Marine Mammal surveys – pre-investigations for offshore wind farms in the area North Sea I

Marine mammals

Energinet Eltransmission A/S

Date: 22. October 2025

Contents

Rev. no.	Date	Description	Done by	Peer reviewed by	Quality assured by	Approved by
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Preface

This report was commissioned by Energinet. It describes results obtained from the two-year marine mammal survey program in connection with the planned construction of the offshore wind farms in the North Sea I area.

The report builds upon existing knowledge, as well as new data and analysis collected and conducted during this program and consists of six main chapters and an initial report summary. Chapter 1 is Introduction and objectives of the report. Chapter 2 provides baseline knowledge for each relevant species in the North Sea. Chapter 3 describes the methods, and Chapter 4 describes the results. In Chapter 5, a status per species is provided and Chapter 6 provides the knowledge gaps and Chapter 7 the references.

Declaration of work contributions

This report was published by NIRAS and prepared by Aarhus University and NIRAS as detailed below. BioConsult and OS Energy (third-party contractors) contributed to offshore survey planning and execution.

Quiet-Oceans (France) have conducted the underwater noise models for the North Sea.

From Section for Marine Mammal Research, Aarhus University: Signe Sveegaard (editor and responsible for field work and report writing of the subjects of harbour porpoise passive acoustics and aerial surveys, quality assurance and handling of CPOD/FPOD data), Emily T. Griffiths (report writing and analysis of the content for noise and other whales), Cristina Marcolin (analysis of the data for noise and dolphins), Saskia Cathrin Tyarks (analysis of the data for dolphins), Mia Lybkær Kronborg Nielsen (analysis of data from array studies of porpoises near turbines), Ellen Rose Jacobs (analysis of data from eight soundtraps near turbines), Jakob Tougaard (field work, analysis and writing of report related to noise and array studies of porpoises near turbines), Rikke Guldborg Hansen (responsible for analysis of aerial harbour porpoise survey data), Floris van Beest (analysis of FPOD passive acoustic harbour porpoise data), Jacob Nabe-Nielsen (writing report related to seals), Anders Galatius (writing report related to seals).

From Section of Zoophysiology, Institute for Biology, Aarhus University: Michael Ladegaard (analysis of decidecade levels at six noise monitoring stations, minke whale call detection analysis, and analysis of data from array studies of porpoises near turbines).

From NIRAS: Line Anker Kyhn (writing of report, field work for aerial marine mammal surveys). Mark Aarup Mikaelsen and Sidsel Marie Nørholm (analysis of USBL noise data, writing of 3.3.6 and 4.4.6).

The comparison of CPOD and FPOD detections was commissioned to Bioconsult who consequently produced a separate report on this subject (Voß & Diederichs 2025). In the present report, a short summary with main results using text directly from the report is inserted in "section 4.1.1.4 Comparison of CPOD and FPOD detections".

The report and associated investigations were financed by Energinet.

Fredrik Oscar Christiansen, Section for Marine Mammal Research Aarhus University was responsible for scientific review and Jesper Fredshavn and Camilla Uldal, DCE – Danish Center for Environment and Energy, Aarhus University, was responsible for quality assurance.

Maria Wilson, NIRAS, was responsible for quality assurance of the report for NIRAS. There is consensus among all contributors with regard to the main conclusions of the report. Søren Granskov gave final approval from NIRAS for the publication.

Energinet wrote the three first paragraphs of the "Introduction and Objectives" and have commented on draft versions of the report and comments as well as author replies will be made available at DCEs homepage: https://dce.au.dk/udgivelser/oevrige-dce-udgivelser/eksterne-udgivelser/2024.

List of key terms

A list of terms (in English and Danish) and their explanations in relation to the Marine Mammal surveys – pre-investigations for offshore wind farms in the North Sea I survey area.

Table 0-1 Terminology including Danish and English terms as well as explanations

English (abbreviation)	Danish	Explanation
Pre-investigation area	Forundersøgelsesområde	The area defined by Energinet as North Sea I pre-investigation area
Survey area	Undersøgelsesområde	The area for which field investigations have been carried out and supplementary data and information have been collected. NSI plus 20 km buffer zone around it.
CI	Konfidensinterval	The 95% confidence interval
CV	Variationskoefficient	The coefficient of variation
DEA	Energistyrelsen	Danish Energy Agency
DPM/Day	Minutter med detektioner per dag	Number of minutes per day where harbour porpoises were detected
DPD	Dage med detektion (marsvin eller delfin)	Detection positive days are days, where either harbour porpoises or dolphins are detected
g(0)	Sandsynligheden for at opdage marsvin på nul-linjen	The combined probability of detecting a harbour porpoise on the track line (aerial surveys)
GW	Giga Watt	Giga Watt
Mother-calf ratio	Mor-kalve ratio	Number of mother-calf pairs in percent of total number of observed adult harbour porpoises
MSFD	Havstrategi-direktivet	Marine Strategy Framework Directive
NSI	NSI	North Sea I
NOVANA	NOVANA	The Danish national monitoring program for aquatic environment and nature, run by the Danish Environmental Protection Agency
OWF	Havvindmøllepark	Offshore Windfarm
PAM	Passiv akustisk monitering	Passive Acoustic Monitoring
PAMGuard	PAMGuard	Acoustic analysis program developed by Doug Gillespie
PDV	Sælpest	Phocine Distemper Virus
SCANS	SCANS	Small Cetaceans in European Atlantic waters and the North Sea (European cetacean Survey Programme)
$\hat{u}_m$	Effektive strip bredde (ESW) under moderate betingelser for at se marsvin	The estimated ESW (Effective strip width) in moderate conditions (aerial surveys)

1. Introduction and objectives

To accelerate the expansion of Danish offshore wind production, the Finance Act for 2022 and the subsequent *Climate Agreement on Green Power and Heat* of 25 June 2022 established the framework for developing a minimum of 9 GW of offshore wind capacity in Danish waters.

To realize these political commitments and significantly increase offshore wind energy production, the Danish Energy Agency has prepared a development plan for offshore wind farms in three designated areas: the North Sea, the Kattegat, and the Baltic Sea. As part of this process, the Agency has initiated a wide range of feasibility studies in the areas, some of which are reported in this report.

The North Sea I area covers approximately 1,400 km2, divided into three sub-areas designated for offshore wind development (Figure 1-1). Located 20-80 km off the coast of West Jutland, each of the three sub-areas will be connected to the onshore grid through designated export cable corridors.

In May 2025, the Danish Parliament adopted the tender framework agreement, which determined that two of the three sub-areas in North Sea I – specifically *Nordsøen I Midt* and *Nordsøen I Syd* – will be included in the first tender round. The third sub-area, *Nordsøen I Nord*, will remain in a pool of potential future tender sites.

The map shows the location of the two sub-areas - *Nordsøen I Midt* and *Nordsøen I Syd* – which will be tendered for in autumn 2025 (Source: ens.dk/energikilder/nordsoeen-i-syd-og-midt-havvindmoelleparker/). The area *Nordsøen I Nord* is north of *Nordsøen I Midt*, whereas the darker blue area to the west is for future development of offshore wind.

The tendering process for Nordsøen I Midt Offshore Wind Farm (OWF) and Nordsøen I Syd OWF will commence in autumn 2025. The deadline for Nordsøen I Midt OWF is set for spring 2026, while the deadline for Nordsøen I Syd OWF will follow in autumn 2027. According to the current schedule, Nordsøen I Midt OWF is expected to be operational by 2032, with Nordsøen I Syd OWF coming online in 2033.

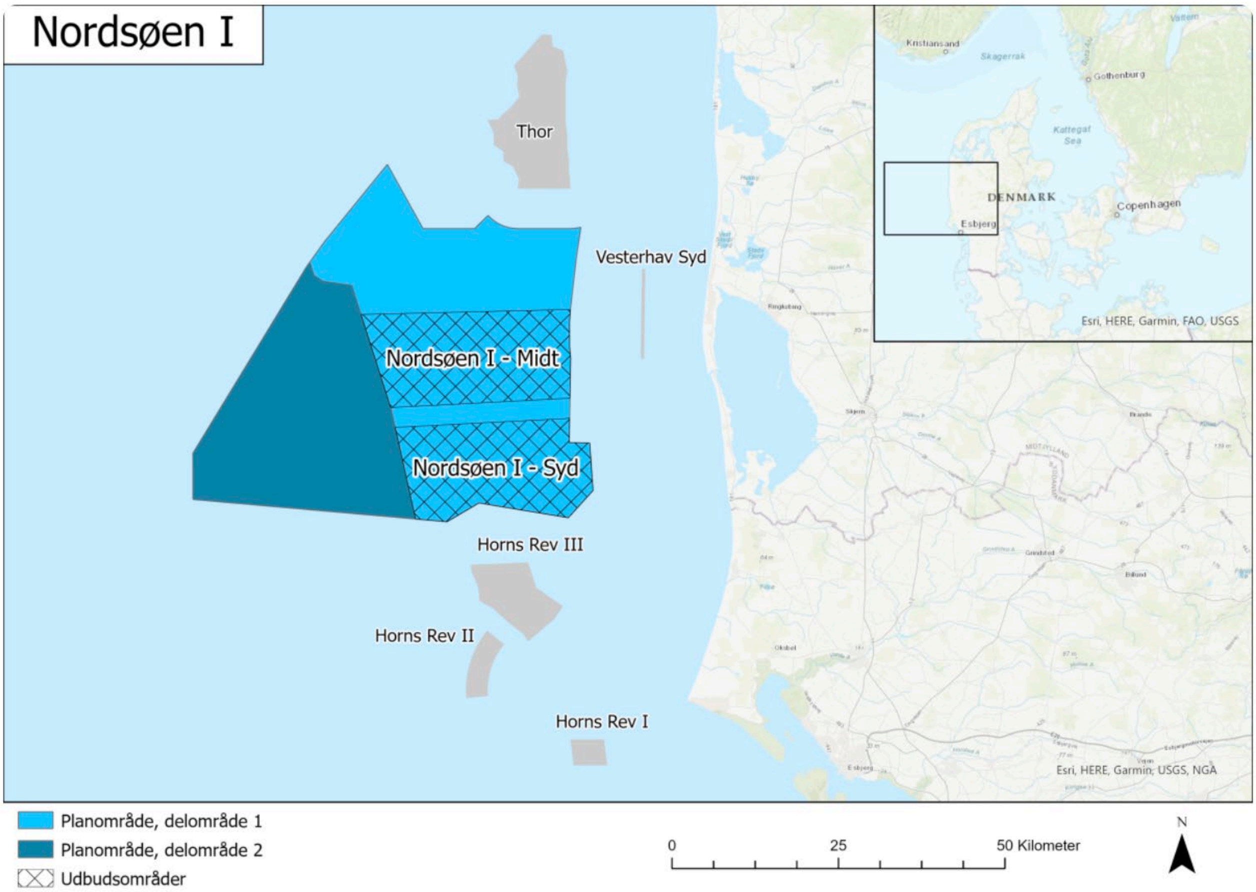


Figure 1-1: Map showing the location of the two sub-areas - Nordsøen I Midt and Nordsøen I Syd – which will be tendered for in autumn 2025 (Source: ens.dk/energikilder/nordsoeen-i-syd-og-midt-havvindmoelleparker/). The area Nordsøen I Nord is north of Nordsøen I Midt, whereas the darker blue area to the west is for future development of offshore wind.

This report concerns baseline data and information on marine mammals. The study was carried out on behalf of Energinet by DCE in collaboration with NIRAS during April 2023–April 2025.

This technical report concerns two years of data collection in the marine mammal work package. The report includes data obtained from eight aerial marine mammal surveys conducted in April, June and August 2023, and in April, June, July, October and November 2024 as well as data from April 2023–April 2025 from 42 PAM stations (9 CPOD/FPOD stations, 6 SoundTrap/FPOD stations and 27 FPOD stations). Furthermore, results from the noise monitoring at North Sea I (NSI), noise recordings of turbine noise at Kriegers Flak offshore windfarm (OWF) and array studies of harbour porpoises and noise at Horns Rev 3 OWF are presented. The results from the field surveys are supplemented with existing data and information compiled from literature studies.

The objective of the environmental pre-investigations was to collect new data and compile existing data and information to be handed over to the future concessionaires as environmental baseline information for the concessionaires' environmental permitting processes. The specific aim of this technical report is to provide updated baseline knowledge on marine mammal presence and usage of the North Sea I area as well as an updated underwater soundscape of the area.

1.1 Survey area

The survey area at North Sea I for examining marine mammals and underwater noise encompasses the pre-investigation area as well as a 20 km buffer around this area (Figure 1-2). The buffer zone of 20 km was chosen since it was assessed to be the largest area in which harbour porpoises could potentially be impacted during the construction due to piling of pin piles/monopiles into the seabed: Several studies have estimated the impact on harbour porpoises during the construction phase of a wind farm, by comparing the presence of harbour porpoises before, during and after construction work has ended. All studies concluded that when using mitigation in the form of soft start/ramp up and acoustic deterrent devices (to empty the core area for harbour porpoises if present) and bubble curtains (to lower the generated noise level), the maximum distance affected ranged between 10 and 15 km (Dähne, et al., 2013; Dähne, et al., 2017; Brandt, et al., 2018).

The survey area is 7,630 km^2 and the depths varies from 1 to 45 m. The sea floor mainly consists of sand and mud (WSP 2024).

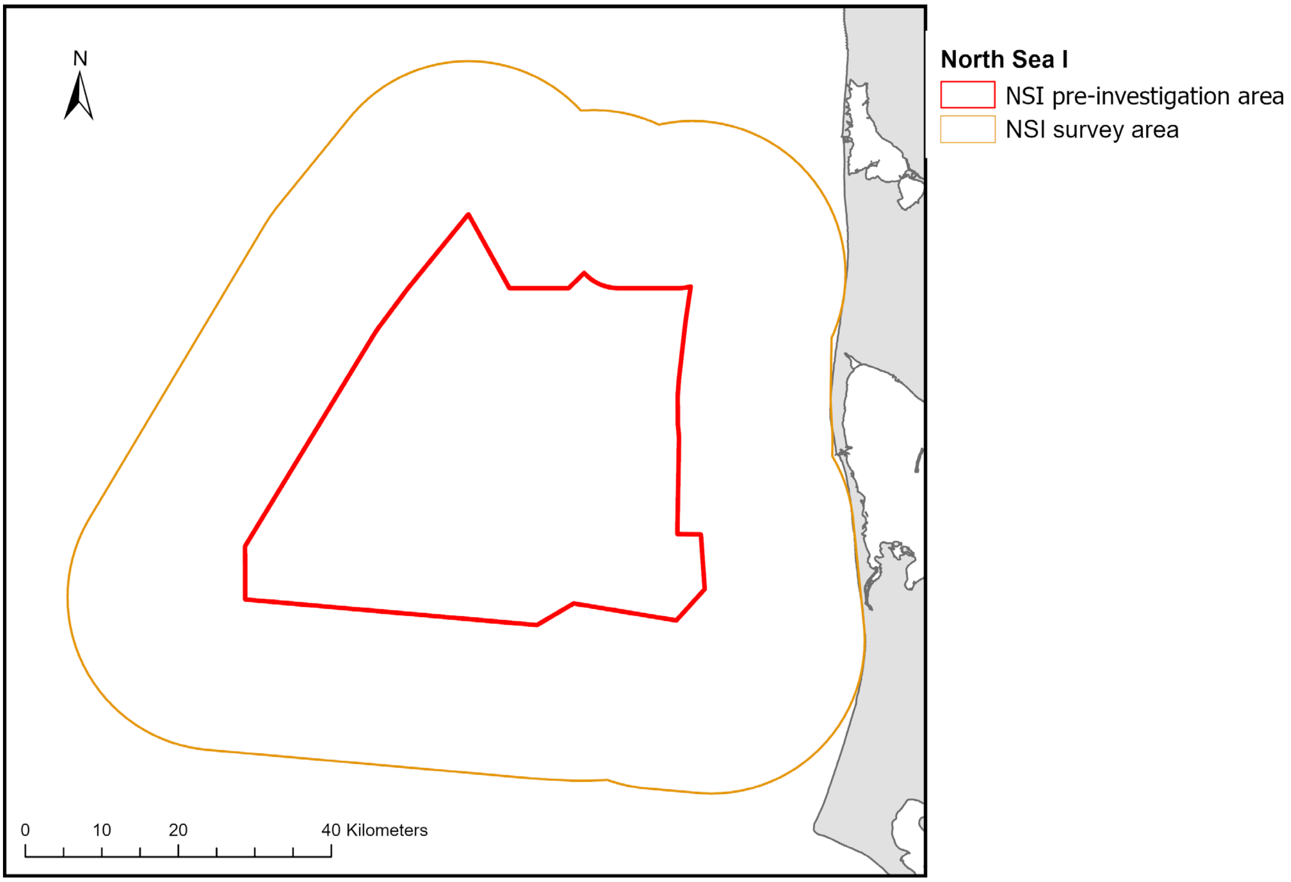


Figure 1-2: The pre-investigation area for North Sea I (red) including and a 20 km buffer zone around it, jointly called the survey area (orange).

2. Existing data and knowledge

The North Sea is inhabited by many different species of marine mammals. The most common species in the area relevant for this project are harbour porpoises (*Phocoena phocoena*), harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*). However, other species of cetaceans also occur at an unknown level in the eastern North Sea, most importantly white-beaked dolphins (*Lagenorhynchus albirostris*) and minke whales (*Balaenoptera acutorostrata*), but several other species such as bottlenose dolphins (*Tursiops truncatus*) and killer whales (*Orcinus orca*) can also be found (Hammond et al. 2013).

This chapter includes all relevant information about the different species before the survey program began and knowledge that became available while the survey was ongoing.

This project did not include collection of new data on the two seal species. Consequently, all information on seals is derived from previous studies in the area and presented in this chapter. The information mainly includes data from seal tagging collected during the Energy Island project northwest of the North Sea I survey area (2022–2023) and aerial survey data from the nearest haul-out sites along the west coast of Jutland. It is not within the scope of this project to conduct new models or analysis of this data. Hence, the existing data from the Energy Island project are presented with focus on their relevance for the North Sea I area.

2.1 Cetaceans

2.1.1 Harbour porpoises

Harbour porpoises are common in the North Sea and the population size is estimated to be stable at around 350,000 individuals (North Sea, Skagerrak and northern Kattegat) throughout the period 1994–2022, as estimated from the four SCANS surveys conducted in 1994, 2005, 2016 and 2022, respectively (Hammond et al. 2002; Hammond et al., 2013; Hammond et al. 2021, Gilles et al. 2023). During SCANS-IV in July 2022, a mean density of 0.55 animals/km^2 was estimated in the North Sea (Gilles et al. 2023). All SCANS data from the North Sea was obtained in the month of July with the same methodology as applied in the North Sea I aerial survey program for cetaceans and the results are therefore directly comparable, although the blocks are larger than the North Sea I survey area. Aerial surveys were also conducted in the North Sea Energy Island area, an area neighbouring (to the northwest, distance to NSI survey area = 8 km) the North Sea I survey area. From April 2022 to July 2023, three aerial surveys were conducted in the North Sea Energy Island survey area as part of the required environmental monitoring program. The area is situated northwest of the North Sea I survey area. Here, the density of harbour porpoises varied between seasons and year e.g. higher density in July 2022 with an estimate of 1.96 individuals/km^2 (95% CI = 1.04-3.16) and lower density in July 2023 with 0.88 individuals/km^2 (95% CI = 0.52-1.45). An aerial survey was also conducted in April 2022, resulting in a density estimate of 0.74 individuals/km^2 (95% CI = 0.38-1.24). Furthermore, all parts of the Danish North Sea and Skagerrak was surveyed in the summer of 2023 in a joined effort between the North Sea Energy Island (Kyhn et al. 2024), the national NOVANA monitoring program (Hansen J.W. & Høgslund S. 2024) and the North Sea I survey program (Sveegaard et al. 2024). The surveys were analysed per strata and subsequently pooled for a total abundance estimate. For the Danish part of the North Sea the overall density was estimated at 0.63 (0.45-0.92), i.e. a little higher than for the entire SCANS area in the North Sea of 0.55 animals/km^2. The total abundance of the Danish part of the North Sea was estimated at 36.916 (26.115-53.836) individuals. No overall data on harbour porpoise abundance in the Danish North Sea exists for other times of the year than the summer season.

The North Sea Energy Island was also studied by means of passive acoustic monitoring (PAM) with 19 stations from November 2021 to November 2023. Harbour porpoises produce "narrow-band, high-frequency" (NBHF) acoustic signals for echolocation, primarily clicks, which are characterized by their limited frequency range and high peak frequencies, typically above 100 kHz and centered around 130 kHz. Harbour porpoises use echolocation for navigation and prey detection. PAM data provides data on relative abundance and if deployed all year, it can also report on seasonal variation in presence. The dataloggers collected data for two consecutive years. The PAM data showed that harbour porpoises were present in the area year-round, with highest relative abundance in June-October, which corresponds to the results of the aerial surveys from spring and summer. The levels of relative abundance varied between the 19 PAM stations, which may have been due to differences in distribution of prey based on abiotic factors such as depth and bottom substrate. Figure 2-1-1 provides an overview of the distribution of relative abundance detected at the 19 stations in the North Sea Energy Island survey area.

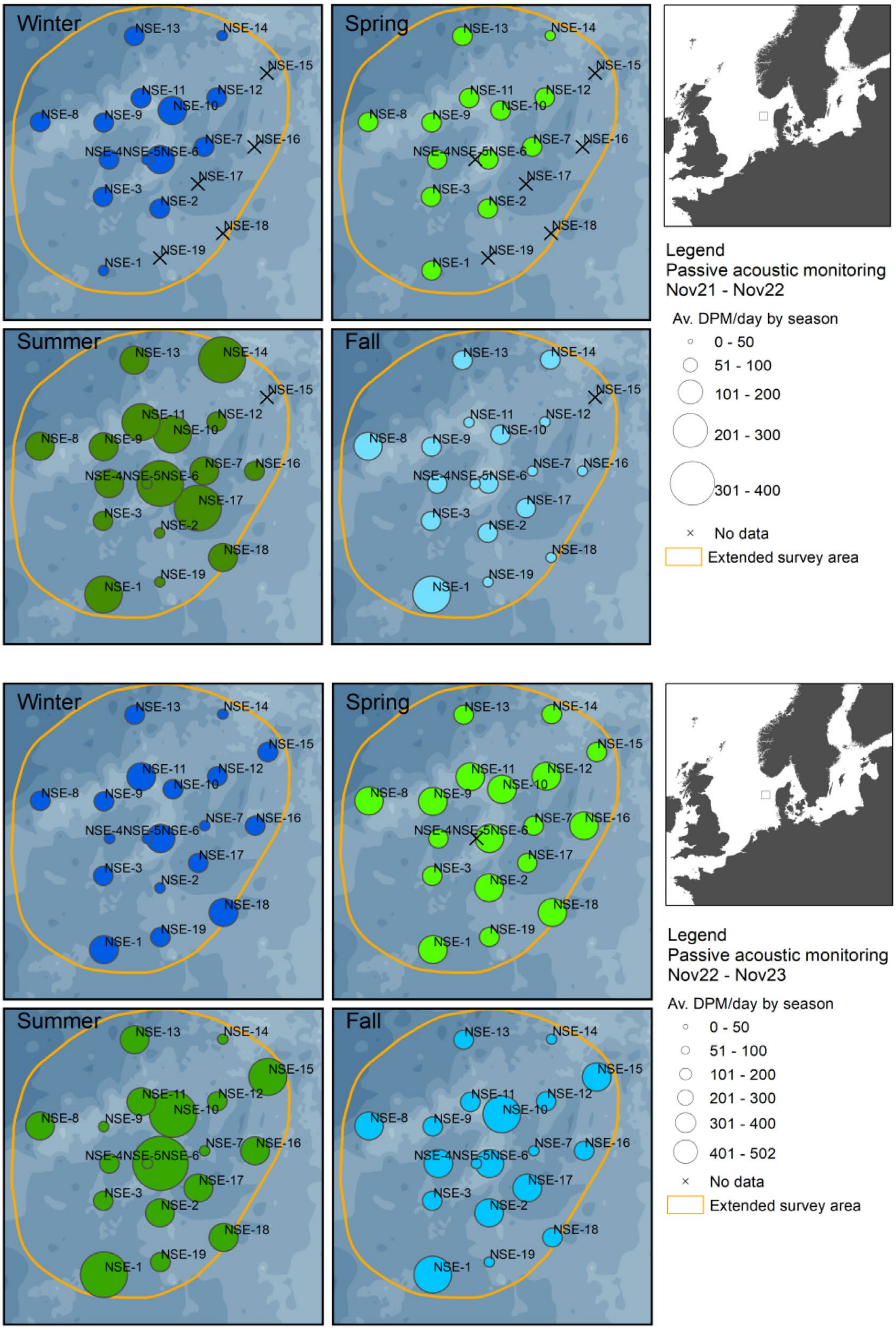


Figure 2-1-1: Data from the North Sea Energy Island survey area (Nov 2021-Nov 2023). The data is divided into seasons and per station. The relative abundance varied between the 19 PAM stations. The overall pattern showed that the levels were highest in summer, coinciding with the calving period.

The distribution of harbour porpoises within the North Sea I survey area was relatively unknown prior to the current monitoring program, since the SCANS' transects are too sporadic to illustrate distribution on a smaller spatial scale and the only other source are a few individually tracked harbour porpoises: Aarhus University has tagged 25 harbour porpoises near Skagen since 2000 as well as 6 porpoises in the Wadden Sea (Figure 2-1-2). The movement of the tracked harbour porpoises showed that the harbour porpoises tagged in Skagen had a preference for the southern slope of the Norwegian Trench, but that they may also explore the areas to the south, including the North Sea I survey area. The six harbour porpoises tagged in the Wadden Sea mainly stayed close to the tagging site and had limited home ranges. However, since only six harbour porpoises were tagged, other individuals from this area may move differently.

Little is known about breeding areas for harbour porpoises in general, as well as in the North Sea. A German study in waters near Sylt (Sonntag et al., 1999) described a calving area based on two aerial surveys one year apart, where they found a calf ratio of 10–17%. The calf ratio is the ratio of mother-calf pairs to single harbour porpoises. This area was also confirmed as a breeding area in later surveys (Gilles et al., 2009; Gilles et al., 2011; Gilles et al., 2016). In the survey program for the North Sea Energy Island conducted in 2022-2023 a similar high mother-calf ratio was found in summer (16%) (Kyhn et al., 2024). These are the only areas examined as breeding areas near the North Sea I survey area.

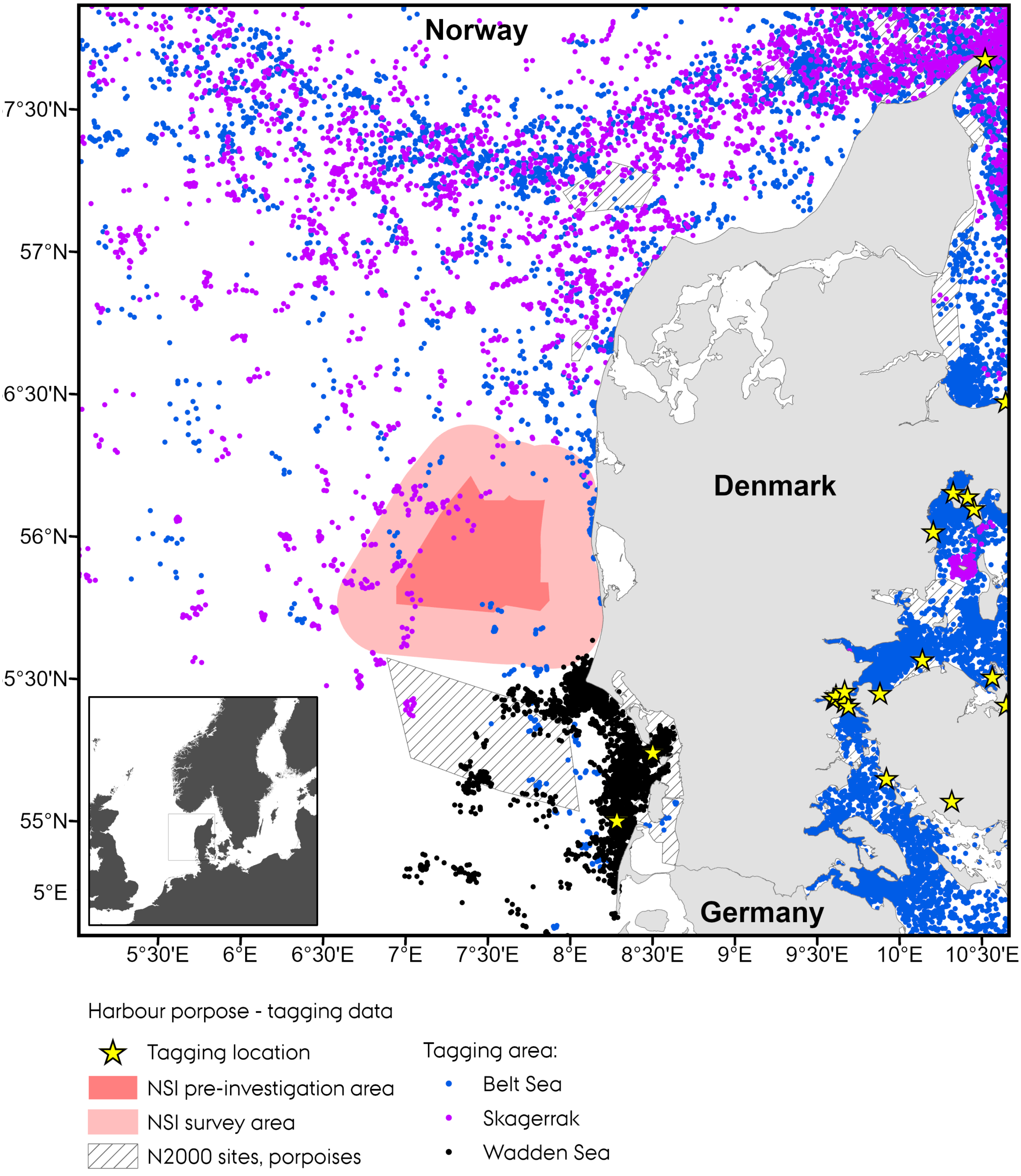


Figure 2-1-2: Positions from harbour porpoises tagged at Skagen (Purple), in the Belt Sea (blue) and in the Wadden Sea (black) from 1997 to 2022. The Natura 2000 areas are shaded.

2.1.1.1 *Vulnerable periods for harbour porpoises in the North Sea*

Newborn harbour porpoise calves are entirely dependent on their mother and continue to be for their first ten to eleven months of life, where they suckle and slowly learn to hunt (Camphuysen and Kropp, 2011) before they become independent (Lockyer, 2003; Teilmann et al., 2007). They are therefore sensitive to disturbances that can lead to mother-calf separation in this period. In the North Sea, calves are born from April to September with a peak in June–July (Sonntag et al., 1999). Mating takes place in the first 1–2 months after the mother gives birth, while she is still nursing her calf. Young harbour porpoises less than 1 year old, and therefore newly weaned, are over-represented in bycatch statistics (Berggren, 1994). The vulnerable period for young harbour porpoises is therefore year-round.

Recent findings from studies on harbour porpoise energetics suggest that mature female harbour porpoises are most vulnerable to disturbances in late summer and the autumn, when they need to increase their energy storage to increase body fat insulation to survive the cold winter months, while at the same time potentially being pregnant and nursing a calf only a few months of age (Gallagher et al. 2021).

Harbour porpoises are listed in annex IV of the Habitats Directive and in the IUCN Red List evaluated as Least Concern in the North Sea (Braulik et al., 2023). Threats according to the IUCN Red List categories are 1) Fishing: bycatch in nets, reduced food availability and habitat destruction, 2) Pollution from industry and agriculture, 3) Noise pollution, 4) Climate and habitat changes, 5) Recreational activities: physical disturbances and noise.

2.1.2 White-beaked dolphins

The global distributional range of white-beaked dolphins is at higher latitudes in the North Atlantic, where the North Sea is part of their southernmost range. White-beaked dolphins are common in the North Sea and the population size has been estimated throughout the period 1994–2022 during the four SCANS surveys conducted in 1994, 2005, 2016 and 2022, respectively (Hammond et al. 2002; Hammond et al., 2013; Hammond et al. 2021, Gilles et al. 2023). During SCANS-IV in July 2022, a mean density of 0.05 animals/km^2 and a total population size of app. 45,000 individuals was estimated for the North Sea (Gilles et al. 2023). All SCANS data from the North Sea as well as data from the North Sea Energy Island survey program (Kyhn et al. 2024) was obtained in the months of July-August with the same methodology as applied in the North Sea I aerial survey program for cetaceans and the results are therefore directly comparable.

In the North Sea I survey area, white-beaked dolphins are only rarely observed (Read et al. 2009, Hammond et al. 2021). However, as stated above, only a few dedicated surveys have been conducted — and only during the summer months - and consequently there is currently limited knowledge on how much and when white-beaked dolphins may occur in the survey area (e.g. Gilles et al. 2023). International surveys (SCANS) have shown that their abundance is known to increase towards the north and west in the North Sea (Hammond et al. 2021, Gilles et al. 2023). There are no migration or movement data for white-beaked dolphins in the North Sea, and their annual presence or migration through the survey area is therefore unknown. Results of the two year PAM survey program for the North Sea Energy Island (2021-2023) showed that white beaked dolphins were present in the North Sea Energy Island survey area all year round. The level of relative abundance was lower than for harbour porpoises and the maximum relative abundance was up to 6 detection positive hours per day.

Similar to other dolphins, the vocalizations produced by white-beaked dolphins can be grouped into three types: echolocation clicks, burst pulses, and whistles. Echolocation clicks are short (< 1 ms) sonar signals with predominant energy in the ultrasonic range that enable animals to acoustically search their environment and forage. Tonal whistles are communication signals used for social interactions and group cohesion. The third group of signals, burst pulses – rapid click sequences with tonal qualities – is a mix of signals produced for sonar (prey capture events) and for communication. For white-beaked dolphins, different ranges of echolocation frequency bandwidths have been reported (see Griffiths et al., 2023 for more information).

2.1.2.1 Vulnerable periods for white beaked dolphins in the North Sea

White beaked dolphin calves are born in summer and mating also takes place in summer, although females are unlikely to mate every year (Galatius and Kinze, 2013). White-beaked dolphin calves were observed in the North Sea Energy Island survey area in July (Kyhn et al. 2024) and both calves and pregnant females have also been observed along the Danish Westcoast and in Inner Danish Waters (Alstrup et al. 2024). During calving and mating and in the months thereafter, the dolphins are vulnerable to disturbances that may lead to mother-calf separation. In other more well-studied dolphin species, the calves are dependent on their mother for several years and without similar studies on white-beaked dolphins, we may assume that it is likely that this species exhibits similar behaviour. White-beaked dolphins are listed in annex IV of the Habitats Directive and evaluated as Least Concern in the North Sea by IUCN (Kiszka and Braulik, 2018). Threats according to the IUCN Red List categories are 1) Fishing: bycatch in nets, reduced food availability and habitat destruction, 2) Pollution from industry and agriculture, 3) Noise pollution, 4) Climate and habitat changes, 5) Recreational activities: physical disturbances and noise.

2.1.3 Minke whales

Minke whales are widely distributed in all oceans, except at latitudes between 0-30°. They are hence mainly found in temperate to polar zones of the oceans (Perrin et al., 2018). Minke whales live in open water and are common in the Danish part of the North Sea (Hammond et al., 2021). Born et al. (2007) investigated population structure of the North Atlantic minke whale populations using a combination of heavy metals, organochlorines and fatty acids. The results showed that the following subpopulations could be determined: 1) A West Greenland group, 2) a central Atlantic group including Jan Mayen, 3) a Northeast Atlantic group including Svalbard, Barents Sea and northwestern Norway and 4) a North Sea group.

The abundance of minke whales in the North Sea has been counted four times during SCANS surveys in 1994, 2005, 2016 and in 2022 (Hammond et al., 2002; Hammond et al., 2013; Hammond et al., 2021; Gilles et al. 2023). The results of the four SCANS surveys suggest an abundance of minke whales in the North Sea of around 10,000 individuals. It is not known whether this number represents the carrying capacity.

Very little is known about minke whale distribution and abundance in Danish Waters. On two occasions, minke whales incidentally caught in a pound net at Skagen were tagged with a satellite transmitter. On both occasions, the whales swam north of the British Isles during autumn and winter (Teilmann, unpublished data), i.e. not through the North Sea I survey area. Minke whales in Danish waters do not belong to a separate Danish population but rather to the North Atlantic population and there are no national management units.

Minke whales have only been observed a few times in the survey area, but similar to white-beaked dolphins there has only been limited dedicated survey effort in this area (Figure 2-1-3), (Hammond et al. 2021). It is likely that minke whales are more common in the deeper waters in the North Sea (Hammond et al. 2021, Gilles et al. 2023) and they are commonly observed in the Danish oil and gas sector (Delefosse et al. 2017). Prior to this project, however, the lack of dedicated surveys meant that there is no specific knowledge of when and how often minke whales use the North Sea I survey area.

Minke whale vocalizations vary greatly across their global geographic range. Around the North Atlantic Ocean, ranging from the Caribbean to the western North Sea, minke whales have been documented producing low-frequency pulse trains (50–400 Hz) (Mellinger et al. 2000, Risch et al. 2013, Risch et al. 2019). Based on these data, an automated pulse train detector was developed and used along the Scottish east coast (Popescu et al. 2013, Risch et al. 2019). Off Scotland, minke whale pulse train detections exhibited seasonal and diel patterns, occurring mostly between June and November in the evening/nautical twilight hours. It is unclear what behavior is associated with the pulse train in minke whales, and therefore whether it is a signal they produce regularly. While it is known that minke whales can produce other vocalizations, no detectors currently exist to automatically search broadband data for these call types.

2.1.3.1 Vulnerable periods for minke whales in the North Sea

It is not known when minke whales are most vulnerable to disturbances. However, minke whales are observed in this part of the North Sea and it is assumed that the area has some significance for the species (Reid et al., 2003). There is not enough knowledge about breeding and nursing to point to specific periods as being more vulnerable than others.

Minke whales are listed in annex IV of the Habitats Directive and evaluated as Least Concern in the North Sea by IUCN (Sharpe and Berggren, 2023). Threats according to the IUCN Red List categories are 1) Fishing: reduced food availability and habitat destruction, 2) Pollution from industry and agriculture, 3) Noise pollution, 4) Climate and habitat changes.

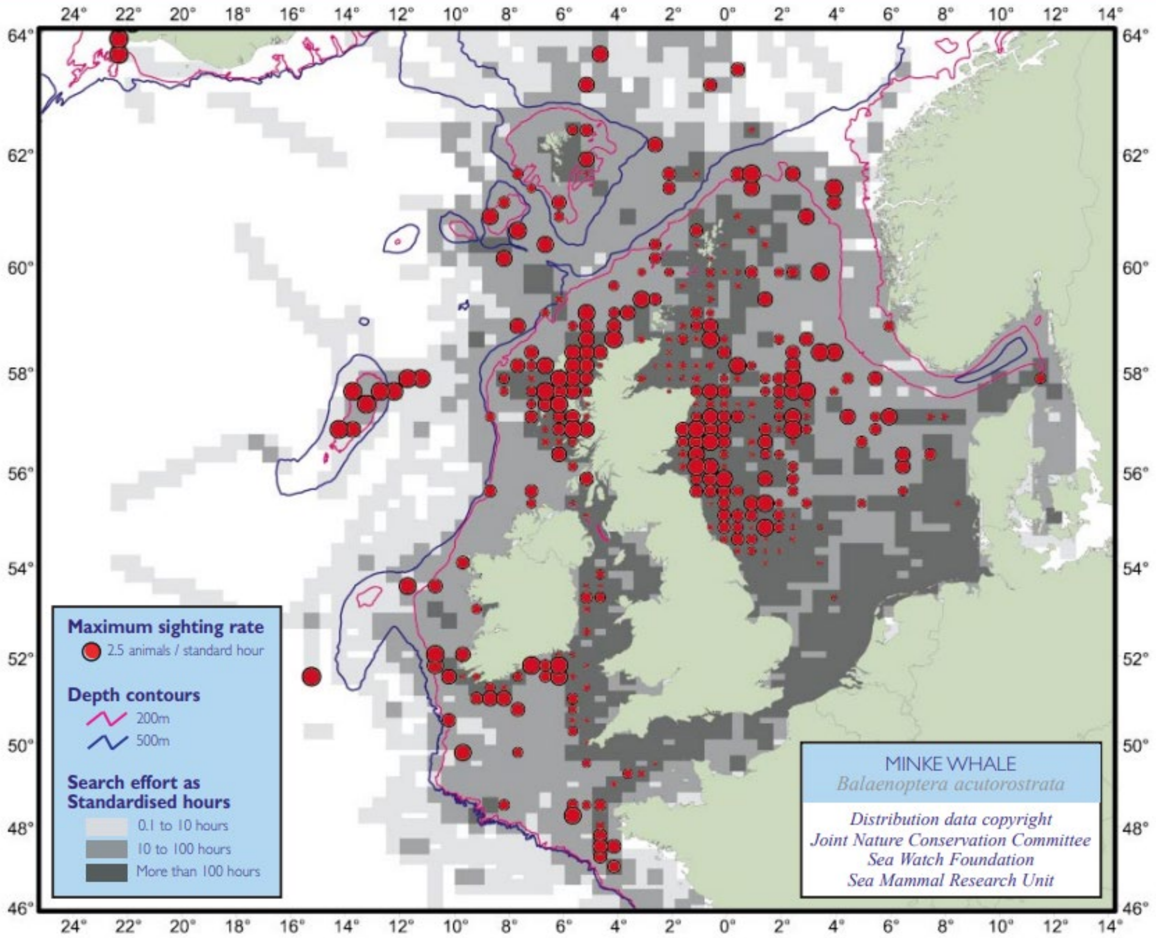


Figure 2-1-3: Minke whale distribution map from Atlas of Cetacean distribution in north-west European waters. From Reid et al. (2003).

2.2 Seals

Harbour seals and grey seals are the only common seal species in the North Sea. The survey area is located between two very important seal haul-out areas, namely the Wadden Sea and the western part of the Limfjord near Thyborøn. Both locations hold important resting and moulting grounds for both seal species. The Danish Wadden Sea is also an important breeding area for harbour seals, and grey seals have begun to use this area for pupping within the last decade as well, although in very small numbers (<10/yr) (Fast-Jensen et al. 2015; Hansen et al. 2023).

2.2.1 Harbour seals

The North Sea I survey area off the Danish west coast may be visited by harbour seals from the Wadden Sea population (Olsen et al. 2014), which is shared between the Netherlands, Germany and Denmark, as well as harbour seals from Nissum Bredning, in the western Limfjord. Seal haul-outs in Nissum Bredning are used by seals from both the Wadden Sea, Kattegat and a separate population of harbour seals in the central Limfjord.

Harbour seals in Denmark have been hunted extensively until their protection in 1976 (Søndergaard et al. 1976). Numbers of harbour seals in Denmark, including the Wadden Sea and Nissum Bredning were severely depleted until the time of their protection, with estimates of 500–600 seals left in the Danish Wadden Sea and 200 in the entire Limfjord (Søndergaard et al. 1976). Since their protection from hunting, the populations have recovered and only declined during the two Phocine Distemper Virus (PDV) outbreaks in 1988 and 2002 (Härkönen et al. 2006). However, during the last decade, the growth of harbour seal populations in both the larger Wadden Sea area (including Germany and the Netherlands) and Limfjord has been slowing down or in some cases declining. While numbers of harbour seals along the Dutch and German North Sea coasts have been stable for the last 12 years (Galatius et al. 2023), there have been substantial decreases in the counts in both the Danish Wadden Sea and Nissum Bredning. This may be indicative of a true decline with increased mortality or lower reproduction, or a redistribution of seals to other areas. The reason behind the decline is not known, but the most likely drivers are disturbance at the haul-outs, depletion of prey and increasing numbers of grey seals.

The numbers of seals counted on land provide information about the trends in the population abundance. With knowledge regarding the proportion of seals hauling out at a particular time, total population abundance can be estimated. Such data are not yet available for Nissum Bredning, while there are sparse data on harbour seal haul-out behaviour from the Dutch Wadden Sea (Ries et al. 1998). They would indicate that approximately 68% of the population is hauling out at a given time during June. These data were, however, obtained in the 1990s and environmental changes, age structure, disturbances and density dependence are likely to affect haul-out behaviour. Data from harbour seals in other parts of their distribution show haul-out rates ranging from 42% to more than 80% during the moulting season in August (Yochem et al. 1987, Härkönen and Heide-Jørgensen 1990, Olesiuk et al. 1990, Thompson and Harwood 1990, Thompson et al. 1997, Ries et al. 1998, Huber et al. 2001, Simpkins et al. 2003, Gilbert et al. 2005, Cunningham et al. 2009, Harvey and Goley 2011, London et al. 2012, Lonergan et al. 2013), with higher rates generally recorded during low tide in areas with high tidal ranges, as is the case in both the Wadden Sea and Nissum Bredning. Thus, a reasonable estimate, without local data would be that 50–80% of the population is hauled out during the moulting season surveys at low tide in August in both areas.

Monitoring of harbour seals in the Danish Wadden Sea was initiated in 1979, and until 1988, the counts showed exponential growth at around 12% per year (Figure 2-1-1). In 1988, an epidemic of PDV struck the harbour seal populations in the inner Danish waters and the North Sea area (Härkönen et al., 2006), and decreased counts in the Danish Wadden Sea from approximately 1500 to 900 individuals. After this, the population again grew at a similar exponential rate, until a second PDV epidemic reduced the counts from around 2500 to 1400 individuals in 2002 (Härkönen et al., 2006). After 2002, the population resumed growth at a high rate, until around 2012, at which time numbers stabilized in the larger Wadden Sea area. In the Danish part of the Wadden Sea, numbers peaked at around 2900 individuals in 2012 and then began to decline, and in 2021, the counts were similar to the level immediately after the 2002 epidemic (Figure 2-1-1). A decline in numbers of harbour seals in the Danish Wadden Sea since 2012 is also reflected in counts from other seasons (Figure 2-2-1). In 1998, aerial monitoring of annual pup production in the Danish Wadden Sea was initiated during the harbour seal pupping season in June. Since 2010, the pup counts have shown a stable trend with 400–600 pups counted annually, without a significant decline as seen in the counts of older seals (NOVANA data, Figure 2-2-2). This may be related to either high levels of pup mortality or to changes in adult haul-out behaviour, with seals spending less time on land during the moulting season than previously due to density dependence.

The survey data used for this report includes harbour seals from the Wadden Sea population (Olsen et al., 2014), as well as Nissum Bredning, in the western Limfjord. With the lack of data on haul-out behaviour from the surveyed areas, a reasonable estimate based on data from other areas would be that 50–80% of the population is hauled out during the moulting season surveys at low tide in August in both areas. This would constitute current abundances of around 2200–3600 harbour seals in the Danish Wadden Sea area and 500–800 in Nissum Bredning.

The seasonal variation of harbour seal on land in both areas is similar to what is seen in other areas, with peaks during the summer months where breeding and moulting take place, and much lower numbers on land in the fall, winter and early spring (e.g., Cunningham et al., 2009; Granquist and Hauksson, 2016; Hamilton et al., 2014; Watts, 1996). This seasonal pattern indicates that longer foraging trips, which would be more likely to involve the area around the North Sea I area, would be more frequent outside the summer period, particularly during winter, when haul-out attendance is lowest.

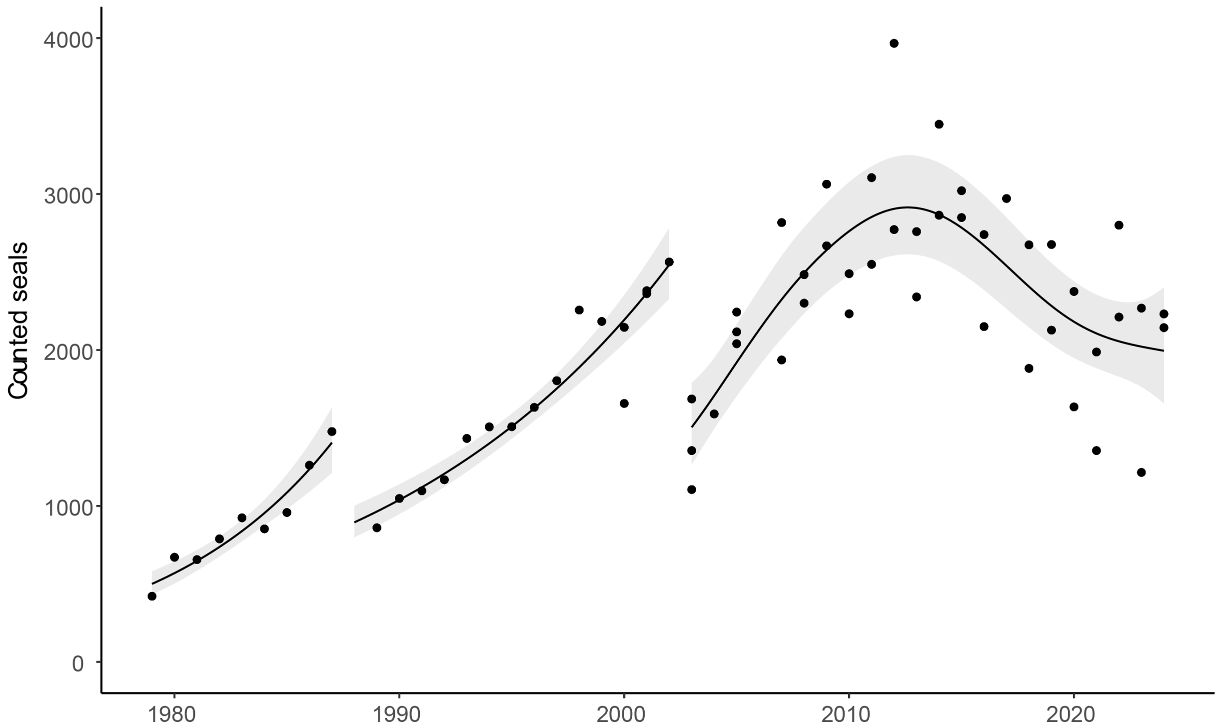


Figure 2-2-1: Aerial survey counts of hauled-out harbour seals in the Danish Wadden Sea during the moult in August 1979–2024. Black line shows estimated annual count index and grey area shows the 95% confidence interval of the estimate. Modelled time series are interrupted by the Phocine Distemper Virus epidemics of 1988 and 2002. The counts do not include seals at sea during the surveys. Data are from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

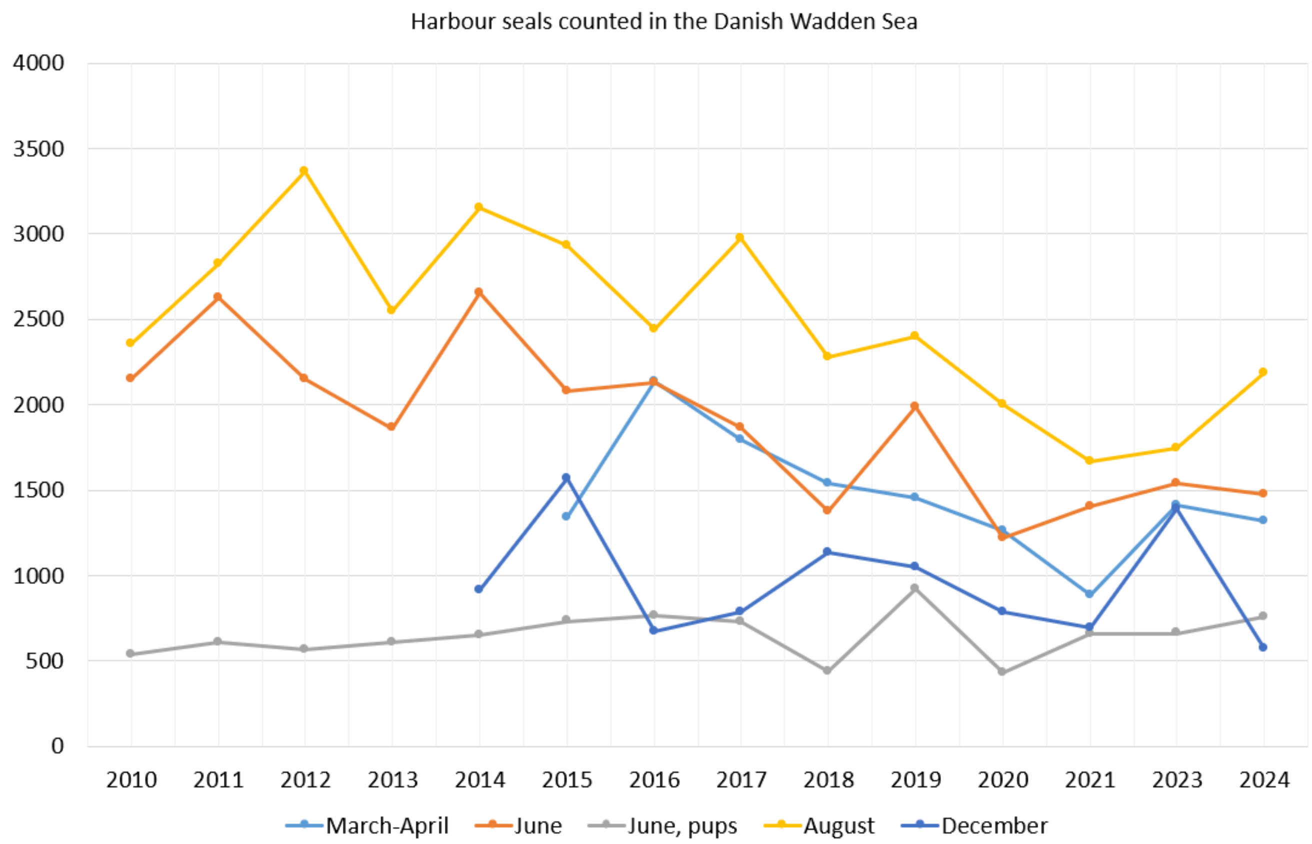


Figure 2-2-2: Harbour seal counts in the Danish Wadden Sea 2010–2024. Data are presented for four counting seasons, with numbers of both pups alone and other seals (minus pups) for June and total number of seals for the other seasons. The counts do not include seals at sea during the surveys. Data are from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

Monitoring of harbour seals in the Limfjord was initiated in 1990. A genetic study revealed that harbour seals in this area derive from two populations: in the inner fjord, seals have a distinct genetic signature and are most likely descendants of the seals inhabiting the fjord until a storm opened a connection to the North Sea in 1825 (Olsen, Andersen et al. 2014), while in the western part of the fjord atNissum Bredning, seals from the Wadden Sea occur along with seals from the inner Limfjord and Kattegat. Seals from the inner Limfjord may occasionally venture into the North Sea (Teilman et al. 2020) but tend to stay in the inner Limfjord. Thus, it is the seals hauling out in Nissum Bredning which are most relevant for the study area. In the inner Limfjord, harbour seal numbers grew from 1990 until the PDV epidemic in 2002 where the estimated index of hauled out seals during the moult was 800 in the inner fjord. After the epidemic, the count dropped to approximately 500 and since then, there has not been significant growth (Figure 2-2-2). In Nissum Bredning, the counts were low before the 2002 epidemic, with around 100 seals on land during the moulting season. Numbers of harbour seals increased substantially in the years following the 2002 PDV epidemic to ca 600 in 2012, but numbers have been declining since then (Figure 2-2-3). Substantially fewer seals are counted during the harbour seal pupping season than during the moulting season, and there are very few pups (a maximum of 17 pups in Nissum Bredning have been counted since pup counts in the Limfjord were initiated in 2016, NOVANA data, Figure 2-2-4). This underlines that Nissum Bredning is not currently an important breeding area and the great majority of the harbour seals using the area go to other localities to breed.

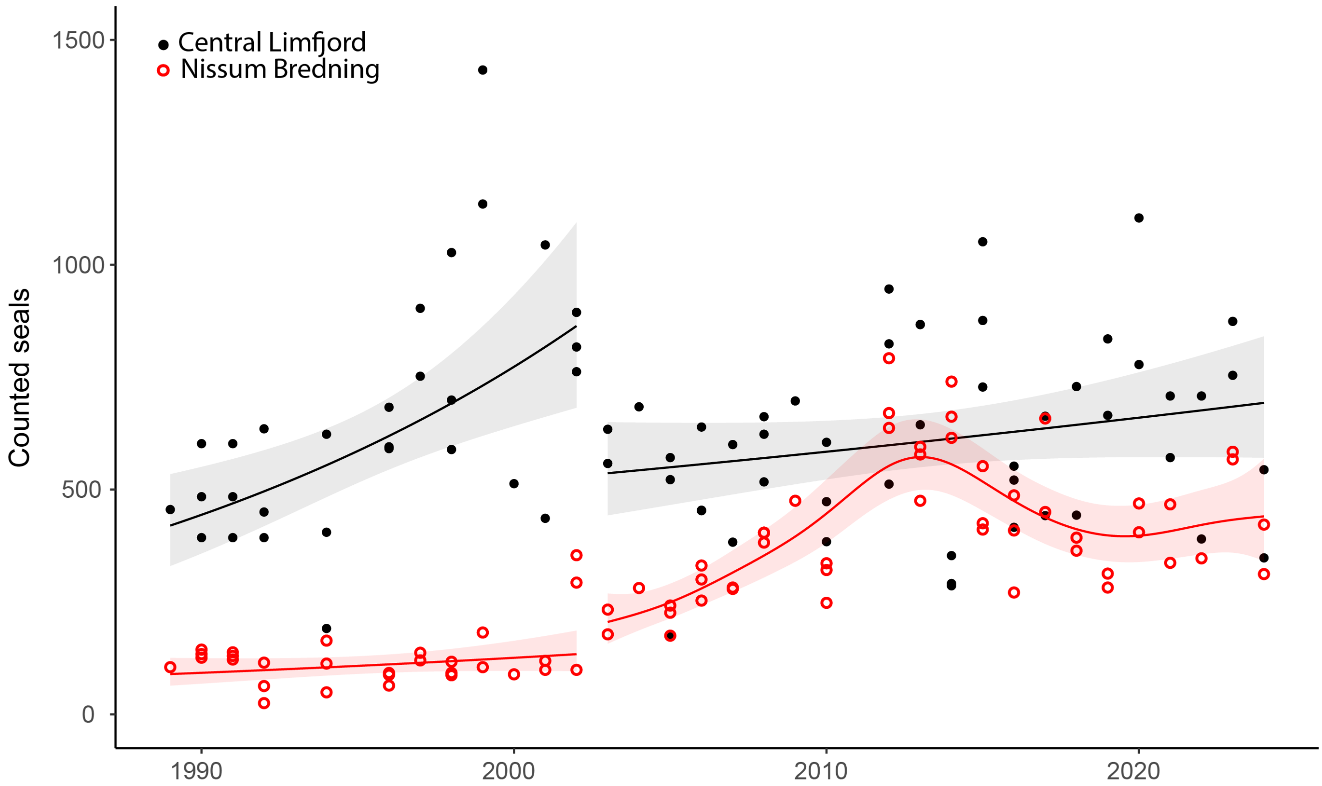


Figure 2-2-3: Aerial survey counts of harbour seals in the Limfjord during the moult in August, 1989–2024. Black line shows estimated annual count index of the central/Inner part of the Limfjord and grey-shaded area shows the 95% confidence interval of the estimate. Red line shows estimated annual count of Nissum Bredning (western part of the Limfjord) and red-shaded area shows the 95% confidence interval of the estimate. Modelled time series are interrupted by the Phocine Distemper Virus epidemic in 2002. The counts do not include seals at sea during the surveys. Data is from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

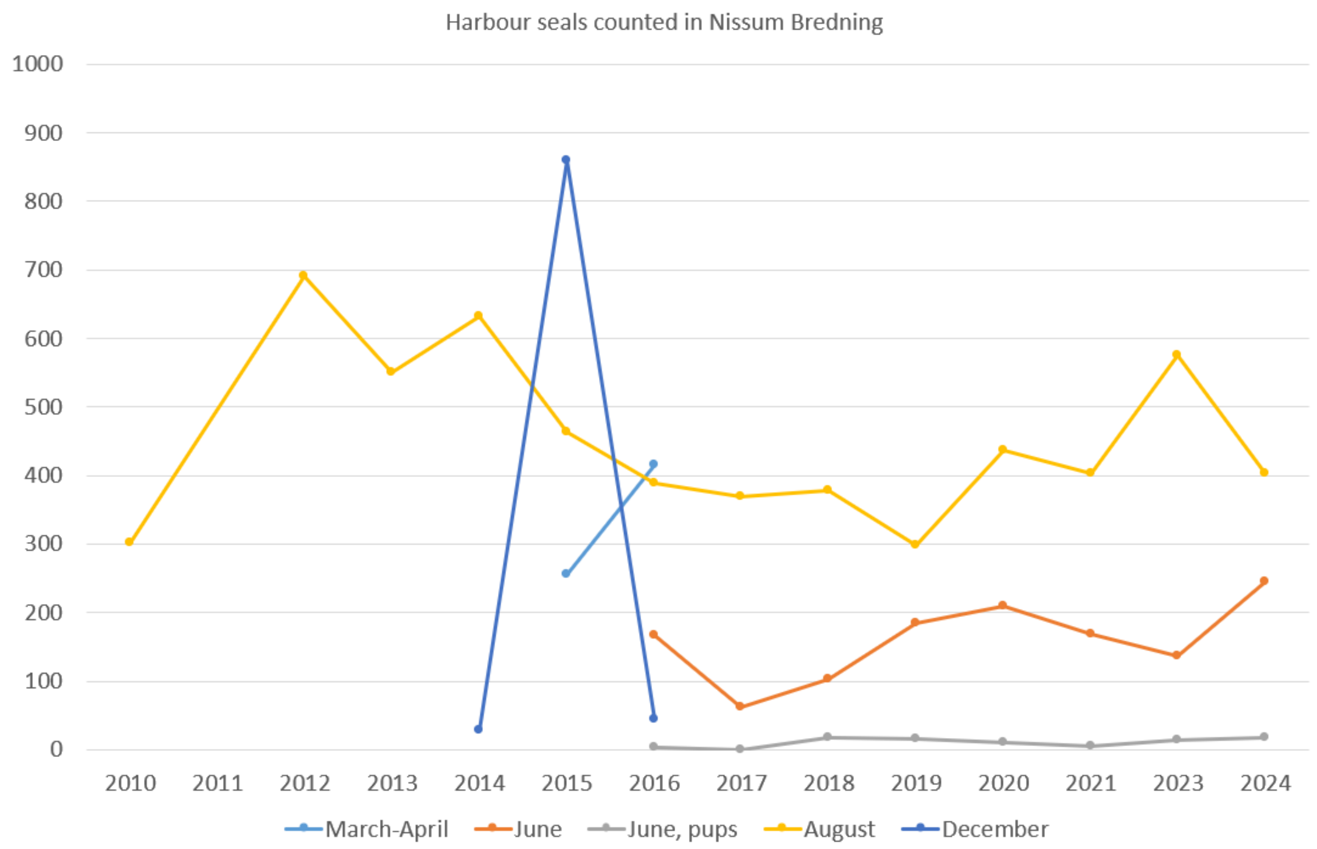


Figure 2-2-4: Harbour seal counts in Nissum Bredning 2010–2024. Data are presented for four counting seasons, with numbers of both pups and other seals (minus pups) for June and total number for the other seasons. The counts do not include seals at sea during the surveys. Data is from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

During the investigations for the Energy Island, seals were counted around the year in both the Danish Wadden Sea and western Limfjord (Kyhn et al. 2024a). The seasonal variation of harbour seals on land in both areas is similar to what is seen in other areas, with peaks during the summer months at which time breeding and moulting take place, and much lower numbers on land in the fall, winter and early spring (e.g. Watts 1996, Cunningham et al. 2009, Hamilton et al. 2014, Granquist and Hauksson 2016) (Figure 2-2-5). A pattern with wider movement range outside the summer period, has previously been documented in harbour seals from Kattegat (Dietz et al., 2013). Thus, it is likely that occurrence of harbour seals is higher in the survey area outside the summer period.

