February). Whereas porpoise activity increased relatively consistently at S10 between late winter and autumn, BU2 showed a high peak in early May and an additional minimum in late July. The pattern at S13 is intermediate.

For all three stations, an increase in porpoise activity was found between 2010/2011 and 2016. While the increase at S10 took place mainly between 2011 and 2012, at BU2 the increase of detection rates took place at a relatively constant rate over the entire recording period. In contrast, porpoise activity at S13 remained relatively constant between 2010 and 2012 and increased after that. Therefore, at S13 the increase in porpoise activity started one year later than at the other two stations. The short-term effect of piling was more pronounced at S10 and S13, which is probably due to the fact that these stations were closer to the wind farms under construction. Most notable here is the coincidence of an increase in porpoise detections and the start of piling events in 2012 for station S10 after having increased already the previous year. After 2012, porpoise activity remained relatively constant on the elevated level. At station BU2, porpoise activity increased at a relatively constant rate between 2010 and 2016. Only in 2014, piling took place in a 20 km radius around the POD station, which coincided with a stagnation of porpoise detections compared to the previous year. 2014 was also the year with nearby piling at BU2. For S13, porpoise activity remained more or less constant from 2010 to 2012, then increased abruptly from 2012 to 2013 with an established high level of porpoise detection rates, even showing a positive trend until 2016.

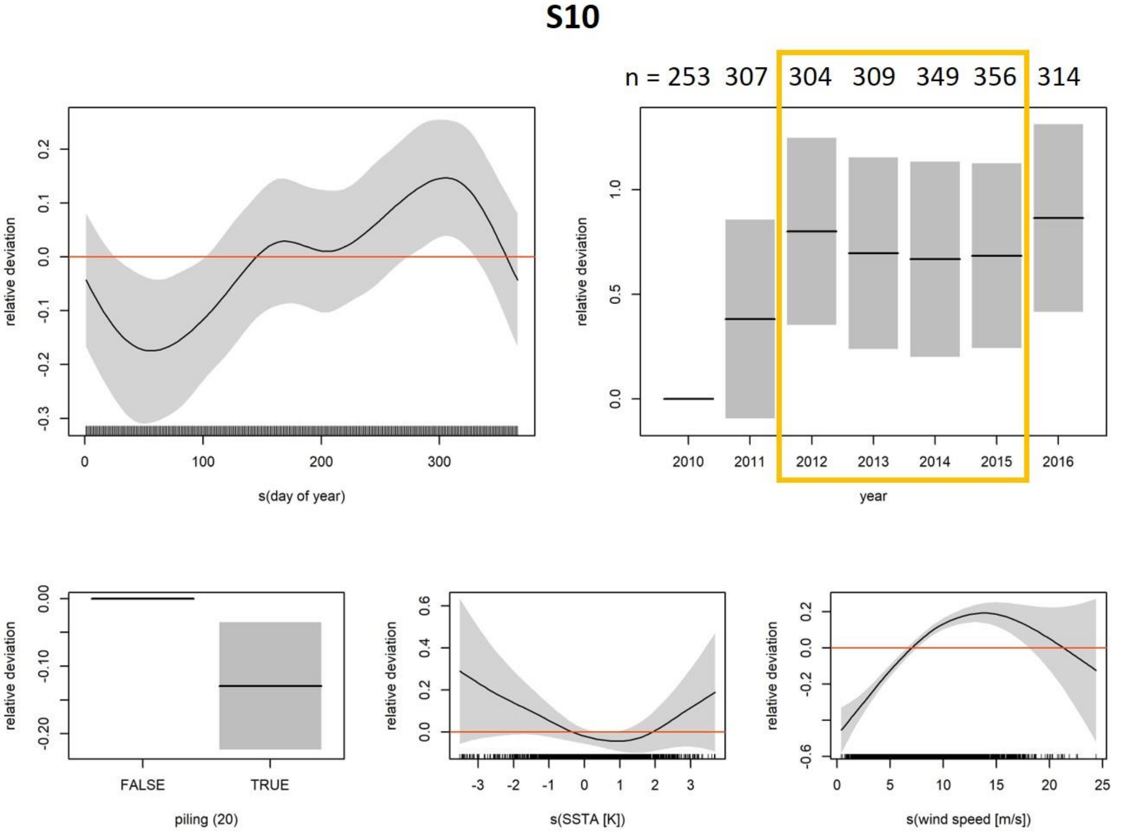


Figure 6.6 *Effects of day of year, year, piling at a distance of ≤ 20 km, SSTA and wind speed on porpoise detection at the station S10. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box. At S10 piling took either place at a distance of <20 km to the monitoring station or at a distance of >50 km to the monitoring station.*

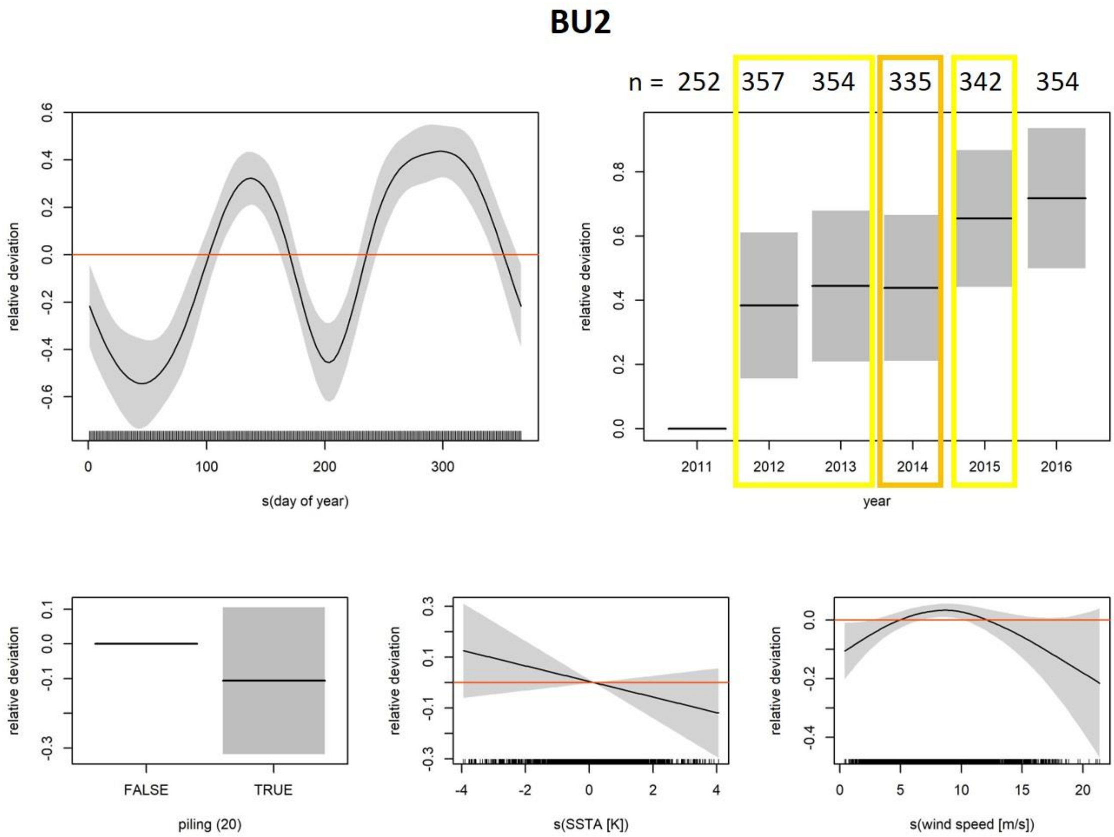


Figure 6.7 *Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station BU2. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.*

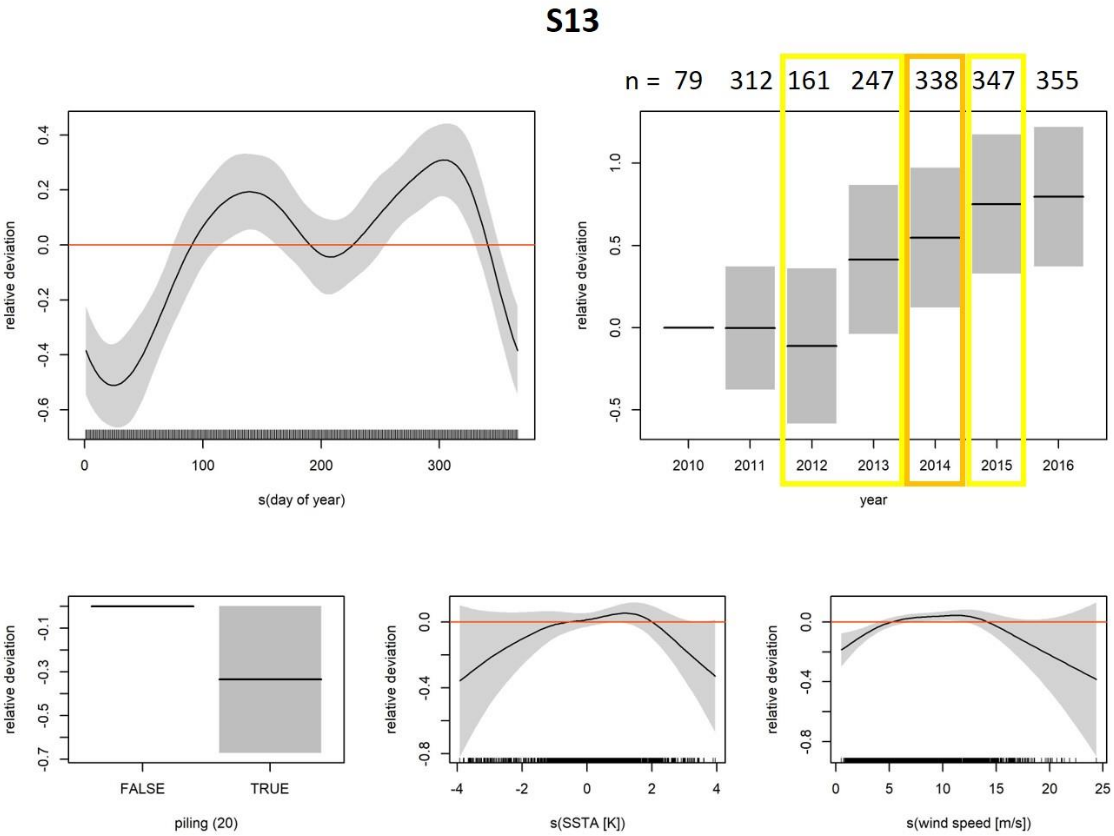


Figure 6.8 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station S13. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.

Subarea 2 (south-western German Bight and adjacent Dutch waters)

In subarea 2, the station MEG 1 recorded data from 2011 to 2016 (and ongoing) (Figure 6.9), whereas BR1 and BR2 were active from 2013 to 2016 (and ongoing) (Figure 6.10 and Figure 6.11). The highest porpoise detection rates at MEG 1 and BR1 were recorded in winter, and at BR2 also in winter with a further peak in late summer. The lowest porpoise detection rates at MEG 1 was recorded during September, while the minimum at BR1 was recorded in June and at BR2 in May.

At MEG 1, porpoise detections remained constant over all years, independent of piling activity. Only during 2011 a slightly (but not significant) higher porpoise activity was recorded, however, data availability for this year was sparse and only consisted of 43 recording days at the end of the year. For BR1, confidence intervals for each year overlap, indicating no significant trends. However, computed mean values decreased from 2013 to 2014, and then increased continuously until 2016. The pattern among years was similar at BR1 and BR2. It was difficult to relate annual changes to piling activity. The first decrease in porpoise activity in BR1 coincides with the start of piling activity at a distance between 20 and 50 km. A causal connection between pile driving and long-term development of porpoise activity seems unlikely as porpoise detection rates increased until 2016, when pile driving was closest to the CPOD station. At BR2, highest porpoise detection rates were found in 2013 with no piling activity. However, values were lower in 2015 with piling further away than in 2014 and 2016 when piling activity took place at distances of less than 20 km.

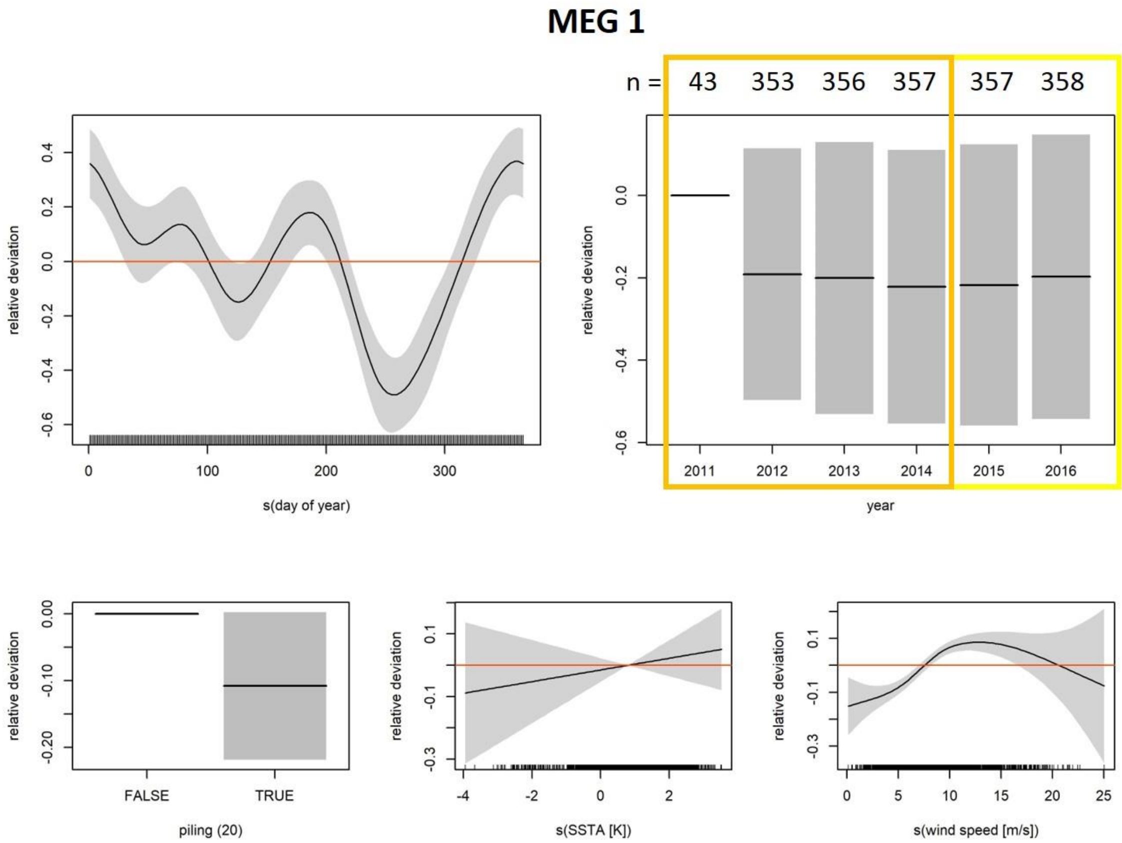


Figure 6.9 *Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station MEG1. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.*

