NERI commissioned report to Sund&Bælt A/S,

Porpoises north of Sprogø before, during and after construction of an off-shore wind farm

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Data sheet

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1 Dansk Resumé

Denne rapport beskriver en undersøgelse af forekomsten af marsvin i området nord for Sprogø i perioden 2008-2010 – før, under og efter byggeriet af Sprogø Havmøllepark. Undersøgelsen er foregået ved hjælp af akustiske dataloggere (såkaldte T-PODs), der er i stand til at registrere marsvins ekkolokaliseringslyde. Undersøgelsen er gennemført som en såkaldt BACI-undersøgelse (Before-After-Control-Impact), hvor forekomsten af marsvin kortlægges både før under og efter etablering af parken og sammenlignes med sideløbende studier i et nærliggende kontrolområde (reference-område).

Storebælt er sammen med Lillebælt og nordlige Øresund hjemsted for nogle af de tætteste forekomster af marsvin i Europa, og det centrale Storebælt, inklusiv området hvor mølleparken ligger, er sammen med andre områder i Danmark udpeget til et særligt beskyttet område (Natura2000 område) for marsvin, i henhold til EUs Habitatdirektiv. Der er derfor særlig bevågenhed omkring etableringen af en havmøllepark i området i forhold til eventuelle påvirkninger af forekomsten af marsvin.

Sprogø Havmøllepark består af 7 vindmøller, hver på 3 MW, anbragt på betonfundamenter, der hviler på havbunden og holdes nede af ballaststen. De er forbundet med 10 kV kabler, der føres til land to steder på Sprogø. Møllerne står nord for Sprogø og er anbragt på en linje med 450 m's afstand på mellem 5 og 10 meters dybde.

Tilsvarende studier på andre, større havmølleparker (Nysted og Horns Rev I + II) har vist at marsvin reagerer negativt på byggeaktiviteterne og i det ene tilfælde (Nysted) ikke var vendt fuldt tilbage til mølleområdet 2 år efter byggeriet var slut. Der kan være flere kilder til forstyrrelsen af marsvinene, men undervandsstøj skønnes at være den væsentligste, idet kraftig undervandsstøj kan høres over meget store afstande.

Sprogø Havmøllepark er en meget lille møllepark (7 møller) i forhold til f.eks. Nysted (72 møller), Horns Rev I (80 møller) og Horns Rev II (91 møller), hvorfor de forventede effekter blev skønnet at være mindre på grund af den kortere byggeperiode. Desuden er installeringen af den type fundamenter der blev brugt (støbte betonfundamenter, der anbringes ovenpå bunden) ikke nær så forstyrrende som de stålfundamenter, der blev anvendt på Horns Rev. På trods af dette, så blev det i miljøkonsekvensvurderingen, der lå til grund for tilladelsen til at bygge parken, forudsat at marsvinene ville blive midlertidigt fordrevet fra byggeområdet under byggeriet, men at de ville vende tilbage igen efter mølleparken var sat i drift.

1.1 Metoder

Forekomsten af marsvin blev undersøgt ved hjælp af akustiske dataloggere. Der blev udsat fire målestationer med dataloggere, to i havmølleparken og to i et kontrolområde længere mod nord i Storebælt, ud for Reersø, hvor dybde og bundforhold er sammenlignelige med forholdene nord for Sprogø. Dataloggerne blev lagt ud og indsamlede data i perioden fra det sene forår til det sene efterår i årene 2008 (før byggeriet, ″baseline″), 2009 (under byggeriet, ″construction″) og 2010 (efter byggeriet ″operation″).

Dataloggerne (kaldet en T-POD, konstrueret af Chelonia Inc., England) består af en hydrofon (undervandsmikrofon) og to skarpe filtre der sorterer marsvinenes ekkolokaliseringslyde (kaldet klik) fra baggrundsstøj. De kan registrere marsvin kontinuerligt i op til 2 måneder ad gangen, hvorefter batterierne skal skiftes og hukommelsen tømmes. Rækkevidden er i gennemsnit omkring 100 m, med ca. 3-500 meter som den absolut største afstand hvorfra et marsvin kan registreres.

Ud fra de registrerede signaler beregnes fire indikatorer for marsvins tilstedeværelse og aktivitet. Disse indikatorer er:

- Marsvin-positive minutter (PPM). Procentdelen af et døgn, hvor marsvin kunne registreres, optalt minut for minut, dvs. hvor mange minutter ud af 1440 minutter på et døgn kunne marsvin høres af T-POD'en.

- Klik per PPM. Antal klik registret per minut, for de minutter hvor der var mindst et klik, udregnet som et gennemsnit over hvert døgn.

- Varighed af besøg (encounters). Den samlede varighed af en serie af marsvineklik, hvoraf ingen klik indenfor hver serie, er adskilt af mere end 9 minutters stilhed.

- Ventetid/interval mellem besøg (waiting time). Tiden mellem de enkelte serier af klik (besøg) hvor der ikke registreres marsvin. Jf. definitionen af et besøg, er et interval altid mindst 10 minutter.

De fire indikatorer udtrykker forskellige forhold ved marsvinenes aktivitet. Således er de marsvin-positive minutter og ventetiden mellem serierne et udtryk for hvor tit der er marsvin omkring målestationen, mens klik per PPM og varigheden af de enkelte serier i højere grad er et udtryk for hvor længe marsvinene opholder sig omkring målestationen og deres akustiske adfærd, når de først er der.

