EFFECTS ON HARBOUR PORPOISES FROM RØDSAND 2 OFFSHORE WIND FARM

Scientific Report from DCE – Danish Centre for Environment and Energy

No. 42 2012

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Data sheet

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Abstract: E.ON Vind Sverige has been commissioned the construction of Rødsand 2 Offshore Wind Farm comprising 90 wind turbines, south of Lolland-Falster, Denmark. The location of the wind farm is 3 km west of the existing Nysted Offshore Wind Farm with 72 turbines. In combination the two wind farms represents the largest wind farm area in the world. Porpoises were monitored by automatic acoustic dataloggers (T-PODs) according to a statistical BACI design and deployed during baseline (Sep 2008-Feb 2009) and during operation (Sep 2011-Mar 2012). These instruments were deployed at 10 stations covering a coastal stretch of 35 km from Gedser to Rødby, including the wind farm area with reference areas on both sides. In addition, background noise at four of the T-POD stations was recorded by automatic noise loggers. In order to assess the potential cumulative effect of two adjacent wind farms, similar data from the Nysted Offshore Wind Farm were also analysed. We found no overall change in echolocation activity over the entire monitoring area from baseline to operation of Rødsand 2 Offshore Wind Farm. Also, there was no significant change in the echolocation activity in Rødsand 2 Offshore Wind Farm relative to each or a combination of the three reference areas, i.e. changes from baseline to operation were similar in the impact and reference areas. Also no significant change in noise levels audible to porpoises was found. This could be due to a generally high noise level in the area, masking the turbine noise or that the noise loggers in the wind farm were deployed between the wind turbines, i.e. at distances ~350-450 m from the turbines. This study also shows that the echolocation activity is still significantly lower in Nysted Offshore Wind Farm since the baseline in 2001-2002, although the difference seem to gradually diminish possibly due to a habituation of the porpoises to the wind farm or better feeding posibilities. We found no cumulative effect of the two wind farms together. The gradual return of porpoises in Nysted Offshore Wind Farm seemed to be unrelated to the construction of Rødsand 2 Offshore Wind Farm. This is the first time the effect of two wind farms next to each other have been studied.

Keywords: Static acoustic monitoring, long-term effect, cumulative effect, BACI design, echolocation, harbour porpoise, *Phocoena phocoena*, offshore wind farm, Rødsand 2 Offshore Wind Farm, Nysted Offshore Wind Farm, porpoise detector, T-POD

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Summary

E.ON Vind Sverige has been commissioned the construction of Rødsand 2 Offshore Wind Farm comprising 90 wind turbines, south of Lolland-Falster, Denmark. The location of the wind farm is west of and adjacent to the existing Nysted Offshore Wind Farm with 72 turbines. The two wind farms are spaced about 3 km and in combination represents the largest wind farm area in the world.

This report investigates the potential effects of the Rødsand 2 Offshore Wind Farm as well as the cumulative effect of both wind farms on harbour porpoises. Porpoises were monitored by automatic acoustic dataloggers (T-PODs) according to a BACI design and deployed during a baseline period from 24 September 2008 to 16 February 2009 and during normal operation from 24 September 2011 to 2 March 2012. These instruments were deployed at 10 stations covering a coastal stretch of 35 km from Gedser to Rødby, including the wind farm area with reference areas on both sides that are assumed to represent the same type of habitat to the porpoises. Instruments were not moved between stations during the study to reduce variation from inter-instrument variation in sensitivity. In addition, background noise at four of the T-POD stations was recorded by automatic noise loggers during 45 days and 49 days during the two monitoring periods, respectively.

In order to assess the potential cumulative effect of two adjacent wind farms, the data from the monitoring program of harbour porpoises at Nysted Offshore Wind Farm were analysed together with the more recent data from the Rødsand 2 Offshore Wind Farm.

The total monitoring period covered 1824 days for all recording instruments in total, almost equally distributed between baseline and operation. Four indicators of harbour porpoise echolocation click activity was extracted, in line with previous studies at other offshore wind farms. These are 1) Click intensity (Clicks/PPM), indicating as the daily average number of clicks produced per minute for minutes where porpoises were recorded, 2) Porpoise positive minutes (PPM), indicating the percentage of minutes per day where clicks were recorded, 3) Encounter duration indicating the duration of porpoise acoustic encounters (defined as separated from pervious encounter by at least 10 minutes of silence), 4) Waiting time, indicating the time between two porpoise acoustic encounters.

Underwater noise in the area showed a pronounced peak in the frequency spectrum around 1000 Hz consistently across all stations. This signal is considered to originate from the deep water shipping lane south of the measuring stations. Systematic differences among stations included a generally lower noise level in the existing wind farm and highest noise level at the easternmost station, which was located close to the sailing route into Gedser harbour. Underwater noise was generally higher during the baseline period in 2008/2009 for all areas, than during the operation period in 20011/2012 probably due to more rough weather conditions in the baseline period. However, the Rødsand 2 area was particularly noisy during the baseline period. This is also partly supported by the number of ships related to the wind farm present in the wind farm area during the baseline period, where exploration and other activities were already started. It is therefore a possi-

bility that the porpoises in the Rødsand 2 area were already affected by noise from ship activity during the baseline period.

We found no overall change in echolocation activity over the entire monitoring area from baseline to operation of Rødsand 2 Offshore Wind Farm. Also, there was no significant change in the echolocation activity in Rødsand 2 Offshore Wind Farm relative to each or a combination of the three reference areas, i.e. changes from baseline to operation were similar in the impact and reference areas. Also no significant change in noise levels audible to porpoises was found. This could be due to a generally high noise level in the area, masking the turbine noise or that the noise loggers in the wind farm were deployed between the wind turbines, i.e. at distances ~350-450 m from the turbines.

This study also shows that the echolocation activity has declined in Nysted Offshore Wind Farm since the baseline in 2001-2002, which is consistent with earlier reports, and has not fully recovered yet. However, when comparing the wind farm area with the reference area in the most recent monitoring period (2011-2012, operation period 4), there was a relatively higher echolocation activity than during the construction period (2002-2003) and operation period 1-3 (2004-2006 and 2008-2009), showing a significant increase from construction to operation period 4 in click PPM and encounter duration as well as significant increases in PPM from operation periods 2 and 3 to operation period 4. This suggests that the strong negative effect on porpoises in Nysted Offshore Wind Farm is gradually diminishing possibly due to a habituation of the porpoises to the wind farm.

We found no cumulative effect of the two wind farms together. The gradual return of porpoises in Nysted Offshore Wind Farm seemed to be unrelated to the construction of Rødsand 2 Offshore Wind Farm. A similar effect on the porpoises at Rødsand 2 Offshore Wind Farm as found for Nysted Offshore Wind Farm could be expected. We have no good explanation for the lacking effect and can only speculate that the elevated noise or changes to the prey availability during the baseline period could have an effect on our results or that there was an already low porpoise presence in the Rødsand 2 area caused by a potential barrier effect by Nysted Offshore Wind Farm, when the animals move along the coast in an east-west direction. This is the first time the effect of two wind farms next to each other have been studied and the potential explanations to the observed differences are pure speculation.

A potential positive effect of the wind farms over time, as organisms grow on the foundations and increase forage possibilities, have not been studied. To fully understand the long term effect of wind farms a continuous monitoring program with detailed information on the behavior of porpoises inside and around wind farms is required.

Dansk Resumé

E.ON Vind Sverige har stået for opførelsen af Rødsand 2 Havmøllepark, som består af 90 møller, syd for Lolland-Falster, Danmark. Havmølleparken er placeret vest for og i forlængelse af Nysted Havmøllepark med 72 møller. De to havmølleparker ligger ca. 3 km fra hinanden og udgør det største samlede område med havmøller i verden.

Denne rapport undersøger den mulige effekt på marsvin af Rødsand 2 Havmøllepark alene og også den kumulative effekt af to nærliggende havmølleparker. Tilstedeværelsen af marsvin blev undersøgt ved hjælp af automatiske akustiske data loggere (T-PODs) udlagt i en baseline periode fra 24. september 2008 til 16. februar 2009 og under normal drift fra 24. september 2011 til 2. marts 2012. Instrumenterne blev udlagt på 10 stationer, som dækker en 35 km lang strækning gennem de to havmølleparker og kontrolområder fra Gedser til Rødby. Instrumenterne blev ikke flyttet mellem stationerne for at reducere variationen forårsaget af sensitivitetsforskelle mellem instrumenterne. Derudover blev undervandsstøjen målt på fire af de ti T-POD stationer med specielle støjloggere i 45 og 49 dage under henholdsvis baseline of drift perioderne.

I relation til kumulative effekter af de to nærliggende havmølleparker, blev data fra de tidligere undersøgelser af Nysted Havmøllepark analyseret sammen med data indsamlet i dette studie.

I alt blev marsvinenes lyde optaget i 1824 dage for alle instrumenterne samlet, hvoraf halvdelen var under baseline- og halvdelen under drifts perioden.. I lighed med tidligere undersøgelser blev fire indikatorer for marsvinene aktiviteter udtrukket fra T-POD dataene. Disse er: 1) Click intensity (Clicks/PPM), udtrykt som et dagligt gennemsnit af ekkolokaliseringsklik i de minutter, hvor der blev optaget marsvinelyde) 2) Porpoise positive minutes (PPM), udtrykt som den procentvise andel af minutter pr. dag hvor marsvinelyde blev optaget 3) Encounter duration, udtrykt som den tid et marsvin kan høres omkring en T-POD (to forskellige marsvineoptagelser skal være adskilt af mindst 10 minutters stilhed, 4) Waiting time, udtrykt som den ventetid, der går mellem to forskellige marsvine encounters.

Undervandsstøjen i det undersøgte område viser en top omkring 1000 Hz på alle stationer. Dette signal forventes at stamme fra sejlruten syd for havmølleparkerne (T-ruten). Der er målt systematiske forskelle mellem stationerne med f.eks. generelt mindre støj i Nysted Havmøllepark og højest støjniveau i det østlige referenceområde nær Gedser Havn. Undervandsstøjen var generelt højere under baseline perioden i 2008/2009 i hele området i forhold til driftsperioden i 2011/2012, hvilket formentlig skyldes mere vind og bølger som øger baggrundsstøjen. Derudover havde Rødsand 2 området et specielt højt støjniveau under baseline perioden. Dette kan delvis forklares med det større antal skibe, der var til stede i forbindelse med forberedelser til byggeriet under baseline perioden. Det er derfor ikke utænkeligt at marsvinene i Rødsand 2 området allerede var negativt påvirket under baseline perioden.

De statistiske analyser viste ingen overordnet forskel i de optagne marsvinelyde på nogen af stationerne fra før byggeriet startede til Rødsand 2 Havmøllepark var i drift. Derudover var der ingen signifikant forskel i marsvinenes ekkolokalisering i Rødsand 2 Havmøllepark sammenlignet med de enkelte eller kombinerede kontrolområder. Dvs. at de relative ændringer i antallet af marsvin i havmølleparken svarede til den, der blev observeret på kontrolstationerne. Ligeledes blev der ikke fundet signifikante ændringer i støjniveauet indenfor det frekvensområde, som er hørbart for marsvin. Dette kan skyldes et generelt højt støjniveau, som maskerer støjen fra havmøllerne, eller at støjloggerne var placeret mellem møllerne i en afstand af ca. 350-450 m.

Dette studie viste også, at der stadig detekteres meget færre marsvin i Nysted Havmøllepark sammenlignet med baseline perioden i 2001-2002, der er dog en tendens til at de gradvis vender tilbage. Ved at sammenligne data fra Nysted Havmøllepark med data fra kontrolområdet i den sidste periode (2011-2012, driftsperiode 4), kan det påvises, at der er sket en gradvis stigning i antallet af marsvin sammenlignet med anlægsperioden (2002-2003) og de efterfølgende driftsperioder 1-3 (2004-2006 and 2008-2009). Signifikant stigning blev målt fra anlægsperioden til periode 4 for "click intensity" (click/PPM) og "encounter duration". For "porpoise positive minutes" (PPM) skete der en signifikant stigning fra periode 1 til 2 og fra periode 2+3 til periode 4. Dette tyder på, at den kraftige negative effekt under og efter byggeriet at Nysted Havmøllepark langsomt er ved at aftage, muligvis fordi marsvinene er ved at vænne sig til havmølleparken.

Vi fandt ikke nogen kumulativ effekt af de to havmølleparker. Den gradvise tilbagevenden af marsvin i Nysted Havmøllepark ser ud til at ske uafhængig af opførelsen af Rødsand 2 Havmøllepark. Man kunne forvente en lignende negativ effekt på marsvin fra Rødsand 2 Havmøllepark, som blev fundet for Nysted Havmøllepark. Vi har ikke nogen god forklaring på den manglede effekt og kan kun gætte på at f.eks. støjen eller de ændrede fødesøgningsmuligheder pga. forberedelserne til byggeriet, som blev igangsat under baseline perioden, kan have haft en negativ indflydelse på antallet af marsvin i havmølle området. Alternativt kunne man tænke sig, at Nysted Havmøllepark har en barriere effekt på marsvin, der svømmer langs kysten fra øst til vest, og at de marsvin der svømmer uden om Nysted også svømmer uden om Rødsand 2 området. Det er første gang nogensinde, at effekten af to nærliggende havmølleparker bliver undersøgt, og de skitserede forklaringer er derfor udelukkende spekulative.

Den positive effekt en havmøllepark måtte have på marsvin, ved at fødegrundlaget forbedres i takt med, at møllefundamenterne gror til, og vil udgøre et kunstigt rev med potentielt flere fisk, er aldrig undersøgt. For at kunne forstå baggrunden for de forskellige resultater, der er observeret i de studerede havmølleparker, er det afgørende at få flere og mere detaljerede data på marsvins adfærd i og omkring havmølleparkerne.

1 Introduction

E.ON. Vind Sverige has been commissioned the construction and operation of a large offshore wind farm (Rødsand 2) west of the existing Nysted Offshore Wind Farm. In this report the pre and post construction monitoring of harbour porpoises with passive acoustic dataloggers (T-PODs) is described and the results presented.

1.1 Description of the area

The Rødsand 2 wind farm area is located south of the islands Lolland and Falster in the Western Baltic (Figure 1.1). The area is dominated by two large sand barriers (Eastern and Western Rødsand), which borders a shallow lagoon from the deeper Fehmern Belt and Kadet Trench. This narrow sandbar runs about 25 km from Hyllekrog to Gedser and is partly exposed at normal water levels in the middle. The shallow lagoon area (depths 0.5-7 m), is an important area for fish, birds, seals and coastal fishery.

Figure 1.1. Satellite image of Fehmarn Belt and the area south of Lolland and Falster. The Rødsand barrier bordering the lagoon is clearly visible. Guldborgsund connects the lagoon to the waters north of Lolland and Falster. Red polygon indicates the area of Rødsand 2 Offshore Wind Farm, while the yellow polygon indicates the area of Nysted Offshore Wind Farm and green polygon the seal sanctuary. Source: GoogleEarth.

The sea floor south of Rødsand and shallower than 10 m depth contour consists primarily of glacial depositions (Hansson 2000). The largest part of the area is covered by sand/silt bottom with larger and smaller ridges and with aggregations of pebbles, gravel and shells scattered throughout the area. A small natural stone reef (Schönheiders Pulle) is located east of Nysted Offshore Wind Farm.

The water in the area is brackish and salinity varies with the freshwater surface flow from the Baltic Sea and influx of more saline bottom water from Kattegat. The tide is weak in the area (less than 0.5 m) and variations in water level are mainly determined by wind and barometric pressure differences between the Baltic proper and the Kattegat/Danish Straits.

1.2 Harbour porpoises

Harbour porpoises reach a maximum length of about 1.8 m and maximum weight about 90 kg. They are relatively short-lived compared to other odontocetes, with an expected lifetime of about 15-20 years (Figure 1.2, Lockyer and Kinze 2003).

Figure 1.2. Harbour porpoises. Photo: Jonas Teilmann.

1.2.1 Reproduction

The breeding period of harbour porpoises begins in late June and ends in late August. Ovulation and conception, typically take place in late July and early August (Sørensen and Kinze 1994). The pregnancy period is about 11 months and the females thus give birth to the single calf in early summer. The calves begin suckling immediately after birth and feed by their mother until the following year possibly until the next calf is born (Teilmann et al. 2007). The females can conceive when they are 3 or 4 years old (Kinze *et al.* 2003). Changes in food resources may influence the reproduction of porpoises. Calves seem to be sighted throughout their range and there may not be any particular breeding/nursing areas (Hammond *et al.* 1995; Kinze *et al.* 2003). However, satellite tracking of adult females show that they may have individual preference for particular areas (Teilmann *et al.* 2004; Teilmann *et al.* 2008).

1.2.2 Foraging ecology

Between 1985 and 2006, the stomach contents of 392 harbour porpoises from the Kattegat, Danish Straits and the western part of the Baltic Sea were studied. The preferred food sources of harbour porpoises in Danish waters comprise 24 fish species. The percent of occurrence in the 392 stomachs was 45% with gobies (*Gobiidae*), 40% with herring (*Clupea harengus*), 33% with cod (*Gadus morhua*), 18% with saithe (*Pollacius virens*), 12% with sprat (*Sprattus sprattus*) and 11% with sandeel (*Ammodytes spp.*) as the six most important groups (Sveegaard 2010).

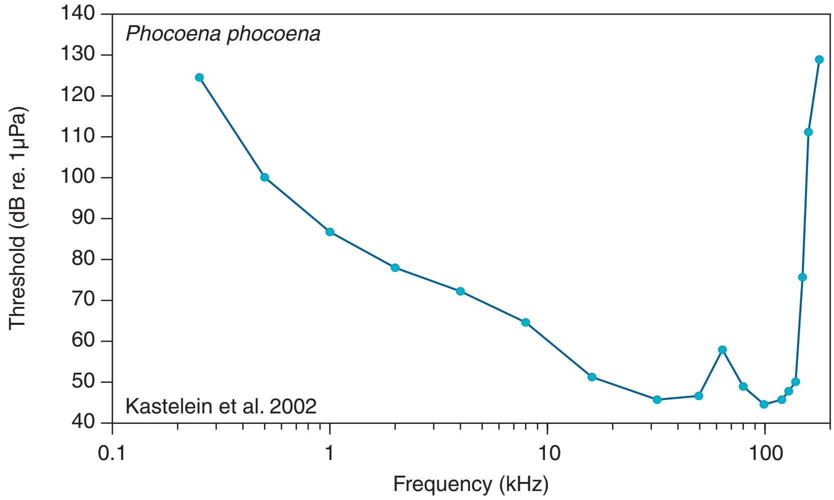
1.2.3 Echolocation and hearing

Like other toothed whales (odontocetes) harbour porpoises have good underwater hearing and use sound actively for navigation and prey capture (echolocation). They produce short ultrasonic clicks (130 kHz peak frequency, 50-100 µs duration; Møhl and Andersen 1973; Teilmann *et al.* 2002) and are able to orient and find prey even in complete darkness. Porpoises tagged with acoustic data loggers indicate that they use their echolocation almost continuously (Akamatsu *et al.* 2005; Akamatsu *et al.* 2007).

Odontocetes have no outer ear and their ear canal is vestigial. Sound does not enter the head through the ear canal, but through the surface of the lower jaw and is transmitted via a channel of fat to the tympanic bulla of the middle ear (Norris 1964; Møhl *et al.* 1999; Brill *et al.* 2001).

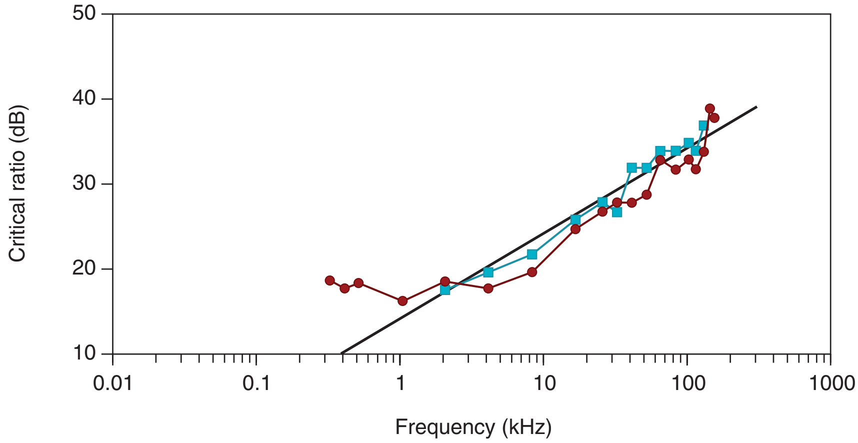
The fundamental measure of an animal's hearing ability is the audiogram, expressing the lowest sound pressures detectable by the animal in quiet conditions measured at different frequencies. Odontocete audiograms are as a whole fairly similar in shape, with range of best hearing in the area 10-100 kHz, and best thresholds around 40-50 dB re. 1 μPa. Hearing thresholds increase slowly with about 20 dB per decade for lower frequencies and increase steeply at high frequencies. Compared to larger odontocetes the harbour porpoise has a higher upper limit of hearing, around 180 kHz (Figure 1.3, Andersen 1970; Kastelein *et al.* 2002).

Figure 1.3. Audiogram of harbour porpoise, measured by behavioural methods (psychophysics). Source: Kastelein *et al.* 2002/2010.



Another central characteristic of auditory systems, especially in the context of influence of noise is the bandwidth of auditory filters. Mammalian auditory systems are conventionally modelled as a bank of narrow bandpass filters. In order for noise to interfere with reception of a particular sound it has to fall within the frequency range of that or those particular filters covering the sound. A general approximation for mammals is that the bandwidth is 1/3 octave throughout the hearing range of the animal (Figure 1.4).

Figure 1.4. Critical ratio measured in two harbour porpoises. Slope of 3 dB/octave (black line) is predicted from a constant Q filter bank. From Kastelein *et al.* (2011).



This is known as a constant Q filter bank (Q is the ratio of centre frequency to bandwidth) and implies that the width of the filters increase with increasing frequency. The filter bandwidth has not been measured directly in harbour porpoises but measurements of the so-called critical ratio is consistent with a constant Q filter bank also for porpoises for frequencies above 1 kHz (Kastelein *et al.* 2011), justifying the use of 1/3-octave filter bandwidths as a first approximation. Below 1 kHz filter bandwidths appears to be wider than 1/3 octave, leading to an underestimation of the audibility and masking capacity of low frequency noise by the 1/3 octave assumption.

1.2.4 Vision

Cetaceans have good vision, although especially odontocetes have small eyes in relation to their body size, compared to other mammals. The eyes are completely adapted to water and vision under low light conditions. The spherical lens makes the eye highly myopic (short-sighted) in air and they are not likely to be able to see objects sharply in air beyond a few meters. Movements however, such as from rotating turbine wings, should be clearly visible to porpoises, even in air.

Porpoises, like other cetaceans and seals, are functionally colour blind (Peich *et al.* 2001).

1.2.5 Other senses

Odontocetes have no sense of smell, whereas taste may play a role, not only in relation to tasting prey, but also in terms of collecting information about the surrounding water. Thus, in the context of anthropogenic impact it is possible that porpoises can taste and will react to harmful and/or distasteful substances in the water.

A magnetic sense, that is the ability to determine the direction of the earth's magnetic field, has only been demonstrated convincingly in a few vertebrates. However, this ability has turned out to be very difficult to explore experimentally (Wiltschko and Wiltschko 1996) and this sensory modality is not nearly as well understood as the other modalities (vision, hearing, smell, electroreception etc.) and it thus is unclear how common this ability is in vertebrates in general. Thus, so far it remains open whether cetaceans have magnetoreceptive capabilities or not.