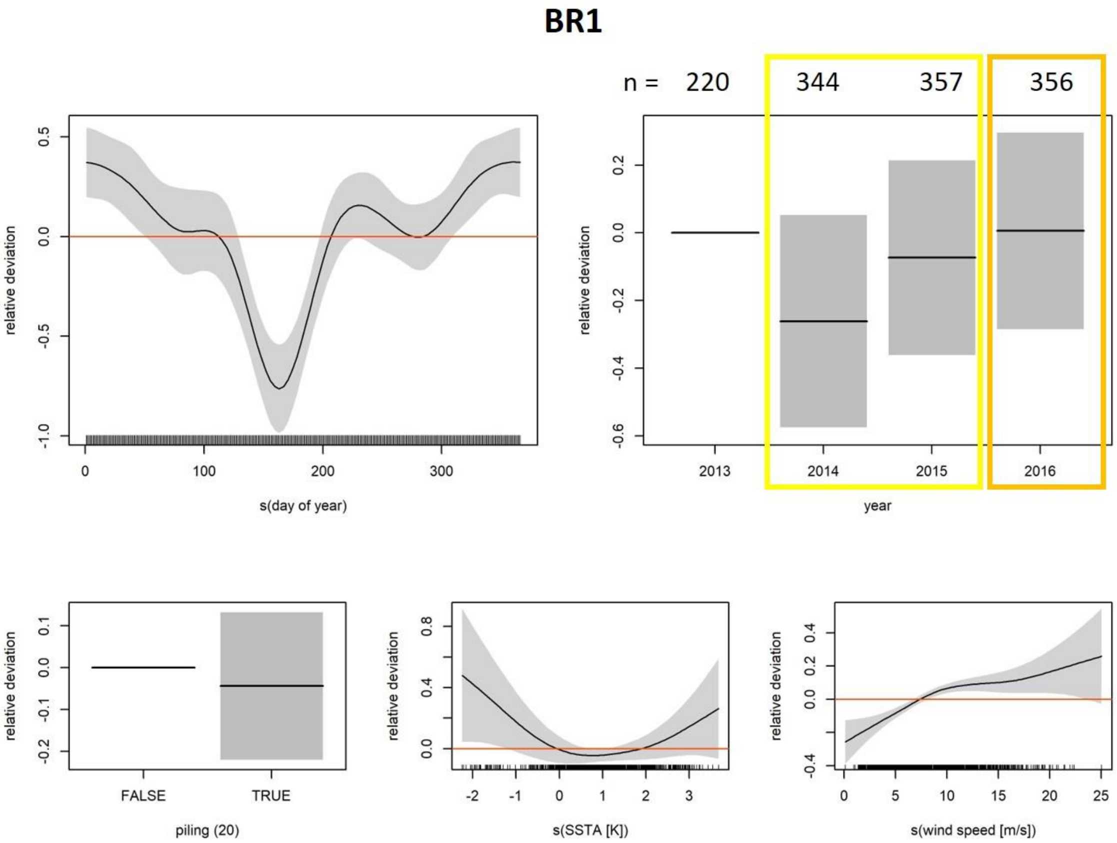


Figure 6.10 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station BR1. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.

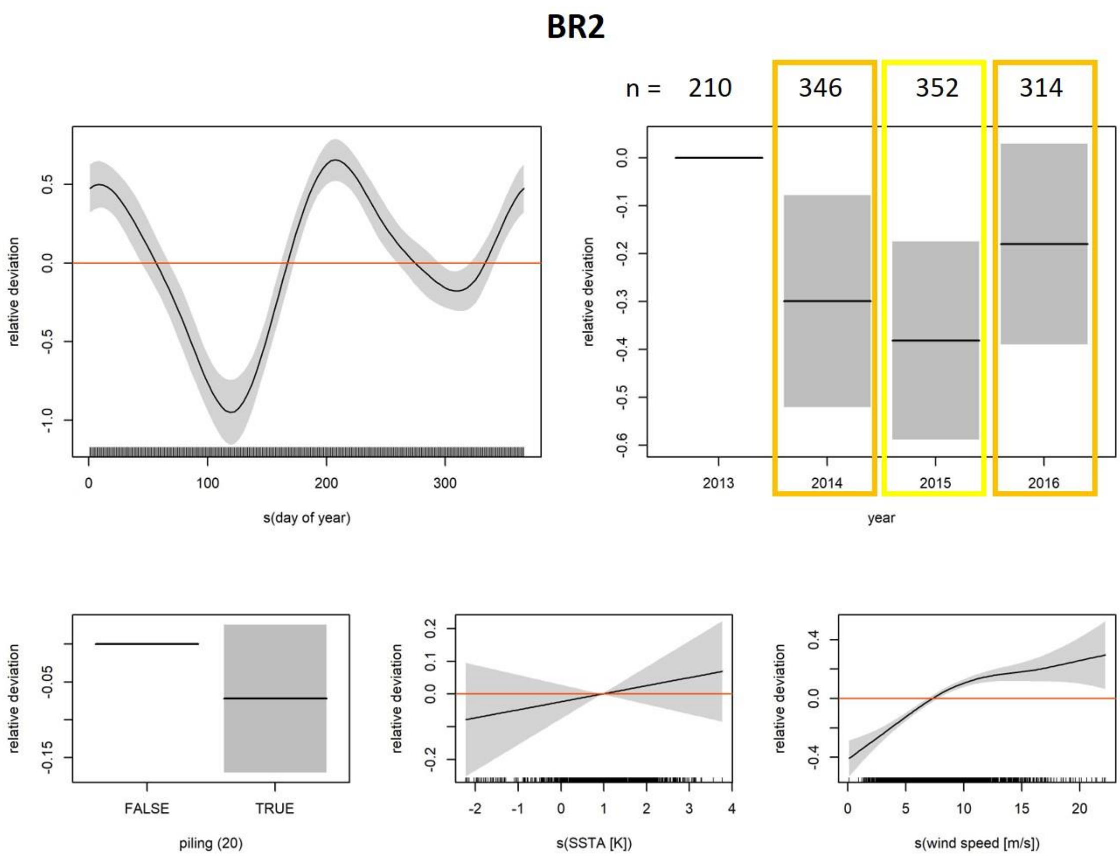


Figure 6.11 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station BR2. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.

Subarea 3 (central German Bight)

In subarea 3, the stations S8, S4 and S3 recorded data from 2010 to 2016 (and ongoing) (Figure 6.12, Figure 6.13 and Figure 6.14) and therefore have the longest continuous recording period of all stations over all subareas. Highest porpoise detection rates at all three stations were found in winter and spring with a maximum in February and early March. Detections decreased abruptly in late April and early May. In early July, a slight increase in porpoise activity was recorded at S8 and S3, while S4 showed a pronounced interim maximum. Detection rates then decreased again, especially at S4 and S3, where a minimum was reached in late September. Afterwards the detections increased again towards the winter.

From 2010 to 2016, porpoise detection rates decreased at all three stations; however, the trend was most pronounced at S4, where detections first fluctuated at a stable level, then dropped rapidly after 2013. At S8, highest rates were recorded in 2010 and decreased toward 2012. Porpoise detection rates then remained relatively constant and was especially low in 2015, then recovering to the level of preceding years in 2016. At S3, the years 2010, 2011, 2013 and 2014 had a higher level of porpoise detection rates, whereas 2012, 2015 and 2016 were characterised by lower levels.

For all stations, it is difficult to relate changes in porpoise detections with intensity of pile driving noise. As such detection rates in 2015 and 2016 were relatively low at all stations, although pile driving activity was farther away than 20 km and, in some instances, even farther away than 50 km. Before 2015, pile driving activities were less than 20 km away from POD stations, but porpoise detection rates remained relatively constant in most years.

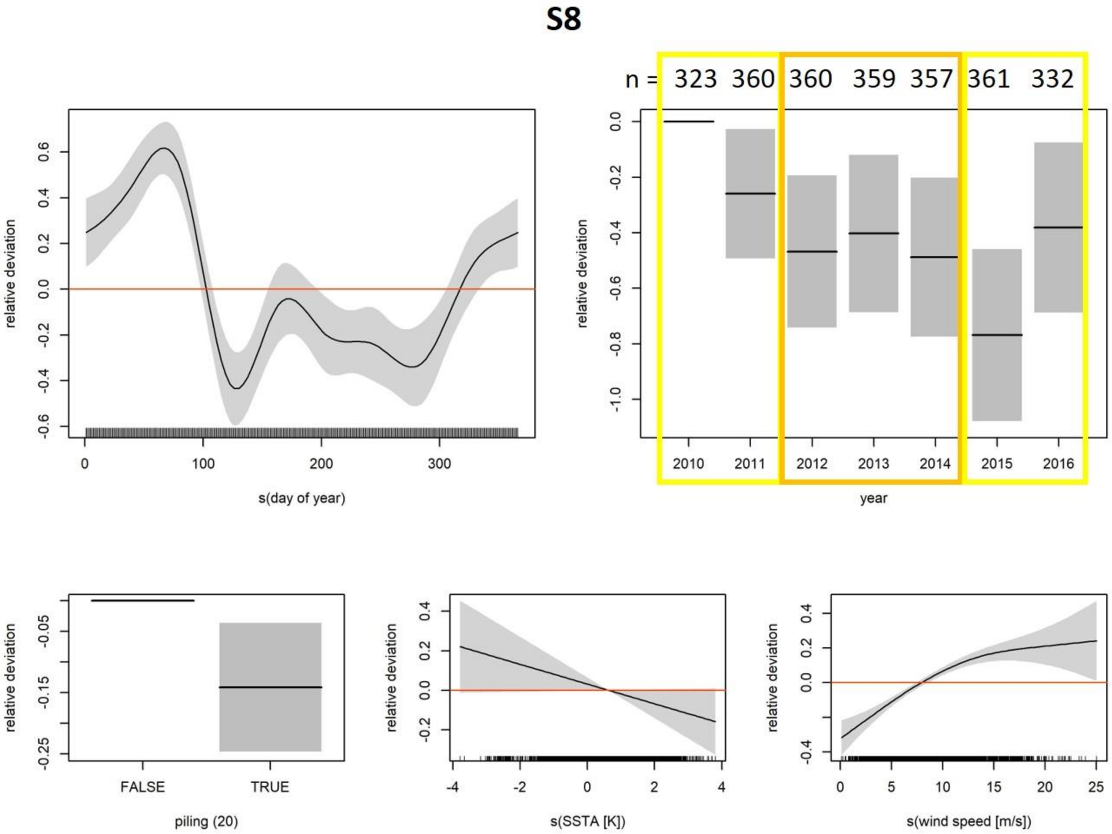


Figure 6.12 *Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station S8. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.*

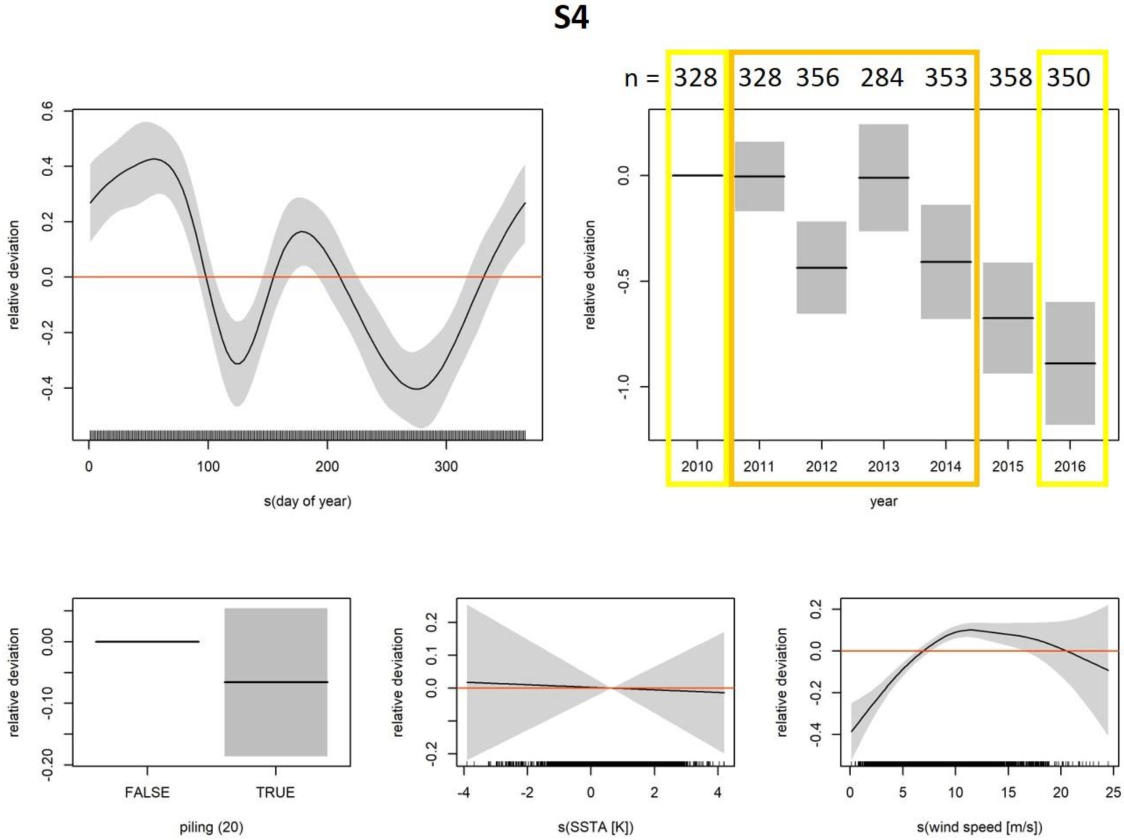


Figure 6.13 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station S4. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.

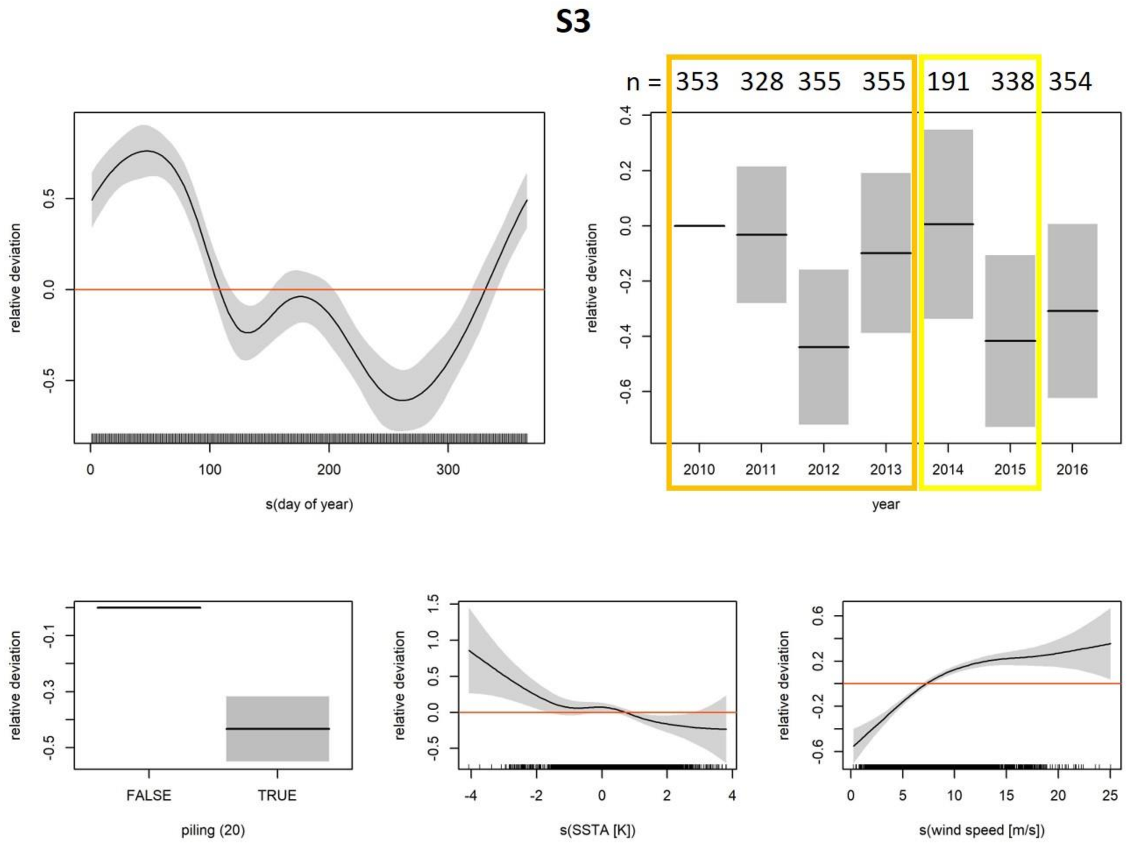


Figure 6.14 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station S3. In 2016, station S3 was translocated some 1.9 km north and was called S3 new since. Data from the new station was included in this analysis. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.