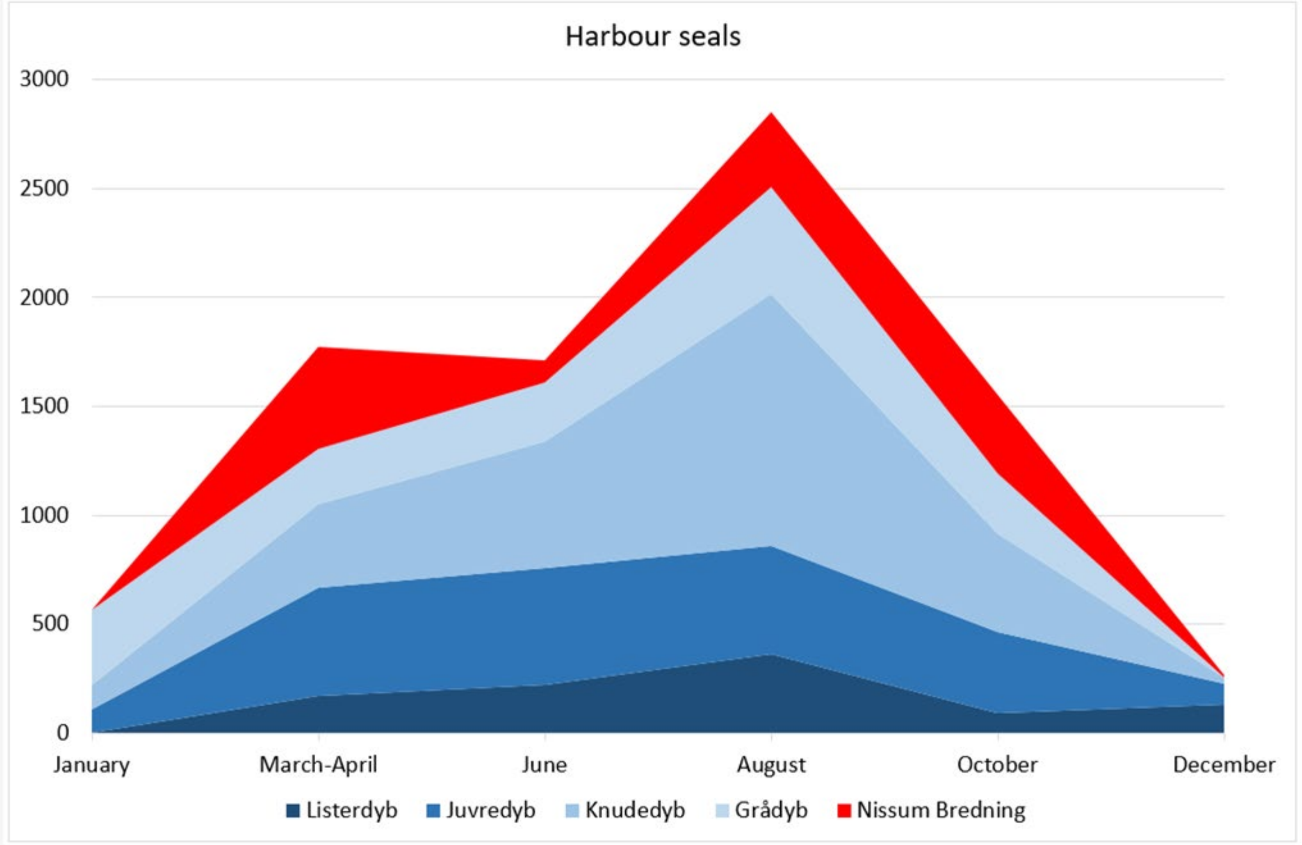


Figure 2-2-5: Counts of hauled out harbour seals from the Wadden Sea (shades of blue for four subareas) and Nissum Bredning (red) from January to December 2022. Y-axis is number of counted seals. Data from Nissum Bredning in January, March–April, October and December and data from the Wadden Sea in March–April and October derive from the Energy Island investigations (Kyhn et al. 2024). Remaining data are from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

2.2.2 Grey seals

Grey seals in the Danish North Sea are part of a larger population in Eastern North Atlantic, centered around the British Isles (Fietz et al. 2016). Grey seals were locally extinct along the European continental coast in the 1500s (Härkönen et al., 2010), except along the Norwegian coast and the population in the Baltic Sea. Seals were later targets of a bounty hunt campaign from 1889 to 1927, during which grey seals went extinct in Danish waters and harbour seals were severely depleted (Olsen et al. 2018). Grey seals were protected in 1967 and two seal reserves were established in the Danish Wadden Sea area in 1979. There were no grey seals in either area at that time. Grey seals from the British Isles have been recolonizing the continental North Sea coasts since the 1950s (Reijnders, Vandijk et al. 1995). At this time, grey seals began to occur in the Dutch and German parts of the Wadden Sea, and in 1985, the first pup was observed in the Netherlands, while grey seal occurrence continually increased in the Dutch and German Wadden Sea areas.

During 2000–2010, grey seals began occurring regularly in small (always fewer than 50) but increasing numbers in the Danish Wadden Sea (NOVANA data). In December 2014, a monitoring program covering the pupping season in late–November to early-January and the moulting season in March–April was initiated. From 2010 until the initiation of the program, numbers counted during the harbour seal moulting and pupping seasons had been growing and this development continued across all seasons after the initiation of the program, peaking with between 300 and 350 seals counted during the moulting seasons of 2019, 2020 and 2021. Since 2019, there has been a tendency for stagnation in the counted numbers (Figure 2-2-6), but there is much variance in the data across all seasons so firm conclusions are not possible. The first grey seal pup was found in Danish Wadden Sea in 2014 and only 12 grey seal pups have been recorded in the Danish Wadden Sea since 2014, peaking with four in 2023–2024 (NOVANA data).

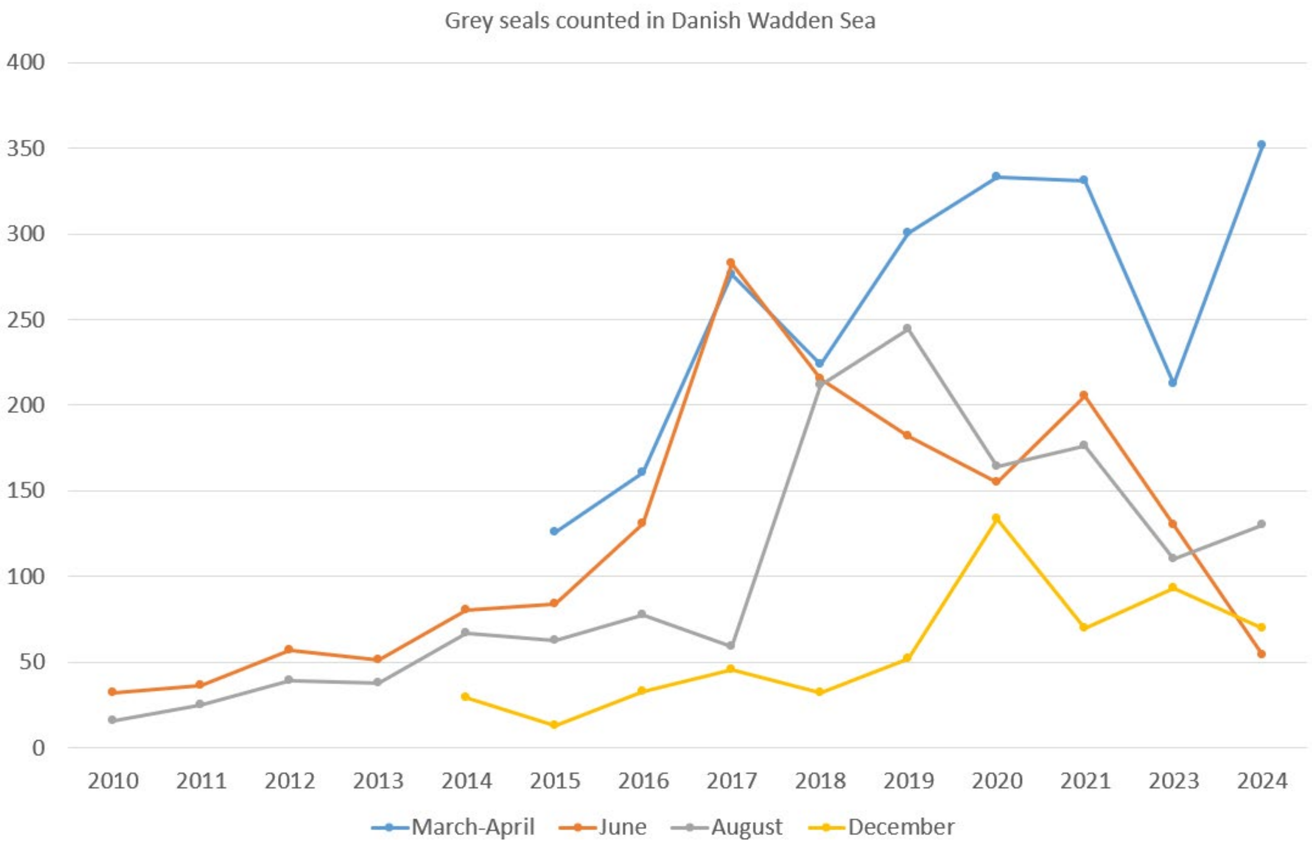


Figure 2-2-6: Grey seals counted in the Danish Wadden Sea 2010–2024. Data are presented for four counting seasons, namely the grey seal moulting season (March–April), harbour seal pupping season (June), harbour seal moulting season (August) and grey seal pupping season (December). Data are from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

In Nissum Bredning, grey seals were first recorded in the harbour seal monitoring program in August 2009, when two grey seals were found. Since then, numbers have increased, with a maximum of 49 seals in August 2021 (Figure 2-2-7). In contrast to the Wadden Sea, the highest counts have not been obtained during the moulting season in March–April, but instead in June and August. It must be noted, however, that counts during the grey seal pupping and moulting seasons were only available for 2014–2016 and 2015–2016, respectively, and again in 2022 (Kyhn et al. 2024a) as the area has not been covered by the grey seal monitoring program. No pups have been recorded in the area and the most likely locality for pupping in the area, Rønland Sandø (south of Thyborøn), which has historically been above the high tide water level, has been prone to flooding in recent years, and may thus not support grey seal breeding.

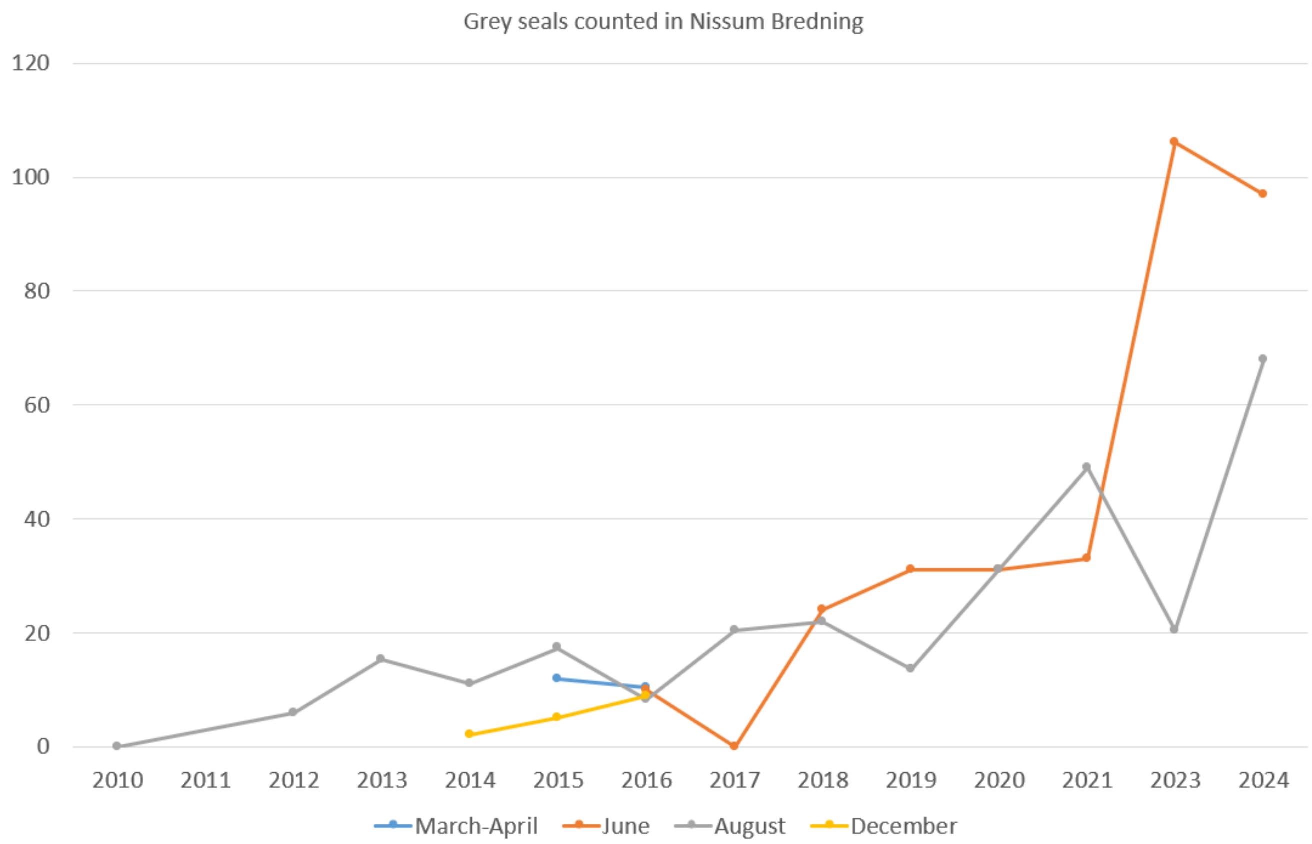


Figure 2-2-7: Grey seals counted in Nissum Bredning 2010–2024. Data are presented for four counting seasons, namely the grey seal moulting season (March-April), harbour seal pupping season (June), harbour seal moulting season (August) and grey seal pupping season (December). Data are from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

Grey seals are fewer in number than harbour seals and are still recolonizing the Danish North Sea after extinction from this area. As such, they have been classified as being in 'unfavourable conservation status' in Denmark according to the EU Habitats Directive (Fredshavn, Nygaard et al. 2019). Numbers of grey seals at the surveyed haul-outs are increasing across all seasons in the Limfjord (Figure 2-2-7), while a decrease has been seen in the Wadden Sea in recent years (Figure 2-2-7). The very low number of pups (max 4 per year for the population) at Danish North Sea haul-outs underline that the recolonization is in a very early phase with few adult females giving birth at the Danish locations. In contrast to the harbour seals, the counts of grey seals are more evenly distributed over the seasons, without peaks during the breeding and moulting periods in winter and spring, but still with a relatively low count in October and a very low count in December (Figure 2-2-8). This may reflect that grey seals of the North Sea observed in Denmark mainly are immature visitors to the area, coming to forage, and use the haul-outs between foraging trips, while most adult seals return to/stay in their core areas to breed and moult.

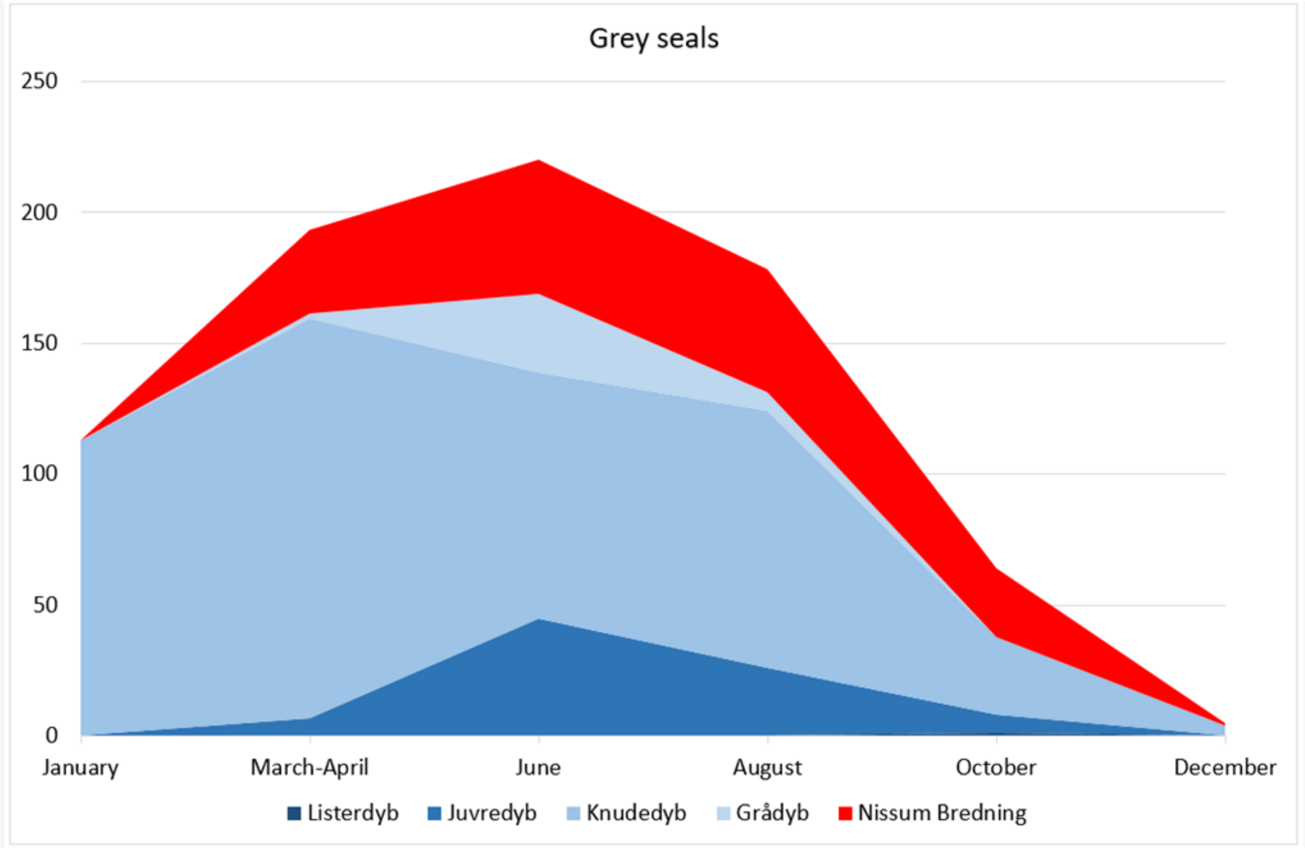


Figure 2-2-8: Counts of hauled out grey seals from the Wadden Sea (shades of blue for four subareas) and Nissum Bredning (red) from January to August 2022. Y-axis is number of counted seals. Data from Nissum Bredning in January, March–April, October and December and data from the Wadden Sea in March-April and October derive from the Energy Island investigations and are owned by Energinet. Remaining data are from the national monitoring program, NOVANA (Hansen & Høgslund 2024).

2.2.3 Seal usage of the North Sea I survey area from tracking data

While counting the seals on land can give information on the general trend of seal abundance in the area, only satellite tracking of seals can give direct information on the movement and distribution of seals at sea. Harbour seals are observed as far offshore as in the Danish oil and gas sector >200 km west of the west coast of Jutland, and grey seals are known to traverse the North Sea, both from the UK and from the Wadden Sea and the Limfjord. All available information on seal tracking from the relevant part of the North Sea are described below.

2.2.3.1 Harbour seals

In 2017–2020, 31 harbour seals were equipped with satellite transmitters in the inner Limfjord. Results showed that none of these seals moved into the North Sea I survey area (Figure 2-2-9). Harbour seals have also been tagged in the Danish Wadden Sea in 2002–2005. Several of these harbour seals moved into the North Sea I survey area. These data are, however, 19–22 years old and may not reflect the movements of seals in the Wadden Sea today. For the Energy Island North Sea survey program, 27 harbour seals were tagged in Thyborøn/Nissum Bredning between May 2022 and March 2023 by Aarhus University and NIRAS (Figure 2-2-10). The methods and results were published in the North Sea Energy Island tagging report (Kyhn et al. 2024b), and the results from that study are used in this report to describe the North Sea I area's importance for the seals at the nearest haul-out site. The movement tracks covered a period of 2–4 months for most seals with most of the positions recorded in the vicinity of the haul-out sites (Figure 2-2-11). Empty parts of individual tracks were fitted with a State-Space

Model (SSM) to fill the gaps and showed how individual seals used different parts of the North Sea (please see Kyhn et al. (2024b) for methods on the fitted movement tracks).

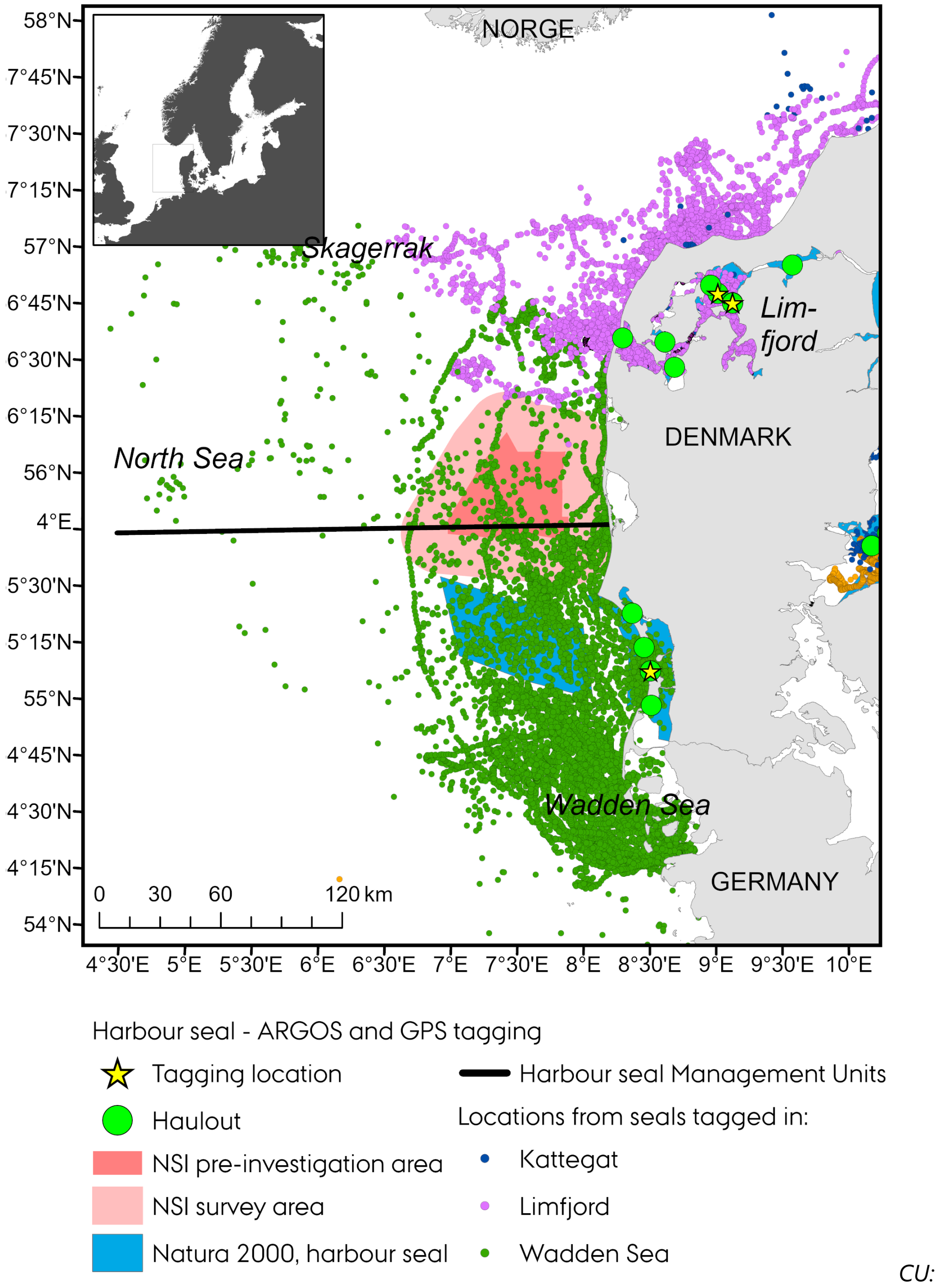


Figure 2-2-9: Map of positions from harbour seals tagged by Aarhus University between 2002 and 2020. The North Sea I investigation area is shown in dark pink and the marine mammal survey area in light pink.

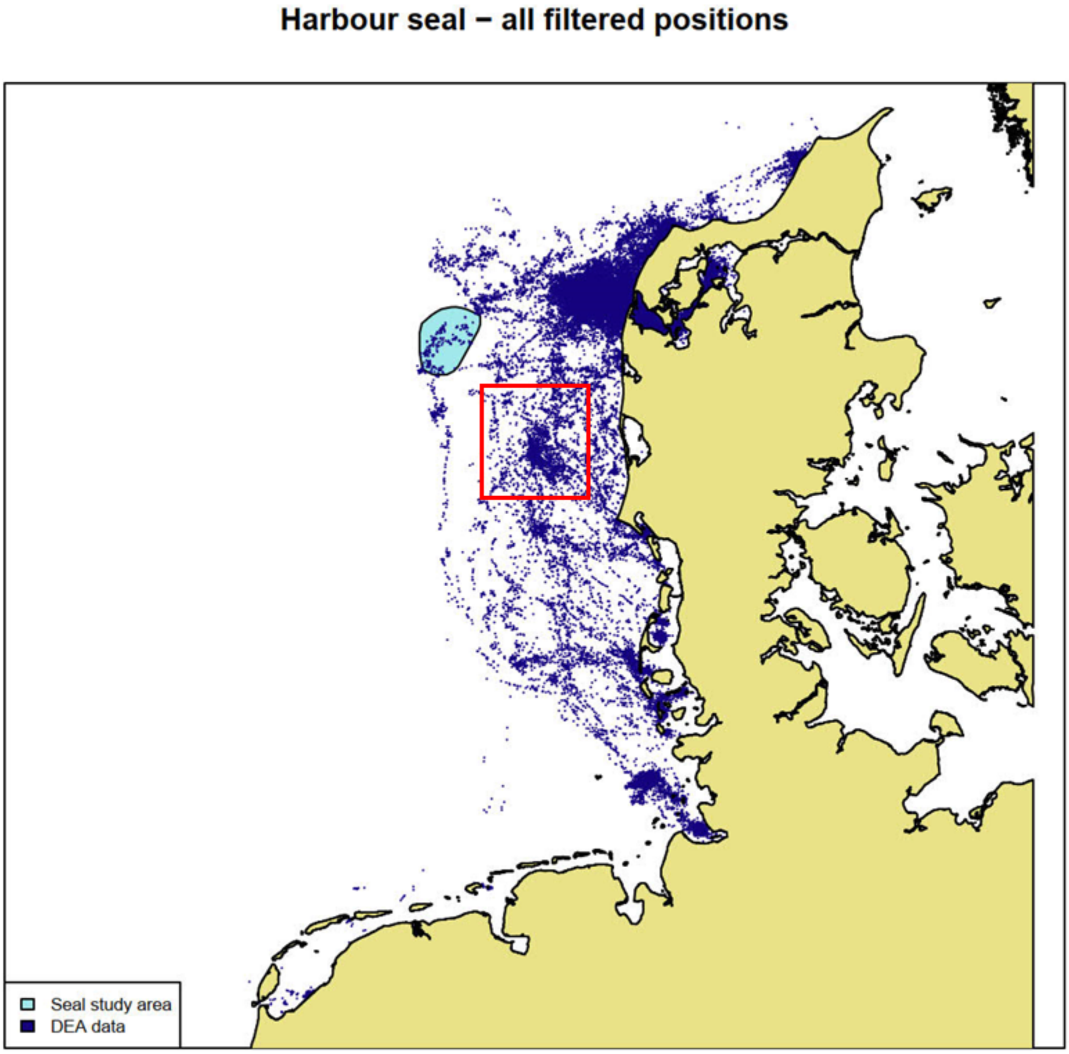


Figure 2-2-10: All filtered positions from the 27 harbour seals tagged in 2022–2023 for the North Sea Energy Island monitoring program. The light blue "Seal study area" was the area previously considered pre-investigation area for construction of an Energy Island. DEA is Danish Energy Agency. The approximate survey area for the North Sea I survey area is indicated by a red square. Modified from Kyhn et al. 2024b.

Data from the North Sea Energy Island tagging program as well as number of harbour seals hauled out at the nearest haul-out sites in August 2021 were used to make a habitat suitability model for harbour seals. The methods are thoroughly explained in Kyhn et al. (2024b). A number of variables were included in the model (sea surface temperature, sea surface salinity, current strength, sea surface height, mixed layer depth, distance to tagging site, water depth and substrate type). The habitat suitability model of harbour seal indicated that the likelihood of observing seals in different parts of the North Sea is related to a range of environmental variables and to distance to haul-out sites (Figure 2-2-11). Models that included all variables (i.e. temperature, salinity, current strength, sea surface height, mixed layer depth, distance to tagging site, water depth and substrate type) were much better than any of the models where one or more predictors were omitted. The best model for harbour seals explained 66% of the variation in seal presence, which is unusually high, which is unusually high, considering that seals cannot be expected to be guided entirely by environmental conditions. These conditions are rather proxies for distributions of prey species, which are expected to be the most important factors determining seal distribution at sea. To decide which model was best we calculated the corrected Akaike Information Criterion (AICc) and based our predictions on the model with the lowest AICc. The habitat suitability maps indicate that the North Sea I survey area – especially the shallow water close to the tagging sites – is frequently used by harbour seals and that the likelihood of encountering seals is particularly high close to areas with numerous seals haul-outs, such as the Wadden Sea.

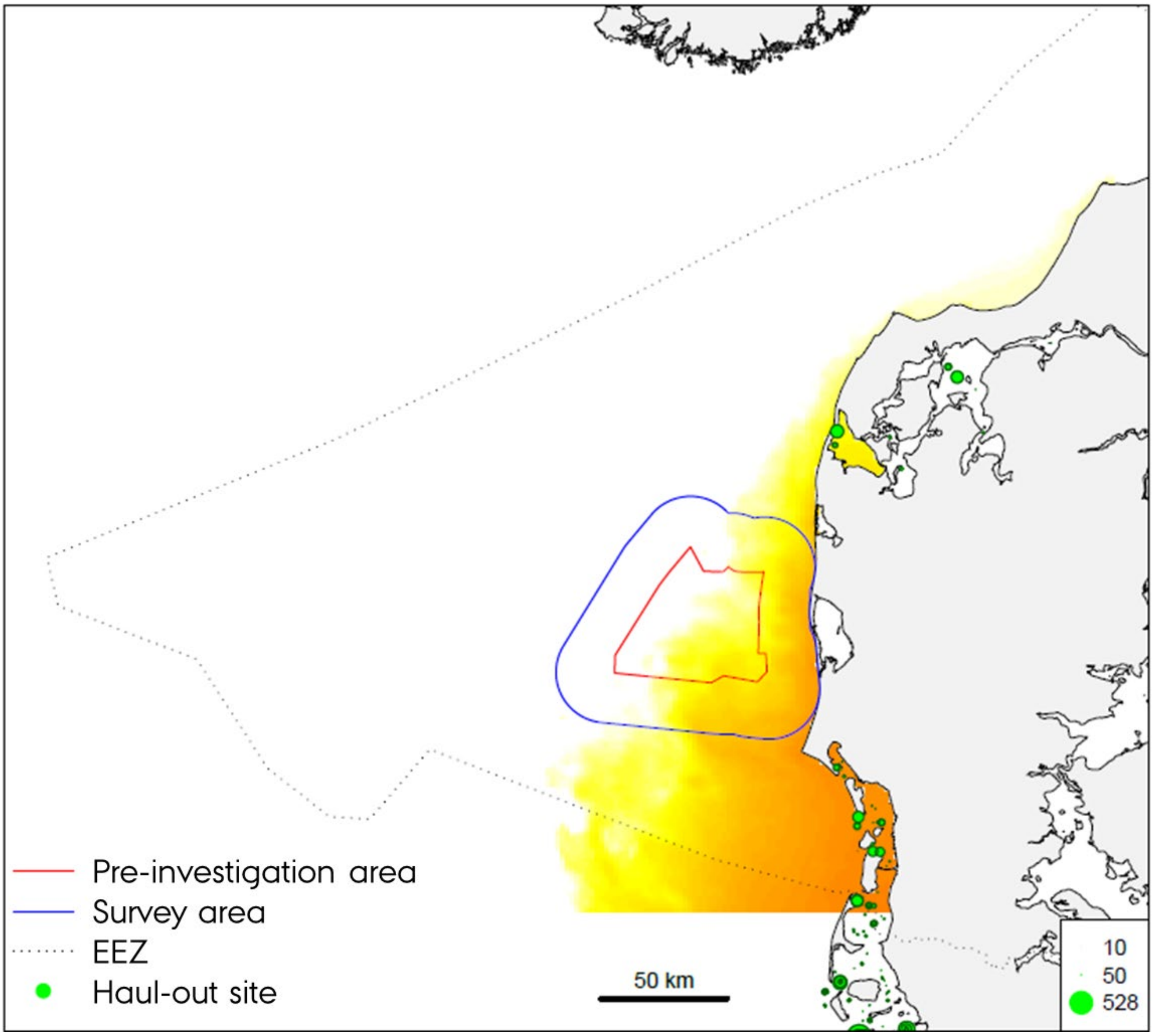


Figure 2-2-11: Habitat suitability map for harbour seals tagged at Thyborøn/Nissum Bredning for the North Sea Energy Island survey program. Green dots are haul-out areas with seals counted in the moulting season (August 2021); the size of the dots is proportional to the number of seals (1–528 seals per haul-out site). Not all German haul-out sites are shown. The colour scale signifies the relative probability that an area is used by seals with red-orange being high and white/yellow being low.

2.2.3.2 Grey seals

Grey seals have a more varied spatial behaviour than harbour seals. Prior to the North Sea Energy Island tagging program, the existing data on grey seals consisted of two grey seals tagged at Thyborøn and four newborn pups at Helgoland (Figure 2-2-12). The newborn pups are likely to have different movement patterns and home ranges than the adult individuals. None of these seals moved into the North Sea I survey area.

During the North Sea Energy Island tagging program, a total of 15 grey seals were tagged in Thyborøn between May 2022 and March 2023 by Aarhus University and NIRAS. Furthermore, 33 grey seals pups were tagged by Stiftung Tierärztliche Hochschule Hannover (TIHO) at Helgoland (Figure 2-2-13). The methods and results were published in the North Sea Energy Island tagging report (Kyhn et al. 2024b). The results from that study are used in this report to describe the North Sea I area's importance for the seals at the nearest haul-out site.

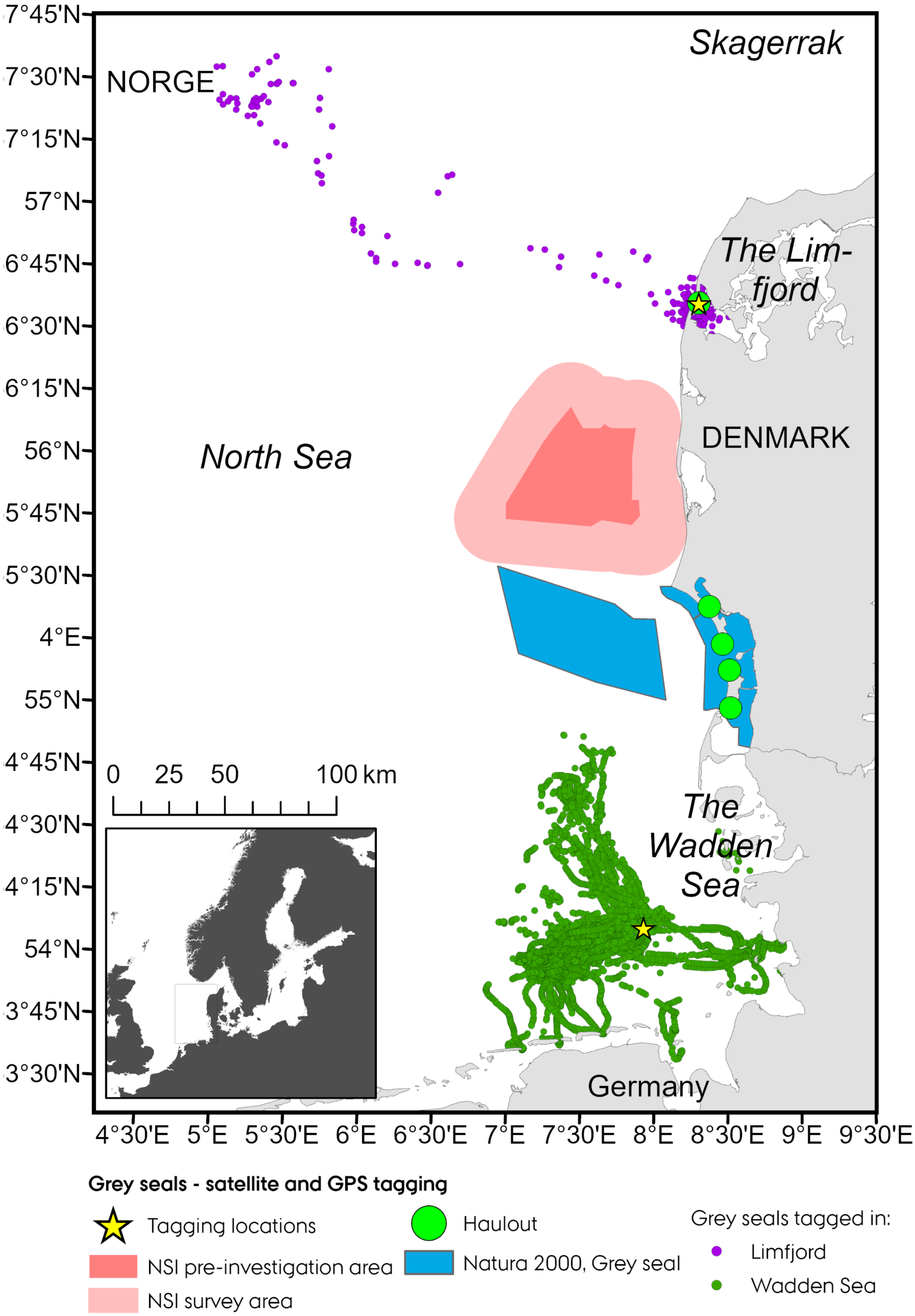


Figure 2-2-12: Map of positions from tagged grey seals between 2015 and 2020. The North Sea I pre-investigation area is shown in dark pink and the marine mammal survey area in light pink.

The habitat suitability model of grey seals from the North Sea Energy Island tagging report (Kyhn et al. 2024b) indicated that the likelihood of observing seals in different parts of the North Sea is related to a range of environmental variables and to distance to haul-out sites (Figure 2-2-14). Models that included all variables (i.e. temperature, salinity, current strength, sea surface height, mixed layer depth, distance to tagging site, water depth and substrate type) were much better than any of the models where one or more predictors were omitted. The best model for grey seals explained 48% the variation in seal presence (please see Kyhn et al. (2024b) for thorough methods and all results). The amount of predicted variation is unusually high, which is unusually high, considering that seals cannot be expected to be guided entirely by environmental conditions. These conditions are rather proxies for distributions of prey species, which are expected to be the most important factors determining seal distribution at sea.

The habitat suitability map indicates that all of the North Sea I survey area is frequently used by grey seals, and that the likelihood of encountering seals is highest in the southern part of the pre-investigation area.

The habitat suitability map for grey seals was not extended to the westernmost part of the Danish exclusive economic zone (EEZ), which is an area that is often visited by animals that haul out in the Dutch part of the Wadden Sea (Sophie Brasseur, pers. comm.). This study did not have access to information about the number of seals on the Dutch haul-out sites, and a prediction for grey seals based exclusively on information from Danish and German haul-out sites would underpredict grey seal densities in the western part of the Danish EEZ.

Grey seal data – ARGOS data

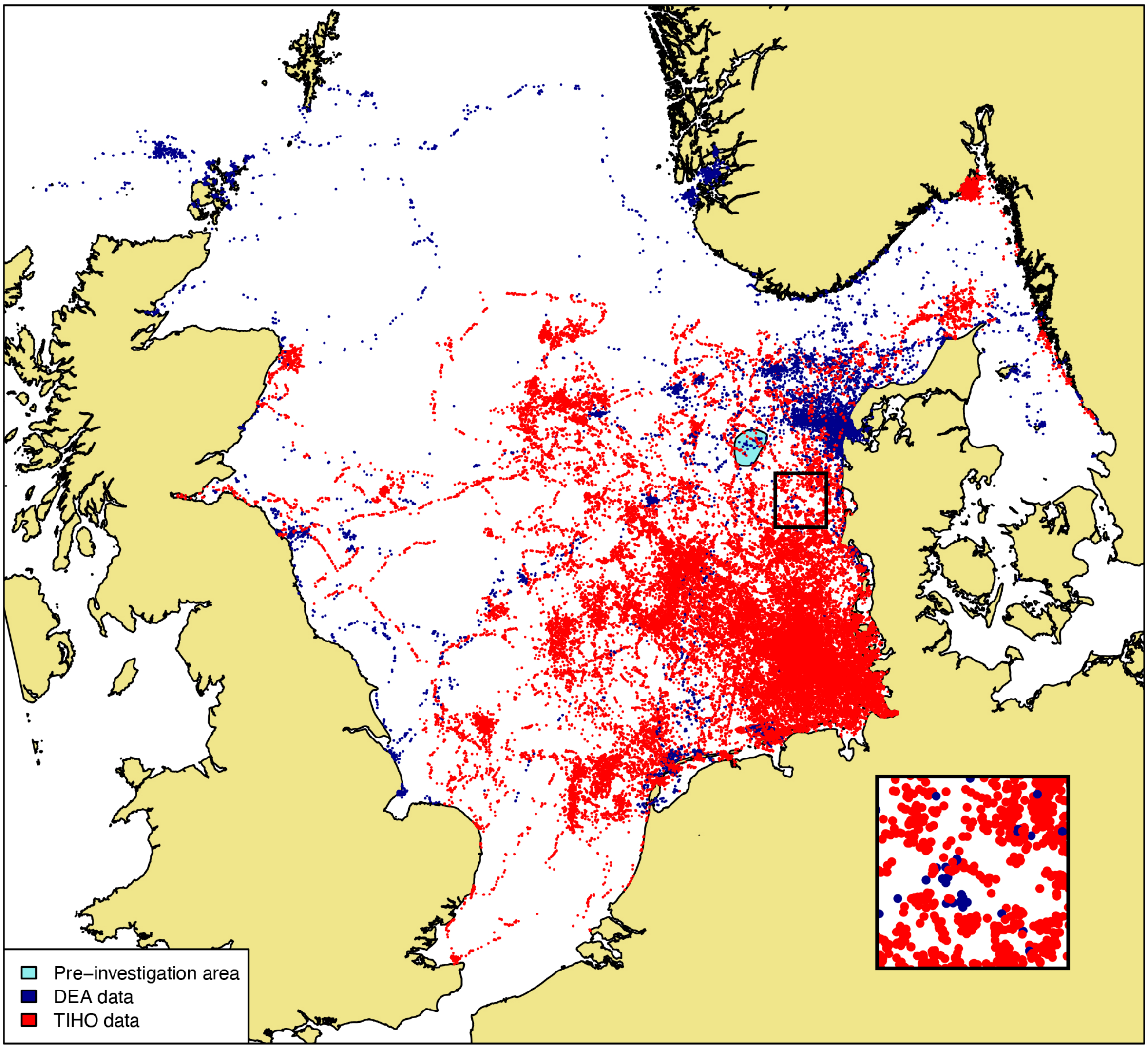


Figure 2-2-13: All filtered positions from the 15 grey seals tagged in 2022–2023 (dark blue dots) for the North Sea Energy Island monitoring program, as well as for 33 newborn pubs tagged at Helgoland. The light blue "Seal study area" was the pre-investigation area previously considered for construction of an Energy Island and 2–3 wind farms. DEA is the Danish Energy Agency and represents the seals tagged for the North Sea Energy Island program. TIHO is Tierärztliche Hochschule, Germany, that contributed data to the North Sea Energy Island tagging program. The map has been copied unmodified from the Energy Island tagging Report (Kyhn et al. 2024b). The approximate area for the North Sea I survey area is indicated in a fat black line (enlarged in the bottom right corner of the figure).

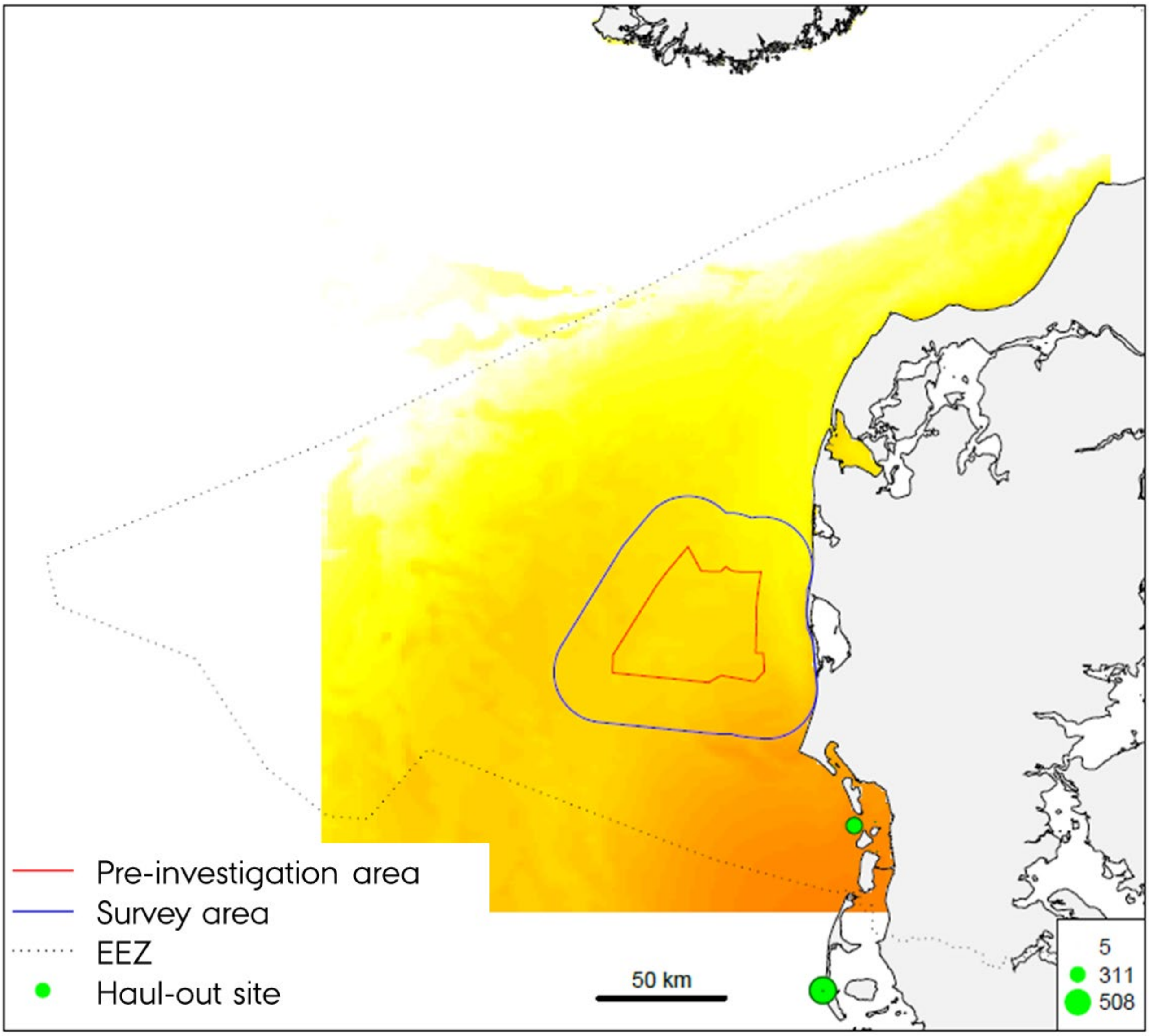


Figure 2-2-14: Habitat suitability map for grey seals tagged at Helgoland and Thyborøn. The green dots show haul-out sites where seals were counted in the moulting season of 2021, i.e., March–April; the size of the dots is proportional to the number of seals (1–508 seals per haul-out site). Not all German haul-out sites are shown. No seals were counted at Thyborøn in 2021. The colour scale signifies the relative probability that an area is used by seals. The habitat suitability map was copied from the Energy Island tagging report (Kyhn et al. 2024b) but superimposed with the North Sea Lot1 survey area. The map uses the EPSG:3035 ETRS89 projection.

The habitat suitability maps indicate that the North Sea I survey area is frequently used by both grey seals and harbour seals. Both species of seals predominately occur in shallow waters close to the tagging sites, and the likelihood of encountering seals is particularly high close to areas were numerous seals haul out, such as the Wadden Sea.

2.3 Underwater soundscape

The present underwater soundscape in the eastern North Sea is dominated by noise contributions from ships in the main shipping lane from the English Channel around Skagen and into the Baltic Sea (Figure 2-3-1, see also Kinneging and Tougaard, 2021). The shipping lane runs just outside the NW edge of the North Sea I pre-investigation area (but inside the North Sea I survey area), creating a gradient in the ship noise from west to east, with decreasing noise levels towards the less trafficked area north of Horns Reef OWF.

Underwater radiated noise from operating wind turbines has been measured for a substantial number of turbines (Figure 2-3-2, Figure 2-3-3). However, all but one set of measurements have been from turbines with a gear box and not of the direct drive type which is likely to be used in future North Sea wind farms. Furthermore, most of the recordings are from smaller turbines and the measurements of a low quality not suitable for use as input into a sound propagation model. Nevertheless, the noise from the turbines are clearly measurable above ambient noise and the combined noise from all turbines in a wind farm, as well as service ships, will add to the existing ambient noise (Tougaard et al. 2020). Earlier measurements on older and smaller turbines (Tougaard et al., 2020) indicate an increasing trend in noise emission with increasing turbine size, quantified by the nominal power output (Figure 2-3-2). More recent measurements on larger turbines (Bellmann et al., 2023) do not show the same trend but indicate that the emitted noise level for turbines above 2 MW nominal power is independent of turbine size (Figure 2-3-3). The noise survey program will therefore obtain relevant data for the creation of a turbine noise source model and use this source model as input in a model to estimate the cumulative impact from wind farms in the investigation area and relate this to other pressures (ships).

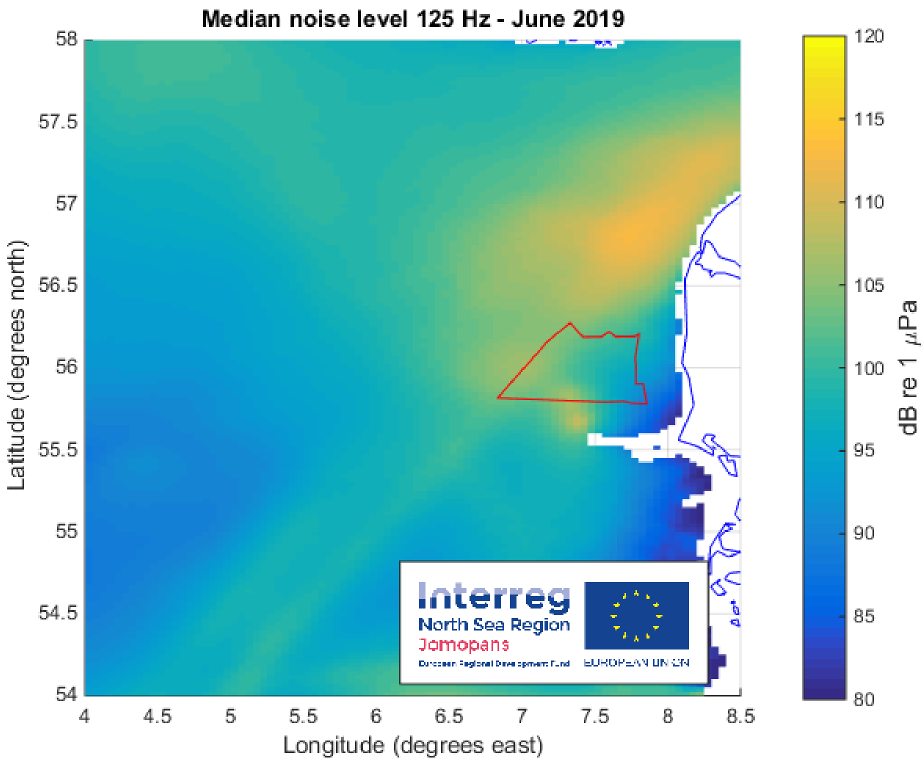


Figure 2-3-1: Existing underwater noise in the eastern North Sea, as modelled by the JOMOPANS project (de Jong et al. (2022)). Map shows median sound pressure level in the 125 Hz decidecade frequency band for the month of June 2019. The pre-investigation area is indicated with a red line (note that this is an older version of the pre-investigation area boundary). Courtesy of the JOMOPANS project.

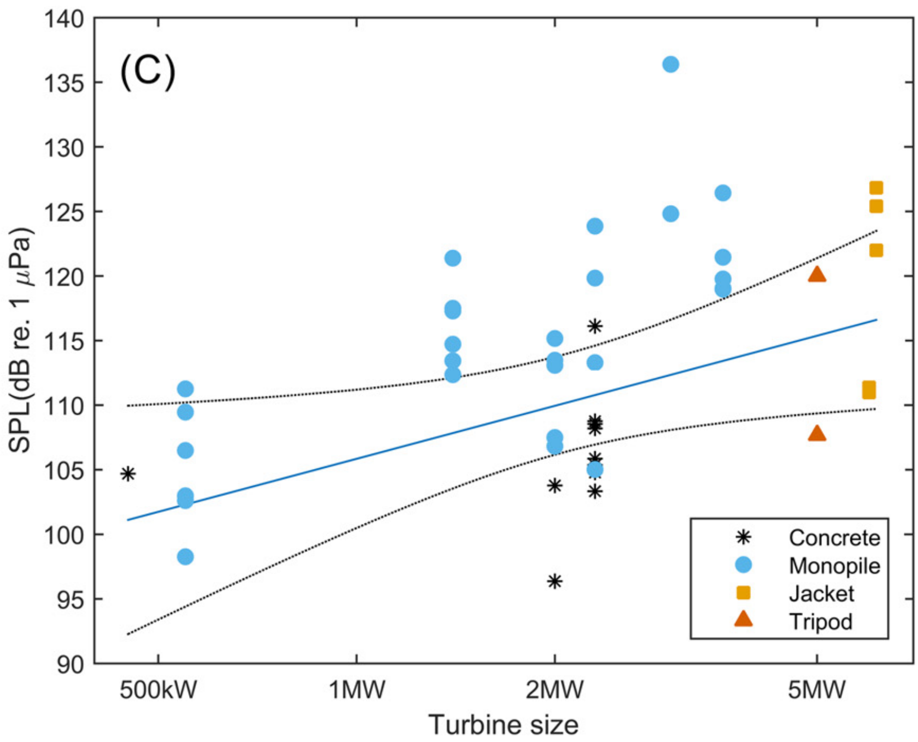


Figure 2-3-2: Influence of turbine size on measured sound pressure levels normalized to a distance of 100 m and wind speeds of 10 m/s. All turbines were with gear boxes except for one turbine (Block Island) which was direct drive (shown in light orange squares). From Tougaard et al. (2020).

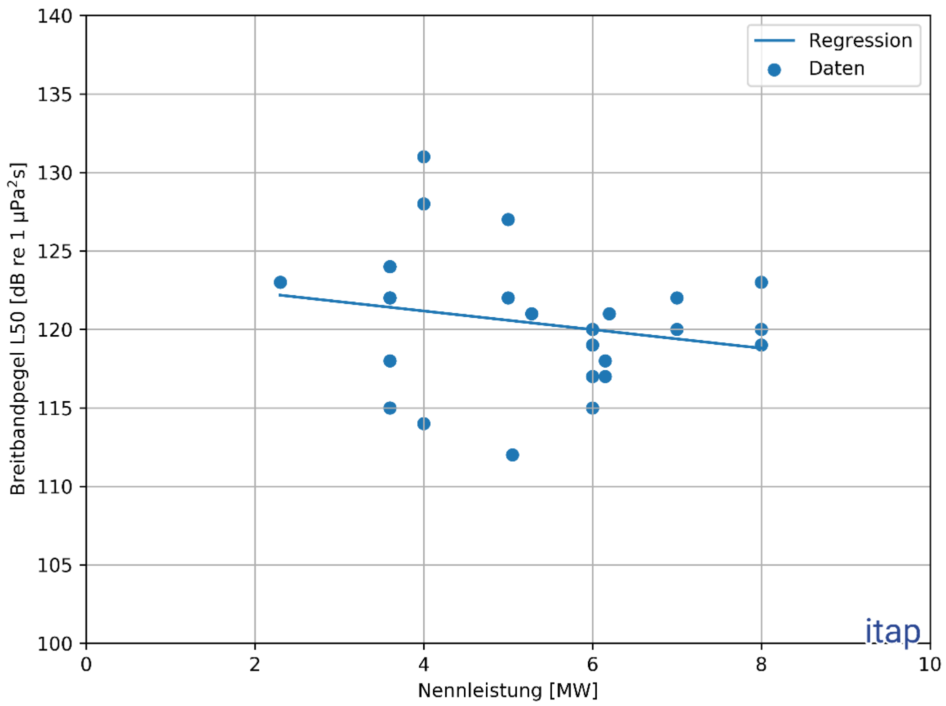


Figure 2-3-3: Broadband noise levels from larger offshore wind turbines, normalized to a distance of 100 m. From Bellmann et al. (2023).