1.2 Resultater af undersøgelsen

Der blev indsamlet data fra i alt 1565 stations-dage fordelt på de fire stationer (382 og 423 dage fra de to stationer i havmølleparken og 244 og 516 dage fra de to stationer i kontrolområdet). Dataene var jævnt fordelt over de tre undersøgelsesår (464 dage i 2008, 425 i 2009 og 676 i 2010).

Dataene påviste en stor og stabil akustisk aktivitet af marsvin i begge områder. Således var der kun 26 stationsdage, svarende til ca 1.6%, hvor der ikke blev registreret marsvin. Medianventetiden mellem serier af marsvineklik (tolket som besøg af en gruppe marsvin omkring målestationen) svingede mellem 54 minutter og 164 minutter og med maksimalt interval mellem besøg af marsvin for de enkelte stationer på mellem 1 og 2 døgn. En usædvanlig høj aktivitet blev set i april måned 2008 på den vestligste station ved Sprogø, med gennemsnitlig PPM på over 15%, svarende til at der blev registreret marsvin i 3.6 timer pr. døgn i gennemsnit.

Der var en udtalt årstidsvariation på alle fire stationer, med minimum i PPM og maksimum i ventetid i august måned, hvilket tages som udtryk for at der var færre marsvin i hele nordlige Storebælt midt på sommeren, sammenlignet med forår og efterår. Der blev ikke indsamlet data fra vintermånederne. Årstidsvariationen i PPM og ventetid var den samme i mølleområdet og kontrolområdet ved Reersø.

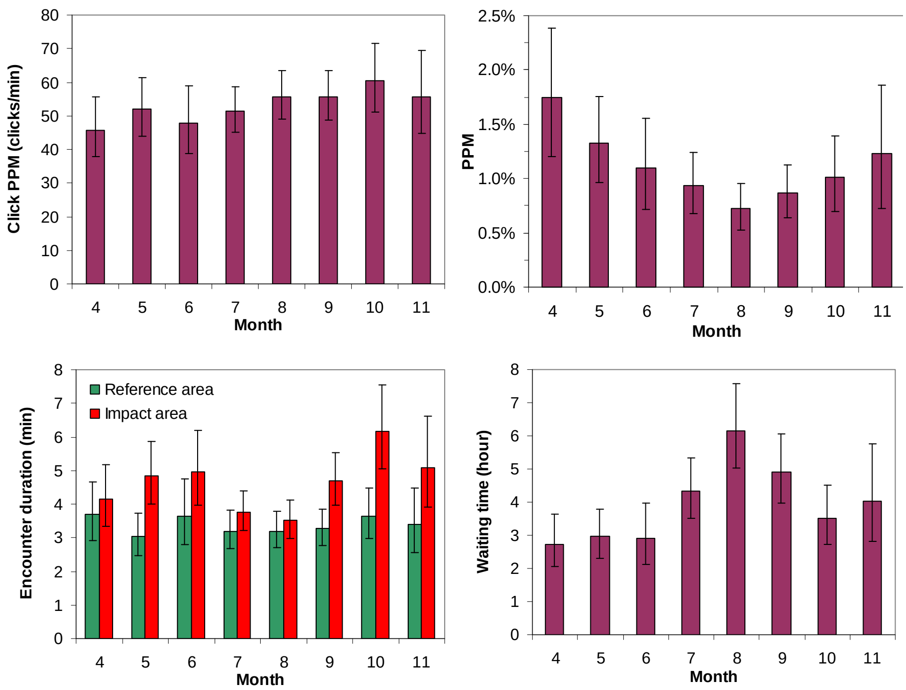

Figure 1.1. Variation i de fire statistiske indikatorer med årstiden. For PPM, klik pr. PPM og ventetid vises månedlige gennemsnit for alle fire stationer, da de ikke var signifikant forskellige, mens varighed af klikserier vises separat for mølleparken (”impact”) og kontrol (”reference”).

Der var ingen tydelig variation i indikatorerne klik per PPM og varighed af klik-serier med årstid, hvilket kan tages som udtryk for at marsvinenes akustiske adfærd var den samme gennem hele perioden. Der var ingen forskel i mønsteret af klik per PPM mellem mølleområde og kontrolområde, men varigheden af klikserierne varierede ikke på samme måde med årstiden i de to områder. I mølleområdet var der således et fald i den gennemsnitlige varighed i juli og august, hvilket ikke sås i dataene fra kontrolområdet.