Subarea 4 (Northern German Bight)

In subarea 4, all three stations BU1, DT2 and DT1 recorded data from 2011 to 2016 (and ongoing) (Figure 6.17, Figure 6.16 and Figure 6.15). All three stations had summer peaks in porpoise activity (maximum in June) and minima in winter (BU1: January, DT2: early November, DT1: late November/early December), acoustic porpoise activity was higher in 2016 than in all preceding years, and changes between 2011 and 2013 were small. At DT2, porpoise detection rates were relatively constant between 2012 and 2014 and increased since then. At BU1 and DT1, the year with the lowest porpoise detection rates was 2014 and the overall increase since 2011 was small.

At station BU1, nearby piling took place in 2014 and 2015. Although 2014 was characterised by low porpoise activity, an increase was recorded in 2014 and 2015. At station DT2, no pile driving activity occurred within a radius of 20 km. From 2013 to 2016, there was pile-driving activity at a distance of up to 50 km from the monitoring stations. However, this was the time span in which porpoise activity increased continuously. At DT1, the years 2013 and 2014 were characterised by low porpoise activity, coinciding with pile driving at a distance of 20 km to the monitoring station.

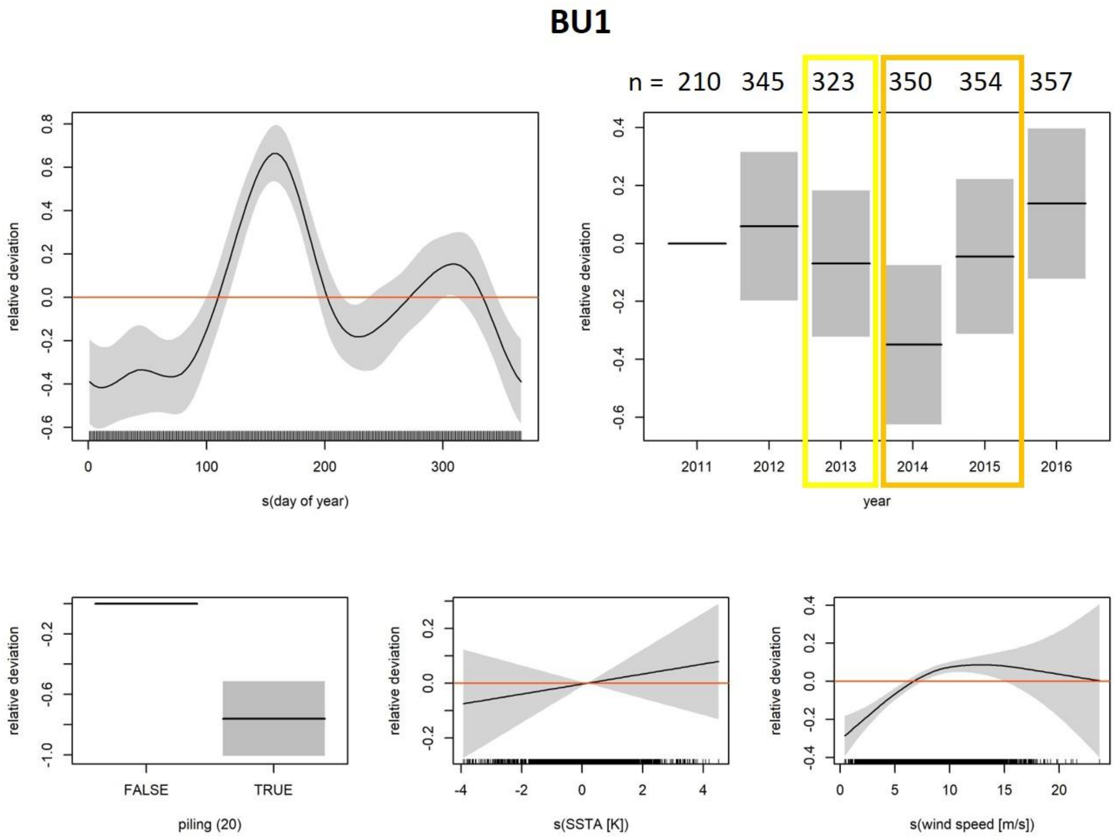


Figure 6.15 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station BU1. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.

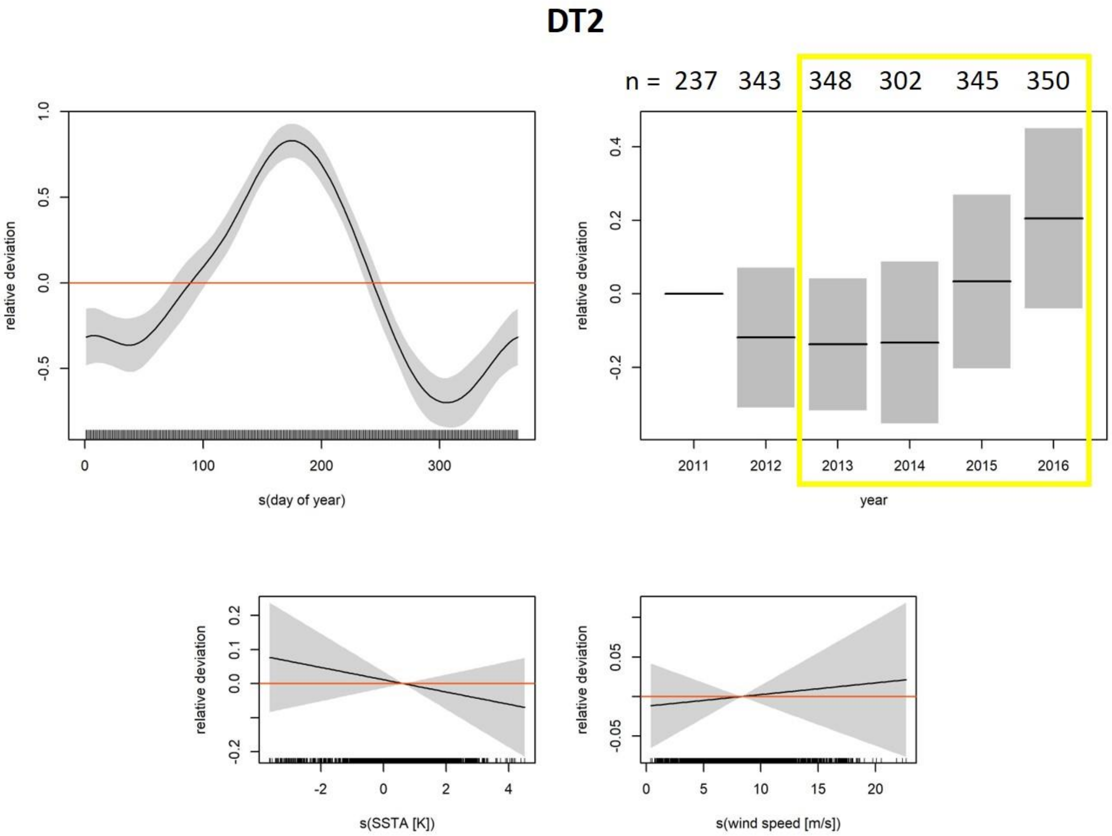


Figure 6.16 Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station DT2. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years where piling occurred only within a radius of 50 km are marked with a yellow box. No piling took place at a distance of less than 20 km distance to the monitoring station.

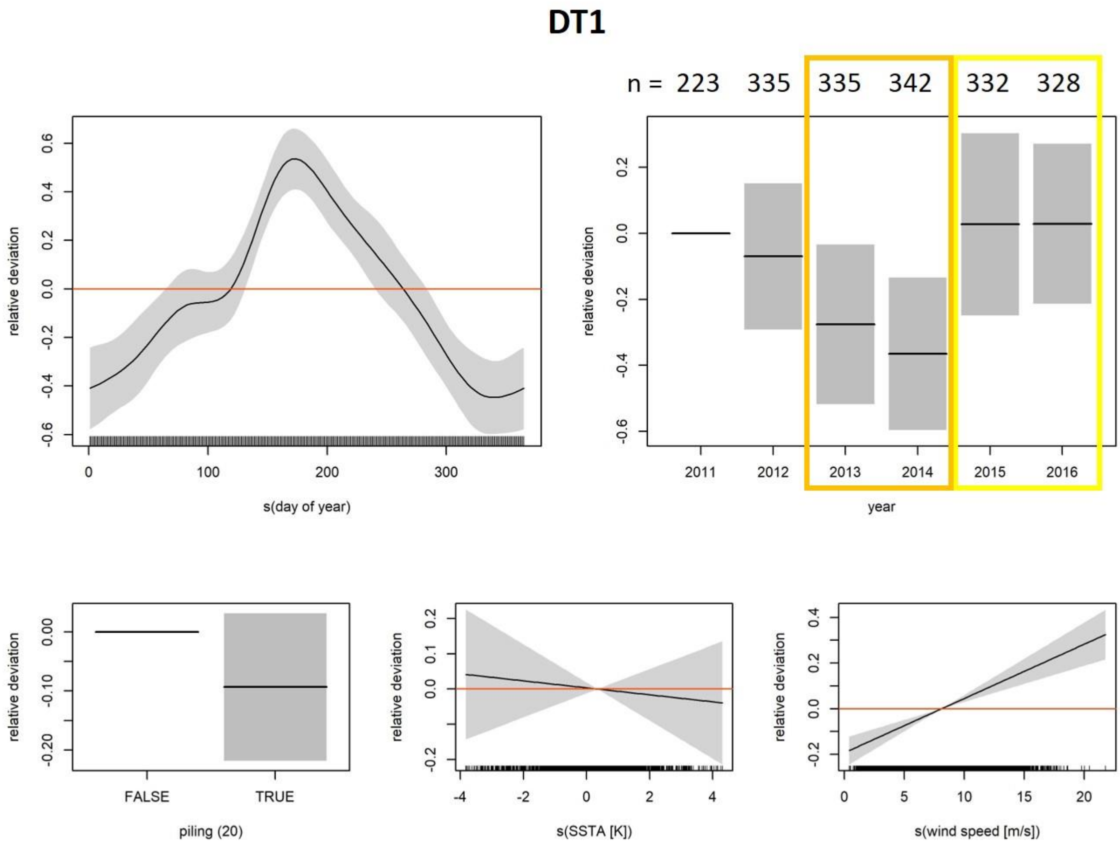


Figure 6.17 *Effects of day of year, year, piling at a distance of 20 km, SSTA and wind speed on porpoise detection at the station DT1. Grey-shaded areas indicate the confidence intervals. The number of recording days per year is indicated (n). Years in which piling occurred within a radius of 20 km to the monitoring station are marked with an orange box, years where piling occurred only within a radius of 50 km are marked with a yellow box.*

6.2.3 Comparing subareas

*Table 6.4 Parameters used in models for comparing subareas and trends among and within subareas. Significance codes: '***' p<0.001, '**' p<0.01, '*' p<0.05, '.' p<0.1, 'n.s.' p≥0.1. Terms for whom no significance estimates are available are assigned by 'n.a.', and terms not included in the model are assigned by '-'.*

variable name	variable type in model	purpose	German Bight model	subarea-yearly-trend model				subarea-season model			
				1	2	3	4	1	2	3	4
dataset			complete	per subarea				per subarea			
dp10m	response		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
day of year	cyclic smooth	seasonal pattern	-	***	***	***	***	-	-	-	-
season subarea	factor	compare effects per season and subarea	***	-	-	-	-	-	-	-	-
season year	factor	compare effects per season and year	-	-	-	-	-	***	***	***	***
year	factor	changes over time	***	***	***	***	***	-	-	-	-
SSTA	smooth	effect of temperature anomalies	n.s.	**	n.s.	.	***	***	n.s.	*	n.s.
all clicks	smooth	correct for technical biases	***	***	***	***	***	***	***	***	***
wind speed	smooth	effect of wind speed	***	***	***	***	***	***	***	***	***
piling	factor	effect of piling in a radius of 20 km	***	***	***	***	***	***	***	***	***

variable name	variable type in model	purpose	German Bight model	subarea-yearly-trend model				subarea-season model			
				1	2	3	4	1	2	3	4
station	random factor	effect of POD-location	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
POD ID	fandom factor nested in station	sensitivity differences between PODs	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
error distribution	quasi-Poisson		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
temporal autocorrelation	ARMA on day (p=1, q=0)	correct for temporal dependence between consecutive days	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
AIC		goodness of model fit	124107.9	26264.78	40963.32	37005.75	19550.29	26413.68	40942.17	36917.88	19546.04
r-squared adjusted		coefficient of determination	0.1660236	0.2212457	0.1772719	0.2379978	0.2360436	0.1910869	0.1553515	0.1796034	0.2238582
number of data records		sample size	79394	18093	26312	21332	13657	18093	26312	21332	13657

German Bight model

In all seasons, porpoise detections were lowest in subarea 3 (Figure 6.18). However, in winter, when porpoise detections within subarea 3 were relatively high, these differences were not as distinct, and porpoises were distributed relatively evenly within the German Bight. The greatest differences in subarea-related porpoise detections were observed in summer, with subarea 4 having had the most detections (Figure 6.18). In spring, levels in porpoise detections within subareas 1, 2, and 4 were not statistically distinguishable, but they were higher than in subarea 3 (Figure 6.18). In autumn, the highest porpoise detection rates were recorded in subarea 1, in winter in subarea 2. This is in line with the yearly phenology within those subareas (Figure 6.20).

The porpoise detection rates recorded over the entire study area increased from 2010 to 2016 (Figure 6.19). The increase was continuous, except from 2013 to 2014, when a noticeable drop in porpoise detections was recorded.

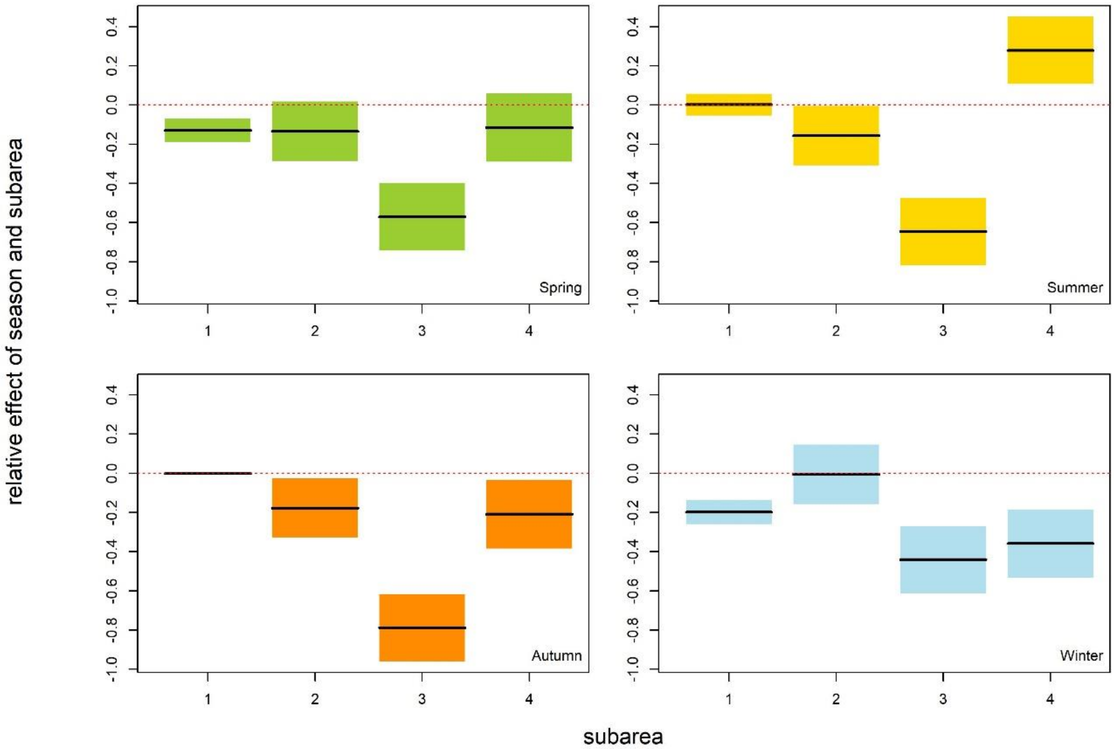


Figure 6.18 Modelled daily porpoise detection rates per subarea and season from 2010 to 2016.