3. Methods and survey(s)

Several different methods are necessary to monitor and document presence, abundance and density of marine mammals, and specific methods are needed to record, analyze and document underwater noise. The survey program was carried out from April 2023 to April 2025. This report includes all data from 2023-2025.

The data collection and analysis are divided into three parts, which will be described in detail in the following sections:

- Passive acoustic monitoring (PAM) of cetaceans
- Aerial surveys of cetaceans
- Underwater noise:
  1) Underwater noise monitoring
  2) Noise levels from turbines
  3) Harbour porpoise movements near operating turbines
  4) Noise exposure maps

3.1 Passive acoustic monitoring of cetaceans

Deployment of passive acoustic monitoring (PAM) systems within the survey area was conducted for two years to study the detailed temporal presence of harbour porpoises and other cetaceans. Two different instruments were used to be able to capture and analyze signals from both harbour porpoises, delphinids and minke whales.

3.1.1 Harbour porpoises

As the harbour porpoise is the most common cetacean species in Danish waters, F-PODs were used as the main PAM system. The F-POD has been specifically developed for detecting harbour porpoise echolocation signals.

The F-PODs have very good temporal resolution but relatively low spatial coverage, since the harbour porpoise detection range of F-PODs is assumed less than 1000 m based on DeRuiter et al. (2010). This is caused by the low source level, high frequency and narrow beam pattern of harbour porpoises and applies to all PAM systems designed to detect harbour porpoises in salt water. Because the presence of harbour porpoises may vary with habitat and hence distribution of various prey species, F-PODs were placed with an evenly distributed grid across the survey area (Figure 3-1-1). This design captures the variation in bathymetry (14–40 m) in the area, which may be an important driver for harbour porpoise distribution, thereby allowing for spatial distribution models to be conducted for each season. The grid spacing was decided based on results from the Danish national monitoring program, NOVANA. Here, power analysis showed that generally five C-POD stations had sufficient power to monitor the Natura 2000 sites in the Inner Danish waters with the density of harbour porpoises given there (Sveegaard et al. In press). The largest of these ("Storebælt og Vresen") is 630 km^2. The NSI survey area is approx. 10 times this size. Thus, by assuming that the NSI survey area holds similar densities of porpoises, then the grid should fit in 50 stations to correspond to the NOVANA program. However, the area is relatively uniform in both bathymetry and sediment types, and therefore less variation in porpoise presence is expected compared to Inner Danish waters. Consequently, it was decided to lower the number to 35 stations. The grid was adjusted to fit this number inside the survey area. After the full two year of monitoring, differences in the annual mean number of PPM per day for each station were statistically tested and quantified using the post hoc Tukey Honest Significant Difference (HSD) tests using an alpha (p-value) of 0.2. We used an alpha level of 0.2 instead of the conventional 0.05 level in all statistical analyses to follow the power analyses thresholds as described below and recommended by the International Council for the Exploration of the Sea (ICES) (2010) for detection of trends in marine mammal monitoring.

To compare with previous studies in the area and examine the long-term trend and stability of harbour porpoises, seven additional stations were deployed (two in the Thor OWF area and five in and near Horns Rev III) (Figure 3-1-1). To facilitate the comparison with previously gathered data, stations in the OWFs (as well as the two stations in the grid located within the areas of Thor OWF and Horns Rev III) were deployed with both C-PODs and F-PODs, as the older studies were conducted with CPODs (which are no longer commercially available). This means that in total 42 stations were deployed. The positions were all approved by the Danish Maritime Authorities on 16th of January 2023 and both Vattenfall (Horns Rev 3 Offshore Wind Farm) and RWE (Thor OWF) approved deployment within the two OWF sites. Metadata for all PAM positions are shown in Table 3-1-1. Statistical analyses of the data collected at Horns Rev 3 Offshore Wind Farm and Thor Offshore Wind Farm were done using generalised mixed effect models. The main purpose of the analyses was to assess differences in harbour porpoise echolocation activity around the wind farms at different years and for Horns Rev 3 Offshore Wind Farm also for differences between the three stations deployed inside the wind farm and the three stations deployed outside the wind farm. PPM per day was fitted as the response variable in all models using a Poisson error distribution and Station ID nested within month as random variables (to account for unbalanced data design). The fixed effect in the model constructed for Thor OWF was called "monitoring period" and was fitted as a 3-factor level (i.e. 2019-2020, 2023-2024 and 2024-2025). A similar model was constructed for Horns Rev 3 Offshore Wind Farm but with the fixed effect variable "monitoring data" comparing data collected in 2012-2013, 2023-2024 and 2024-2025 and fitted as an interaction with the placement of the stations (i.e. inside or outside the OWF). Differences in harbour porpoise echolocation activity between years and placement were then estimated using a Tukey post-hoc test for mixed models. For all models, statistical differences in PPM per day between years and placements were considered with a P-value <0.20 as explained above.

Table 3-1-1: Metadata for all PAM stations. FPODs and CPODs record harbour porpoises. A SoundTrap is a wideband acoustic recorder aimed for cetacean detections other than harbour porpoises, and noise.

StationID	Longitude	Latitude	Equipment - Cetacean	Depth (m)
NS1	6.5290	55.7760	FPOD	-41
NS2	6.6906	55.8746	FPOD + SoundTrap	-39
NS3	6.7018	55.6842	FPOD	-37
NS4	6.8652	55.7824	FPOD	-35
NS5	6.8547	55.9729	FPOD	-39
NS6	6.8441	56.1634	FPOD + SoundTrap	-39
NS7	7.0390	55.6900	FPOD	-32
NS8	7.0286	55.8810	FPOD	-32
NS9	7.0197	56.0710	FPOD	-35
NS10	7.0099	56.2615	FPOD	-36
NS11	7.2033	55.7879	FPOD	-29
NS12	7.1960	55.9784	FPOD	-33
NS13	7.1871	56.1690	FPOD + SoundTrap	-34
NS14	7.1765	56.3594	FPOD + SoundTrap	-34
NS15	7.3763	55.6949	FPOD	-23
NS16	7.3684	55.8855	FPOD + SoundTrap	-24
NS17	7.3601	56.0771	FPOD	-30
NS18	7.3522	56.2665	FPOD	-34
NS19	7.5397	55.7923	FPOD	-16
NS20	7.5325	55.9829	FPOD	-26
NS21	7.5251	56.1734	FPOD	-33
NS22	7.5197	56.3639	FPOD	-32
NS24	7.7079	55.8895	FPOD	-23
NS25	7.7015	56.0814	FPOD + SoundTrap	-30
NS27	7.8851	55.6053	FPOD	-14
NS28	7.8797	55.7959	FPOD	-20
NS29	7.8742	55.9864	FPOD	-23
NS30	7.8686	56.1770	FPOD	-27
NS31	7.8630	56.3676	FPOD	-26
NS32	8.0512	55.7020	FPOD	-17
NS33	8.0465	55.8926	FPOD	-20
NS34	8.0418	56.0832	FPOD	-14
NS35	8.0371	56.2737	FPOD	-21
HR3_1	7.6081	55.7148	CPOD/FPOD	-17
HR3_2	7.6725	55.6485	CPOD/FPOD	-12
HR3_3/NS	7.7141	55.7012	CPOD/FPOD	-19
HR3_4	7.7908	55.7348	CPOD/FPOD	-18
HR3_5	7.8519	55.7173	CPOD/FPOD	-16
HR3_6	7.9010	55.7487	CPOD/FPOD	-18
T2	7.5437	56.2799	CPOD/FPOD	-32
T3/NS26	7.6946	56.2706	CPOD/FPOD	-31
T4	7.6816	56.3391	CPOD/FPOD	-29

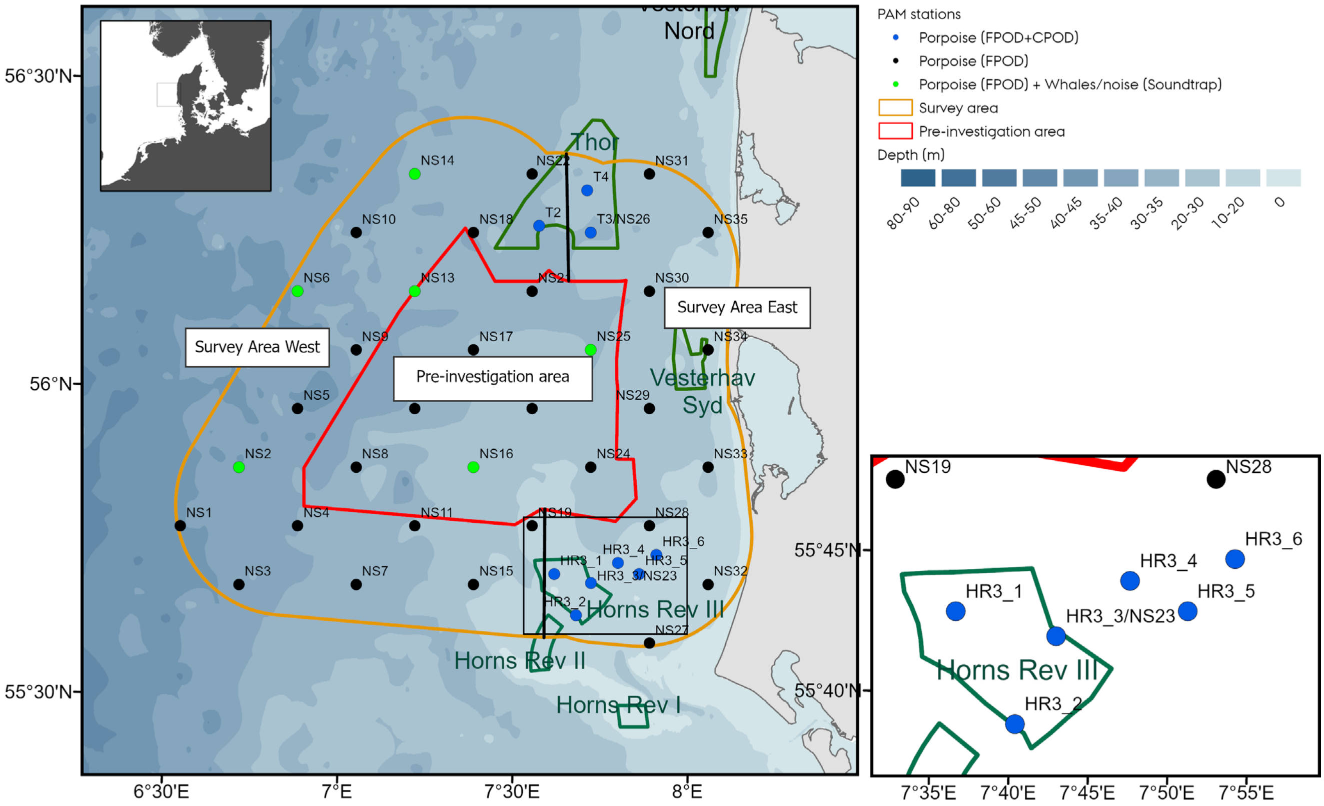


Figure 3-1-1: Overview of the PAM program with 42 stations in the survey area. Six of these have SoundTraps for broadband species monitoring/noise measurements (green positions), 9 have both F-PODs and C-PODs (blue positions) and the rest only F-PODS (black positions). The PAM stations were placed following a regular grid. For result illustration purposes, the stations were divided into groups: the pre-investigation area, the survey area west and survey area east (division lines marked in burgundy).

A 6 m yellow surface buoy (type N225/6) was used "to guard" the F-POD at each monitoring station by informing trawling vessels of their presence. The setup was developed by Bioconsult SH and has been used successfully in several projects e.g. at Thor OWF and Horns Rev III OWF - both located within the current survey area.

The surface buoy was connected to the equipment by a rope along the sea bottom (see sketch of setup in Figure 3-1-2). All surface buoys were equipped with a satellite transmitter allowing us to monitor their continuous presence. In case a buoy was removed by trawlers or hit by a vessel, its location could be followed, which allowed us to regain it. The stations were serviced approximately every third month, and data was downloaded and validated immediately after each survey.

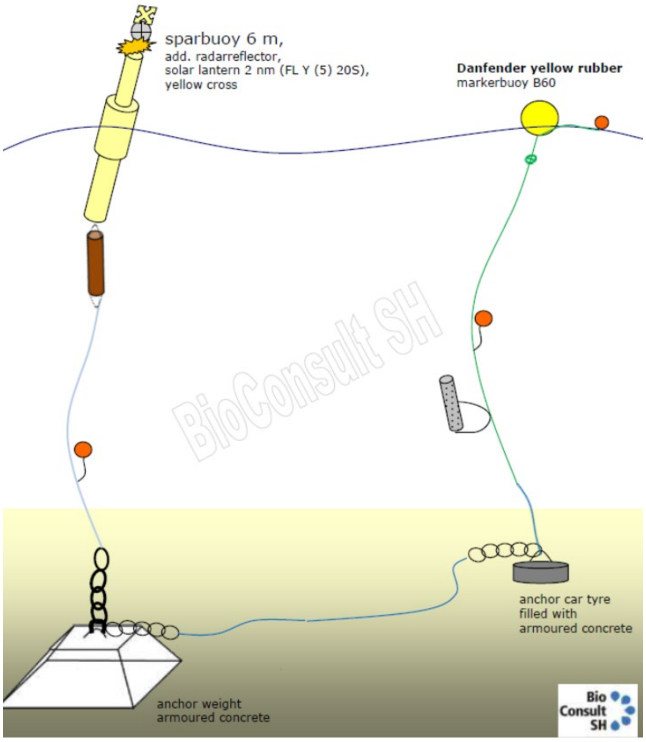


Figure 3-1-2: PAM setup. The surface buoy is connected to a large concrete anchor. The concrete anchor is connected with a rope to a smaller cement tyre anchor which is connected to a small rubber float at the surface. The recording device (F-POD, C-POD and/or Sound trap) is positioned on the rope approx. 2 m from the sea floor.

3.1.1.1 Analysis of FPOD data

Data from FPODs are analyzed using the program FPOD.exe (Chelonia Ltd.). Here, the recorded CHE files are converted to FP1 files, where click events are found according to an inbuild algorithm. FP1 files are then converted to FP3 files where clicks are ascribed to trains of various origin. These are as follows: Narrow Band High Frequency (NBHF) origin, which in the North Sea is exclusively harbour porpoises; delphinid origin; and (shipborne) sonar origin. Each click train is associated with a likelihood ratio, related to the probability that it originated from the source it was classified as (NBHF, Delphinids or sonar). Here only click trains of high or moderate likelihood of arriving from NBHF species were exported and used for analyses. Data from the day of deployment and the day of retrieval were discarded to exclude effects of the service vessel on presence of harbour porpoises from the analysis. To assess variation in harbour porpoise presence, FPOD data exported as Porpoise Positive Minutes (PPM) per day was summarized and graphically illustrated across months, stations, and each of the three areas (project area and the two buffer zones: east and west). In FPOD.exe data are exported using the following train filters: Quality High and Moderate for the "NBHF" and "Other cetaceans" filter. A porpoise positive minute is a minute with at least one porpoise click recorded from a click train in the category high or moderate likelihood of arriving from a NBHF source . Graphs show either the absolute values of PPM per day or the mean and standard error around the mean (SEM).

To model any spatial and temporal variation in harbour porpoise presence as a function of environmental conditions, acoustic Species Distribution Maps (aSDMs) were generated based on generalized additive models (GAMs). Separate GAMs were developed for each month in each monitoring period (Period 1: Apr 2023- Mar 2024 and period 2: Apr 2024-Mar 2025) using PPM per day as the response variable. Eleven environmental features were considered as predictor variables including bathymetry, seabed slope, seabed rugosity (i.e. ruggedness), distance to nearest sandeel spawning ground, sea bottom temperature, sea surface temperature, sea surface salinity, sea surface height, current velocity, and mixed layer thickness. Raster data on the environmental features were obtained through the open-access online sources Copernicus and Emodnet and subsequently linked to the stations via their geographical coordinates and the date of recording. Multicollinearity among the 11 candidate predictor variables was substantial with variance inflation factor >20 and Spearman's rho >0.7 for various variable combinations. Based on a backwards, stepwise procedure, we removed seabed rugosity and sea bottom temperature as these produced variance inflation factors <5 and Spearman's rho <0.6. All uncorrelated environmental predictor variables (N=8) were fitted in the monthly GAMs as a smoothed term with shrinkage, which allows for uninformative terms to be penalized to zero, effectively making them linear. To ensure smooth functions reflected plausible biological relationships, the number of knots (k) was restricted to 4, as higher knots lead to increasingly complex functions that are difficult to explain biologically. Station ID was included as a random intercept so that the relationships in the models were estimated across PAM stations rather than data points, ensuring that data-rich stations did not have a disproportionate influence on the overall trends. Spatial autocorrelation in the data was estimated by incorporating the interaction between the XY coordinates of each station as a smoothed term.

For each monthly model, the regression coefficients were used to predict and map variation in harbour porpoise presence across the area. To do so, a prediction layer of PPM was generated for each day of the month which was then used to calculate the mean. To assess differences in harbour porpoise presence in the area between monitoring period 1 and 2, the monthly mean predicted presence maps for the period Apr 2023-Mar 2024 were subtracted from the maps for the period Apr 2024-Mar 2025 i.e. April 2023 was subtracted from April 2024 and so on. This generated a heat map showing differences between the two monitoring years.

Besides area-wide differences in harbour porpoise presence, differences in harbour porpoise presence between the two monitoring periods, were also estimated at the scale of each PAM station. To do so, a generalized linear model was constructed for each PAM station separately using a Poisson error distribution. The mean PPM per day per month was fitted as the response variable in each model and monitoring period as the explanatory 2-factor variable.

3.1.2 Other cetaceans

The presence of other relevant cetaceans with a focus on white beaked dolphins and minke whales within the survey area was unknown prior to this study. These species are usually found in deeper waters, and therefore their presence was assumed to be confined to the deeper, western waters of the survey area. The F-POD is not able to detect low frequency sounds below 20 kHz, such as those produced by minke whales, and echolocation clicks from dolphins are at present unlikely to be categorized correctly with F-PODs (Cosentino et al., 2024). Instead, cetacean vocalizations from species other than harbour porpoises (echolocation clicks and communication sounds) were captured by broadband sound recorders (ST600HF SoundTraps, Ocean Instruments, New Zealand), which were deployed along with F-PODs at selected stations, mainly in deeper waters, though with coverage in each quarter of the survey area. Thus, at six of the PAM stations, SoundTraps (see Figure 3-1-1) were deployed for recording other cetaceans and underwater noise. This enables documentation of seasonal presence of other cetacean species and provided the noise recordings needed to determine potential exposure of harbour porpoises to underwater noise. The SoundTraps are broadband sound recorders and have an integrated hydrophone, with a frequency response of 20 Hz–150 kHz and a sensitivity range between 174.4–176.7 dB re. 1 µPa/V. To capture the full bandwidth of marine mammal vocalizations, including delphinid echolocation clicks, the marine mammal stations were programed to record with a sampling rate of 384 kHz on a 45-minute on per hour duty cycle to allow recording for three months at a time. It is not possible to record continuously for three months at a time, which was the service interval in the survey program, due to battery and memory limitations. Forty-five minutes per hour was selected as these sound recordings will also be used in the noise analysis, which requires a minimum of 30-minute sound files (Verfuß et al., 2015). However, from February 2024 and onwards a duty cycle of 30 minutes on per hour was selected to maximize battery/memory life, due to the erratic service interval of the PAM stations caused by weather. This change allowed full temporal coverage for up to five months.

Recordings from each deployed instrument was individually assessed for usable data, also known as quality assurance/quality control (QA/QC), therefore a preliminary analysis outside of the detection and classification of marine mammals and noise processing was conducted, to remove periods of recordings that were not representative of the conditions in the surroundings. Additionally, the recordings from each deployment were quality checked to ensure the broadband recorders captured the marine soundscape without so-called parasitic signals of internal origin (self-noise of the electronics) or external origin (noise from the mooring).

3.1.2.1 Delphinid analysis

Following the QA/QC, data was analyzed with the open access software platform PAMGuard (Gillespie, et. al. 2008) to detect and classify possible whistles and click encounters from odontocetes, by means of built-in and custom detectors and classifiers (Griffiths et al., 2023). One detector was tasked with finding dolphin whistles, and another tasked with finding echolocation clicks and burst pulses from non-porpoise odontocetes. After a manual review of the detector results, whistles and clicks were categorized to species groups, as far as possible. An event was defined as the time between the start and end of recorded odontocete vocalizations. By definition, events were separated by at least 10 minutes before a new event began. Non-porpoise odontocetes are notoriously difficult to classify to species based on acoustics alone but are very easy to separate from harbour porpoises. Most often, encounters could be classified into either of two groups: white-beaked dolphins, identified by spectral banding in both echolocation and burst pulses, and 'other delphinids', which contains all other sources of dolphin signals such as killer whales (*Orcinus orca*), long-fined pilot whales (*Globicephala melas*), bottlenose dolphins (*Tursiops truncatus*), white-beaked dolphin, and potentially Atlantic white-sided dolphin (*L. acutus*). Not all white-beaked dolphin events contain spectral banding, and therefore it is possible that some events categorized as ''other delphinid' also contain white-beaked dolphin encounters. To investigate if there was a diurnal pattern in dolphin events, the time between sunrise and sunset needed to be normalized, since daylight varies dramatically throughout the year in the survey area. Sunrise and sunset times were extracted in R based on the solar azimuth, solar elevation, and the declination angle of the sun (Meeus et al., 1991). Daylight was normalized between 0 (sunrise) and 1 (sunset), while nighttime was normalized between -1 (sunset) and 0 (sunrise) per day around the center of the study area (56°N & 7°30'E).

The data collection methods in this study are identical to data collected during the North Sea Energy Island survey program (Kyhn et al. 2024a) but differ in recording length. As for the North Sea Energy Island analysis, the review of broadband data for odontocete vocalizations is highly time-consuming and therefore duty-cycling analysis was employed. This approach has been shown to not have a significant impact on the ability to detect odontocete vocal activity (Kyhn et al. 2024a). However, in the North Sea Energy Island survey program, which duty-cycled 10–12 minutes per 15, the individual sound files were for North Sea I able to be treated as snapshots, i.e. a time window in which animal presence was documented in a point-transect survey style that ignored animal movement and correlation (Buckland, 2006). If one of the four quarters/sound files per hour contained a dolphin detection, that was then considered a detection positive hour (DPH) for delphinids. To make the methods used here more directly comparable to those within the North Sea Energy Island monitoring program, 15-minute intervals between the start and end time of each deployment were generated. How the measured recordings overlapped with those snapshot intervals were then observed. Using this method, it is possible to calculate how many hours from the deployment were included in the duty-cycled delphinid analysis (Figure 3-1-2). The calculation of DPH per deployment was then based on hours available for analysis, rather than the full deployment timeframe. This method is robust and comparable to changes in recording length, measuring how much coverage there was available per hour.

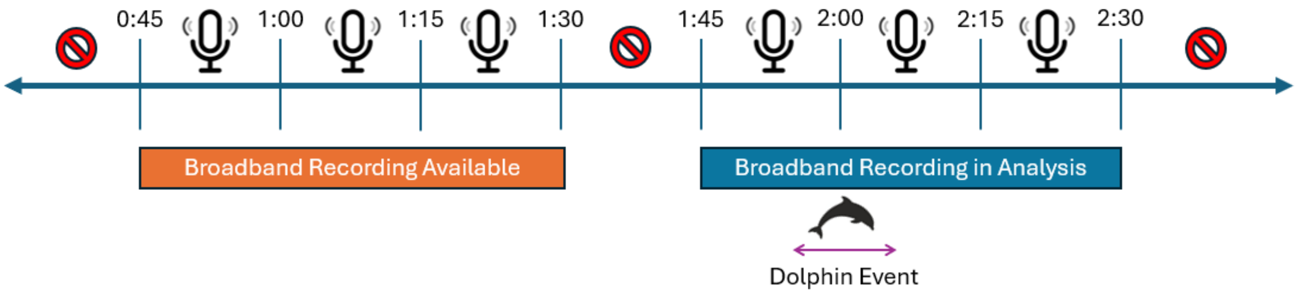


Figure 3-1-2: Overview of snapshot data processing. Each hour is divided into four 15-minute quarters, based on the start times of the sound file. If a dolphin event duration spans two quarters included in analysis, it is counted in both quarters, as this is how the data would have been counted in the North Sea Energy Island survey program (Kyhn et al. 2024a).

3.1.2.2 Minke Whale Analysis

Based on survey observations, the North Sea is a known habitat for minke whales, and there exists published methods to detect and classify minke whale low frequency pulse trains from autonomous recordings (Risch et al., 2013; Risch et al., 2014; Risch et al., 2019). These methods have been used to help monitor minke whale migration and seasonal use of western North Atlantic waters and have been successfully applied to the Moray Firth along the east coast of Scotland, which is inhabited by the same minke whale population as the North Sea. The North Sea I original acoustic survey design for minke whales was to employ the methods developed by Risch et al. to Danish waters. Risch et al. (2019) targets the minke whale pulse train.

The published version of the Risch minke whale detector is not feasible for this report due to issues with the XBAT (Figueroa & Robbins, 2008) platform no longer being supported or maintained. In the past year, however, the tool has been redesigned and integrated into the ketos python framework (MERIDIAN 2020). While this revised tool is still in beta development, access was granted to test the tool on this data. Therefore, it should be noted that when the revised tool undergoes peer-review, it may be changed and thus the results may vary. Using the same periodic subsampling from the odontocete analysis, the new minke whale detector was run on 25% of all stations, ensuring that at least one 45-minute or 30-minute file would be analyzed per four hours for full temporal coverage of the survey. The output of the detector is a csv file which contains the times minke whale vocalizations may have been detected. Additionally, the detector generates clips for each detection, as well as a jpg file of each clip. This allows for the results to be manually audited and verified, as minke whale pulse trains can sometimes resemble the frequency and rhythm of large vessel propellers or USBL signals, causing the detector to produce false positives.

3.2 Aerial surveys of cetaceans

Aerial cetacean surveys were conducted to obtain information on abundance across seasons within the survey area. However, since the hours of daylight are few and the weather likely to be poor in the winter, the aerial cetacean surveys were planned to be conducted from April to November. Four surveys were planned per year: one in spring and autumn respectively, and two during the summer months. The aerial surveys also provided information on the presence and distribution of calves to determine whether the survey area is a potential calving ground or not.

Aerial surveys using observers is at present the only method for abundance estimation comparable to previously conducted surveys in and near the area e.g. the annual NOVANA aerial harbour porpoise surveys in the southern North Sea and Skagerrak (Hansen & Høgslund 2021) and the international SCANS surveys, lastly conducted in July 2022 (Gilles et al. 2023).

Aerial surveys of cetaceans followed pre-designed transect lines that ensured equal coverage probability within one full day's survey (average transect length was 83 km and the total length 1084 km). The aerial surveys were conducted by three experienced observers on board the aircraft (Partenavia 68 with bubble windows): two observers positioned at the bubble windows and one data collector. During line transect distance sampling, the perpendicular distance of a harbour porpoise sighting to the track line was measured with a clinometer. The distances are used in the abundance analyses to estimate the effective strip width covered by the plane. To measure the distance, the plane flies at a constant altitude of 600 feet (183m) and at a constant speed of 100 knots. Transect lines are defined in a parallel design of east-west lines in the investigation area i.e. perpendicular to the depth contours as recommended for this method. This means that the data is representative of the entire survey area (Figure 3-2-1). OWFs cannot be covered, as it is not allowed to fly at the aforementioned altitude over windfarms. OWFs are therefore excluded in all the performed aerial surveys.

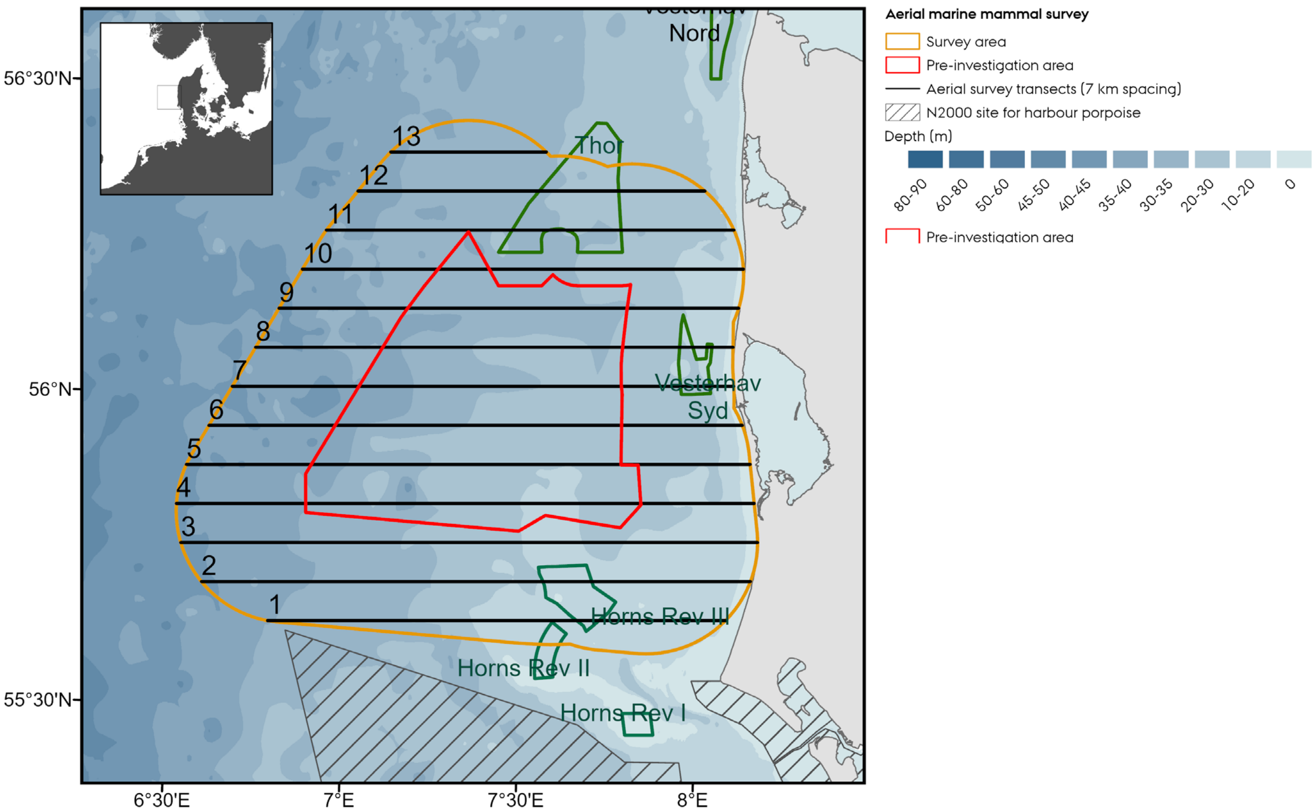


Figure 3-2-1: Overview of the aerial survey program for marine mammals in the investigation area. The transect lines are placed with a distance of 7 km. Note that OWFs were not covered due to survey altitude.

During the aerial surveys, all detected marine mammals were recorded and the location and number of observations per species were documented. Marine mammals were also observed during the aerial bird surveys (for details see the North Sea I Technical report for birds). These data are included in the presentation of dolphins and minke whale presence. However, because these data are collected with a different methodology and at a different height, these observations cannot be included in the density calculations.

3.2.1 Analysis of aerial survey data

After the survey, the collected data was analyzed to estimate abundance and density. This was only possible for harbour porpoises. The ratio of calves in relation to adult harbour porpoises were also estimated.

Analysis of abundance and density was conducted in the software R using a special script developed during SCANS-IV. The analyses included variables such as weather and sea state to estimate the abundance and densities in the observation period.

The number of harbour porpoise sightings within an area depends not only on the number of individuals observed, but also on the probability of the individual being visible (called availability bias) and the probability of an observer detecting it (called perception bias). The parameter quantifying the combined probability is known as g(0). This factor has been estimated during previous surveys conducted in German and Danish waters by using the "racetrack" method. Details of the racetrack method and the analyses are described in Hiby and Lovell (1998) and Hiby (1999). For the analysis of data from the survey area, the observer team, methodology and the survey plane were consistent with the one used during SCANS-IV in 2022 in European (incl. Danish) waters and thus the g(0) value and other relevant information such as the effective strip width used during SCANS-IV (Gilles et al. 2023) was applied. The major advantage of this method is that it takes into account both availability and perception bias with the same data collected.

Harbour porpoise abundance in the survey area (v) was estimated as:

$$\hat{N}_v = \frac{A_v}{L_v}\left(\frac{n_{gsv}}{\hat{\mu}_g} + \frac{n_{msv}}{\hat{\mu}_m}\right)\bar{s}_v$$

Where A_v is the area of the stratum, L_v is the length of transect line covered on-effort in good or moderate conditions, n_{gsv} and n_{msv} are the number of sightings collected in good conditions and moderate conditions respectively, $\hat{u}_g$ is the estimated effective strip width (ESW) in good conditions, $\hat{u}_m$ is the estimated ESW in moderate conditions and $\bar{S}_v$ is the mean observed group size in the stratum. ESW will be small if the weather conditions are poor and larger in good condition. Coefficients of variation (CVs) and 95% confidence intervals (CIs) were estimated by bootstrapping (999 replicates) within strata, using transects as the sampling units. More details on survey method and abundance estimation are described in Scheidat et al. (2008), Gilles et al. (2009), Hammond et al. (2013) and Nachtsheim et al. (2021).

3.3 Underwater noise

The potential exposure to underwater noise and vibrations was investigated to create a model that combines information on the distribution of marine mammals, the reaction of these animals to relevant noise sources, and underwater noise exposure maps. Thus, this work consists of three parts:

1. Creating noise exposure maps encompassing the exposure levels from all combined noise sources prior to the construction of the proposed wind farm. These maps are conceptually similar to the JOMOPANS maps (Figure 2.4) but updated with actual ship traffic from 2023 and including noise emission from operating wind turbines (see further description below).

2. Gain knowledge on how harbour porpoises react to the included noise sources, in particular operating wind turbines. This includes recordings of operating turbines at different wind speeds and field recordings of harbour porpoise presence near operating turbines.
3. Overlaying model combining part 1-2 (as done by Faulkner et al. 2018, see further description below).

3.3.1 Noise monitoring

The existing underwater noise in the survey area was monitored as an integral part of the PAM monitoring for dolphins and minke whales (see section 3.1.3 on cetacean PAM analysis). Broadband acoustic recorders, the SoundTrap ST600HF (Ocean Instruments, Inc.) were deployed at six of the 42 PAM stations. The recorders were programmed to record broadband sound in the range 10 Hz to 192 kHz. For baseline noise, the recordings were analyzed in decidecade bands[1] from 10 Hz to 80 kHz with a time resolution of 1 second, in accordance with JOMOPANS data processing standards (Ward et al, 2021). The processed data were used to calibrate the Quonops sound propagation model developed and used by QuietOceans (see below). The decidecade band level will be made available for future impact assessments of individual wind farms, as they are in the format commonly used to share this type of data, exemplified by the ICES continuous noise register, maintained for the regional seas' conventions HELCOM and OSPAR. Aggregated results are reported in the form of monthly statistics (distributions of decidecade levels described by exceedance levels L_5, L_{10}, L_{25}, L_{50} (median), L_{75}, L_{90}, and L_{95}). Exceedance levels are the upper percentiles and the L_5 exceedance level for example thus represents, in the distribution of noise within a time period, the sound pressure level value which noise measurements exceed 5% of the time.

3.3.2 Turbine noise

Underwater noise emission from operating wind turbines were obtained by deploying a noise recorder (Soundtrap ST600) approximately 100 m from a turbine on two occasions: once in Kriegers Flak Offshore Wind Farm and once in Horns Reef 3 Offshore Wind Farm (Figure 3-3-1). These two wind farms were selected because they are among the largest wind turbines currently in operation offshore in Danish waters and they each represent different technologies: direct drive and gearbox drive[2], respectively. Deployment and recovery of the recorder in Horns Rev 3 was done by AU's vessel Niisa, sailing from Hvide Sande. Deployment time was 1 month to allow recordings of as wide a range of wind speeds as possible. Measurements from a turbine of the direct drive type, anticipated to be a common type in the projects at Thor Offshore Wind Farm and the North Sea I, were obtained by deployment of a noise recorder at a turbine in Kriegers Flak Offshore Wind Farm. Deployment and recovery were by AU's vessel Niisa, sailing from Trelleborg. Deployment time was three months. Information about wind speed (10 minute averages) was obtained from the operator of the wind farms, in both cases Vattenfall.

[1] Decidecade bands have a bandwidth of 1/10 of a decade, corresponding to 23% of the centre frequency of the band. The bandwidth of the successive decidecade bands therefore increase with increasing centre frequency, but the ratio of bandwidth (in Hz) to the centre frequency remains constant independently of the frequency. See ISO 18405 standard for underwater acoustics terminology.

[2] In a direct drive turbine, the generator is driven directly by the main axle and thus rotates with the same speed as the wings. In turbines with a gearbox, the generator rotates with a different speed than the wings, sometimes variable. As the main source of underwater noise from the latter type is known to be caused by the gearbox (the noise from meshing of gears), it is expected that direct drive turbines will have a different noise profile than the turbines with a gear box.

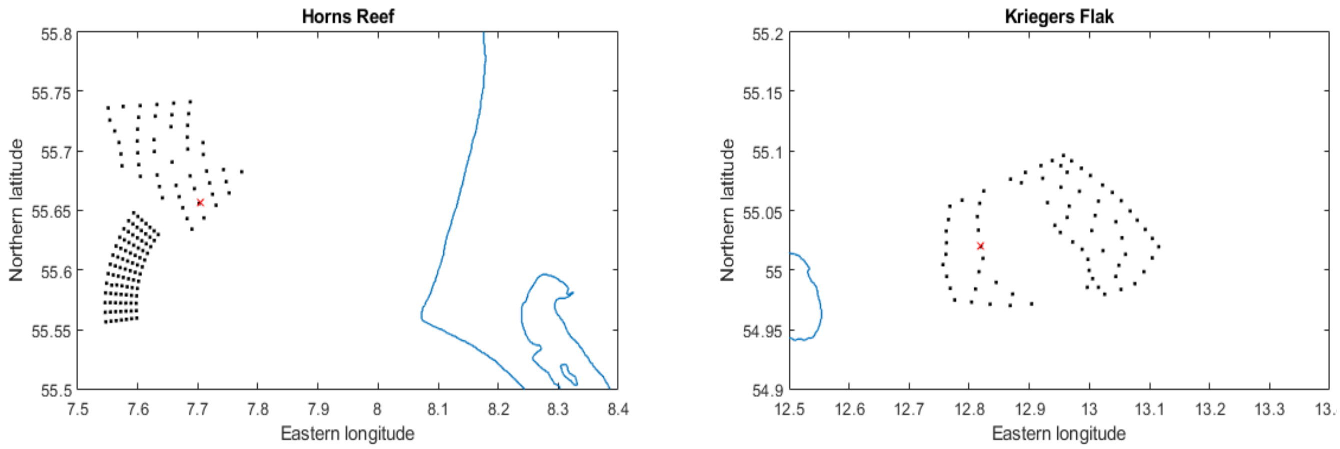


Figure 3-3-1: Position of noise recorders (Sound-trap ST600) approximately 100 m from a turbine in Horns Reef 3 Offshore Wind Farm (Left) and Kriegers Flak Offshore Wind Farm (right).

3.3.3 Harbour porpoise presence near operating turbines

3.3.3.1 4-channel arrays

Offshore wind turbines radiate noise to the underwater environment. This noise originates in the nacelle, from the generator, bearings and gear box (if present) and is propagated down through the tower and into the water (Pangerc et al., 2016; Tougaard et al. 2020). As absolute noise levels are not high, the noise is likely only audible to harbour porpoises within hundreds of meters of the foundation. This means that the presence of harbour porpoises close to the foundations must be accurately mapped in order to assess the potential exposure of the animals to the noise. This is achieved by means of acoustic tracking, making use of the echolocation signals that are emitted by the animals almost continuously. By measuring the difference in arrival time of the same signal at different locations by means of small-aperture 3D multi-hydrophone array , the accurate bearing of the vocalizing animal can be determined (Figure 3-3-2), and from the crossing point of multiple bearing estimates, the animal position is obtained (Wahlberg et al. 2001, Madsen and Wahlberg 2007, Macaulay et al. 2017).

Thus, to study the presence of harbour porpoises with high spatial resolution near turbine foundations, two 4-channel hydrophone arrays were deployed near existing wind turbines at Horns Rev III (Table 3-3-1).

Table 3-3-1: Dates and position of array deployments at Horns Rev 3 Offshore Wind Farm.

Deployment	Position ID	Recorder	Deployment dates	N. latitude (dec.degr.)	E. longitude (dec.degr.)	Distance to turbine (m)	Recording time
1	Array1	RTsys	7/9-10/9/2023	55.655	77.014	125	~24 hours
	Array2			55.655	77.034	103	
2	Array1	ST4300	7/9-10/9/2023	55.655	77.020	102	~24 hours
	Array2		19/3-8/4/2024	55.655	77.034	108	~4 days
3	Array1	ST640	19/1-8/2/2025	55.655	77.016	122	~21 days
	Array2		19/1-9/2/2025	55,655	77.040	134	~22 days

While the general methodology has been applied before, for example to track harbour porpoises around tidal turbines in Scotland (Macauley et al. 2017, Malinka et al., 2018; Gillespie et al. 2021), the methodology requires adaptation to offshore wind turbines and the environmental conditions in the North Sea. The methodology was adapted through the following steps:

A. Construction of a first version of the array, test of electronics, calibration (summer 2023).

B. Test of array conducted in Aarhus harbour (August 2023).

C. Test of methods for deployment and recovery of the array from boat, conducted in Bay of Aarhus (August 2023).

D. First deployment at Horns Reef 3 (September 2023, Figure 3-3-3).

E. Development of the methods for analysis, modification of array, switch to new datalogger type, the SoundTrap ST4300 (winter 2023/24).

F. Second deployment at Horns Reef 3 with two small-aperture 4-channel arrays and ST4300 loggers (March 2024, Figure 3-3-3).

G. Further work on analysis procedures with the data from second deployment (spring and summer 2024).

H. Third deployment at Horns Reef 3 with array setup as in the second deployment, but with new ST640 loggers for longer deployment time (January 2025, Figure 3-3-3).

I. Additional work on analysis procedures with the larger dataset obtained in third deployment (spring/summer 2025).

Deployments and recovery were done with AU's boat Niisa.

The first deployment with the RTsys recorder system (RESEA, RTsys, France; equipped with HTI99 hydrophones) had a very short endurance time, about 24 hours, limited by battery life and memory capacity. Deployment and recovery were also found to be difficult due to the large size of the array. A smaller version of the array (see Figure 3-3-3) was developed, and a different recorder was used, the SoundTrap ST3400, also with HTI99 hydrophones. This recorder had a longer endurance, about 4 days in the deployment in March 2024, but still below expectations. In the third deployment in January 2025 the newest 4-channel recorder, SoundTrap ST640, also with HTI99 hydrophones, was used, and it recorded continuously for ~21 days. The first two deployments were deployed with a surface bouy and the third deployment was deployed with an acoustic release system.

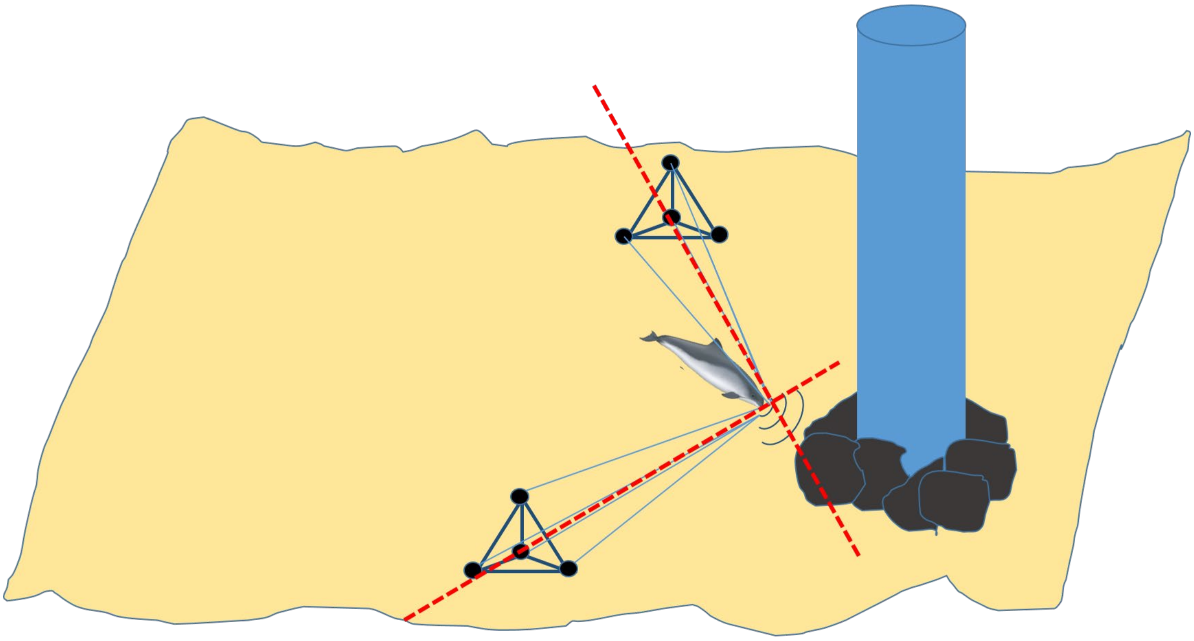


Figure 3-3-2: Illustration of setup to study fine scale movements of harbour porpoises near a turbine foundation (blue tube): two 4-channel hydrophone arrays (marked in black) near an existing wind turbine at Horns Reef III. Each 4-channel array is equipped with four hydrophones (black dots) and mounted on a tripod (black lines). Based on the differences in time of arrival of received echolocation clicks on each hydrophone element (because of differences in distances - blue lines) the bearing from each 4-channel array to the harbour porpoise can be determined (dotted red line) and the porpoise position can then be estimated from the crossing point of the two bearings.

Data processing and analysis is consistent between the March 2024 and January 2025 deployments. The four acoustic sensors on each array were sampled and digitized by a SoundTrap, ST4300 or ST640 logger, from where the data was offloaded as synchronized 4-channel wav-files. The wav-files were analyzed using PAMGuard, an open-source software developed for detection and analysis of marine mammal vocalizations (Gillespie et al. 2008, www.pamguard.org). For a transient to be classified as a harbour porpoise click, the energy in the frequency band from 110 to 160 kHz had to exceed the 50 to 100 kHz band by 6 dB, and the 160 to 192 kHz band by 3 dB. Further, the signal duration of harbour porpoise clicks had to be within 10 to 250 μs, when measured as the duration between the -6 dB points on either side of the peak of the amplitude envelope, and the signals were required to perform between 5 to 50 zero-crossings over this duration. Bearing estimates were then obtained from the PAMGuard Click Detector module, which estimates bearing to sound sources for small-aperture arrays based on time-of-arrival-differences (TOAD) measured as the difference between click detection times on each channel with the detection time being defined by the -6 dB point before the peak of the amplitude envelope. An example of what the raw recordings look like is provided in the screenshot in Figure 3-3-4.

The outputs of the PAMGuard click analyses were exported using scripts from the PAMGuard Matlab repository (https://github.com/PAMGuard/PAMGuardMatlab) to MATLAB (version 2024a, MathWorks, Natick, Massachusetts, USA) for postprocessing and visualization of the results. Harbour porpoise detections were plotted as PPMs per hour for each array.

Next, the harbour porpoise bearings had to be translated into position estimates. The harbour porpoise bearings extracted from PAMGuard were bearings relative to the xyz-configuration of each array but given that the two arrays were deployed with unknown azimuth rotation when lowered to the seafloor, the bearing estimates had to be corrected relative to the azimuth offset from true North. To achieve this, a bearing was estimated from each array to a sound source with a known position. For the March 2024 deployment, this was done using the sound from the closest wind turbine (5-min example of this noise is shown in Figure 4-4-5 and Figure 4-4-6 top panel) and for the January 2025 deployment, this was done using pings emitted from an acoustic device lowered from the deployment vessel while recording the gps location of the vessel. To estimate array positions using turbine noise, a 1-hour window of recordings was extracted from each array and down-sampled 100 times, as the dominant noise emission from the wind turbine is below 1 kHz. Because this noise emission is a continuous signal, unlike the harbour porpoise clicks, a time-of-arrival difference could not be estimated directly from the recorded waveforms but could instead be estimated in the frequency domain by computing the phase difference between all channel pairs for each array. A difference in phase for a given frequency between two channels is directly proportional to a difference in time-of-arrival. Inspection of spectrograms made from the raw data showed that turbine noise had a consistent peak in the 40 to 100 Hz range, which was therefore used for the spectral analysis, where the intensity over this frequency band was split into xyz-components from which the azimuth and elevation to the sound source was then estimated. To estimate array positions using emitted pings at known locations, the recording during the emitted pings were processed using a similar click detection module as the harbour porpoise clicks. This produced estimated azimuth and elevation of the pings that could be exported to MATLAB. Bearings to harbour porpoises were then corrected for this array-to-sound source azimuth from wind turbine noise or emitted pings. To turn the harbour porpoise bearings into bearings relative to true North, the bearing estimates were then further corrected for the compass bearing from the known latitude and longitude coordinates of each array position towards the known position of the wind turbine or the vessel that emitted pinger sounds. A localized click from a single array will provide an estimated bearing to the harbour porpoise but not provide information on the distance. To estimate the distance to a harbour porpoise at the time of a click, the crossing point of the estimated bearing from both arrays has to be determined (Illustrated in Figure 3-6). Because the two arrays were not likely to be ensonified by a harbour porpoise echolocation beam at exactly the same time, the bearings to the harbour porpoises were divided into 5-s median bearing estimates and bearing crossing points were then computed whenever bearing estimates were available for both arrays over the same 5-s time windows. This 5-s duration was chosen under the considerations that longer windows would increase the likelihood that both arrays would be ensonified and shorter time windows decrease the distance that the harbour porpoise is able to swim (a typical swim speed is on the order of ~2 m/s). The bearing crossing points were extracted as latitude and longitude coordinates and based on these positions, distance to the turbine could be estimated for each localized click.

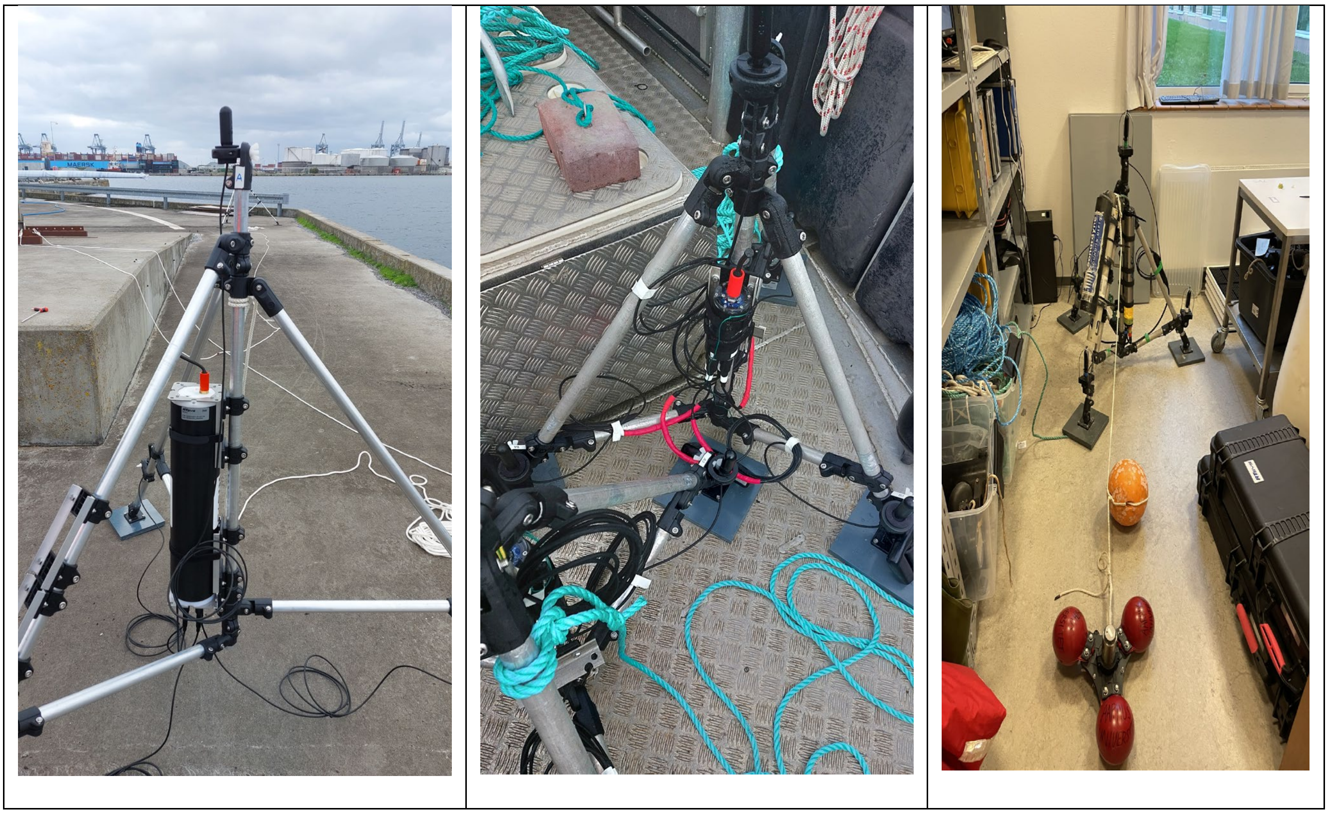


Figure 3-3-3: The tripod array. Left: original 140 cm array, with RTsys recorder mounted (black cylinder in middle). Middle: Reduced 70 cm array with Soundtrap ST4300 mounted in middle. Right: Small array with the SoundTrap ST640 recorder mounted in the middle, acoustic release system mounted on one leg of the array and an iridium beacon mounted on the rope to send signal when surfacing).

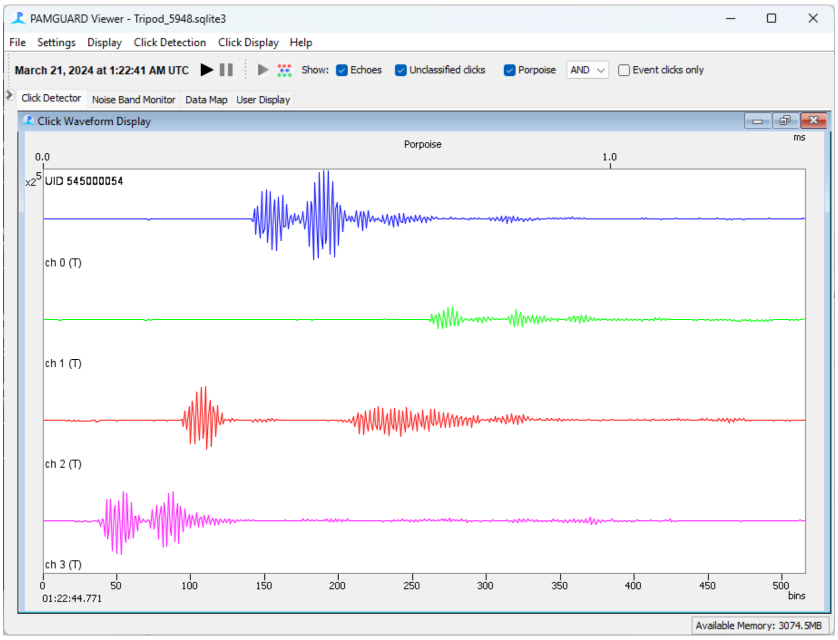


Figure 3-3-4: Screenshot from the PAMGuard software, showing a single harbour porpoise echolocation click recorded on each of the four hydrophones. Time is on the x-axis, sound pressure on the y-axis. Due to the spatial separation between the hydrophones the click arrives with different delays at the four hydrophones. The trailing signals after the initial pulse are reflections from the surface, the seabed or the array itself and are filtered out in the later analysis. The duration of the recording segment shown is about 1.3 ms.

Following positioning of all possible harbour porpoise clicks, the analysis was carried out to test if harbour porpoises were attracted to the wind turbine. To test this, we compared the estimated distances of localized harbour porpoise clicks to the turbine and a reference point. The reference point chosen was directly opposite from the turbine with comparable distances to each of the two arrays (See Figure 3-3-5). By comparing harbour porpoise localizations between these two sites, it ensures that the detection probability is similar. Additionally, the localized clicks were filtered to only include clicks within 100 meters of either the turbine or the reference point (n = 1927). This 100 m buffer ensures that a localized click is only included once in the analysis, as further distances would lead to data points being included for both the turbine and the reference point. These distances to either the turbine or the reference point was used to test if porpoises were localized closer to the turbine compared to the reference point. If there is no effect of the turbine on harbour porpoises, there would be no difference in the distribution of distances between the turbine and the reference point. Contrary, an attraction to the turbine would be indicated by a significant difference between distances to the turbine and the reference point, with clicks more likely to be detected at shorter distances at the turbine compared to the reference point. An example of the distribution of distances in an attraction, deterrence or no effect scenario is shown in Figure 3-3-5.

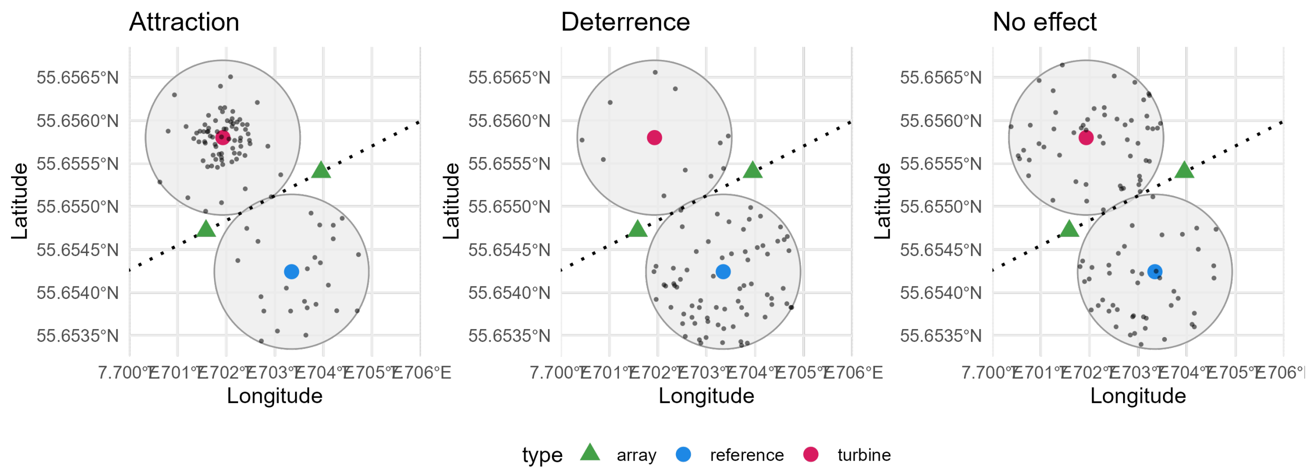


Figure 3-3-5: Illustration of the setup of the two arrays (green triangles) near a wind turbine (red point) and the reference point (blue point) with simulated harbour porpoise localization to illustrate possible scenarios. The array line is represented by a dotted line through the two array positions. The grey points represent simulated examples of where harbour porpoise clicks may be localized in an attraction (left), deterrence (mid) and no effect (right) scenario. In the attraction-scenario we expect localizations to cluster close to the turbine, in the deterrence scenario we expect that localizations appear more closely around the reference point and if there is no effect we expect that localizations are evenly spaced around the turbine and the reference point.

Given the structure of the response data - right-skewed, right-truncated distances bounded between 0 and 100 m with a high degree of autocorrelation of observations occurring close in time – the distances were linearly rescaled to between 0 and 1 with a Beta GLMM (logit link). This included day as a random effect to account for daily clustering, a site-specific precision model to accommodate heteroscedasticity due to site-specific variance, and an AR(1) correlation of a per-minute sequential index within day-by-site to capture temporal dependence. Diagnostics test showed no violations using the minute-aggregated data. It should be noted that harbour porpoise presence is currently only tested on one turbine and in order to extrapolate to other offshore wind farms, the experiment should be repeated at different locations, bottom substrates and types/sizes of turbines.