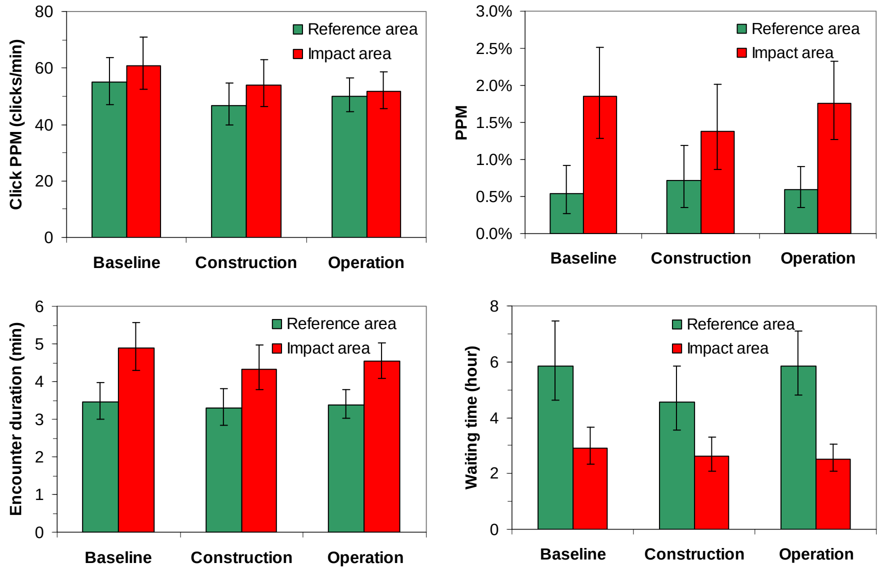

Figure 1.2. Middelværdier af de fire indikatorer for marsvins tilstedeværelse og adfærd i mølleområdet ("Impact") og kontrolområdet ("Reference"). Lodrette linjer indikerer 95% konfidensintervaller. Indikatorerne PPM og interval mellem serier af marsvineklik ("waiting time") var hhv. højere og lavere for mølleområdet, hvilket peger på tilstedeværelsen af flere marsvin ved Sprogø i forhold til området ved Reersø. Der var ingen signifikante forskelle i fordelingen mellem de to områder gennem de tre år (BACI-effekten), hvilket betyder at der ikke kan påvises en effekt (positiv eller negativ) af mølleparken på forekomsten af marsvin i Mølleområdet.

Der var systematiske forskelle mellem de to områder for indikatorerne PPM, ventetid og varighed af klikserier, men ikke for klik pr. PPM. Højere værdier for PPM og varighed og kortere ventetid i mølleområdet peger på at der igennem alle tre år var flere marsvin ved Sprogø end ved Reersø og at de opholdt sig længere af gangen i nærheden af målestationerne når først de var i området.

Med hensyn til effekten af mølleparken, så var ingen af de fire indikatorer signifikant forskellige mellem de tre undersøgelsesår. Med andre ord, så kunne en signifikant ændring i tilstedeværelsen af marsvin ikke påvises i mølleområdet hverken under byggeriet eller i det efterfølgende år hvor parken var i normal drift ($p>0.05$ i alle 4 tilfælde).

1.3 Konklusion

Undersøgelsen dokumenterer en stor og stabil forekomst af marsvin i nordlige Storebælt, med højere akustisk aktivitet nord for Sprogø i forhold til vest for Reersø. Der kunne ikke påvises statistisk signifikante ændringer i marsvineforekomsten i mølleområdet, hverken under byggeriet af mølleparken i 2009 eller det første år med normal drift. Det udelukker naturligvis ikke at der har været en effekt under byggeperioden, men hvis der har været en sådan påvirkning, så har effekten enten været kortvarig og forbundet til bestemte, kortvarige aktiviteter, eller været af så lokal karakter at effekten ikke kunne måles på målestationerne, der af sikkerhedsmæssige årsager var anbragt ca. 500 m fra nærmeste mølle.

Fraværet af en tydelig effekt af byggeriet kan bero på flere faktorer, der ikke nødvendigvis udelukker hinanden:

- Utilstrækkelig styrke i den statistiske test (BACI-analysen). Hvis der ikke er tilstrækkeligt med data kan man ikke opnå tilstrækkelig statistisk styrke (β) til at forkaste nul-hypotesen (at der ikke var en effekt), på trods af at der faktisk var en effekt (Type II fejl). Dette er dog ikke sandsynligt, idet der er tilstrækkeligt med styrke i datasættet til, at vise signifikante forskelle mellem de to områder og mellem årstiderne.

- Mølleparken er lille (7 møller) i forhold til andre mølleparker, hvor tydelige effekter kunne ses.

- Der forekom ikke aktiviteter, der genererede meget kraftig undervandsstøj, således som det var tilfældet ved Nysted og Horns Rev

- Der er en meget stor trafik af både fragtskibe og lystbåde tillige med et vist fiskeri med trawl i området, hvilket gør det til et område, der i forvejen har et højt niveau af undervandsstøj og andre forstyrrelser.

- Igennem en ca. 10-årig periode forud for dette studie blev Storebæltsforbindelsen bygget, hvilket indebar en stor trafik af specialskibe og aktiviteter ikke ulig det, der blev gennemført under byggeriet af mølleparken (blot i mindre målestok), hvilket kan have givet en tilvænning til den type aktiviteter.

Da området som nævnt er et område med et i forvejen højt niveau af forstyrrelser kan fraværet af effekter af byggeriet således ses som tegn på at marsvinene i området er vant til forstyrrelser af denne type og kan leve med dem. Der kan imidlertid også være tale om at forstyrrelserne har pågået i så lang tid at de mest sensitive marsvin for længst har fortrukket fra området og at det derfor kun er de tolerante dyr der er tilbage. En sådan effekt er dog meget svær at påvise når først forstyrrelsen er etableret.