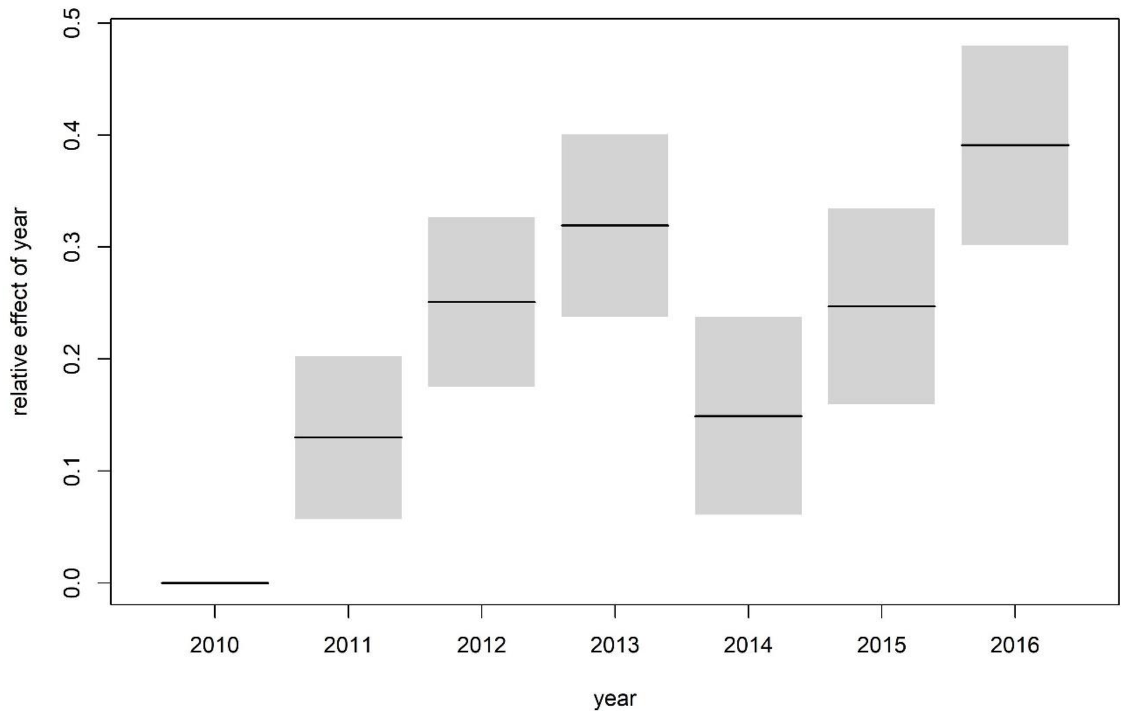


Figure 6.19 Modelled daily porpoise detection rates per season from 2010 to 2016.

Subarea-seasonal-trend model

Phenology of daily porpoise detection rates differed greatly between subareas (Figure 6.20). Generally, subarea 1 and 4, located in the northern and eastern part of the German Bight, showed highest porpoise detection rates in summer. In contrast, subarea 2 and 3, located in the central and southern part of the German Bight and adjacent Dutch waters, had a characteristic winter peak of porpoise activity.

In subarea 1, which lies in the eastern German Bight north of Heligoland, the maximum of porpoise detection rates was recorded in early June. Detections subsequently decreased until early August. The time between September and early November was characterised by moderately high rates. Lowest porpoise activity was found during winter with a minimum in February (Figure 6.20).

Within subarea 2, highest porpoise detection rates were recorded from December to March. Afterwards, activity decreased rapidly until it reached its minimum in May. A local maximum occurred at the end of July/in early August and a local minimum in late September (Figure 6.18).

In subarea 3, highest detection rates were recorded in winter. A smaller peak was found in summer (Figure 6.20).

A pronounced summer peak and a strong depression in winter characterised the seasonal phenology of subarea 4 (Figure 6.20). The overall highest porpoise detection rates were recorded in June, the lowest in January.

Seasonal phenology of porpoise detections was rather similar in subarea 2 and subarea 3 (Figure 6.20). However, the magnitude of porpoise activity was always greater in subarea 2 (Figure 6.18).

In winter, the peak was more pronounced in subarea 2 than in subarea 3, both subareas reached the peak within the winter maximum in late February (Figure 6.20). Minima in porpoise detections in subarea 2 occurred in late April and local a minimum in October. In subarea 3, both minima were at the same level.

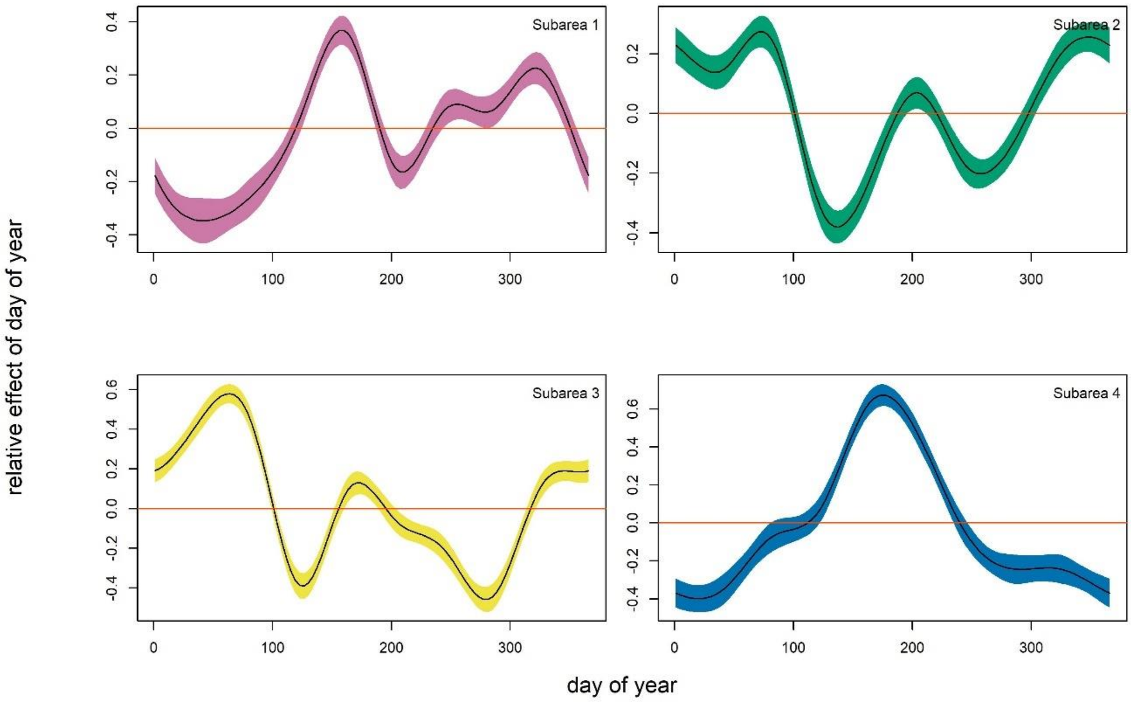


Figure 6.20 Seasonality of porpoise activity in the four subareas within the period from 2010 to 2016 (or 2011 to 2016 for subarea 4).

As a further factor, piling activity was included into the model. To this end, all data at a pile driving day were classified as influenced by piling if piling took place within a radius of up to 20 km from the POD monitoring position. Reduced detection rates were found during pile driving days (Figure 6.21). The influence of pile driving was very distinct in all subareas. However, the y-axis has a different scale in each subarea model, as every model was calculated on a separate dataset, meaning, that the effect of pile driving is slightly smaller in subarea 2 than in the other subareas.

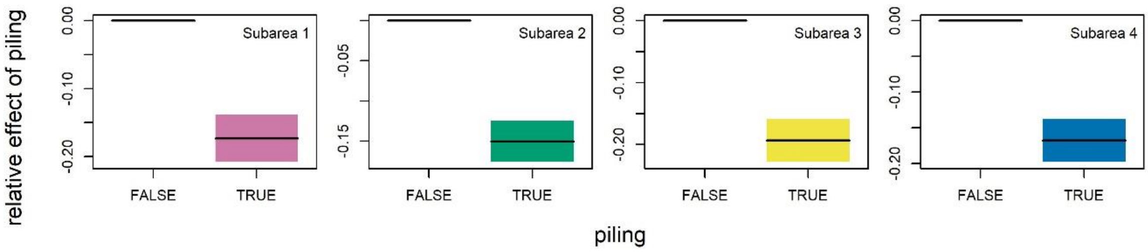


Figure 6.21 Effects of pile driving at a distance of 20 km around piling locations on porpoise detection rates in the four subareas of the Dutch/German North Sea in the period from 2010 to 2016 (for subarea 4: 2011 to 2016).

The development over time in acoustic porpoise activity between 2010 and 2016 was different between subareas (Figure 6.22). While porpoise activity increased in subareas 1 and 2, it decreased in subarea 3. In subarea 4, the time series started with data from 2011 and since then no trend was visible in either direction.

The model included short-term effects of pile driving within a radius of 20 km. We found that porpoise detections were significantly lower during piling days, which is in line with the results from chapter 4.1. Although the global hourly Gescha 2 CPOD dataset provided a minimum effect range of 17 km with effects lasting for 38 hrs (chapter 4.1), there could be smaller disturbance effects left in the daily data on days before or after piling which might negatively influence the explanatory power of year as a factor (Figure 6.22). Therefore, we summed up the number of piling events per subarea and year (Table 6.5) and took them into account when interpreting the changes in porpoise activity over the years (Figure 6.22).

In Subarea 1, a continuous increase in acoustic porpoise activity was recorded, with a minor decrease in 2014, which happened to be the year with by far the most piling events in that subarea. However, porpoise detection rates were much smaller in 2010 and 2011, when piling had not yet started in that subarea (Table 6.5 and Figure 6.22).

Only in 2010, no pile driving occurred in subarea 2. With the start of pile driving in 2011, porpoise activity increased concurrently. The highest level of pile-driving activity occurred in 2015, followed by 2016. In these years, both Gemini wind farms were built (with similar noise levels as no noise mitigation was applied). From 2012 until 2014 detection rates decreased; from 2015 to 2016 rates increased back to the level of 2012. It is concluded that no detectable effects of pile driving on general numbers of porpoises in this subarea occurred (Table 6.5 and Figure 6.22).

For subarea 3, pile driving took place mainly in 2011, but also 2012 when BARD Offshore 1 was built (predominantly without NMS). Although pile-driving activity did not decrease in 2013, porpoise activity increased again. In the following years, pile-driving activity decreased further, and at the same time porpoise activity decreased as well. The year 2015 was characterised by the lowest porpoise detection rates in the entire study period in this subarea, which at the same time had been the only year without any pile-driving work within that subarea (Table 6.5 and Figure 6.22).

In Subarea 4, moderate pile driving took place between 2013 and 2015. Over these years, porpoise detection rates decreased and increased again so that no effect of pile driving on the porpoise activity could be inferred (Table 6.5 and Figure 6.22).

Some years with seemingly decreasing porpoise detections coincided with high piling activities (e. g. 2014 in subarea 1; Table 6.5 and Figure 6.22). Sometimes moderately high pile-driving activity coincided with low porpoise detections, such as in subarea 3 in year 2012. In other years, such as in subarea 2 in year 2015 and subarea 3 in year 2011, the most intense pile-driving work coincided with high porpoise detection rates.

Table 6.5 *Number of piling events per subarea. Definition of subareas is based on position of CPODs and not on piling locations. The number of erected OWFs cannot be derived from the number of piling events. The OWF Butendiek is positioned between subareas 1 and 4. Therefore, piling events in this wind farm counted both for subarea 1 and 4; colour code: red: years with more than 100 piling events per subarea, orange: years with more than 50 piling events per subarea, blue: years with 10 to 50 piling events per subarea, pale green: years with less than 10 piling events per subarea, green: no piling event within subarea. The same colours are used in Figure 6.22 to illustrate the effects of pile driving.*

Subarea	2010	2011	2012	2013	2014	2015	2016
Subarea 1	0	0	33	95	175	16	0
Subarea 2	0	29	21	7	78	264	60
Subarea 3	37	109	78	81	8	0	72
Subarea 4	0	0	0	86	87	66	10
total	37	138	132	269	266	345	163

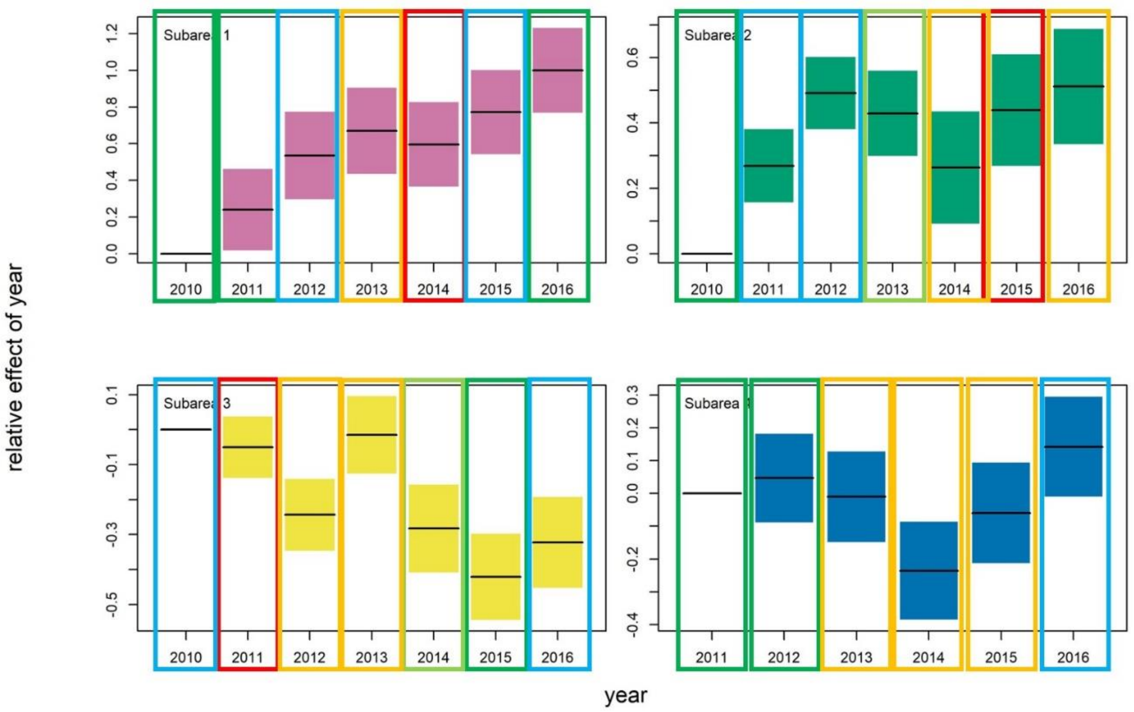


Figure 6.22 *Development in porpoise activity in the four subareas in the German Bight in the period from 2010 to 2016 (or 2011 to 2016 for subarea 4). Red: years with more than 100 piling events per subarea, orange: years with more than 50 piling events per subarea, blue: years with 10 to 50 piling events per subarea, pale green: years with less than 10 piling events per subarea, green: no piling event within subarea. Number of pile-driving events per subarea and year are summarised in Table 6.5.*