Until fairly recently it was believed that no mammals had electroreceptive abilities, but it has been conclusively demonstrated that the duckbilled platypus has electroreceptive organs along the edge of the bill and uses these in prey capture (Proske and Gregory 2003). Since then several other mammals have been suspected of possessing electroreceptive capabilities and very recently it has been convincingly demonstrated in the Tucuxi dolphin (Sotalia fluviatilis) from the Amazon River (Czech-Damal *et al.* 2011). So far, however, there is no evidence of this ability in porpoises or other marine species of odontocetes.

1.3 Abundance

Porpoises are present throughout the south-western Baltic, with a relatively sharp gradient towards the Baltic proper east of Rügen, where porpoises are very rare. Several sources of information on animal presence and in some cases also densities are available. The various sources of data are not directly comparable, due to different methodology and area covered.

1.3.1 SCANS I and II

The two SCANS surveys, conducted in 1994 and 2005, represents the largest coordinated effort to map the distribution and abundance of cetaceans, including harbour porpoises in European waters. They were conducted in July both years and thus represent summer distribution of animals. An estimated population size in the North Sea and adjacent waters of about 300,000 was estimated in both 1994 and 2005 (Hammond *et al.* 2002; Hammond in prep.). In the Inner Danish Waters (Skagerrak, Kattegat, Belt Seas and Western Baltic) the abundance of harbour porpoises during summer was 27,769 (cv=0.45) in 1994 and declined to 10,865 (cv=0.32) in 2005 (Sveegaard 2010).

1.3.2 Dedicated aerial surveys

A survey of harbour porpoise abundance in the Bay of Kiel and waters around Fyn was conducted in 1991 and 1992 (Heide-Jørgensen et al. 1992; 1993). The results are consistent with the general pattern from SCANS and other surveys that especially the Great Belt is a high density area with decreasing densities towards the Western Baltic.

43 aerial surveys covering the entire German EEZ in the Western Baltic were carried out in 2002 to 2006 (Figure 1.5). Most sightings were observed west of the line between Darss and Møn, however, in one survey in July 2002 a lot of porpoises were observed in the far eastern part of the area (Figure 1.5).

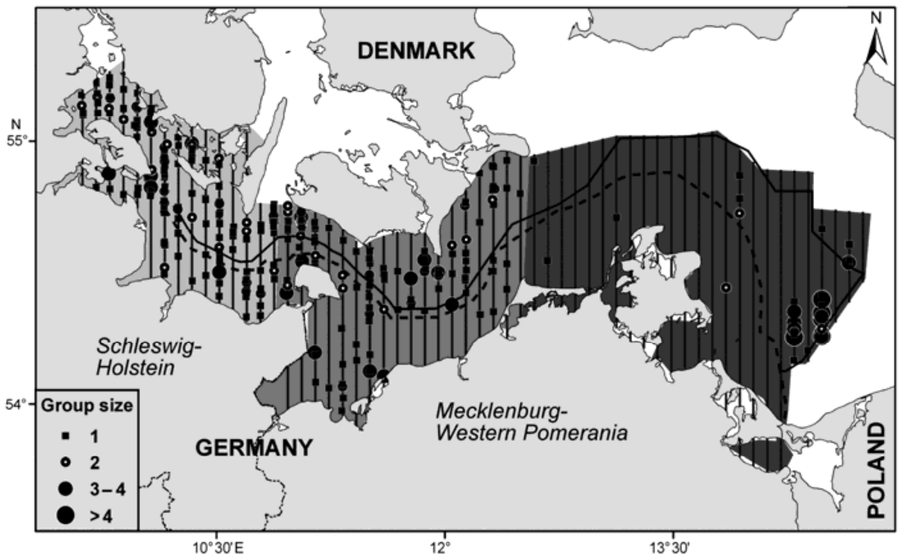


Figure 1.5. Sightings on 43 aerial surveys carried out from 2002 to 2006 (Scheidat *et al.* 2008).

1.3.3 Satellite telemetry

In the years 1997-2007 64 harbour porpoises incidentally live caught in Danish pound nets were equipped with satellite transmitters. Individual animals were tracked for up to 349 days. The animals were caught mainly in the Belt Seas and along the east coast of Jutland. From the data it is evident that animals cover extensive areas and tagged animals moved around in most areas in Kattegat, the Belt Seas and the south-western Baltic. Fewer animals moved into Øresund and east of Møn. A cluster of locations was seen in the Kadet Trench east of Gedser, in Fehmarn Belt, as well as south of Hyllekrog around the Rødsand 2 Offshore Wind Farm area (Figure 1.6. Sveegaard *et al.* 2011).

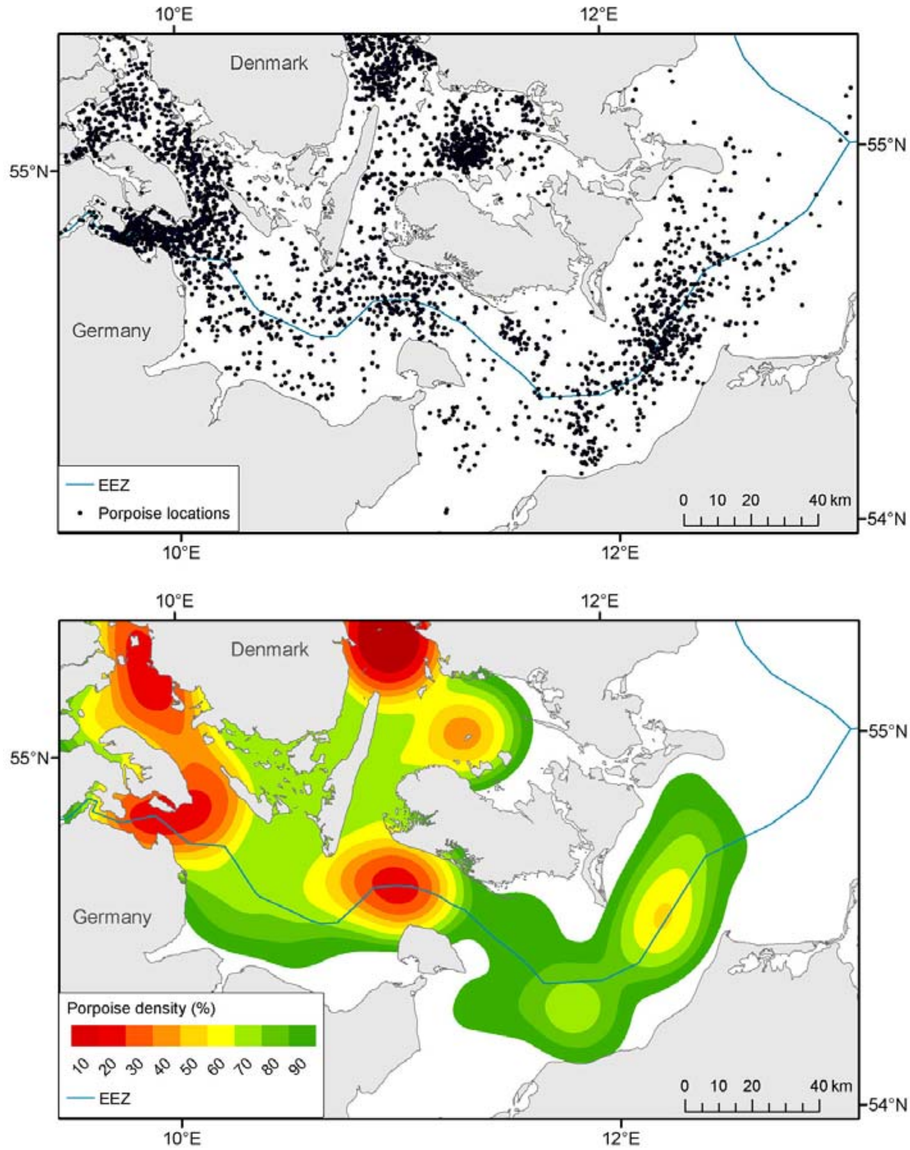


Figure 1.6. Locations from the harbour porpoises equipped with satellite transmitters in part of their range in the Danish Belt Seas and western Baltic from 1997 to 2007. Black dots in upper map indicate one daily position from each satellite tagged porpoise. Coloured areas in bottom map indicate kernel home ranges with darker red indicating higher concentration and darker green lower concentration of animals (Teilmann *et al.* 2008; Sveegaard *et al.* 2011).

1.3.4 T-POD acoustical data

Several studies have used autonomous acoustic dataloggers (T-PODs) that record the echolocation sound of porpoises, to study porpoises in the Western Baltic. One study (Verfuss et al. 2007) has T-POD data from a large number of permanent stations throughout the German Baltic. During the monitoring program at Nysted Offshore Wind Farm T-PODs was also used to monitor the effect of the construction and operation of the wind farm (Carstensen *et al.* 2006; Tougaard *et al.* 2006a).

T-POD data from the German monitoring program are consistent with sighting data, showing a general east-west gradient in abundance with few animals encountered east of Darss (Figure 1.7).

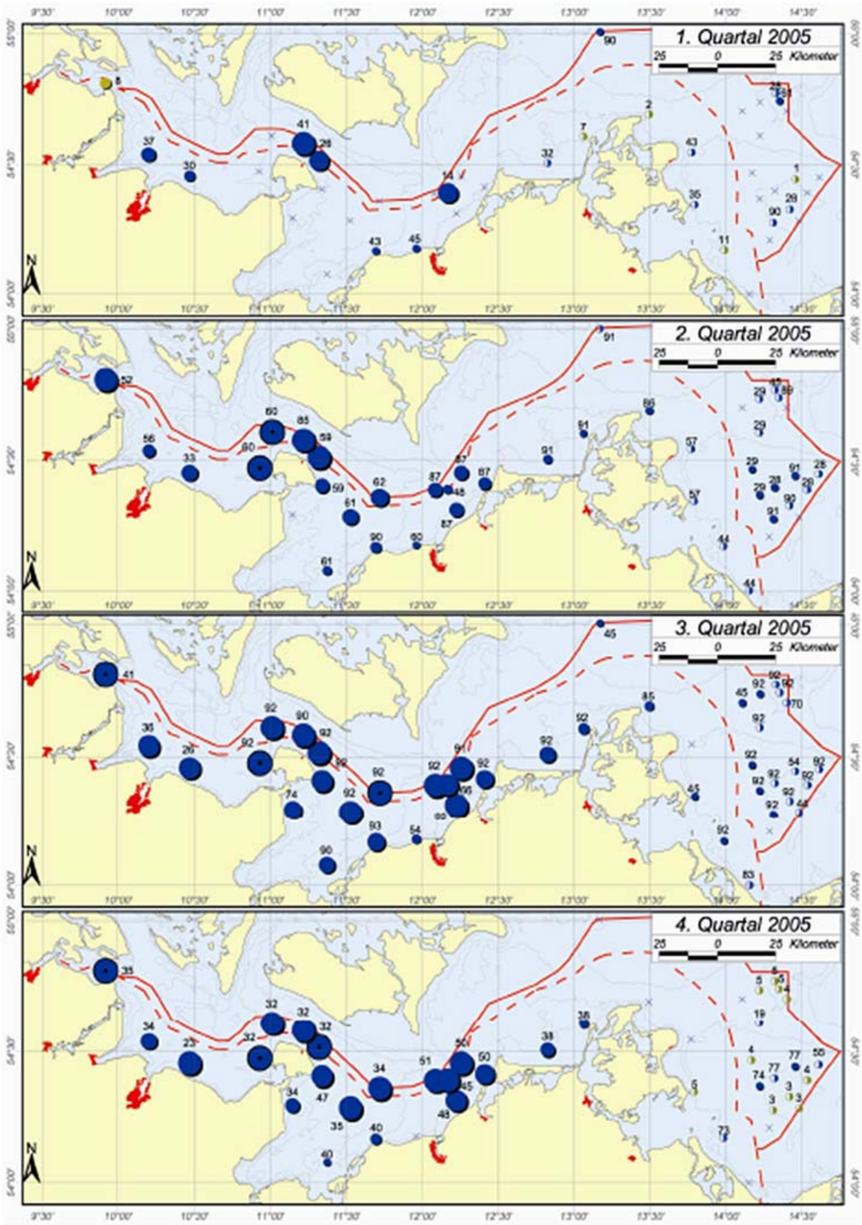


Figure 1.7. Porpoise detections on T-PODs at permanent deployments in the German part of the Western Baltic during 2005. Size of symbols indicates percentage of days with recordings of porpoise signals. Number above symbols indicates deployment days in period (Verfuss *et al.* 2007).

T-POD data from investigations in connection with construction of Nysted Offshore Wind Farm shows a pronounced seasonal pattern in porpoise abundance (Figure 1.8). Two parameters, porpoise positive minutes and waiting time between encounters are shown (see Materials and Methods for explanation). Very few porpoises are encountered during winter months (January-March), with on average about one encounter at the T-POD per week, compared to the peak during summer, where several encounters were recorded daily.

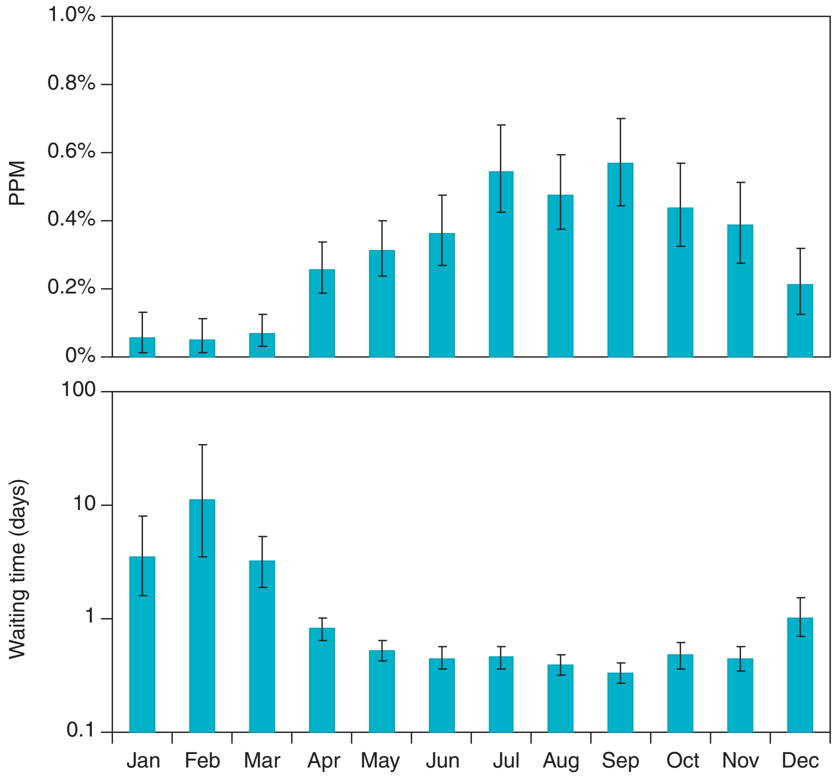


Figure 1.8. Seasonal means for the two indicators porpoise positive minutes (PPM) and waiting time between acoustic encounters. PPM indicates the proportion of the day where porpoise clicks can be recorded. Waiting time indicates the silent time between groups of porpoise clicks. Error bars indicate 95% confidence limits for the mean values (Tougaard *et al.* 2006a).

Although T-PODs have been deployed at several different locations in Danish waters and elsewhere, it is not possible to compare measurements directly. Different hardware versions and settings of T-PODs have been used in different studies and it is not possible to translate these data into exact number of animals in the area. Nevertheless, it is probably safe to say that fewer animals in general are present in the Rødsand area, compared to a high density area such as Horns Reef in the North Sea. On Horns Reef, porpoises were on average encountered more than 10 times per day at the peak of activity in summer, i.e. 10 times more often than in the Rødsand area (Tougaard *et al.* 2006b).

1.4 Protection

The harbour porpoise is listed in Annex II and IV of the Habitats Directive (92/43/EEC), Annex II of the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention), Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals (CMS, Bonn Convention) and Annex II of the Convention on International Trade in Endangered Species (CITES), and it is covered by the Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS), and by the Convention on the Protection of the Marine environment of the Baltic Sea (HELCOM).

The annex IV of the Habitats Directive, among other implies that "*Member States shall take the requisite measures to establish a system of strict protection for the animal species listed in Annex IV (a) in their natural range, prohibiting: ... (b) Deliberate disturbance of these species, particularly during the period of breeding, rearing, hibernation and migration ...*" (article 12).

The ASCOBANS agreement states among other that member states are obligated to "*Work towards ...(c) the effective regulation, to reduce the impact on the animals, of activities which seriously affect their food resources, and (d) the prevention of other significant disturbance, especially of an acoustic nature*" (Annex to Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (New York, 1992)).

2 Materials and methods

2.1 Stations and deployment period

During the pre and post construction of Rødsand 2 Offshore Wind Farm both acoustic activity from porpoises as well as background noise were recorded. Porpoise activity was recorded by means of T-PODs and noise was recorded simultaneously by noise loggers. The instruments were placed at ten stations (HF1-10) including two reference stations near Gedser east of the two wind farms (HF1-2), two inside the Nysted Offshore Wind Farm (HF1-2), (HF1-4 were also monitored during pre and post construction of Nysted Offshore Wind Farm; Tougaard *et al.* 2006a), three stations were placed inside the Rødsand 2 Offshore Wind Farm area (HF5-7) and three reference stations west of Rødsand 2 Offshore Wind Farm (HF8-10). All stations were placed in similar habitats at 7.5-11 meter depths on an east-west direction covering about 35 km (Figure 2.1 and table 2.1).

The four stations used during monitoring of Nysted Offshore Wind Farm are included to be able to determine the cumulative effect of two wind farms next to each other. To be able to compare the results from the former monitoring program with the present it was necessary to deploy both the old T-PODs (hardware V1) and the newer version (hardware V5).

Battery capacity and memory in the T-PODs is under normal conditions sufficient for continuous operation for one month or more. The time series obtained from the T-POD signals contained some gaps where the T-PODs were not deployed or specific T-PODs were not operating properly for various technical reasons. However, fortunately no T-PODs were lost during the baseline, but T-POD #737 at position HF2 was malfunctioning during the operation period and therefore a new T-POD (#796) was deployed at the same position for substitution. At position HF10 T-POD #644 used during the baseline was replaced by another T-POD (#777) during the operation period. The T-PODs have consistently been deployed at the same positions with the exception of these minor changes (Table 2.2 and 2.3). Four positions (HF1-4) were monitored simultaneously with two T-PODs of different versions (V1 and V5), with the aim of intercalibrating with the previous monitoring program for the environmental impact assessment (EIA) carried out at Nysted Offshore Wind Farm (see below). Thus, there has not been any major exchange of T-PODs between positions that would severely bias the statistical analyses due to differences in T-POD sensitivity.

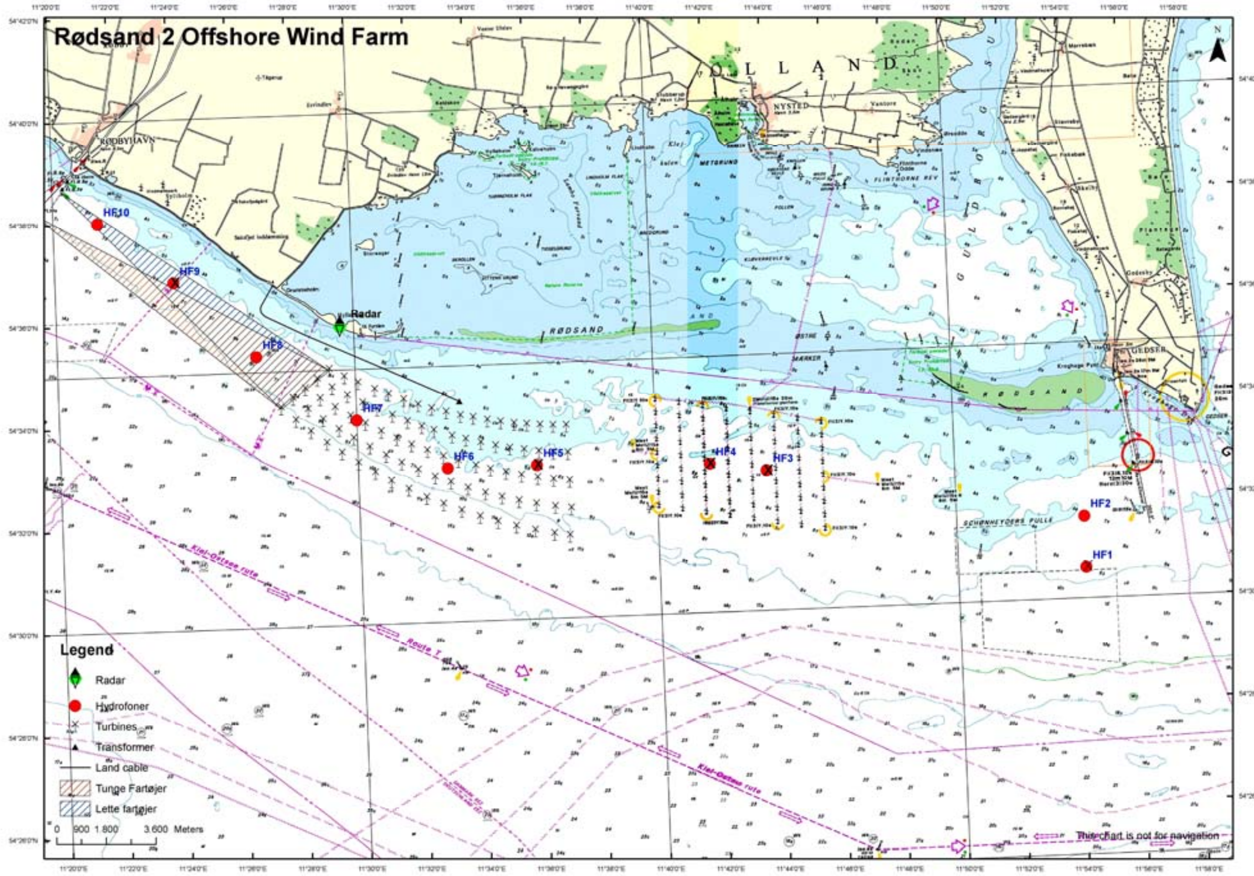


Figure 2.1. Map of the study area with red dots indicating the T-POD stations and black crosses the noise logger positions. Nysted Offshore Wind farm is shown in the middle while Rødsand 2 Offshore Wind Farm is shown to the west.

Table 2.1. List of stations, their coordinates and water depth as well as location of T-PODs and noise loggers during pre- and post-construction.

Station	Name	Position (WGS84)	Depth	T-POD number	Noise logger
HF1	Reference S	54°30,60N 11° 54,30E	11 m	733/ 4	5
HF2	Reference M	54°31,60N 11° 54,30E	7.5 m	737/796/9	
HF3	Impact E	54°32,73N 11° 43,70E	9 m	743/71	
HF4	Impact W	54°32,90N 11° 41,80E	8.5 m	744/56	3
HF5	Rødsand 2 Øst	54°33,00N 11° 36,00E	7.5 m	745	2
HF6	Rødsand 2 Midt	54°33,00N 11° 33,00E	7.5 m	750	
HF7	Rødsand 2 Vest	54°34,00N 11° 30,00E	8 m	751	
HF8	Reference Rødby Øst	54°35,30N 11° 26,70E	8.5 m	757	
HF9	Reference Rødby Midt	54°36,80N 11° 24,00E	8 m	805	4
HF10	Reference Rødby Vest	54°38,00N 11° 21,50E	8 m	644/777	

Table 2.2. Overview of T-POD and Noise logger recordings by station during the three deployment periods during pre-construction.