I forhold til havmølleparken må det imidlertid konkluderes at en eventuel effekt af byggeriet ikke har været målelig og sandsynligvis har været minimal på marsvinene i området. Hvis der er en blivende påvirkning, så rækker den maksimalt nogle få hundrede meter ud fra møllerne, hvis den overhovedet er til stede.

2 Summary

This report describes a study of the abundance of harbour porpoises (*Phocoena phocoena*) in the waters north of the island Sprogø in the central Great Belt. The study was conducted in the years 2008-2010, before, during and after construction of a small offshore wind farm.

The Great Belt is together with the Little Belt and the northern Sound home to some of the highest densities of harbour porpoises in European waters and together with other areas designated as specially protected areas as part of the Natura2000 network. This also means that there is increased attention surrounding construction of an offshore wind farm within the boundaries of the Natura2000 area.

The wind farm consists of 7 turbines, each 3 MW and placed on concrete gravitational foundations, held in place by ballast rocks. They are placed on a line, separated by 450 m, running parallel to the coast of Sprogø.

The abundance of porpoises and the possible impact of construction and operation of the wind farm was studied by means of passive acoustic dataloggers (T-PODs) in a BACI-design (Before-After-Control-Impact), in line with previous studies in other offshore wind farms in Denmark and abroad. Four measuring stations were established; two in the wind farm area (impact) and two in a reference (control) area further north in the Great Belt, in an area with comparable bathymetry and hydrography.

From the collected registrations of porpoise echolocation clicks four statistical indicators were derived, again in line with previous studies. These indicators were porpoise-positive minutes (PPM), expressing the fraction of a day, counted minute by minute, in which porpoise clicks could be detected; clicks per PPM, expressing the average number of porpoise clicks per minute, for minutes where at least one click was detected; Encounter duration, being the duration of groups of clicks, never separated by more than 9 minutes of silence; and finally waiting time, being the intervals between acoustic encounters.

The data collected from spring to autumn in the three monitoring years 2008 (baseline, 2009 (construction) and 2010 (operation) showed systematic variation with month of year, reaching lowest abundance in August and with parallel changes in abundance in the wind farm area and the control. There was a consistent and statistically significant difference in acoustic activity between the two areas, indicating a general higher abundance of porpoises in the central Great Belt, compared to the more northerly reference area.

With respect to effects of the wind farm, no significant BACI-effect was found for any of the four indicators. This indicates that no significant increase or decrease in acoustic activity in the wind farm area not explained by general variations in the entire Great Belt could be observed.

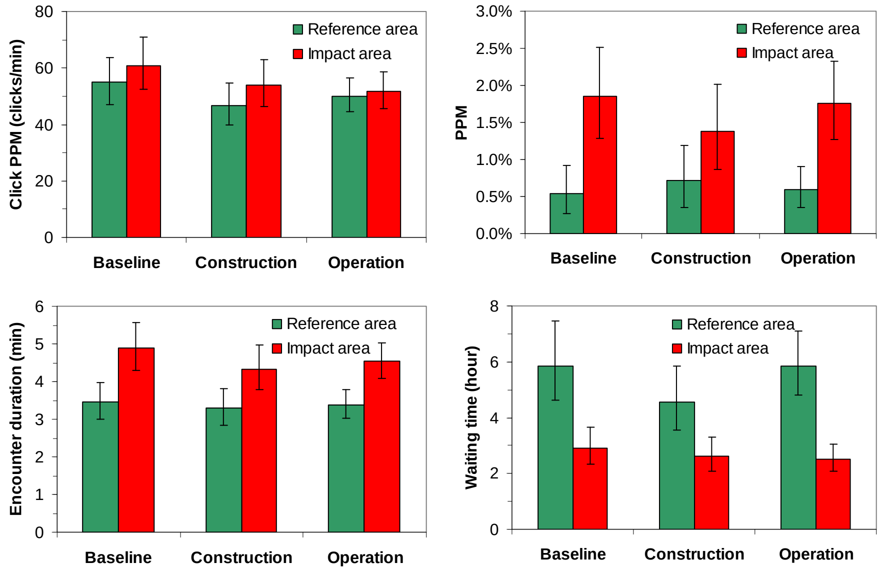

Figure 2.1. Mean values of the four statistical indicators in the wind farm area (impact) and control (reference). Error bars indicate 95% confidence intervals. The indicators PPM and waiting time were significantly different between the two areas, but there was no significant change in the ratio between the four indicators over the three monitoring years (BACI-effect), i.e. neither construction nor operation caused a significant (positive or negative) effect on porpoise abundance.

Thus, the study documents a large and stable occurrence of porpoises in the central Great Belt, in line with several other studies where different methods were used. Secondly, no statistically significant effect of the wind farm on abundance of porpoises could be shown. This is in contrast to the studies at other wind farms and also runs counter to the expectations of the environmental impact assessment, where a partial displacement from the wind farm area was expected during construction. The absence of a statistically significant effect can be due to several factors, not mutually exclusive:

- Insufficient statistical power (Type II error). This is unlikely to be the case in the present dataset, as a very large amount of data was collected and fairly evenly distributed across stations and monitoring years. Furthermore significant seasonal patterns and general differences between areas support the notion of a robust dataset with good statistical power.

- The small size of the wind farm (7 turbines) compared to the much larger wind farms previously studied (72 turbines or more).