Subarea-season model

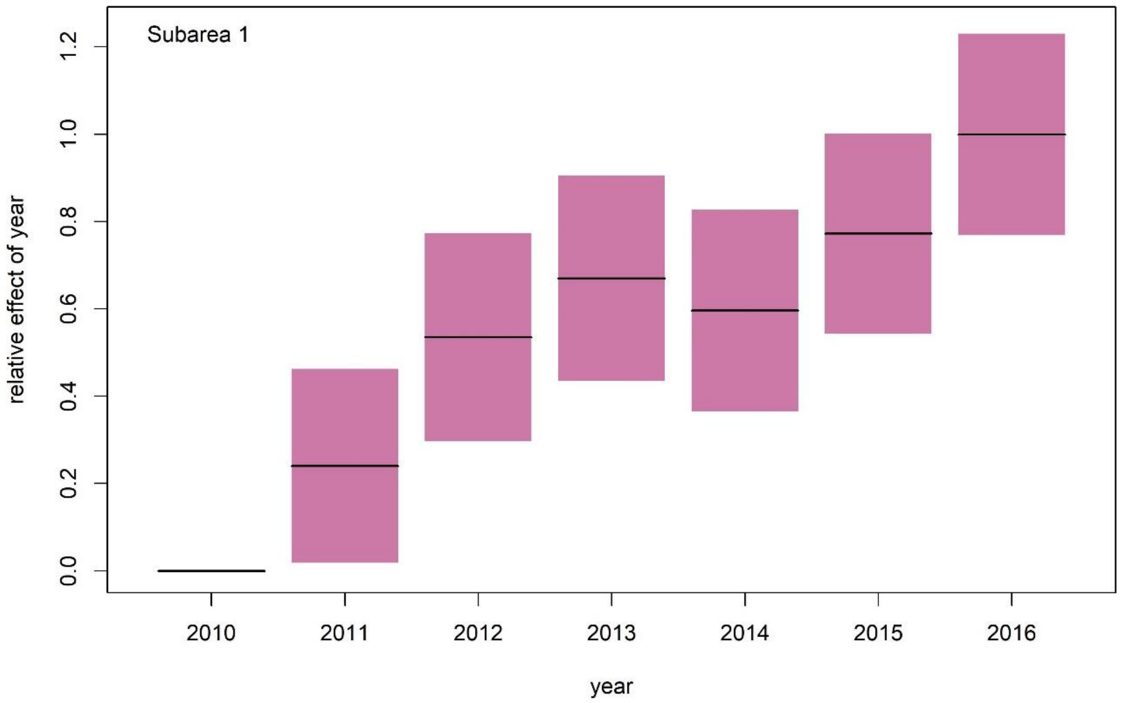
In the following, the annual change per subarea is related to season. This was done because an increase in acoustic porpoise activity could have been caused by e. g. an intense increase of porpoise activity in a single season, or by a moderate increase of porpoise activity in all four seasons.

In subarea 1, a general increase of porpoise detection rates was recorded (Figure 6.23). This increase was visible in all four seasons, with the least increase being in autumn (Figure 6.23).

From 2010 to 2016 in subareas 2 as well as 1, an increase in porpoise detections was observed, with the relative magnitude of increase being smaller in subarea 2 (Figure 6.23 and Figure 6.24). In contrast to subarea 1, this increase was relatively constant over all four seasons in subarea 2.

A completely different trend was observed in subarea 3, where porpoise detections decreased over the study period (Figure 6.25). On a seasonal level, this trend was visible in summer and even more so in winter. During autumn and spring, the activity pattern remained constant over the years.

In subarea 4, neither a generally increasing nor decreasing trend was visible in recorded porpoise detections; overall detections remained relatively constant over the study period (Figure 6.26). Apart from spring, when detections in 2016 were higher than in 2011, detections remained relatively constant over the years and no clear trend was observable (Figure 6.26).



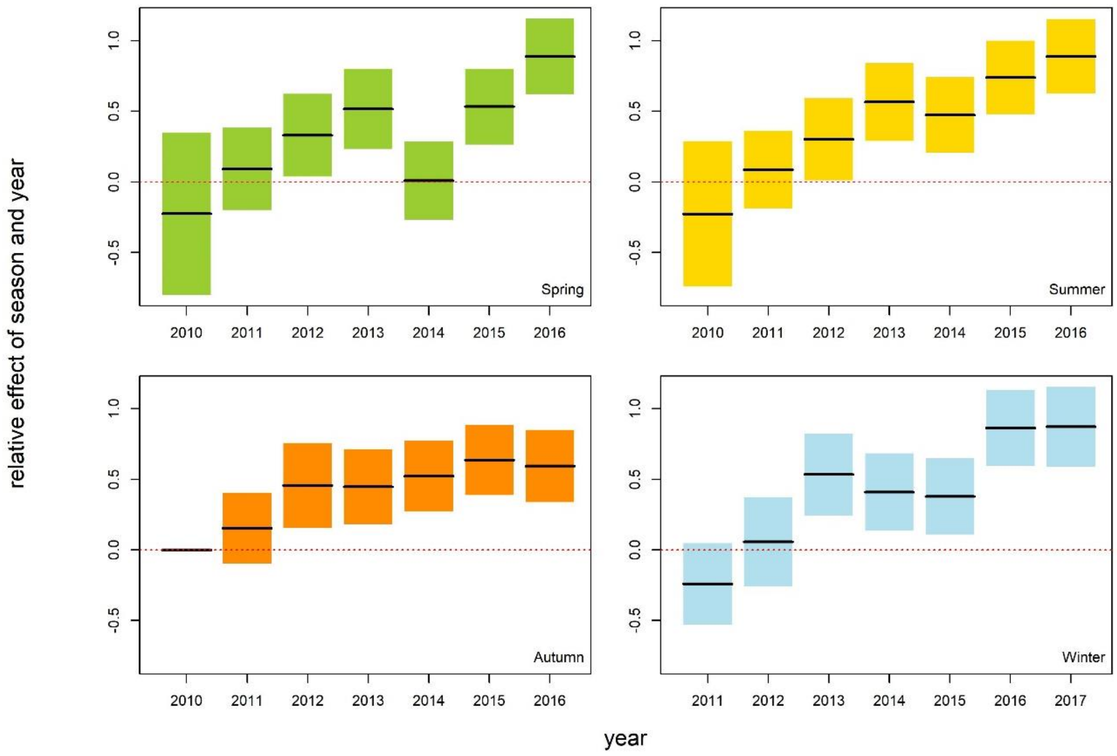


Figure 6.23 Changes in daily porpoise detection rates in subarea 1 in the period from 2010 to 2016, derived from the entire dataset and relative to the seasons. Winter activity is related to the detection rates at the beginning of the referenced year and to the rates during the preceding year. As such, winter 2011 refers to November 2010 to February 2011.

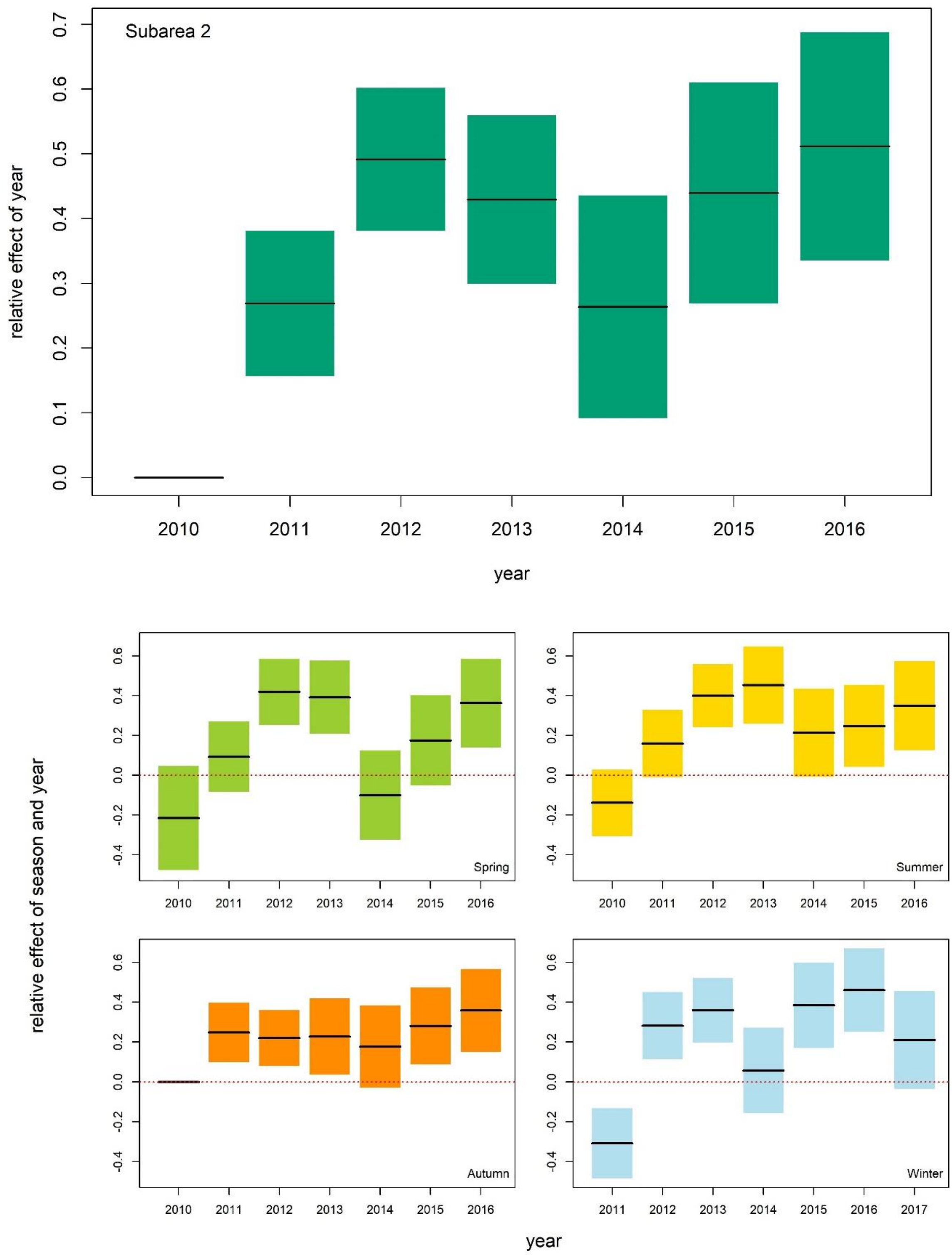


Figure 6.24 *Changes in porpoise activity in subarea 2 in the period from 2010 to 2016, derived from the entire dataset and relative to the seasons. Winter activity is related to the detection rates at the beginning of the referenced year and to the rates during the preceding year. As such, winter 2011 refers to November 2010 to February 2011.*

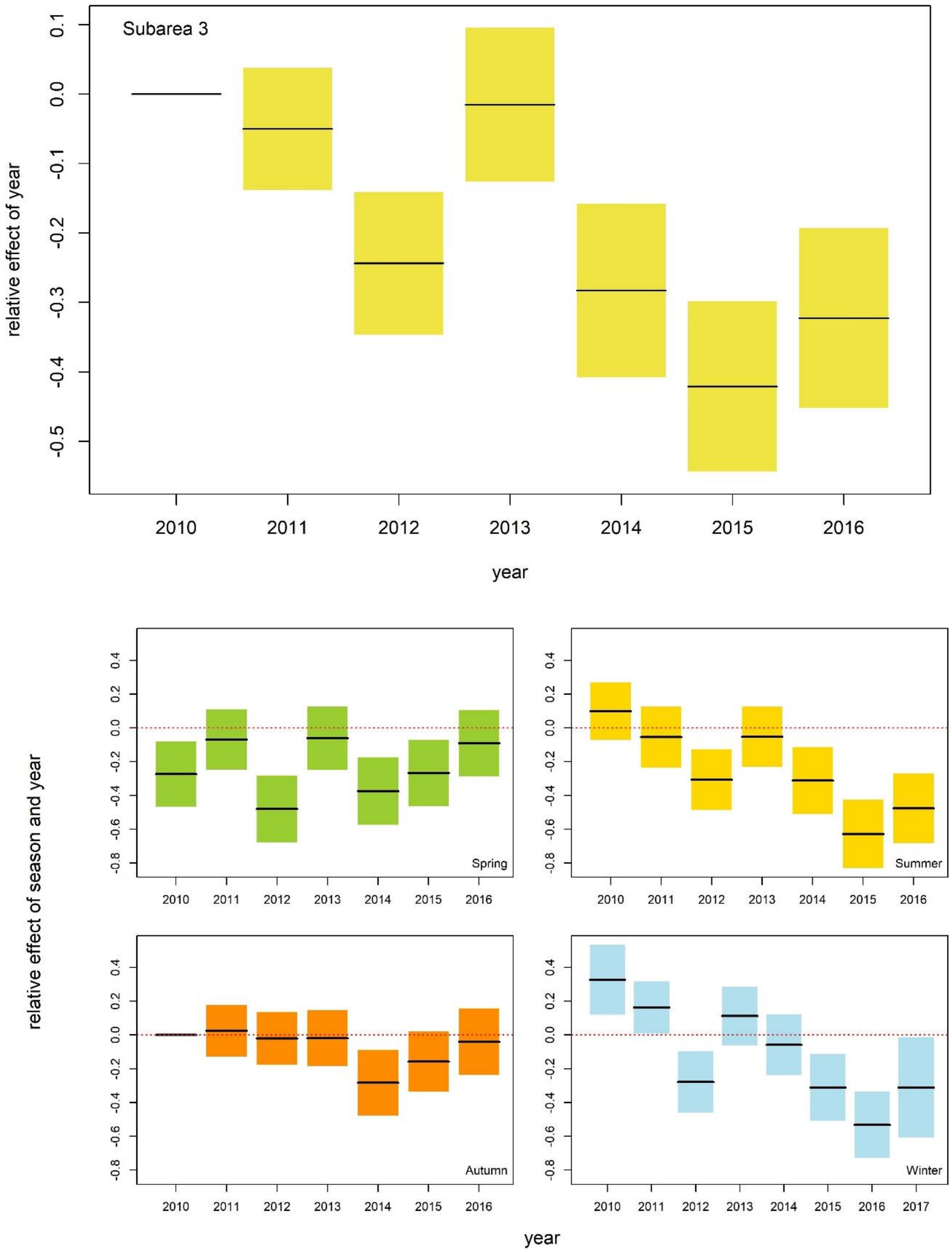


Figure 6.25 *Changes in porpoise activity in subarea 3 in the period from 2010 to 2016, derived from the entire dataset and relative to the seasons. Winter activity is related to the detection rates at the beginning of the referenced year and to the rates during the preceding year. As such, winter 2011 refers to November 2010 to February 2011.*