Station	T-POD/Noise logger	Period 1	Period 2	Period 3	Total number of days
		24 Sep 08 - 31 Oct 08	4 Nov 08 - 10 Dec 08	21 Jan 09 - 16 Feb 09	
HF1	733	19%	100%	0%	45
	4	17%		0%	7
	Noise 5	100% (31 Oct 08 - 23 Nov 08)		100% (21 Jan -12 Feb)	45
HF2	737	15%	100%	0%	43
	9	15%		41%	18
HF3	743	97%	100%	100%	100
	71	8%		40%	15
	Noise 1	0%			0
HF4	744	97%	100%	100%	97
	56	72%		72%	56
	Noise 3	100% (31 Oct 08 - 23 Nov 08)		100% (21 Jan -12 Feb)	45
HF5	745	25%	100%	100%	74
	Noise 2	100% (31 Oct 08 - 23 Nov 08)		100% (21 Jan -12 Feb)	45
HF6	750	29%	100%	100%	76
HF7	751	90%	100%	100%	98
HF8	757	100%	100%	100%	102
HF9	805	100%	100%	100%	102
	Noise 4	100% (31 Oct 08 - 23 Nov 08)		100% (21 Jan -12 Feb)	45
HF10	644	86%	11%	100%	66

Table 2.3. Overview of T-POD and Noise logger recordings by station during the two deployment periods during post-construction.

Station	T-POD/Noise logger	Period 1	Period 2	Total number of days
		24 Sep 11 - 10 Jan 12	16 Jan 12 - 2 Mar 12	
HF1	733	58%	0%	60
	4	6%	0%	7
	Noise 5	100% (29 Sep-20 Oct 2011 and 17 Jan 12 Feb 2012)		49
HF2	796	0%	32%	15
	9	20%	53	45
HF3	743	70%	100%	118
	71	20%	55%	46
HF4	744	57%	85%	98
	56	20%	0%	21
	Noise 3	100% (29 Sep-20 Oct 2011 and 17 Jan 12 Feb 2012)		49
HF5	745	19%	100%	66
	Noise 2	100% (29 Sep-20 Oct 2011 and 17 Jan 12 Feb 2012)		49
HF6	750	39%	0%	42
HF7	751	64%	100%	115
HF8	757	56%	100%	98
HF9	805	48%	93%	93
	Noise 4	100% (29 Sep-20 Oct 2011 and 17 Jan 12 Feb 2012)		49
HF10	777	63%	100%	101

2.2 T-PODs – principle of operation and characteristics

The T-POD or POrpoise Detector is a small self-contained data-logger that logs echolocation clicks from harbour porpoises and other cetaceans (Figure 2.4). It is developed by Nick Tregenza (Chelonia, UK). It is programmable and can be set to specifically detect and record the echolocation signals from harbour porpoises. Detailed descriptions and discussions of the methodology of using T-PODs in monitoring effects of wind farms can be found in previous reports and papers (e.g Tougaard *et al.* 2006a,b; Carstensen *et al*. 2006).

The T-POD consists of a hydrophone, an amplifier, a number of band-pass filters and a data-logger that logs echolocation clicks. It processes the recorded signals in real-time and only logs time and duration of sounds fulfilling a number of acoustic criteria set by the user. These criteria relate to click-length (duration), frequency spectrum and intensity, and are set to match the specific characteristics of echolocation-clicks.

The T-POD relies on the highly stereotypical nature of porpoise sonar signals. These are unique in being very short (50-150 µs) and containing virtually no energy below 100 kHz (Figure 2.2). Main part of the energy is in a narrow band 120-150 kHz, which makes the signals ideal for automatic detection. Most other sounds in the sea, with the important exception of boat echosounders, are characterised by being either more broadband (energy distributed over a wider frequency range), longer in duration, with peak energy at lower frequencies or combinations of the three. In addition echosounders has a more regular pattern than porpoise echolocation.

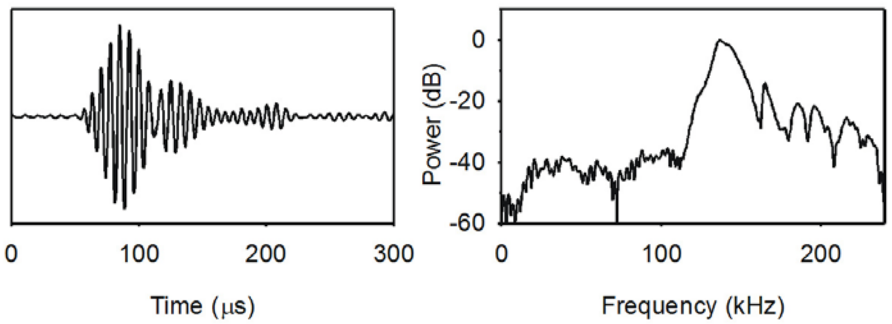


Figure 2.2. Porpoise click time signal (left) and power spectrum (right). There is virtually no energy present below 100 kHz (the curve below 100 kHz represents background noise of the recording).

The actual detection of porpoise signals is performed by comparing signal energy in a narrow filter centred at 130 kHz with another narrow filter centred at 90 kHz. Any signal, which has substantially more energy in the high filter relative to the low and is below 200 microseconds in duration is highly likely to be either a porpoise or an echosounder.

Some spurious clicks of undetermined origin (e.g. background noise and cavitation sounds from high-speed propellers) may also be recorded. These, as well as boat echosounders are filtered out by analysing intervals between clicks using special T-POD software. Porpoise click trains are recognisable by a gradual change of click intervals throughout a click sequence, whereas boat echosounders have highly regular repetition rates (almost constant click intervals). Clicks of other origin tend to occur at random, thus with highly irregular intervals.

No other cetacean regularly found in the Baltic has sonar signals that can be confused with porpoise signals.

The T-POD operates with six separate and individually programmable channels. This allows for e.g. one channel to log low frequency boat activity while the remaining channels log porpoise echolocation activity. However, in this study all channels had identical settings for each type of T-POD: V1 of V5 (Table 2.4). V5 is a further development of V1 using new hard- and software but the principle of the two instruments are the same. The difference in sensitivity between the two versions will be dealt with in the Results section.

Table 2.4. T-POD filter settings used in this study. * value depend on calibration.

	T-POD V1	T-POD V5
A filter frequency	130 kHz	130 kHz
B filter frequency	90 kHz	92 kHz
Ratio A/B	5	-
A filter sharpness (arbitrary unit)	5	4
B filter sharpness (arbitrary unit)	18	
Sensitivity	0.35	8-11*
Noise filter	-	+
Scan limit	240	None
Minimum click length	10 µs	10 µs
Swith angle	254	75

Each of the six channels records sequentially for 9 seconds, with 6 seconds per minute assigned for change between channels. This gives an overall duty cycle of 90% (54 seconds per minute). In order to minimise data storage requirements only the onset time of clicks and their duration are logged. This is done with a resolution of 10 µs. The absolute accuracy of the timing of each recording is much less, due to drift in the T-PODs clock during deployment (a few minutes per month). This drift is of concern when comparing records from another T-POD deployed simultaneously or a noise logger. Clicks shorter than 10 µs and sounds longer than 2550 µs were discarded.

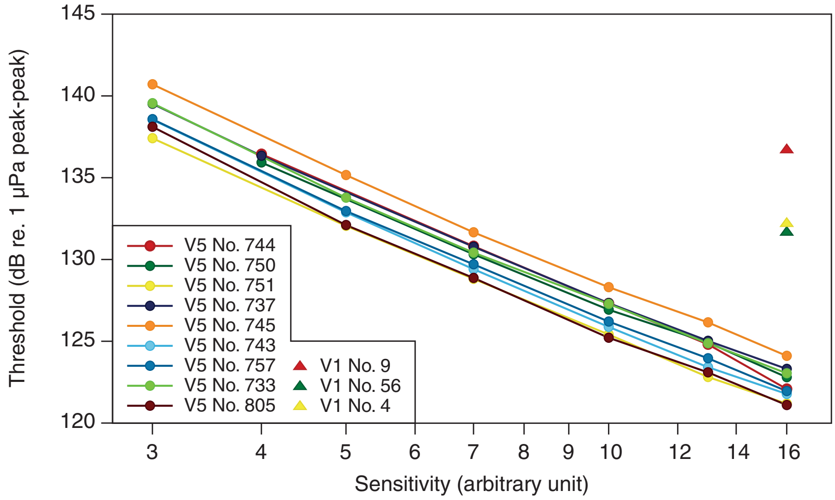
The hydrophone of the T-POD has a resonance frequency of 120 kHz and is cylindrical and thus in principle omnidirectional (equally sensitive at all angles of incidence) in the horizontal plane.

Prior to the first deployment the T-PODs were calibrated in a circular cedar wood tank, 2.8 m deep, 3 m diameter located at University of Southern Denmark's research facility in Kerteminde. T-PODs were fixed in a holder with the hydrophone pointing downwards and placed 0.5 m below the water surface. A projecting hydrophone (Reson TC4033) was placed in the same depth, 1 m from the T-POD. Calibration signals were 100 µs pulses of 130 kHz pure tones, shaped with a raised cosine envelope. Signals were generated by an Agilent 33250A arbitrary waveform generator. Projector sensitivity was measured prior to calibration by placing a reference hydrophone (Reson TC4034) at the position of the T-POD hydrophone.

T-PODs were presented with groups of 130 kHz pulses of decreasing sound pressure. Threshold was defined as the sound pressure level at which 50% of the transmitted pulses were recorded by the T-POD. Thresholds were determined for 6 out of the 16 possible sensitivity settings and for four different angles of incidence (all in the horizontal plane). Average thresholds across the four angles of incidence are shown in Figure 2.3 for the T-PODs used in this study. V1 T-PODs are significantly less sensitive compared to V5 T-PODs (see also intercalibration section below) and were only used with the most sensitive settings (corresponding to the settings used in the previous study at Nysted Offshore Wind Farm).

Following calibration the settings of V5 T-PODs were adjusted to match as closely as possible a sensitivity of 127.5 dB re 1 µPa. One V1 T-POD (No. 71) could not be calibrated for technical reasons (faulty tilt switch, which prevented the T-POD from operating in an upside-down position used in the calibration setup).

Figure 2.3. Calibration curves for T-PODs used in this study.



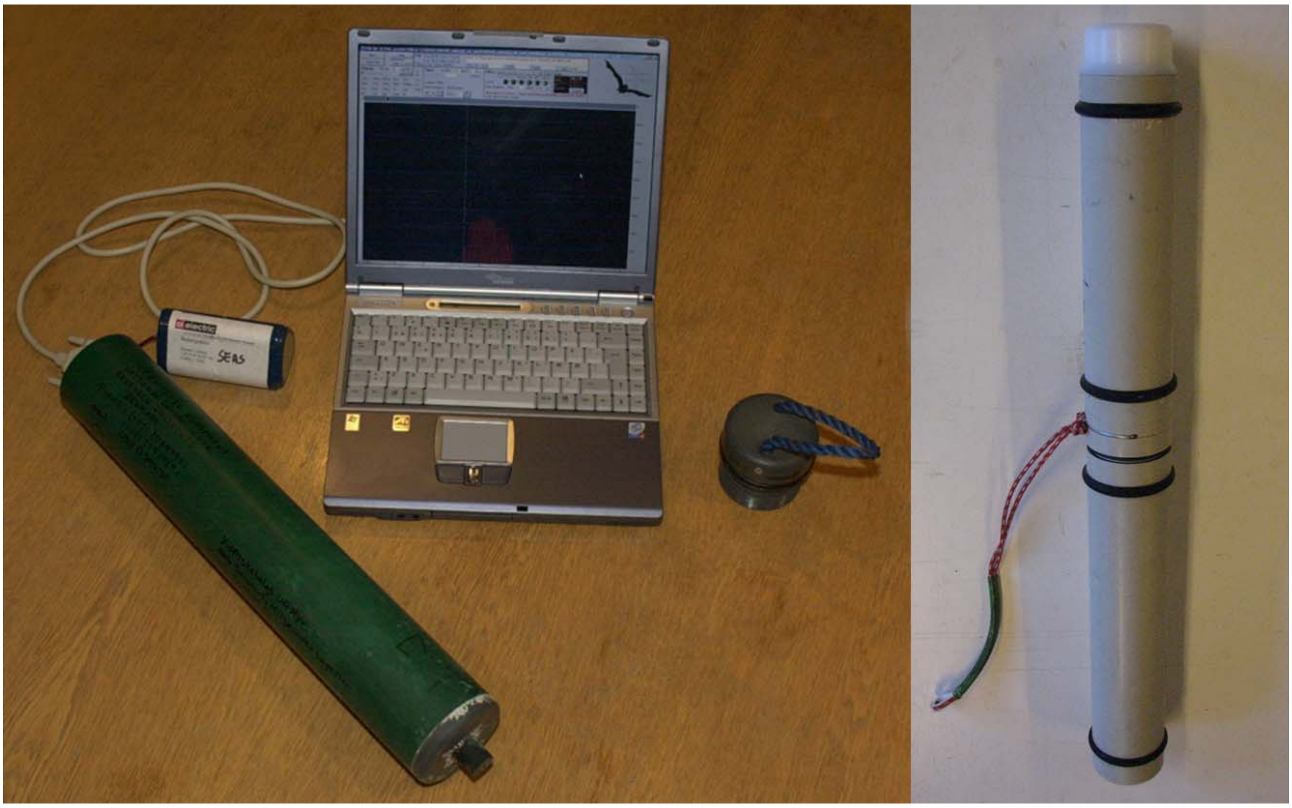


Figure 2.4. To the left: an open T-POD V1 connected to a computer. The hydrophone can be seen as a small attachment sticking out in the lower end of the T-POD. To the right a T-POD V5 is shown. The hydrophone is embedded in white polypropylene on the top of the instrument.

The V1 T-PODs are equipped with 8 MB memory and powered by 6 D-cell type batteries, providing power for a little more than one month. V5 T-PODs have 128 MB memory and is powered by 15 D-cell type batteries, which can power the unit for up to 60 days. The memory will normally fill in 1-4 month depending on echolocation activity, background noise and software settings.

Data from the T-POD can be downloaded with a parallel or USB cable for storage on a PC. Data was downloaded with the T-POD.exe program (version 5.1 for V1 T-PODs and 8.23 for V5 T-PODs) designed for communication with the T-POD and subsequent analysis of data. Figure 2.5 shows an example of downloaded data. Harbour porpoise echolocation clicks were extracted from the background noise using a filtering algorithm that filters out non-porpoise clicks such as cavitation noise from boat propellers, echosounder signals and similar high frequency noise. This filter has several classes of confidence of which the second highest class (“cetaceans all”) was used. Data were exported in ASCII format for statistical analysis after filtering.

The detection range of the V1 and V5 T-POD has been determined in the field and shows a maximum range of 350 m from the T-POD, with a detection function decreasing with increasing distance (Kyhn et al. 2012), however the detection function is strictly dependent on the detection threshold of the individual T-POD.

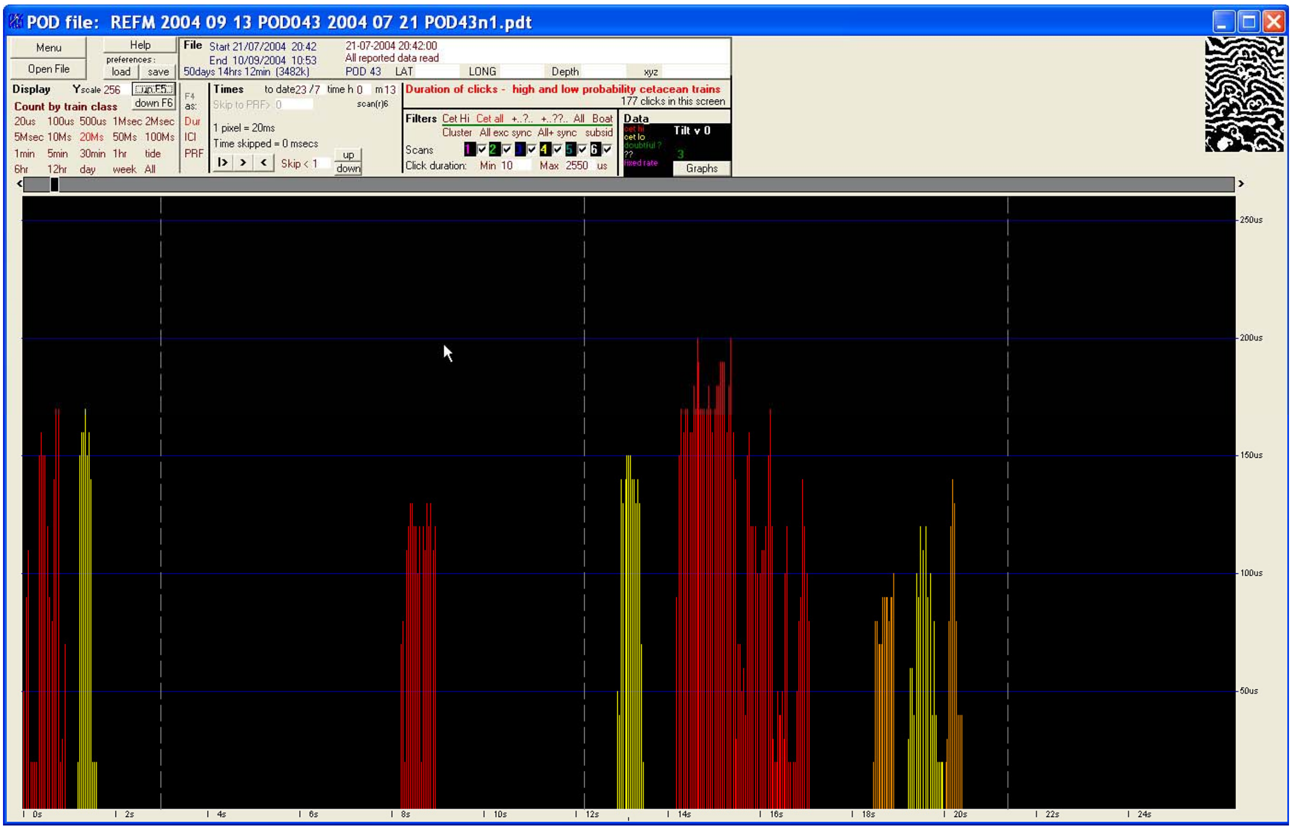


Figure 2.5. Screen snapshot from the T-POD.exe software. Several series of porpoise clicks can be seen as vertical bars. Time in seconds is shown on the X-axis, and the duration of each click is shown on the Y-axis.

2.3 Mooring of T-PODs and Noise loggers

Field experiments have shown that T-PODs deployed near the bottom record a higher level of harbour porpoise echolocation activity than those deployed simultaneously near the surface (Nick Tregenza pers. comm.). The T-PODs in this study have all been moored about 1 m above the bottom. The mooring method is shown in Figure 2.6, 2.7 and 2.8.

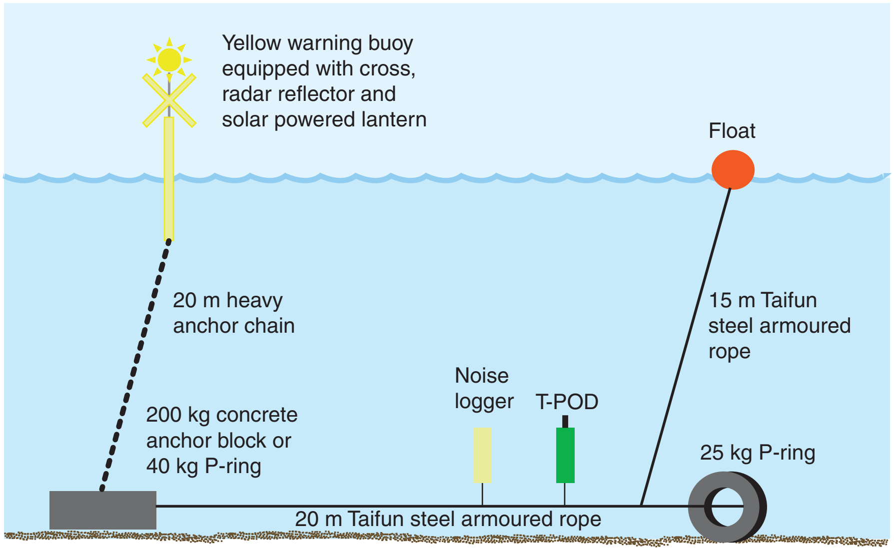


Figure 2.6. The deployment system used for mooring T-PODs and Noise loggers. The set-up has been designed so that the instruments can be lifted to the surface by hand by pulling in the red float.

Figure 2.7. Deployment of the 10 buoys at Rødsand 2 in September 2008.

Figure 2.8. The buoy system seen from the surface. The red float is used to retrieve the instruments without pulling the heavy anchor up.

2.3.1 Porpoise activity indicators from T-POD signals

Four indicators were calculated from the T-POD signals extracted from the T-POD software with a 1 minute resolution. This signal, denoted x_t, describes the recorded number of porpoise clicks per minute and consisted of many zero observations (no clicks) and relatively few observations with click recordings. The click activity per minute was aggregated into daily observations of:

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

Click/PPM Click intensity $= \dfrac{1}{N\{x_t > 0\}} \sum_{x_t > 0} x_t$

Another approach was to consider the recorded click as a point process, i.e. separate events occurring within the monitored time span. Therefore, we considered x_t as a sequence of porpoise encounters within the T-POD range of detection separated by silent periods without any clicks recorded. Porpoise clicks were often recorded in short-term sequences consisting of both 1-minute observations with and without clicks. Such short-term sequences were considered to belong to the same encounter although there were also silent periods (no minute clicks) within the sequence. We decided to use a silent period of 10 minutes to separate two different encounters from each other. This threshold value was determined from graphical investigation of different time series of x_t. Thus, two click recordings separated by a 9 minute silent period would still be part of the same encounter. Converting the constant frequency time series into a point process resulted in two new indicators for porpoise echolocation activity.

Encounter duration = Number of minutes between two silent periods.

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

This implied that waiting times had a natural lower bound of 10 minutes, and that encounters potentially included zero minute recordings. Encounter duration and waiting times were computed from data from each T-POD deployment individually identifying the first and last encounters and the waiting times in-between. Consequently, each deployment resulted in one more observation of encounter duration, since the silent periods at beginning and end of deployment were truncated (interrupted) observations of waiting times. Encounter duration and waiting time observations were temporally associated with the time of the midpoint observation, i.e. a silent period starting 30 September at 12:14 and ending 1 October at 1:43 was associated with the mean time of 30 September 18:59 and categorised as a September observation.

2.3.2 Statistical analysis

The objectives of the statistical analyses were twofold:

1) to assess the effect of Rødsand 2 Offshore Wind Farm by comparing the relative change between designated impact and reference areas from baseline to post-construction, and
2) to assess the long-term effect of Rødsand Offshore Wind Farm in the Nysted Offshore Wind Farm and reference area (cumulative effect).

For the first objective, the Rødsand 2 Offshore Wind Farm was designated as the impact area, whereas Nysted reference area, Nysted Offshore Wind Farm and Rødsand 2 reference area constituted the control areas, to allow for testing the effect in the impact area versus all reference areas combined as well as the reference areas individually. For the second objective, only data from Nysted Offshore Wind Farm and Nysted reference area were used, as impact and control area, respectively. The long-term effect was assessed across 6 periods: 1) Baseline period (November 2001 – June 2002), 2) Construction period (July 2002 – November 2003), 3) Operation period 1 (December 2003 – December 2004), 4) Operation period 2 (January 2005 – December 2005), 5) Operation period 3 (September 2008 – February 2009), and 6) Operation period 4 (September 2011 – March 2012), noting that operation periods 3 and 4 are the same as the baseline and post-construction periods for Rødsand 2 in objective 1.

The indicators were analysed according to a modified BACI-design (Green 1979) that included station-specific and seasonal variation as well. Variation in all four indicators reflecting different features of the same porpoise echolocation activity were assumed to be potentially affected by the following factors (5 fixed and 2 random) and combinations thereof:

- *Area* (fixed factor having 2 levels) describes the spatial variation between control and impact area.
- *Subarea(area)* (fixed factor having 4 levels) describes the spatial variation between the three reference areas (Rødsand reference area, Nysted Offshore Wind Farm and Nysted reference area). This factor was used for the Rødsand EIA only, since there was no subdivision for the long-term assessment at Nysted Offshore Wind Farm.
- *Station (area subarea)* (random factor having 10 levels for Rødsand EIA and 5 levels for the Nysted long-term assessment) describes the station-specific variation (HF1-HF10 or ImpE, ImpN, ImpE, RefM and RefS) within area and subareas.