3.3.3.2 8 soundtraps near turbines

To strengthen our knowledge of harbour porpoise use of the areas near turbines, and to assess the variation among turbine sites, 8 PAM-stations (ST600 Soundtraps) were deployed in pairs at four turbines (E05, C05, F06, and F07; Figure 3-3-6, Table 3-3-2) from 04/11/2024 to 10/01/2025 i.e. in the second year of this survey program. One SoundTrap, deployed at turbine F07, stranded and was recovered on 28/12/2024; however, most SoundTraps had stopped recording before then, so data collection was not impacted. Each recording lasted a variable amount of time but the time period 04/11/2024 to 03/12/2024 was recorded on all eight SoundTraps and was thus used in this analysis. Before deployment, each hydrophone was calibrated. SoundTraps were set on the high gain setting at a sampling frequency of 384 kHz. After retrieval, data were offloaded and analyzed in MATLAB and R.

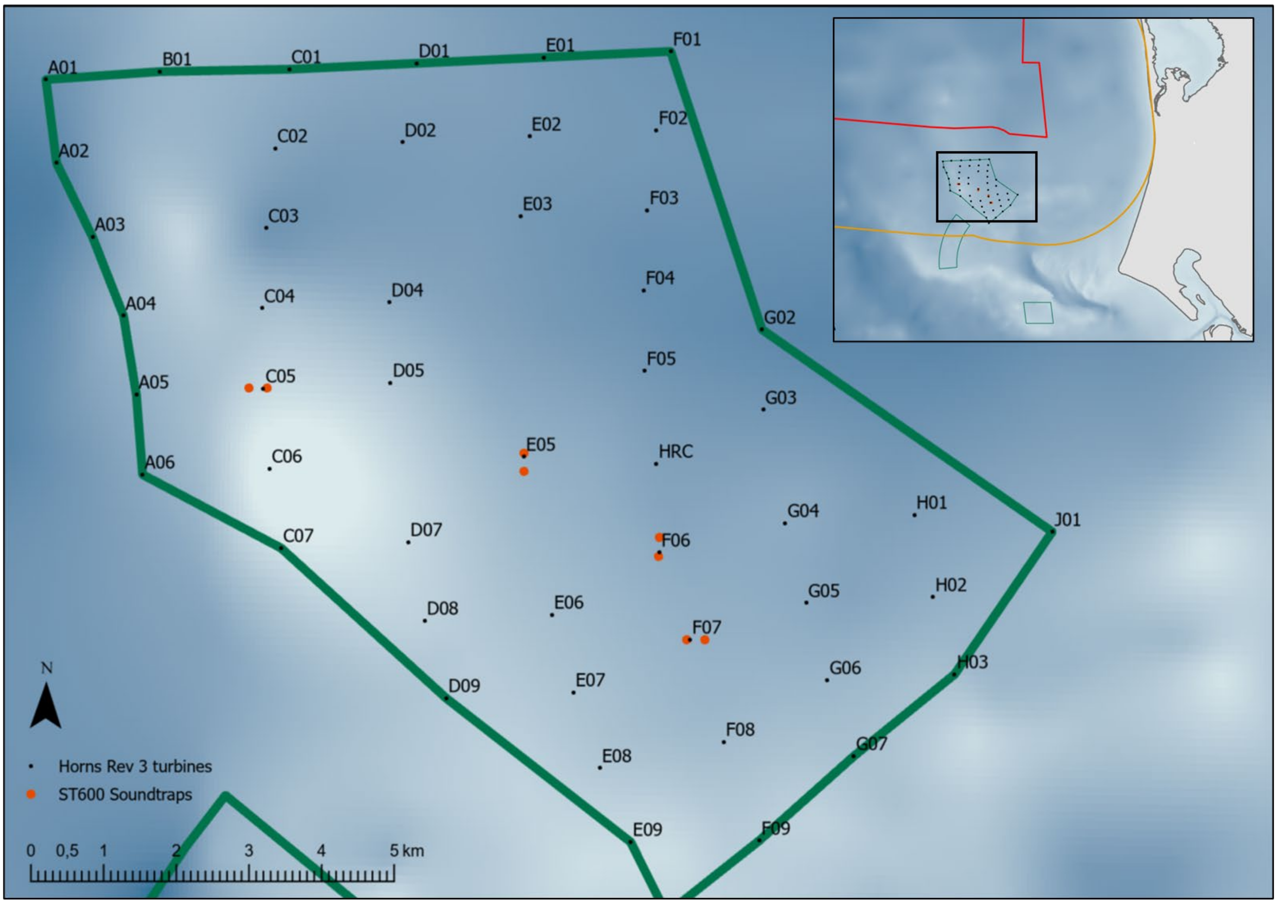


Figure 3-3-6: Map of the four turbines and the 8 Soundtraps included in this analysis.

Table 3-3-2: Hydrophone deployment metadata.

Hydrophone ID	Station	Distance from Station	Porpoise-Positive Hours (04/11/2025 - 03/12/2024)
8719	E05	200	405
8720	F06	200	415
8721	E05	50	462
8722	F06	50	441
8731	F07	50	447
8732	C05	200	156
8733	F07	200	451
8734	C05	50	145

Decidecade levels were calculated for all deployments in 1 s bins from 10 Hz to 158 kHz using a custom MATLAB script. Decidecade levels at 125 Hz and 315 Hz were compared to production data from the turbine by which it was located for one deployment (8734) and the 315 Hz noise level was found to better track the turbine production (Figure 3-3-7), so was selected for further analysis.

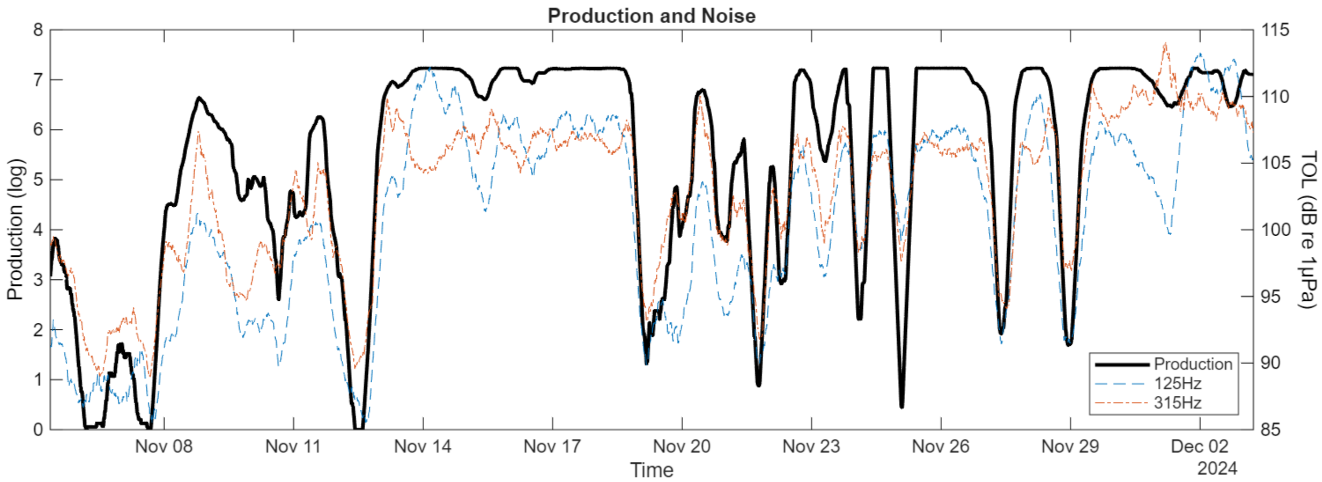


Figure 3-3-7: Turbine production compared to 1-sec decidecade noise level, at 125 and 315 Hz. The bold black line tracks production while the evenly dashed blue line tracks 125 Hz noise and the unevenly dashed orange line tracks 315 Hz. This was examined for hydrophone 8734, located 50 m from turbine C05.

Harbor porpoise click detection was done using DPorCCA (Cosentino, 2020; https://www.porpoiselady.org/dporcca), a custom-built MATLAB app specially designed to detect harbor porpoise clicks in full-spectrum hydrophone data. DPorCCA was selected for click detection after comparison with PAMGuard's click detector (Figure 3-3-8). While PAMGuard processed more quickly, the output required significant post-processing filtering to eliminate false positives.

DPorCCA was less computationally efficient but produced virtually no false positives, upon manual spot inspection. DPorCCA was run with the default click detector settings: pre-filtering with a 4-order Butterworth filter, minimum frequency set to 100 kHz and maximum at 150 kHz, with a 15 dB threshold. The trigger filter used a 0.1 short filter and an 0.00001 and 0.000001 long filter. Clicks were identified with 40 pre-samples and 40 post-samples, set to a minimum length of 90 samples and a maximum of 1024 samples, with a minimum separation of 100 samples. Only high quality detections (0.999999 certainty threshold) were used in further analysis.

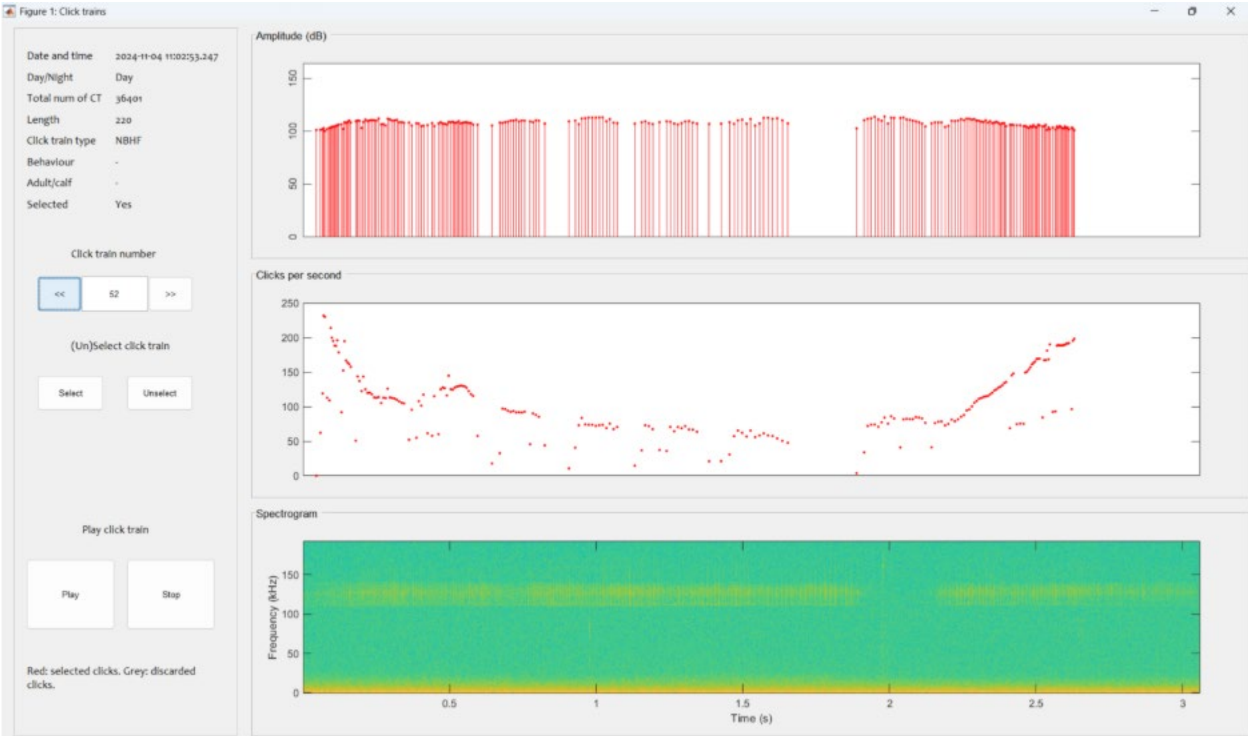


Figure 3-3-8: A screenshot from DPorCCA showing a high quality classified click train from hydrophone 8731.

Click trains were exported to MATLAB for further processing. Because two hydrophones were positioned at one turbine, a minimum of 150 m apart, it is conceivable that some very loud click trains could be recorded on both hydrophones at once, although we believe the typical detection range to be less than 100 m (pers. comm, Mel Cosentino). In order to ensure that clicks were not duplicated on both hydrophones, we filtered the clicks by amplitude to only include the top 25th percentile from each hydrophone, so only loud, close-by click trains were included in detection-positive minutes. Given the detection range of ~100 m, harbour porpoises were included in the analysis up to a distance of approximately 300 m from the wind turbine. Detection-positive minutes were then collected into detection-positive minutes per hour as the analyzed unit of measure.

Statistical modeling was carried out in RStudio using the brms package (v. 2.22.0, Bürkner, 2017). Several environmental factors were extracted for the time period in question, including time of day (day or night, as determined by the US Naval Observatory's Astronomical Applications Department, available freely online at https://aa.usno.navy.mil/data/RS_OneYear), tidal flow (ebb or flow, as determined by Danmarks Meterologiske Institut at the location Grådyb Barre), noise level (from the decidecade levels calculated at each SoundTrap), the turbine at which the hydrophone was located (E05, C05, F06, or F07), and the distance from that turbine (either 50 or 200 m). A Bayesian generalized linear mixed model with zero-inflation and a negative binomial distribution was fitted for the full dataset. The response variable was detection-positive minutes per hour, with fixed effects of distance from the turbine, time of day, tidal flow, and noise level, and a random effect of location. Because there were many hours with no porpoise detections, the data was modeled as zero-inflated, with a separate zero-inflation probability for each site. Alternative model structures were explored using leave-one-out cross-validation. Because one site, C05, had significantly fewer porpoise detections at both distances, we also ran separate statistical analyses on site C05 alone and the other three sites together without C05.

3.3.4 Noise exposure maps

Previous studies show that the main sources of underwater noise prior to the construction of an offshore wind farm are ship traffic (see section 2.3). Neighboring wind turbines such as Horns Rev III may also influence the soundscape on a smaller spatial scale. The noise exposure map represents the underwater noise exposure map from a 2023 scenario and thus includes the Horns Rev OWFs but not the newly constructed Vesterhav Syd OWF and the planned Thor OWF. Monthly maps of the total noise from natural sources (wind and waves), ships (including wind farm service vessels) and wind turbines were modelled by the Quonops modelling framework by the company Quiet-Oceans (Brest, France). The wind farms included in the modelling are those that are in operation in the Danish North Sea by the end of 2023 (Table 3-3-3). Only noise from operational activities is included in the model, i.e. noise from construction and pre-construction surveys at the planned or newly constructed wind farms at Thor and Vesterhav Syd were not included, as these activities were short-term.

Table 3-3-3: Wind farms included in the modelling scenario within the survey area.

Wind Farm	Turbines	Turbine type	Generator and gearbox
Horns Rev 1	80	Vestas V80-2.0 MW	3 stage planetary gear
Horns Rev 2	91	Siemens SWT-2.3-93	3-stage spur/planetary gear
Horns Rev 3	49	Vestas V164-8.0	Planetary gear

Based on the measurements of underwater noise from operating turbines (described above), and the measurements in the literature (Bellmann et al., 2023), two source models for the turbines were developed, one for turbines with gear box and one for direct drive generators. The cumulative noise contribution from the wind farm area and surroundings was modelled and compared to the contribution from natural sources (wind and waves) and shipping. The model was calibrated and validated against the measurements from the six PAM stations during year 1 of this survey as well as measurements from the North Sea Energy Island survey program (Kyhn et al., 2024). The cumulative exposure levels of the noise within the survey area were modelled by the same model, by including turbines from all existing wind farms in the survey area (Table 3-3-3) thereby allowing a quantification of total exposure to noise and vibrations and a separation of the contribution into natural sources, ships, and wind turbines + service vessels.

The noise exposure maps represent monthly statistics of the noise between April 2023 and March 2024. They were generated from all available information about individual sources of noise in the area. For every hour (referred to as a 'snap-shot') of the modelling period the position and speed of all ships in the area were obtained from AIS and VMS data (obtained from the Danish Shipping Authority and the Danish Fisheries Agency, respectively). Based on the type of each ship, its length and speed, the noise emission (source level) was estimated from a standard model (RANDI3-JE, MacGillivray and de Jong, 2021). Positions of individual wind turbines were obtained from the Danish Energy Agency. For each snap-shot, the radiated noise from each individual turbine was also modelled based on the source models developed, which links noise emission of individual turbines to wind speed including the influence of turbine size (nominal power rating) and type (gear box or direct drive). Wind speed at the location and time of the snapshot were obtained from meteorological hind-cast models. The noise radiated from all individual sources were fed to a sound propagation model, which modelled the sound propagation (by parabolic equations methodology) into the surrounding waters. The individual contributions from all sources were summed and added to the natural ambient noise in each modelling grid cell of the model. The natural (wind driven) noise was modelled from the wind speed (from the hind-cast models) and locally determined curves relating wind speed and underwater noise (Knudsen- or Wenz-curves, Knudsen, 1949; Wenz, 1962). All snapshots for each monthly model were combined into spatially explicit distributions, i.e. representations of the statistical distribution of noise levels in each particular grid cell of the modelling area. For each grid cell, this monthly distribution is described by a selected number of percentiles. The output of the Quonops model is therefore maps representing selected monthly percentiles of the noise distribution, i.e. maps representing the noise level exceeded a specified proportion of the time. In addition to these total noise levels, the excess level is also represented, which is defined as the elevation of the noise level caused by the non-natural sources, obtained by subtracting the natural ambient noise (i.e. wind, waves and vessels before) from the total noise level (after).

3.3.5 Overlaying model

The underwater noise exposure maps for the survey area (described above in 3.3.4) were overlayed with the comparable twelve monthly distribution maps of harbour porpoises based on PAM data. For the harbour porpoise, this enabled the area where animals may respond to underwater noise and vibrations to be assessed (in line with what was done by Faulkner et al. 2018 and in the HELCOM HOLAS 3 assessment, HELCOM 2023). Maps of the noise distribution related to the harbour porpoises' reaction threshold was overlayed with the harbour porpoise distribution map. Based on measurements of reactions of individual wild harbour porpoises to ship noise (Wisniewska et al., 2018), supported by reviews of other available data (Tougaard 2021), a reaction threshold for ship noise was established as 96 dB re 1 μPa in the 16 kHz decidecade frequency band. Due to the stereotypic frequency spectra of ship noise (e.g. MacGillivray and de Jong, 2021), it is possible to extrapolate this threshold via auditory frequency weighting into the low frequency bands used for noise modelling, even though harbour porpoises have very poor hearing at these low frequencies. For ship noise, this resulted in a proxy threshold of 115 dB re 1μPa in the 125 Hz decidecade band (Tougaard et al, 2023). Thresholds for turbine noise for harbour porpoises may be higher than this (i.e. more noise is required before animals react), as it has been shown that harbour porpoises are less responsive to noise below 2 kHz than to noise above (Dyndo et al., 2015), and measurements show that there is no significant energy in the turbine noise above ambient at frequencies above 1 kHz (Tougaard et al. 2020, Bellmann et al., 2023).

3.3.6 Impact of geophysical survey noise on presence of harbour porpoises

During the first year of the North Sea I survey program, geophysical and geotechnical surveys were carried out simultaneously within the North Sea I pre-investigation area. Therefore, an additional study was jointly initiated by NIRAS, Aarhus University and Energinet with the objective to investigate whether the presence of active geophysical survey vessels using USBL (Ultra-Short BaseLine) acoustic positioning systems had an impact on the baseline data regarding the presence of harbour porpoises in the North Sea I survey area. The study was carried out concurrently with the North Sea I Marine Mammal pre-investigations and is reported in full in a separate report (Mikaelsen et al. 2025). In this report a brief summary is included.

Geophysical surveys utilize USBL systems to keep track of their underwater equipment. The system works similar to an underwater GPS with signals sent from a transceiver on the survey vessel to the towed equipment with a transponder unit, and back to the survey vessel. Since the survey vessel's position is known from a satellite-based GPS system, the position of the equipment underwater can be calculated from the acoustic return signals. A USBL system consists of a master signal from a transceiver and one or several transponders on the equipment used underwater. USBL systems emit signals at frequencies at 19-32 kHz and source levels known to cause displacement of harbour porpoises. A previous study found modelled impact at distances up to app. 3.0 km in the North Sea (JASCO 2022).

The effects of USBLs on the presence of harbour porpoises has not previously been studied and different approaches were therefore tested to find the most optimal method to possibly correct for the impact of underwater noise from the geophysical and geotechnical surveys caused by active USBL systems on baseline data. All methods are thoroughly explained in Mikaelsen et al. (2025) and only summarized here. Results are shown in chapter 4.4.6 below. The basic approach was as follows:

- Assess the magnitude of the problem.
- Identify USBL signals in the broadband data from SoundTraps and develop an algorithm to automatize this analysis.
- Examine the influence of USBL signals on FPOD detection levels and determine impact.
- "Correct" the original FPOD dataset by taking out the impacted data.

Data was collected with the 42 F-PODs and 6 SoundTraps from April 2023 to November 2023. Three of the broad-band stations were located inside the geophysical and geotechnical survey area, which was identical to the North Sea I pre-investigation area and therefore defined 'impact stations': NS13, NS16 and NS25. Three SoundTrap stations were located outside (defined 'control stations': NS2, NS6 and NS14). Figure 3-3-9 provides an example of presence of geophysical survey vessels in the survey area on a single day, 18 June 2023. In the broadband data, USBL pulses were found and distance to nearest survey vessel calculated.

For each pulse the source level was back-calculated and from that the potential impact range calculated based on the harbour porpoise behaviour criterion $L_{p,rms,125ms,VHF}$ = 103 dB re. 1 mPa.

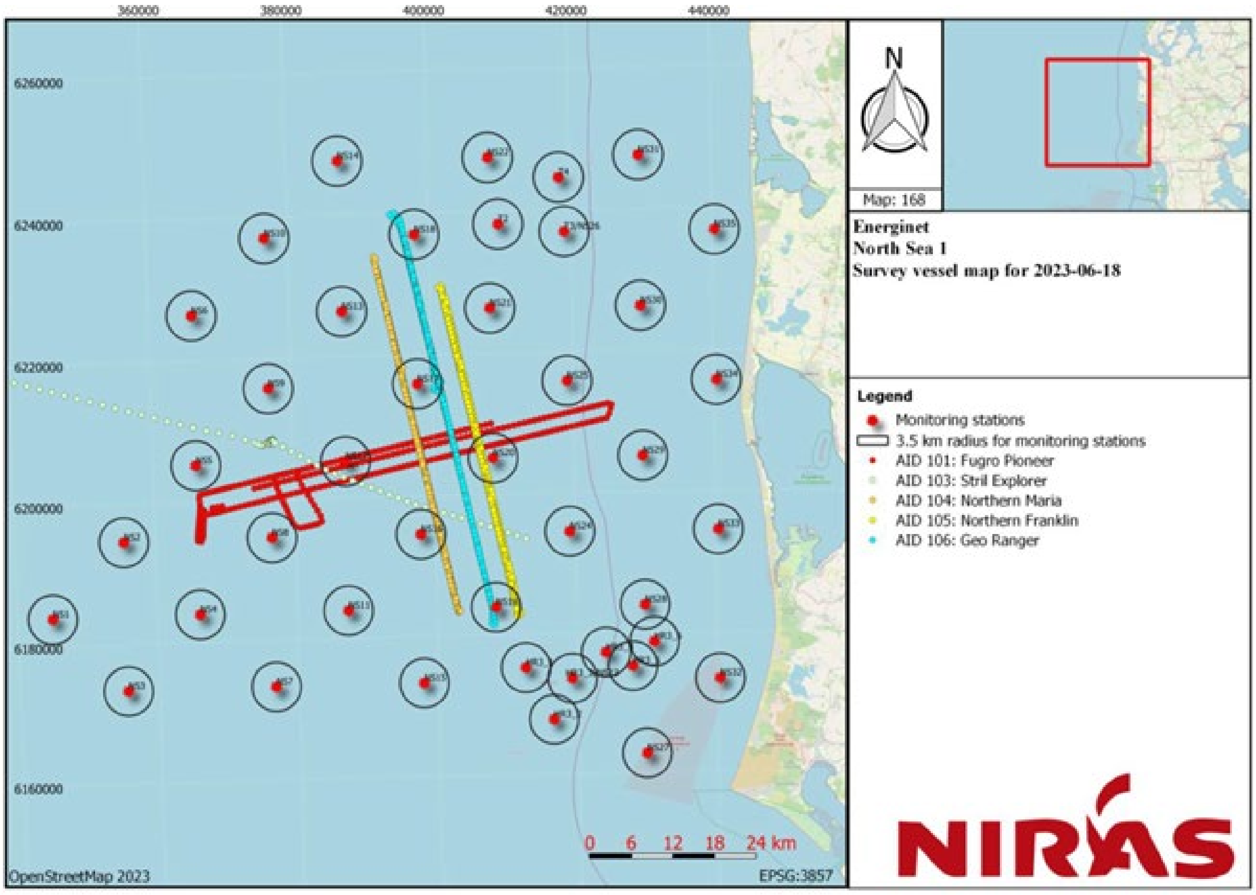


Figure 3-3-9: Example of day-map for June 18, 2023. The position data for active survey vessels are shown by five individually coloured tracks. Red dots indicate the F-POD and F-POD+SoundTrap stations labelled with the station ID. The black circles around each measurement station indicate the 3.5 km expected maximum USBL impact zone based on JASCO 2022.

During the analysis, it became evident that USBL and USBL-like signals were not solely emitted by geophysical and geotechnical survey vessels. A significant portion of these signals were assigned to unidentified sources. It was found that some of these unknown vessels were likely trawlers, which utilize various USBL systems to monitor their trawls and measure their catch. Analysis was therefore split into USBL signals from geophysical and geotechnical surveys and USBL signals from other sources.

From the F-POD data, three indices of harbour porpoise presence were calculated: porpoise positive minutes (PPM), clicks per minute (CPM), waiting time, i.e. time between consecutive harbour porpoise acoustic encounters, and waiting (USBL-HP) which is time between a geophysical USBL signal to the first harbour porpoise encounter. The effects of USBL use and received level were estimated using mixed-effect statistical models.

4. Results of survey(s)

4.1 Passive acoustic monitoring of cetaceans

The passive acoustic monitoring program was aimed at harbour porpoises (FPODs), delphinids and minke whales (SoundTraps). The results of all surveys are presented in the sections below.

4.1.1 Harbour porpoises

4.1.1.1 FPOD results

In April 2023, 42 PAM stations were deployed in the survey area (Figure 3-1-1). The original plan was to service every station approximately every three months. This turned out to be unrealistic since it took so long to service the PAM stations that the weather often turned bad before the service could be finished. Consequently, the service (performed primarily by Bioconsult) was ongoing with service trips almost every month and with each service trip prioritizing the stations that had been deployed the longest. This proved to be a successful method.

The FPOD and CPOD can record for at least 5 months upon deployment and little data was lost due to battery depletion. For both years, 86% of the possible days of data collection was successfully retrieved and for 36 stations >75% of data were recovered (Table 4-1-1, Figure 4-1-1, Figure 4-1-2, Figure 4-1-3). This is considered a high level of data retrieval. However, some data were lost which may be attributable to several reasons, such as stations being caught in trawling gear or pushed/dragged by a passing ship, or battery or equipment failure. As an example, station NS01 moved 10 km southwest in May 2023. which was likely because it was accidentally dragged by a ship. Furthermore, the first chosen brand of acoustic releasers (Sonardyne) performed unexpectedly poorly and released prematurely, which also caused data loss. Furthermore, during the winter storm of December 2023, the acoustic releaser stations were moved by the large waves to a location 2–3 km from the deployment positions. One of these stations was later found (NS23_HR3-3) while others were lost. Due to the problems with the releaser stations, the three acoustic releaser stations in Horns Rev 3 OWF were deployed with GPS-transmitters for year two to provide a warning if they surfaced prematurely. This helped us to retrieve and rapidly redeploy,and in the second year, few data were lost from the Horns Rev 3 stations.

In Figure 4-1-1, Figure 4-1-2 and Figure 4-1-3 porpoise positive minutes (PPM, i.e. number of minutes per day with minimum one harbour porpoise click detected) per station are shown for each of the three areas, the "Pre-investigation area", "Survey area West" and "Survey area East", respectively. Visual inspection of the figures shows that there are large variations in harbour porpoise detections both between days, month and stations.

Table 4-1-1: Overview of days with harbour porpoise data on each of the 42 stations during the North Sea I PAM program from April 2023 to March 2025. Causes for stations with less than a full recording month vary from stations being trawled or pushed by a passing ship, battery or equipment failure. Furthermore, all retrieval, service and deployment days were excluded from the analysis.

Station	2023									2024												2025			%suc-cess
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	
HR3_1	2										4	31	30	30	30	31	30	30	31	30	31	6	18	25	51
HR3_2			20	2	29	29	29	26	30	31	29	31	30	30	30	31	30	30	31	30	18		18	31	81
HR3_3					31	30	31	30	20		4	31	30	30	30	31	30	30	31	30	31	19	18	31	74
HR3_4		13	30	31	30	29	30	29	29	30	28	31	11		13	31	30	29	31	30	31	31	27	31	86
HR3_5	14	31	29	31	30	30	31	29	31	31	29	31	15		12	31	30	29	31	30	31	31	27	31	92
HR3_6	14	31	30	31	29	30	31	29	30	31	28	31	24		12	31	30	29	31	30	31	31	27	31	93
NS1	12	15			26	30	31	29	31	30	29	31	30	30	30	31	30	29	14				11	31	71
NS10	9	31	30	31	30	30	31	30	30	31	28	31	29	31	30	31	30	30	30	30	31	31	27	31	100
NS11	13	31	30	30	31	30	31	29	31	28	29	31	30	31	29	31	31	29	31	30	31	31	28	31	100
NS12					25	30	31	28	30	30	29	30	30	30	30	31	30	26	31	30	31	31	27	31	84
NS13	11	31	30	31	1						2	31	21				19	30	30	30	31	31	27	31	55
NS14	9	31	30	31	30	30	31	28			3	31	17			22	11		13	30	31	31	27	31	67
NS15	13	31	29	30	31	30	30	27	30	28	28	30	24		13	31	30	24	16	30	31	31	27	31	89
NS16	11	31	30	31	29	30	26		27	29	27	31	29	30	29	31	30	29	31	30	31	31	27	31	94
NS17	10	31	29	31	29	30	30	28	30	30	29	31	28	31	30	31	30	30	30	30	31	31	27	31	100
NS18	9	31	30	31	30	30	31	29	30	31	29	30	29	31	30	31	30	30	30	30	31	31	27	31	100
NS19	12	31	30	30	31	29	29	29	28	27	28	30	29		13	31	30	29	31	30	25		3	31	84
NS2	12	31	30	31	30	30	31	30	31	3	3	29	28	31	29	31	30	30	15				11	31	75
NS20	11	31	30	31	29	30	31	30	28	8				13	30	31	30	29	31	30	31	31	28	31	82
NS21	10	31	30	31	30	30	31	29	30	31	29	31	21			23	30	30	30	30	31	5	3	31	82
NS22	9	31	30	30	30	30	30	28	31	31	29	31	29	31	30	31	30	30	30	30	31	30	28	31	100
NS24	13	31	30	30	29	30	31	24	30	31	29	31	29	22	30	31	30	29	31	30	31	31	27	31	99
NS25	10	31	30	31	30	30	31	29			2	31	21			23	31	30	31	30	31	31	27	31	77
NS27	16	31	30	31	31	30	5	10	29	31	29	30	30	17	30	31	30	29	31	30	31	31	27	31	93
NS28	15	31	30	31	29	29	31	19			2	31	30	31	29	31	30	29	31	30	31	31	28	31	87
NS29	10	31	30	31	5			2	31	31	29	31	29	30	30	31	30	29	31	30	31	31	27	31	84
NS3	12	31	30	31	30	30	31	29	23	24	29	30	30	30	30	31	30	29	31	30	31	31	27	31	99
NS30	10	31	30	31	30	30	30	27	30	29	29	31	20			23	30	26					2	31	67
NS31	9	31	30	31	30	30	31	27	29	31	28	31	29	17			18	30	30	30	31	30	28	31	87
NS32	16	31	29	31	29	30	31	29	31	31	29	31	10		12	31	30	29	31	30	31	31	27	31	92
NS33	10	31	30	31	30	30	31	29	31	30	29	31	30	17	12	31	30	29	31	30	31	31	27	31	96
NS34	10	31	30	30	30	29	25	2	29	28	29	30	19			23	30	29	31	30	31	31	27	31	84
NS35	9	31	30	31	30	30	31	26	30	29	29	31	16			23	30	30	30	30	31	30	28	31	88
NS4	12	31	30	30	4					23	29	30	30	30	30	31	30	29	31	30	31	31	27	31	79
NS5	11	31	30	31	30	30	31	30	30	28	29	31	29	31	30	31	24	30	30	30	31	31	27	31	100
NS6	9	30	30	30	30	29	31	29	1		3	31	21			22	30	30	32	30	31	31	28	31	77
NS7	12	31	30	31	30	30	31	30	8	24	29	30	30	30	29	31	30	24					11	31	76
NS8	11	31	30	31	30	30	31	29	29	30	29	31	30	30	30	31	30	30	30	30	31	31	27	31	100
NS9	11	31	30	31	30	30	31	30	31	27	28	31	29	31	30	31	30	30	30	30	31	31	27	31	100
T2	9	31	30	31	30	30	31	28	31	30	29	31	29	31	30	31	30	30	30	30	31	29	28	31	100
T3	9	31	30	31	30	30	31	27		23	29	31	29	30	30	31	30	30	30	30	31	21			85
T4	9	31	30	31	30	29	31	29	31	31	29	30	24	31	30	31	30	30	30	30	31	21			90

Figure 4-1-1: Porpoise Positive Minutes (PPM) per day for each station within the Pre-investigation area (See Figure 3-1-1) April 2023 – March 2025.Vertical dotted line indicates the split between the first and second year of this survey program.

Figure 4-1-2: Porpoise Positive Minutes (PPM) per day for each station within the "survey area East" (See Figure 3-1-1) April 2023 – March 2025. Vertical dotted line indicates the split between the first and second year of this survey program.

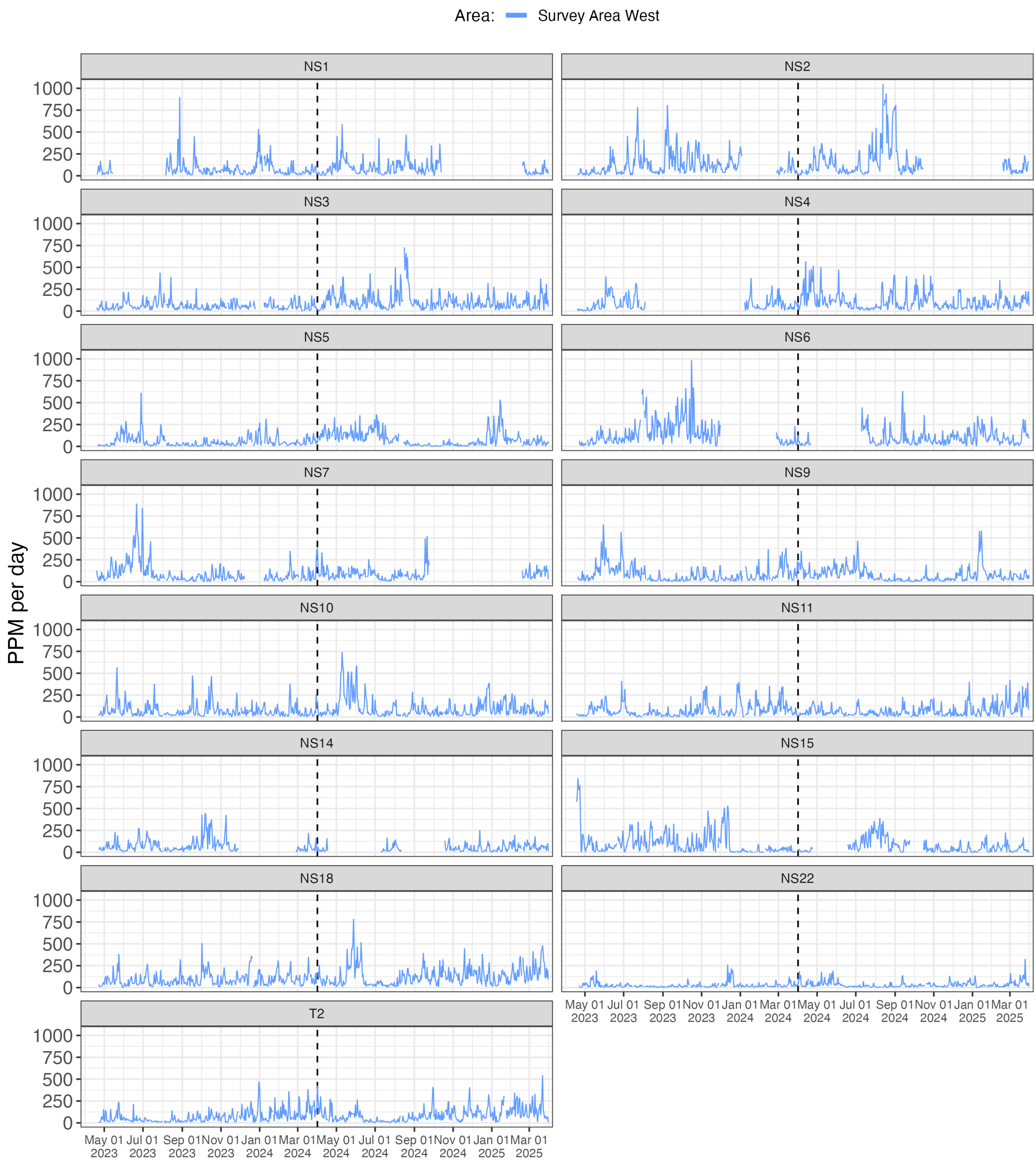


Figure 4-1-3: Porpoise Positive Minutes (PPM) per day for each station within the "survey area West" (See Figure 3 1-1) April 2023 – March 2025. Vertical dotted line indicates the split between the first and second year of this survey program.

Figure 4-1-1, Figure 4-1-2 and Figure 4-1-3 were combined on monthly averages in Figure 4-1-4 and compared for each monitoring year (Y1: Apr23-Mar24 vs. Y2: Apr24-Mar25) for each of the three areas. Upon visual inspection, little variation was found: all monthly averages were between 50 and 150 PPM with individual station peaks up to 450 PPM. No clear seasonal variations was detected. The annual averages of PPM per day for each station were compared between Y1 and Y2. On this scale, 83% of all stations had higher average level of PPM in Y2 than in Y1. Furthermore, 100% of stations within the pre-investigation area where the geophysical and geotechnical surveys took place in Y1 had higher average PPM in Y2 compared to Y1. These comparisons were tested statistically following the method in Sveegaard et al. (In press) and this showed that the difference was statistically significant on 19 of the 35 stations (alpha = 0.2) (Appendix 1).

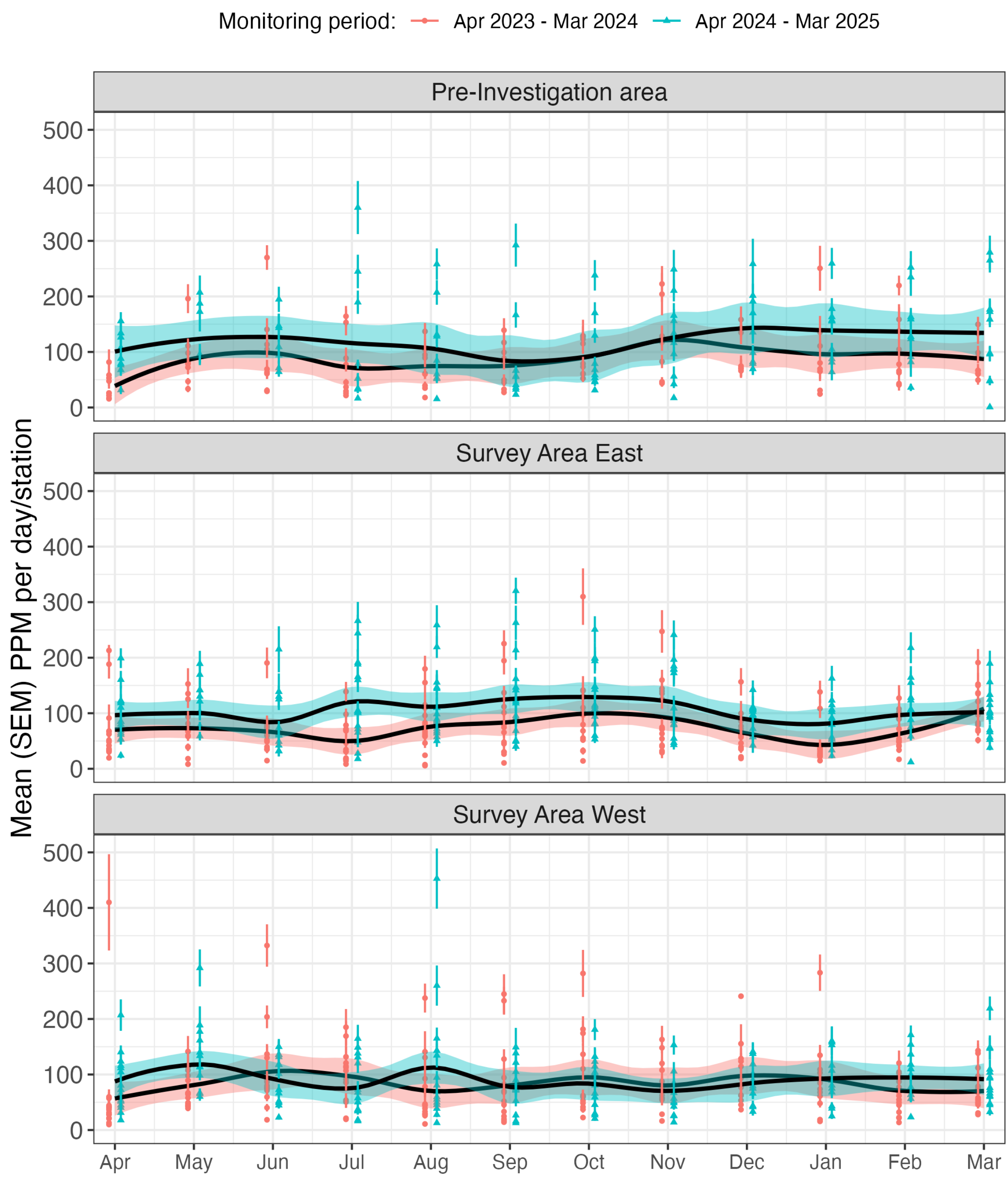


Figure 4-1-4: Porpoise positive minutes (PPM) per day/month for each monitoring period (period 1: Apr 2023-Mar 2024 and period 2: Apr 2024-Mar2025) for each of the three areas; Pre-investigation area, Survey Area East and Survey Area West. The black solid lines indicate the period-specific average for each area with the light red and blue shading indicating the 95% confidence interval.

4.1.1.2 Predicted maps of acoustic Species Distribution Models of harbour porpoises

Monthly models of PPM per day for each of the two years revealed considerable spatial and temporal variation in harbour porpoise presence in the survey area (Figure 4-1-5 and Figure 4-1-6).

The models for Y1 explained on average 50.68% (min= 42.4% in May and max=66.6% in April) of the deviation in the data and for Y2, 51.54% (min=42.5% in February and max 68.3% in August) were explained (Table 4-1-1). Bathymetry and seabed slope did not correlate strongly with harbour porpoise acoustic activity, while PPM per day generally declined with increasing distance from sandeel spawning grounds.

The dynamic forcing variables: mixed layer thickness, sea surface salinity, temperature, sea surface height and current velocity explained most of the variation in the data and all correlated with PPM per day in a non-linear fashion that differed between months (Appendix 2) likely due to seasonal changes in environmental conditions and thus prey availability in the area.

The PAM distribution models showed no clear seasonal trend or pattern in distribution, and even subsequent months were most often very different from each other. Furthermore, there was no correlation between the modelled distribution in one month in Y1 compared with the same month in Y2 (Figure 4-1-7). This indicates that there were no specific parts of the area with high or low importance for harbour porpoises. Instead all parts may at any part of the year be important for harbour porpoises as they follow their prey in and out of the North Sea I survey area.

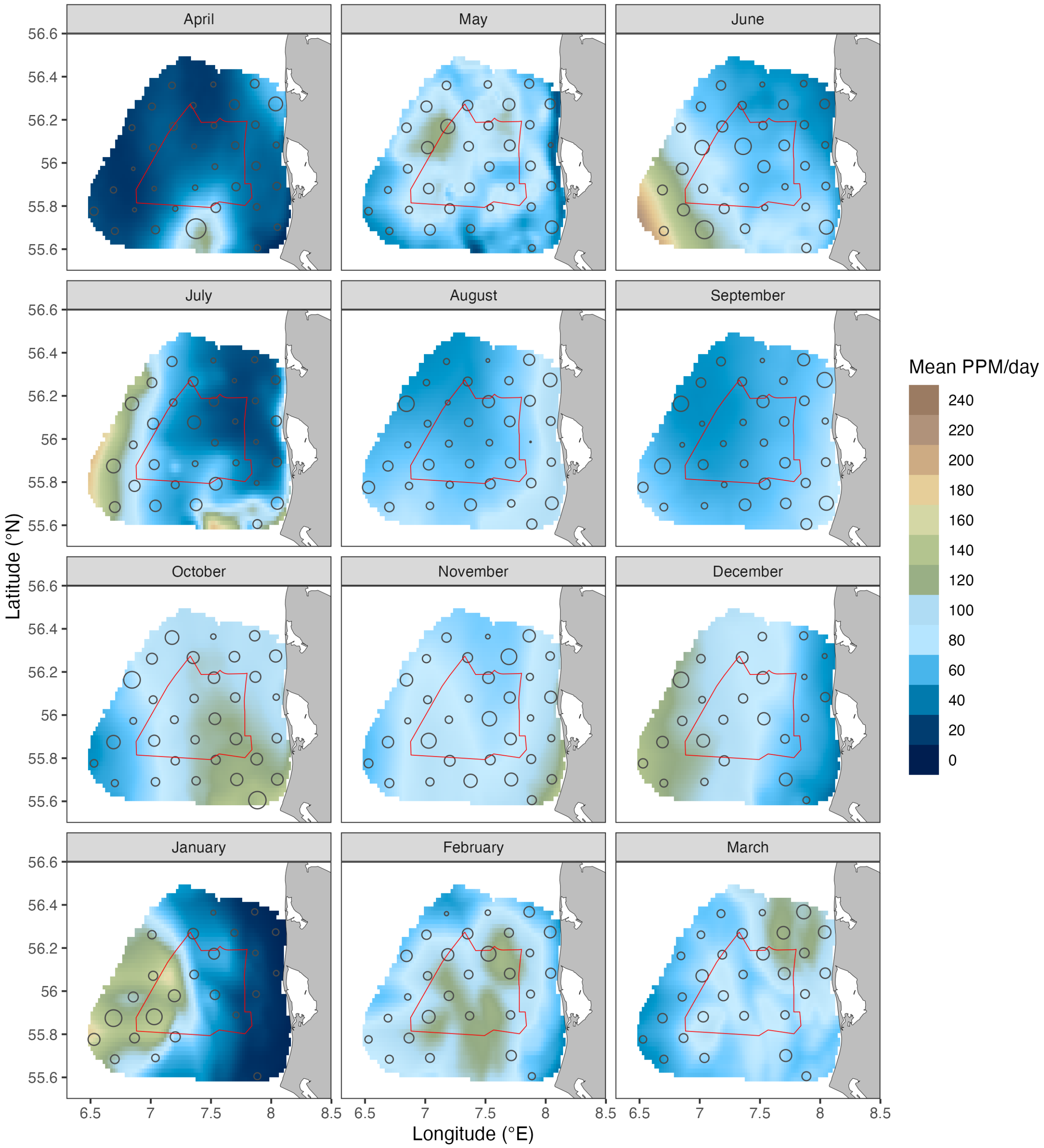


Figure 4-1-5: Monthly maps of the predicted mean PPM per day across the survey area from April 2023 to March 2024. Black circles indicate the mean PPM per day detected by each station during a specific month. The red line indicates the pre-investigation area.

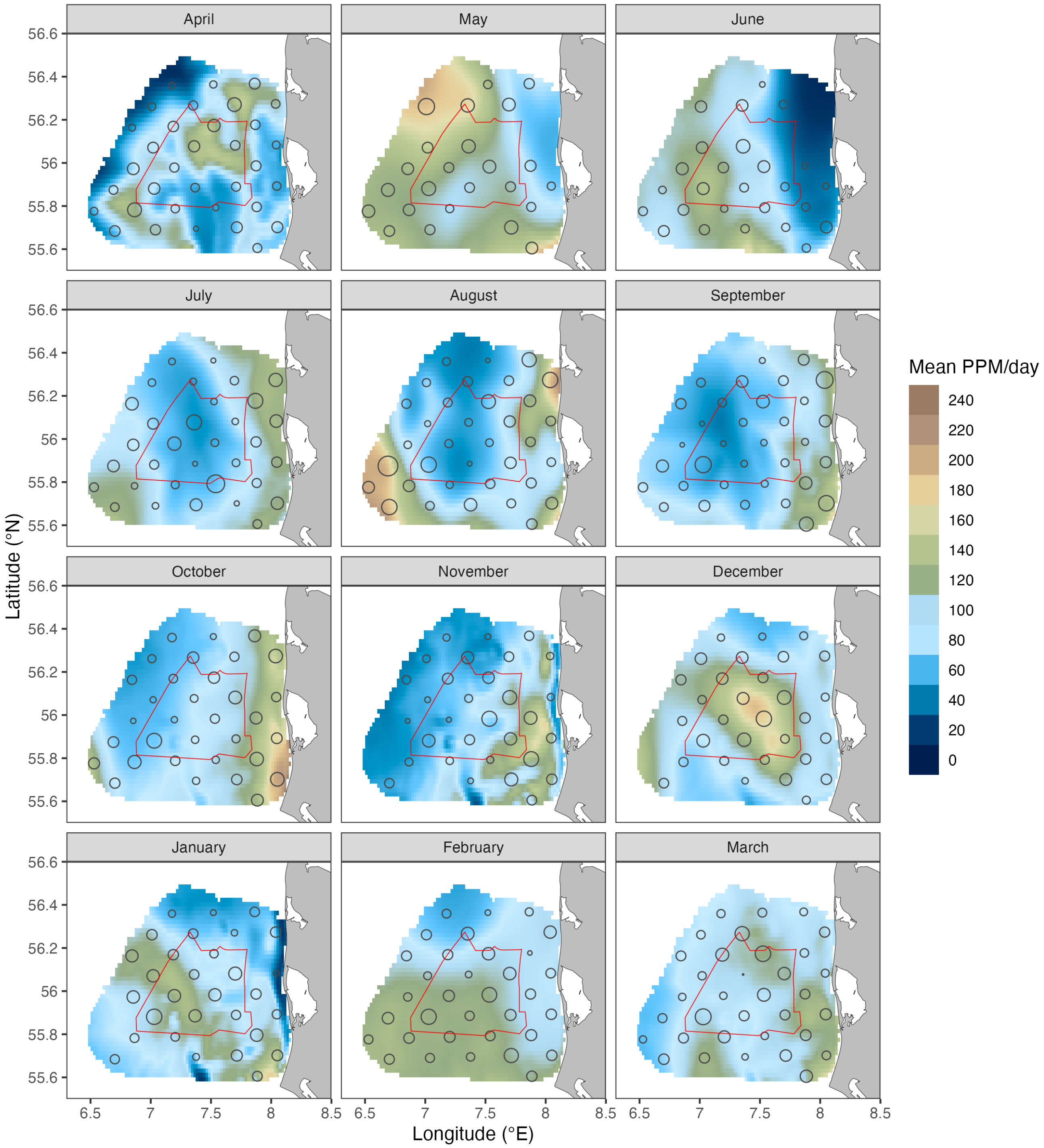


Figure 4-1-6: Monthly maps of the predicted mean PPM per day across the survey area from April 2024 to March 2025. Black circles indicate the mean PPM per day detected by each station during a specific month. The red line indicates the pre-investigation area.

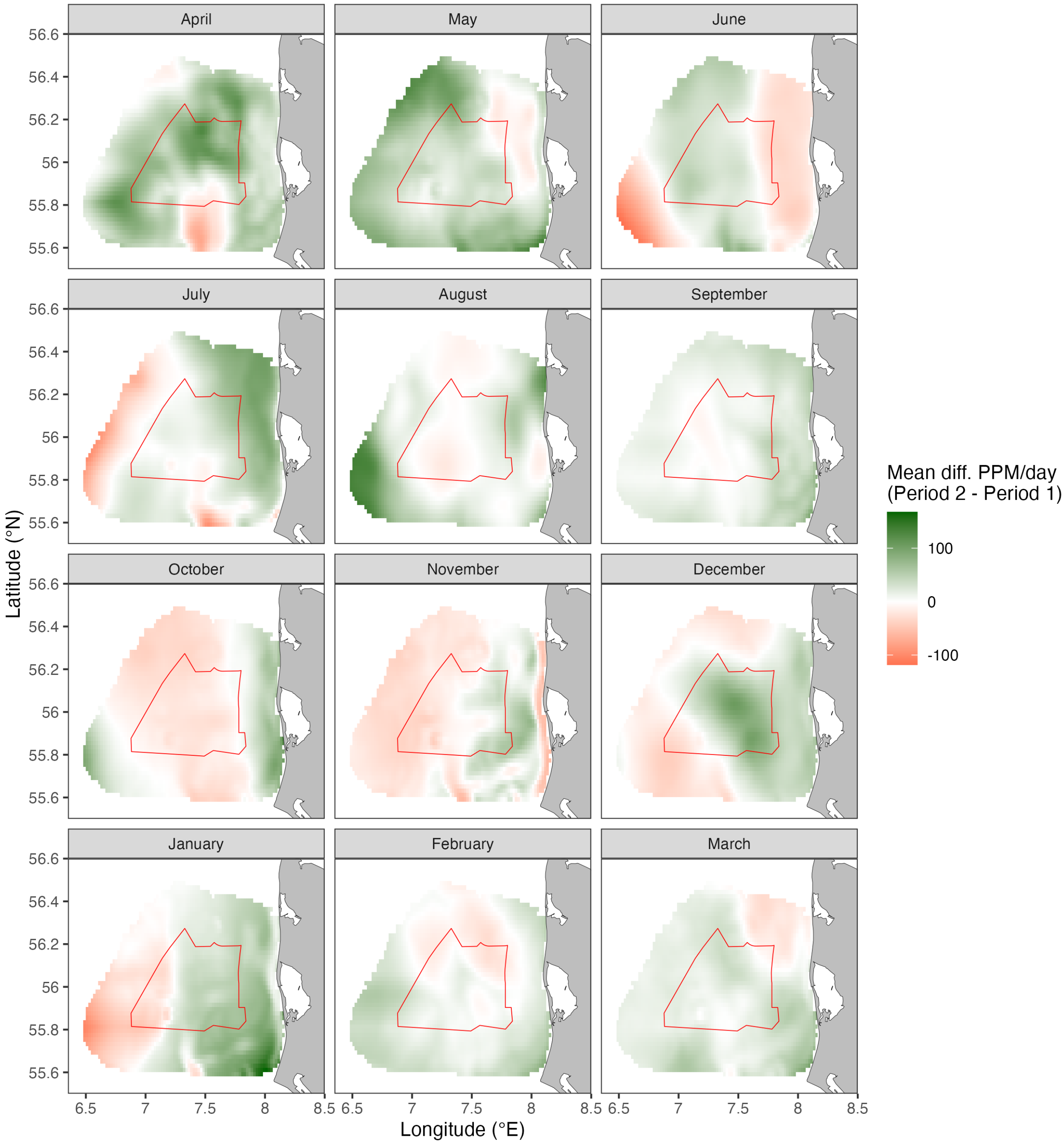


Figure 4-1-7: Monthly maps of the difference in the predicted mean PPM per day across the survey area between monitoring periods with Period 1: April 2023 to March 2024 and Period 2: April 2024 to March 2025. The red line indicates the pre-investigation area.

Table 4-1-2: Overview of the deviance explained (%) and adjusted R^2 for each period-specific monthly acoustic Species Distribution Model. The means across all months are provided at the bottom of the table.

	Period: Apr 2023 - Mar 2024		Period: Apr 2024 - Mar 2025	
Model month	Deviance explained (%)	R^2adjusted	Deviance explained (%)	R^2adjusted
April	66.6	0.617	47.1	0.462
May	42.4	0.427	47..2	0.456
June	54.8	0.543	49.7	0.477
July	49.3	0.421	62.6	0.637
August	45.2	0.402	68.3	0.651
September	57.7	0.559	56.9	0.545
October	45.7	0.438	50.5	0.487
November	46.4	0.41	54.6	0.493
December	53.6	0.511	42.6	0.438
January	58.9	0.591	44.8	0.415
February	44.4	0.391	42.5	0.402
March	43.1	0.396	51.7	0.52
Mean	50.68	0.476	51.54	0.499

4.1.1.3 Comparison of CPOD detections over time

In order to compare levels of harbour porpoise detections over time, six stations at or near Horns Rev 3 Offshore Wind Farm and three stations within the planned Thor OWF were redeployed at the same positions that were monitored during the pre-investigations for these offshore wind farms using CPODs (Dec-2012 to Nov-2013 at Horns Rev 3 and Dec-2019 to Nov-2020 at Thor OWF). The CPOD data for both years (Y1: Apr23-Mar24 and Y2: Apr24-Mar2025) collected during this project are displayed in Figure 4-1-8 for the three Thor OWF deployments and in Figure 4-1-9 for the six Horns Rev 3 deployments.

The Thor Offshore Wind Farm is being constructed in 2025 after the data collection for the North Sea I survey program and consequently no large change in the habitat has occurred since the baseline survey in 2019-2020. However, here the annual mean PPM per day was significantly higher ($p=0.002$) in Y1 (mean= 42.5, lower 95% CL= 31.8, upper 95% CL=53.2) compared to 2019–2020 (mean= 15.1, lower 95% CL=11.8 upper 95% CL=18.4). And furthermore, the Y2 annual mean PPM per day was also significantly higher ($p<0.001$) (mean= 81.7, lower 95% CL= 65.8, upper 95% CL=97.6) compared to Y1. In Y1 and Y2 there seem to be a seasonal trend with higher levels of harbour porpoise detections from February to May and November to December while the summer months from June to September hold lower levels.

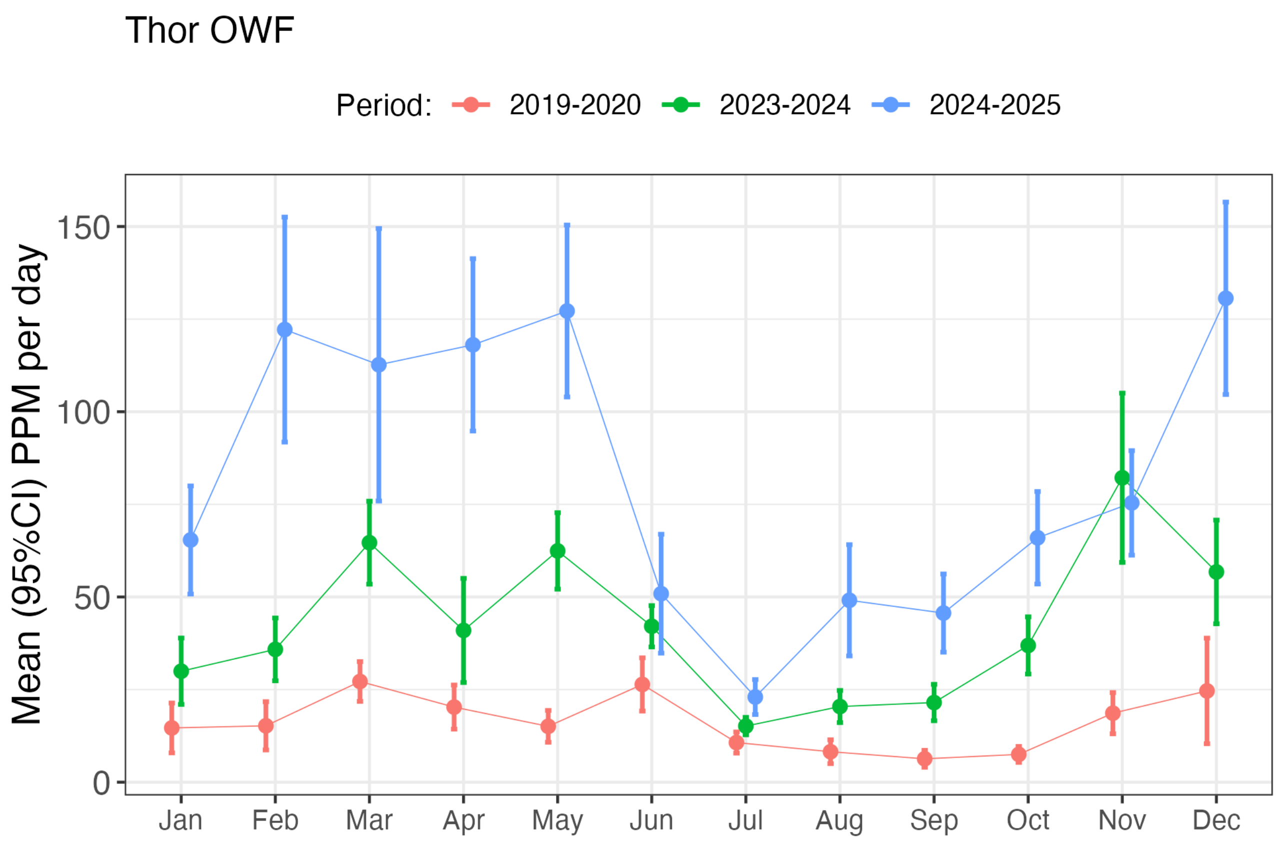


Figure 4-1-8: Average (95% CI) porpoise positive minutes (PPM) per day across months for the three CPOD stations deployed in the planned Thor OWF area in Dec19 to Nov20, Apr23 to Mar24 and Apr24 to Mar25.