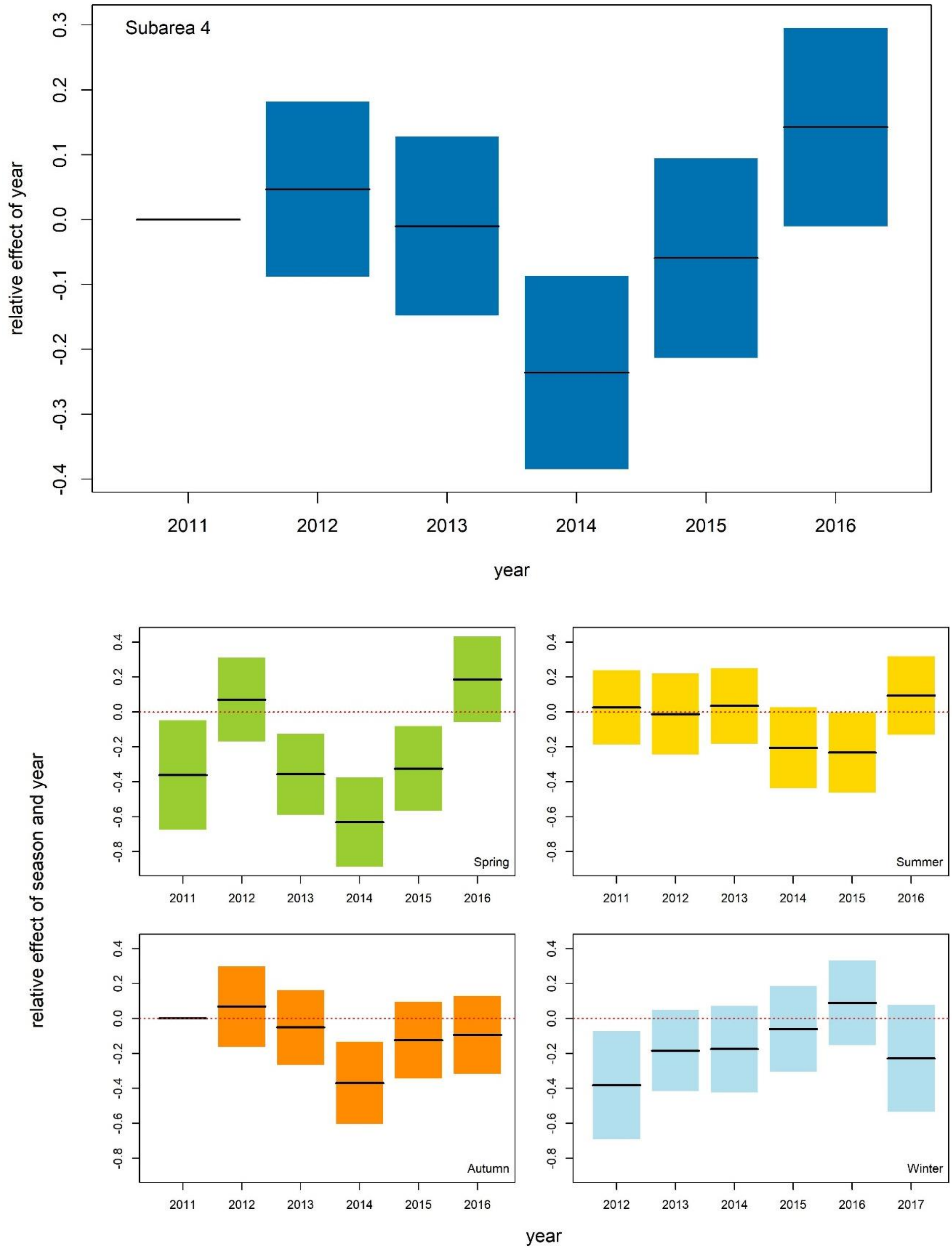


Figure 6.26 Changes in porpoise activity in subarea 4 in the period from 2010 to 2016, derived from the entire dataset and relative to the seasons. Winter activity is related to the detection rates at the beginning of the referenced year and to the rates during the preceding year. As such, winter 2012 refers to November 2011 to February 2012.

6.2.4 Habituation and Sensitisation

Studying habituation or sensitisation usually requires assessing behavioural changes of a clearly defined population or specific individuals. As we do not have any data or a study design suitable for this question, we need to estimate possible habituation or sensitisation processes based on changing porpoise detections. In our study, we cannot know whether we keep recording the same individuals or different animals. Therefore, we assume that at least some of the animals will already have been exposed to piling events and might – if necessary – have learned to adapt their behaviour accordingly. If such an adaption involves fleeing from the piling event more decisively, remaining closer to a pile driving location/returning faster into this area, or a strong change in vocalisation behaviour, then we might be able to observe changes of acoustic porpoise activity per day. We therefore expect the depression in detections on piling days to become less distinct if harbour porpoises habituated over the years to piling events and to become more distinct if sensitisation took place. This means that if there is neither habituation nor sensitisation the detection patterns for days with and days without piling should remain similar over the entire study period. The reverse conclusion, i. e. that in the absence of any distinct pattern neither sensitisation nor habituation of porpoises to piling occurs, is not valid. In this case we can neither prove such processes, nor can we prove that they are not happening.

Habituation and sensitisation processes in relation to a disturbance source do have a temporal and a spatial component. Since up to date there is, to our knowledge, no literature on the temporal aspect of habituation or sensitisation processes in porpoises, we assume that these processes might occur on a yearly basis. The spatial aspect is intertwined with the spatial effect gradient of piling. We chose to concentrate on the global maximum effect range of approximately 20 km from a pile driving site (Table 6.6). Obviously, also habituation and sensitisation processes are likely to occur spatially differently pronounced, due to which fact we formulated a more detailed model. The subdivision of the piling factor into three levels (no piling, piling 10-20 km, piling 0-10 km), however, did not lead to a better insight into habituation and sensitisation processes, and we thus present this model in the Appendix.

*Table 6.6 Parameters used in habituation models. Significance codes: '***' p<0.001, '**' p<0.01, '*' p<0.05, '.' p<0.1, 'n.s.' p≥0.1. Terms for whom no significance estimates are available are assigned by 'n.a.', and terms not included in the model are assigned by '-'.*

variable name	**variable type in model**	**purpose**	**subarea**			
			1	**2**	**3**	**4**
dataset			per subarea			
dp10m	response		n.a.	n.a.	n.a.	n.a.
day of year	cyclic smooth	yearly phenology	***	***	***	***
pile20 year	factor	changes over time; comparing patterns with (20 km radius from monitoring station) and without piling	***	***	***	***
SSTA	smooth	effect of temperature anomalies	**	n.s.	*	***
all clicks	smooth	correct for technical biases	***	***	***	***
wind speed	smooth	effect of wind speed	***	***	***	***
station	random factor	effect of POD-location	n.a.	n.a.	n.a.	n.a.
POD ID	random factor nested in station	sensitivity differences between PODs	n.a.	n.a.	n.a.	n.a.
error distribution	quasi-Poisson		n.a.	n.a.	n.a.	n.a.
temporal autocorrelation	ARMA on day (p=1, q=0)	correct for temporal dependence between consecutive days	n.a.	n.a.	n.a.	n.a.

variable name	variable type in model	purpose	subarea			
			1	2	3	4
AIC		goodness of model fit	26255.99	40953.16	36997.59	19512.1
r-squared adjusted		coefficient of determina-tion	0.2212342	0.1774293	0.2388981	0.2413218
number of data rec-ords		sample size	18093	26312	21332	13657

We formulated a model suitable to capture habituation and sensitisation processes on a yearly basis within 20 km from the piling location, by using a combined factor for year and piling (pile20 year (Table 6.6), based on Gescha 1 (BioConsult SH et al. 2016). No indication for an ongoing process of habituation or sensitisation was found in any of the four subareas (Figure 6.27). However, a strong minimum in porpoise detections on piling days in year 2014 in subarea 4 is noteworthy. Although detections decreased much more rapidly on piling days than on days without piling in subarea 4 between 2013 and 2014, the overall pattern does not prove a sensitisation of harbour porpoises to piling (Figure 6.27). In none of the four subareas, we detected an indication for habituation or sensitisation of harbour porpoises to piling.

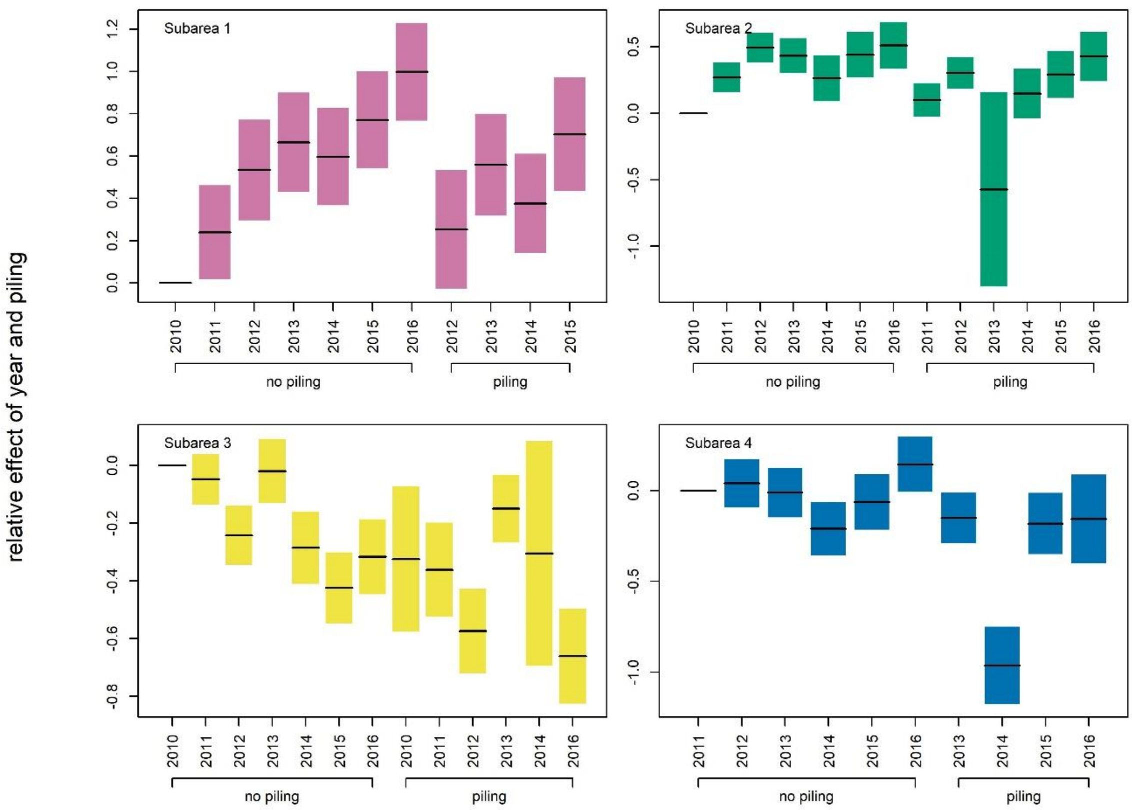


Figure 6.27 Assessing possible habituation or sensitisation processes by comparing "long term trends" for days with and without piling in a 20 km radius around the POD station.

6.3 Discussion

Although passive acoustic monitoring by CPODs is difficult to translate into absolute animal density estimates, it are well suited to estimate relative differences or changes in porpoise abundance (Kyhn et al. 2012; Mikkelsen et al. 2016). In contrast to flight data, porpoise activity is recorded constantly over a long period of time and thus provides a more robust dataset than temporal snap shots of a few hours per month. The downside of this method is that porpoises are detected within a radius of ca. 300 m around a single recording device, and only if the porpoise focuses its vocalisation on the POD. On the other hand, data came from various projects broadly spread over the German North Sea covering a large spatial area which compensates for the disadvantage of strongly spatially restricted recordings. The resulting dataset allowed a good insight into porpoise dynamics in the German Bight.

6.3.1 Long-term trends

Analyses of single stations as well as entire subareas aimed at revealing potential spatially differing trends in porpoise activity within the German Bight from 2010 to 2016. In two subareas, mainly in the eastern, and – less pronounced – in the southern part of the German North Sea and adjacent Dutch waters, we found an increasing trend, while porpoise densities remained relatively constant in the Northern Part and decreased in the central part – an area which generally showed the lowest porpoise detection rates (subarea 3).

The results show that harbour porpoises occur at higher densities in the north-eastern part of the German Bight in summer (subarea 1 and 4), and at higher densities in the central and south western part of the German Bight (subarea 2 and 3) in winter. Within the German Bight, porpoises were distributed more homogenously in winter than in summer. This is generally in line with results from aerial survey studies (e. g. GILLES et al. 2009; PESCHKO et al. 2016). However, in contrast to the common monthly snapshots of flight data CPODs register porpoise activity almost every day of the year. Therefore, data from CPODs are much more detailed, less prone to temporally stochastic events, and hence results might be considered more robust. GILLES et al. (2009) described the Northern German Bight as a hotspot for porpoises in summer especially for mothers and calves, information not available by CPOD data. During spring and autumn, porpoises were more evenly distributed in the German North Sea, but overall numbers decreased in autumn and during winter time, indicating emigration from the German Bight during winter.

We found higher daily porpoise detection rates in winter for the subarea 2 and 3 which are positioned in the (south-)western part of the German Bight. CAMPHUYSEN (2011) found high sighting rates of porpoises for the western Dutch coast between December and March, especially in February and March, and low numbers from April to autumn which corresponds well with our results from subarea 2. Another area with higher porpoise densities in winter was the central part of the North Sea (subarea 3), however its importance for porpoises especially in winter decreased in recent years. From shifts in porpoise detection rates, it can be assumed that at least part of the porpoises spent the summer in areas of the eastern German Bight and winter in the western part of the North Sea. However, tagging studies supporting this assumption are missing and so this deduction still needs to be proven. Another possible deduction of our results would be that part of the porpoises staying over summertime in the Eastern German Bight spent the winter somewhere further north. However, nothing is known about such migration routes. Some tagged porpoises from Skagerrak area migrated more than 900 km in one direction, but none entered our study area which is approximately 450 km to swim from Skagerrak (SVEEGAARD et al. 2011; TEILMANN et al. 2013).

Comparing findings from single stations within respective subareas to the observed trends in the subareas indicates that subareas were chosen well as our samples consistently support the findings. It is interesting, that in our small sample of single-station analyses, the distance to the closest OWF was obviously not important.

Our results fit into the picture of changing harbour porpoise abundance patterns in the North Sea described e. g. by HAMMOND et al. (2013) who showed that porpoise densities decreased in the northern part of the North Sea, especially around Scotland, and increased in the southern North Sea, especially around England from 1994 to 2005. Also, CAMPHUYSEN (2004, 2011) and HAELTERS et al. (2011) reported an increasing number of porpoises along the Belgian and Dutch North Sea where they have been virtually absent until the late 1990s. For the neighbouring German areas, increasing numbers of porpoises were found since 2002 (GILLES et al. 2009; PESCHKO et al. 2016).

This means that porpoise densities were, in an historical context, relatively high when our study period started in 2010, and the still increasing trend despite the start of pile driving activities was, in some subareas, also visible in our data. Some years with seemingly decreasing porpoise detections coincided with high piling activities (e. g. 2014 in subarea 1; Figure 6.22), but in other years the opposite was the case and high piling activities coincided with increasing porpoise detections

(e. g. 2015 in subarea 2; Figure 6.22). It is, however, impossible to rule out a negative effect of pile-driving activity on long-term changes in porpoise activity from this data. At least we can show that the occurrence of porpoises within the German Bight is not decreasing, which in turn could be a concern due to the continued expansion of offshore wind power during the last eight years.

The effect of pile driving on survival and fertility and the consequences on population level is currently discussed among scientists. Estimates for influence of pile driving on population level predicted only slight declines of 0.5 % in the North Sea (KING et al. 2015). This is also in line with recent result from models by NABE-NIELSEN et al. (2018) who could provoke population responses in their model output only with a disturbance radius larger than 20 km. If disturbance radii were 20 km or smaller, changes in porpoise population were indistinguishable from normal fluctuations (NABE-NIELSEN et al. 2018). If the disturbance radius was expanded up to even 200 km, the model of NABE-NIELSEN et al. (2018) predicted larger impacts if wind farms were constructed geographically ordered and over a short period of time. Those criteria were not met in the German Bight.