- *Period* (fixed factor having 2 or 6 levels) describing the difference between the baseline and post-construction periods or among baseline, construction and operation 1-4 periods.
- *Month* (fixed factor having 6 levels (September through February) for the Rødsand EIA and 12 levels (all months) for the Nysted long-term assessment) describes the seasonal variation by means of monthly values.
- *Podtype* (fixed factor having 2 levels) describes the difference between V1 and V5 T-PODs.
- *Podid*(random factor having 16 or 14 levels for the two objectives) describes the random variation between different T-PODs for V1 and V5 separately.

Four of the fixed factors (main factors *area*, *period*, *month* as well as nested factor *subarea(area)*), and their 7 interactions, described the spatial-temporal variation in the echolocation activity, whereas *podtype* described a potential difference in the indicators obtained with V1 versus V5 T-PODs. The use of different T-POD versions was assumed not to interact with the spatial-temporal variation, and consequently interactions between *podtype* and all the spatial-temporal components (first 5 factors in the list above) were disregarded in order to limit the model. Thus, variations in the echolocation indicators, after appropriate transformation, were assumed Normal-distributed with a mean value described by the equation for:

Objective 1: Rødsand Environmental Impact Assessment

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

Objective 2: Nysted long-term assessment

$$\begin{aligned} \mu_{ijkl} &= area_i + period_j + area_i \times period_j \\ &+ month_k + area_i \times month_k + period_j \times month_k + area_i \times period_j \times month_k + podtype_l \end{aligned} \quad (2)$$

Random effects of the model included *station(area subarea)* and any derived interactions with the fixed spatial-temporal factors in (1) and (2) as well as *podid(podtype)* that had a version-specific variance, i.e. different magnitude of variation between T-PODs for V1 and V5. For the Rødsand EIA random effects also included the interactions *period×month*, since there was no replication of months within periods to allow testing this as a fixed effect, and derived interactions from this term combined with *area* and *subarea(area)*.

The reason for modelling station-specific variation as a random factor, as opposed to the models used in the environmental impact assessment of Nysted Offshore Wind Farm (Tougaard et al. 2006), was that exploratory analyses of the data did not indicate systematic gradients with distance from land as was observed with deployments closer to land (RefN and ImpN in the Nysted Offshore Wind Farm EIA). These results suggested a smaller scale and non-systematic random behaviour. The station-specific variation also included differences between T-PODs used to characterise the echolocation activity at that station.

The temporal variation in the indicators was assumed to follow an overall fixed seasonal pattern described by monthly means, but fluctuations in the harbour porpoise density in the region on a shorter time scale may potentially give rise to serial correlations in the observations. For example, if a short waiting time is observed the next waiting time is likely to be short as well. Similar arguments can be proposed for the other indicators. In order to account for any autocorrelation in the residuals we formulated a covariance structure for the random variation by means of an ARMA(1,1)-process (Chatfield 1984) subject to observations within separate deployments, i.e. complete independence was assumed across gaps in the time series.

Transformations, distributions and back-transformations were selected separately for the different indicators by investigating the statistical properties of data (Table 2.5). The data comprised an unbalanced design, i.e. uneven number for the different combinations of factors in the model, and arithmetic means by averaging over groups within a given factor may therefore not reflect the "typical" response of that factor because they do not take other effects into account. Typical responses of the different factors were calculated by marginal means (Searle et al. 1980) where the variation in other factors was taken into account.

Table 2.5. List of transformation, distributions and back-transformation employed on the four indicators for harbour porpoise echolocation activity.

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

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

Waiting times had a natural bound of 10 minutes imposed by the encounter definition, and we therefore subtracted 9 minutes from these observations before taking the logarithm in order to derive a more typical lognormal distribution. Applying the log-transformation had the implication that additive factors, as described in Eqs. (1) and (2), were multiplicative on the original scale. This meant that e.g. the seasonal variation was described by monthly scaling means rather than additive means. Variations in the four indicators were investigated within the framework of generalised linear mixed models (McCullagh and Nelder, 1989), and the significance of the different factors in Eqs. (1) and (2) was tested using F-test (type III SS) for the normal distribution (SAS Institute 2003).

The factor *area×period*, also referred to as the BACI effect, described a step-wise change (e.g. from baseline to post-construction) in the impact area different from that in the reference area. Marginal means for the different factors of the model were calculated and back-transformed to mean values on the original scale. For log-transformed indicators such contrasts can be interpreted by calculating

$$\exp(\text{BACI contrast}) = \frac{E[\text{Impact, post - construction}]}{E[\text{Impact, baseline}]} \cdot \frac{E[\text{Control, baseline}]}{E[\text{Control, post - construction}]} \qquad (3)$$

i.e. the exponential of the contrast describes the relative change from the baseline to the construction period in the impact area relative to the reference area. Similar calculations were carried out for the BACI contrasts between the impact area and any of the three reference subareas in the Rødsand EIA as well as for different combination of periods in the Nysted long-term assessment.

The statistical analyses were carried out within the framework of mixed linear models (Littell et al. 1996) by means of PROC MIXED in the SAS system. Statistical testing for fixed effects (F-test with Satterthwaite approximation for denominator degrees of freedom) and random effects (Wald Z) were carried out at a 5% significance level (Littell et al. 1996). The F-test for fixed effects was partial, i.e. taking all other factors of the model into account, and non-significant factors were removed by backward elimination and the model re-estimated, although effects pertaining to the BACI testing (*period*, *area* and *subarea(area)*) were retained for displaying their level of significance.

2.4 Underwater noise measurements

Noise is regarded as the most likely source of disturbance from the operating wind turbines although little is known about other effect like presence of structures and changes in prey availability. Underwater noise issues are in general more difficult to address than similar issues on land, due to the fact that very few measurements of natural background noise and noise from human activities are available. Thus, the ability to quantify noise exposure and link it to observations of marine mammals is central for determination of cause and effect relationships.

Underwater noise from sources that vary unpredictably in time such as operating turbines, as well as background noise should be recorded by autonomous systems capable of continuous recording over longer periods. Recently such an instrument has been developed (DSG datalogger from Loggerhead Instruments, Florida, Figure 2.9). This unit can be deployed on the seafloor or suspended in the water column and will record noise continuously (for low frequency noise) or intermittently (for high frequency noise) for periods up to several weeks. This not only allows for recordings to be obtained from rare events and under unfavourable conditions (poor weather) but also allow a direct correlation between actual noise exposure and echolocation activity from porpoises recorded by the T-PODs.

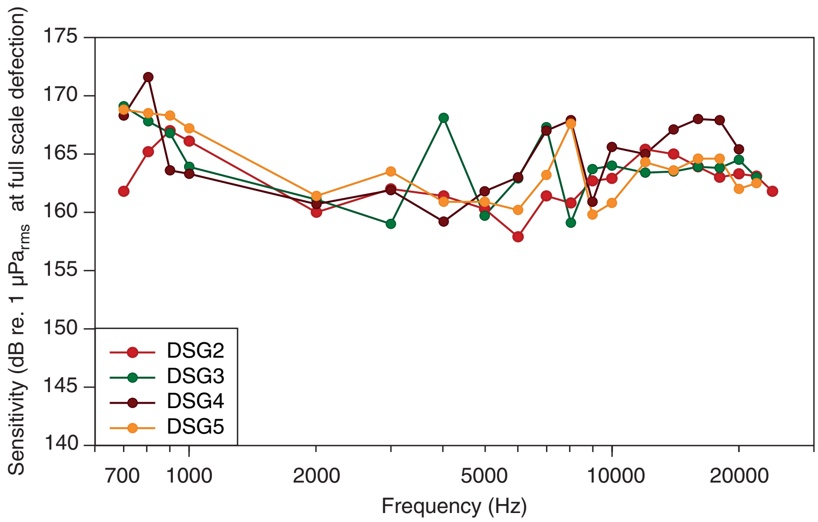
Underwater noise was measured by DSG-dataloggers (Loggerhead Instruments, Florida). The DSG logger consist of a sensitive hydrophone (HTI-96 MIN, Hich Tech Inc, Mississippi, sensitivity -186 dB re. 1 V/µPa) and a data acquisition board with a 16 bit A/D converter operating at up to 80 ksamples/s. Recorded data are stored on a SD-ram card for later downloading to a computer. Recordings can be duty-cycled according to a specified schedule. Memory capacity was 16 GB, corresponding to about 2½ days of continuous recording in deployments in 2008 and 2009. In 2011 and 2012 32 GB cards were used.

Figure 2.9. DSG-recorder from Loggerhead Instruments. Measuring about 50 cm in height. The black rubber extension is the hydrophone.

For this study the loggers were duty-cycled in a schedule with 30 seconds recorded every 6 minutes throughout the day. This translates into 22 ½ days of recording on an 8.3% duty cycle. The rationale for the chosen schedule is a balance between retaining a high temporal resolution and at the same time have recordings of sufficient duration to characterize the noise. One sample every 6 minutes will reliably capture changes in natural background noise, which is mainly determined by the weather and is likely sufficient to record representative samples of ship noise and other anthropogenic disturbances. Except for ships that pass very close to the noise logger, the sampling schedule will assure that close to maximum values are recorded. Duration of each sample was 30 s, which is sufficiently long to allow for an adequate statistical description of the noise within each sample. For stationary Gaussian noise the recording time required to determine average noise intensity with a reasonable confidence interval (+/- 1 dB) is given by the lowest frequency one which to include in the analysis, such that $2*F_{low}*T > 200$. This means that with a lower limiting frequency of 20 Hz, at least 5 seconds of noise is needed to determine the average (RMS) power. Natural background noise is not completely stationary and longer recording time is thus required to obtain sufficient confidence at the lowest frequencies, which is why 30 seconds was chosen as recording time.

DSG-loggers were individually calibrated in a circular wood tank (3 m diameter, 2.8 m depth) filled with sea water. Tone pulses (10 cine wave cycles) were generated by an Agilent 33250A arbitrary waveform generator and projected to the logger by an underwater loudspeaker (Clark Synthesis AQ339, Lubell Labs, Inc.) placed 1.25 m below the surface and 1.8 m from the logger. On the DSG-logger a reference hydrophone was attached (Reson TC4013) which allowed for monitoring of incident sound pressure. Calibration of the reference hydrophone was done with a Brüel&Kjær 4229 Pistonphone calibrator. Some variation in sensitivity with frequency was found in the loggers (Figure 2.10) but this was consistent across loggers (a small decrease in sensitivity from 2000 to 6000 Hz and an increase at higher frequencies). The data from the four loggers are thus considered to be directly comparable. Due to the small size of the tank and the loudspeaker it was not possible to calibrate below 700 Hz.

Figure 2.10. Sensitivity of DSG-loggers determined in tank calibration.



DSG-loggers were deployed together with T-PODs at four of the 10 stations approximately 2 meters above the bottom. The four units recorded for 49 days during baseline and 45 days during post construction (Table 2.2 and 2.3).

Raw recordings were analysed by means of a MatLab routine (FiltBank, by Christophe Couvreur, Faculte Polytechnique de Mons, Belgium) which performed a one-third octave analysis of each 30 second recording. Each 30 second recording was thus reduced to 29 measurements of average (rms) sound pressure level across 29 overlapping frequency bands with centre frequencies in the range 25 Hz to 16 kHz (one-third octave bands according to ISO and ANSI standards).

2.4.1 Statistical analyses

The objectives of the statistical analyses were similar to the first objective in the analysis of T-POD recordings:

- to assess the effect of Rødsand 2 Offshore Wind Farm by comparing the relative change in the noise signal between designated impact and reference areas from baseline to post-construction.

One DSG-logger was deployed in the impact area (HF5) and three DSG-loggers were deployed in the reference area (HF1, HF4 and HF9). These three stations allowed for investigating the random spatial variation. Deployments in October-November 2008 and January-February 2009 comprised the baseline period, whereas deployments in September-October 2011 and January-February 2012 comprised the post-construction period. The noise recordings were aggregated to hourly observations of 1) 1/3-octave band levels at 100 Hz, 1kH, and 10kHz, 2) broadband sound pressure level over the entire spectrum (25 Hz to 16 kHz), and 3) noise level weighted according to the audiogram of porpoises, paralleling the A-weighting performed in human audiology.

These noise data were analysed according to a modified BACI-design (Green 1979) that described the spatial-temporal variation, including differences between stations, daily and diurnal variations. Variation in the five noise signals were assumed to be potentially affected by the following factors (3 fixed and 2 random) and combinations thereof:

- *Area* (fixed factor having 2 levels) describes the spatial variation between control and impact area.
- *Station (area)* (random factor having 4 levels) describes the station-specific variation (between HF1, HF4, HF5, and HF9) within area.
- *Period* (fixed factor having 2) describing the difference between the baseline and post-construction periods.
- *Date(period)* (random factor having 101 levels) describing the temporal variation over the days of deployment in the two periods.
- *Hour* (fixed factor having 24 levels) describing the diurnal pattern.

The three fixed factors and their four interactions described the main spatial-temporal variation in the noise levels, whereas the random factor *station(area)* accounted for spatial differences between stations within the reference area and the random factor *date(period)* described variations in the noise level caused by meteorological conditions and varying shipping intensity, etc. Since the DSG-loggers were deployed during the same periods, temporal variations between days could be factored out, i.e. the potential effect of changing meteorological conditions and ship traffic could be removed by considering relative changes between impact and reference areas. Combinations of *station(area)* and the temporal factors described random variations in the temporal variations between stations, whereas combinations of *date(period)* with hour described random fluctuations in the diurnal noise patterns between days in the two periods. The noise signals were approximately Normal-distribution and no transformation was applied. Thus, variations in noise levels were assumed to be Normal-distributed with a mean value described by:

$$\begin{aligned}\mu_{ijklm} &= area_i + period_j + area_i \times period_j \\ &+ hour_k + area_i \times hour_k + period_j \times hour_k + area_i \times period_j \times hour_k\end{aligned} \tag{3}$$

The factor *area×period*, also referred to as the BACI effect, described a step-wise change (e.g. from baseline to post-construction) in the impact area different from that in the reference area. Similarly, the factor *area×period×hour*, described a relative change from baseline to post-construction in the diurnal pattern between the reference and impact areas. Thus, two main hypotheses were investigated for the overall objective: 1) to investigate an overall relative change in the noise level, and 2) to investigate a relative change in the diurnal noise pattern, assuming that noise from the offshore wind farm may increase the overall noise level and therefore reduce the diurnal pattern from ship and boat traffic.

Marginal means for the different factors of the model were calculated and back-transformed to mean values on the original scale. For log-transformed indicators such contrasts can be interpreted by calculating

$$\exp(\text{BACI contrast}) = \frac{\mathrm{E}[\text{Impact, post - construction}]}{\mathrm{E}[\text{Impact, baseline}]} \cdot \frac{\mathrm{E}[\text{Control, baseline}]}{\mathrm{E}[\text{Control, post - construction}]} \tag{3}$$

i.e. the exponential of the contrast describes the relative change from the baseline to the construction period in the impact area relative to the reference area. Similar calculations were carried out for the BACI contrasts between the impact area and any of the three reference subareas in the

Rødsand EIA as well as for different combination of periods in the Nysted long-term assessment.

2.5 Ship traffic in the Rødsand 2 area

The statistical framework followed that for the porpoise indicators, however, with the main difference that non-significant factors were not removed as this was not necessary due to the balanced design. The baseline monitoring of harbour porpoises started shortly before the first ships entered the area for initial preparations for the dredging work. As indicated in table 2.6 ships related to the wind farm construction had on average 8.2 days without boat activity in 2008/09. The number of ships on days with ship activity was on average 2.3 ships in 2008/09. Variety of ships and the work carried out increased from a few dredging ships making exploratory preparations in 2008 to several dredgers, jack-ups, dredger barges, split barges, tow vessels and crew boats in 2009. In 2011/12 during normal operation of the wind farm, smaller service ships were present in the wind farm almost every day. Only 2.8 days per month were without boat activity. The average number of ships per day on days with ship activity was 1.5. This implies that during baseline there were more ship in the wind farm area towards the end of this period than during the operation phase, however, on average there were more days with boat activity during operation. It is important to note that the ship activity during baseline was carried out by larger ships and probably with more noisy activities than the smaller service ships taking personnel to and from the different turbines. The noise from larger ships have most energy at lower frequencies than the fast service vessels and although the noise from the fast vessels should be more audible to porpoises due to this high frequency emphasis, the frequency dependent absorbtion of sound in water means that the noise from the fast vessels will attenuate faster with distance than the ship noise. This is supported by the noise measurements during baseline and operation, which showed a relatively higher noise level during the baseline period inside the Rødsand 2 area compared to the other areas in contrast to the operation period where the noise inside the Rødsand 2 area was lower than in the reference areas (see section 3.6.1 for more details).

Table 2.6. Number of ships related to construction and operation of the wind farm entering the Rødsand 2 wind farm area during the baseline and post-construction period. *Only the 7 days from instruments were deployed (24-30 September) is included.

Baseline Sep 2008 - February 2012	September	October	November	December	January	February	Mean
Mean Number of ships on active days	0.7	1.5	1	2	4	5.7	2.3
Days with no ship activity	2*	8	15	15	2	1	8.2

Operation Sep 2011 - February 2012	September	October	November	December	January	February	Mean
Mean Number of ships on active days	2.3	1.9	1.3	1.1	1	1.1	1.5
Days with no ship activity	0*	2	1	6	4	1	2.8

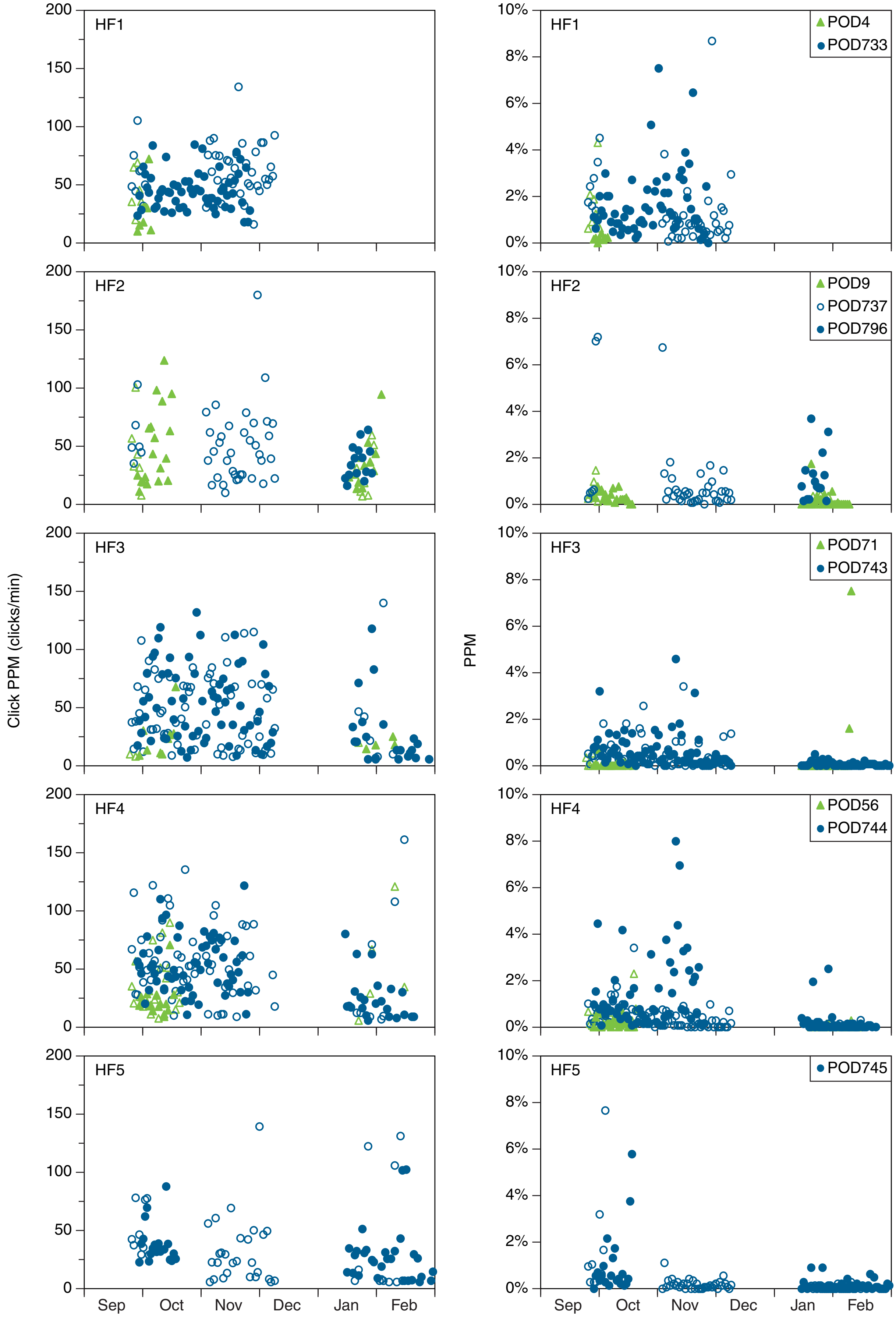
3 Results and Discussion

The echolocation activity of harbour porpoises in the Rødsand 2 region has been assessed by means of porpoise detectors (T-PODs) described above. The first T-PODs for the baseline monitoring of Rødsand 2 Offshore Wind Farm were deployed 24 September 2008 and the baseline extended until 16 February 2009 when all T-PODs were recovered. The post construction (impact or operation period) monitoring lasted from 24 September to 2 March 2012. Similar data sets were collected in the two periods with data for up to 102 and 118 days per unit in the two periods, respectively. The time series obtained from the T-POD signals contain some gaps where the T-PODs were out of the water for service or because they were not operating properly. However, fortunately no T-PODs have been lost during the study and individual T-PODs were deployed at the same stations. Due to malfunctioning T-PODs at station HF2 and HF10 were replaced with other V5 T-PODs with similar sensitivity. Four stations (HF1-4) were equipped with two T-PODs of different versions (V1 and V5) for intercalibration with the previous monitoring program at Nysted Offshore Wind Farm. Thus, there has not been any exchange of T-PODs between stations during the study that could bias the statistical analyses due to differences in T-POD sensitivity. Furthermore, the possibility of comparing with previous T-POD studies using a less sensitive T-POD (V1) is now possible.

The 10 stations with T-PODs have been grouped into 4 areas: Old reference area (HF1 and HF2), Old impact area (HF3 and HF4), New impact area (HF5, HF6 and HF7), and New reference area (HF8, HF9 and HF10). Four of the stations are identical to the stations used when monitoring the effect of Nysted Offshore Wind Farm (HF1 ~ RefS, HF2 ~ RefM, HF3 ~ ImpE, HF4 ~ ImpW). Moreover, at these four stations the very same T-PODs as used in the Nysted Offshore Wind Farm monitoring were used.

3.1 Daily statistics

Click PPM and PPM were calculated from the T-POD recordings (Figure 3.1). There was a total of 1846 days with T-POD monitoring data from the 10 positions (899 during baseline and 947 during operation period) with number of deployment days ranging from 52 at HF1 to 153 at HF4 during the baseline and from 62 at HF2 to 169 at HF3 during the post-construction period (Table 2.3). A total of 219 days were recorded with V1 T-PODs and 1627 were recorded with V5 T-PODs, and there were 152 deployment days with simultaneous recordings at the same positions using V1 and V5. There were only 1340 days with click recordings, because 27% of the deployment days were silent, mostly in January and February. Temporal variations and variation between positions and PODs were relatively smaller for intensities (click PPM) compared to frequencies (PPM). For the 10 positions the coefficients of variation varied between 42% and 130% for click PPM and between 98% and 254% for PPM.