The construction of Horns Rev 3 Offshore Windfarm was finished in 2019. The baseline survey included six stations; three which are now located inside the wind farm and three located outside the wind farm to the east. Here we did not find any clear seasonal trend although PPM/day per month of the three separate periods varied across years (Figure 4-1-9). However, there were approximately two-fold times higher detection levels inside the windfarm compared to outside (Table 4-1-3). This was tested in a comparison between 'inside' and 'outside' for each deployment period (P1: original data Dec12-Nov13, P2: Apr23-Mar24 and P3: Apr24-Mar25) which showed that the annual mean PPM per day for the three stations located inside the wind farm was significantly ($p<0.05$) higher than outside for all three periods. This means that even before the wind farm was built, the area inside was used more by harbour porpoises than the neighboring area outside and furthermore that this distribution did not change by the construction of wind farm.

For the annual mean PPM/day inside the wind farm, the third monitoring period Apr24-Mar25 was significantly higher than both the first ($p=0.105$) and the second ($p=0.002$) monitoring period (Table 4-3). Outside the wind farm, the second period was significantly lower than both the first period ($p=0.007$) and the third period (<001).

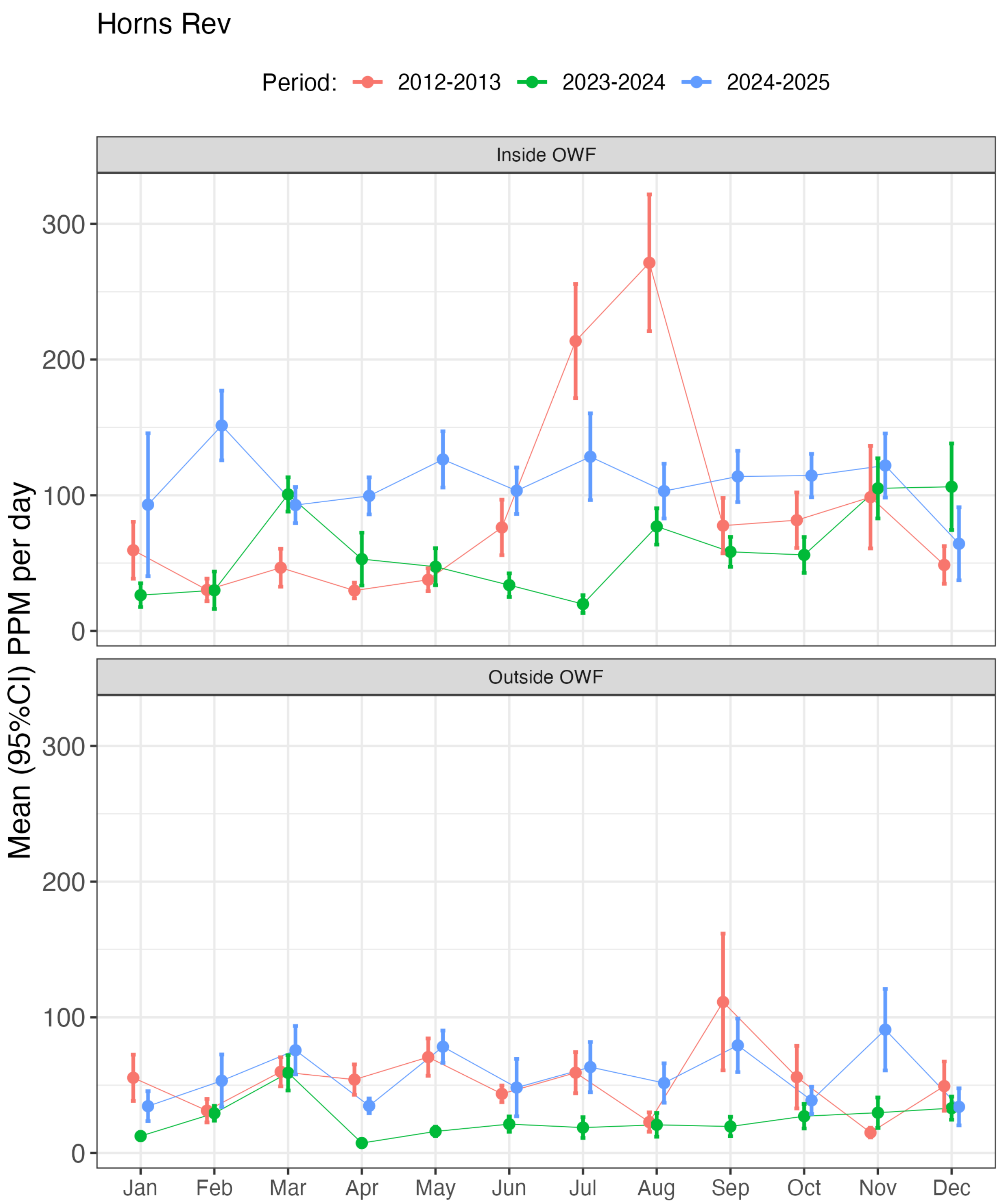


Figure 4-1-9: Average (95% CI) porpoise positive minutes (PPM) per day and month for three CPOD stations deployed within the Horns Rev 3 Offshore Wind Farm area (HR3) (HR3_1-3, Top panel) and outside (HR3_4-6, lower panel) in Dec12 to Nov13, Apr23 to Mar24 and Apr24 to Mar25.

Table 4-1-3: Annual mean (95% CI) PPM/day for three CPOD stations deployed within the Horns Rev 3 Offshore Wind Farm area (HR3) and near but outside in P1: Dec12-Nov13, P2:Apr23-Mar24 and P3: Apr24-Mar25.

Area	Annual mean (95% CI) PPM/day/month		
	P1: 2012-2013	**P2: 2023-2024**	**P3: 2024-2025**
Inside HR3 OWF	80.7 (51.5–109.8)	61.5 (46.5–76.4)	111.2 (94.3–128.1)
Outside HR3 OWF	49.3 (38.8–59.8)	25.5 (18.5–32.5)	56.0 (42.4–69.7)

4.1.1.4 Comparison of CPOD and FPOD detections

This part of the study was commissioned to Bioconsult SH and details are explained in Voß & Diederichs (2025). Here, only a short summary is given. The text is modified from Voß & Diederichs 2025, and some tables are modified to simplify the results and only include the most relevant information.

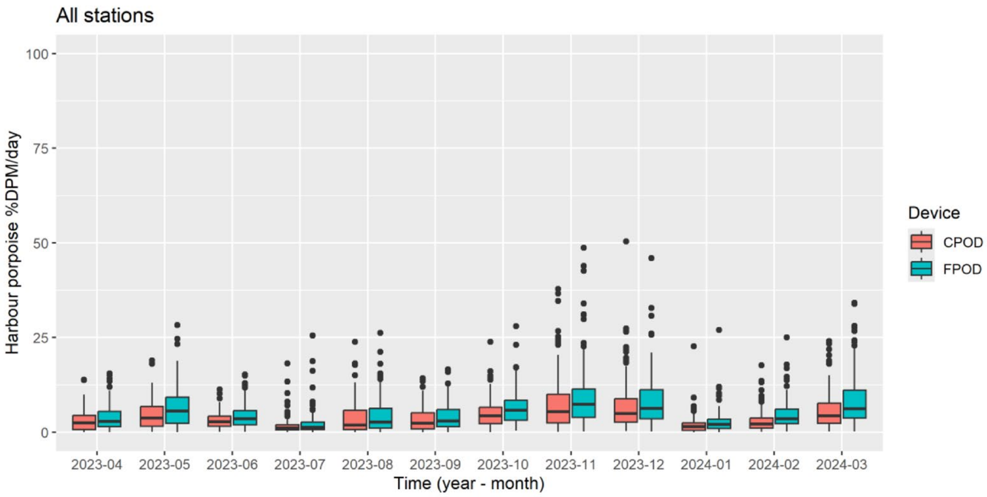
CPODs and FPODs were continuously deployed at 9 monitoring stations between April 2023 and March 2025 to compare detection rates of the two types of Passive Acoustic Monitoring devices (Table 4-1-4). During the study period, an average of 492 CPOD days per station and 450 FPOD days per station were included. The data were analysed and exported according to the methodology described in Voß & Diederichs 2025. When analysing data from CPODs and FPODs for comparison between the two devices, only the KERNO classifier was used. Therefore, in this chapter, all comparisons are based on data generated using the KERNO classifier as well as the two highest quality classes for both CPODs and FPODs ("high" and "moderate").

Table 4-1-4: Geographical positions, depth (m) and deployment periods of the deployed FPODs and CPODs. PODs were deployed from April 2023–March 2025 (Modified from Voß & Diederichs 2025).

Station ID	Latitude (°N)	Longitude (°E)	Depth (m)
HR3_1	55.7148	7.6081	-17
HR3_2	55.6485	7.6725	-12
HR3_3/NS23	55.7012	7.7141	-19
HR3_4	55.7348	7.7908	-18
HR3_5	55.7173	7.8519	-16
HR3_6	55.7487	7.901	-18
T2	56.2799	7.5437	-32
T3/NS26	56.2706	7.6946	-31
T4	56.3391	7.6816	-29

In general, harbour porpoise detection rates of CPODs and FPODs were comparable – irrespectively if harbour porpoise detection rates were calculated on a daily (%DPD/m = %Detection Positive Day/Month), hourly (%DPH/d = %Detection Positive Hour/Day) or 10-minute block (%DP10M/d= %Detection positive 10 minutes/Day) . However, the FPOD generally recorded more clicks than the CPOD – again irrespectively of the temporal scale (Figure 4-1-10). Both the CPOD and FPOD recorded detections on nearly every day. With the CPOD, an average detection rate of 99.2 %DPD/m was calculated, whereas with the FPOD, an average detection rate of 99.5 %DPD/m was calculated (Table 4-1-5). The correlation test showed that the CPOD detection rate and the FPOD detection rate correlated significantly when using the temporal scale %DPD/m (Table 4-1-6). Furthermore, the t-test showed no significant difference between the two detection rates.

However, when analysing the data on a minute basis (Figure 4-1-11), an average detection rate of 5.6 %DPM/d was recorded with the CPOD, whereas an average detection rate of 6.6 %DPM/d was recorded with the FPOD (Table 4-1-5). The correlation test showed that the CPOD detection rate and the FPOD detection rate correlated significantly when using the temporal scale %DPM/d (Table 4-1-6). However, the t-test showed a significant difference between detection rates of the two devices.



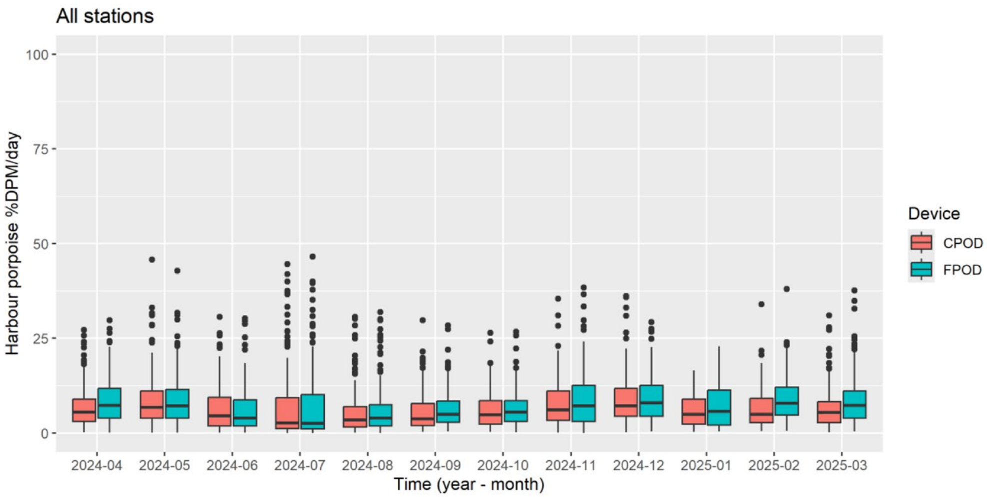


Figure 4-1-10: Harbour porpoise detection rates using the temporal scale %DPM/d from CPOD devices with the KERNO classifier (red) and from FPOD devices with the KERNO classifier (blue) during the study period (April 2023 – March 2025; first year of monitoring = upper graph and second year of monitoring = lower graph) averaged over all stations in the Danish North Sea; data set adjusted for background noise; only complete recording days and only the two highest data quality classes used; FPOD quality classes "high" and "moderate" (From Voß & Diederichs 2025).

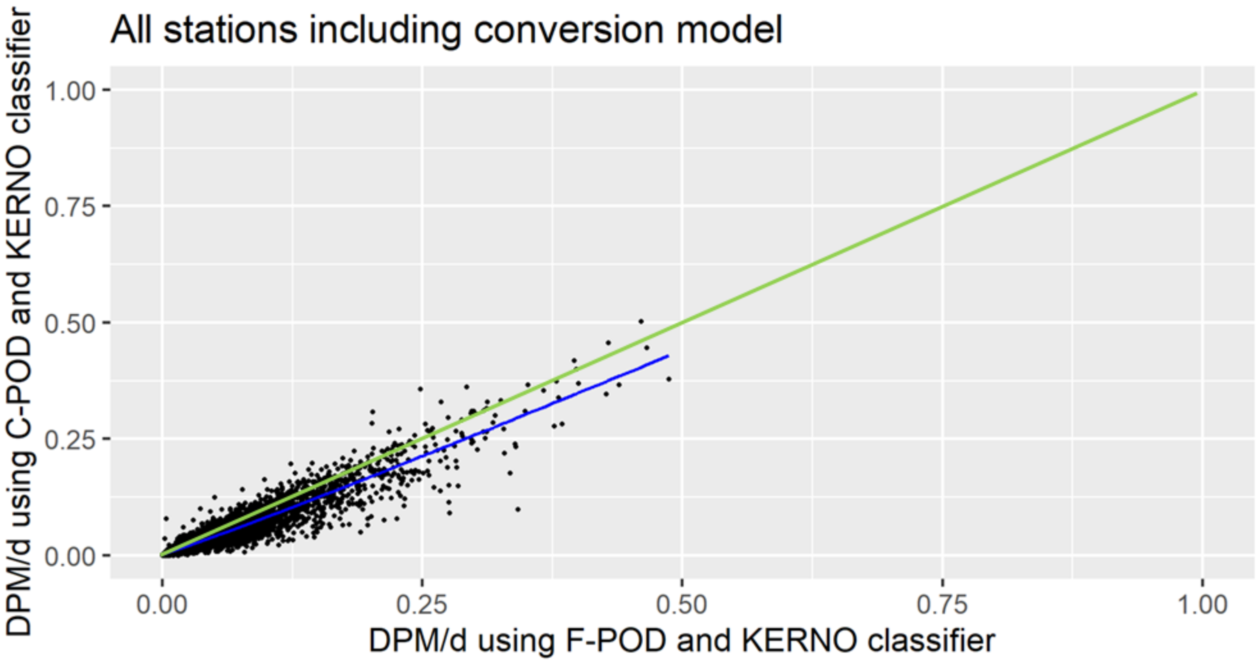


Figure 4-1-11: Comparing harbour porpoise detection rates using the temporal scale %DPM/d from CPOD devices with the KERNO classifier and from FPOD devices with the KERNO classifier during the study period (April 2023 – March 2025) averaged over all stations in the Danish North Sea I survey area; the blue line is a curve fitting using a generalised log-logistic model; the model had a residual standard error of below 0.05 (From Voß & Diederichs 2025). The green line with an intercept of 0 and slope of 1 show how a perfect relationship would have looked like.

*Table 4-1-5: Results of the t-test comparing the detection rates using different temporal scales averaged over all stations in the Danish North Sea 1 survey area: signif. codes: '***' = 0.001 (Modified from Voß & Diederichs 2025). FPOD quality classes "high" and "moderate".*

Unit	**Av. CPOD detection rate**	**Av. FPOD detection rate**	**t**	**df**	**p-value**
%DPD/m	99.17	99.45	-0.85	319	0.4
%DPM/d	5.550	6.625	-7.6	7156	4e-14 ***

*Table 4-1-6: Results of the correlation test comparing the detection rates using different temporal scales averaged over all stations in the Danish North Sea I survey area: signif. codes: '***'=0.001. DPD = Detection Positive Day. DPM = Detection Positive Minutes. FPOD quality classes "high" and "moderate". (Modified from Voß & Diederichs 2025).*

Unit	**Sample estimate: cor**	**t**	**df**	**p-value**
%DPD/month	0.6471	11	183	<2e-16 ***
%DPM/day	0.920	157	3611	<2e-16 ***

The harbour porpoise detections of the two PAM devices were temporally comparable but the number of detections varied: At 4 out of 9 stations, the detection rates of FPODs were significantly higher than the detection rates of CPODs. Importantly, the average difference in detection rates of CPODs and FPODs were not consistent. Overall, based on this study, the differences in detection rates seem to depend on the temporal scale of data analysis (e.g. %DPM/d or %DPD/m). Further studies should examine effects of study site, sample size, detection range of devices/their sensitivity and POD software used.

4.1.2 Other cetaceans

All efforts were made to ensure that broadband recorders, called ST600 hereinafter, were deployed at the six dedicated stations for the full two-year survey period. Nevertheless, gaps did occur in the data coverage due to servicing delays, recorder battery life, equipment loss, and equipment failure. In addition to the equipment loss listed in Table 4-1-7, the ST600s deployed at station NS06 between 2023-12-02 and 2024-02-26 and at station NS14 between 2025-02-18 and 2025-04-01 experienced leaks and flooded, leading to a loss of data. All other gaps in the data are due to delays in equipment servicing as the batteries became exhausted. Data available for this report is summarized in Table 4-1-7.

Table 4-1-7: Broadband recording coverage for the full survey duration, by month and year. Table lists the hours of data available for analysis per month, the number of hours analyzed in this report after subsampling, and the resulting percent of hours analyzed. Months with low or no hours available for analysis are due to either a) servicing delays (no color), b) end of battery life (no color), c) loss of equipment (orange), or d) equipment failure (blue).

	NS02			NS06			NS13			NS14			NS16			NS25		
Year - Month	Hours Available	Hours Analyzed	Percent Analyzed	Hours Available	Hours Analyzed	Percent Analyzed	Hours Available	Hours Analyzed	Percent Analyzed	Hours Available	Hours Analyzed	Percent Analyzed	Hours Available	Hours Analyzed	Percent Analyzed	Hours Available	Hours Analyzed	Percent Analyzed
2023-04	288	144	50.0%	216	162	75.0%	264	198	75.0%	216	108	50.0%	264	198	75.0%	240	180	75.0%
2023-05	744	372	50.0%	744	558	75.0%	744	558	75.0%	744	372	50.0%	744	558	75.0%	664	497	74.8%
2023-06	720	360	50.0%	720	540	75.0%	720	540	75.0%	720	360	50.0%	720	540	75.0%	0	0	
2023-07	131	65	49.6%	39	29	74.4%	330	242	73.3%	470	233	49.6%	137	102	74.5%	0	0	
2023-08	632	474	75.0%	708	354	50.0%	0	0		706	354	50.1%	611	611	100.0%	600	599	99.8%
2023-09	720	541	75.1%	160	80	50.0%	0	0		720	359	49.9%	720	720	100.0%	720	720	100.0%
2023-10	564	422	74.8%	0	0		0	0		567	280	49.4%	474	467	98.5%	556	554	99.6%
2023-11	0	0		0	0		0	0		24	12	50.0%	0	0		0	0	
2023-12	0	0		0	0		696	523	75.1%	744	372	50.0%	696	348	50.0%	720	720	100.0%
2024-01	552	414	75.0%	0	0		744	558	75.0%	744	373	50.1%	744	372	50.0%	744	606	81.5%
2024-02	212	141	66.5%	72	72	100.0%	527	407	77.2%	354	207	58.5%	321	205	63.9%	315	248	78.7%
2024-03	744	372	50.0%	744	744	100.0%	744	744	100.0%	744	744	100.0%	744	520	69.9%	744	743	99.9%
2024-04	716	451	63.0%	709	607	85.6%	506	505	99.8%	707	705	99.7%	698	432	61.9%	693	692	99.9%
2024-05	744	744	100.0%	744	372	50.0%	0	0		744	744	100.0%	732	731	99.9%	744	744	100.0%
2024-06	720	720	100.0%	720	361	50.1%	381	381	100.0%	720	720	100.0%	720	720	100.0%	720	720	100.0%
2024-07	744	744	100.0%	204	102	50.0%	203	202	99.5%	200	198	99.0%	744	744	100.0%	181	180	99.4%
2024-08	746	744	99.7%	469	469	100.0%	465	465	100.0%	0	0		746	744	99.7%	448	224	50.0%
2024-09	720	720	100.0%	720	720	100.0%	720	720	100.0%	0	0		568	567	99.8%	710	371	52.3%
2024-10	416	415	99.8%	743	742	99.9%	728	726	99.7%	312	312	100.0%	0	0		744	524	70.4%
2024-11	0	0		720	720	100.0%	720	720	100.0%	720	720	100.0%	0	0		720	487	67.6%
2024-12	0	0		744	545	73.3%	744	744	100.0%	711	710	99.9%	0	0		744	374	50.3%
2025-01	0	0		499	248	49.7%	744	744	100.0%	0	0		0	0		744	375	50.4%
2025-02	264	132	50.0%	240	240	100.0%	287	274	95.5%	0	0		240	240	100.0%	113	46	40.7%
2025-03	744	374	50.3%	744	744	100.0%	744	744	100.0%	0	0		744	744	100.0%	744	372	50.0%
2025-04	25	12	48.0%	26	25	96.2%	26	25	96.2%	0	0		50	49	98.0%	122	60	49.2%

Each ST600 was expected to record for approximately 90 days, which requires servicing every three months. It is important to note that the ST600s at station NS25 on 2023-04-20 and station NS06 on 2023-08-02 were equipped with lower ampere-hour batteries, which had a much shorter life than calculated. For further deployments, those batteries were replaced with higher ampere-hour batteries.

Several stations suffered from rig noise, or noise which originates from the mooring itself or from the nearby surface buoy (Figure 4-1-12). The presence of this interference makes it very difficult to actively search for cetaceans in the soundscape, as the noise is often broadband and therefore can trigger automated detectors causing false positive detections. It can also mask actual odontocete vocal behavior, leading to false negatives. This issue was particularly prominent between February and August 2024, because the buoy moorings were adjusted in the winter of 2024, and more chain was exposed near the bottom anchor relatively close to the ST600 hydrophone. This took one recording cycle to notice (as there was an equipment servicing in April 2024), therefore this issue impacts at least two deployments. To adjust for this, since the bottom anchor moorings could not be changed back, the ST600s were moved up the mooring line to sit 8 m above the seabed (instead of 2 m above) to add physical distance between the noise source and the acoustic sensor. Due to this interference, the number of detections may be lower than the actual acoustic density of dolphins in the survey area and the reported level of dolphin detections should thus be regarded as conservative.

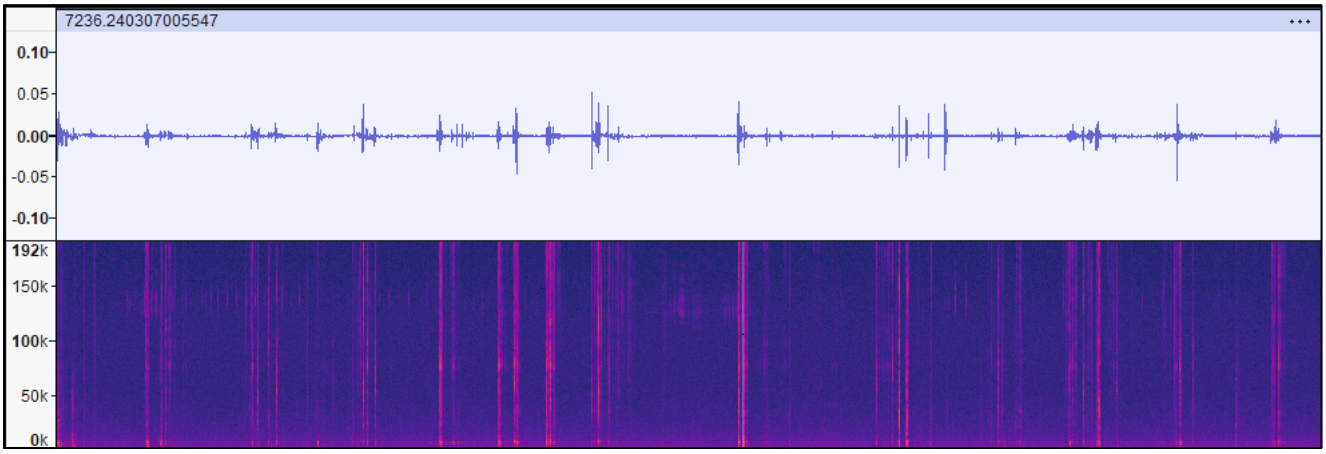


Figure 4-1-12: Example of rig noise, specifically from a loose chain on the rig, on 7 March 2024 at station NS25. The top panel is the linear waveform of the signal, and the bottom is a spectrogram between 0-192 kHz. The window is approximately 7 seconds long. The noise is broadband and fills up the entire spectrum where present.

4.1.2.1 Minke Whales

For the Minke whale analysis, 45- or 30-minutes per four hours for all data were analyzed between April 2023-March 2025. The rebuilt beta detector did not detect any occurrences of minke whale pulse trains. This does not mean that minke whales do not use the area, only that they are not detected. This may be due to several reasons e.g. that they do not regularly produce a readily identifiable signal in these waters, that noise conditions mask potential minke whale pulse trains, or that the tool is not functioning properly as it is still in beta development. However, while reviewing the 'Whistle & Moan Detector' output for delphinids, which overlaps in frequency range with the minke whale pulse train, no pulse trains were detected.

4.1.2.2 Delphinid Analysis

Detections were tallied for both white-beaked dolphins and uncategorized delphinids. Across all stations and deployments, there were a total of 295 detection positive snapshots (i.e. a time window in which animal presence was documented), which resulted in 212 detection positive hours (0.4% of hours analyzed). Within these data, there were 21 instances of dolphin acoustic activity that could not be confidently associated with white-beaked dolphins (Table 4-1-8), three of which overlapped with white-beaked dolphin acoustic events at station NS14 in July and December of 2023, and at station NS02 in March 2025. These events were separately counted, because while they could have been white-beaked dolphins, white-beaked dolphins do travel in multi-species groups, and these click trains could not be positively categorized as white-beaked dolphin. Due to the low number of unclassified detections, these events were removed from further analysis and all descriptions of dolphin positive hours hereafter refer to white-beaked dolphin detections.

Table 4-1-8: All unidentified delphinid positive hours found within this study, and if that hour also contained a white-beaked dolphin event.

Datetime	Concurrent with WBD event	Station
2023-05-19 13:00:00	0	NS02
2023-05-26 00:00:00	0	NS06
2023-07-02 00:00:00	1	NS14
2023-12-02 00:00:00	1	NS14
2024-03-08 04:00:00	0	NS16
2024-03-26 06:00:00	0	NS13
2024-03-27 06:00:00	0	NS14
2024-04-24 21:00:00	0	NS02
2024-04-28 01:00:00	0	NS02
2024-04-28 02:00:00	0	NS02
2024-05-06 23:00:00	0	NS14
2024-05-11 03:00:00	0	NS14
2024-05-18 22:00:00	0	NS16
2024-06-17 15:00:00	0	NS06
2024-06-26 12:00:00	0	NS02
2024-07-08 10:00:00	0	NS16
2024-07-09 02:00:00	0	NS13
2024-10-03 03:00:00	0	NS06
2024-11-10 17:00:00	0	NS14
2025-03-08 00:00:00	1	NS02
2025-03-16 20:00:00	0	NS02

Detection positive hours (DPH) were generated for white-beaked dolphin events, based on the hours available for analysis per station and deployment and the 273 white-beaked dolphin detection positive snapshots. The ratio of detection positive days (DPD), or the presence of white-beaked dolphin bioacoustic activity within any snapshot of a given day, was higher at the most northwestern stations in the study area, though no station recorded detection positive days more than 17.5% per month (Figure 4-1-13).

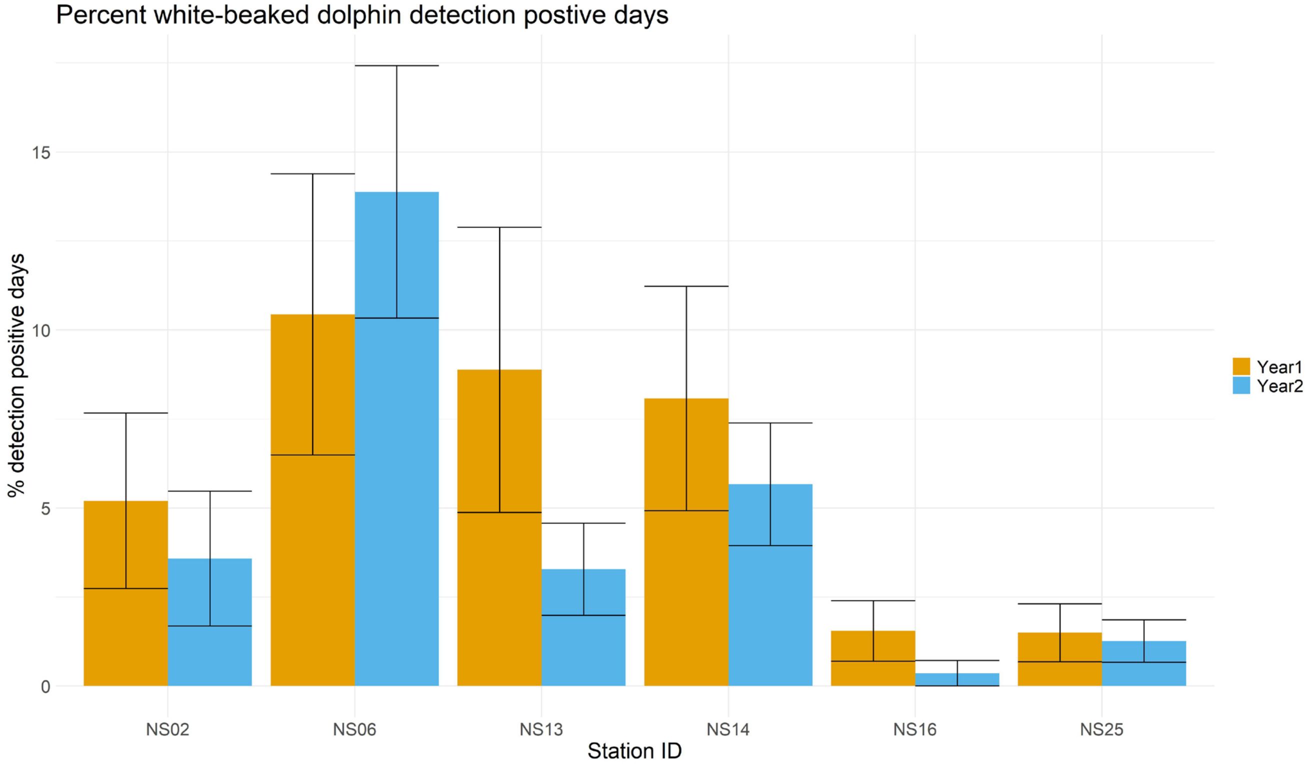


Figure 4-1-13: Percent white-beaked dolphin positive days across all deployments and stations, separated by year. Each bar is the mean percent of porpoise positive days each month, presented with the standard error.

From the hours included in this analysis, less than 1% per month contained instances of white-beaked dolphin bioacoustic activity (Figure 4-1-14). This follows as the majority of days within a given month were negative for dolphin bioacoustic activity. The highest number of acoustic detections were observed at NS13 in July 2023, with one day having four dolphin positive hours, the max recorded per day across the study. However, the confidence interval of 1.2% at station NS13 indicated a large variability of acoustic detections of white-beaked dolphins for that particular month. All stations showed similar patterns of acoustic detections (except Station NS25) in early summer months following a drop during autumn months and another rise in the winter. The northwestern stations in general had slightly higher acoustic detections than their southeastern counterparts, suggesting a higher presence/habitat use in the offshore marine environment.

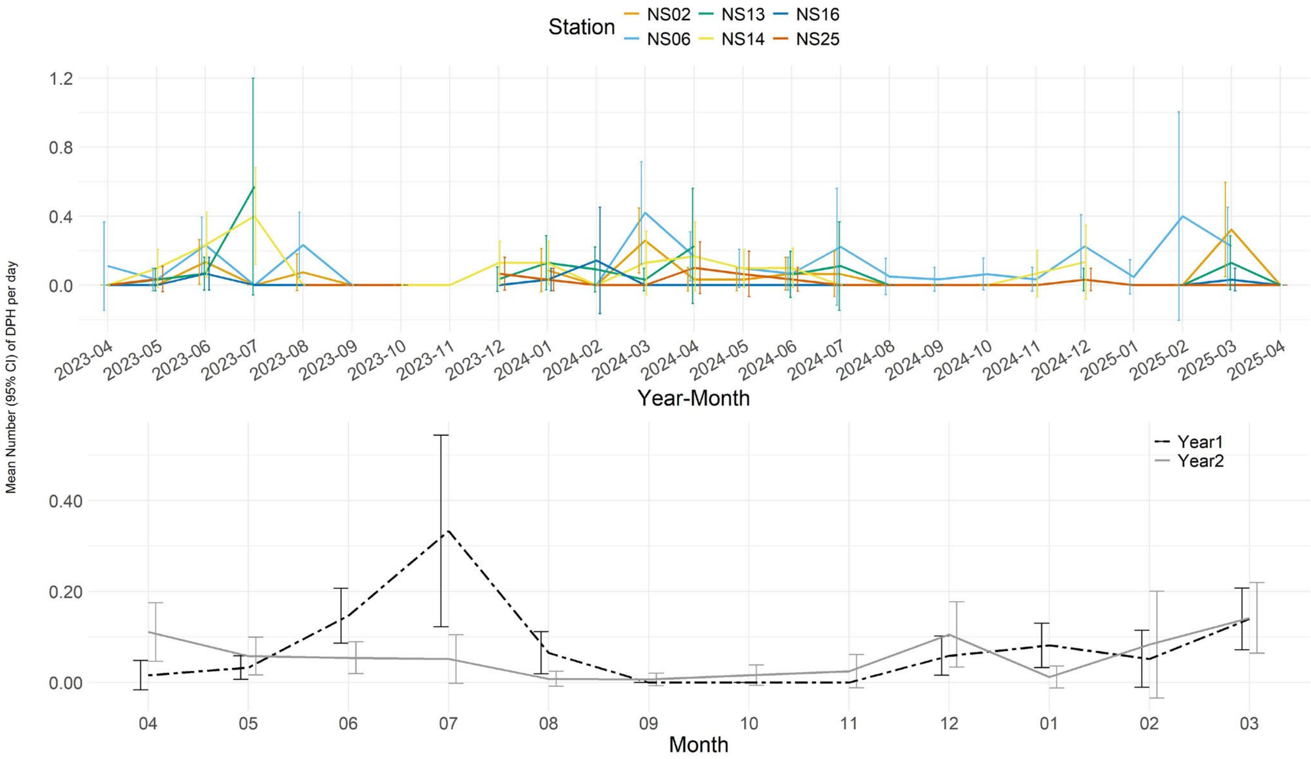


Figure 4-1-14: Average detection positive hours (DPH) for white-beaked dolphins per month in the study area for the entire survey, presented with 95% confidence intervals. Top Panel shows these data by month and station, while the bottom panel shows these data across all stations for the full survey period, separated by year.

Generally, even with the limited detections within the survey area, there were nearly twice as many detection positive snapshots at night (n=179) than during the day (n= 94). When looking at the diurnal patterns of white-beaked dolphin activity, snapshots provide a more detailed overview as to the length of activity than detection positive hours. Globally, dolphin groups are more acoustically active at night, including dolphins in the North Atlantic (Cascão et al, 2020; Cohen et al., 2023). Danish white-beaked dolphins demonstrated similar trends during the North Sea Energy Island survey program in an adjacent area in 2021–2023, however in much higher detection levels (Kyhn et al, 2024a). In Figure 4-1-15, a high presence of bioacoustic activity is shown throughout the night, with a sharp increase in the predawn hours, and some activity during the day. This activity coincides with what is known about acoustic activity from tagged white-beaked dolphins in Iceland, where all presumed foraging activity occurred between 01:30 and 07:00 UTC on 3 August 2006, when ambient light levels were low (n=1) (Rasmussen et al. 2013).

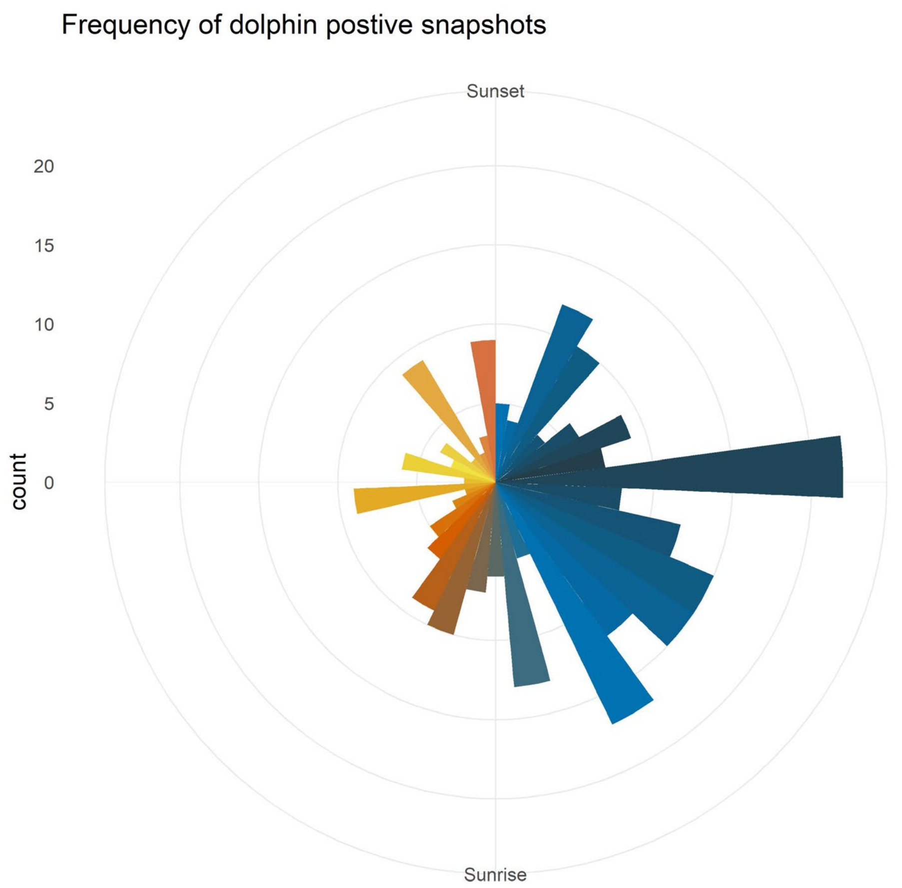


Figure 4-1-15: Diurnal pattern of detection positive snapshots (DPSS) for white-beaked dolphins at all stations against normalized time (sunset-sunrise: -1 - 0; sunrise-sunset: 0 - 1).

4.2 Aerial surveys of harbour porpoise

Four aerial surveys were planned during 2023, however due to poor weather in autumn 2023, only three surveys were carried out, on the 12th of May, 14th of June and the 2nd of August 2023. It was therefore decided to move the missing autumn survey to the autumn of 2024. Thus, five surveys were conducted in 2024, namely on the 22nd of April, 24th of June, 19th of July, 4th of October, and 7th of November. The result of each survey is described below.

4.2.1 Aerial surveys 2023

The three surveys were all completed in good weather conditions and the results are shown in Table 4-2-1. The total planned survey transect length was 1084 km. However, but due to the presence of the Vesterhav Syd (for the august survey) and Horns Rev 3 offshore wind farms, where the survey route had to deviate to fly around or above, the realised effort was shorter.

Table 4-2-1: Data and results from the three aerial surveys conducted during the North Sea I survey in 2023. CV = Coefficient of Variation. Total length of planned transects is 1084 km. "Completed effort" only includes effort covered with good or moderate observer sightability.

Survey date	Completed effort (km)	Abundance (95% Confidence Interval)	Density (95% Confidence interval)	Mean group size	No. harbour porpoises (incl. calves)	No. calves	Calf ratio	CV
12/05/2023	848	4814 (2771–7935)	0.63 (0.36–1.04)	1.14	73	0	0%	0.26
14/06/2023	855	22,206 (14,924–31,182)	2.91 (1.95–4.08)	1.31	311	32	10%	0.19
02/08/2023	862	3572 (1968–6155)	0.47 (0.26–0.81)	1.35	68	14	21%	0.3

Harbour porpoise aerial survey 12th May 2023

During the survey conducted the 12th May 2023, all transects were covered except for the part of the transects that crosses the Horns Rev 3 Offshore Wind Farm. Consequently, these parts are excluded in all surveys (Table 4-2-1). Observations were conducted in Beaufort Sea State 1-3, and 77% were conducted in Sea State 1 or 2. Beaufort Sea State is a definition of wave height and used here to determine when the waves were too high (when above 2) for observing harbour porpoises.

The subjectively assessed sightability for each observer is displayed in Figure 4-2-1. Here, 38% of the effort was conducted in either good or moderate conditions. The sightability was particularly poor in the western part of the survey area, which for example can be reduced due to strong glare. Variation in sightability is included and adjusted for in the Distance sampling analysis when calculating the abundance.

In total, 73 adult harbour porpoises were observed (Table 4-2-1). There were no observations of calves, defined by a much smaller individual next to a large individual. It was not possible to determine if any of the porpoises seen in pairs were a mother with a large and nearly weaned calf. The harbour porpoise observations were distributed across the aerial survey area. The abundance of harbour porpoises in the survey area was estimated to 4814 harbour porpoises (95% CI = 2771–7935; CV = 0.26). The average density within the area was 0.63 individuals/km^2 (95% CI = 0.36–1.04).

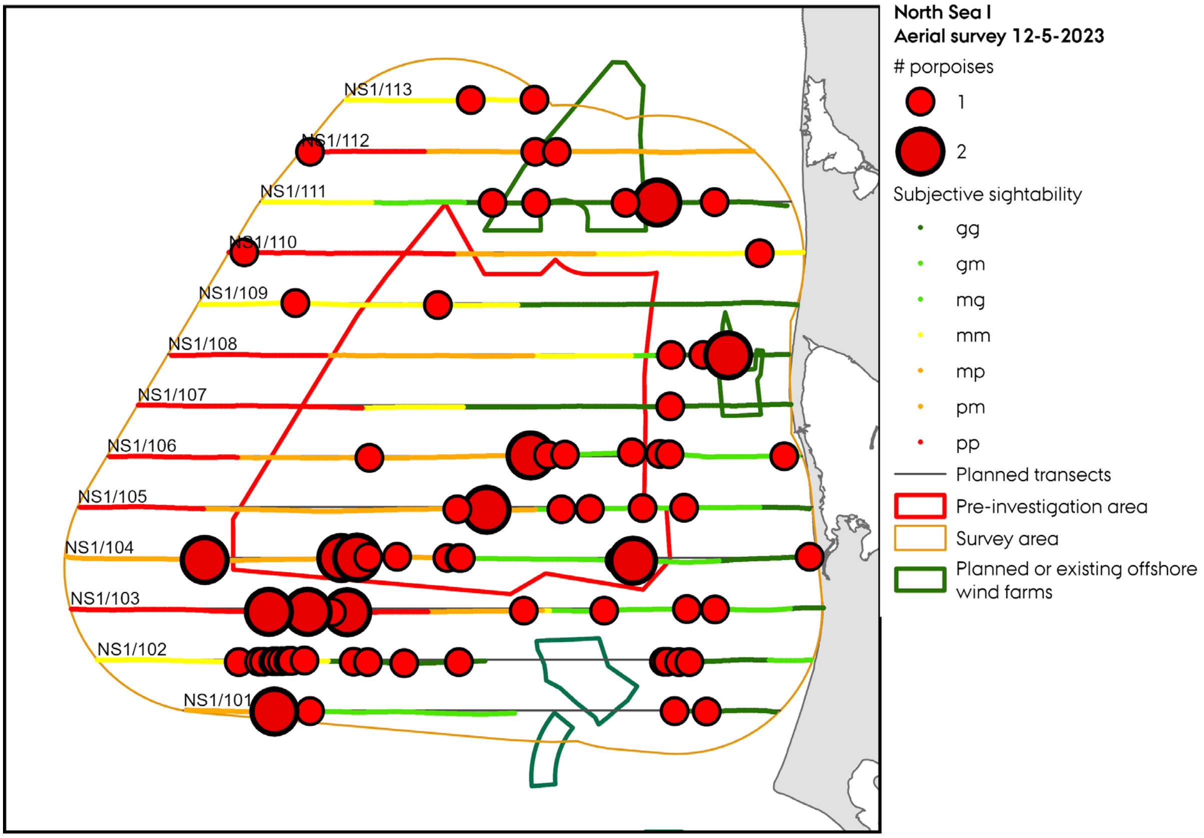


Figure 4-2-1: Harbour porpoise observations during the aerial survey on the 12th of May 2023. The size of the dots indicates the group size at each observation. The observer assessed sightability is indicated in colours from green to red for each observer side (left-right in relation to the direction of the plane) of the plane (g=good, m=moderate, p=poor).

Aerial harbour porpoise survey 14th June 2023

On the 14th June 2023 survey, there were optimal survey conditions and 92% of transects were covered in Sea State 1. The subjectively assessed sightability for each observer is displayed in Figure 4-2-2. Here, 98% of the effort was conducted in either good or moderate conditions, while 2% were conducted with lower sightability. Variation in sightability is included and adjusted for in the Distance sampling analysis for calculating the abundance. Due to military activity, the western part of the four most southern transects could not be covered.

During this survey, 311 harbour porpoises were observed in total and 32 of these were calves, which gave a mother-calf pair ratio of 10% (Table 4-2-1).

Few porpoises were observed near the Vester Hav Syd offshore wind farm. The turbines of this wind farm were piled into the seabed during the early spring of 2023 and multiple construction vessels were still in the area (Figure 4-2-2) which may have contributed to this. Throughout the survey, many large schools of fish were seen at the surface making the water appear to "boil". It was not possible to determine the species, but it appears likely that these fish could be contributing to the high level of harbour porpoise observations.

The abundance of harbour porpoises in the survey area was estimated to 22,206 harbour porpoises (95% CI = 14,924–31,182; CV = 0.19) with a density of 2.91 individuals/km^2 (95% CI = 1.04–3.16) (Table 4-2-1). This is 4.6 times as many as compared to the May survey. For comparison, the densities from the Danish national aerial surveys in Skagerrak and the Southern North Sea was respectively 0.54 individuals/km^2 on average for the period

2017–2021 and maximum 0.85 individuals/km^2 in 2017 for Skagerrak, and on average 0.75 individuals/km^2 (2011–2021) and maximum 1.22 individuals/km^2 in 2014 in the southern North Sea.

In German North Sea waters, however, similar and higher densities than the North Sea I survey area have been estimated particularly at the German Dogger Bank (Nachtsheim, 2021) indicating that there may be several high-density areas (or hot spots) in the North Sea and that the North Sea I survey area may be one of them. The density of 2.91 porpoises per km^2 is the highest ever detected in the Danish North Sea.

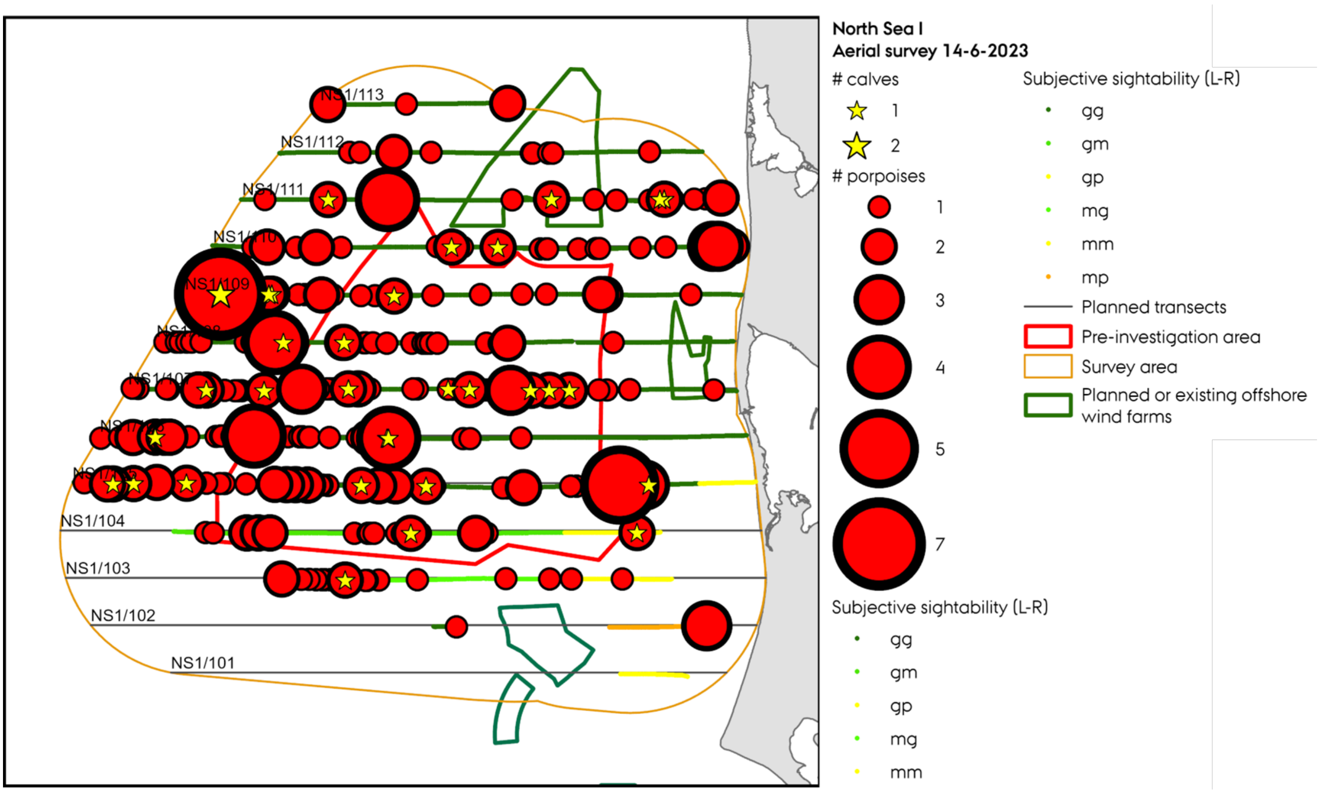


Figure 4-2-2: Harbour porpoise observations during the aerial survey on 14th June 2023. The size of the dot indicates the group size at each observation and a star indicates one or more harbour porpoise calves. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, p=poor).

Aerial harbour porpoise survey 2nd of August 2023

On the 2nd of August 2023 survey, the weather was generally good and 75 % of transects were covered in Sea State 1 or 2. Furthermore, 60% of the effort was conducted in Good or Moderate sightability (Figure 4-2-3). During this survey, 68 harbour porpoises were observed in total, with 14 of these beingcalves (small animal next to a large animal), which gives a mother-calf pair ratio of 21%, which indicates that this may be an important area for calves (Table 4-2-1).

The abundance of harbour porpoises in the survey area was estimated to 3,572 harbour porpoises (95% CI = 1,968–6,155; CV = 0.30), with a density of 0.47 individuals/km^2 (95% CI = 0.26–0.81) (Table 4-2-1). This is comparable to the porpoise abundance and density estimated in May 2023, but six times less than the abundance and density estimated for the June 2023 survey.

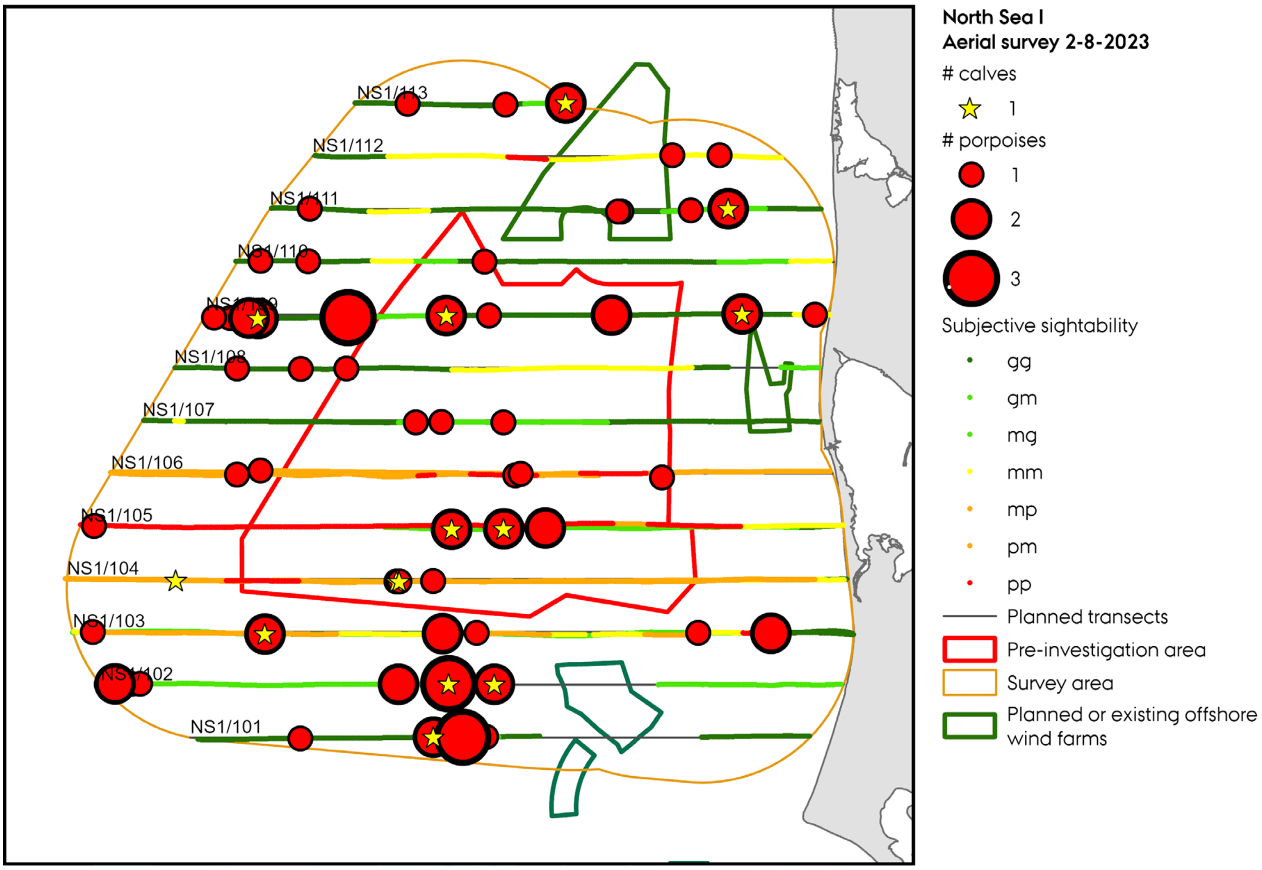


Figure 4-2-3: Harbour porpoise observations during the aerial survey on 2nd August 2023. The size of the dot indicates the group size at each observation and a star indicates one or more harbour porpoise calves. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, P=poor).

4.2.2 Aerial surveys 2024

The results of the five surveys are shown in Table 4-2-2.Table 4-2-2 Data and results from the five aerial surveys conducted during the North Sea I survey in 2024. CV = Coefficient of Variation. Total length of planned transects is 1084 km.

Survey date	Completed effort with good or moderate sightability (km)	Abundance (95% Confidence Interval)	Density (95% Confidence interval)	Mean group size	No. harbour porpoises (incl. calves)	No. calves	Calf ratio	CV
22-04-2024	920	7756 (5249–10,987)	1.02 (0.69–1.44)	1.08	135	0	0%	0.19
24-06-2024	1041	6074 (3818–9326)	0.80 (0.50–1.22)	1.28	106	13	12%	0.22
19-07-2024	806	6139 (5281-12,946)	1.07 (0.69-1.70)	1.33	105	12	14%	0.23
04-10-2024	633	3012 (1688–7129)	0.54 (0.22–0.93)	1.36	38	3	9%	0.34
07-11-2024	929	4474 (3080–6604)	0.59 (0.40–0.87)	1.35	53	6	13%	0.20

Aerial harbour porpoise survey 22nd of April

During the survey the 22nd April 2024, all transects were covered but due to active military areas, parts of five transects (one in the north and four near Horns Rev 3 wind farm) were only partly surveyed. Observations were conducted in Beaufort Sea State 1-3, and 82% were conducted in Sea State 1 or 2. The subjectively assessed sightability for each observer is displayed in Figure 4-2-4. Here, 91% of the effort was conducted in either good or moderate conditions, which indicates optimal conditions. Variation in sightability is included and adjusted for in the Distance sampling analysis when calculating the abundance.

In total, 135 adult harbour porpoises were observed, which is the highest number of observations in 2024 (Table 4-2-2). There were no observations of calves. The abundance of harbour porpoises in the survey area was estimated to 7756 harbour porpoises (95% CI = 5249–10,987; CV = 0.19). The average density within the area was 1,02 individuals/km^2 (95% CI = 0.69–1.44). The observations were spread out across the survey area but were concentrated in the northeastern and the southwestern part of the area.

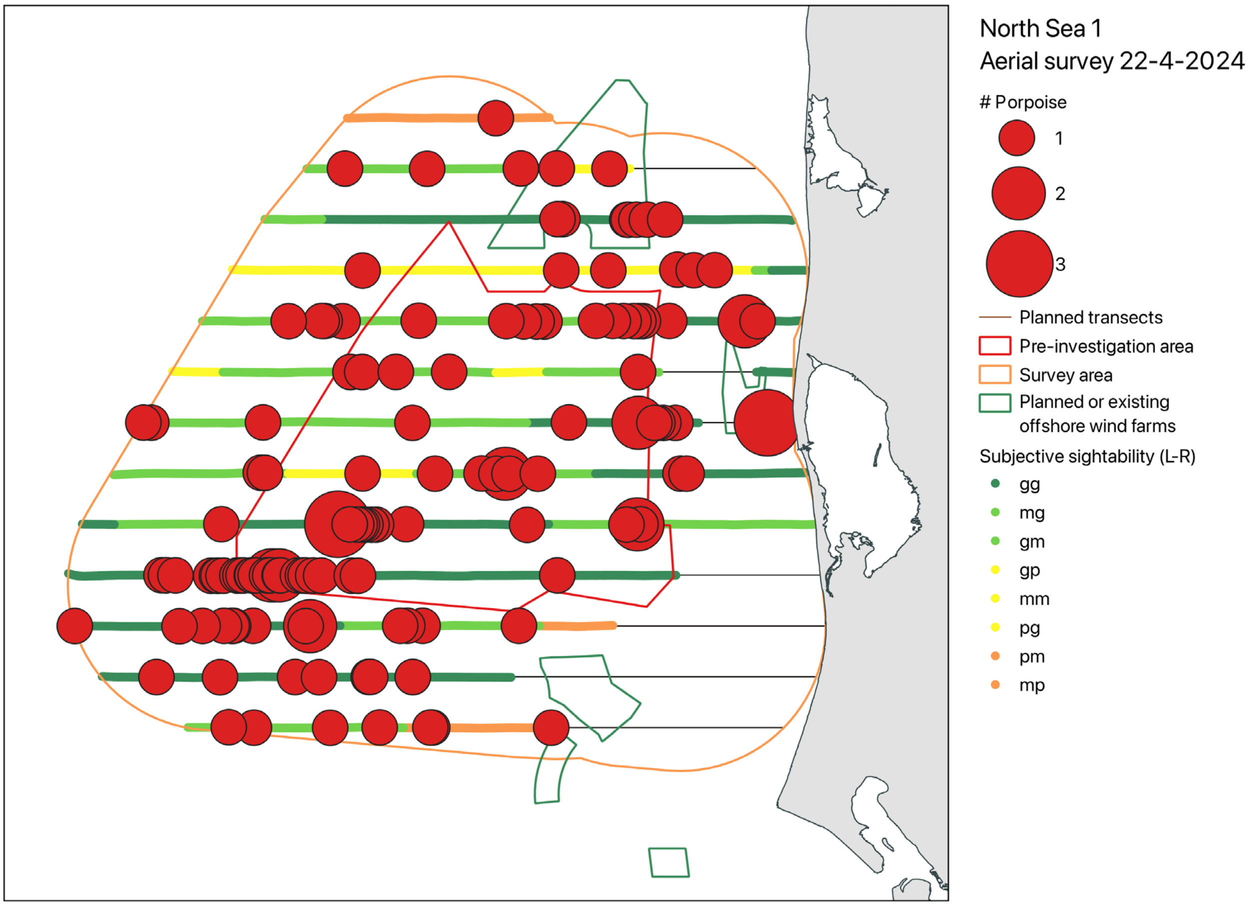


Figure 4-2-4 Harbour porpoise observations during the aerial survey on the 22nd of April 2024. The size of the dots indicates the group size at each observation. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, p=poor).