- Absence of particularly noisy activities during construction. In contrast to the three other wind farms studied, no pile driving of sheet piles or monopiles were conducted at Sprogø.

- High levels of ship traffic, leisure boat traffic and also bottom trawling in the area means that the general level of disturbances is high as is the expected background noise level.

- Prior history of a major construction work in the area (the Great Belt Connection), which may mean that some animals have prior experience and thus can habituate faster.

Thus, any disturbance caused by construction of the wind farm appears to have been sufficiently small to be unnoticeable at the measuring stations, located about 500 m from the nearest turbine. Thus the impact on porpoises, both short term and long term appears to have been negligible.

Due to the special conditions surrounding this particular offshore wind farm in this particular location it is not safe to extrapolate this result to larger wind farms and/or wind farms located in other areas with different levels of other disturbances.

Porpoise in the northern Great Belt. Foto J. Teilmann.

3 Introduction

This report describes monitoring of harbour porpoises in connection to the construction and first year of operation of a small offshore wind farm north of Sprogø, Great Belt, Denmark. The work was initiated in 2008 with collection of baseline data in connection to preparation of the Environmental Impact Assessment (Sveegaard *et al.* 2008), continued through 2009 during construction and concluded in 2010 with collection of data from the first year of operation.

3.1 Porpoises in Great Belt

Harbour porpoises are abundant in most of the Danish waters, and in particular the three belts (Little Belt, Great Belt and the Sound) appears to be very important to porpoises (Sveegaard *et al.* 2011b).

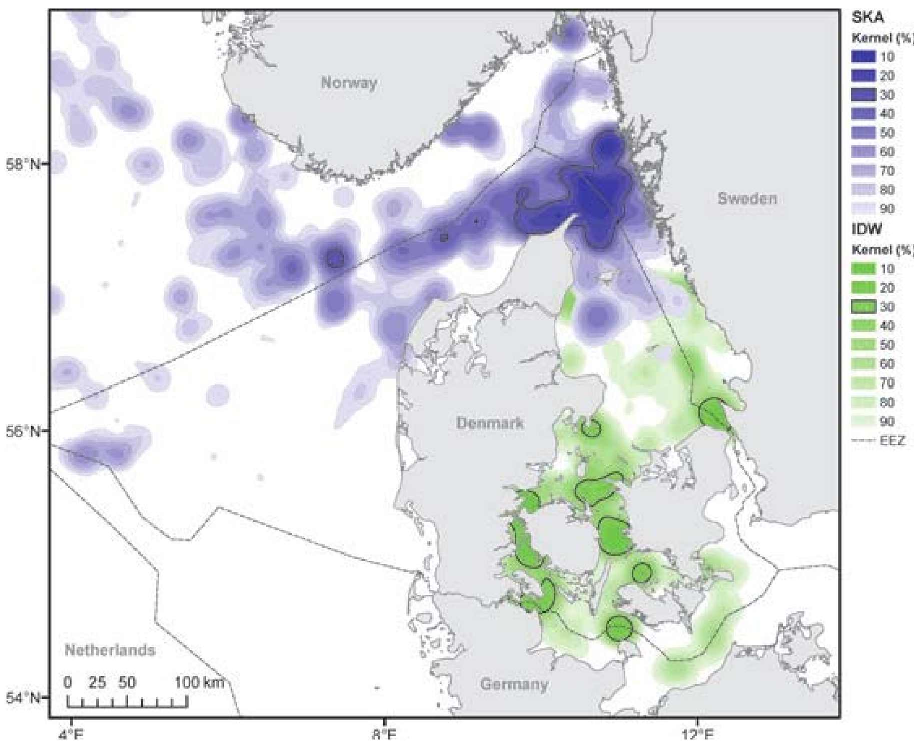

Figure 3.1. All year distribution of harbor porpoises *Phocoena phocoena* tagged between 1997 and 2007 displayed by fixed kernel density based on one location every four days from each other. The Inner Danish waters (IDW) group are shown in green (*N* = 38 porpoises, *n* = 950 locations) and the Skagerrak group (SKA) are shown in blue (*N* = 26 porpoises, *n* = 665 locations). Black line indicates high-density areas defined as the 30% kernel contour. From Sveegaard *et al.* 2011b

3.1.1 Protection

The harbour porpoise is a protected species, primarily due to inclusion on both appendix II and appendix IV of the European Commission Habitats directive (EU Kommissionen 1992). Following this directive the Danish Nature Agency has designated special marine areas of conservation aimed at protecting among others harbour porpoises (Miljøministeriet

2007; Miljøministeriet 2010). One of these habitat areas is located in the Great Belt and includes the wind farm north of Sprogø (SAC no. 100).