HF1
HF2
HF3
HF4
HF5
POD4
POD733
POD9
POD737
POD796
POD71
POD743
POD56
POD744
POD745
Click PPM (clicks/min)
PPM
200
150
100
50
0
10%
8%
6%
4%
2%
0%
Sep
Oct
Nov
Dec
Jan
Feb

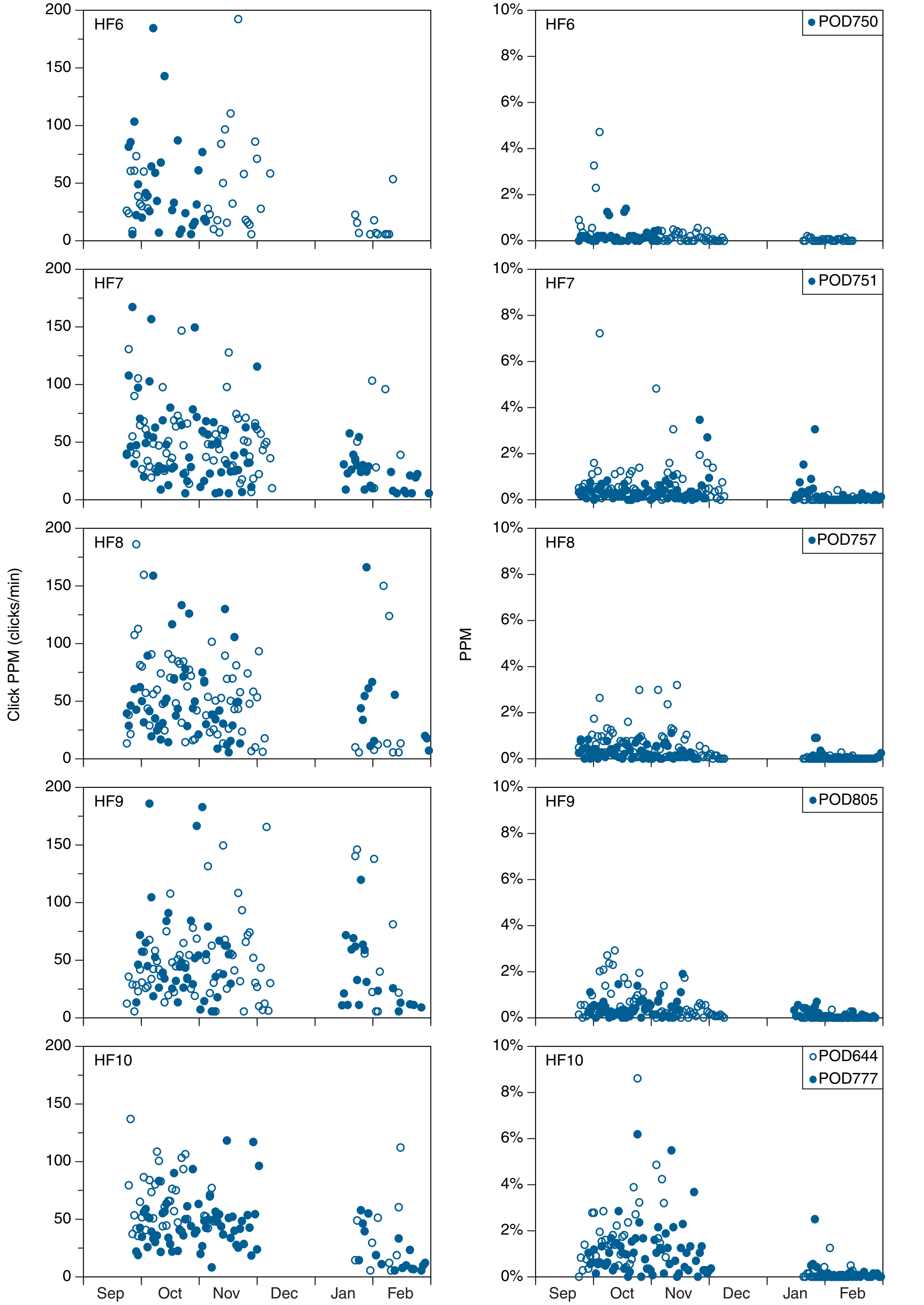


Figure 3.1. Click PPM (left panel) and PPM (right panel) extracted from T-POD data collected during the baseline (September 24th 2008 to February 16th 2009; open symbols) and the post-construction/operation period (September 29th 2011 to March 2nd 2012; filled symbols). Different symbols mark observations derived from different T-PODs (triangles = V1, circles = V5). A few click PPM estimates (19 observations) and one PPM observation exceeded the plotting range (not shown).

There were pronounced differences between months over both the baseline and post-construction periods, even though these covered 6 out of 12 months only (September-February). Click PPM was generally higher during September-December than in January and February, a pattern consistently observed across both periods (Figure 3.1). These tendencies were also pronounced for PPM and many of the days without any recorded echolocation activity were observed in the months of January and February. Spatial differences were also apparent, but due to seasonal differences the statistics in Table 3.1 are not comparable since they cover different months of monitoring and different versions of T-PODs.

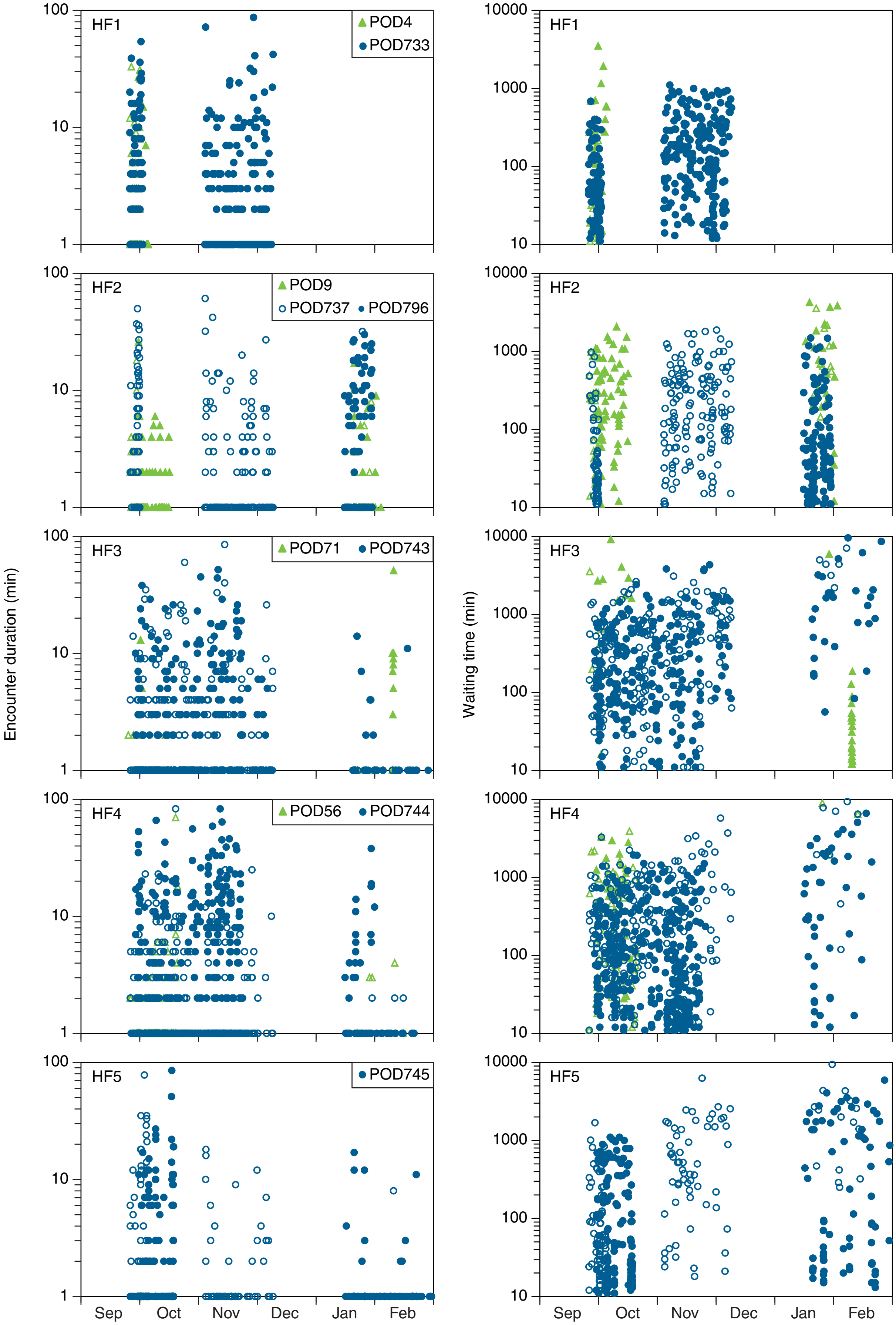
Table 3.1. Statistics of the two daily indicators monitored in the baseline and post-construction periods for Rødsand Offshore Wind Farm. Number of days with PPM is equal to the number of deployment days, whereas number of days with click PPM can be less due to days without any click recordings (missing value of click PPM).

Period	Area	Posi-tion	Click PPM (clicks/minute)					PPM (%)				
			N	Min	Median	Mean	Max	N	Min	Median	Mean	Max
Baseline	Nysted ref.	HF1	52	16.0	56.6	59.8	134.2	52	0.07	0.90	1.41	8.68
		HF2	56	6.9	42.9	46.7	180.0	61	0.00	0.42	0.78	7.19
	Nysted WF	HF3	74	6.7	39.3	45.9	140.0	115	0.00	0.07	0.32	3.40
		HF4	95	5.6	48.6	53.3	225.2	153	0.00	0.14	0.28	3.40
	Rødsand WF	HF5	50	5.6	29.4	52.1	386.7	74	0.00	0.07	0.33	7.65
		HF6	44	5.6	26.9	37.5	192.2	76	0.00	0.07	0.26	4.71
		HF7	77	6.7	47.8	55.2	242.2	98	0.00	0.28	0.55	7.22
	Rødsand ref.	HF8	78	5.6	50.5	57.6	224.9	102	0.00	0.21	0.49	3.19
		HF9	79	5.6	42.0	53.6	240.0	102	0.00	0.21	0.45	2.92
		HF10	49	5.6	53.0	59.5	136.9	66	0.00	0.69	1.15	8.61
Operation	Nysted ref.	HF1	67	10.0	42.5	43.1	84.6	69	0.00	1.11	1.48	7.50
		HF2	47	11.1	33.3	40.7	123.7	62	0.00	0.31	0.46	3.68
	Nysted WF	HF3	99	5.6	34.0	44.0	131.9	169	0.00	0.07	0.35	7.51
		HF4	96	5.6	36.4	44.1	222.0	120	0.00	0.21	0.79	7.99
	Rødsand WF	HF5	49	5.6	24.8	35.4	212.8	68	0.00	0.14	0.40	5.78
		HF6	32	5.6	33.7	52.4	216.7	43	0.00	0.14	0.23	1.39
		HF7	90	5.6	30.4	50.0	557.8	117	0.00	0.14	0.31	3.47
	Rødsand ref.	HF8	62	5.6	41.7	49.6	166.1	100	0.00	0.07	0.21	1.11
		HF9	64	5.6	41.3	50.9	231.1	95	0.00	0.14	0.27	1.90
		HF10	80	5.6	39.8	45.6	420.0	104	0.00	0.35	0.82	10.49

3.2 Encounter statistics

Encounter duration (n=5558) and waiting time between encounters (n=5500) were calculated from the T-POD data (Figure 3.2). The lowest number of encounters (Table 3) during the baseline period were observed inside the Rødsand 2 area at HF5 (n=153) and HF6 (n=146), whereas HF1 had the highest number of encounter (n=384) despite relatively few deployment days (Table 3.2). In the post-construction period the number of encounters ranged from 99 at HF6 to 590 at HF1. Overall there were inevitably fewer waiting times than encounters since the first and last silent period of each separate T-POD recording could not be determined.

The relative variation in encounter duration had a CV=157-226% and for waiting time it ranged from 142-265% for the 10 positions. Both duration and waiting time distributions were strongly skewed to the right with observations exceeding 1 hour for encounter duration and 5 days for waiting time (Figure 3.2).



Encounter duration (min)
Waiting time (min)
HF1
POD4
POD733
HF2
POD9
POD737
POD796
HF3
POD71
POD743
HF4
POD56
POD744
HF5
POD745
Sep
Oct
Nov
Dec
Jan
Feb

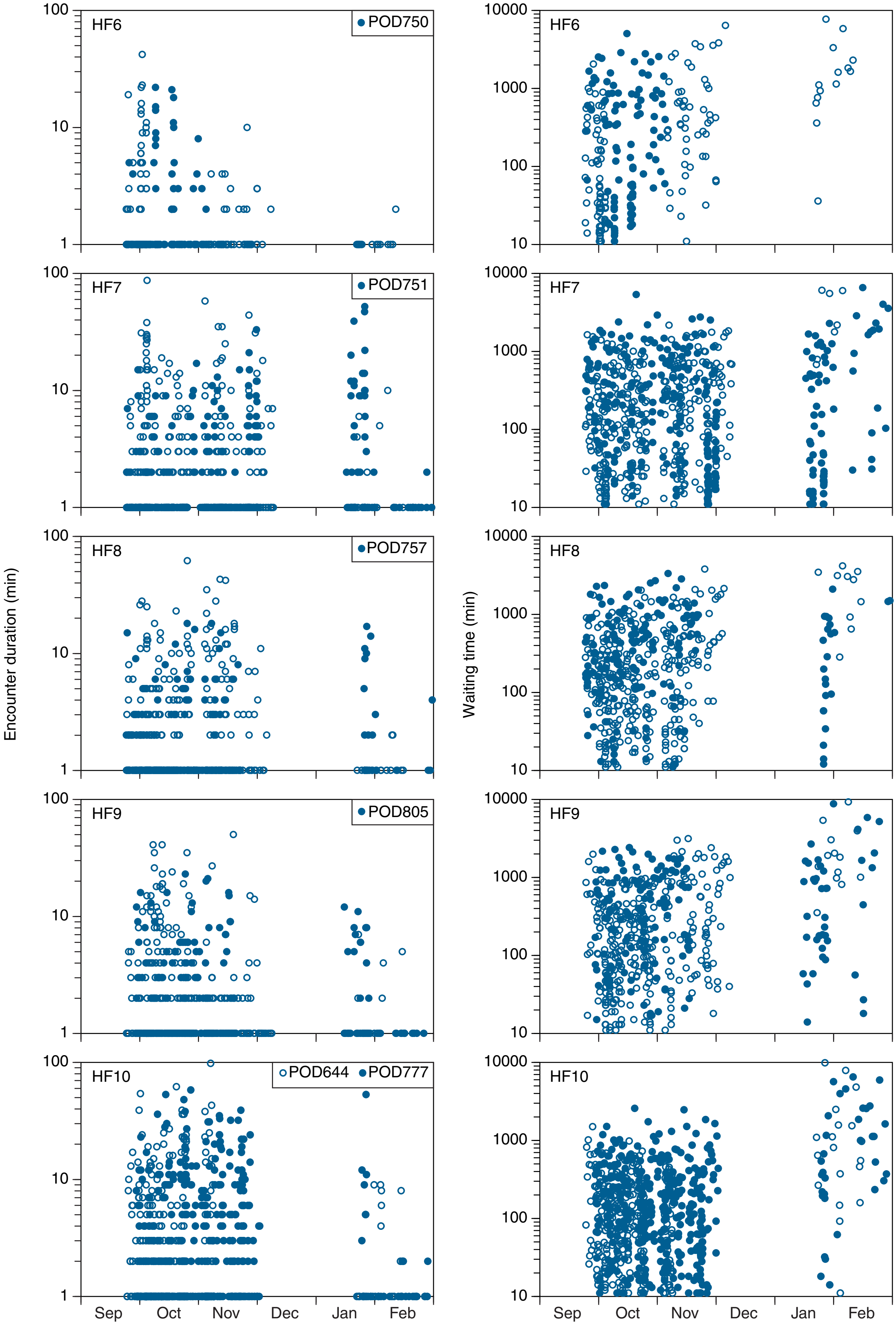


Figure 3.2. Encounter duration (left panel) and waiting time (right panel) extracted from T-POD data collected at Rødsand during the baseline (September 24th 2008 to February 16th 2009; open symbols) and the post-construction period (September 29th 2011 to March 2nd 2012; filled symbols). Different symbols mark observations derived from different T-PODs (triangles = V1, circles = V5). Six encounter observations and eight waiting time exceeded the plotting range (not shown). Note the log-scale on the y-axis.

There was also a clear tendency for encounters to be shorter and waiting times to be longer in January and February 2009 (Figure 3.2), corresponding to the observed pattern for click PPM and PPM (Figure 3.1). These indicator plots strongly indicate a pronounced seasonality in porpoise click activity for the 6 month covered by T-POD monitoring.

Table 3.2. Statistics of encounter duration and waiting time in the baseline and operation periods for Rødsand 2 Offshore Wind Farm.

Period	Area	Posi-tion	Encounter duration (minutes) N	Min	Median	Mean	Max	Waiting time (minutes) N	Min	Median	Mean	Max
Baseline	Nysted ref.	HF1	384	1.0	2.0	5.2	87.0	381	11	85	175	1101
		HF2	260	1.0	1.0	4.9	101.0	256	11	129	302	3565
	Nysted WF	HF3	190	1.0	1.0	5.0	85.0	185	11	377	693	7041
		HF4	287	1.0	1.0	3.7	83.0	282	11	200	721	16964
	Rødsand WF	HF5	153	1.0	1.0	4.4	78.0	150	11	182	656	9394
		HF6	146	1.0	1.0	2.8	42.0	143	11	164	637	7695
		HF7	326	1.0	1.0	4.7	87.0	323	11	148	408	11412
	Rødsand ref.	HF8	319	1.0	1.0	4.1	62.0	316	11	163	420	11038
		HF9	320	1.0	1.0	3.8	50.0	317	11	146	424	9304
		HF10	313	1.0	2.0	6.1	138.0	310	11	101	273	9860
Operation	Nysted ref.	HF1	590	1.0	1.0	5.3	112.0	588	11	73	156	3486
		HF2	218	1.0	1.0	3.8	30.0	215	11	81	332	4226
	Nysted WF	HF3	312	1.0	1.0	5.0	52.0	308	11	199	668	13597
		HF4	427	1.0	2.0	7.1	151.0	424	11	108	374	6630
	Rødsand WF	HF5	207	1.0	1.0	3.8	85.0	205	11	54	444	5920
		HF6	99	1.0	1.0	2.7	22.0	98	11	288	601	5043
		HF7	297	1.0	1.0	3.5	52.0	295	11	166	547	14115
	Rødsand ref.	HF8	164	1.0	1.0	2.7	18.0	162	11	429	841	23344
		HF9	160	1.0	1.0	3.5	23.0	158	14	414	824	11826
		HF10	386	1.0	2.0	6.5	203.0	384	11	144	364	6512

3.3 Rødsand 2 Offshore Wind Farm

The model for spatial-temporal variation as well as T-POD specific variation (Eq. 1) and an ARMA(1,1) correlation structure was computed for the 4 indicators. All the random factors of the model, with the exception of the ARMA(1,1) correlation structure, were found to be insignificant and therefore removed from the model. Within the fixed factors the interactions *month×area* and *month×subarea(area)* were not significant for any of the four indicators, except for *month×area* in the model for encounter duration that was marginally significant (P=0.0171). Overall, this suggests that the echolocation activity followed the same seasonal pattern in both the reference and impact area as well as among the three subareas. Significant differences were found between V1 and V5 T-PODs for all indicators (Table 3.3), clearly demonstrating that V5 T-PODs were more sensitive and recorded higher echolocation activity than V1 T-PODs.

Table 3.3. Significance testing of fixed effects in Eq. (1) for the four indicators after removing non-significant fixed and random effects, while retaining main effects and factors related to the BACI analyses.

Fixed effects	Click PPM			PPM		
	DFs	F	P	DFs	F	P
Area	1, 24.6	6.52	0.0178	1, 41.3	8.24	0.0064
subarea(area)	2, 25.8	2.01	0.1841	2, 45.5	12.29	<0.0001
Period	1, 28.8	1.91	0.1778	1, 45.6	0.47	0.4973
period×area	1, 26.1	0.19	0.6702	1, 42.4	0.09	0.7598
period×subarea(area)	2, 27.2	0.02	0.9813	2, 46.8	1.42	0.2529
Month	5, 127	17.08	<0.0001	5, 168	16.18	<0.0001
Podtype	1, 54.7	15.46	0.0002	1, 59.2	14.03	0.0004

Fixed effects	Encounter duration			Waiting time		
	DFs	F	P	DFs	F	P
Area	1, 197	4.81	0.0294	1, 131	0.01	0.9188
subarea(area)	2, 114	1.24	0.2935	2, 132	22.48	<0.0001
Period	1, 120	0.00	0.9988	1, 138	3.01	0.0852
period×area	1, 120	2.18	0.1420	1, 133	0.05	0.8264
period×subarea(area)	2, 116	1.64	0.1986	2, 134	5.45	0.0053
Month	5, 298	3.95	0.0018	5, 366	12.63	<0.0001
Podtype	1, 165	8.21	0.0047	1, 178	5.93	0.0159

Only waiting time did not show a significant difference between reference and impact area, whereas echolocation activity was significantly higher in the reference area than the impact area (Table 3.3) when assessed by click PPM (39.4 versus 32.6 clicks/min), PPM (0.23% versus 0.09%), and encounter duration (3.3 versus 2.9 min). Both PPM and waiting time had significant differences between the three subareas with Nysted reference having the highest PPM (0.54%) and shortest waiting times (~10 h), and with Rødsand 2 reference area and Nysted Offshore Wind Farm having similar PPM (0.11-0.13%) and waiting times (24-27 h). These latter echolocation activities were comparable to those inside Rødsand 2 Offshore Wind Farm (PPM ~ 0.09% and waiting time ~ 18 h). The random variation among stations within subareas was not significant, indicating that Nysted reference area generally had the highest echolocation activity, and that Rødsand 2 reference and the two wind farm areas were more similar.

There was no overall change in echolocation activity from baseline to operation for any of the four indicators (Table 3.3). Moreover, there was no significant change in the echolocation activity in the impact area relative to the reference area (*period×area*), i.e. changes from baseline to operation were similar in the impact and reference areas (Figure 3.3). This was even the case when comparing the changes from baseline to operation among the three reference subareas (*period×subarea(area)*), except that waiting times (only significant indicator, cf. Table 3.3) generally increased in the Rødsand 2 reference area and decreased in Nysted Offshore Wind Farm and Nysted reference area. However, there were no significant BACI effect when testing the change in the impact area against the three reference subareas separately (Rødsand 2 reference: P=0.0775, Nysted Offshore Wind Farm: P=0.1529, and Nysted reference: P=0.7539). The relative change, assessed by the BACI contrast (Eq. 2), ranged from -15% (encounter duration) to +12% (PPM), showing both positive and negative relative changes in the echolocation activity. The lack of uniformity and significance in the BACI tests clearly suggests that it is unlikely that the change in echolocation activity in the impact area is different from that observed in the reference area.