Aerial harbour porpoise survey 24th of June

During the survey the 24th June 2024, all transects were covered and only the parts over Horns Rev 3 wind farm were omitted since we had to change altitude to fly above the turbines. All effort were conducted in Beaufort Sea

State 1-2. The subjectively assessed sightability for each observer is displayed in Figure 4-2-5. Here, 86% of the effort was conducted in either good or moderate conditions, which indicates good conditions.

In total, 93 adult harbour porpoises and 13 calves were observed resulting in a mother/calf ratio of 12% (Table 4-2-2). The harbour porpoise observations were distributed across the aerial survey area but with few observation in the coastal zone (0-20 km from land). The abundance of harbour porpoises in the survey area was estimated to 6074 harbour porpoises (95% CI = 3818–9326; CV = 0.22). The average density was 0.80 individuals/km² (95% CI = 0.50–1.22).

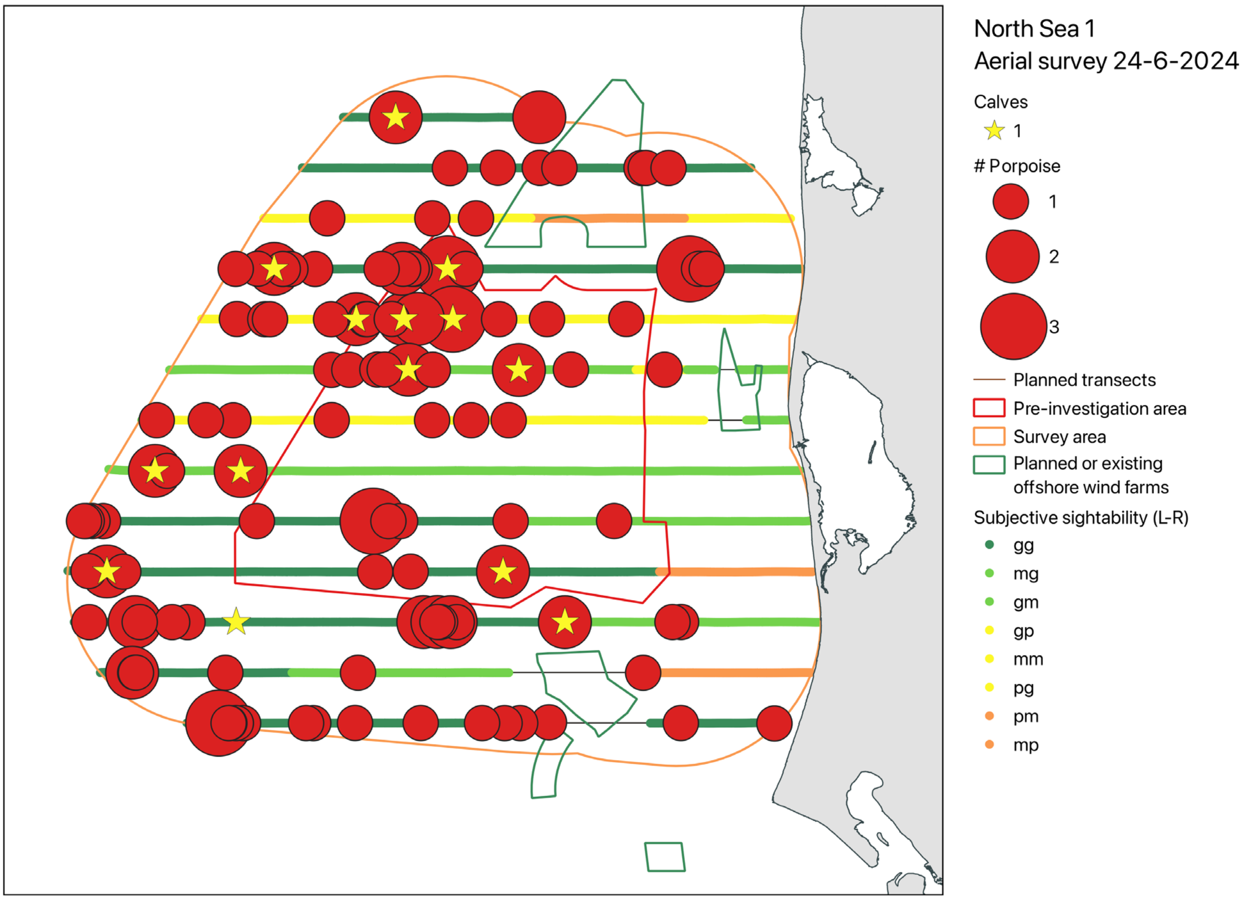


Figure 4-2-5: Harbour porpoise observations during the aerial survey on the 24th of June 2024. The size of the dots indicates the group size at each observation. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, p=poor).

Aerial harbour porpoise survey 19th of July

During the 19th July 2024 survey, 80% of transects were covered in Sea State 1 og 2. The subjectively assessed sightability for each observer is displayed in Figure 4-2-6. Here, 91% of the effort was conducted in either good or moderate conditions.

During this survey, 105 harbour porpoises were observed in total and 12 of these were calves, which gave a mother-calf pair ratio of 14% (Table 4-2-2). The observations were mainly distributed in the southeastern half of the survey area i.e. very different from the June survey were there were few observations near the coast.

The abundance of harbour porpoises in the survey area was estimated to 6139 harbour porpoises (95% CI = 5281–12,946; CV = 0.23) with a density of 1.07 individuals/km² (95% CI = 0.69–1.70) (Table 4-2-2).

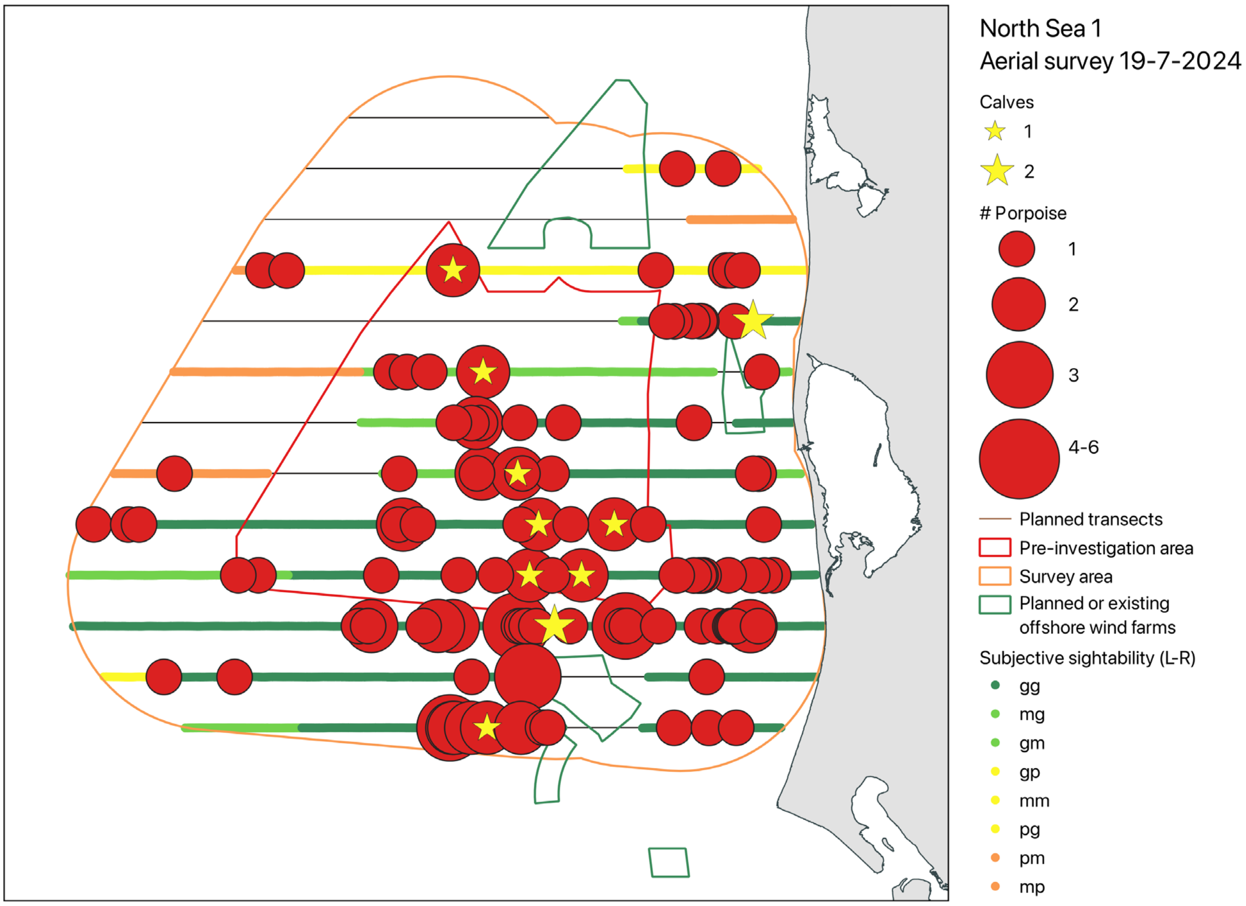


Figure 4-2-6: Harbour porpoise observations during the aerial survey on the 19th of July 2024. The size of the dots indicates the group size at each observation. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, p=poor).

Aerial harbour porpoise survey 4th of October

During the 4th of October 2024 survey, the survey was limited by the weather because the time with sufficient daylight was short and the wind and sea were only sufficiently low for a small window. However, since the survey programme had been on standby for good weather since September 1, it was decided to proceed with the survey, but to cut off every third transect to save time. This naturally resulted in the lowest effort in 2024 as well as the highest CV (Table 4-2-2). 85% of transects were covered in Sea State 1 og 2. The subjectively assessed sightability for each observer is displayed in Figure 4-2-7. Here, 88% of the effort was conducted in either good or moderate conditions.

During this survey, 38 harbour porpoises were observed in total and 3 of these were calves, which gave a mother-calf pair ratio of 9% (Table 4-2-2). The observations were mainly distributed in the southern half of the survey area.

The abundance of harbour porpoises in the survey area was estimated to 3012 harbour porpoises (95% CI = 1688–7129; CV = 0.34) with a density of 0.54 individuals/km² (95% CI = 0.22–0.93) (Table 4-2-2). This is the lowest abundance estimated in 2024. The calculations were corrected for the lower effort (which often result in higher variability=CV and larger confidence intervals) so this is not the reason.

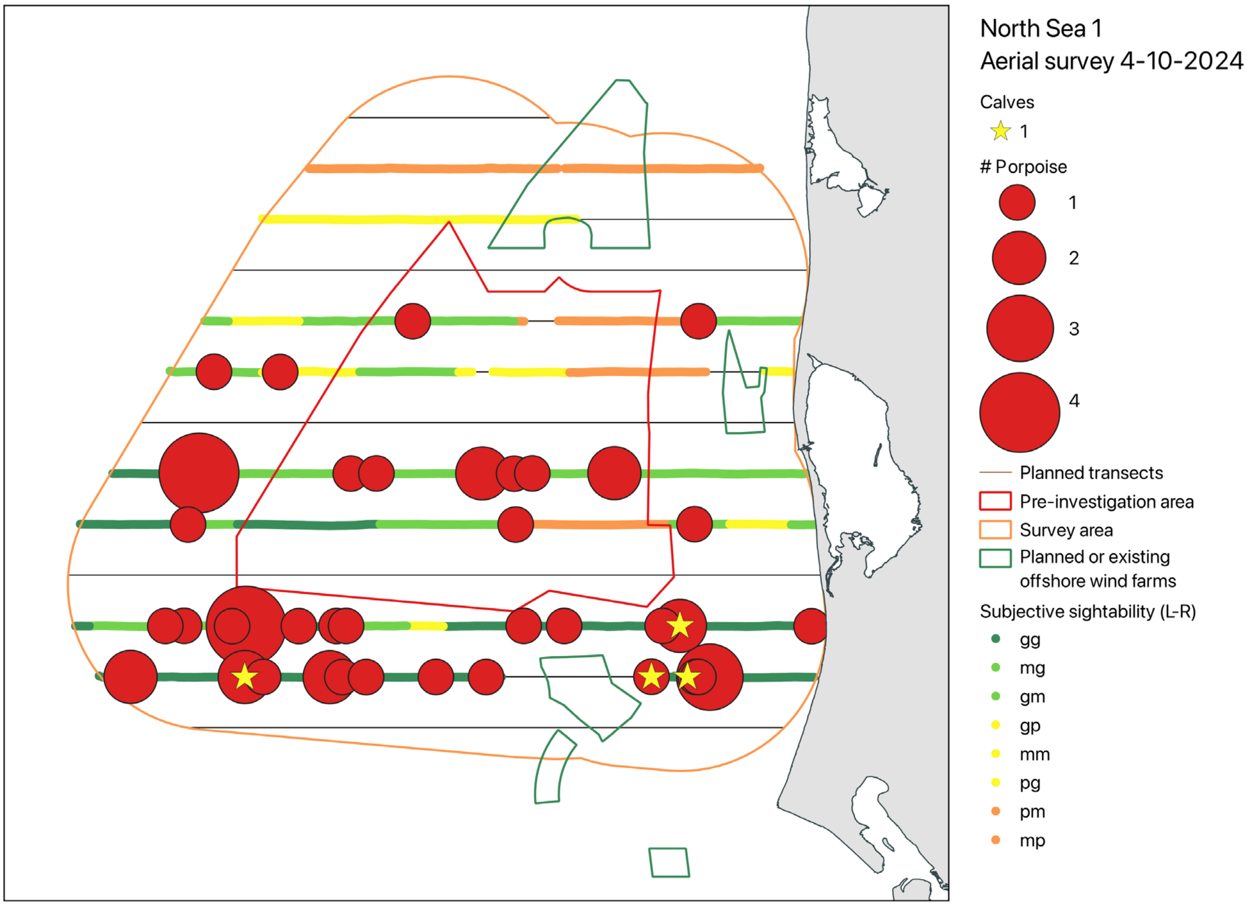


Figure 4-2-7: Harbour porpoise observations during the aerial survey on the 4th of October 2024. The size of the dots indicates the group size at each observation. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, p=poor).

Aerial harbour porpoise survey 7th of November

During the 7th of November 2024 survey, clouds in the northwestern corner of the survey area and high turbidity in the water near the coast in the southeastern area, resulted in parts of these transects not being covered. Furthermore, due to short daylight and some wind, only 66% of transects were covered in Sea State 1 and 2. The subjectively assessed sightability for each observer is displayed in Figure 4-2-8. Here, 95% of the effort was conducted in either good or moderate conditions.

During this survey, 53 harbour porpoises were observed in total and 6 of these were calves, which gave a mother-calf pair ratio of 13% (Table 4-2-2). The observations were distributed throughout the survey area.

The abundance of harbour porpoises in the survey area was estimated to 4474 harbour porpoises (95% CI = 3080–6604; CV = 0.20) with a density of 0.59 individuals/km² (95% CI = 0.40–0.87) (Table 4-2-2).

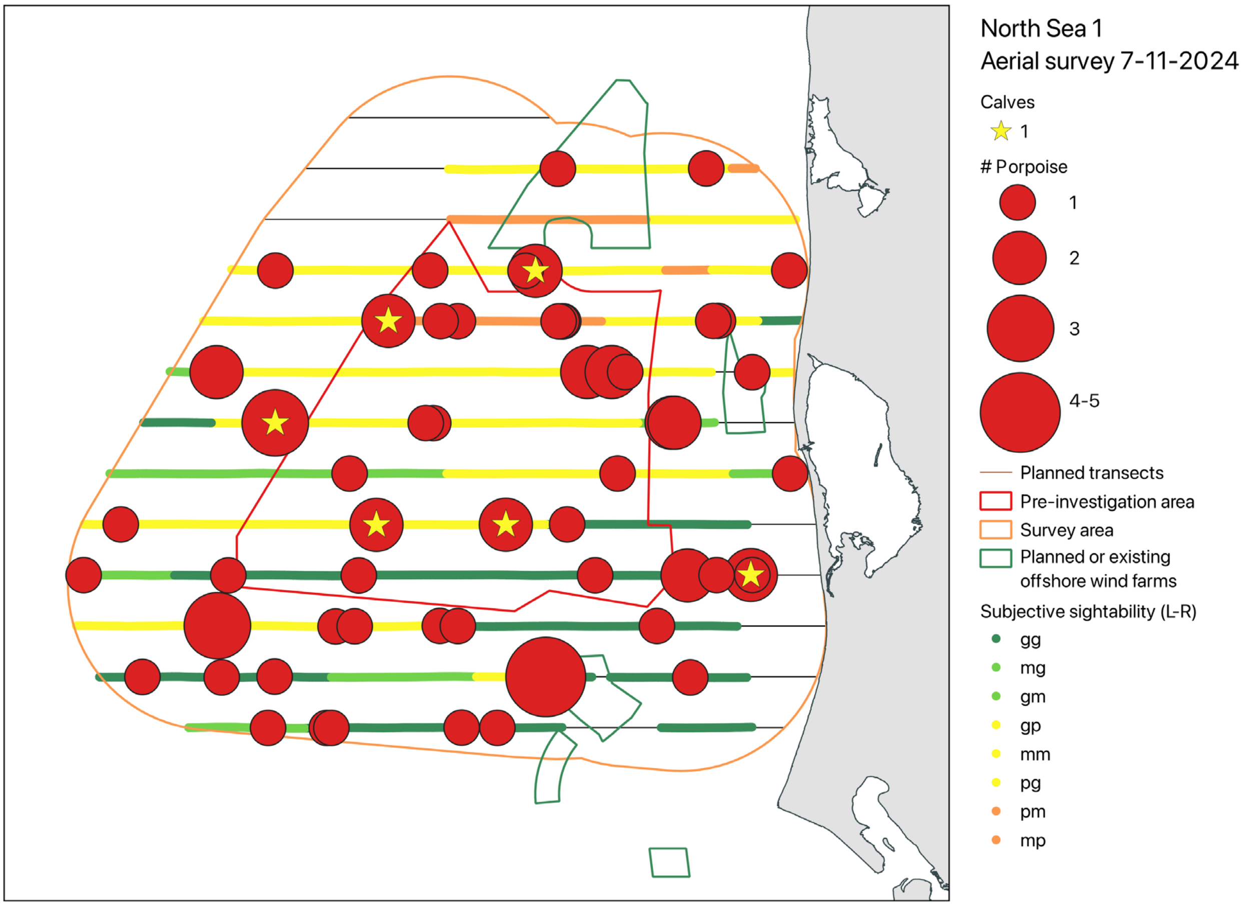


Figure 4-2-8: Harbour porpoise observations during the aerial survey on the 7th of November 2024. The size of the dots indicates the group size at each observation. The observer assessed sightability is indicated in colours from green to red for each observer side of the plane (g=good, m=moderate, p=poor).

4.2.3 Conclusion aerial harbour porpoise surveys

The results of the eight surveys conducted during 2023 and 2024 indicate that the number of harbour porpoises in the area vary across seasons and year with an average across surveys around 7250 individuals in the area and a density of 1,00 individuals/km² (Figure 4-2-9). These numbers are "inflated" by the June 2023 survey, where the hitherto unseen number of porpoises were observed resulting in a density of 2.91 ind./km² and an abundance of 22,206 harbour porpoises. On that particular survey, the water was "boiling" with fish schools and both minke whales and white-beaked dolphins were observed in the survey area, clearly following the fish into the area. Thus, based on these eight aerial surveys, it is concluded that harbour porpoise will at most times be present the North Sea I survey area at varying densities (between 0.53 and 1.07 individuals per km2) but at some particular periods follow the prey into the area and therefore occur in significantly higher densities.

During the summer surveys in 2023 and 2024, calf rations were found between 10% and 21%. A study in German waters near Sylt (Sonntag et al., 1999) described a calving area based on two aerial surveys one year apart where they found a calf ratio of 10–17%. This area was confirmed as breeding area in later surveys (Gilles et al., 2009; Gilles et al., 2011; Gilles et al., 2016). Consequently, it is likely that the North Sea I survey area also should be categorized as a breeding area for harbour porpoises.

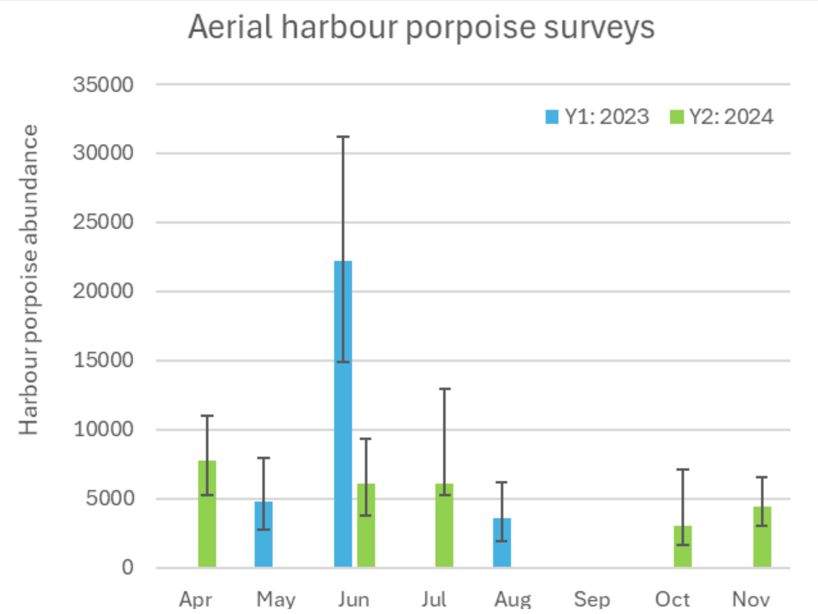


Figure 4-2-9: Comparison of the estimated abundance within the NSI Survey area during the eight aerial harbour porpoise surveys conducted in 2023 and 2024 during the NSI pre-investigation monitoring program. For details on results see Table 4-2-2.

4.3 Aerial surveys other cetaceans

Other marine mammals were observed during the marine mammal surveys, but also during the bird surveys in both 2023 and 2024. Altogether, six bird surveys and three marine mammal surveys were conducted between April 2023 and March 2024 as well as eight bird surveys and five marine mammal surveys from April 2024 to March 2025, providing data on other cetaceans in the area. In Y1 a total of 7 minke whales, 10 white beaked dolphins of which one was a calf, 2 common dolphins and 2 unidentified whales were observed (Figure 4-3-1). Some of the whales were observed “off effort” i.e. not on the planned transects, but within few kilometres off the survey area. They have been included here since they are so close to the survey area that it is likely that they would also use the survey area.

The number of observations of white-beaked dolphins confirm that this species utilises the area regularly during summer and perhaps more sporadically during winter where only 1 white-beaked dolphin was observed (November). However, since the majority of surveys were conducted in the spring and summer, more surveys are needed to confirm this. The seven minke whales were observed between March and July 2023 (1 in March and 6 in June–July) suggesting that this is mainly a Spring-Summer habitat for minke whales. For further information on whales see chapter 4.1.2 on wideband recordings of cetaceans. For the bird surveys, the plane was kept at a survey height of 200 feet vs 600 feet during marine mammal surveys. For larger whales and dolphins, where the main aim is to note whether they are present in the area, the results from both types of surveys are usable.

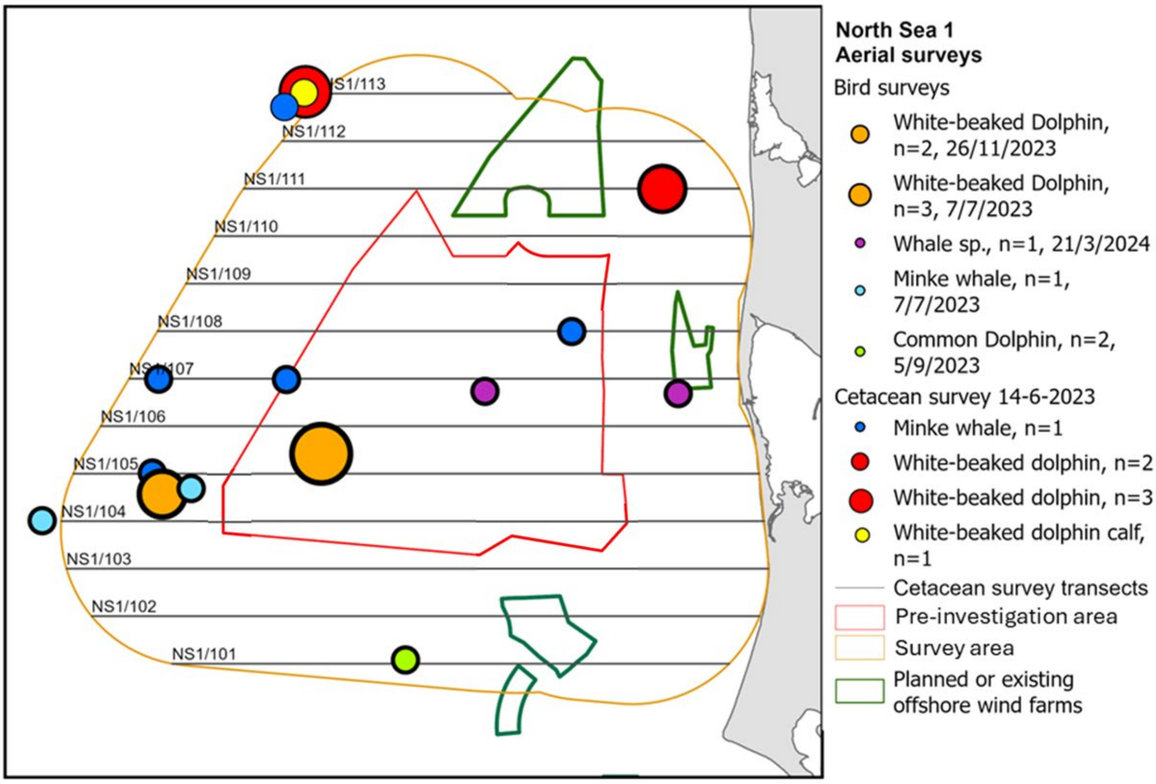


Figure 4-3-1: Observations of cetaceans other than harbour porpoises during bird and cetacean surveys from April 2023 to March 2024.

In Y2, fewer whales were observed (Figure 4-3-2). Throughout the eight bird surveys (conducted on 17-04-2024, 12-07-2024, 18-9-2024, 07-11-2024, 12-12-2024, 1-2-2024, 14-02-2025 and 19-03-2025), only two white-beaked dolphins were observed (in April 2024) and no other dolphin or whale species was seen. Similarly, the only species observed during the cetacean surveys were white-beaked dolphins. Here, five individuals were observed including one calf during the June survey. All observations were located in or near the 20 km buffer zone around the NSI project area.

It is unclear why the cetacean observations in Y1 and Y2 were so different, but it should be kept in mind that in general there were few observations. The results do however agree with the acoustic detections of the six broad-band recording stations in Y2, having less detections than in Y1 (Section 4.1.2.2). The most likely explanation for the observed differences is that it is stochastic as there are too few observations from too few surveys to draw general conclusions from.

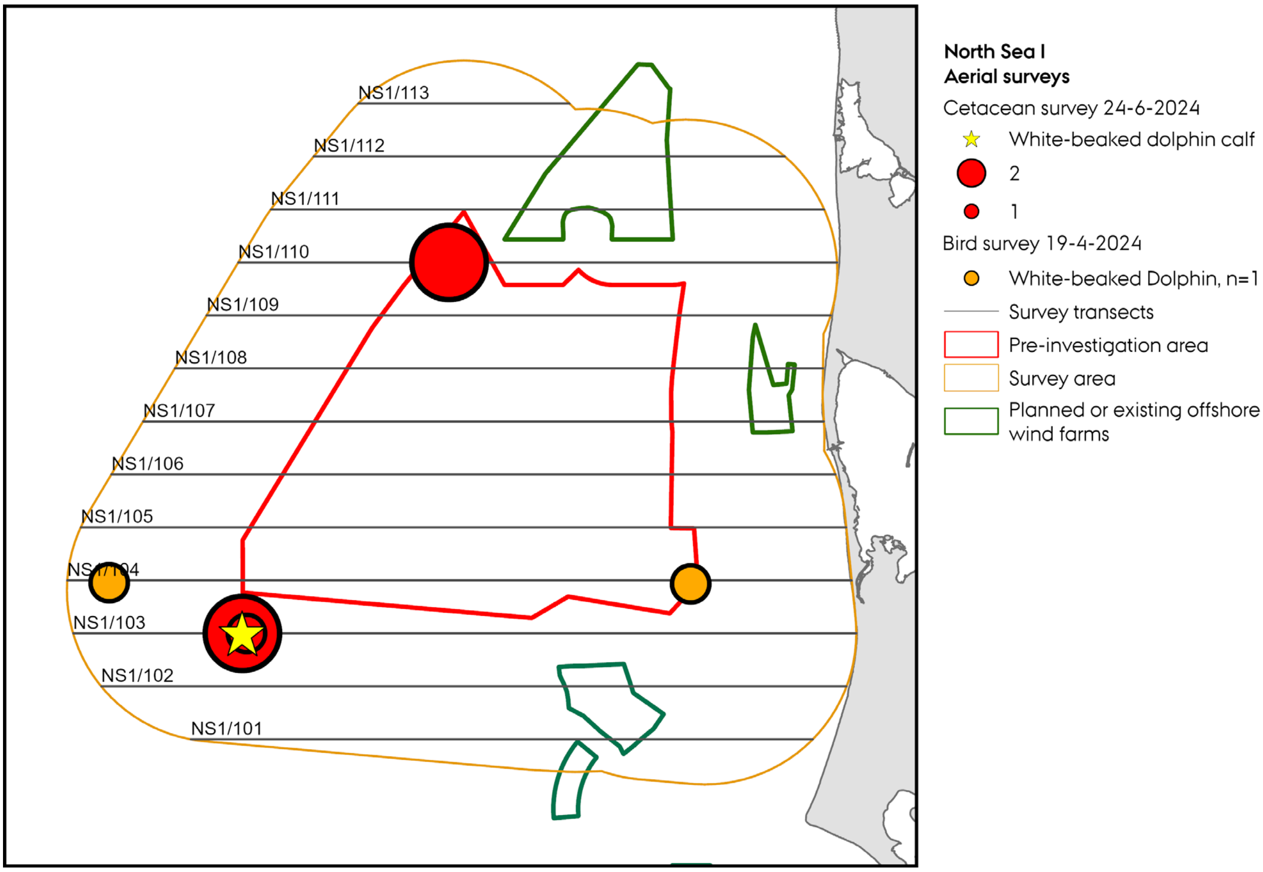


Figure 4-3-2: Observations of cetaceans other than harbour porpoises during bird and cetacean surveys from April 2024 to March 2025.

4.4 Underwater noise

Monitoring of underwater noise follows a stepwise pattern, where the first focus is the collection of baseline data on ambient noise and noise from turbines in operation, to be used as input for soundscape modelling; second is collection of high-resolution mapping of harbour porpoise presence around individual turbines and the soundscape modelling itself; third is the overlay of soundscape maps and fine-scale data with harbour porpoise abundance mapping.

4.4.1 Noise monitoring

Calibrated and quality-assured decidecade band levels were obtained from six monitoring stations inside and around the project area (table 4-6). Noise data presented were used to calibrate the Quiet Oceans noise exposure maps (discussed in detail in section 4.4.4). Data included in this analysis is based on data availability when Quiet Oceans required calibration data for their model. Overall statistics of the noise spectra are shown in Figure 4-4-1, which will be used in calibrating/validating the noise propagation model and for future impact assessments. The median spectra (purple lines in Figure 4-4-1) have pronounced peaks between 50 and 125 Hz, consistent with spectra from areas with high levels of ship noise. The sharp decrease for frequencies below 50 Hz is caused by the shallow waters, as the long wavelengths of the lower frequencies cannot physically propagate in shallow water. The apparent increase in noise above 10 kHz, as seen the median spectra intersects with the lower noise level, is due to the self-noise of the sound recorders, This shows that the recordings are limited at lower sound levels in the upper frequencies by the electronic noise in the recorder, and not by the ambient noise. This means that lower ambient noise conditions than those indicated in the figure likely did occur above 10 kHz, but could not be recorded due to self-noise.

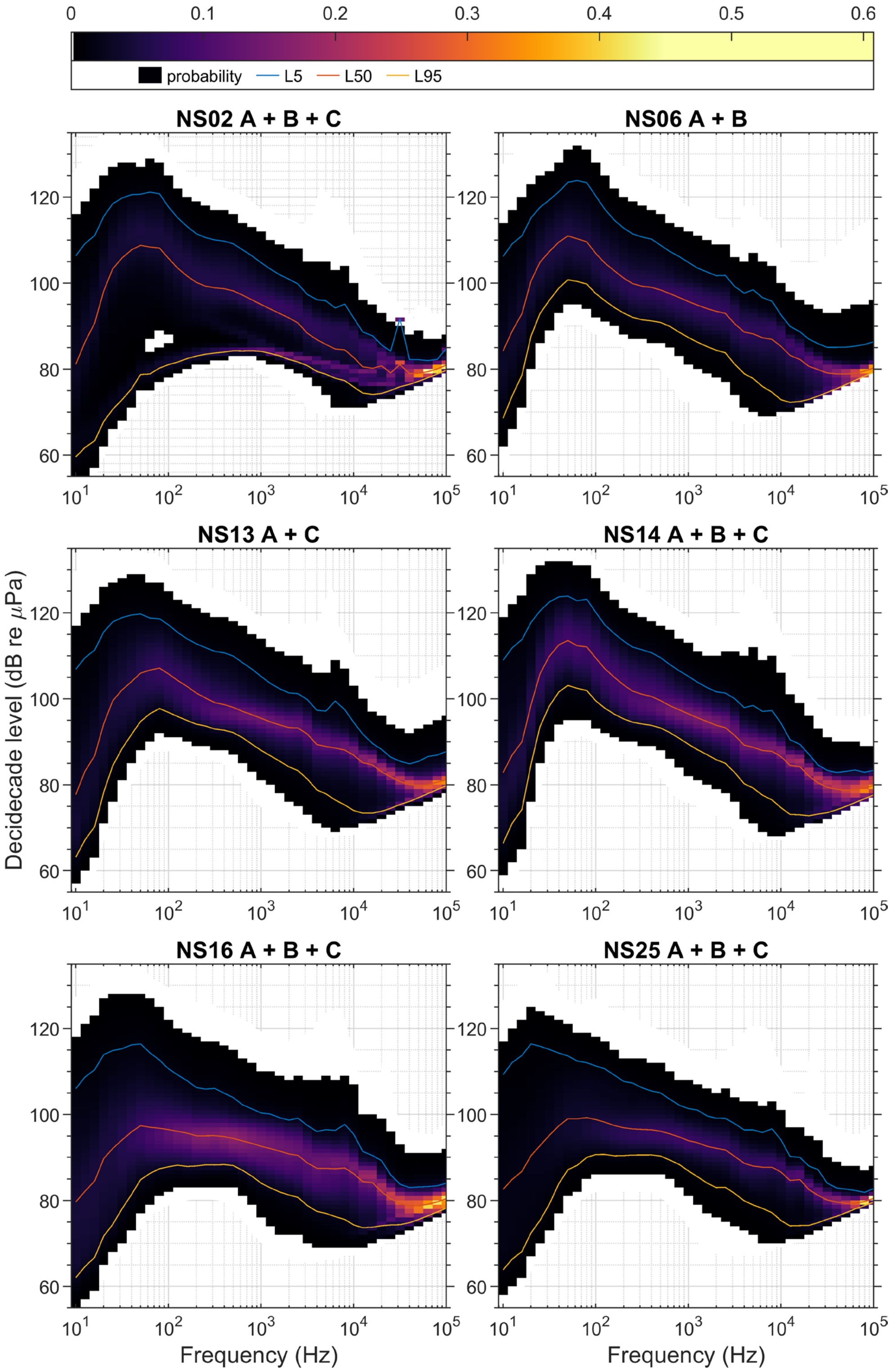


Figure 4-4-1: Statistical representation of decidecade frequency spectra of the ambient noise recordings from the six dedicated noise monitoring stations from three deployment periods: A (April-July 2023), B (August – October 2023) and C (December 2023 – February 2024). Data included in this figure was used to calibrate the Quiet Oceans Noise Exposure Maps. Distributions were created from sequential 1 second averages of the noise level within each decidecade band. The colour coding shows the probability of occurrence (density function) of the different sound pressure levels within each frequency band, with lighter colours representing higher probability of occurrence. The red line represents the median (L_{50}), yellow and blue line the lower and upper 5^{th} percentiles, L_{95} and L_5, respectively.

Results from three selected frequency bands are shown in Figure 4-4-2 (63 Hz), Figure 4-4-3 (125 Hz) and Figure 4-4-4 (2 kHz) as detailed examples. The three bands (63 Hz, 125 Hz and 2 kHz), are recommended by the HELCOM manual for noise monitoring (HELCOM, 2018). The figures indicate monthly medians and selected percentiles for the months with available data for each station. Levels are generally stable across stations and time, with a few exceptions. The possible causes behind exceptions, such as the generally lower levels on station NS02 during deployment C have not been investigated.

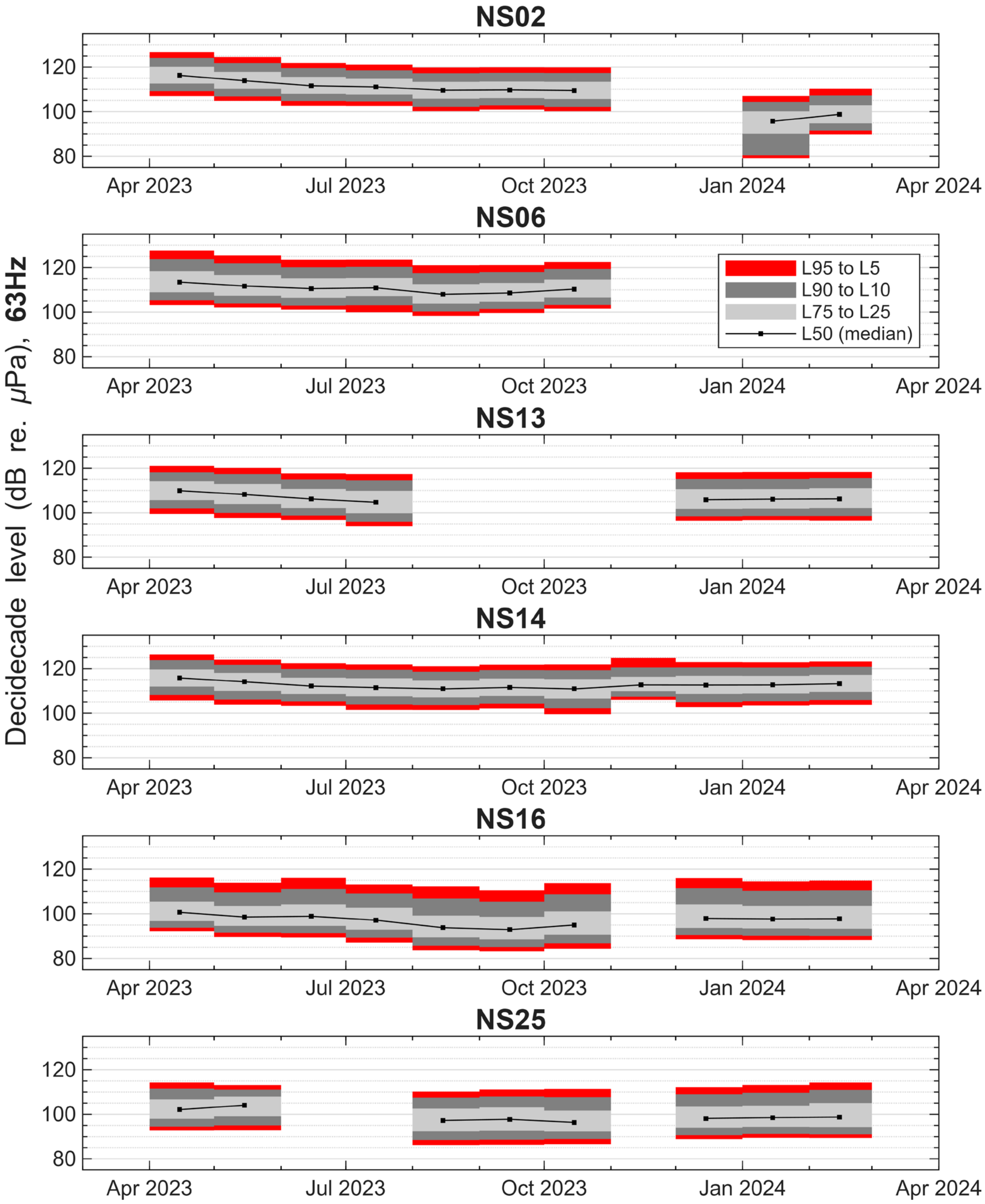


Figure 4-4-2: Monthly statistics of the 63 Hz decidecade band from the noise recordings at the six dedicated monitoring stations from three deployment periods: A (April-July 2023), B (August – October 2023) and C (December 2023 – February 2024). Data included in this figure was used to calibrate the Quiet Oceans Noise Exposure Maps. For each month selected exceedance levels are indicated by the coloured bands. The solid line indicates the monthly median (L_{50}).

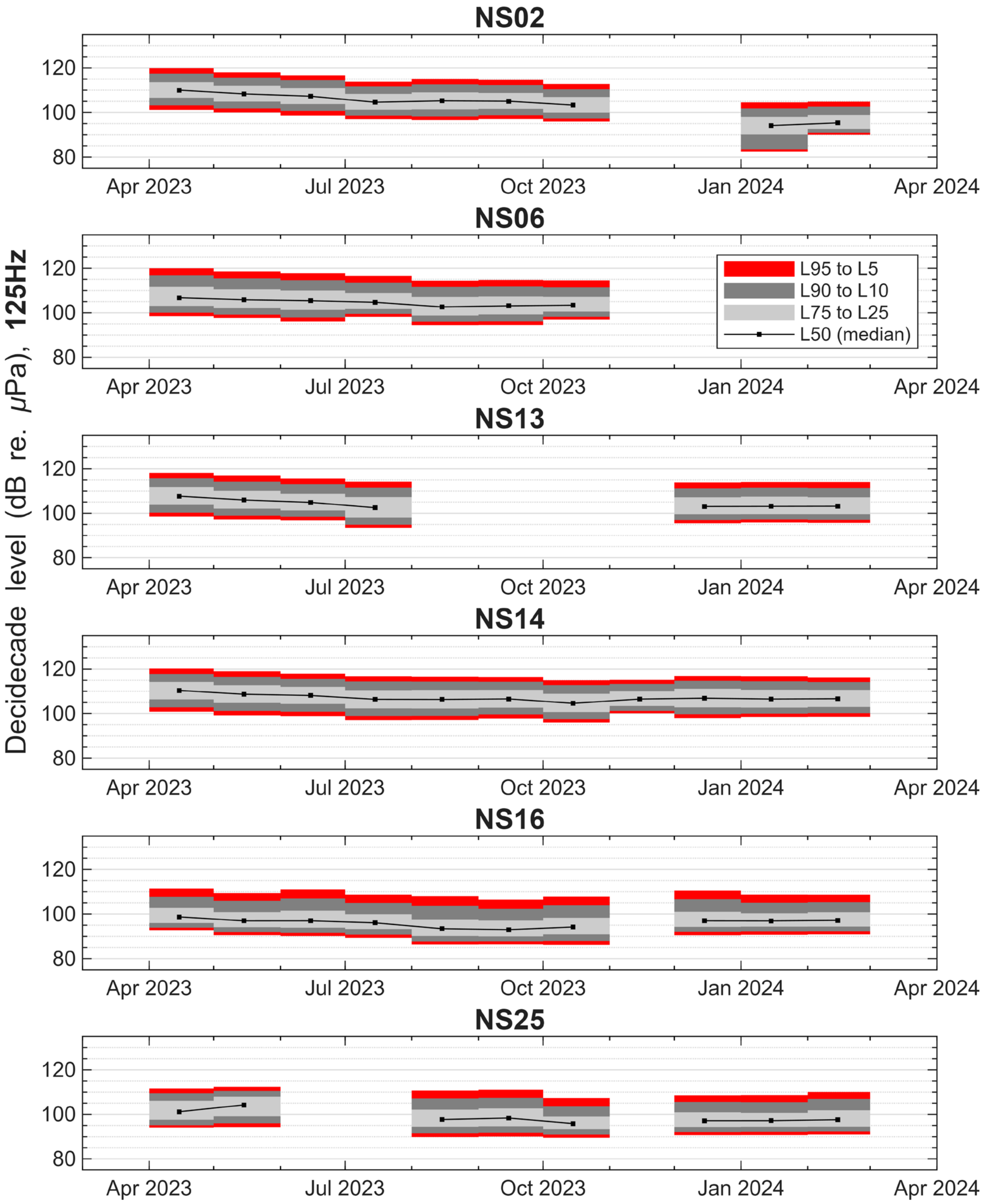


Figure 4-4-3: Monthly statistics of the 125 Hz decidecade band from the noise recordings at the six dedicated monitoring stations from three deployment periods: A (April-July 2023), B (August – October 2023) and C (December 2023 – February 2024). Data included in this figure was used to calibrate the Quiet Oceans Noise Exposure Maps. For each month selected exceedance levels are indicated by the coloured bands. The solid line indicates the monthly median (L_{50}).

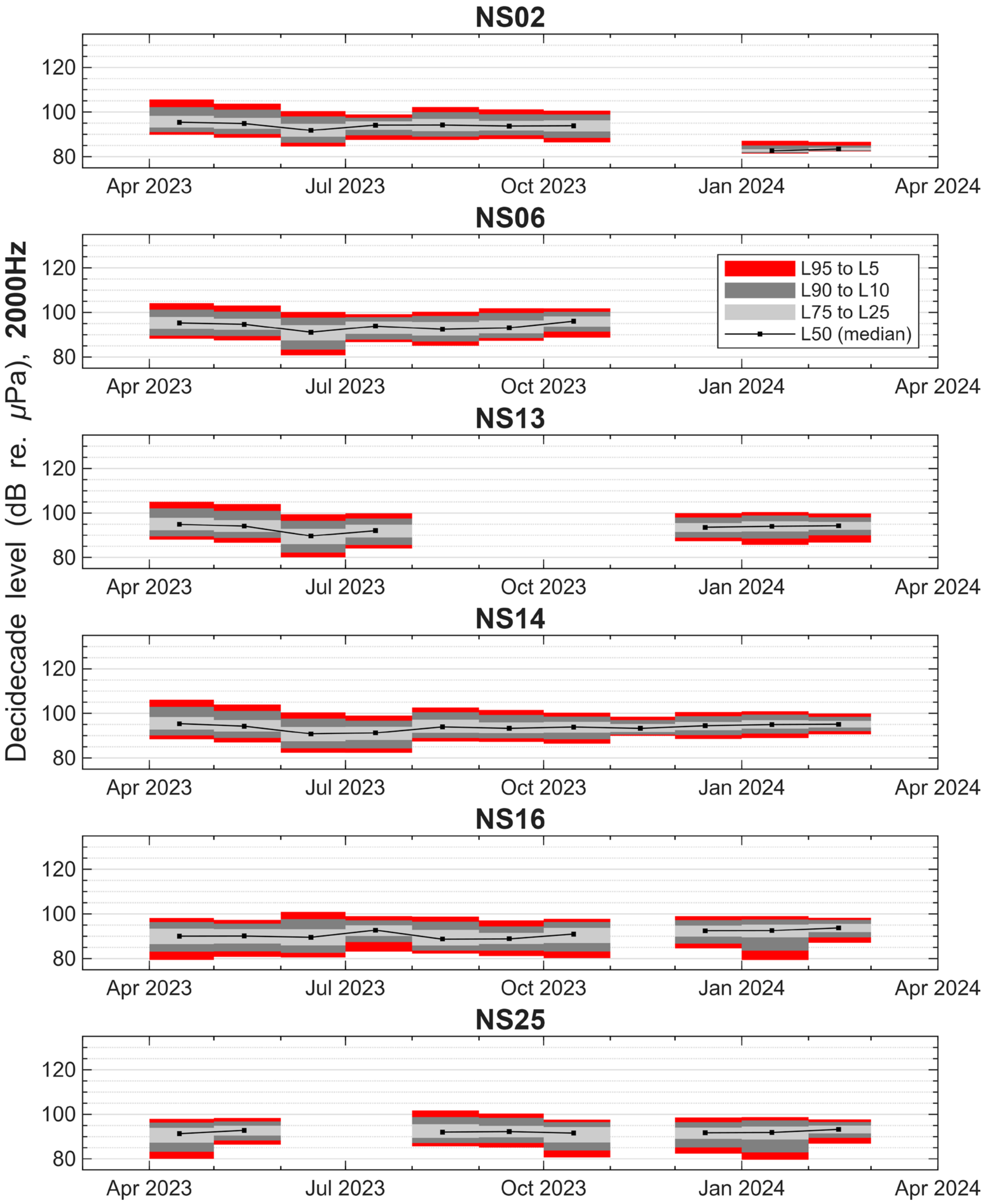


Figure 4-4-4: *Monthly statistics of the 2 kHz decidecade band from the noise recordings at the six dedicated monitoring stations from three deployment periods: A (April-July 2023), B (August – October 2023) and C (December 2023 – February 2024). Data included in this figure was used to calibrate the Quiet Oceans Noise Exposure Maps. For each month selected exceedance levels are indicated by the coloured bands. The solid line indicates the monthly median (L_{50}).*

4.4.2 Turbine noise

Noise recorders were placed close to individual turbines in two existing wind farms, in order to measure the noise from operational turbines. The turbines were selected to represent the largest turbines in operation in Danish waters and of two different types: one with gear box (Horns Reef 3) and one with direct drive technology (Kriegers Flak). Deployment and data collection are indicated in Table 4-4-1. Example noise profiles illustrating prominent noise bands are shown for each location in Figures 4-4-5 and 4-4-6.

Table 4-4-1: Obtained recordings of turbine operational noise. The difference in recording distance between the two sites adds a small bias to the results, with the recordings at Kriegers Flak expected to be a few dB higher than the recordings at Horns Reef 3, simply because the recorder was closer. This difference is difficult to correct for without proper modelling of sound propagation but is not expected to exceed 4 dB and likely less than this[3].

Wind farm	Turbine ID	Latitude (Decimal degrees)	Longitude (Decimal degrees)	Distance from turbine	Turbine type	Nominal capacity	Data collection period
Kriegers Flak	10O	55.0197	12.8180	98 m	Siemens Gamesa SG 8.0-167 DD	8.4 MW	2023/06/20– 2023/09/26
Horns Reef 3	F08	55.6566	7.7040	152 m	Vestas V164	8.3 MW	2023/11/26– 2024/01/09

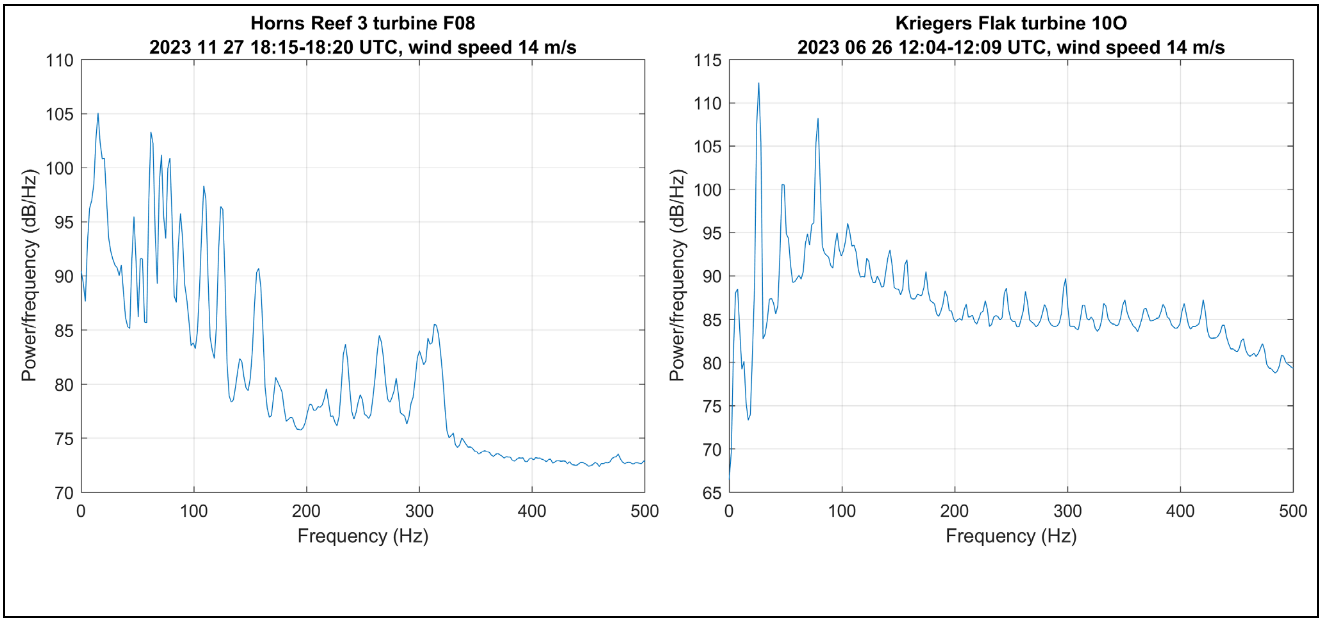


Figure 4-4-5: Power density spectra (Welch average) of the 5-minute sample recordings shown in Figure 4-4-6. Down sampled to 1920 Hz sample rate from the original recording at 192 kHz sample rate. FFT size 1024, Hann window, 50% overlap, analysis bandwidth 1.9 Hz.

Noise recordings were analyzed in decidecade bands from 10 Hz to 80 kHz, with a 10-minute time resolution ($L_{p,ddec,10min}$). This time resolution was selected to match the time resolution of wind speed data, obtained from the operator of the wind farms (Vattenfall) as 10-minute averages. The wind data allowed the analysis to be broken up by wind speed in bins of 1 m/s from 0 m/s to 25 m/s. For each wind speed interval, the decidecade spectrum was computed. Examples are shown in Figure 4-4-7. Figure 4-4-8 shows a waterfall plot of all frequency spectra, broken up by wind speed classes. Individual relationships between wind speed and decidecade level are shown for the lower frequency bands and selected higher frequency bands in Figure 4-4-9 and Figure 4-4-10.

[3] For a point source in a free field, the sound pressure level 98 m from the source is expected to be 3.8 dB higher than at 156 m ($= 20\log_{10}\left(\frac{156}{98}\right)$), but in practice it is likely less, due to the reflections from sea surface and sea floor. Note also that the measurement precision of the instruments is ± 1 dB.

Recordings from Kriegers Flak were dominated by ship noise from the nearby shipping lane, visible in the spectra in the bands between 63 Hz and 1000 Hz and identifiable as ship noise because levels are unaffected by wind speed. Clearly visible in the recordings are also two strong tonal peaks in the 25 Hz and 80 Hz bands, respectively. These peaks are most pronounced at wind speeds above approximately 10 m/s. Below 10 m/s the frequency of the peaks appears variable, and they are absent at the lowest wind speeds, where the turbine is not rotating.

Recordings from the turbine at Horns Reef 3 are much less contaminated by ship noise, visible as a lower noise floor. Numerous and very variable peaks are present in the spectra below 500 Hz, attributable to the turbine and likely originating in the gear box. The dominant peaks increased in amplitude with increasing wind speed. Not enough measurements were available at wind speeds low enough (0–1 m/s) for the turbine to be stopped (Figure 4-4-7).

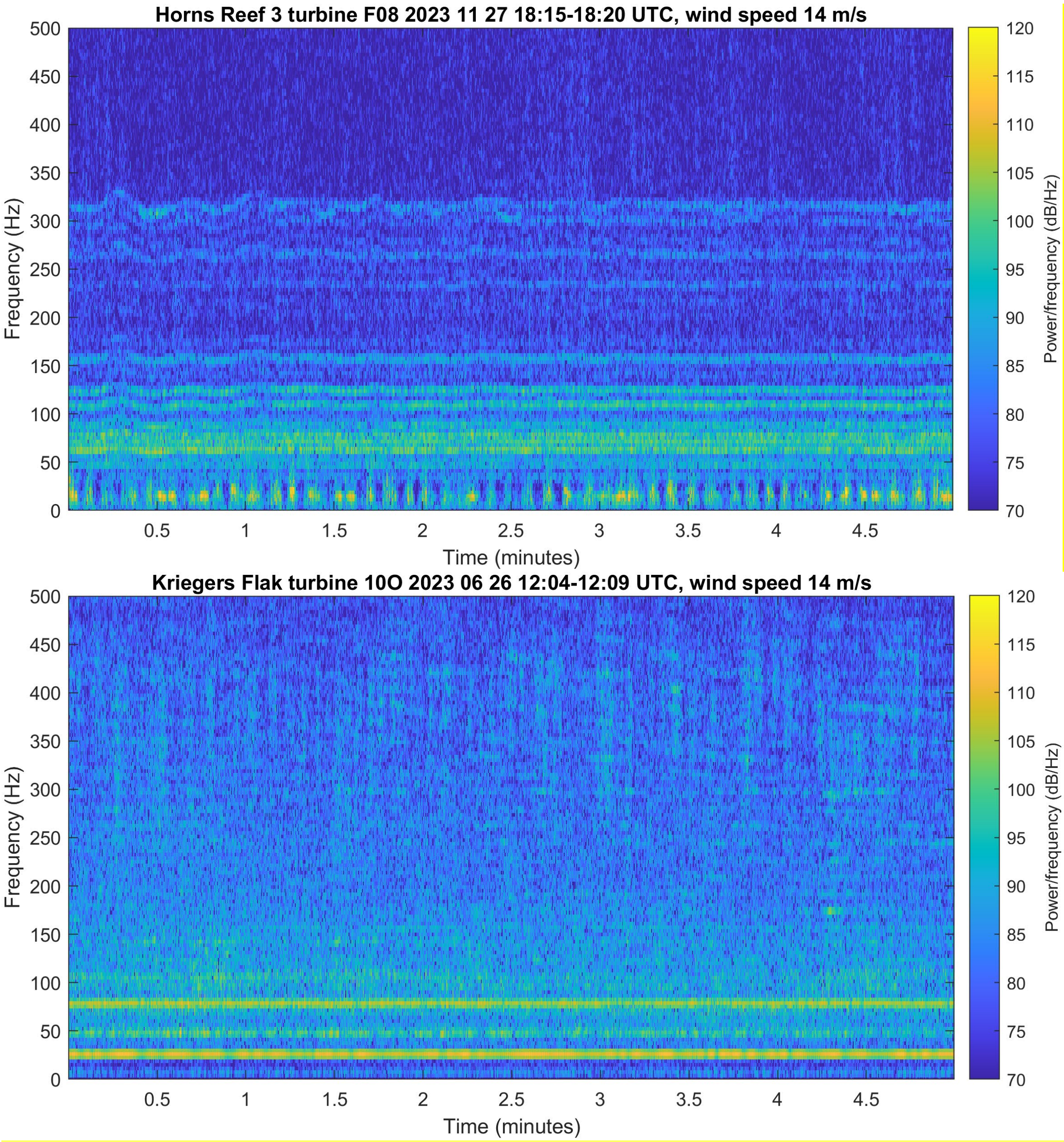


Figure 4-4-6: Spectrograms of 5-minute samples of noise recordings from a turbine with gearbox (Horns Reef 3, Vestas V164, 8.3 MW) and a turbine with direct drive (Siemens Gamesa 8.0 167-DD, 8.4 MW), both recorded at a wind speed of 14 m/s (10 minute average) and at a distance of approximately 100 m from the foundation. Down-sampled to 1920 Hz sample rate from the original recording at 192 kHz sample rate. FFT size 512, overlap 87.5%, Hann window.