In overall, harbour porpoise activity increased in our study in two out of four subareas, was stable in one subarea and decreased in the fourth subarea, the central part of the North Sea. Our findings therefore show that a single statement on long-term trends for the whole German Bight alone would not be appropriate. Combining information of porpoise detection rates for the whole study area from 2010 to 2016 with regionally more detailed trends, as has been done by dividing the study area into different subareas, was more adequate. We found different trends in magnitude and direction for the single subareas, and in overall porpoise detection rates have increased in total from 2010 to 2016 for the study area.

6.3.2 Habituation

It is known that harbour porpoises can habituate to disturbance by noise, as was shown by a study examining the length of pinger-induced deterrence effects to the number of disturbance events over the time span of several days (COX et al. 2001). COX et al. (2001) could show that porpoises habituate relatively quickly to pingers, as the animals fled only 50 % as far from the noise source within four days. However, those findings were not supported by experiments with repetitive exposure to continuous noise in captive porpoises (KASTELEIN et al. 2008). Moreover, pile-driving noise or, more generally speaking, construction noise of wind farms has several other characteristics: 1) Pingers generally operate at a far lower source level than pile driving, 2) construction work consists of a wide variety of noise with various characteristics (sonar and other ship noise, pinger and seal scarer and pile driving activity; see chapter 4.2.3), and 3) noise emission is more irregular compared to pingers which emit noise from one location in the same way over several days. Although pile-driving noise has impulsive characteristics, is very loud and clearly perceivable over many kilometres, it has many variable features. Noise characteristics differ for each piling site because of different seabed characteristics, different noise-mitigation systems, different foundations, different hammers etc. In contrast to the study by COX et al. (2001), the source of disturbance is also geographically not static since pile-driving locations takes place at different positions. Therefore, it can be assumed that it may be more difficult to habituate to such disturbance for porpoises. Our results are in line with findings on missing habituation in porpoises to high-frequency noise from vessels, where no clear effects of habituation were observed (DYNDO et al. 2015). In play-back experiments of broadband pile driving sounds, KASTELEIN et al. (2013) also found no short-term effects that would suggest habituation.

Common to all these studies is that a sample of specific individuals was used to study habituation or sensitisation processes and to ensure that those individuals were re-exposed a known number of times to disturbance events. For our study, we were not able to use such data and thus we needed to search for indications of habituation or sensitisation in form of changing harbour porpoise detections on piling days, compared to days without piling. The shortcoming of this approach is that we cannot possibly know whether we re-monitor the same, or different individuals over the years. We thus assumed that a considerable percentage of the animals will be exposed to piling events more than once over the period of our study and consequently had the opportunity to adapt their behaviour accordingly. If such an adaption involves more rapid or more reluctant fleeing from the piling location, returning slower or faster to the piling location, or even merely a strong change in vocalisation behaviour during piling events, then we should be able to observe changes of acoustic porpoise detection rates per day.

In our data analyses, we found varying strong reactions to construction work (see also analyses of short-term data for single wind farms (chapter 4.1), but reaction distances and times did not change over the years. The absence of a distinct pattern does not, however, mean that there was no habituation or sensitisation processes going on. It simply means that the driving factors are so complicated that we cannot disentangle and identify them.

6.3.3 Conclusion

The reasons for increase and decrease of porpoise detection rates in different subareas remain unclear. Porpoises are highly mobile animals and therefore increases in porpoise detections in different subareas do not necessarily imply that the population has increased, but may also indicate a shift of porpoise distribution patterns within the North Sea. In fact, such a shift was assumed by HAMMOND et al. (2013), as porpoise density decreased in the northern part of the North Sea and increased in the southern part, although estimates for the entire population remained relative constant (HAMMOND et al. 2013). Reasons for this shift are unknown and could a. o. be related to prey availability. The apparent increase in relative attractiveness of the southern North Sea is therefore not necessarily due to an increase of attractiveness of the area itself but could also be due to a decrease of attractiveness in other areas, e. g. the northern North Sea.

7 GENERAL DISCUSSION

The Gescha 2 study evaluates small-scale and large-scale responses as well as population-level effects of noise-mitigated pile driving on harbour porpoises in the German North Sea.

Since the previous study of Gescha 1 (2009-2013) noise-mitigation technology has considerably improved. To analyse the effect of noise-mitigation systems (NMS), Gescha 2 data (2014-2016) were compared to and combined with a large part of the Gescha 1 data (2010-2013). Hence, the entire study period lasted from 2010 to 2016.

As noise mitigation improved, noise levels of mitigated pilings investigated for Gescha 2 were mostly below the mandatory noise-protection criterion of the German Federal Maritime and Hydrographic Agency (BSH) of 160 dB SEL_{05} in 750 m distance to the piling locations (BSH 2013), and by on average 9 dB lower when compared to Gescha 1. As the unit of noise level (dB) is on a logarithmic scale, a reduction of almost 10 dB equals a nearly 10-fold reduction of the noise level. It was therefore expected that due to significantly improved NMS the disturbance range and duration regarding porpoise reactions should have been reduced accordingly.

The results of this study indicate

- that at a close range (less than 5 km from construction sites) porpoises were not completely absent but hourly detection rates from passive acoustic monitoring using CPODs were reduced by less than 60 % on average (the same was found for Gescha 1 data).
- that the large variation among projects cannot be explained by differences of noise levels from pile driving.
- that despite strongly lowered broadband noise levels from pile driving, no reduction in porpoise responses was found.
- that besides pile driving also other construction-related activities contribute to the observed disturbance effects.
- that seal scarers cause effects as strong as those of piling within a distance of at least 1500 m.
- that no habituation or sensitisation to piling activities in the German Bight took place.
- that despite strong short-term effects, harbour porpoise detection rates showed signs of an increase in the German Bight from 2010 to 2016 (but there was a strong year-to-year fluctuation).

Small-scale and short-term effects

Though not all harbour porpoises react in the same manner to impulsive noise (VAN BEEST et al. 2018), a considerable proportion of these animals respond to construction activities at offshore wind farms by leaving the area up to a certain distance and timespan (BRANDT et al. 2018; BIOCONSULT SH et al. 2016). The onset of behavioural reactions during pile driving occurred at noise levels from 140 up to 152 dB re 1 µPa²s SEL, according to different studies (BioConsult SH & IfAÖ 2010, 2014; Brandt et al. 2011; Haelters et al. 2012; Dähne et al. 2013; BioConsult SH et al. 2014).

Marine mammals may respond to underwater noise for two different reasons:

1. Loud noise may impair the hearing abilities and lead to physical damage.

2. Marine mammals may feel uncomfortable with noise of lower levels if it is unusual to their natural habitat; it might then be perceived as a threat.

It is a common observation that animals do not respond uniformly to anthropogenic disturbance, but that their response shows a high individual variation, as well as variation among sites and different phases of their annual cycle. The differences among individuals exposed to similar stimuli is often discussed as a form of risk-taking, similar to a response to predation when for example hungry animals are more likely to take a risk than repleted animals (Frid & Dill 2002). In the same way, it is expected that the tolerance of marine mammals to underwater noise depends not only on loudness of a signal but also on the status of the individual. Although some authors suggest general behavioural thresholds, for example a given value above the hearing threshold (Tougaard et al. 2015), there is increasing evidence that various characteristics of a noise source apart from loudness, here especially the context of a disturbance, defines the strength of a response (Ellison et al. 2011). This means that no uniform response to a certain noise signal can be expected, but that regional and seasonal variation of a response will be the rule rather than the exception.

Even though, due to differing habitat characteristics and habitat use, a uniform response of harbour porpoises to pile driving and other construction-related noise-intense activities was not to be expected across different OWFs or even construction sites, an average response was still assessable by different monitoring and statistical modelling methods. Aerial surveys were suitable to directly show spatial avoidance behaviour during and shortly after pile driving if flights took place at those times. CPODs, well suited for continuous acoustic monitoring at selected localities, allowed for a fine-scale temporal resolution and thus were most appropriate for the assessment of the effect change over time. The adequate assessment of the spatial effect range, however, depends on a wide range of available distances of CPOD monitoring positions to construction sites, which was not always given for the present study. In combination, both aerial surveys and passive acoustic monitoring using CPODs provided a consistent picture of the effect range and duration of OWF construction activities on harbour porpoises in the southern North Sea.

Based on hourly CPOD data analysed under the same model approach used in the Gescha 1 study and including all mitigated piling events (so-called Classic-type or Cl-type models), a response of porpoises to mitigated pile driving was found up to a distance of 17 km for Gescha 2 and 15 km for Gescha 1. Digital aerial surveys provided similar results: For the Gescha 2 OWFs, a maximum displacement distance between 11.4 km and 19.5 km was found. With observer-based aerial survey data of the Gescha 1 study, an effect range of up to 19 km during pile driving was reported (BioConsult SH et al. 2016). However, a strong variation in effect ranges for single OWFs was detected in Gescha 1 (BioConsult SH et al. 2016) and Gescha 2. These variations show how much porpoise reactions were project-dependent, so that effect ranges might not primarily have been dependent on loudness alone but also on site-specific characteristics and/or other peculiarities. In order to investigate whether cumulative effects due to significantly faster piling sequences during Gescha 2 caused stronger displacement effects, the dataset was further reduced to a subset of piling events that were at least three days apart. This dataset was considerably less susceptible to possible cumulative effects and the base for so-called Reference-type models. However, similar to the CI-type models, hourly porpoise detection rates were reduced by 20 % in alike distances during pile driving with both Gescha projects (13 km from Gescha 2 construction sites; 11 km from Gescha 1 construction sites). CPOD data from both Gescha studies showed that detection rates for the close-range distance class of up to 5 km from construction sites were reduced by not more than 60 %. Thus, not all animals left the affected area. Following, not only the effect range but also the effect strength at a certain distance has to be taken into account when evaluating piling effects. Because nearly all pilings in the Gescha 2 study period were accompanied by a well-functioning NMS, resulting in broadband noise levels mostly below 160 dB SEL_{05} in 750 m distance to the piling location, those far-reaching spatial effects, with at the same time an effect strength in the close range similar to that found by Gescha 1, were an unexpected result. This raised the question why we still found such far-reaching and strong effects?

Considering literature findings, the effect ranges found by Gescha 2 for mitigated pilings (Table 4.9) were not far from those of unmitigated pilings (TOUGAARD et al. 2009: >20 km; BRANDT et al. 2011: 18 km; HAELTERS et al. 2012, 2015a: 20-22 km; DÄHNE et al. 2013a: 20 km; BIOCONSULT SH 2014: 17 km (tripods); NEHLS et al. 2016: 15 km; ROSE et al. 2016: 20-25 km). This came as a surprise, since from different studies it is known that disturbance of porpoises by impulsive sound is clearly related to the noise level: The higher the noise level the stronger the displacement effect (BIOCONSULT SH et al. 2016; DÄHNE et al. 2017; TOUGAARD & DÄHNE 2017). Thus, noise mitigation should reduce effect ranges, which was e. g. shown by a study of DÄHNE et al. (2017) who found an effect range of 12 km with pile driving for the OWF DanTysk mitigated by bubble curtains, compared to 18-25 km effect ranges with unmitigated pile driving at other OWFs. Similarly, at the OWF Trianel Windpark Borkum Phase I (BW2), noise-mitigated piling with the effective noise-mitigation system BBC2 led to a reduction of the disturbed area by even 90 % (effect range 7 km) compared to unmitigated piling (effect range 25 km), whereas the less effective system BBC1 only led to a reduction of the disturbed area by 56.4 % (effect range 16 km) (NEHLS et al. 2016; ROSE et al. 2016). At BW2, a difference of only 4 dB in piling-noise levels between a BBC1 and BBC2 caused a strong difference in the effect range. Also Gescha 1 showed that noise-mitigated piling led to reduced disturbance ranges, compared to unmitigated piling (BIOCONSULT SH et al. 2016). Principally, the situation was analogous to the improvement of noise-mitigation technology from Gescha 1 to Gescha 2, which, however, resulted in no further reduction of effect ranges. In the following section we will discuss why the improvement of NMS did not further reduce the impact ranges on porpoises.

The effect duration of pile driving on harbour porpoise detections was similar for Gescha 2 and Gescha 1, even though Gescha 2 pilings were better mitigated. With our Reference-type models we found that in the vicinity of pile driving the detection rates were reduced from 17 hours before to 18 hours after Gescha 2 pilings, and from 15 hours before to 15 hours after Gescha 1 pilings. With the Classic-type models, we found an effect duration of 23 hours with Gescha 2 and 25 hours with Gescha 1 data in 3 km distance to piling; after pile driving, the effect duration was 38 hours with Gescha 2, and 30 hours with Gescha 1 data. The results of Gescha 2 were within the range of other studies which reported negative effects lasting for up to two days within close vicinity of foundations piled without noise mitigation (Tougaard et al. 2009; Brandt et al. 2011; BioConsult SH et al. 2014; BioConsult SH & IfAÖ 2014).

What might have been the reasons that caused no reduction in the effect range and duration of Gescha 2 pilings, even though pile driving was conducted under improved noise mitigation? We discuss five explanatory approaches, which might either have been the sole explanation or, more likely, might have led to those unexpected findings in one or the other combination.

1. A stereotypical response of harbour porpoises to noise within a certain noise-level range may be hypothesised, but has has not been subject of research so far. When noise levels initiating this stereotypical answer are exceeded, animals might swim away for a certain time and distance, irrespective of the source noise level within a certain range of noise. This kind of response of harbour porpoises to pile driving is included into the DEPONS model approach (van Beest et al. 2018). DEPONS also takes into account that the initial noise level at which a reaction occurs may depend on the physical condition of the animal: Weaker animals are less likely to change their behaviour and withstand negative effects longer (van Beest et al. 2018). Only for higher piling-noise levels a positive correlation with response distance would exist according to this hypothesis, so that improvement of NMS would only show desirable results if piling noise would be reduced from high sound levels where the effect range is correlated with sound levels to intermediate levels where the stereotypical response occurs, or if noise levels are reduced below the noise-level range for a stereotypical response. The hypothesis is supported by our model results. For pilings not prone to cumulative effects we found a noise level of around 165 dB of the SEL_{05} at 750 m distance below which the response range during hours of piling did not further decrease (Figure 4.13). The model outcome indicates that the range of the displacement effect does not change much at sound levels below 165 dB. This might be explained by animals maintaining a certain minimum escape distance independent of the respective noise level if it is within a certain intermediate noise-level range. Thus, animals may react stereotypically as soon as pile-driving noise exceeds a certain individually differing unknown threshold level that has to be regarded in the context of a seasonally and site-specific different condition of animals. In contrast, the hypothesis is not supported by studies showing continuously decreasing effect ranges below 165 dB (Brandt et al. 2011, BioConsult SH 2014, Nehls et al. 2016, Rose et al. 2016). However, regarding piling-noise levels we only had access to the broadband SEL_{05} cut off at 20 kHz, so we could not refer to noise levels being weighted according to the hearing spectrum of harbour porpoises; hence, we might not have dealt with the noise relevant for porpoises.