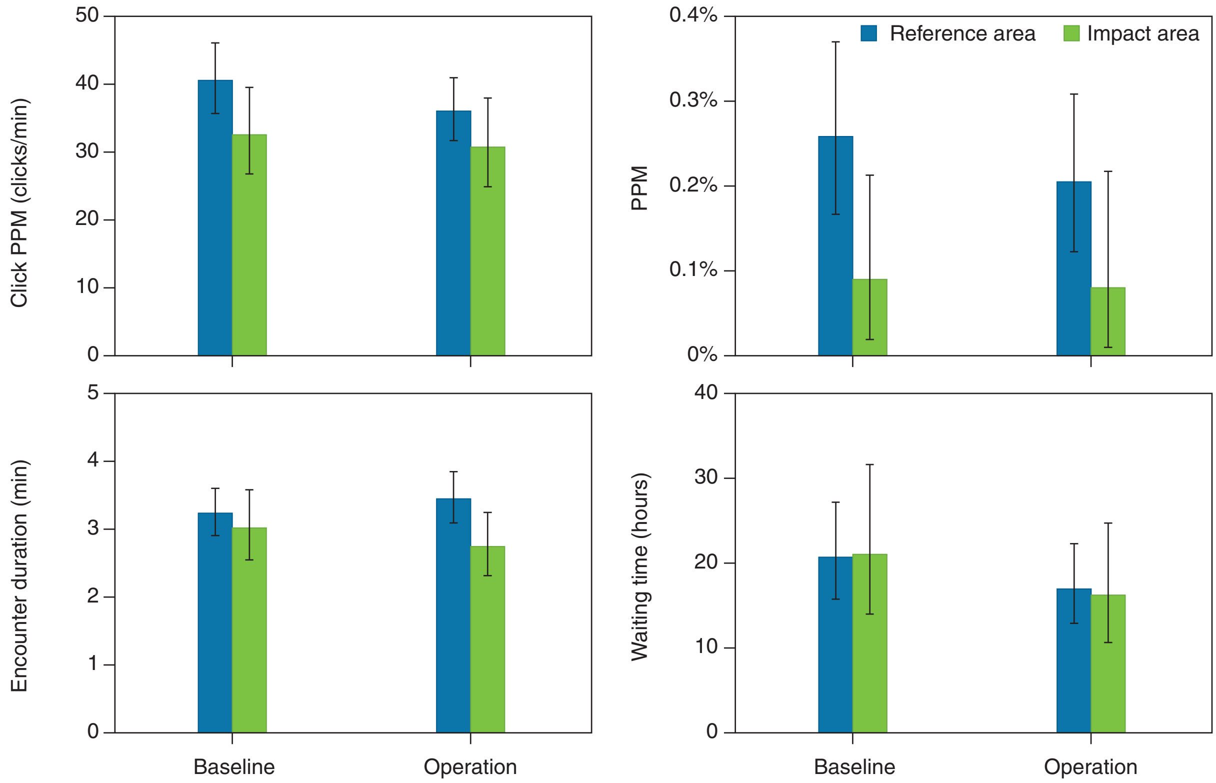


Figure 3.3. Mean values for combinations of area and period back-transformed to the original scale for combinations of the two areas and the two periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in sub-areas and months have been accounted for by calculating marginal means.

The variation between the six months with T-POD recordings during the baseline and operation periods was highly significant for all four indicators (Table 3.3), when other significant sources of variation were taken into account. All indicators demonstrated highest echolocation activity in October and lowest echolocation activity in February (Figure 3.4), consistent with the seasonal variation found during investigations of the Nysted Offshore Wind Farm (Tougaard *et al.* 2006a, Carstensen *et al.* 2006) and showing that monitoring in the present study generally covered months with medium to low echolocation activity. Click PPM was 47 clicks/min in October and declined to 20 clicks/min in February. Similarly, PPM varied from 0.43% in October to 0.04% in February showing the porpoise clicks were recorded 10 times more frequent in October than in February. Variations across months in encounter duration were smaller from 3.5 min in October to 2.3 min in February, whereas waiting times increased more than factor 5 from 9.2 h in October to 48 h in February.

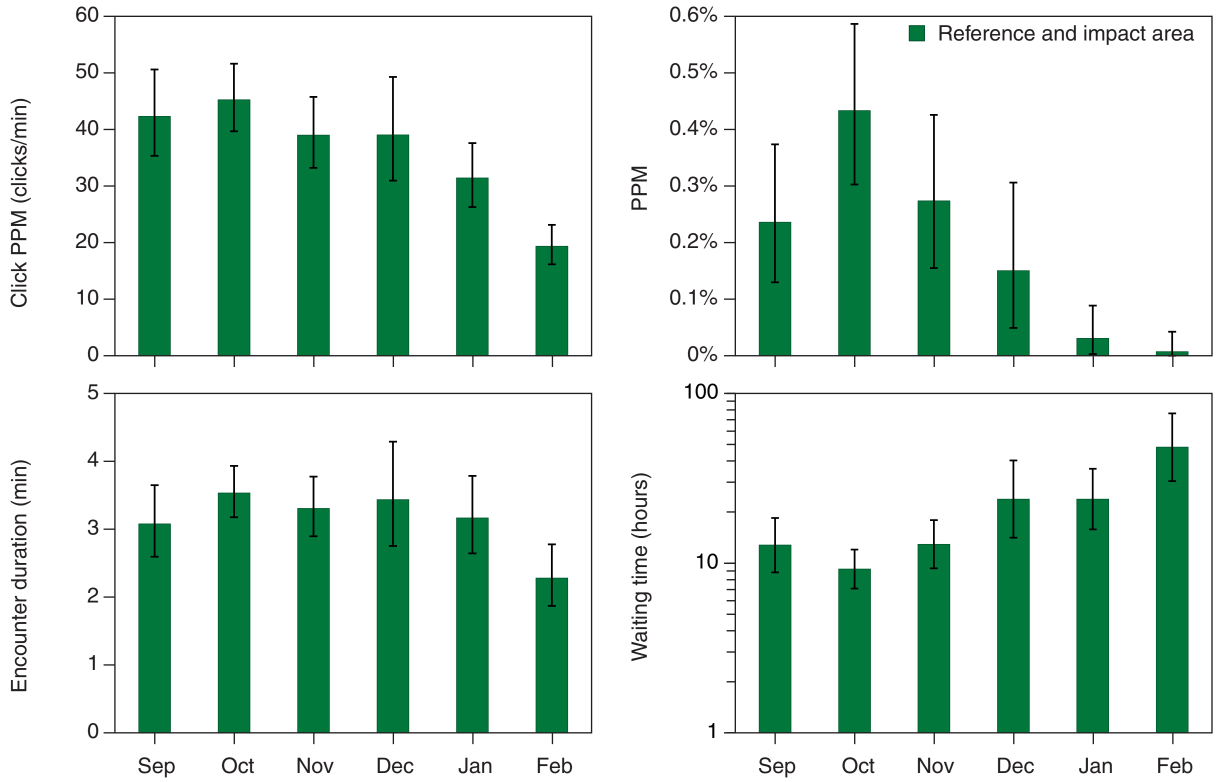


Figure 3.4. Monthly means for the four indicators after back-transformation. Error bars show 95% confidence limits of the mean values. The covariation with other factors in Eq. (1) has been accounted for by calculating marginal means.

3.4 Nysted long-term assessment

For the Nysted Offshore Wind Farm long-term assessment analysis (Eq. 2) all random factors, except for the ARMA(1,1) covariance structure for all four indicators and *period×month×station(area)* for encounter duration and waiting time were found insignificant and removed from the model. For all four indicators the fixed factors *area×month*, *period×month* and *area×period×month* were also not significant and consequently removed from the model. Overall, this suggests that the echolocation activity followed the same seasonal pattern in both the reference (HF1-2) and impact (HF 3-4) area as well as across the different periods. Significant variation between T-POD V1 and V5 were found for all indicators (Table 3.3), clearly demonstrating that V5 T-PODs were more sensitive and recorded higher echolocation activity than V1 T-PODs.

Table 3.4. Significance testing of fixed effects in Eq. (1) for the four indicators after removing non-significant fixed and random effects, while the main effects and factors related to the BACI analyses were retained.

Fixed effects	Click PPM			PPM		
	DFs	F	P	DFs	F	P
Area	1, 74.6	26.04	<0.0001	1, 127	101.05	<0.0001
Period	5, 83.4	1.98	0.0901	5, 133	17.13	<0.0001
period×area	5, 72.5	4.37	0.0016	5, 122	7.10	<0.0001
Month	11, 221	4.23	<0.0001	11, 325	15.38	<0.0001
Podtype	1, 165	8.67	0.0037	1, 208	30.62	<0.0001
Fixed effects	**Encounter duration**			**Waiting time**		
	DFs	**F**	**P**	**DFs**	**F**	**P**
Area	1, 28.1	2.96	0.0964	1, 65.9	57.22	<0.0001
Period	5, 38.8	3.12	0.0185	5, 86.5	9.50	<0.0001
period×area	5, 29.1	1.30	0.2893	5, 68	3.65	0.0055
Month	11, 37	1.24	0.2952	11, 80.5	10.07	<0.0001
Podtype	1, 429	11.84	0.0006	1, 350	11.30	0.0009

Echolocation activity was significantly higher in the reference area than the impact area for all indicators except encounter duration (Table 3.4), with 49.1 versus 36.1 clicks/min for Click PPM, 0.71% versus 0.25% PPM, and 8.8 versus 22.3 hours for waiting time. Based on PPM and waiting time the mean echolocation activity was almost 3 times higher in the reference area. Significant changes were also found across the six periods (baseline, construction and operation 1-4) for all indicators except click PPM. Echolocation activity was highest during the baseline for all indicators and lowest during the construction period for all indicators except encounter duration (Figure 3.5). During the four operation periods there was a general increasing echolocation activity, although operation period 2 had the highest PPM and encounter duration. The random variation among stations was not significant, indicating that there was no smaller-scale spatial variation in echolocation activity within the reference and impact area.

The BACI effect was significant for all indicators except encounter duration (Table 3.4). However, this factor only described that there were significant relative changes between the impact and reference areas across all periods, whereas which specific periods may have caused this significant change were demonstrated by calculating BACI contrasts (Table 3.4). The relative changes across periods are shown in Figure 3.5. The significant BACI effect for click PPM was mainly caused by a 57% relative decline in the impact area from the baseline to construction period and a 70-80% increase from the construction period to operation periods 2-4. PPM was reduced in the impact area relative to the reference area by factor 5-10 from the baseline to the other periods, except for the operation period 4 when the relative change was only a factor of 3.5. There was a relative reduction in PPM from operation period 1 to operation period 2, followed by a relative increase from operation period 2 and 3 to operation period 4. There was no overall relative change between the impact and reference area across periods for encounter duration, albeit one of the contrasts was borderline significant. Waiting times in the impact area increased 4-6 times relative to the reference area from the baseline to the construction and operation periods 2 and 3, whereas the relative change from baseline to the operation period 4 was only about factor of 3 and borderline significant (Table 3.5).

Table 3.5. The relative change between the impact and reference area from one period to another given as percentage (cf. Eq. 3) and the P-value for the contrast. Significant BACI contrasts are highlighted in bold.

BACI contrast	Click PPM		PPM		Encounter duration		Waiting time	
Baseline ~ construction	**43%**	**0.0004**	**11%**	**<0.0001**	74%	0.0950	**475%**	**0.0011**
Baseline ~ operation1	**61%**	**0.0373**	**20%**	**0.0002**	95%	0.7842	**397%**	**0.0027**
Baseline ~ operation2	74%	0.1954	16%	**<0.0001**	92%	0.5939	**495%**	**0.0004**
Baseline ~ operation3	77%	0.3076	11%	**<0.0001**	84%	0.3657	**599%**	**0.0005**
Baseline ~ operation4	72%	0.2048	29%	**0.0047**	108%	0.7035	**287%**	**0.0406**
Construction ~ operation1	**143%**	**0.0343**	178%	0.2458	128%	0.0892	84%	0.6303
Construction ~ operation2	**173%**	**0.0014**	140%	0.1869	123%	0.1193	104%	0.9026
Construction ~ operation3	**181%**	**0.0021**	99%	0.3277	113%	0.4449	126%	0.5852
Construction ~ operation4	**169%**	**0.0088**	262%	0.0931	**145%**	**0.0364**	61%	0.2579
Operation1 ~ operation2	121%	0.2661	**79%**	**0.0186**	96%	0.7601	125%	0.5077
Operation1 ~ operation3	127%	0.2215	55%	0.0596	88%	0.4400	151%	0.3224
Operation1 ~ operation4	118%	0.4044	147%	0.4661	113%	0.4743	72%	0.4558
Operation2 ~ operation3	105%	0.8086	70%	0.8891	92%	0.5742	121%	0.6285
Operation2 ~ operation4	98%	0.9078	**186%**	**0.0078**	117%	0.3140	58%	0.1871
Operation3 ~ operation4	93%	0.7488	**265%**	**0.0230**	128%	0.1897	48%	0.1268

In summary, the echolocation activity generally declined after the baseline and has not fully recovered yet. However, it is noteworthy when comparing the impact area with the reference area that the operation period 4 (i.e. post-construction period) had relatively higher echolocation activity than during the construction period and operation period 1-3, showing a significant increase from construction to operation period 4 for click PPM and encounter duration as well as significant increases in PPM from operation periods 2 and 3 to operation period 4.

The seasonal variations in the four indicators were all significant (Table 3.5) and revealed a similar and consistent pattern of porpoise echolocation activity (Figure 3.6), comparable to those reported in Tougaard *et al.* (2006a) and Carstensen *et al.* (2006). Echolocation showed a unimodal seasonal pattern with low activity during winter and high activity during summer. Click PPM varied from 26 clicks/min in February to 56 clicks/min in May, PPM varied from 0.13% in February to 0.78% in September, encounter duration varied from 2.6 min in February to 4.2 min in April, and waiting times varied from 59 hours in February to 5.6 in August. The largest seasonal variations were observed for PPM (factor 6) and waiting times (factor 10).

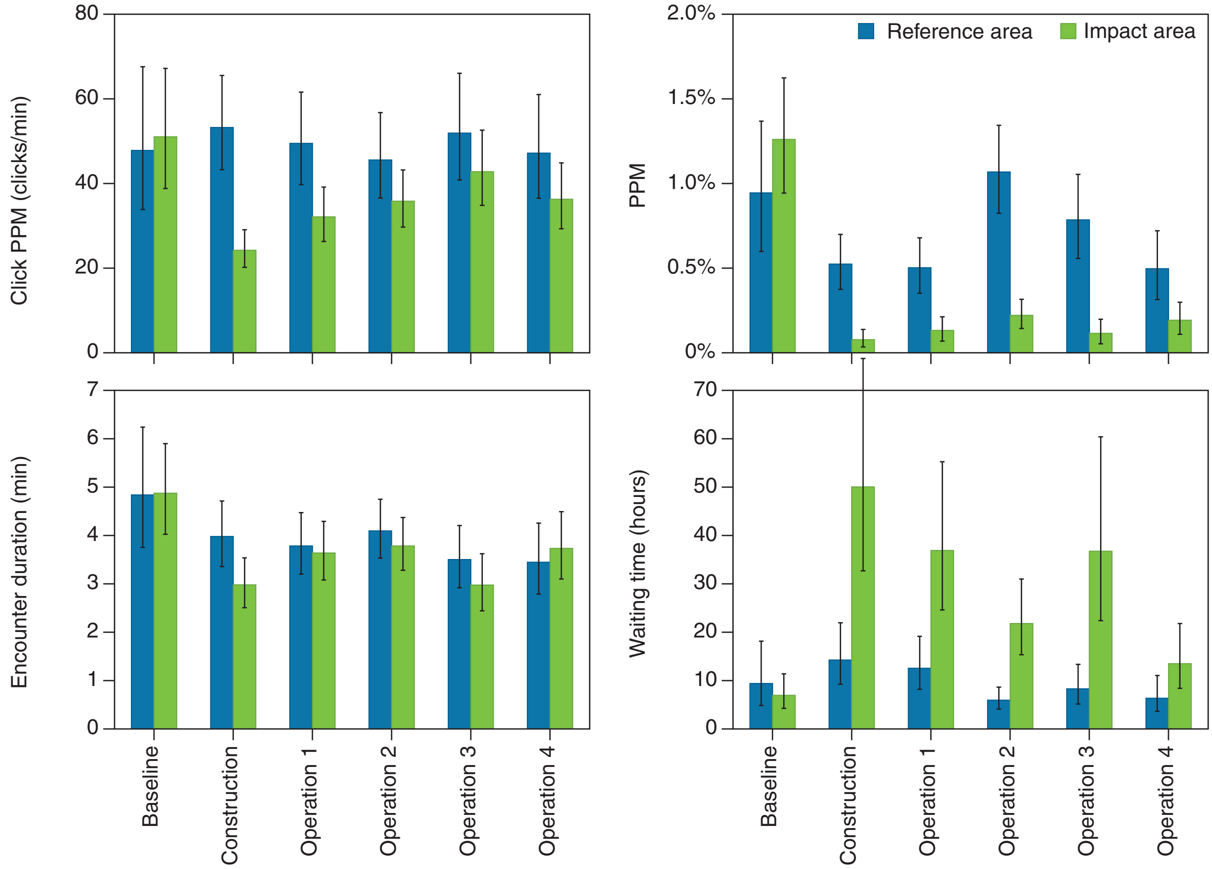


Figure 3.5. Mean values for combinations of area and period back-transformed to the original scale for combinations of the two areas and the six periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in months and T-POD versions have been accounted for by calculating marginal means.

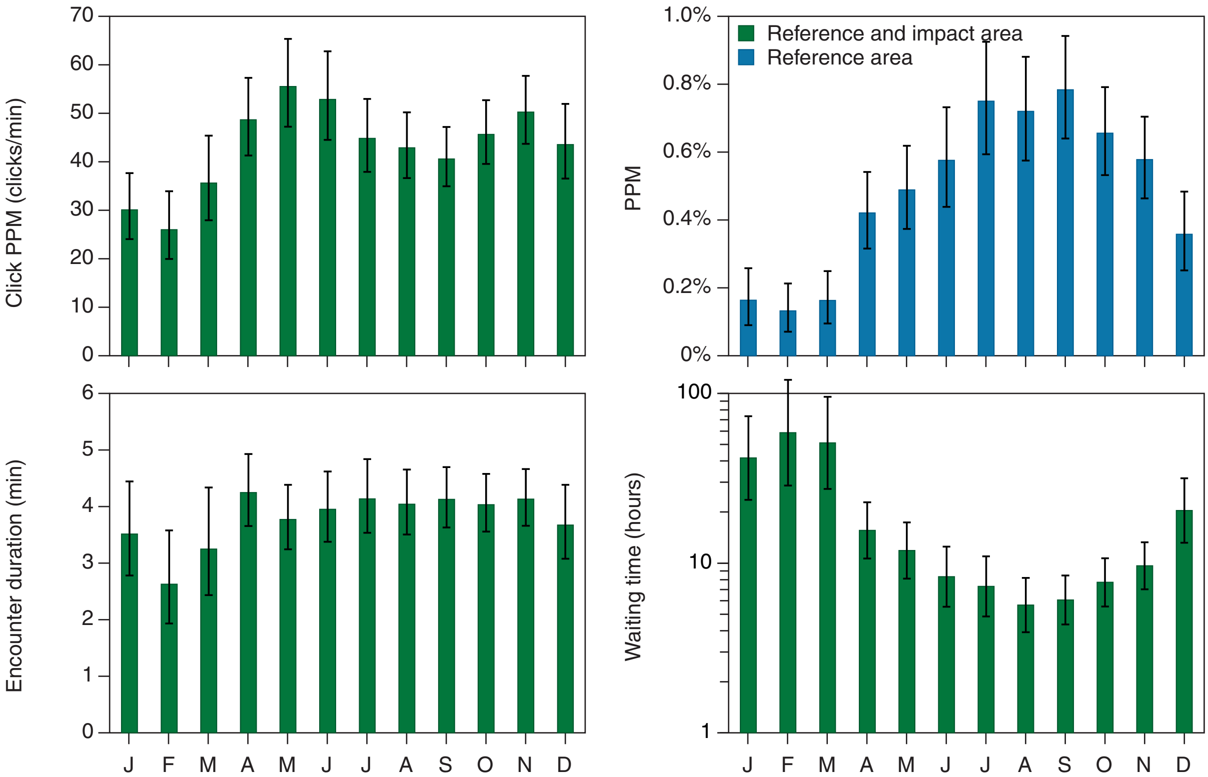


Figure 3.6. Monthly means Nysted reference and impact areas combined showing the four indicators after back-transformation. Error bars show 95% confidence limits of the mean values. The covariation with other factors in Eq. (2) has been accounted for by calculating marginal means.

3.5 Comparison of V1 versus V5 T-PODs

For the four positions (HF1-HF4) two T-PODs, one of V1 and one of V5, were deployed simultaneously. The two different types of T-PODs were compared using daily indicators that had a fixed temporal resolution that allowed for pairing these data from the two T-PODs deployed at the same station. The indicators derived from different types of T-PODs at the same station were related by means of least squares regression to investigate if the two types of T-PODs produced comparable echolocation activity. However, since the T-PODs may have started and ended logging at different times of the day, indicators covering an entire day were included only. This test is stronger than the BACI model (Eq. 1), because the daily indicators from the two different T-POD types are paired such that short-term temporal variation (between days) is accounted for.

Combining the Click PPM and PPM indicators for days with both V1 and V5 T-PODs recording simultaneously resulted in 83 and 152 indicators values for Click PPM and PPM, respectively. There were significant correlations between the values obtained by the two types of T-PODs, but the slopes of the intercalibration curves were also significantly different from 1 suggesting that V1 generally recorded less echolocation activity (Figure 3.7). It should also be stressed that the intercalibration analysis clearly indicated a proportional effect for the transformed indicators, as the intercept in both regression analyses was not significantly different from zero (P=0.0867 for Click PPM and P=0.1458 for PPM).

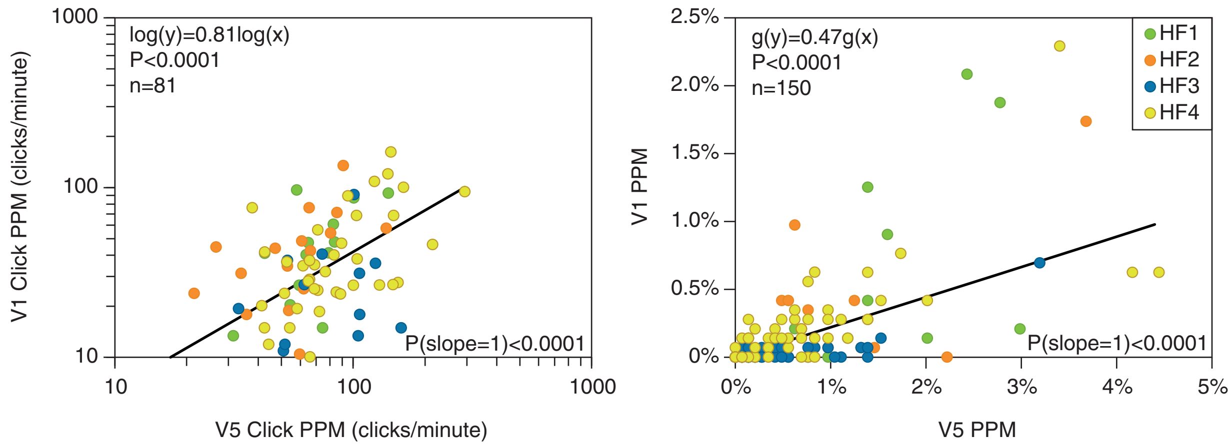


Figure 3.7. Intercalibration of V1 and V5 T-PODs by means of the daily indicators, Click PPM and PPM. Regressions were carried out on transformed variables (see Materials and methods) but are shown using the back-transformations. Two observations of click PPM and two observations of PPM were excluded as outliers and not included in the regression, because they had a large influence on the regression lines (two shown with open symbols and two out of the plotting range).

For Click PPM the resulting intercalibration curve was $y=x^{0.81}$ showing that V1 records relatively fewer clicks when there is high echolocation activity. For PPM there were approximately 50% fewer minutes per day with echolocation activity for V1. Thus, the model and the stronger paired intercalibration test signify that V5 T-PODs record significantly higher echolocation activity than V1 T-PODs.