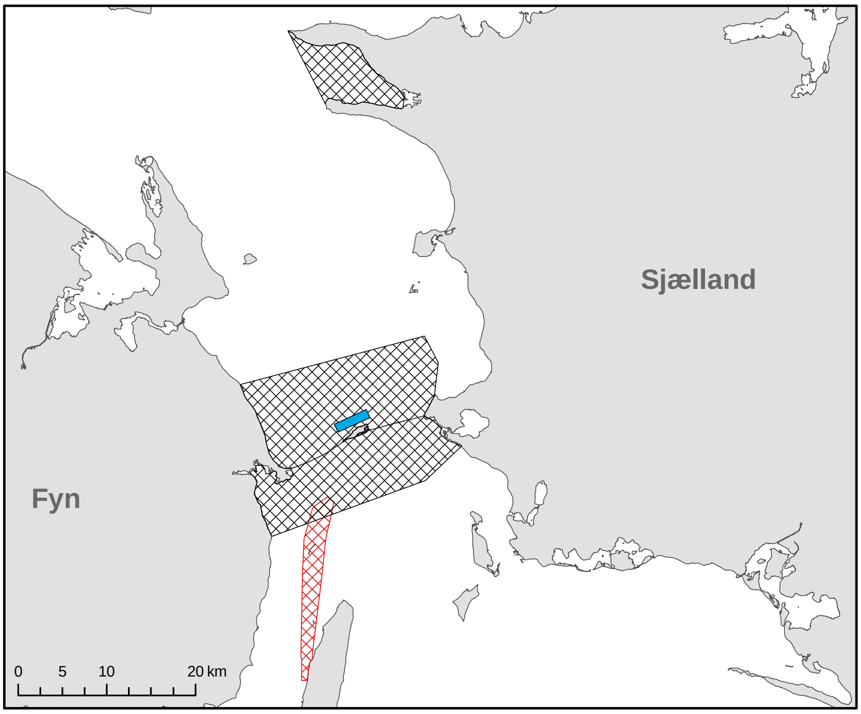

Figure 3.2. Sprogø offshore wind farm (blue area) located north of Sprogø and the Great Belt connection (line) and inside the special area of conservation "Great Belt" (Natura 2000 area, crosshatched. Shown are also two adjacent Natura2000 areas, Kalundborg Fjord to the north and Vresen, to the south (in red).

The fact that the waters around Sprogø were designated as Natura2000 area was not in itself prohibitive for construction of the wind farm, but naturally placed extra responsibility on the builder in terms of minimising disturbance during construction.

3.2 The wind farm

Figure 3.3. Turbines seen from north-eastern tip of Sprogø Photo: Sund&Bælt A/S.

The wind farm consists of 7 Siemens Windpower 3 MW turbines, placed in 5-10 m of water on the north side of Sprogø. The turbines are placed on a line parallel to the coast and with 450 m between turbines. Turbines are connected by a 10 kV cable (alternating current) buried 1 m into the seabed and connected via two other 10 kV cables to shore on Sprogø.

The foundations are gravitational foundations made of concrete and placed on a gravel bed on the sea bottom. Compared to steel monopile foundations, which are commonly used in more exposed locations, such as the North Sea, installation of gravitational foundations takes longer time, but does not involve emission of high-intensity underwater noise as the noise generated by impact pile driving of the steel monopile foundations (Tougaard *et al.* 2009a). Once in place and filled with ballast rocks the foundation quickly overgrows with algae and epifauna and thus becomes an artificial reef (Petersen and Malm 2006; Leonhard and Pedersen 2006).

Figure 3.4. Left: Placement of foundation on the seabed by means of a large floating crane. Right: schematic drawing of turbine mounted on the foundation, which is placed on top of the gravel bed and held in place by ballast rocks. The foundation is protected from scour on the sides. The inverted cone at the top helps to protect the foundation against ice in winter. Photo and graphics: Sund&Bælt A/S.

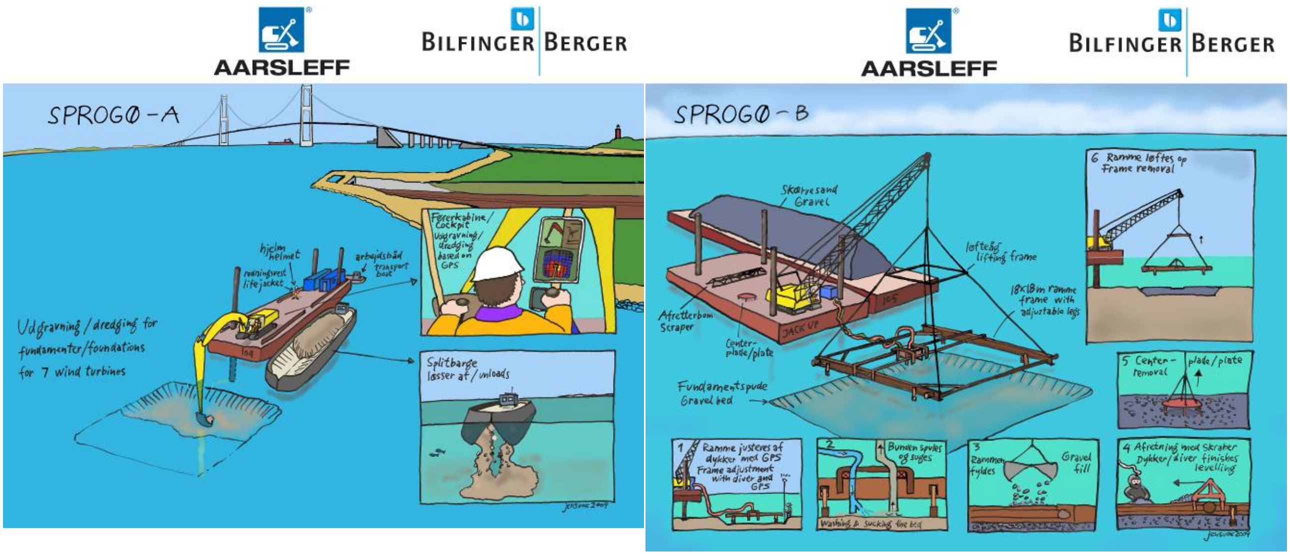

Figure 3.5. Preparation of the seabed for foundations. Left: by means of a dredger, the top layer of sediment is removed and deposited elsewhere. Right: The seabed is thoroughly prepared by rinsing with water and filled up with gravel, carefully levelled out by means of the iron frame and movable boom. Much of the underwater work is diver assisted. Graphics: Sund&Bælt A/S.