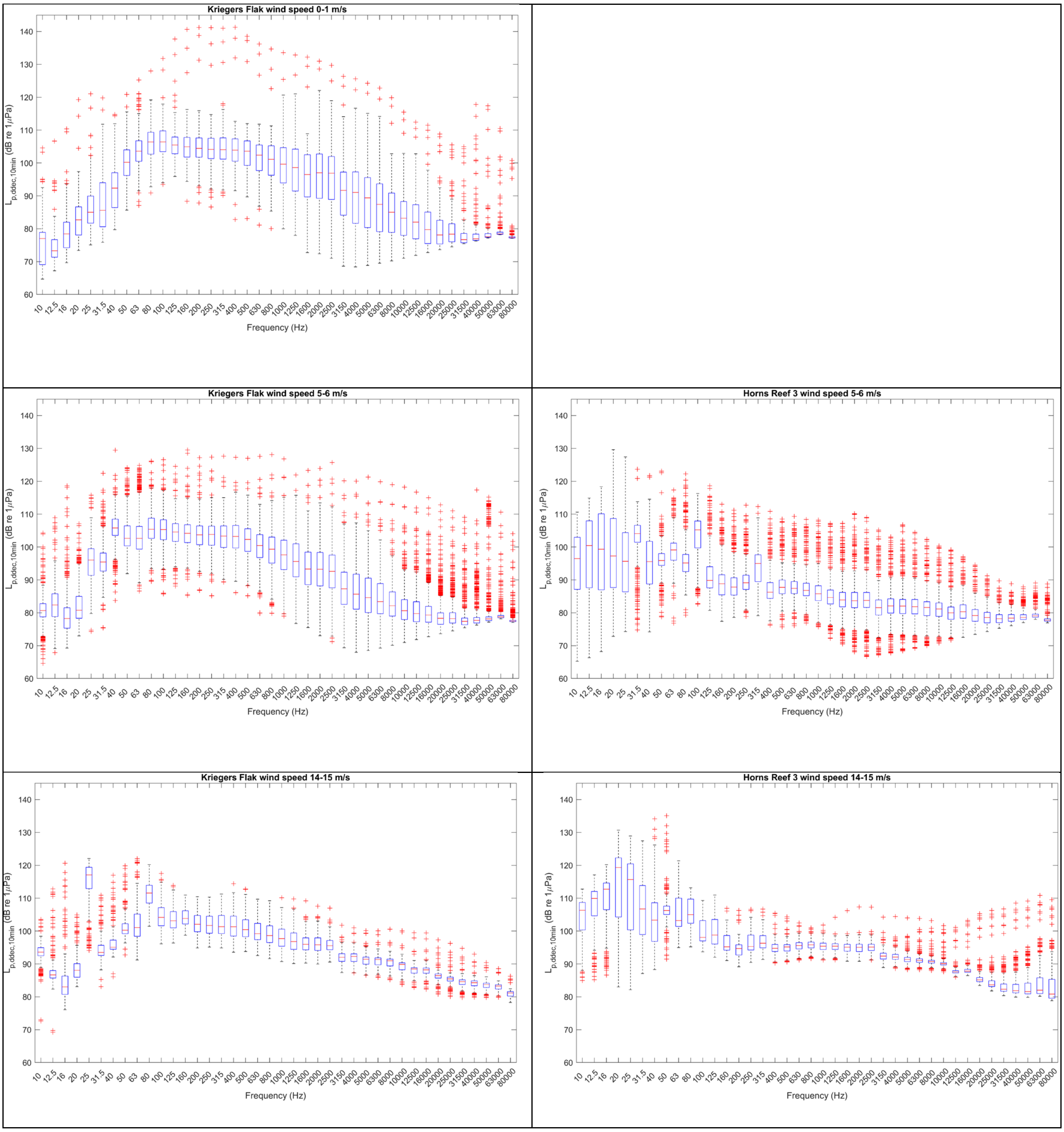


Figure 4-4-7: Left: Decidecade frequency spectra of wind turbine noise recorded from an 8.4 MW direct drive turbine at Kriegers Falk (left) at three different wind speeds. The top panel is the spectrum when the turbine is not turning, middle panel is at low wind speed, just above cut-in speed (when the blades start rotating and generating power) and bottom panel is at high wind speed, where the turbine is likely operating at full nominal capacity. Note the pronounced peaks at 25 Hz and 80 Hz in the turbine noise from Kriegers Flak at high wind speed. Right: Similar spectra for an 8.3 MW turbine with gear box in Horns Reef 3

offshore wind farm. Insufficient data were available for the lowest wind speeds. Note the generally elevated levels at the lowest frequencies (below 100 Hz) compared to the spectra from Kriegers Flak.

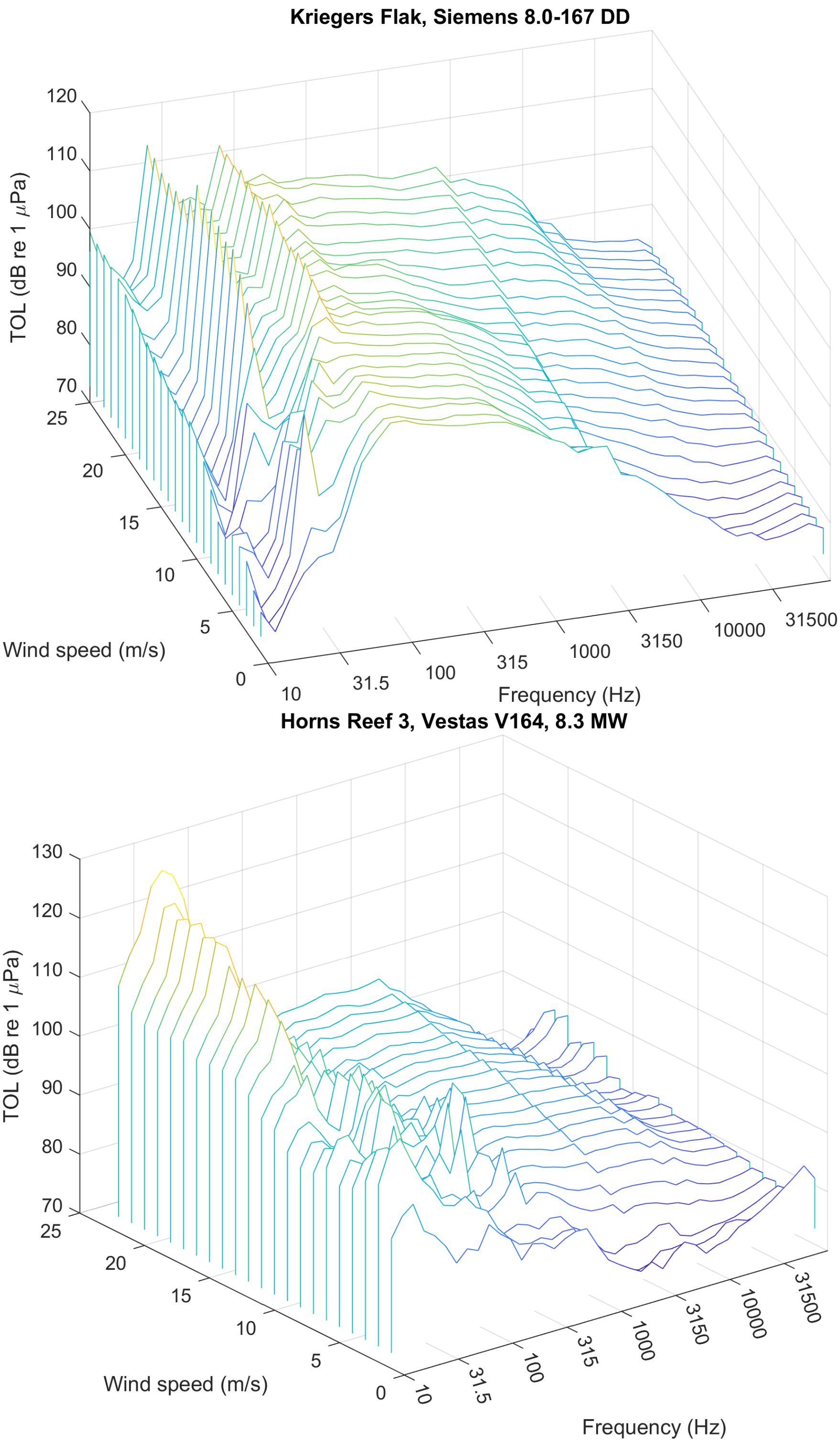


Figure 4-4-8: Top: Median decidecade (denoted as TOL) frequency spectra of wind turbine noise recorded from an 8.4 MW direct drive turbine at Kriegers Flak at different wind speeds. Note the peaks of the turbine noise at 25 Hz and 80 Hz, absent or variable at lowest wind speeds; the contribution from ships in the bands between 63 Hz and 1 kHz, unaffected by the increase in wind speed; and the increasing contribution of wind noise at higher wind speeds in the bands up to 10 kHz. Bottom: Median decidecade (denoted as TOL) frequency spectra of wind turbine noise recorded from an 8.3 MW turbine with gear box in Horns Reef 3 at different wind speeds. Note the variable peaks of the turbine noise at frequencies below 500 Hz, increasing with wind speed; and the increasing contribution of wind noise at frequencies up to 10 kHz.

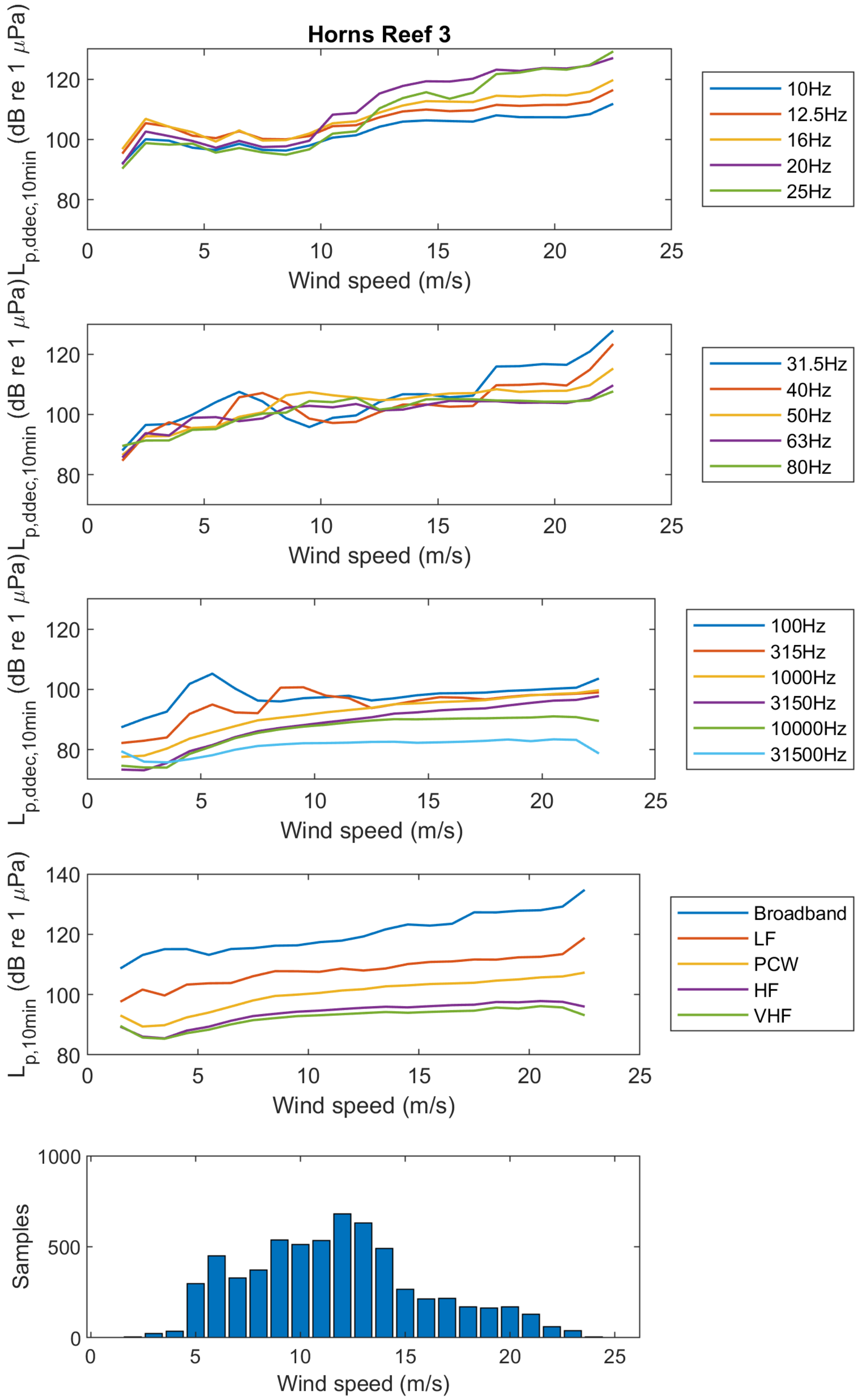


Figure 4-4-9: Relationship between wind speed and sound pressure level recorded from a Vestas V164-8.0 MW turbine with gearbox in Horns Reef 3. Top three subplots indicate decidecade levels in different frequency bands. Fourth subplot indicate the combined (total) sound pressure level at different wind speeds, given both as broadband (unweighted) and weighted sound pressure levels according to different functional hearing groups of marine mammals (LF: low-frequency cetaceans, PCW: phocid

carnivores in water, HF: high-frequency cetaceans, VHF: very high-frequency cetaceans, Southall et al. (2019)). Bottom bar graph indicates the number of 10-minute intervals available for each wind speed class.

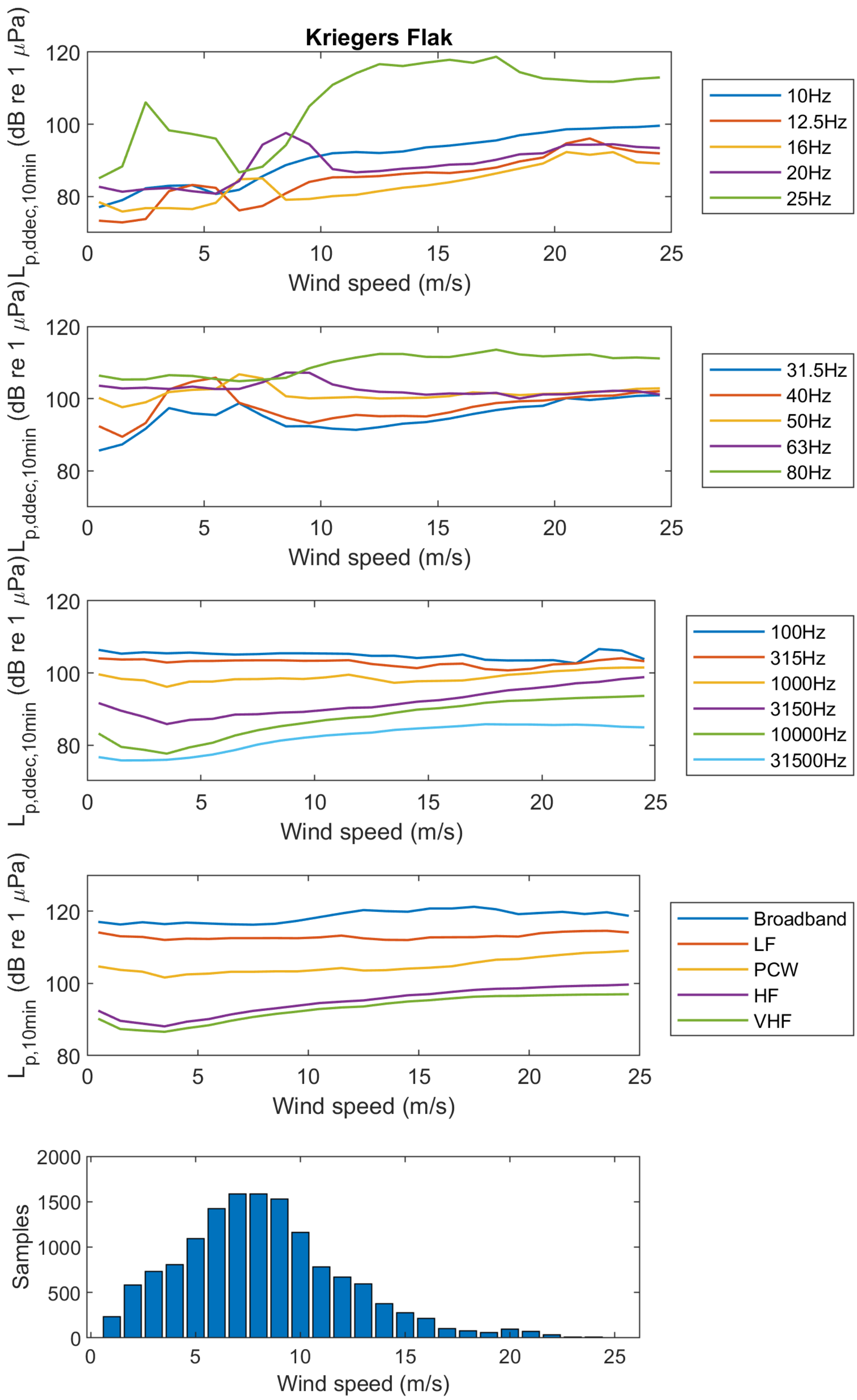


Figure 4-4-10: Relationship between wind speed and sound pressure level recorded from a Siemens-Gamesa 8.0-167 8.4 MW direct drive turbine at Kriegers Flak. Top three subplots indicate decidecade levels in different frequency bands. Fourth subplot

indicate the combined (total) sound pressure level at different wind speeds, given both as broadband (unweighted) and weighted sound pressure levels according to different functional hearing groups of marine mammals (LF: low-frequency cetaceans, PCW: phocid carnivores in water, HF: high-frequency cetaceans, VHF: very high-frequency cetaceans, Southall et al. (2019)). Bottom bar graph indicates the number of 10-minute intervals available for each wind speed class.

4.4.3 Harbour porpoise presence near operating turbines

4.4.3.1 4-channel arrays

The first deployment in 2023 resulted in about 24 hours of recording (recorder RTsys). While this proved that the general recording methodology worked, the amount of data collected was insufficient, and a second deployment with new recorders with higher endurance was conducted in 2024 (recorder ST4300) and again in 2025 (recorder ST640). Below are the results from the analysis of these recordings presented.

Harbour porpoise signals were found in recordings from both recorders during the March 2024 and January 2025 deployments and an overview is given in Figure 4-4-11. One of the selection criteria for including a minute as porpoise positive was that a click should be recorded on all of the four channels and with a signal-to-noise ratio (SNR) of all clicks of 10 dB or more. This is a stricter criterion than those used on the single-channel systems (C-PODs, F-PODs etc.), which may lead to lower detection rates. Nevertheless, the detection rates of 1-27% porpoise positive minutes (PPM) per day resemble the rates of up to 20% PPM per day reported from the F-PODs deployed inside the wind farm (Figure 4-4-12), but because the detection criteria are different, the detection rates cannot be compared directly between the 4-channel arrays and single channel recordings to for example conclude that porpoise densities are higher or lower in the immediate vicinity of the turbine location, where the 4-channel arrays were deployed.

Individual segments of porpoise clicks were identified in the recordings and bearings determined from the time-of-arrival differences between the clicks recorded on the four different hydrophones. The bearing estimates form fragmented line segments corresponding to the bearing to nearby harbour porpoises together with numerous outliers that are likely the result of imprecise detection times of low Signal-to-Noise Ratio (SNR) clicks or detections of reflections rather than the direct signals. One example of a recording with two sequences of harbour porpoise clicks, separated by about 3 seconds, is shown in Figure 4-4-12.

The top panel shows the received amplitude of the echolocation clicks, which display a characteristic repetitive variation up and down, consisting with the sideways scanning behaviour observed in echolocating porpoises. As the animal turns its head from side to side, in order to ensonify the space in front of it with its narrow sound beam, a receiver in a fixed location (such as PAM equipment) will observe the sound beam repeatedly scanning across the hydrophone, causing the sinusoidal-like amplitude modulation. The bottom panel shows the bearing to the sound source determined on a click-by-click basis from the time-of-arrival differences on the four hydrophones of the array. The first sequence has several outliers, likely caused by errors in the localization algorithm due to a low signal-to-noise ratio. The main part of the data points falls along a gradually changing line, consistent with a swimming animal, where the bearing to the array changes gradually over the few seconds the encounter lasts. At around time mark 21:27:23 there is a discontinuity in the trace, which can either be due to the inherent precision of the localization[4], or – less likely – a second animal close to the first. The second click train, starting at time marker 21:27:29, has a bearing that is a natural continuation of the bearings from the first event. This suggests that both trains originate from the same animal, which moved in an arch from 270 degrees to 180 degrees relative to the array within the 12 second duration.

[4] The outliers tend to fall at discrete distances from the main body of the data points. This is due to the characteristics of the porpoise clicks (see Figure 3-7), where errors in determining time-of-arrival differences tend to occur at integer steps of the period of the 130 kHz signal, i.e. the best match between two channels is found with an offset of an integer number of wave cycles from the true time-of-arrival difference.

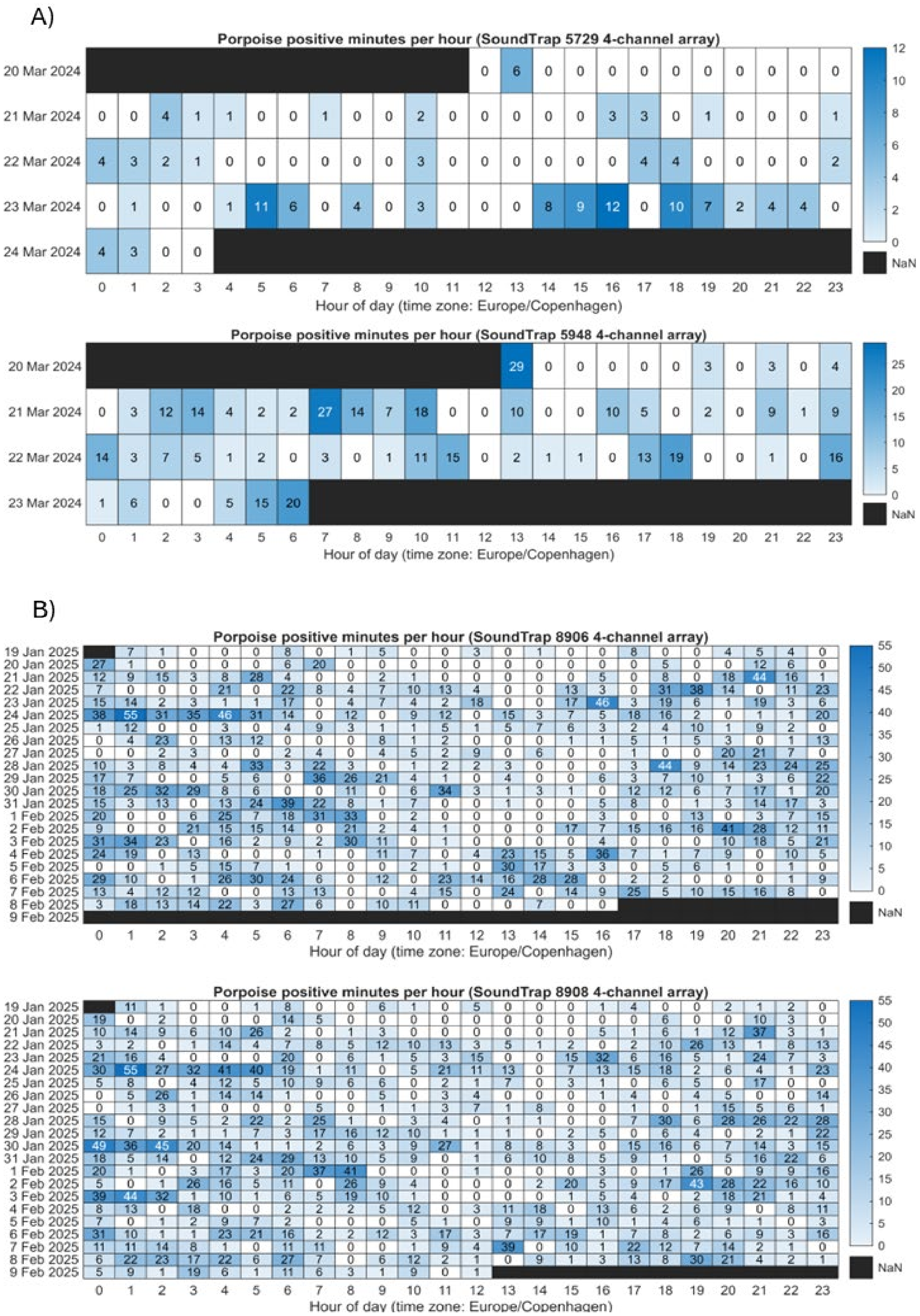


Figure 4-4-11: Overview of the recordings obtained during the deployment in March 2024 (A) and January 2025 (B). For each hour of recordings, the number of minutes containing porpoise clicks on all four channels of the recording is indicated. For accurate positioning to be possible, clicks must be recorded on both arrays.

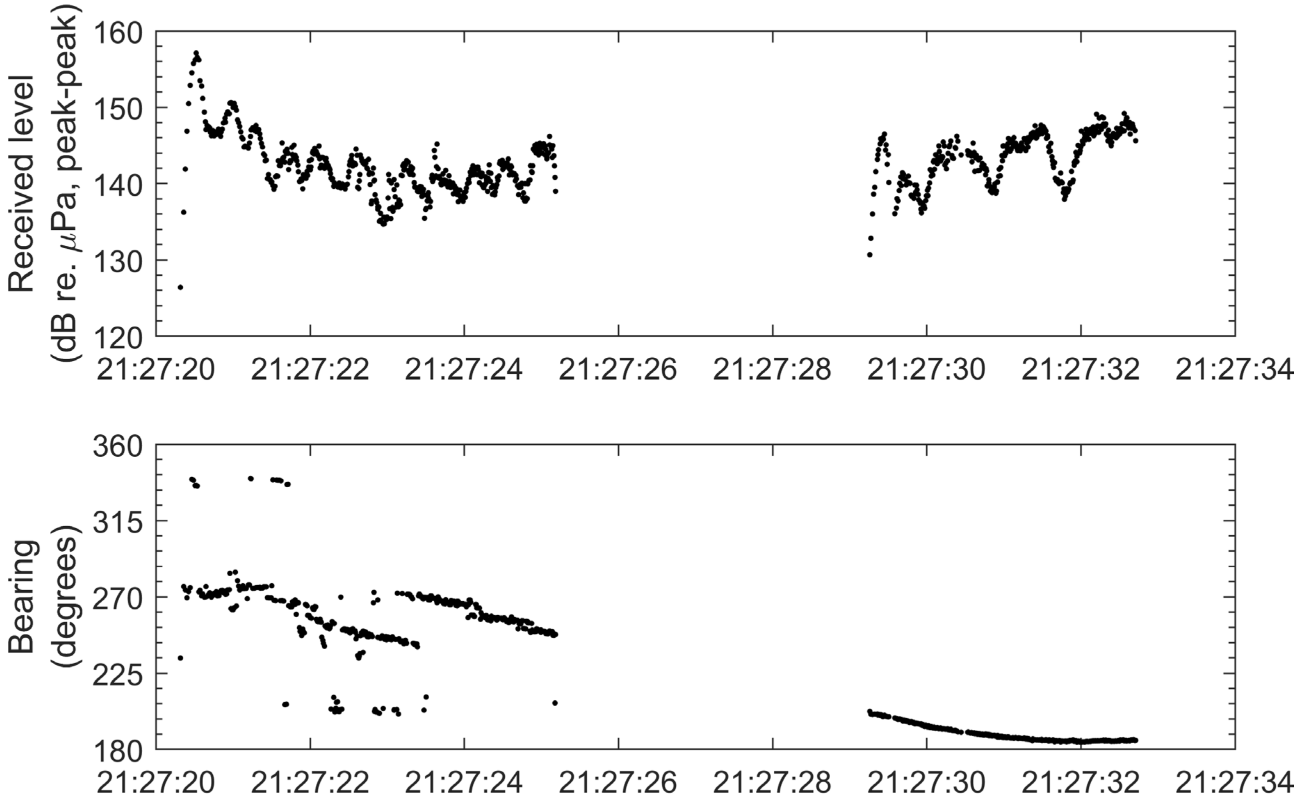


Figure 4-4-12: Example of recording of two sequences of several hundred harbour porpoise clicks. Top panel shows the received sound pressure level at the top hydrophone. Bottom panel shows the bearing from the array to the vocalizing harbour porpoise.

While recordings from a single small-aperture array can only provide direction to the porpoise, not distance, it is possible to estimate distance if one bearing can be determined from each of the two arrays at the same time, or at least not further apart in time to justify that the error caused by the animal moving slightly between bearing estimates can be ignored. Such a positioning with cross-bearings from the two arrays were done for both the March 2024 and January 2025 deployment data, where click trains separated by less than 5 seconds on the two arrays were combined. In the March 2024 data, a total of 120 events were identified and in the January 2025 data a total of 5114 events were identified with this criterion. These events are plotted in Figure 4-4-13.

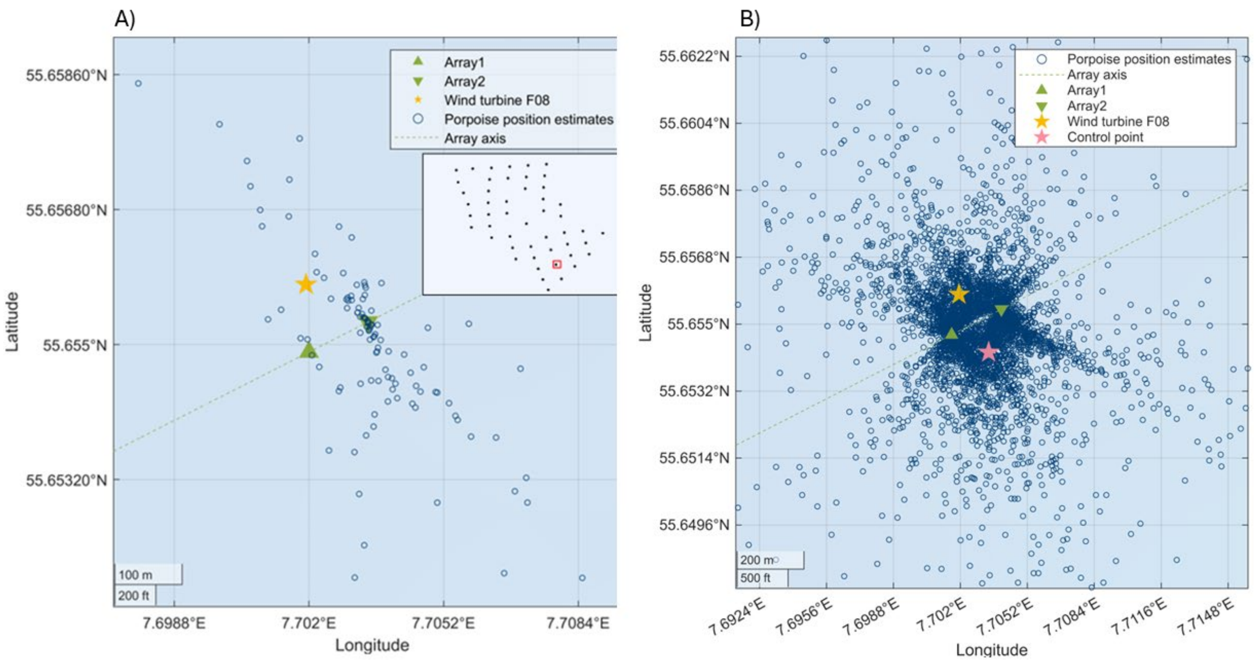


Figure 4-4-13: Map of the array and wind turbine positions together with the porpoise position estimates. A) This map shows 110 out of the total of 120 porpoise position estimates from the deployment in March 2024 in a map grid of 100m. Insert shows the Horns Reef 3 wind farm with the position of the main map indicated by the red rectangle. B) This map shows all 5114 porpoise position estimates from the deployment in January 2025 in a map grid of 200 m. The turbine and reference point positions are represented by a yellow and red star, respectively. The dotted green line going through the two array positions (green triangles) is the array line.

The results show that consistent bearings can be assigned to the harbour porpoise clicks in the recordings, which is the requirement for determining the position of the animals relative to the turbine. Harbour porpoises were positioned very close to the arrays, but also to the turbine. The distance from the turbine to each data point is summarized in the histogram in Figure 4-4-14 for deployments in both March 2024 and January 2025. For the deployment in March 2024, there appears to be a clustering of positions around the eastern array and along a line running approximately NW-SE through this array and east around the turbine. Upon recovery of the March 2024 arrays, it was discovered that the eastern array had toppled over during deployment and had been slightly deformed under its own weight. This deformation was included in the localization algorithm but may have resulted in a bias towards certain bearings in the analysis[5]. Another possibility is also that porpoises have a preferred route when swimming past the turbine. Harbour porpoises are known to use structures on the seabed as 'land marks' in their navigation (Verfuss et al. 2005) and may even have used our array as such a landmark. However, in the much larger dataset of harbour porpoise position estimates from the ~21 day-deployment in January 2025,

[5] All array configurations have variable precision in localization, depending on the angle of incidence. For each pair of hydrophones, the precision is highest along the midline perpendicular to the point between the two hydrophones, whereas the precision deteriorates substantially towards the line running through the two hydrophones, the so-called 'end-fire' positions.

the points do not cluster in a similar way. Instead, the positions are evenly spread out on both sides of the array line, taking into account the decline in precision towards the 'end-fire' angles (closer to and along the array line).

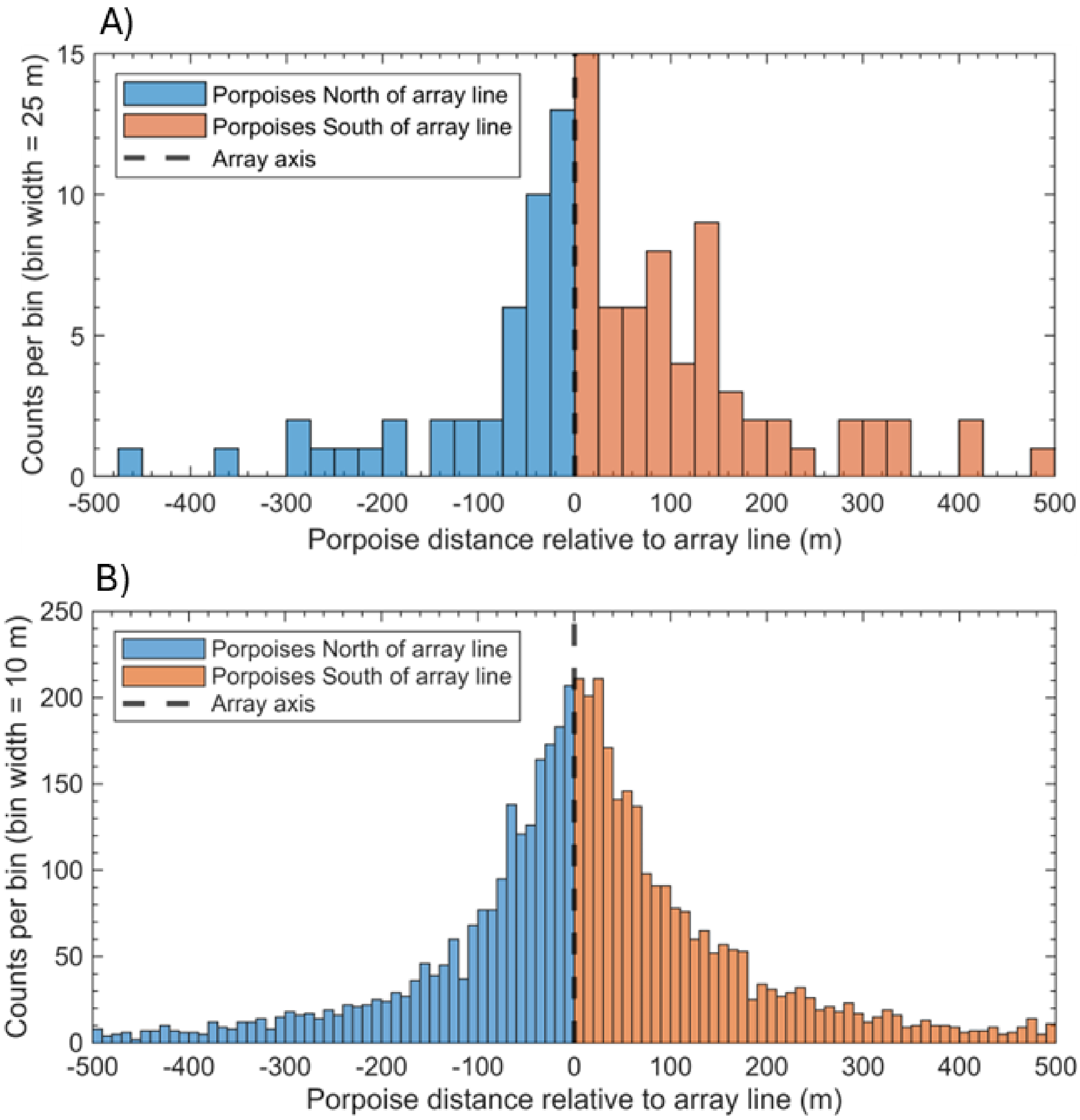


Figure 4-4-14: Histogram showing harbour porpoise distribution relative to the axis going through the two array positions. Distances to positions North of the array line (same side as the wind turbine) are shown in blue and plotted with negative distance values, and positions South of the array line are shown in red with positive values. A) Shows data from March 2024 deployment. Histogram bin width is 25 m. 11 out of 120 data points exceed the ±500 m distance limit of the x-axis. B) Shows data from January 2025 deployment. Histogram bin width is 10 m. 492 out of 5114 data points exceed the ±500 m distance limit of the x-axis. Note the different magnitude of the y-axis between the A and B plot.

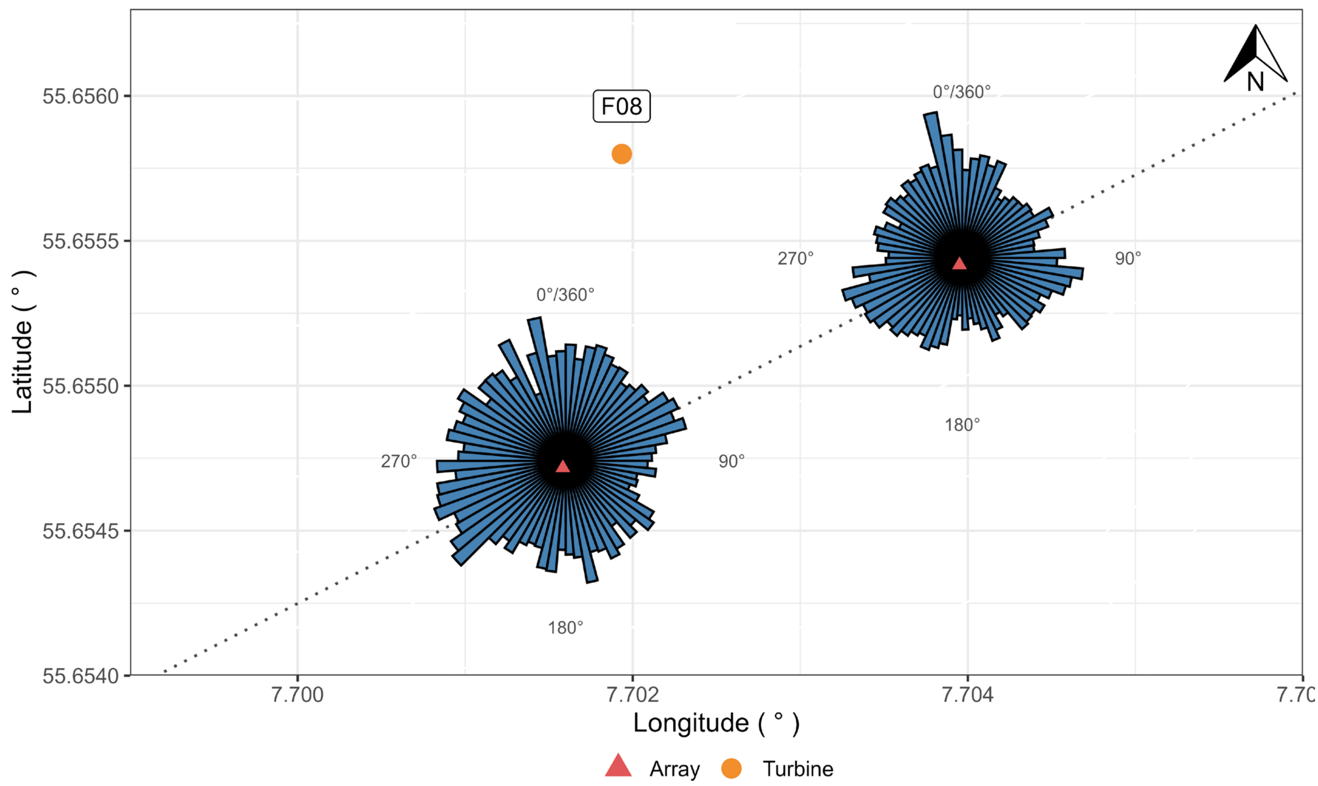


Figure 4-4-15: Map of turbine (circle) and 4-channel array locations (triangles). The dotted line represents the array line as described above. At the location of the arrays a circular histogram represents the distribution of estimated bearing to classified harbour porpoise clicks (bin width = 10).

The estimated harbour porpoise positions are generally within ranges of a few hundred meters from the two arrays for both the March 2024 and January 2025 deployment (March 2024: >80% within 300 m, >90% within 500 m; January 2025: >70% within 300 m, >85% within 500 m), which agrees with the expectation that porpoise clicks are detectable over maximum ranges up to approximately a kilometer depending on the click source level and detection threshold (DeRuiter et al. 2010). Based on the bearing of all classified clicks, there is an indication from the Northern array that harbour porpoises appear more in a N, SW or SE direction, whereas the bearing of classified clicks around the Southern array occur more evenly (Figure 4-4-15). Overall, based on the distribution of harbour porpoise bearings no visible pattern around the wind turbine emerges. To test the pattern of distribution of the localized harbour porpoise clicks, the distances of clicks to the turbine were compared to the distance of clicks to a reference point using a Beta GLLM model (Figure 4-4-13B). The Beta GLMM model with per-minute distances, an AR(1) correlation structure and site-specific precision estimated that mean distance proportions are 0.669 (turbine) and 0.668 (reference). Back transformed to distance in meters, this corresponds to mean distances of 67.3 m to the turbine compared to 67.1 m to the reference point in the 0-100 m analysis area (ratio = 1.003). This difference in distance to turbine versus reference point was not significant (logit $\beta = 0.006$, SE = 0.069, $p = 0.93$). This does not show, however, that attraction or deterrence effects are non-existing near the turbine, but if such opposing effects do exist, this study points to the net effect being neutral. Since the Beta GLMM includes a discrete correlation structure that assumes evenly spaced observation time, we ran a sensitivity analysis where we modelled the distance in meters using a Bayesian GLMM with a truncated Lognormal likelihood, as this includes a continuous measure of time-correlation. This analysis supported our finding that there is no difference in the distance between estimated harbour porpoise positions around the turbine compared to the reference point: posterior ratio of expected distances was 0.992 (95% Credible Interval 0.389-2.297) and a posterior probability of attraction of P (Distance_turbine < Distance_reference) = 0.515. The results from both models are also supported by the pattern of estimated harbour porpoise positions plotted in Figure 4-4-13 and the bearing to harbour porpoise clicks in Figure 4-4-15, both of which also indicate that harbour porpoises are neither attracted nor deterred by the wind turbine.

4.4.3.2 8 soundtraps near turbines

The difference between hydrophones deployed at 50 m from an operating turbine and 200 m from an operating turbine, as well as differences between turbines, were modeled. A Bayesian generalized linear mixed model with zero-inflation and a negative binomial distribution was fitted for the full dataset (Table 4-4-2). The model was run with 4 chains, each with 11,000 total iterations, a warmup of 1000 iterations, and thinning set to 10. All model coefficients converged (Rhat = 1).

Table 4-4-2: Full BRMS model summary.

Coefficient	**Estimate**	**Est. Error**	**Lower-95% CI**	**Upper-95% CI**
~Location sd(Intercept)	0.52	0.31	0.21	1.36
Intercept	2.81	0.49	1.88	3.76
Zi_Intercept	-1.09	0.09	-1.27	-0.92
Distance (200m)	0.04	0.04	-0.04	0.13
Noise	0.00	0.00	-0.01	0.00
Time of Day (Night)	-0.12	0.04	-0.20	-0.03
Flow (Flood)	-0.16	0.04	-0.24	-0.08

A main focus of this investigation was the impact of distance, i.e. whether there are differences in detection-positive minutes per hour (DPM/H) between the hydrophones at 50 m versus at 200 m. Here, we saw a weak positive estimate, but a confidence interval crossing zero. This suggests a weak, but distinctly uncertain, increase in DPM/H at 200 m compared to 50 m (Figure 4-4-16).

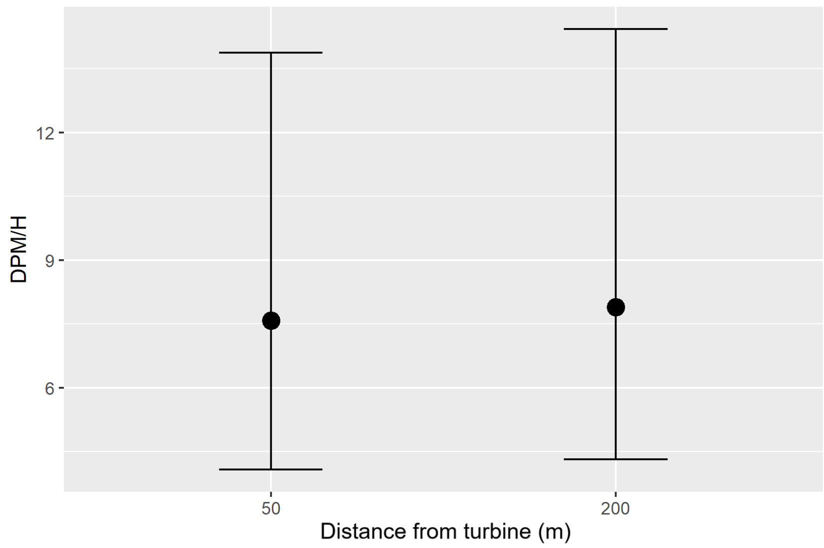


Figure 4-4-16 Conditional effects plot showing the impact of distance when all other factors are held at their average (continuous) or reference level (categorical). There is a weak and uncertain positive estimate at 200m compared to 50m from the turbine.

Similarly, noise had little to no impact on DPM/H (Figure 4-4-17). However, time of day showed a modest negative trend at night, suggesting fewer detections at night. Similarly, there was a modest negative trend at flood tide, suggesting fewer detections at night as well.

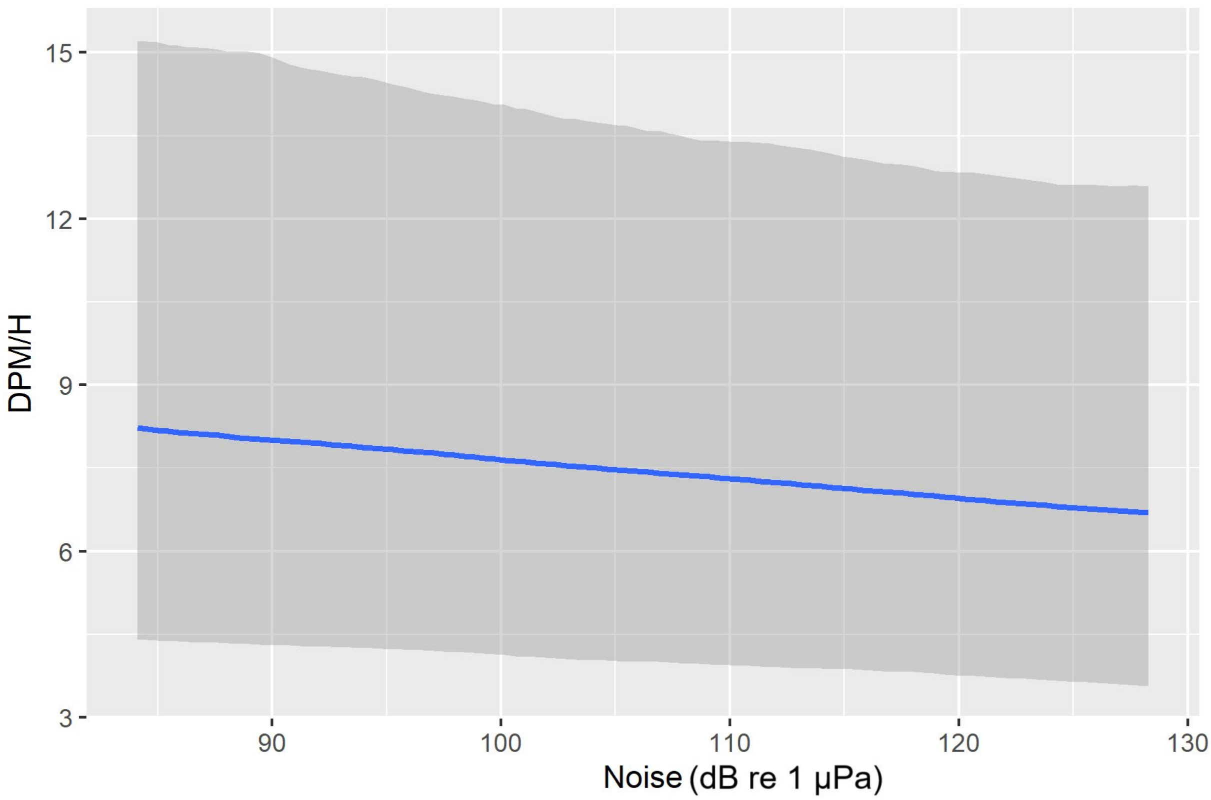


Figure 4-4-17 Conditional effects plot showing the impact of noise when all other factors are held at their average (continuous) or reference level (categorical). Grey shading indicates the 95% credible interval. Extremely large credible intervals show that the effect of noise is weak.

Interestingly, the random effect of location had a positive effect with a wide confidence interval, suggesting variability in DPM/H by location. This is confirmed by the significant zero-inflation intercept, which varies by location, suggesting a different probability of excess zeroes at each location. Examining the conditional effects, it becomes clear that a single turbine, C05, was driving this variation—there were many fewer hours without any detection-positive minutes than the other three turbines (Figure 4-4-18). This suggests that not all turbines were visited by harbor porpoises at the same rates. While turbines E05, F06, and F07 had average DPM/H values that were extremely comparable, turbine C05 was extremely different.

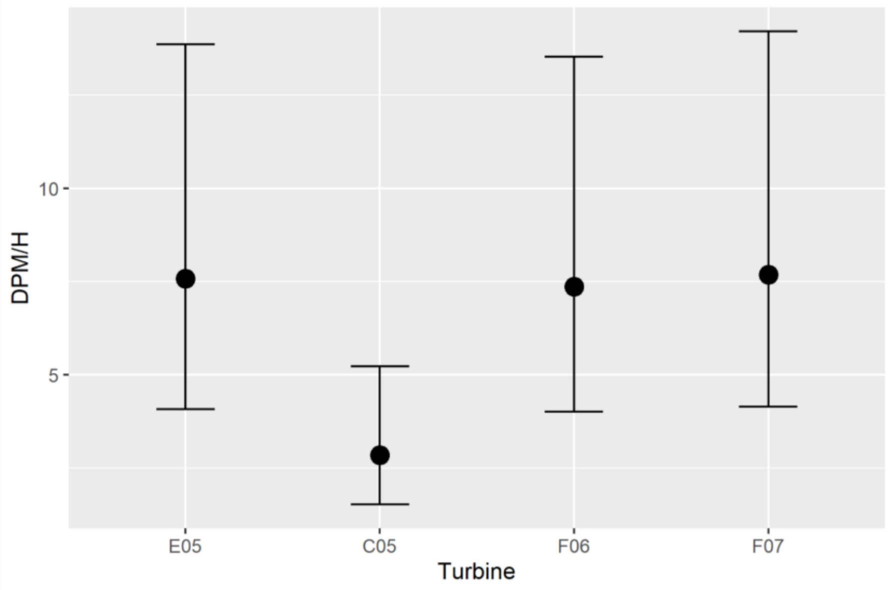


Figure 4-4-18 Conditional effect of location (turbine) on DPM/H, with all other factors held at average (continuous) or their reference level (categorical). Turbine C05 has significantly lower DPM/H counts, driven by an excess of zeroes.

To investigate the differences between the high-detection sites (turbines E05, F06, and F07) and low-detection site (turbine C05), separate models were run for turbine C05 and the other turbines (Table 4-4-3, Table 4-4-4). Both models followed mainly the same structure, with DPM/H from the top 25th percentile as the response variable, with distance from the turbine, noise level at 315 Hz, and tidal flow as fixed effects. Because of the separation by locations, no random effect for location was included. Models were zero-inflated with a negative binomial distribution. Each model was run with 4 chains, each with 11,000 total iterations, a warmup of 1000 iterations, and thinning set to 10. All model coefficients converged (Rhat = 1).

Table 4-4-3: Low-detection turbine model summary (turbine C05).

Coefficient	Estimate	Estimated Error	Lower-95% Confidence Interval	Upper-95% Confidence Interval
Intercept	9.31	1.11	7.17	11.49
Distance (200m)	-0.38	0.18	-0.73	-0.03
Noise	-0.08	0.01	-0.10	-0.06
Time of Day (Night)	-0.64	0.17	-0.98	-0.31
Tidal Flow (Flood)	-0.06	0.17	-0.40	0.27

Table 4-4-4: High-detection turbine model summary (turbines E05, F06, and F07).

Coefficient	Estimate	Estimated Error	Lower-95% Confidence Interval	Upper-95% Confidence Interval
Intercept	1.88	0.39	1.12	2.64
Distance (200m)	0.11	0.04	0.02	0.20
Noise	0.01	0.00	0.00	0.01
Time of Day (Night)	-0.04	0.04	-0.13	0.04
Tidal Flow (Flood)	-0.15	0.04	-0.24	-0.07

Interestingly, in both models, the effect of distance from the turbine was significant, but in opposite directions (Figure 4-4-19). While at the low-detection site, there was a modest but significant increase in detections at 50m, at the high-detection site, there was an equal increase in detections at 200m instead. This suggests significant variability in the near-turbine habitat use by harbour porpoises between turbine locations.

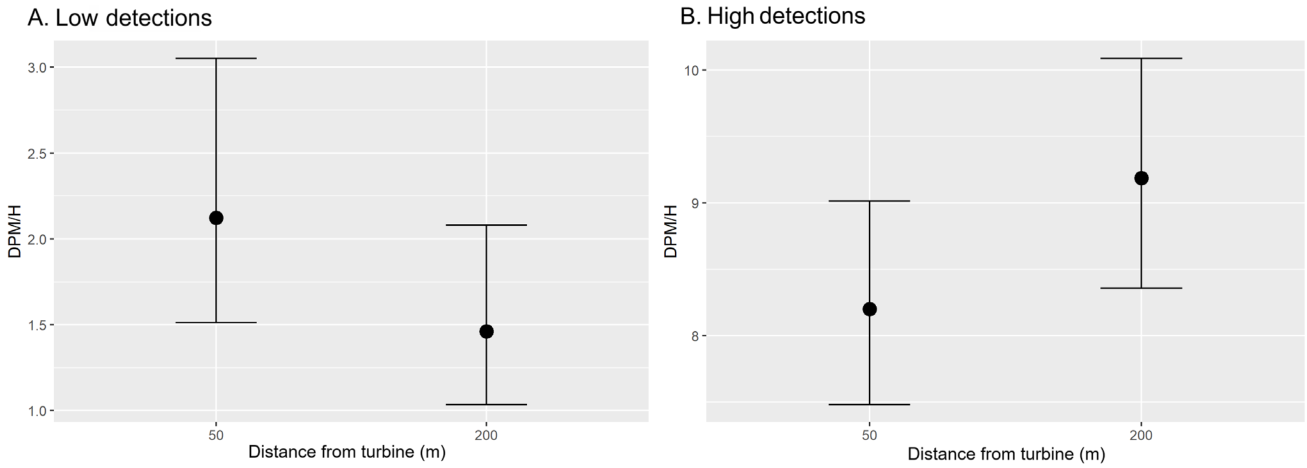


Figure 4-4-19 Conditional effects plots of hydrophone distance, for the low-visitation turbine (C05) and the high-visitation turbines (E05, F06, and F07). Both models show significant effects, but the low-visitation model shows an increase in DPM/H at 50m and the high-visitation model shows an increase in DPM/H at 200m.

While noise and time of day showed no effect on the high-detection model, there was a small but significant decrease in detections with increasing noise in the low-detection model and an additional strong decrease in detections at night. In the full model, it is then likely that turbine C05 drove the effect of time of day. Conversely, the tidal flow showed no effect on the low-detection model, but showed a moderate decrease in detections during flood tide in the high-detection model, likely driving that effect in the full model.

Additionally, the low-detection model showed a much higher intercept, despite a higher probability of zeros, suggesting a bimodal distribution of detections. Although there were many more zero values, indicating no harbour porpoise presence, when there are non-zero values, they tend to be quite high, suggesting that harbour porpoises are visiting the site infrequently but stay for longer periods when they do.

This pattern, unique from the other three sites, suggests that the behavioral patterns around this turbine were significantly different than the other turbines, justifying a separate modeling procedure for low- versus high-detection sites. The full model showed no effect of distance due to pooling between locations, when separating the locations showed that there were significant effects, just in opposing directions. Additionally, because the contrast between turbine C05 and the other turbines in probability of zeros and average DPM/H, the full model overestimated the probability of zeros and underestimated the dispersion at turbine C05.

While all models converged and we believe the estimates to be reliable, model fit could be substantially improved. The current model structures were selected with a compromise between adequate representation of the data and comprehensibility. Future investigations should pursue truncated models to better reflect the structure of DPM/H.

4.4.4 Noise exposure maps

Underwater noise exposure maps, separated into contributions from current sources. Modelling was conducted for the 125 Hz decidecade band, which is a standard frequency band for modelling for the Marine Strategy Framework Directive criterion D11C2. It can also be used as a proxy for estimating responses to ship noise, in line with the methodology used for the HELCOM HOLAS 3 assessment.

Monthly statistical maps were produced between April 2023 and March 2024. Each map layer represents the statistics of the noise in the 125 Hz decidecade band, as described in section 3.3.4. Two maps were used for each month, one expressing the 5% exceedance level (L_5, equal to the upper 5th percentile) and one expressing the 10% exceedance level (L_{10}). The original plan was to use the median i.e. the 50% exceedance level, but the noise levels estimated to disturb harbour porpoises was at all times below 20% and so only 5% and 10% were included. The maps should therefore be interpreted so that the noise level indicated in each grid cell (approximately 100–200 m x 100–200 m rectangles) was exceeded in 5% and 10% respectively, of the individual snap shots modelled for that particular month.

The 5% and 10% exceedance level noise layers are shown in Figure 4-4-20 and Figure 4-4-21, respectively. The main dominant feature is the shipping lane, running SW to NE in the outer, western edge of the survey area. There is some variation across the seasons, with noise from vessel traffic related to Hvide Sande port in the middle of the eastern area appearing in summer and autumn (May through October, most notable in June) and higher noise levels in the shipping lane in spring (April and May). In these maps, a boundary has been overlayed where the 5% or 10% exceedance level was at or above 115 dB re 1µPa in the 125 Hz decidecade band, as this indicates the behavioral threshold for harbour porpoises (Tougaard et al, 2023, see section 3.3.5).