3.6 Noise monitoring

The noise on all stations varied considerably from recording period to recording period and also showed more gradual changes over periods from hours to days. The latter variation is most certainly due to changes in weather and hence wind driven wave motion, which is the main natural source of background noise in the low frequency bands. An example of variation in noise level at one station (HF5 inside Rødsand 2 Offshore Wind Farm) during one deployment (Jan-Feb 2009) and in 10 selected frequency bands is shown in Figure 3.8.

If we zoom in on a single day (Figure 3.9) some differences and similarities among stations become evident. The noise at all stations (less pronounced at HF1) is dominated by an almost continuous band of noise in the range from 500 Hz to 2 kHz. The source of this noise is most likely ships in the nearby deep-water shipping lane. This noise is likely to have a strong low frequency emphasis in the deep water channel itself but due to the shallow water at the recording stations (about 10 m) the lowest frequencies are prevented from propagating into the waters of the loggers and only the mid-frequency components reach the hydrophones. There are periodic fluctuations in the shipping noise which likely can be attributed to individual ships passing but without knowledge about the actual traffic on this particular day individual ships cannot be separated. One possible exception is the event recorded around 6:00 at station HF9 with peak power around 1.2 kHz. This pattern is repeated about half an hour later at station HF5, a little later again at HF4 and around 8:00 at station HF1. Although we have no additional evidence, this could very likely originate from one particularly noisy ship passing from west to east, or alternatively a ship passing the stations at closer range than the deep water channel.

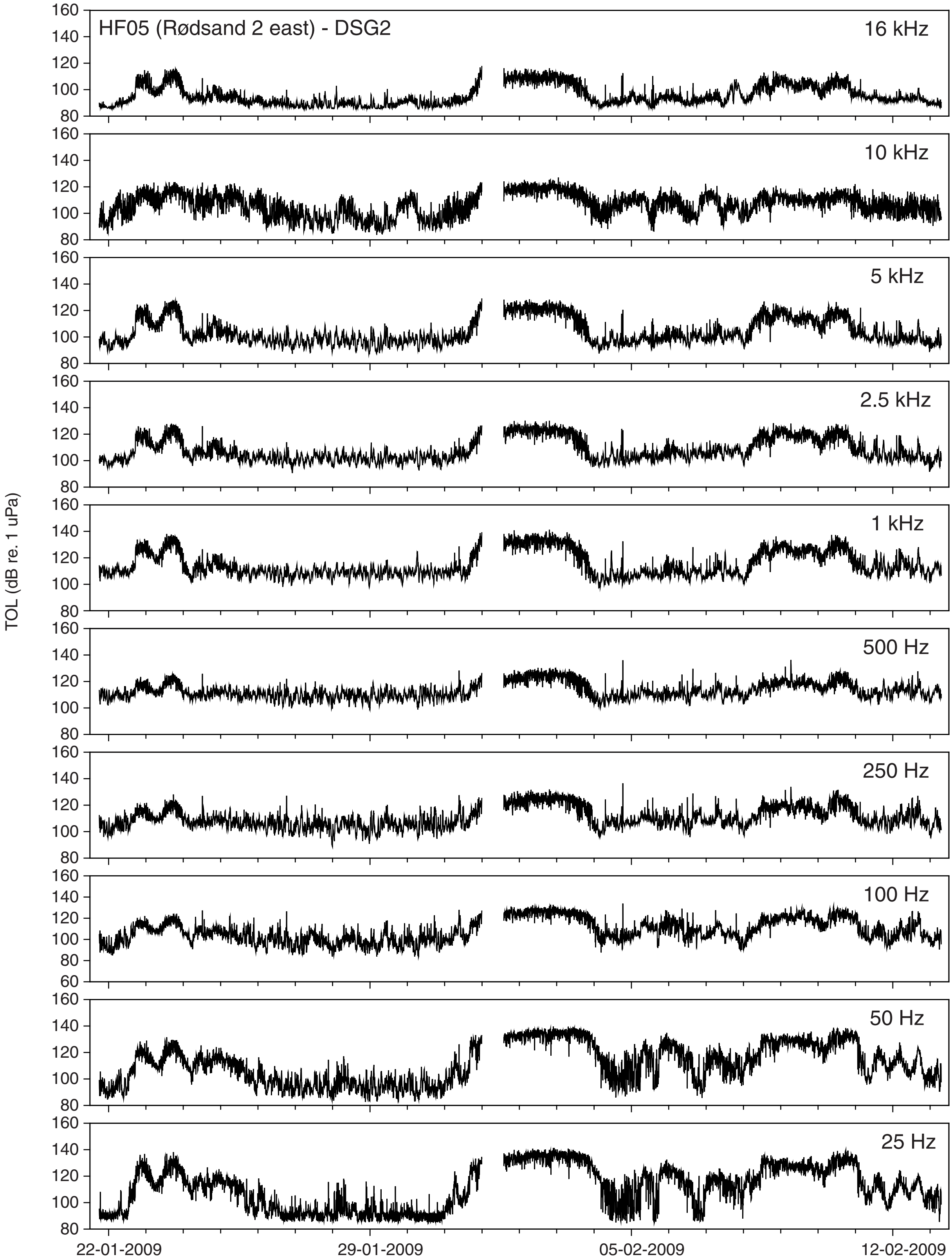


Figure 3.8. Fluctuations in underwater noise measured at station HF5 in the period 21.1.2009 to 13.2.2009, separated into 10 one-third octave bands. For unknown reasons the logger failed to record during 14 hours on the 1st of February.

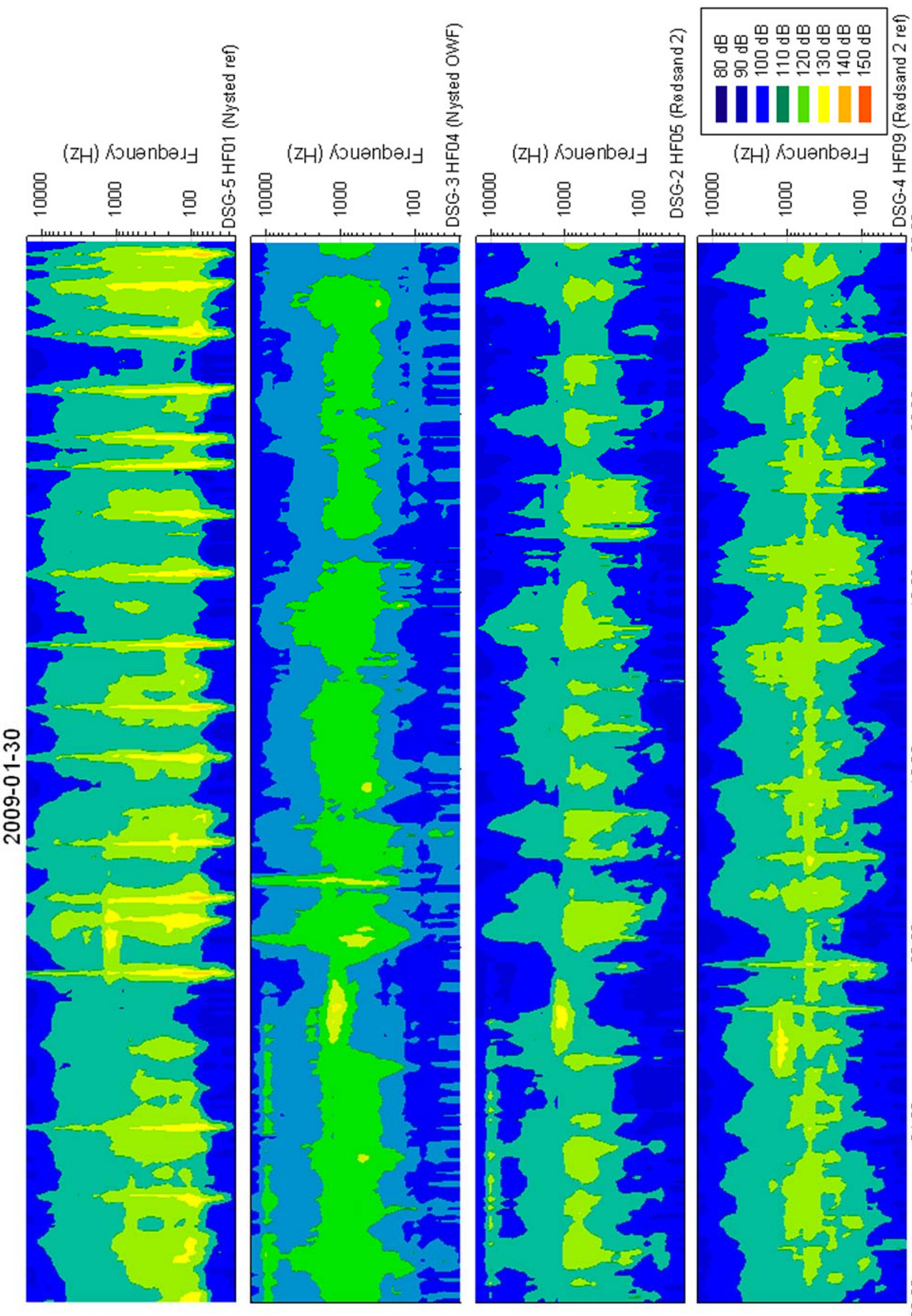


Figure 3.9. Summary of underwater noise recorded on the 30th of January 2009 at four different recording stations (HF1, 4, 5 and 9).

On station HF1 additional events of short duration occur at apparently regular intervals. The repeating pattern is pronounced if only one frequency band is considered (Figure 3.10). A likely source for the sharp peaks in the noise at station HF1 is the ferry from Gedser to Rostock, which leaves or arrives 10 times per day and passes very close by station HF1.

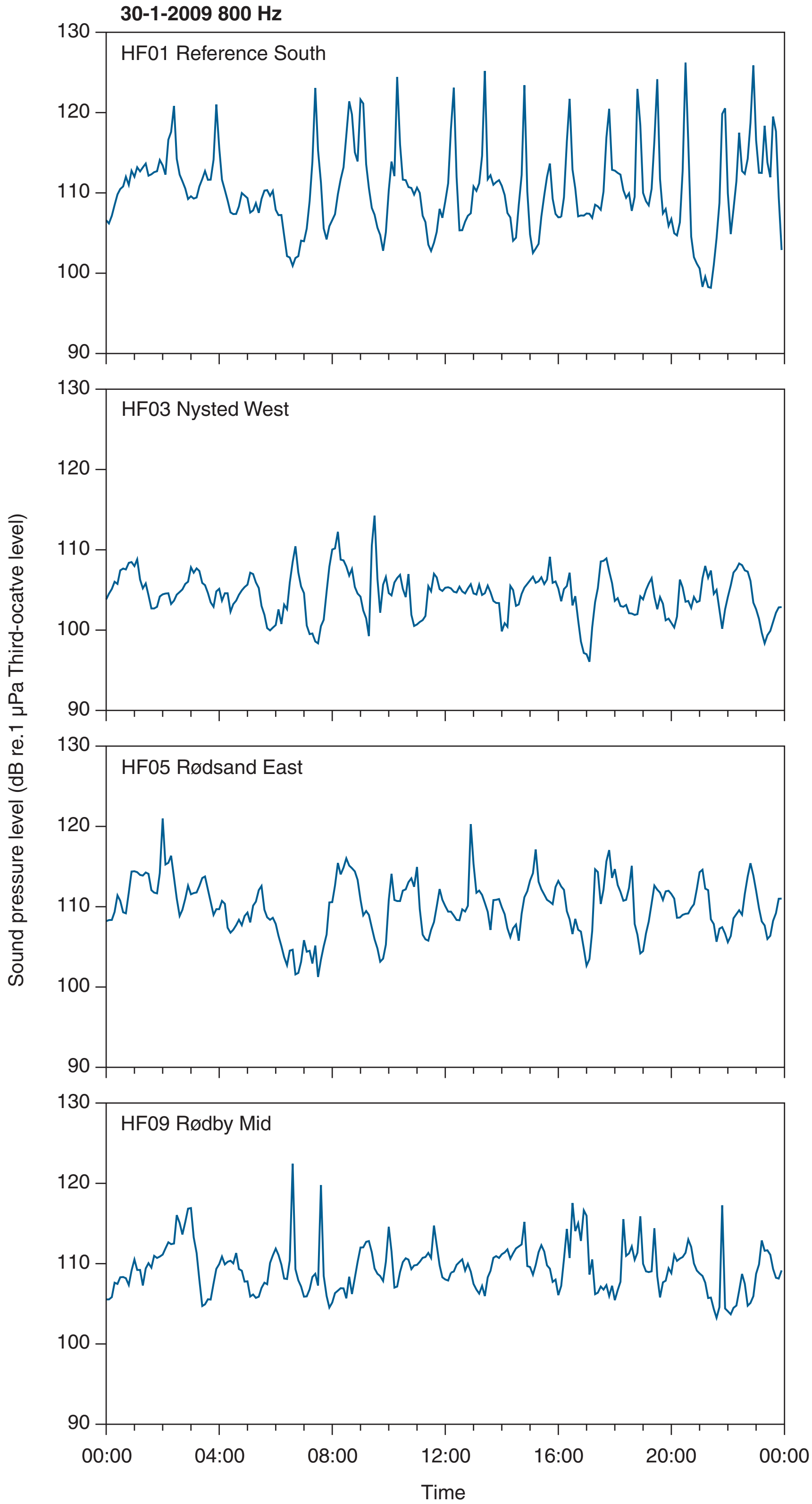
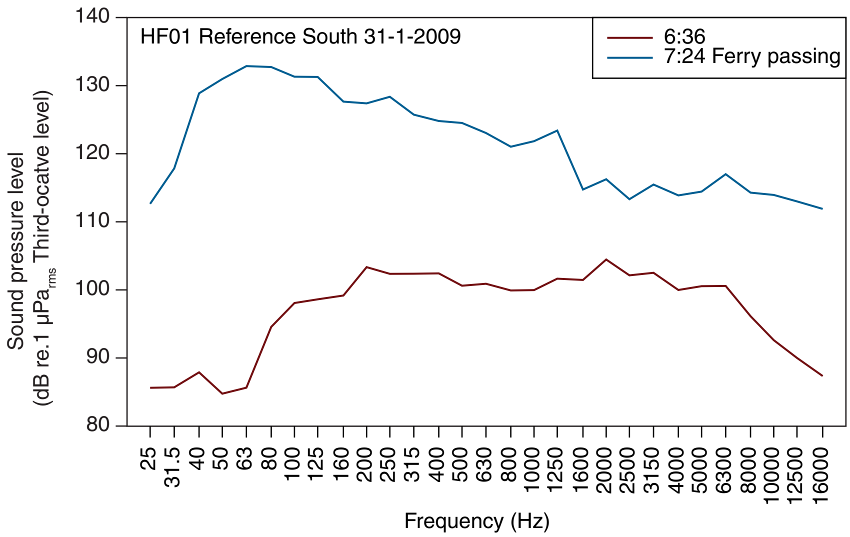


Figure 3.10. Fluctuations in noise over 24 hours measured in the 800 Hz third-octave band on all four measuring stations.

The passage of a ferry is associated with not only large changes in sound pressure but also changes to the frequency content. Figure 3.11 shows the frequency spectrum of the noise recorded on two occasions spaced 1 hour apart, first (presumably) without ships nearby and secondly (presumably) with the ferry from Rostock (arriving to Gedser 7:45) passing close by. Note the very large increase in noise level across all frequency bands, most noteworthy below a few hundred Hz, where it is up to 40-50 dB.

Figure 3.11. Third-octave frequency spectra from station HF01, close to the ferry route into Gedser harbour.



A second example of noise data is shown in Figure 3.12. These recordings were made 3 days later than the recordings in Figure 3.9 during which the weather changed to much more windy conditions. Note the general increase in noise across all frequency bands and at all four stations, but also that the band around 1 kHz is still visible. Events which could be interpreted as passing ships can no longer be discerned in the noise as these are masked by the increased wave-generated noise. As for the recording three days earlier, the lowest noise levels were found inside the existing wind farm (station HF4) and highest levels at the station close to Gedser Harbour (HF1).

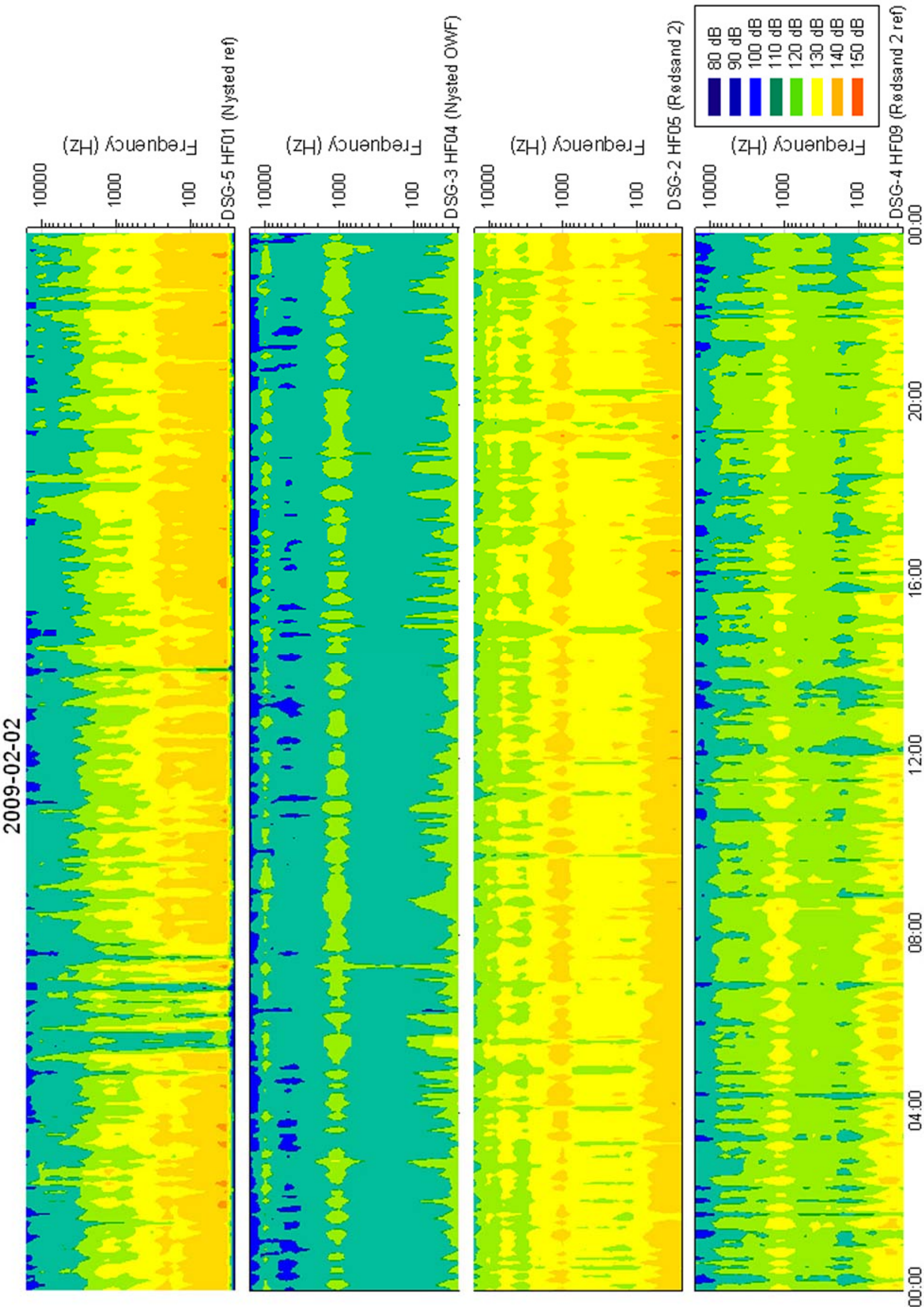


Figure 3.12. Summary of underwater noise recorded on the 2nd of February 2009 at four different recording stations (HF1, 4, 5 and 9). Compare to Figure 3.6.2.

3.6.1 Median noise spectra

From the noise recordings median noise spectra could be calculated. For each third-octave band the 5, 25, 50, 75 and 95% percentiles were calculated. The 95% percentile represents the level exceeded in 95% of the recordings, i.e. representative of the noise when it is about as quiet as it gets. Likewise the 5% percentile represents about the loudest levels encountered in the recordings. Third-octave spectra show high levels of noise on all four stations with median levels at or above 100 dB re. 1 µPa at most third-octave frequencies and at all stations.

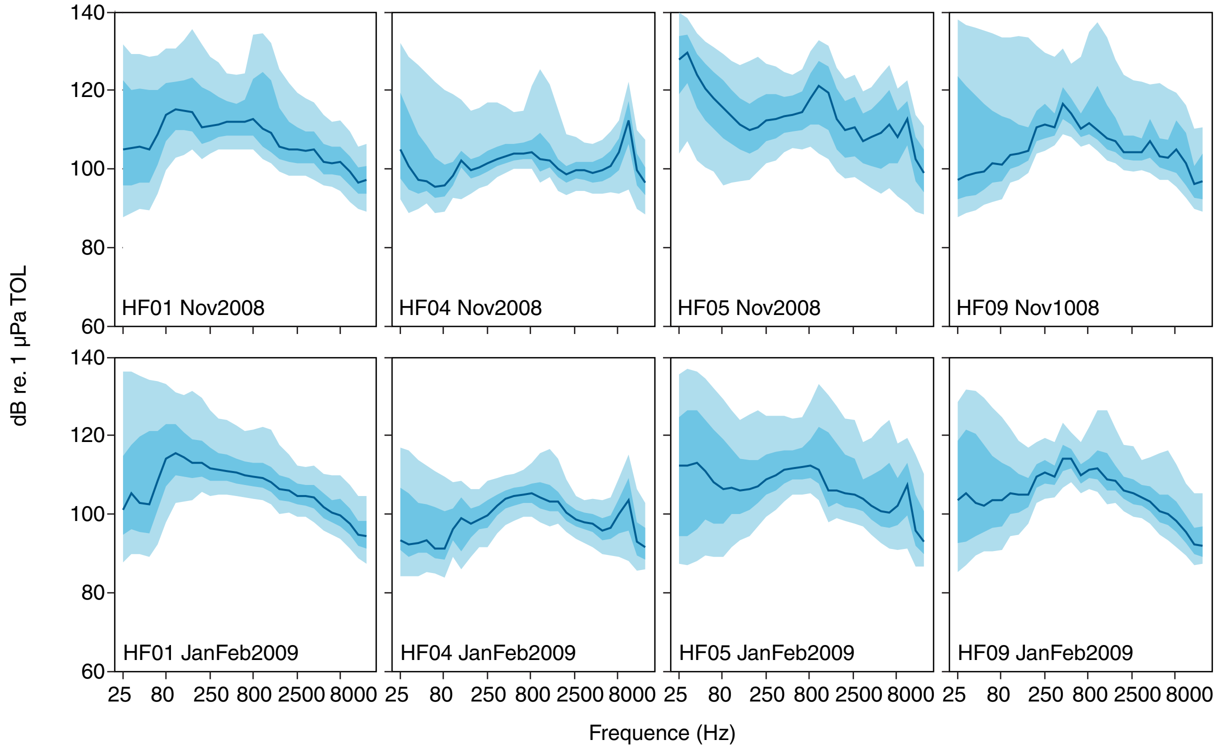


Figure 3.13. Median noise spectra and upper and lower percentiles, all expressed in third-octave bands. Top row shows deployment in 2008, bottom in 2009, both before construction of the wind farm.

The median spectra shows the same peak in noise energy at intermediate frequency bands, from around 100 Hz to 1 kHz, likely due to ship noise. Peaks at higher frequencies are present in some recordings. Their origin is unknown, but could be noise from the mooring such as rattling of the anchor chain, which is clearly audible on some recordings.