2. Seal scarer noise may cause displacement effects on porpoises similar to those of moderate piling noise. Also to this type of noise might animals exhibit a stereotypical response by swimming away to a minimum distance that may well be above 2 km (seal scarer effects up to 7.5 km were shown by Brandt et al. 2013). Effect ranges might thus partly reflect a porpoise response to the seal scarer rather than to piling noise. These devices were applied at all Gescha 1 and Gescha 2 OFWs, except for Gemini where another type of harassment device was used (FaunaGuard). Accordingly, porpoise detections were already found to decrease if the seal scarer noise exceeded a broadband level of 119 dB SEL (Brandt et al. 2013a), but only if piling noise levels exceeded 143 dB SEL (Brandt et al. 2018b). When modelling sound propagation of frequency-weighted noise levels (U.S Dept. of Commer., NOAA 2016) we found indi-

cations that even in up to 20 km distance weighted noise levels for the seal scarer were above those of piling noise (Figure 3.4), which would theoretically allow for strong effects of a seal scarer on harbour porpoises. In further support, we showed that in 1.5 km distance to construction sites the effects of a seal scarer were at least as strong as piling effects (Figure 5.2). However, seal scarers were also used at OWFs DanTysk and Sandbank. Both projects are located approximately 15 km apart from others in a similar area. Whereas DanTysk foundations were piled in 2013 with NMS under development and noise levels averaged at 167 dB SEL_{05} in 750 m, Sandbank was constructed in 2015 with a well-functioning NMS reaching average noise levels of 159 dB SEL_{05} in 750 m. Both projects used the seal scarer as standard methodology. At DanTysk, the response range was 6 km during pile driving, whereas based on the same approach the response range for Sandbank was 25 km. Thus, seal scarer effects cannot be the only explanation, but still might have contributed to the fact that no improvement of effect range and duration from Gescha 1 to Gescha 2 was found.

3. Shipping and other construction-related noise may cause a response of porpoises already some hours before deterrence and piling occurs, but also during and after piling when boat-traffic effects may add to piling effects. Animals might react directly to this type of noise (Barlow 1988; BioConsult SH 2010; Hermannsen et al. 2014; Dyndo et al. 2015; Wisniewska et al. 2018), or by learning that noise-intense piling follows soon. For those animals leaving the area before piling starts a further improvement of NMS would be to no avail. A reduction of detection rates before deterrence and pile driving was shown for most OWFs investigated during both Gescha studies, so it can safely be assumed that displacement effects of construction-related noise (most probably ship-related noise) exist. A decline of detection rates even before piling and deterrence was found in up to 15 km distance for Gescha 2 (Figure 4.24). Within a closer range of 10 km, detection rates were reduced from 0.54 DPH (s.e.: 0.007) during the phase Baseline (>24 hours before piling) to only 0.41 DPH (s.e.: 0.018) during the phase Traffic (1-3 hours before piling) (Table 4.11). Relevant construction-related noise comprises ship sonars and thrusters (Kastelein et al. 2017), lowering of the legs of jackup barges, boats carrying anchors with long chains in order to fix the construction vessel at the piling site, and pre-blows of the bubble curtain for blowing sand out of the hose some hours before noise mitigation officially starts. The effects of boat traffic might have been at least as severe with the Gescha 2 OWFs as with Gescha 1 OWFs, since improved noise mitigation also comes at the cost of more ships in the area carrying and applying one or more noise-mitigation systems. Even though response distances of high-frequency cetaceans like harbour porpoises of more than 10 km to vessel noise are not described so far, other activities (e. g. scratching noise of jackup barges) might have had farther-reaching effects.

4. Cumulative effects of subsequent pilings on harbour porpoises are more likely to have occurred with Gescha 2 than with Gescha 1 wind farms, as piling schedules became tighter over time. Such cumulative effects could have outweighed the benefits of improved noise mitigation. However, Reference-type models on effect range and duration, which were less affected by cumulative piling effects, found differences between Gescha 1 and 2 that were similar to those found by the Classic-type models. Likewise, Gescha 1 found no indication for cumulative piling effects (BioConsult SH et al. 2016). On the other hand, longer pilings within the combined Gescha 1 and Gescha 2 dataset had stronger effects at short distances with the Classic-type model on the whole dataset (where cumulative effects were more likely to occur as all mitigated pilings were included), but not with the Reference-type model on the dataset re-

duced to more segregated pilings (thus with a lower probability of cumulative effects being included). We conclude from these findings that within a close range around construction sites the effects of longer piling duration may be more severe if such piling takes place within a tight construction schedule.

5. OFW projects differed in terms of habitat characteristics. Since the response of harbour porpoises to disturbance also depends on habitat use and habitat characteristics, the unexpectedly high effect range found by Gescha 2 might be due to habitat differences outweighing the positive effects of improved noise mitigation. But also the heterogeneous quality of the data available for analysis might have been relevant. Among the OWFs suitable for analysis, the largest minimum effect range during pile driving was found at OWF Sandbank (25 km); only half of that range was found at Amrumbank West, Butendiek and Nordsee One (12-13 km). The extraordinarily high effect range at Sandbank might be explainable by particularities of that area which is presumably rich in the seasonally preferred but patchily distributed prey of sandeels (fat-rich fish preferred by adult porpoises and especially important for lactating females) and sand gobies (due to their small size preferred by juvenile porpoises) (LEOPOLD 2015). The densities of these fish species, which were high in that area, turned out to be a significant explanatory variable in global models on hourly CPOD and aerial survey data. Hence, the area around Sandbank is obviously a preferred one for harbour porpoises in spring and summer (see seasonal aerial survey analysis: chapter 4.2). On the other hand, at OWF DanTysk in the same region but with other local characteristics, a response of porpoises during pile driving was found in only up to 5-10 km distance by Gescha 1, even though pilings were louder than those for Sandbank (BIOCONSULT SH et al. 2016). Concluding, even in relatively similar areas in terms of harbour porpoise presence and phenology the response of these animals to construction noise can be quite different, a fact possibly being related to specific habitat and prey-distribution characteristics that overlay the effects of anthropogenic noise. But also the season when piling takes place might be relevant. Highly variable spatio-temporal patterns of porpoises were found to indicate a great flexibility of these animals in variable environments (ZEIN et al. 2019).

Among the OWFs, a special focus was on Gemini due to the fact that all pilings were unmitigated. Additionally, the response of porpoises to pile driving for this wind farm was used as a major reference regarding impacts of unmitigated piling on harbour porpoises for the DEPONS individual-based modelling approach (VAN BEEST et al. 2015; NABE-NIELSEN et al. 2018), causing a great interest in comparing the data of this wind farm to the results of the German projects accompanied by noise mitigation measures. Our modelled range (13 km [s.e.: 11-17 km]) and duration (5 hours [s.e.: 3-6 hours]) of piling effects is more or less in line with CPOD results of NABE-NIELSEN et al. (2018) (deterrence range: 9 km; effect duration: 5 hours within close range), and GEELHOED et al. (2018a) (effect range: 10-20 km; effect duration: 6-10 hours in up to 10 km distance). When comparing the effect duration found at Gemini with effect durations found at the Gescha 2 OWFs with noise-mitigated pile driving and the operation of a seal scarer, 5 hours was by far the lowest value. The modelled response range of 13 km was within the range of most Gescha 2 OWFs (except for Sandbank), which is interesting since pile driving for Gemini was unmitigated and a larger effect range and duration would have been expected (however, piling-noise levels were not assessed at Gemini). One difference between Gemini and the other investigated OWFs was the usage of the seal scarer at the latter, whereas at Gemini a FaunaGuard was used. The FaunaGuard is especially designed to disturb porpoises, but it is operated at lower noise levels (VAN DER MEIJ et al. 2015). GEELHOED et al. (2018a) found no negative effects of the FaunaGuard on the acoustic activity of harbour porpoises at Gemini. Still, the peculiarities of the construction process at Gemini, compared to that of most other OWFs in the North Sea, as well as the farther-reaching effects of unmitigated pile driving at most other OWFs (TOUGAARD et al. 2009; BRANDT et al. 2011; HAELTERS et al. 2012, 2015; DEGRAER et al. 2013; DÄHNE et al. 2013; NEHLS et al. 2016; ROSE et al. 2016) renders Gemini less suitable to be representative for the majority of OWFs in the North Sea in population models. Instead, it would be desirable to base population models on a variety of wind farms.

In summary, the large avoidance distance of harbour porpoises to pile driving might have resulted from a combination of the aspects discussed above: Stereotypical escape distance over an intermediate noise-level range; stereotypical escape distance regarding the noise of seal scarers; ship and other construction-related noise that already prior to the start of deterrence drives out a large amount of animals; cumulative effects due to fast piling sequences. But above all, high seasonal and inter-annual variability of harbour porpoise occurrence in the North Sea due to habitat characteristics could have masked construction-related effects and led to heterogeneous results.

Large-scale and long-term population-level effects

As the effects of OWF construction activities on survival and fertility of harbour porpoises and possible consequences on the population level are currently discussed among scientists (e. g. KING et al. 2015; NABE-NIELSEN et al. 2018), a major question of the Gescha study was whether such activities in the German Bight had large-scale and long-term consequences for this species within the study area. This topic was assessed by analysing daily porpoise detection rates obtained by CPODs during the years 2010 to 2016, and by evaluating digital aerial survey data of the years 2014 to 2016. CPODs are best suited to monitor small areas continuously and even allow for the evaluation of relative shifts in abundance (KYHN et al. 2012; MIKKELSEN et al. 2016; CARLÉN et al. 2018). CPOD data for the present study originated from various OWF projects broadly spread over the German North Sea and covering a large spatial area. Therefore, the disadvantage of strongly spatially restricted recordings was partly compensated, and the resulting dataset allowed for a good insight into large-scale porpoise dynamics in the German Bight. Digital aerial surveys provide absolute densities and cover greater spatial areas without larger gaps but are restricted to discrete survey dates (more or less monthly). The aerial surveys of Gescha 2 covered large parts of the German Bight and were conducted by three digital methods, which was accounted for in the models by including method as a factor.

Regarding the seasonal pattern of occurrence in the study area, harbour porpoises expressed highest summer densities and detection rates in the north-eastern part of the German Bight, a region that is also described as a high-density area in summer for porpoises by GILLES et al. (2009). In winter, less porpoises were recorded in the German Bight, with highest densities and detection rates in the south-western part of the area. Following, at least a part of the porpoise population spent the summer in eastern areas and the winter in western areas of the North Sea. Harbour porpoises were distributed more homogenously in winter than in summer within the German Bight. Overall numbers decreased in autumn and during winter, indicating emigration from the German Bight during winter, possibly to Dutch and Belgian waters where highest densities are found in late winter and early spring (CAMPHUYSEN 2011; GILLES et al. 2016b). Generally, our results are in line with those of aerial survey studies from literature (e. g. GILLES et al. 2009, 2016; VISQUERAT et al. 2015; PESCHKO et al. 2016).

Digital aerial survey data of the years 2014 to 2016 showed that it made a difference whether a wind farm was under construction within the study area, or not. During the construction phase, which comprised cumulated effects of construction activities and ship traffic between piling events, a lower overall presence of porpoises around active OWFs (those under construction) was found, compared to the remaining survey area. When looking at daily CPOD data, some years with decreased porpoise detections coincided with strong piling activities (e. g. 2014 in subarea 1). However, in other years the opposite was true, and strong piling activities coincided with increasing porpoise detections (e. g. 2015 in subarea 2). When looking at long-term trends of daily harbour porpoise detection rates, spatial differences occurred among the investigated subareas. In the eastern and, less pronounced, the southern part of the German North Sea and adjacent Dutch waters, we found an increasing trend from 2010 to 2016, whereas porpoise detections remained relatively constant in the northern part and decreased in the central part of the study area. The latter subarea, however, was less important for harbour porpoises, as it generally showed low porpoise detection rates. Regarding the entire study area, porpoise detection rates increased from 2010 to 2016. Hence, even though we could not completely rule out a negative effect of offshore construction activities on population level in the study area, such an effect was unlikely to have occurred when considering the combined Gescha 1 and 2 dataset. In this respect, our results are in line with recent estimates of the effects of pile driving on porpoise abundance, predicting only a slight population decline of maximal 0.5 % in the North Sea (KING et al. 2015). They are furthermore in accordance with newest results obtained by application of the DEPONS model (NABE-NIELSEN et al. 2018). By simulating cumulative piling effects in the North Sea within the DEPONS model, these authors found only minor and short-term population-level declines if disturbance radii of single pilings were in the range of 20-50 km. If disturbance radii were 20 km or smaller, changes in porpoise population were even indistinguishable from normal fluctuations (NABE-NIELSEN et al. 2018). Only if disturbance radii were extended up to 200 km, and wind farms were constructed geographically ordered and over a short period of time, the DEPONS model predicted more severe population-level consequences. The latter assumptions were clearly not met by OWF construction activities in the German Bight. In overall, we found minimum effect ranges of 15-17 km (25 km only for OWF Sandbank) which, according to the DEPONS model, would have meant that population-level changes were unlikely to be detectable. This was affirmed by our results from analyses of long-term trends in the study area.

A slightly increasing trend of daily detection rates from 2010 to 2016 in the study area was found, even though a considerable year-to-year fluctuation occurred. Generally, harbour porpoise distribution patterns in the North Sea are prone to shifts over time. HAMMOND et al. (2013) showed that from 1994 to 2005 porpoise densities decreased in the northern part of the North Sea around Scotland, while densities at the same time increased in the southern part around south-western England. Estimates for the entire population remained relatively constant, also in consecutive years until 2016 (HAMMOND et al. 2017). Pointing in the same direction, CAMPHUYSEN (2004, 2011) and HAELTERS et al. (2011) reported increasing numbers of porpoises in the Belgian and Dutch North Sea where these animals have almost been absent until the late 1990s. Similarly, for the neighbouring German waters increasing numbers of porpoises have been found since 2002 (GILLES et al. 2009; PESCHKO et al. 2016). As to the fluctuation of porpoise detection rates within our study area with an increase and decrease in certain subareas, the reasons for these shifts remain unclear. Porpoises are highly mobile animals and therefore an increase in porpoise detections in a certain subarea does not necessarily imply that the population has increased, but might also indicate a distributional shift of porpoises within the North Sea, as shown by HAMMOND et al. (2013). Reasons for regional shifts are unknown and might among others be related to prey availability. The apparent increase of the attractiveness of the southern North Sea might therefore not necessarily be tantamount to a real increase of attractiveness of the area due to possibly improved habitat and food conditions but could also be related to a decrease of attractiveness of the north-western North Sea. Around Scotland, overfishing (FREDERIKSEN et al. 2004) led to reduced sandeel populations, and warmer waters due to climate change caused a mismatch between the timing of copepod prey availability and larval sandeels (VAN DEURS et al. 2009; GREEN 2017), which in the end resulted in a higher mortality of harbour porpoises in the north-western North Sea due to starvation (MACLEOD et al. 2007) or a shift of these animals to the southern North Sea (GILLES et al. 2009). In conclusion, regarding long-term population-level changes of harbour porpoises in the North Sea, food availability is probably a major driving factor, whereas cumulative OWF construction activities in the German Bight up to now have no measurable effect on harbour porpoise population level.

Conclusion

Even though noise-mitigation technology has improved considerably from Gescha 1 to Gescha 2, the effect range and duration before, during and after pile driving has not been reduced. Possible positive effects of improved NMS might have been counteracted by the presence of more service ships and vessels in the area, due to a tighter pile-driving schedule and the fact that often more than one NMS was applied. Furthermore, we found a large heterogeneity in response distances both among Gescha 1 and Gescha 2 wind farms. This could not be brought into relation to average piling noise within single projects. Accordingly, no clear reduction of impact ranges between Gescha 1 and Gescha 2 was found, although a considerable noise reduction was achieved (noise reduction from on average 167 dB in Gescha 1 to 158 dB SEL_{05} in Gescha 2).

Therefore it has to be asked whether the further reduction of pile-driving noise must currently be regarded as the main issue concerning the protection of harbour porpoises, or whether any additional positive effect is counteracted by construction noise other than piling, e. g. from construction and service ships as well as from the applied deterrence measures, which raises the question whether the maximum positive effect of noise mitigation might already have been achieved regarding current construction procedures.

On a larger spatial and temporal scale, the regional harbour porpoise population did not seem to have been negatively affected by still relatively large effect ranges of pile driving and other construction-related activities. Harbour porpoise detections in total even increased over the period of the Gescha 1 and Gescha 2 studies (2010-2016). Following, environmental factors and habitat characteristics appeared to be more relevant for long-term porpoise abundance trends in the German Bight than possible negative long-term effects due to pile driving and other construction-related activities.

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