3.3 Impact from wind farms

The central question in the context of offshore wind farms and marine mammals is whether the construction and operation of these have an impact (positive or negative) on the abundance and behaviour of the animals in the area and ultimately the number of animals and finally if this impact is acceptable or not. Even if the ultimate goal may be to address impact at population level, this is rarely possible since the population structure may not be known and the habitat of individuals is much larger than the area covered by the wind farm.

In general, the affecting factors are divided into disturbing factors, which one way or the other all have a negative impact on the animals (small or large); changes to the habitat, which can have both positive and negative effects; and exclusion of fishery, which is only positive.

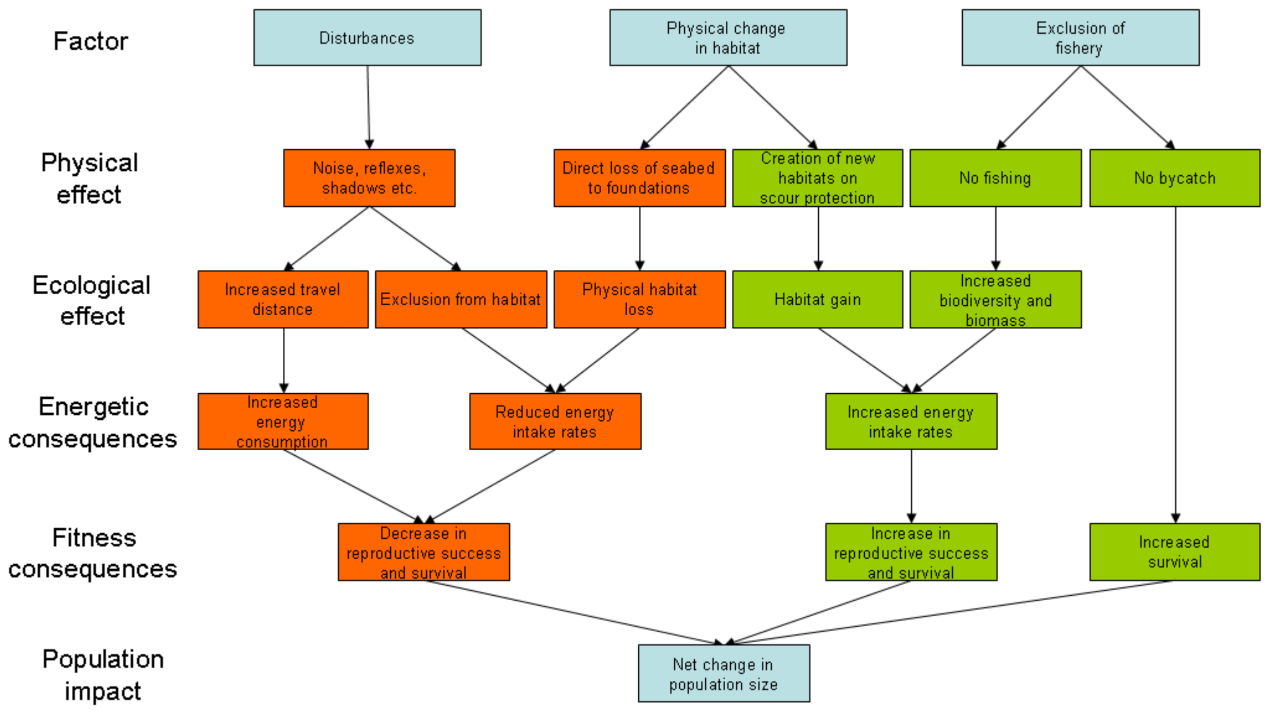

Figure 3.6. Potential effects of offshore wind farms on marine mammals. Factors with negative effect are shown in red; factors with positive effects are shown in green. Disturbance is the dominant factor during construction, whereas all three factors could play a role during operation of the wind farm. Adapted from Fox et al. 2004.

3.3.1 Construction

Construction of an offshore wind farm is an operation of considerable magnitude and contains several components capable of affecting porpoises. A general negative effect of construction has been documented several times (Carstensen *et al.* 2006; Tougaard *et al.* 2006a; Tougaard *et al.* 2006b). In particular, specific effects of pile drivings have been documented (Tougaard *et al.* 2009a; Bailey *et al.* 2010; Brandt *et al.* 2011), and this activity is likely to be the single most disturbing activity during construction.

The increased traffic of smaller and larger boats and ships to and from the construction site will be another source of disturbance, most likely primarily due to the elevated levels of underwater noise. No measurements of general background noise during construction of an offshore wind farm is available, so no good estimates of magnitude of this impact is available and very little is known about how porpoises react to underwater noise from boats and ships.