There are clearly differences in the noise spectra between stations and also between periods. If mean sound pressure levels are compared across stations and periods, as in Figure 3.13 (baseline) and Figure 3.14 (post-construction), it is evident that noise levels in general were higher in 2008-2009 compared to 2011-2012. This is most likely a general effect of weather and although recordings were made approximately at the same time of year the weather will not be exactly the same. During the baseline period in 2008-09 the lowest levels of noise were recorded inside Nysted Offshore Wind Farm and loudest levels, 10-15 dB above Nysted, were recorded in the Rødsand 2 Offshore Wind Farm area. In 2011-12, after construction of Rødsand 2, the pattern has changed and average noise levels in Rødsand 2 were comparable to levels in Nysted Offshore Wind Farm.

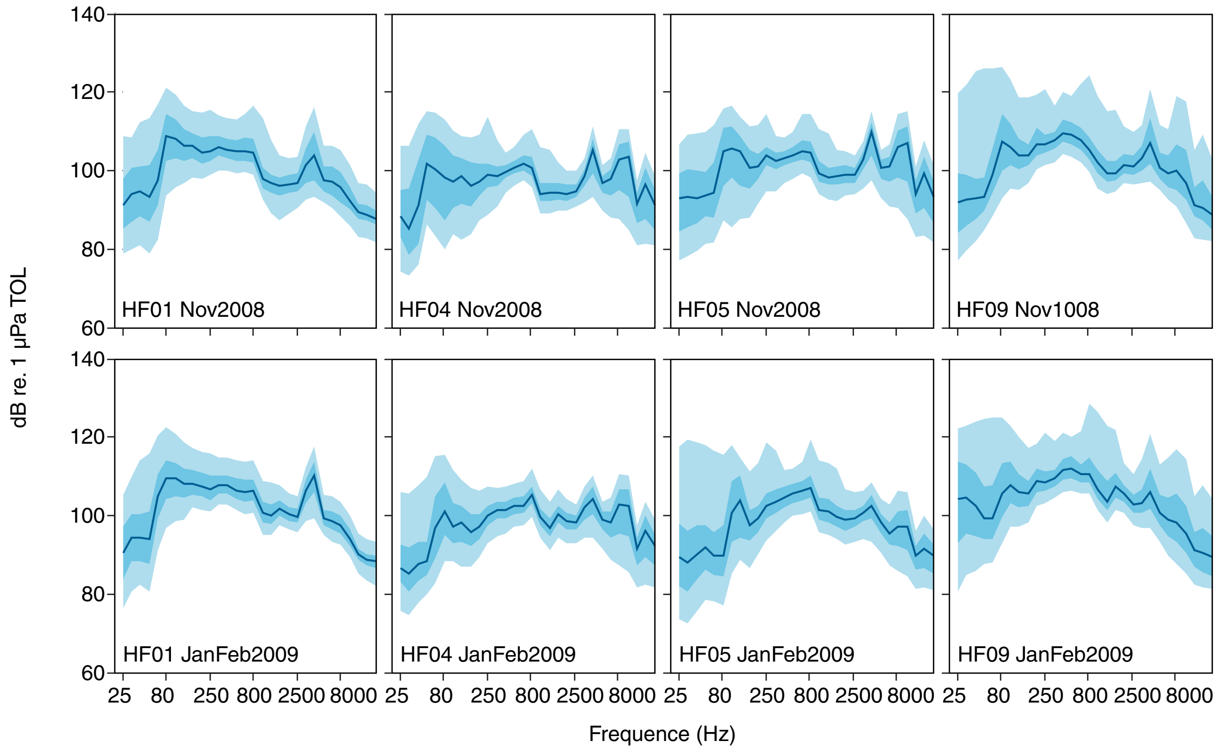
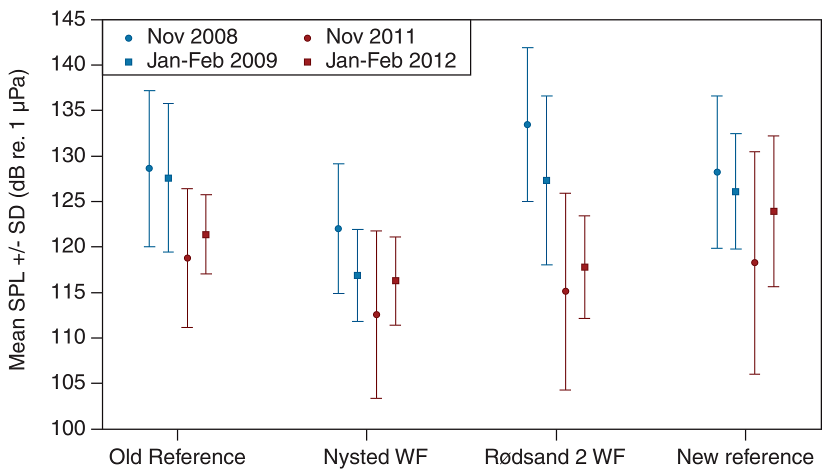


Figure 3.14. Median noise spectra and upper and lower percentiles, all expressed in third-octave bands. Top row shows deployment in 2011, bottom in 2012, both during operation of the wind farm.

Figure 3.15. Mean sound pressure level (SPL), unweighted and separated into the four stations and four deployments.



A correlation of noise in the two wind farm areas was made, in order to elucidate potential sources underlying these differences. Figure 3.16 shows noise level in Nysted vs. noise level in Rødsand 2 at the same time for each of the recording intervals in 2009 and 2011, before and after construction of Rødsand 2, and divided into three frequency bands. In general, there is a good correlation between recordings at the two stations, supporting the notion of wind and waves as the overall most dominating source of noise, probably together with ships in the shipping lane. In the 1 kHz band, which is a band where ship noise is particularly visible above background noise in these shallow waters, there is a pronounced deviation from the general correlation, however. In 2009 there are many periods with more noise in Rødsand 2 than in Nysted, visible as a blob of points to the right, below the positive diagonal of the figure. There is a similar, but much weaker blob on the other side of the diagonal, indicating periods with more noise in Nysted than in Rødsand 2. The pattern is also visible in the 100 Hz band, although not as pronounced, but not in the 10 kHz band. The two blobs are likely to originate from ships close to the recording stations, i.e. inside the wind farm areas, as these ships would be clearly audible on the closest recording station but less so on the other, more distant station. The data thus suggests that the high levels of noise observed inside the Rødsand 2 area during baseline was due to ships in the area. This could be ships connected to the initial stages of construction (mainly dredging) but also fishing vessels another smaller ships sailing along the coast, avoiding the Nysted Offshore Wind Farm, but passing through the Rødsand 2 area. The smaller deviations from the correlation seen towards the Nysted side could likely be connected to the service boats which sail between the turbines on a regular basis.

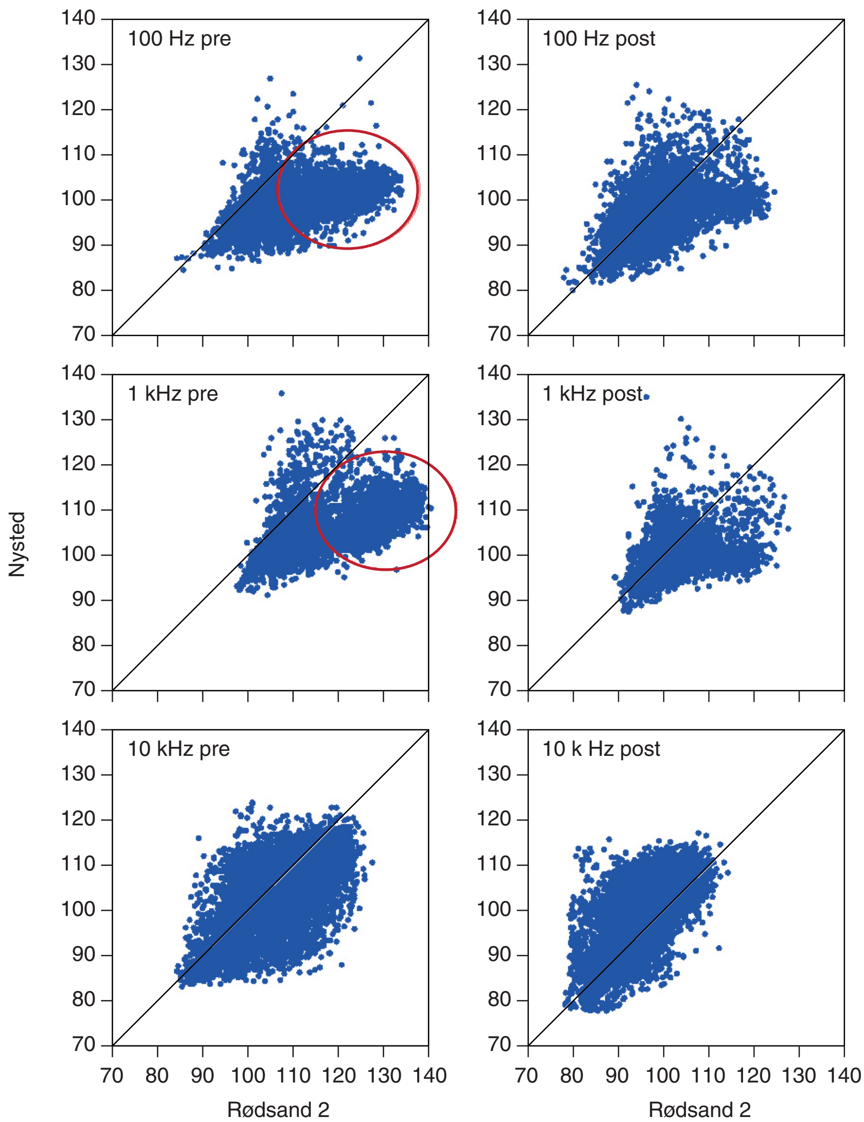


Figure 3.16. Correlation between noise in the old wind farm (Nysted) and the new wind farm (Rødsand 2), measured for all pairs of recordings at three different 1/3-octave bands. Large concentration of points below the diagonal in the baseline period (inside red circles) indicate higher noise levels in Rødsand 2 area than Nysted, indicative of local sources (i.e. ships inside the Rødsand 2 area).

After construction of the wind farm the pattern is still present, but significantly reduced, i.e. it appears that the ship traffic inside Rødsand 2 Offshore Wind Farm is considerably lower than during the baseline period. Clearly the dredging ships were not present after end of construction but it is also conceivable that ships sailing along the coast and which used to sail through the area now passes around on the outside of the wind farm and thus contributes less to noise levels inside the wind farm. On the contrary side is of course service vessels in Rødsand 2, which would not have been present during the baseline period. These service vessels may be the main source for the deviation from correlation on the Rødsand 2 side.

3.6.2 BACI analysis of noise levels

The only significant variation in the noise signal was the general decrease in noise level from the baseline to the post-construction (Table 3.6), most pronounced for the 1 kHz band. This frequency is mostly associated with meteorology, so it is likely that the baseline period could have been more windy relative to the post-construction.

Table 3.6. Significance testing (P-values) of fixed effects in Eq. (3) for the five noise signals. Significant (P<0.05) factors are emphasized in bold.

Fixed factor	100 Hz	1 kHz	10 kHz	25 Hz – 16 kHz	Audiogram-weighted
area	0.9490	0.5710	0.3956	0.7114	0.1515
period	0.2015	**0.0213**	0.0636	**0.0300**	**0.0336**
area×period	0.3995	0.1801	0.2483	0.1075	0.0741
hour	**0.0349**	0.5275	0.1521	0.4968	0.1920
area×hour	0.6329	0.6344	0.2723	0.8458	0.4274
period×hour	0.9378	0.9963	0.7637	0.9804	0.7778
area×period×hour	0.2034	0.8968	0.4426	0.2056	0.5777

There was no significant change in the impact area relative to the reference area for any of the analysed noise signals, suggesting that there was no increase in noise levels associated with the operation of the wind farm relative to the reference area. In fact, for all noise signal the decrease in noise from baseline to post-construction was larger in the impact area than in the reference area, albeit not significantly larger (Figure 3.17).

There was a significant diurnal variation in the 100 Hz band only, with generally higher noise from 6 in the morning to 21 in the evening. The pronounced diurnal pattern suggests that the noise is most likely associated with human activity and the frequency suggests the noise to originate from ships. Thus, it is likely that the significant diurnal pattern is associated with the ferry routes to Germany and ship/boating activity in general. The diurnal pattern in the impact area did not change from baseline to post-construction relative to that in the reference area, suggesting that there was no significant change of the diurnal noise pattern associated with the operation of the wind farm.

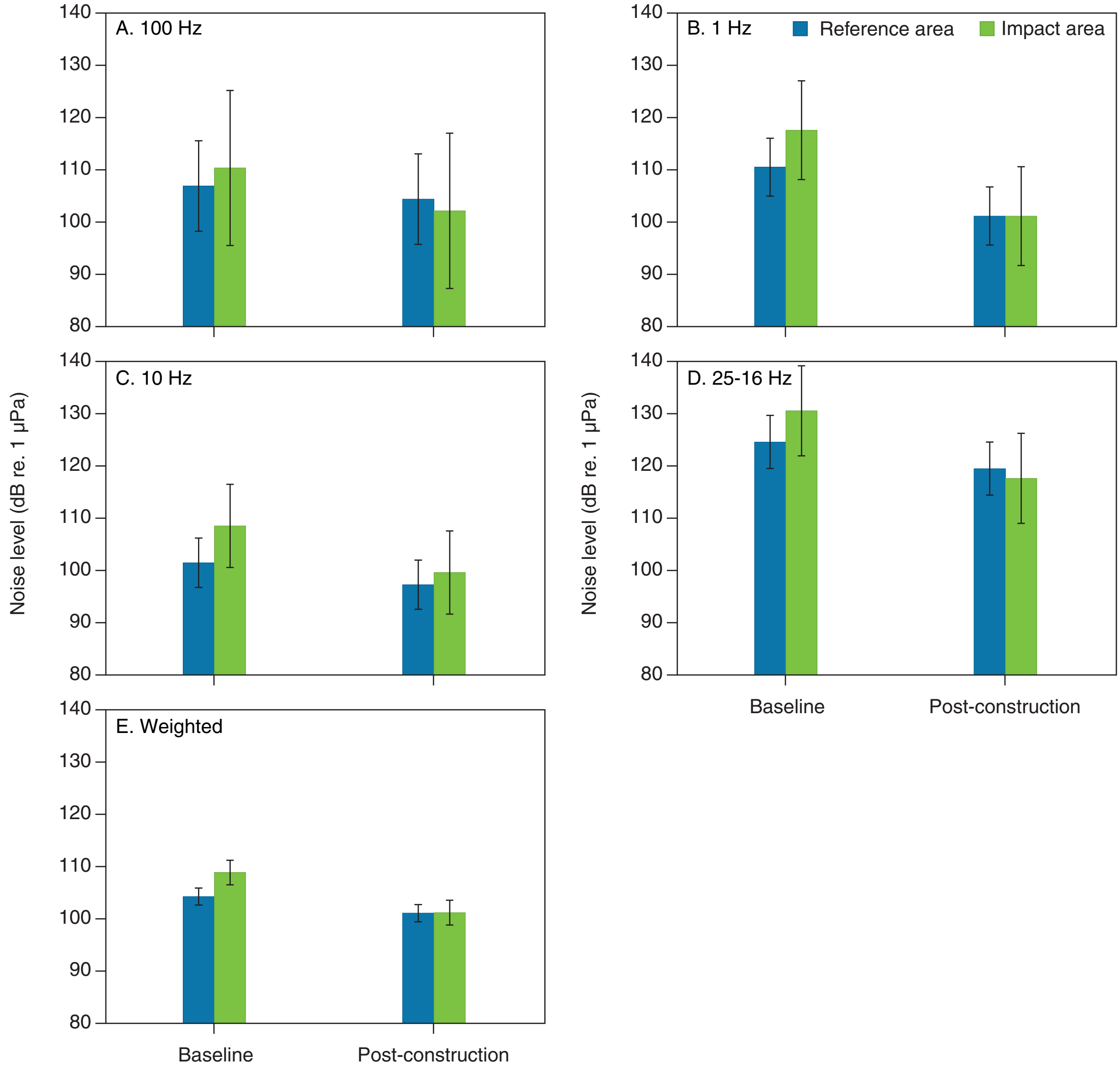


Figure 3.17. Mean noise levels at different frequencies and frequency bands for combinations of area and period. Error bars mark the 95% confidence limits for the mean values.

4 Conclusion

This study has successfully collected acoustic data on harbour porpoise echolocation activity. At ten stations T-PODs were placed from 24 September 2008 to 16 February 2009 before the Rødsand 2 Offshore Wind Farm was constructed and from 24 September 2011 to 2 March 2012 during normal operation of the wind farm. The 10 stations included three stations inside Rødsand 2 Offshore Wind Farm, three in a reference area west of the Rødsand 2, two inside the neighbouring Nysted Offshore Wind Farm east of Rødsand 2 and two in a reference area east of Nysted wind farm. In addition background noise was recorded at four stations (one in each reference area and two in Rødsand 2 wind farm). Although the instruments (T-POD and noise loggers) did not record during the full period, sufficient data have been collected to analyse for a potential effect on the order of 10-20% measured by echolocation activity indicators.

The ten stations have similar porpoise densities and the same seasonal fluctuations during the baseline period. This implies that all stations can be used to evaluate the effect of the wind farm.

There was no overall change in echolocation activity from baseline to operation throughout the entire study area for any of the four indicators (Click PPM, PPM, Encounter duration and Waiting time). Also, there was no significant change in the echolocation activity in Rødsand 2 Offshore Wind Farm relative to each of the three reference areas or all these areas combined, i.e. changes from baseline to operation were similar in the impact and reference areas. It was also found that the overall noise level decreased from the baseline to the operation, but this decrease was common to both the impact and reference area and there are no indications that the noise level in Rødsand 2 Offshore Wind Farm should have increased relative to the reference area. Particularly, no significant effect on noise levels audible to porpoises was found. This could be due to a generally high noise level in the area, masking the turbine noise or that the noise loggers in the wind farm were deployed between the wind turbines, i.e. at distances ~350-450 m from the turbines.

This study also shows that the echolocation activity generally has declined in Nysted Offshore Wind Farm since the baseline in 2001-2002 and has not fully recovered yet. However, when comparing the wind farm area with the reference area in operation period 4 (2011-2012), there is a relatively higher echolocation activity than during the construction period (2002-2003) and operation period 1-3 (2004-2006 and 2008-2009), showing a significant increase from construction to operation period 4 in click PPM and encounter duration as well as significant increases in PPM from operation periods 2 and 3 to operation period 4. It is therefore likely that the strong negative effect on porpoises in Nysted Offshore Wind Farm is gradually diminishing possibly due to a habituation of the porpoises to the wind farm or possibly an increase in prey due to an artificial reef effect around the turbine foundations.

Contrary to the findings at Nysted Offshore Wind Farm, no significant negative or positive effects were found at Horns Rev I (Tougaard et al. 2006c), whereas the results from Egmond aan Zee showed a pronounced and significant increase in harbour porpoise acoustic activity inside the operating wind farm, compared to the baseline (Scheidat et al. 2011). The cause for this increase is unknown, however, the area is known for heavy ship traffic and intensive trawling, so the ban of shipping and fishing inside the wind farm may have provided a “sanctuary” for the porpoises (Scheidat et al. 2011).

The monitoring programs were all designed to use a BACI design to determine if the animals avoided the wind farm areas both during construction and/or operation of the wind farms. This is probably the most powerful method to apply, but the data does not reveal specific explaining factors like noise, presence of the turbines, boat traffic or change in prey availability were responsible for the observed effects. The only exception is pile drivings. However, it is likely that the negative effect on porpoises from the construction could be due to a combination of disturbance from the different construction activities, involving boat traffic, with associated underwater noise, as well as disturbance to the seabed with resuspension of sediment etc. Secondary effects, where prey species of fish were deterred by the construction and operation activities are also possible. There are no clear explanations to the slow recovery at Nysted and why this negative effect was not observed at Horns Rev, Egmond aan Zee and Rødsand 2. One possible explanation to the stronger response at Nysted may be that the area is a less essential habitat to porpoises than the other areas and that the porpoises do not necessarily have a strong incentive to search for food in an area with disturbances. Another possible explanation is that Nysted Offshore Wind Farm is located in a relatively sheltered area in the Baltic, whereas Horns Rev and Egmond aan Zee has a high exposure to wind and waves in the North Sea resulting in higher natural background noise. Thus, at Nysted the signal to noise ratio is higher and therefore the relative noise level from the turbines is louder and more audible to the porpoises at greater distances than at Horns Rev and Egmond aan Zee. However, this will not explain the observed differences between Nysted and Rødsand 2.

We found no cumulative effect of the two wind farms together. The gradual return of porpoises in Nysted Offshore Wind Farm seemed to be unrelated to the construction of Rødsand 2 Offshore Wind Farm. A similar effect on the porpoises at Rødsand 2 Offshore Wind Farm, as found for Nysted Offshore Wind Farm, could be expected. We have no good explanation for the lacking effect and can only speculate that the elevated noise or changes to the prey availability during the baseline period could have an effect on our results or that there was an already low porpoise presence in the Rødsand 2 area caused by a potential barrier effect by Nysted Offshore Wind Farm, when the animals move along the coast in an east-west direction. This is the first time the effect of two wind farms next to each other have been studied and potential explanations to the observed differences is pure speculation.

A year-round monitoring in the near future would show if Rødsand 2 and Nysted Offshore Wind Farms have the same seasonal variations in porpoise activity and if the porpoises in Nysted Offshore Wind Farm will fully recover and return to the level prior to construction. Furthermore, it would show if the Rødsand 2 Offshore Wind Farm and reference area will show increasing porpoise activity. This could indicate that the Rødsand 2 areas are recovering from the wind farm construction simultaneously with Nysted wind farm and thereby showing a long term effect of the whole area after the first wind farm was constructed. Finally, detailed information on the behavior of porpoises inside and around wind farms is required to determine the potential avoidance behavior.

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EFFECTS ON HARBOUR PORPOISES FROM RØDSAND 2 OFFSHORE WIND FARM

E.ON Vind Sverige has been commissioned the construction of Rødsand 2 Offshore Wind Farm comprising 90 wind turbines, south of Lolland-Falster, Denmark. The location of the wind farm is 3 km west of the existing Nysted Offshore Wind Farm with 72 turbines. In combination the two wind farms represents the largest wind farm area in the world. Porpoises were monitored by automatic acoustic dataloggers (T-PODs) according to a statistical BACI design and deployed during baseline (Sep 2008-Feb 2009) and during operation (Sep 2011-Mar 2012). These instruments were deployed at 10 stations covering a coastal stretch of 35 km from Gedser to Rødby, including the wind farm area with reference areas on both sides. In addition, background noise at four of the T-POD stations was recorded by automatic noise loggers. In order to assess the potential cumulative effect of two adjacent wind farms, similar data from the Nysted Offshore Wind Farm were also analysed.

We found no overall change in echolocation activity over the entire monitoring area from baseline to operation of Rødsand 2 Offshore Wind Farm. Also, there was no significant change in the echolocation activity in Rødsand 2 Offshore Wind Farm relative to each or a combination of the three reference areas, i.e. changes from baseline to operation were similar in the impact and reference areas. Also no significant change in noise levels audible to porpoises was found. This could be due to a generally high noise level in the area, masking the turbine noise or that the noise loggers in the wind farm were deployed between the wind turbines, i.e. at distances ~350-450 m from the turbines. This study also shows that the echolocation activity is still significantly lower in Nysted Offshore Wind Farm since the baseline in 2001-2002, although the difference seem to gradually diminish possibly due to a habituation of the porpoises to the wind farm or better feeding posibilities. We found no cumulative effect of the two wind farms together. The gradual return of porpoises in Nysted Offshore Wind Farm seemed to be unrelated to the construction of Rødsand 2 Offshore Wind Farm. This is the first time the effect of two wind farms next to each other have been studied.

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