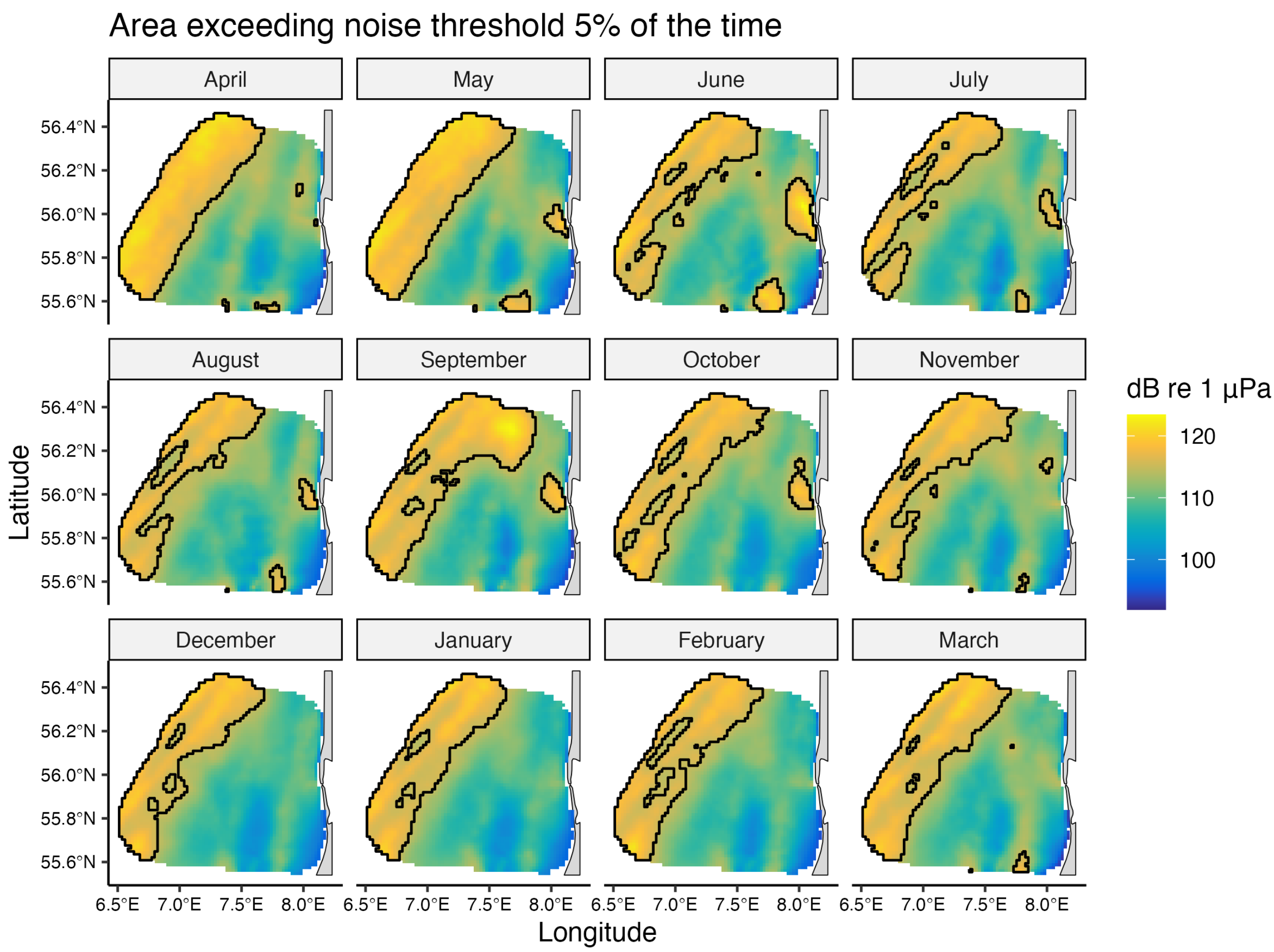


Figure 4-4-20: Maps of the 5% exceedance level in the 125Hz decidecade frequency band for April 2023 through March 2024. The sound pressure level ($L_{p,125Hz\ ddec}$, unit dB re 1 µPa/decidecade) measured on a short time scale of a few seconds (the temporal scale of the individual snap shots modelled every hour of the month) in each point of the map is expected to be equal to or higher

than the level corresponding to the colour 5% of the time. The map therefore represents the loudest events that occur in the survey area for each month. The overlayed black polygons represent areas where sound pressure levels ($L_{p,125Hz\ ddec}$) exceed 115 dB re 1 µPa) (i.e., the noise level above which harbour porpoises are expected to respond) 5% of the time, indicating that reactions to the noise is expected to occur on average 5% of the time.

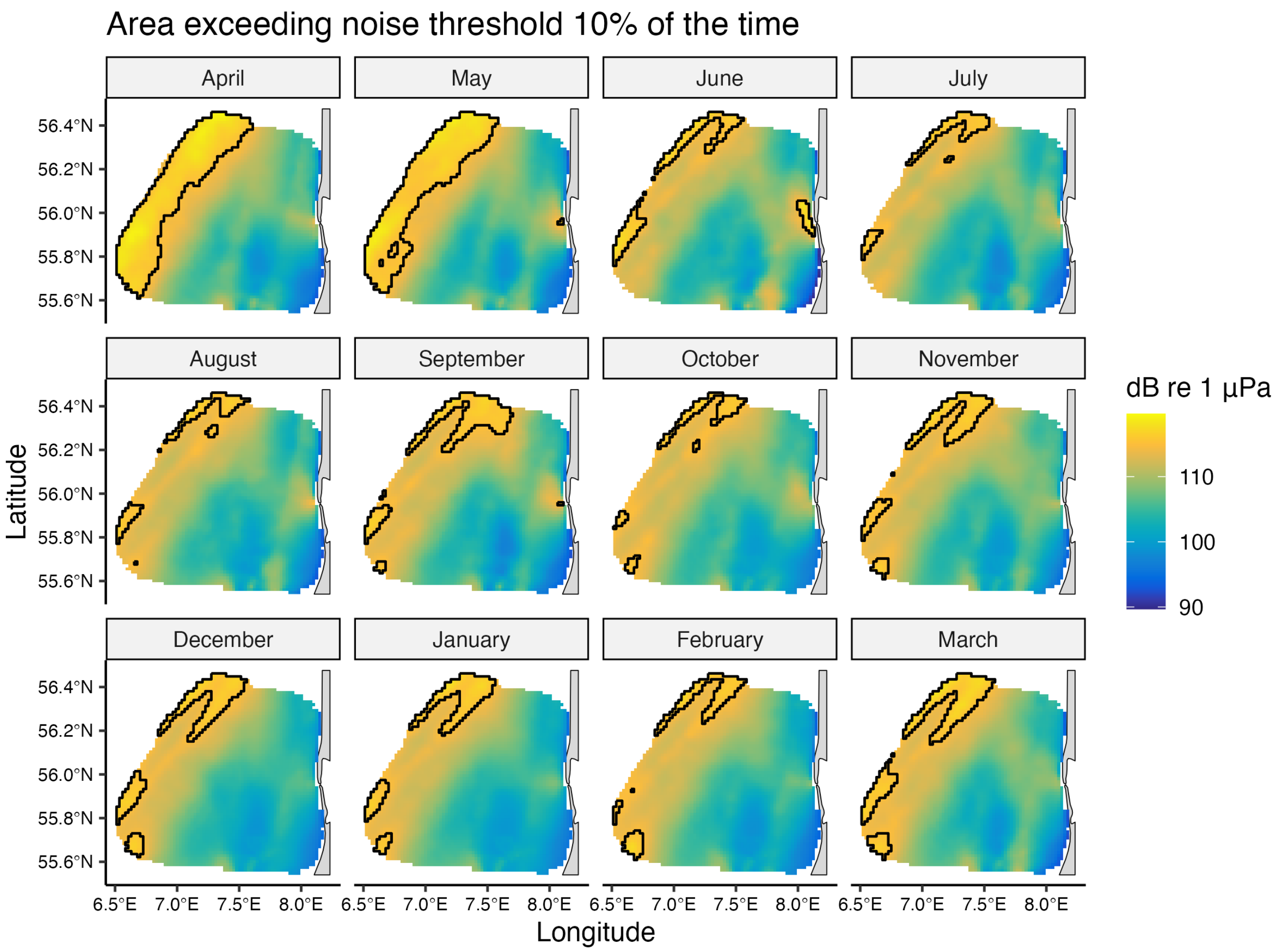


Figure 4-4-21: Maps of the 10% exceedance level in the 125Hz decidecade frequency band for April 2023, through March 2024. The sound pressure level ($L_{p,125Hz\ ddec}$, unit dB re 1 µPa/decidecade) measured on a short time scale of a few seconds (the temporal scale of the individual snap shots modelled every hour of the month) in each point of the map is expected to be equal to or higher than the level corresponding to the colour 10% of the time. The map therefore represents the loudest events that occur in the survey area for the four months. The overlayed black polygons represent areas where sound pressure levels ($L_{p,125Hz\ ddec}$) exceed 115 dB re 1 µPa) (i.e., the noise level above which harbour porpoises are expected to respond) 10% of the time, indicating that reactions to the noise is expected to occur on average 10% of the time.

4.4.5 Overlaying model

The underwater noise exposure maps for the survey area (Figure 4-4-20 and Figure 4-4-21) were overlayed with monthly distribution maps of harbour porpoises based on the collected PAM data (Figure 4-1-5 and Figure 4-1-

6). This enables the area where animals may respond to underwater noise and vibrations to be assessed. Following the Faulkner et al. (2018) guidelines, the steps to evaluate the impact of underwater noise on marine life include:

I. identifying noise exposure criteria (i.e., the noise level above which animal responses are expected), and
II. compute “effect zones” (i.e. the combination of noise model prediction and noise exposure criteria).

The monthly predicted harbour porpoise distribution was thus overlayed with a map of the effect zones based on a noise exposure criterion of 115 dB re 1 µPa in the 125 Hz decidecade band (Tougaard et al., 2023), see section 3.3.5 above. Within this effect zone, harbour porpoises are expected to be exposed to noise levels sufficiently high to induce behavioural reactions in the animals 5% or 10% of the time. We used effect zones corresponding to the 125Hz frequency band - 5% exceedance level (i.e., the level exceeded 5% of the time, see “3.3.1 Noise monitoring”) and 10% exceedance level, respectively (Figure 4-4-22 and Figure 4-4-23)

The maps indicate that there is little variation across the seasons in the area where noise exceeds the 115 dB level particularly at the 5% level and that the area above the criterion level mainly coincides with areas with a relatively high porpoise density (>120 PPM per day) for both the 5% and the 10% exceedance level. This is supported by the extracted quantities (median of the average PPM per day and per 1.5km^2 and summarised impact, i.e., the median multiplied by the area size) of the monthly overlayed maps inside the threshold area (Table 4-4-5, Figure 4-4-23).

The extracted values indicate that while the impact is relatively stable throughout the year, the risk of behavioural reactions increases in spring (May), as there is the largest number of animals exposed to levels above 115 dB. This is most evident at the 10% exceedance level. Note that the exceedance levels correspond to harbour porpoises being exposed above the criterion level 5% and 10% of the time, respectively. This means that 95% (for the 5%) to 90% (for the 10%) harbour porpoises inside the polygons will not be exposed to noise levels that they are expected to react to. However, since both PAM and aerial survey data points to the distribution of porpoises in the NSI survey area to be highly varied, these overlaying models should be interpreted with some caution.

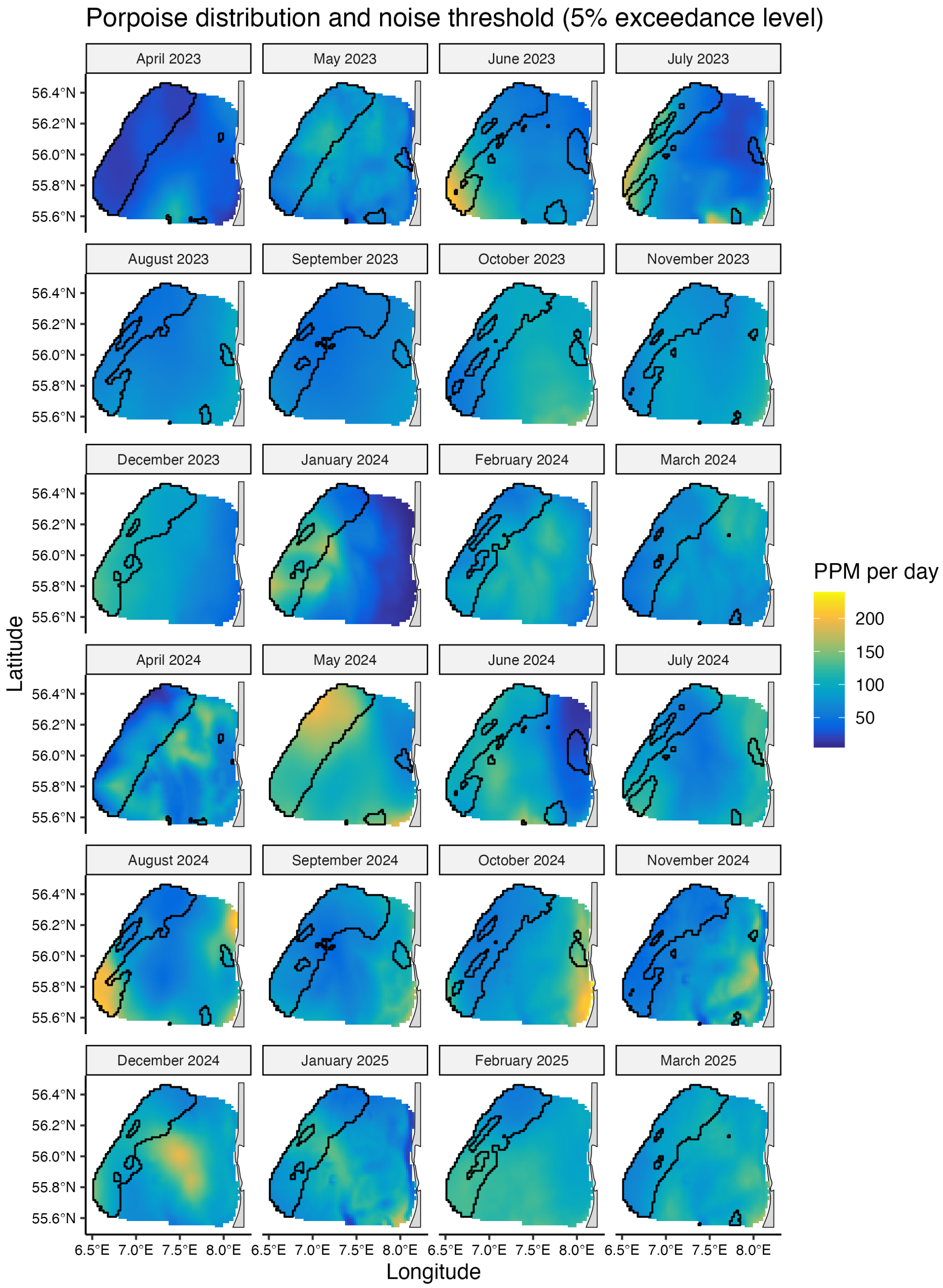


Figure 4-4-22 Overlayed PAM model with the area of expected impact from noise (the 5% exceedance level in the 125Hz de-cidecade frequency band) on harbour porpoises (≥ threshold value, black lined polygon) PPM is 'Porpoise Positive Minutes', and high values (yellow) indicate areas where porpoises are predicted to occur more frequently.

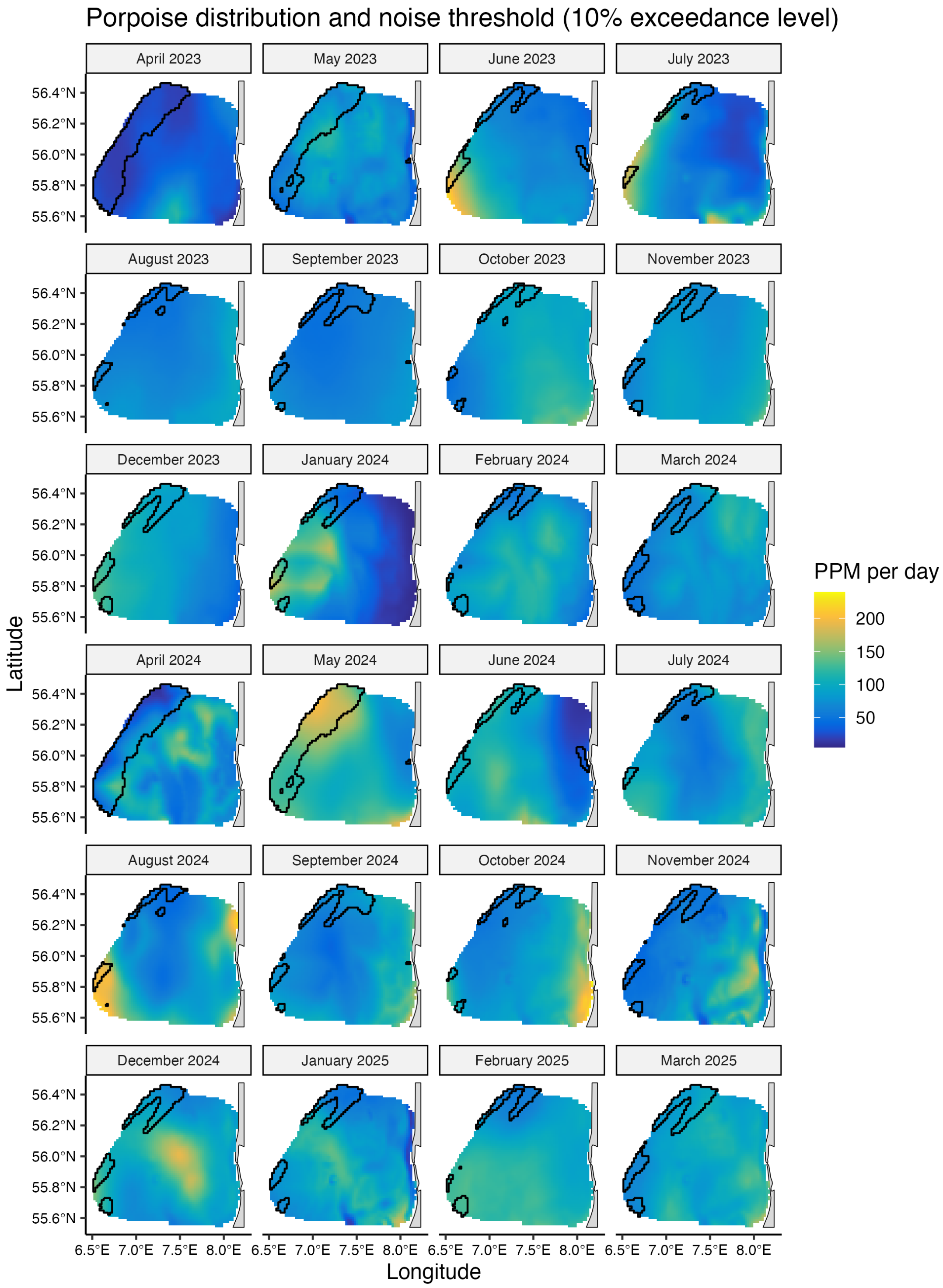


Figure 4-4-23 *Overlayed PAM model with the area of expected impact from noise (the 10% exceedance level in the 125Hz decidecade frequency band) on harbour porpoises (≥ threshold value, black lined polygon) PPM is 'Porpoise Positive Minutes', and high values (yellow) indicate areas where porpoises are predicted to occur more frequently.*

Table 4-4-5: Quantities of harbour porpoise density extracted from inside the threshold areas from the 5% and 10% exceedance level maps (see figure 4-35 and 4-36). The area is the total area inside the threshold area. The summarised impact is the median PPM per day multiplied by the area impacted at each exceedance level.

	Median PPM per day		**Area (km^2)**		**Summarised impact**	
Month	5% exceedance	10% exceedance	5% exceedance	10% exceedance	5% exceedance	10% exceedance
April 2023	22	22	2983	1934	65489	41706
May 2023	79	76	3063	1797	241542	136163
June 2023	70	64	2658	573	187058	36733
July 2023	89	68	1937	336	171676	22737
August 2023	56	50	2158	368	121570	18341
September 2023	55	54	3188	749	176911	40599
October 2023	87	94	2665	345	233176	32496
November 2023	76	73	2371	619	180591	45285
December 2023	106	97	2302	758	244971	73803
January 2024	117	64	2416	655	282111	42128
February 2024	83	67	2396	480	199119	31958
March 2024	69	68	2729	900	187832	61405
April 2024	72	56	2983	1934	215589	107602
May 2024	141	153	3063	1797	432813	275856
June 2024	100	104	2658	573	265163	59444
July 2024	86	76	1937	336	166676	25668
August 2024	72	49	2158	368	154961	18191
September 2024	70	75	3188	749	223636	56235
October 2024	66	67	2665	345	175030	22983
November 2024	51	51	2371	619	120850	31553
December 2024	100	95	2302	758	230317	72142
January 2025	82	67	2416	655	197555	43618
February 2025	96	62	2396	480	231017	29779
March 2025	88	85	2729	900	238856	76521

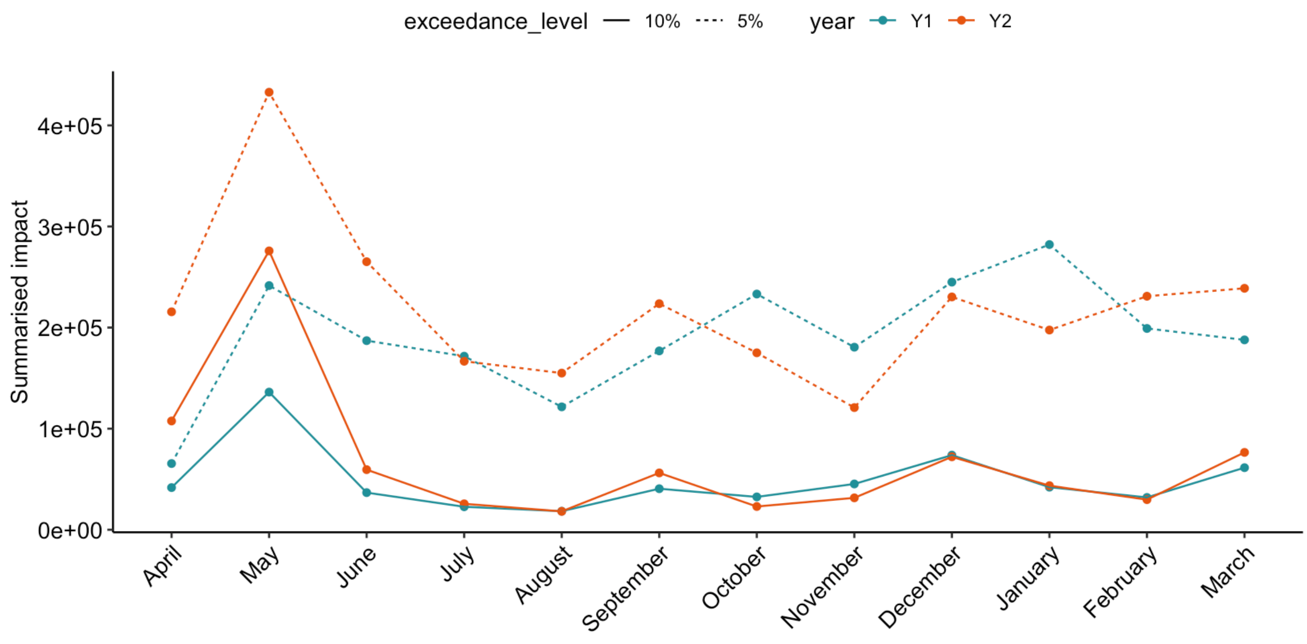


Figure 4-4-24: Summarised impact (i.e., median PPM multiplied by the area where noise levels are expected to impact harbour porpoises behaviour) from April 2023 through March 2025 for exceedance levels 5% and 10%.

4.4.6 Impact of geophysical survey noise on presence of harbour porpoises

During the collection of baseline PAM data for North Sea I, also geophysical and geotechnical surveys were conducted. Geophysical and geotechnical surveys often use USBL (Ultra Short Baseline) during their surveys - an underwater communication system used to map the position of underwater equipment. USBL systems use a high source level, that has previously been recorded in the North Sea, where an impact range of around 3 km for harbour porpoises was calculated (Pace et al. 2021), which could potentially affect the results of the baseline study. Therefore, a study was conducted to examine the effects of the simultaneous geophysical and geotechnical surveys and baseline acoustic surveys of harbour porpoises. In this chapter a summary of results with examples are presented, while all results can be read in the report of Mikaelsen et al. (2025).

4.4.6.1 Impact ranges

Based on the harbour porpoise behavioural reaction criterion of Lp,rms,125ms,VHF = 103 dB re. 1 mPa., impact ranges *varying* between 1 km and 5.5 km were predicted from the recordings of USBL signals from the geophysical and geotechnical surveys. An example of a vessel passage documenting the received level at the broadband recorder is shown in Figure 4-4-25. In this example, the behavioural reaction criterion was exceeded at a distance of 4000 m from the sensor. The back-calculated source level however varied a lot between different vessel passes, even for the same vessel, and thereby the same USBL equipment, recorded on different days. This was assessed with respect to weather, but there was no correlation (see Mikaelsen et al. 2025). It was therefore assumed that the USBL systems in question had automatic gain control and could adjust source level automatically, or that the operators changed the settings during the survey.

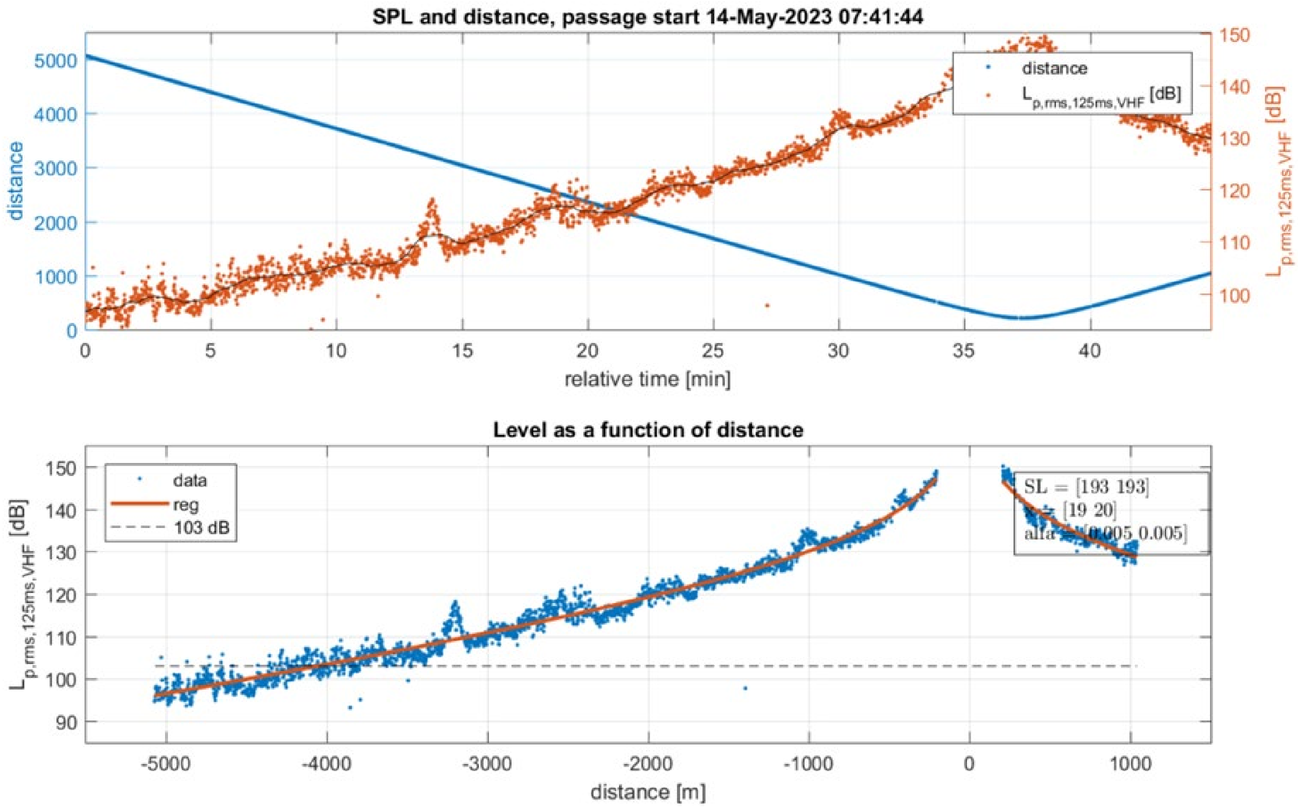


Figure 4-4-25: Survey vessel "Northern Maria" pass at F-POD + Broadband recorder station NS25 on May 14, 2023. Vessel distance and recorded USBL SPL ($L_{p,rms,125ms,VHF}$) are shown in top panel as a function of the time. In the bottom panel, $L_{p,rms,125ms,VHF}$ for individual USBL pulses is plotted as a function of vessel distance to NS25. A regression line (orange) was established based on the custom equation "$L_{p,rms,125ms,VHF} = SL - x * log10(dist) - \alpha * dist$". The empty space between the two series of data is equal to the minimum distance the survey vessel had to the NS25 station. A horizontal line at 103 dB is also shown to indicate the harbour porpoise behavioural reaction threshold of $L_{p,rms,125ms,VHF}$ = 103 $dB\ re\ 1\mu Pa$.

4.4.6.2 Effects on harbour porpoise presence

The results of the generalized additive mixed models (GAMM) models run on PAM data extracted as PPM, CPM (Clicks per minute) and waiting time between USBL signal and next harbour porpoise click train showed that PPM and CPM decreased with increasing received level of USBL pulses. Conversely, waiting time increased with increasing received level (PPM and waiting time are shown in Figure 4-4-26). The statistical models showed that waiting time from USBL pulse to first harbour porpoise encounter on average increased to 196 minutes (95% confidence intervals: 154 – 239 minutes) as opposed to periods without USBL pulses where the average waiting time between consecutive harbour porpoise encounters was 66 minutes (95% confidence intervals: 31-102 minutes).

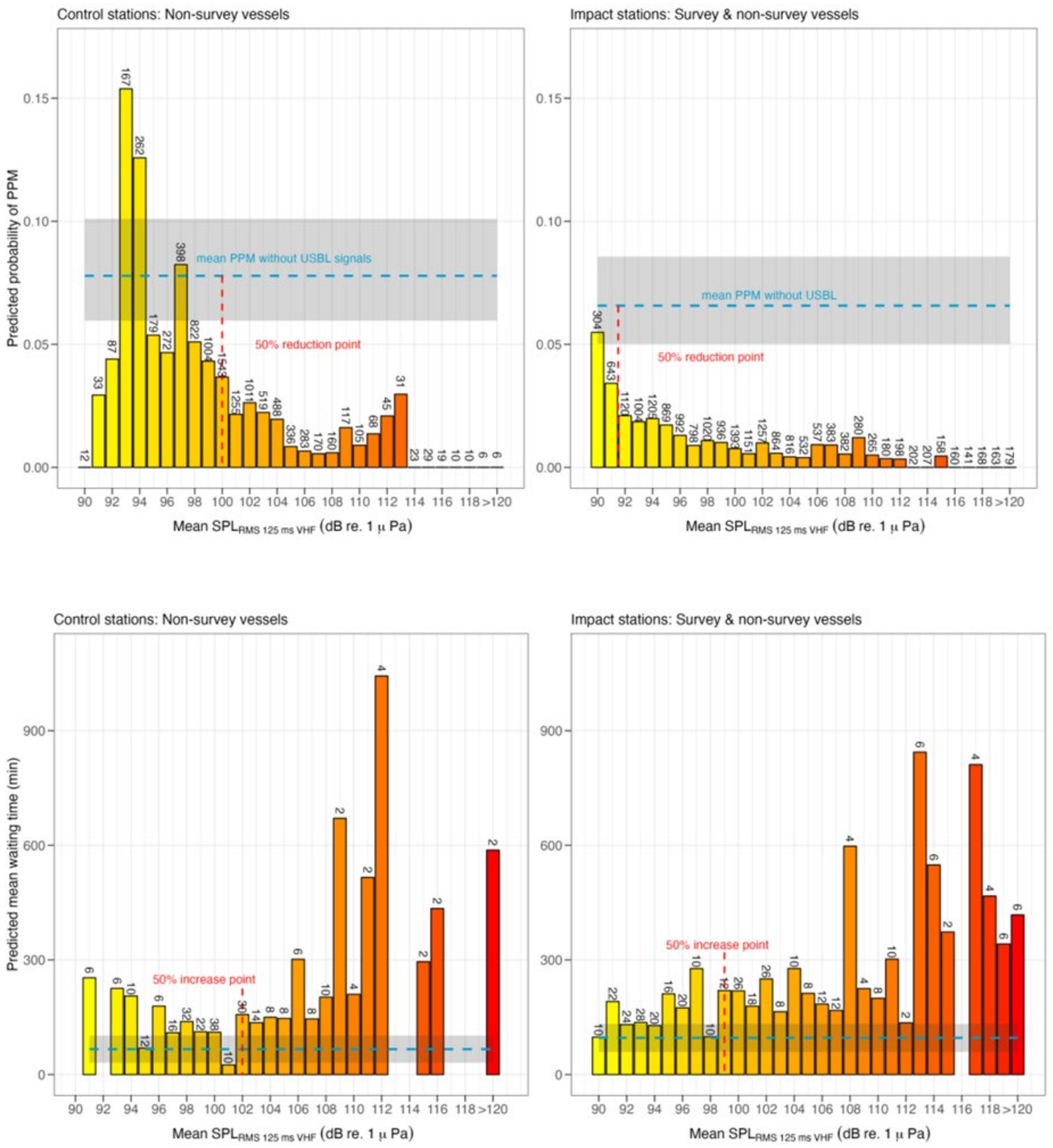


Figure 4-4-26: Bar plots showing the predicted mean PPM (using output of the control-impact generalized linear mixed effect models - *GLMERs) in the top panel and the predicted mean waiting time (USBL-HP) in minutes in the lower panel, for each rounded SPL value for non-survey vessels at control stations (left panel) and for survey and non-survey vessels at impact stations (right panel). Also shown is the mean predicted PPM and waiting time (USBL-HP) during periods without USBL signals (horizontal dashed blue line) with the corresponding 95% CI (grey area) for both control and impact stations. The vertical dashed red line indicates the SPL value at which the PPM or waiting time (USBL-HP) declined by 50% compared to the mean predicted PPM during periods without USBL signals. The number above each bar is n, i.e. number of minutes included in that bar.*

Additionally, the GAMM analyses clearly revealed variation in diel echolocation activity between stations and, moreover, between periods with and without USBL signals (Figure 4-4-27). Specifically, at stations NS2, NS6 and

NS14 (i.e. control stations without USBL signals from survey vessels), the model-based predicted mean CPM and PPM were generally highest during the nighttime hours 20:00 to 02:00. Moreover, the predicted mean CPM and PPM were generally higher during periods without USBL signals than during periods with USBL signals detected from sources other than survey ships. In contrast, at stations NS13, NS16 and NS25 (i.e. impact stations with USBL signals detected from survey ships and other sources), the model based predicted mean CPM and PPM were generally highest during the daytime hours 10:00 to 15:00. Also, at these impact stations, the predicted mean CPM and PPM were much higher during periods without USBL signals than during periods with USBL signals from survey vessels as well as other sources. During periods with USBL signals from survey vessels, CPM and PPM did not show any clear diel pattern and instead were consistently low across all 24-hours.

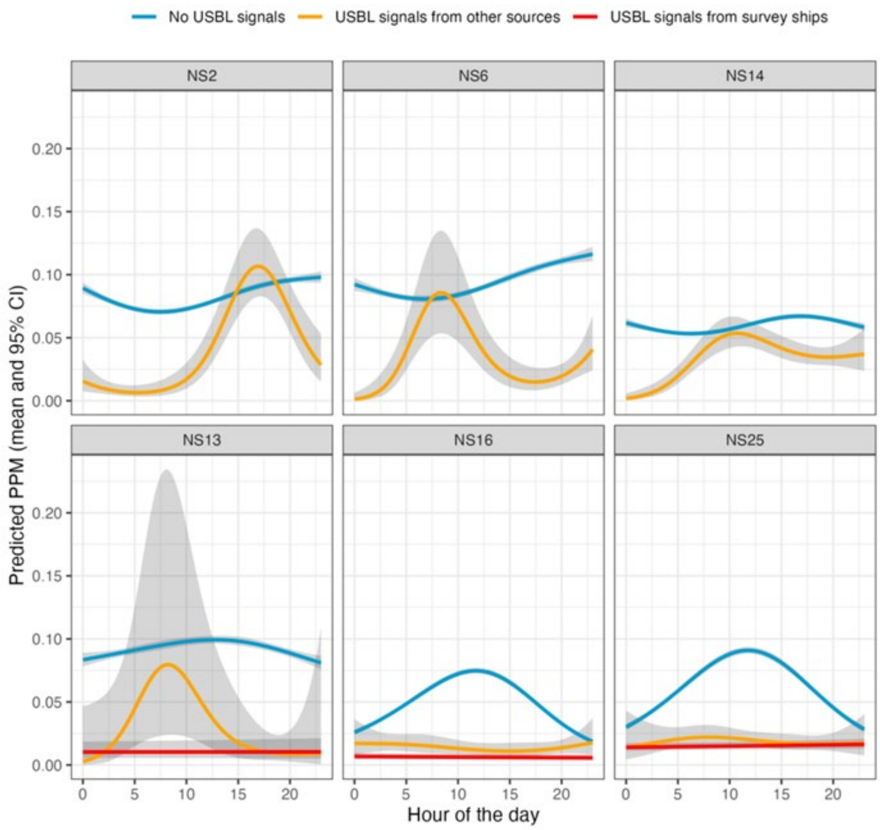


Figure 4-4-27: Graphical output of the GAMM analysis estimating diel variation in the mean probability of porpoise positive minutes (PPM) for each of the 6 stations, and for each USBL type (no USBL signals in blue, USBL signals from other sources in orange, and USBL signals from survey ships in red). The 95% confidence interval around the predicted mean PPM is given in grey. Results for control stations (NS2, NS6, NS14) are provided in the top row, while results for the impact stations (NS13, NS16, NS25) are provided in the bottom row of the figure.

4.4.6.3 *Estimating and correcting for the impact of USBL signals to assess baseline data of harbour porpoises*

The results showed that the baseline data collected for harbour porpoises in the North Sea I survey area was biased during the presence of geophysical survey vessels. Therefore, five scenarios were tested in an attempt to compensate (i.e. exclude affected baseline data) for the impact of geophysical survey vessel presence, on F-POD detections, evaluated in effectiveness by examining change in PPM and CPM. Please see Mikaelsen et al. (2025) for details and results.

The approach that had the most consistent results was to remove the waiting time – the first 239 minutes (mean + 95% CI rounded to nearest minute) following geophysical survey vessel presence within 5.5 km distance of the F-POD stations (max impact range), from each of the impact stations. Hereafter, mean CPM and PPM per month was recalculated to test for effect on the entire dataset. The recalculated CPM and PPM for all tested F-POD datasets, consistently showed an increase in mean values, indicating that the approach had a compensating effect (effect on PPM is shown in Figure 4-4-28).

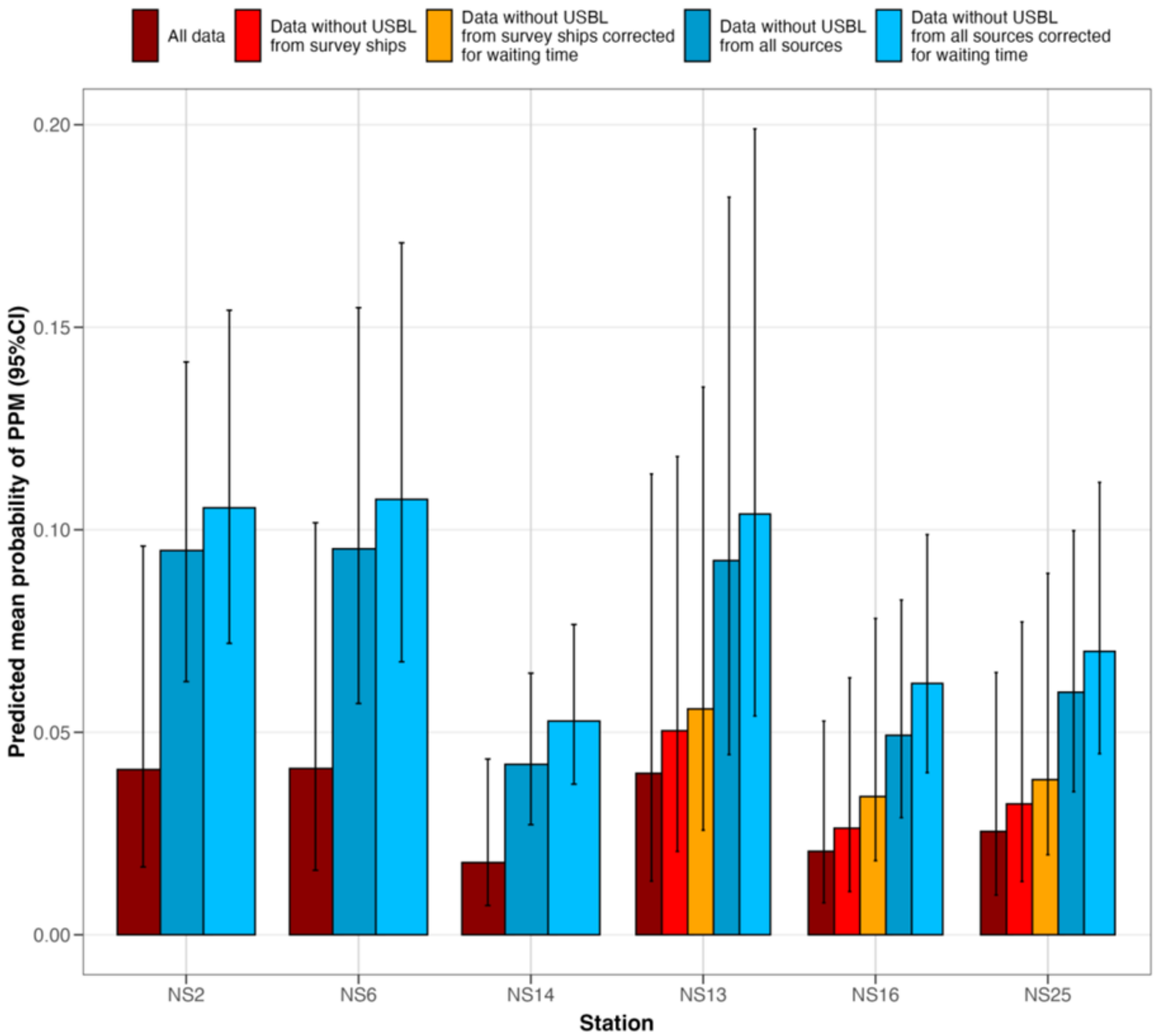


Figure 4-4-28: Bar plot showing the predicted mean (95% CI in black) probability of porpoise positive minutes (PPM) for each dataset and station. Stations NS02, NS06 and NS14 were part of the control area (i.e. no survey vessels detected and only other sources emitting USBL signals), while NS13, NS16 and NS25 were part of the impact area (i.e. survey vessels detected as well as other sources emitting USBL signals). The five different datasets that were considered included "All data" (dark red bars) representing the full dataset with all USBL signals included. The dataset indicated with red bars is a subset of the full dataset from which all minutes with USBL signals from survey vessels were removed. The dataset indicated with orange bars is a subset of the full dataset from which all minutes with USBL signals from survey vessels were removed as well as the 238.9 minutes following the last USBL detection of a survey vessel (based on the predicted upper 95% CI of harbour porpoise waiting time at impact stations shown in Figure 4-4-26.). The dataset indicated with dark blue bars is a subset of the full dataset from which all minutes with USBL signals from all detected sources were removed. Finally, the dataset indicated with light blue bars is a subset of the full dataset from which all minutes with USBL detections were removed as well as the 238.9 minutes following the last USBL detection of a survey vessel and the 261.4 minutes following a the last USBL detection from another source (based on the predicted upper 95% CI of porpoise waiting time (USBL-HP) at impact stations shown in Figure 4-4-26).

Of the five approaches tested, the final approach required the smallest amount of data to be excluded from the dataset; 18.3% of minutes in the dataset for the three tested impact stations.

This approach makes it possible to adjust data. In the end, the FPOD data of the baseline survey was not corrected partly due to the high level of unidentified USBL signals in the area, and it must be assumed that the data represents a minimum of potential harbour porpoise activity in the NSI survey area.

5. Conclusion

5.1 Harbour porpoise

Prior to the present monitoring program, harbour porpoise presence in the North Sea I survey area has only been assessed during the four SCANS surveys conducted during July–August (1994, 2005, 2016 and 2022). These surveys provided broad scale snap shots and had only sporadic parts of a few transect lines in or near the survey area (Hammond et al., 2002; Hammond et al., 2013; Hammond et al., 2021; Gilles et al. 2023). Therefore, no data were available to assess the development in abundance of harbour porpoises in the survey area. The results of the four published SCANS surveys suggest that the harbour porpoise population as a whole is stable in the North Sea.

The data collected in the North Sea I PAM survey baseline study shows that harbour porpoises were present at all 42 stations in the survey area throughout the year, but with large variation between the daily detection levels at all stations. On a monthly temporal scale, there is little variation across the year.

The monthly models of PPM per day in 2023 and 2024 also showed considerable spatial and temporal variation in harbour porpoise presence in the survey area. The models explained on average ~50% of the deviation in the data, which is considered very high for such models. Of the explanatory variables, PPM per day generally declined with increasing distance from sandeel spawning grounds and the dynamic forcing variables: mixed layer thickness, sea surface salinity, temperature, sea surface height and current velocity explained most of the variation in the data. Furthermore, they all correlated with PPM per day in a non-linear fashion that differed between months likely due to seasonal changes in environmental conditions and thus prey availability in the area.

The PAM distribution models showed no clear seasonal trend or pattern in distribution and even subsequent months were often very different from each other. Together with the graphs of PPM per day, this indicates that the North Sea I survey area continuously had a varied level of harbour porpoise presence. It may vary from day to day from high to low levels throughout the year, which is also shown in the levels of harbour porpoise abundance found in the aerial surveys.

The comparison of harbour porpoise detections over time in the planned Thor Offshore Wind Farm showed that the mean PPM per day was significantly higher in 2023–2024 compared to 2019–2020 and that 2024-2025 was significantly higher than 2023-2024. At the Horns Rev 3 Offshore Windfarm (which commenced operation in 2019), we found approximately two-fold times higher detection levels inside the windfarm compared to outside. Furthermore, the annual mean PPM per day for the three stations located inside the wind farm was significantly higher ($p<0.05$) than outside for all three periods. This means that even before the wind farm was built, the area inside was used more by harbour porpoises than the neighboring area outside and furthermore that this distribution did not change by the construction of wind farm. We found no clear trend in harbour porpoise detections per year across the six Horns Rev 3 stations. The relative abundance of porpoises was higher in 2012-2013 and 2024-2025 and lowest in 2023-2024.

The comparison of CPOD and FPOD detection rates, showed that levels of detections on CPODs and FPODs were similar but with the FPOD generally recording slightly more porpoise detections than the CPOD. This means that the absolute level of porpoise detections from the two passive acoustic devices are not directly comparable, but that the relative levels are.

The results of the eight surveys conducted during 2023 and 2024 indicate that the number of harbour porpoises in the area vary across seasons and year with an average across surveys around 7250 individuals in the area and a density of 1,00 individuals/km2 (Figure 4-2-9). These numbers are “inflated” by the June 2023 survey, where the hitherto unseen number of porpoises were observed resulting in a density of 2.91 ind./km2 and an abundance of 22,206 harbour porpoises. On that particular survey, the water was "boiling" with fish schools and both minke whales and white-beaked dolphins were observed in the survey area, clearly following the fish into the area. Thus, based on these eight aerial surveys, it is concluded that harbour porpoise will at most times be present the North Sea I survey area at varying densities (between 0.53 and 1.07 individuals per km2) but at some particular periods follow the prey into the area and therefore occur in significantly higher densities. The observed calf ratios in both June 2023 and 2024, July 2024 and August 2024 indicate that the North Sea I survey area may be an important breeding area for harbour porpoises in the North Sea. During the summer aerial surveys in 2023 and 2024, calf rations were found between 10% and 21%. A study in German waters near Sylt (Sonntag et al., 1999) described a calving area based on two aerial surveys one year apart where they found a calf ratio of 10–17%. This area was confirmed as breeding area in later surveys (Gilles et al., 2009; Gilles et al., 2011; Gilles et al., 2016). Consequently, it is likely that the North Sea I survey area also should be categorized as a breeding area for harbour porpoises.

Both PAM and aerial survey data illustrate that there was extensive variation in harbour porpoise density in the survey area between days. It is likely that variations in prey availability is a major driver for this finding. Another possible explanation could be the influence of geophysical and geotechnical surveys. The specific study examining effects of USBL signals on presence of harbour porpoises showed that USBL pulses scare harbour porpoises away, and that the waiting time increased significantly until the next harbour porpoise detection following a USBL signal. The study also found a possible method to correct the PAM data. However, this method requires SoundTraps at all PAM stations, which was not the case for the North Sea I survey program. It can therefore only be speculated that some of the variation in PAM data can be attributed to the presence of geophysical and geotechnical surveys using USBL, which can cause avoidance responses in harbour porpoise. Aerial surveys represent snap shots in time as the survey plane covers the area over a single day only. It is therefore expected that there can be large differences between survey dates, but also between the two methods.

5.2 White-beaked dolphin

To date, the only studies examining presence of dolphins in the North Sea are the four SCANS aerial distance sampling surveys conducted in July–August (1994, 2005, 2016 and 2022) (Hammond et al., 2002; Hammond et al., 2013; Hammond et al., 2021; Gilles et al., 2023) and the North Sea Energy Island survey program in 2022-2023 conducted in the northeastern Danish North Sea (Kyhn et al., 2024a). The present study provides the first data on dolphin presence in the eastern North Sea off the southern Danish coast.

White-beaked dolphins were observed during aerial surveys for both marine mammals and birds. The PAM data did reveal some detections of white-beaked dolphins and other delphinids in the data evaluated for this report. Even with relatively few white beaked dolphin detections, there are increases in detection positive hours (DPH) during the spring and summer across both years, which coincides with the calving, nursing and mating period for white-beaked dolphins in the summer months. This fits well to the white-beaked dolphin mother-calf pairs observed during the cetacean aerial survey on 14th of June 2023. Most of the detections were recorded on the northwestern stations, or within the deeper waters along the shelf, which is consistent with our knowledge of their habitat use (Kinze, 2009). Most of the bioacoustic activity was captured during nighttime hours, indicating that the animals may be using the shelf waters within the study area for feeding. Due to the low detection rate, it is unlikely that this region constitutes an important part of the animal's habitat, however it is not possible to make any definitive assessment based on these limited data.

5.3 Minke whales

The presence of minke whales in the North Sea has only been documented during the four July-August SCANS surveys (1994, 2005, 2016 and 2022) (Hammond et al., 2002; Hammond et al., 2013; Hammond et al., 2021; Gilles et al. 2023) and during the North Sea Energy Island survey program (Kyhn et al., 2024a). The SCANS data indicate the population of minke whales in the North Sea is stable and that the North Sea I area is likely on the edge of the distribution of this population.

During the aerial survey program, six minke whales were observed in the area in June and July 2023. There were no observations of minke whales during the five surveys in 2024. This is insufficient to evaluate the status of the area for minke whales, but enough to confirm that they are present in the area at least in the summer months. No minke whales were detected in the acoustic data. This should however not be seen as evidence of absence, but could also result from low call rates, low animal density, or production of calls outside the repertoire the detector searched for.

5.4 Seals

Seals were not part of the survey program for the North Sea I area but information from existing data and published scientific reports and articles are presented. See section 3.2 for a review on occurrence and distribution at haul-outs.

5.4.1 Seal use of the North Sea I project area

The habitat suitability maps show that both species of seals are predominately found close to the places where they haul out, and that the likelihood of encountering seals is relatively high in the North Sea I survey area. This corresponds to the pattern obtained by observing the filtered satellite tracking data although the habitat suitability map for harbour seals suggests that the North Sea I survey area is more frequently used than a visual inspection of the satellite tracking data would indicate. This is related to the high number of seals on haul-out sites in the Wadden Sea. The available tagging data of harbour seals also indicate that the North Sea I survey area is mainly used by seals from the Wadden Sea and not the Limfjord population. For a stronger baseline dataset on seals, it is recommended to focus on the haul-out sites in the Wadden Sea and supplement the existing data.

5.5 Noise

The noise monitoring data from year one of this study were analyzed, modelled, and are now available as baseline data for subsequent impact assessments and projects. Noise levels which exceeded the harbour porpoise behavioral response threshold were more concentrated along the known shipping lane along the west edge of the survey area, and around large commercial ports. Concern has been raised about the contribution from geophysical survey ships in the project area in 2023 and the associated likely disturbance on harbour porpoises. This potential contribution from survey systems and associated equipment, most notably the underwater telemetry system USBL, was not quantified in the analysis presented here.

Underwater noise from two operating wind turbines, one with and one without gearboxes, were obtained. These recordings show that overall noise levels and frequency content are in line with what is to be expected from extrapolation of existing data from other turbines (Bellmann et al. 2023). The noise for both turbine types is only audible above ambient noise at low frequencies, below 1 kHz. As seals and harbour porpoises have poor hearing at these low frequencies, the audibility of the noise is low for these species. For harbour porpoises, the range of audibility is predicted similar to what has been suggested previously (Tougaard et al. 2022), i.e. a few hundred meters maximum.

Localization of harbour porpoises within 150 m of an operating turbine highlighted that harbour porpoises move within a few hundred meters from the two arrays as localized positions were primarily within 300 meters and they appear in no clear clustering pattern. Additionally, the analysis to test whether localized porpoise positions were closer to the turbine compared to a reference point with comparable detection probability, showed no clear effect of the turbine on harbour porpoises (neither attraction, nor deterrence).

In the analysis of differences in harbour porpoise detections between 50 and 200 m from four different turbines, no clear reef effect on the scale investigated with this data was found. While a mild attraction was found at one turbine with relatively low harbour porpoise detections, the other three turbines with much higher rates of harbour porpoise detections showed the opposite. If a reef effect does exists, it may be at a larger geographic scale than the 200 m distance from individuals turbines as investigated here. Our results underscores the importance of investigating the microhabitats within a windfarm, as the usage of the habitat around a turbine is not uniform among turbines.

6. Data and knowledge gaps

6.1 Lack of data on seal distribution in the survey area

It is important to note that the habitat suitability maps for the North Sea I survey area are based on a relatively small sample of tagged seals, and that it would have been preferable to tag more seals closer to the area of interest to improve the predictions for this area. Particularly, both grey and harbour seals tagged at locations in the Danish Wadden Sea would have been desirable. Additionally, the data is skewed in terms of sex (mostly males) and age (mostly adult harbour seals, mostly juvenile grey seals) and may thus not be representative of the entire population. TIHO only tagged juvenile grey seals less than a month of age, and their results are therefore representative of naïve juvenile grey seal pups, adapting to the marine environment and developing their foraging skills. For the North Sea Energy Island survey program, mainly adult harbour seals were tagged. TIHO tagged grey seals at Helgoland in January–February, whereas AU/NIRAS tagged grey seals of mixed age in March 2023, May 2022 and September 2022 and at Thyborøn for the North Sea Energy Island survey program (2023), providing data throughout the annual cycle from the latter area. Data are currently being received from 26 harbour seals tagged in the Danish Wadden Sea by Aarhus University in 2025, these data will be available for future analyses.

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Appendix 1

Statistical comparison of the annual average PPM at each station between Y1 (Apr23-Mar24) and Y2 (Apr24-Mar25). Bold p-value indicates statistically significant difference between years (alpha=0.2)

Mean (95% CI) PPM/day/month				
Station name	Area	Apr 2023 - Mar 2024	Apr 2024 - Mar 2025	p-value
NS12	Pre-Investigation area	67.5 (43.6–91.5)	85.4 (54.5–116.3)	0.42
NS13	Pre-Investigation area	90.1 (44.1–136.1)	105.3 (82.1–128.4)	0.55
NS16	Pre-Investigation area	61.4 (43.3–79.4)	80.6 (51.0–110.3)	0.30
NS17	Pre-Investigation area	83.0 (44.0–122.0)	103.3 (60.6–146.0)	0.50
NS19	Pre-Investigation area	70.6 (49.0–92.2)	91.7 (31.5–151.9)	0.50
NS20	Pre-Investigation area	91.5 (54.7–128.4)	145.7 (97.0–194.3)	**0.10**
NS21	Pre-Investigation area	115.5 (86.8–144.3)	141.2 (99.5–182.8)	0.32
NS24	Pre-Investigation area	69.9 (49.7–90.0)	88.3 (69.6–107.1)	**0.20**
NS25	Pre-Investigation area	90.3 (69.2–111.4)	139.9 (103.3–176.4)	**0.03**
NS8	Pre-Investigation area	122.4 (85.3–159.4)	206.8 (168.8–244.7)	**0.01**
HR3_1	Survey Area East	152.5 (90.9–214.0)	125.2 (93.2–157.1)	0.47
HR3_2	Survey Area East	69.5 (45.6–93.3)	111.0 (89.6–132.3)	**0.02**
HR3_3/NS23	Survey Area East	119.4 (89.1–149.6)	119.5 (86.4–152.7)	0.99
HR3_4	Survey Area East	21.3 (12.3–30.4)	56.8 (43.4–70.1)	**<0.01**
HR3_5	Survey Area East	46.0 (34.0–58.0)	85.5 (63.9–107.1)	**<0.01**
HR3_6	Survey Area East	62.7 (49.3–76.0)	143.2 (103.7–182.7)	**<0.01**
NS27	Survey Area East	83.3 (40.5–126.1)	109.8 (83.7–135.9)	0.31
NS28	Survey Area East	64.9 (45.8–84.0)	125.2 (94.4–156.0)	**0.01**
NS29	Survey Area East	46.7 (31.9–61.6)	100.4 (78.5–122.3)	**<0.01**
NS30	Survey Area East	60.0 (42.9–77.1)	100.0 (33.7–166.4)	**0.15**
NS31	Survey Area East	90.1 (61.5–118.7)	104.3 (72.7–135.9)	0.52
NS32	Survey Area East	118.1 (89.6–146.6)	139.6 (108.3–171.0)	0.33
NS33	Survey Area East	77.7 (61.4–93.9)	88.9 (72.5–105.4)	0.35
NS34	Survey Area East	62.1 (40.5–83.7)	79.9 (52.5–107.3)	0.32
NS35	Survey Area East	114.5 (78.0–150.9)	154.0 (99.8–208.3)	0.24
T3/NS26	Survey Area East	95.0 (56.9–133.2)	99.1 (68.3–130.0)	0.87
T4	Survey Area East	59.5 (38.3–80.7)	69.0 (45.4–92.6)	0.56
NS1	Survey Area West	76.6 (54.3–98.8)	91.8 (65.1–118.6)	0.40
NS10	Survey Area West	70.6 (56.4–84.9)	98.3 (59.6–137.0)	**0.20**
NS11	Survey Area West	74.9 (56.4–93.4)	72.5 (54.6–90.3)	0.86
NS14	Survey Area West	69.4 (40.7–98.1)	50.0 (41.0–58.9)	0.24
NS15	Survey Area West	115.3 (54.9–175.6)	64.6 (35.7–93.6)	**0.17**
NS18	Survey Area West	89.0 (72.3–105.7)	131.7 (103.2–160.2)	**0.02**
NS2	Survey Area West	125.8 (80.0–171.6)	151.8 (73.2–230.3)	0.56
NS22	Survey Area West	25.3 (16.9–33.6)	33.6 (23.1–44.1)	0.24
NS3	Survey Area West	61.4 (50.6–72.2)	108.8 (80.3–137.4)	**<0.01**
NS4	Survey Area West	74.1 (46.0–102.1)	108.2 (79.7–136.7)	**0.13**
NS5	Survey Area West	52.1 (32.5–71.6)	83.8 (51.6–116.0)	**0.11**
NS6	Survey Area West	151.3 (99.4–203.1)	98.1 (75.0–121.1)	**0.09**
NS7	Survey Area West	87.8 (41.9–133.7)	88.7 (69.9–107.6)	0.98
NS9	Survey Area West	82.0 (50.4–113.6)	77.3 (49.4–105.2)	0.83
T2	Survey Area West	68.0 (47.0–89.0)	94.5 (70.5–118.6)	**0.12**

Appendix 2

Period-specific response curves showing the estimated association between the eight environmental conditions and monthly variation in PPM per day across the survey area. The left two columns show the response curves for NSI monitoring period 1 (Apr 2023-Mar 2024) and the right two columns show the response curves for NSI monitoring period 2 (Apr 2024-Mar 2025) Note that the bottom two panels show the effect of station name, which was included as a random effect and the XY coordinates of the stations were included to account for spatial autocorrelation on a weekly basis.