The seabed where the foundations are placed and cables are buried is inevitably disturbed during construction. Unless the resuspension of material is very large it is unlikely to affect porpoises, although secondary effects through redistribution of prey may be possible.

3.3.2 Operation

The construction and operation of the turbines create changes in the physical environment which may influence porpoises directly and indirectly. It is thus possible that the physical presence of the turbines has a negative effect, i.e. that animals will be reluctant to enter an area with new large unfamiliar structures. Most concern surrounds underwater noise from operating turbines as a factor potentially affecting porpoises.

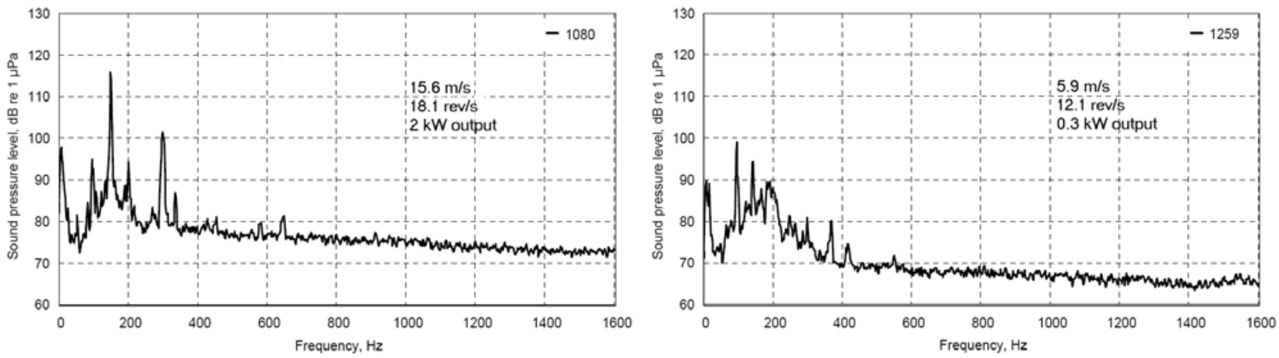

Figure 3.7. Measurements of noise from turbine in Horns Rev Offshore Wind Farm running close to maximum power rating (left) and at low level (right). Measurements were made with a Reson TC4032 hydrophone mounted 2.5 m above the seafloor 87 meters from the turbine foundation and recorded on an MP3 recorder at 128 kbps and normalised to a distance of 100 m. Turbine noise consists of multiple peaks at discrete frequencies, which rise above the background noise. From Betke (2006).

Based on measurements of other offshore wind turbines, the noise from the operating wind turbines is expected to be of relatively low intensity and frequency (Madsen *et al.* 2006). A number of measurements from other turbines exist and all share common features of low absolute sound levels and no significant energy at frequencies above 500-1000 Hz. One example from Horns Rev is shown in Figure 3.7. Apparently, there is little difference in the radiated underwater noise from monopile and gravitational foundations. One measurement which stands out is from Utgrunden wind farm (Ingemansson Technology AB 2003). Noise from these turbines is considerably higher in intensity (approx 10 dB) and with considerable energy at higher frequencies than the other wind farms. The reason why these turbines differ from the rest is unknown, but may have to do with the foundation on solid bedrock, in contrast to the hard sand in the other wind farms. The foundations at Sprogø are similar to the foundations at Middelgrunden offshore wind farm and although the turbines are larger than Middelgrunden, there seem to be no simple relationship between nominal capacity of turbines and emitted noise. Measurements from Middelgrunden indicate that they generate noise with intensity and spectral emphasis comparable to most other turbines from which measurements are available (Tougaard *et al.* 2009b).

3.3.3 Changes in habitat

The construction of an offshore wind farm on sandy bottom will inevitably cause changes to the habitat. First of all is the direct loss of habitat to foundations and scour protection (protection from erosion). The absolute size of the area covered by foundations and scour protection is marginal, however, and any effects on the habitat are likely to be overshadowed by the changes that will occur as a consequence of introduction of hard substrates, that extend up in the water column. These will inevitably be colonised by algae and filter feeding epifauna and create an artificial reef (Petersen and Malm 2006) and represent a permanent enrichment of biomass and biodiversity. Studies on colonisation of foundations at Nysted Offshore Wind Farm have shown that the species composition on the turbine foundations is identical to the species composition at a close by natural stone reef - Schönheiders Pulle (Birklund 2005). No studies have demonstrated neither positive nor negative effects of artificial reefs on porpoises.

4 Methods

The presence of harbour porpoises was assessed by means of passive acoustic monitoring with a BACI-design. In brief, a monitoring with two stations inside the wind farm area (termed "impact") and two in a reference area further north (termed "reference"). The reference area was selected to be comparable to the impact area with respect to bottom topography and hydrography, although not necessarily identical. By monitoring porpoise activity before, during and after construction in both areas it is possible to identify a differential response in the impact area, that is a change from baseline to construction and/or operation independent of natural variation from year to year, which is assumed to be captured by the variation in the reference area. This approach to studying impact of offshore wind farms on harbour porpoises has been used in several previous studies, including Nysted (Carstensen *et al.* 2006), Horns Reef I (Tougaard *et al.* 2006b) and the Dutch wind farm Egmond aan Zee (Scheidat *et al.* 2009).

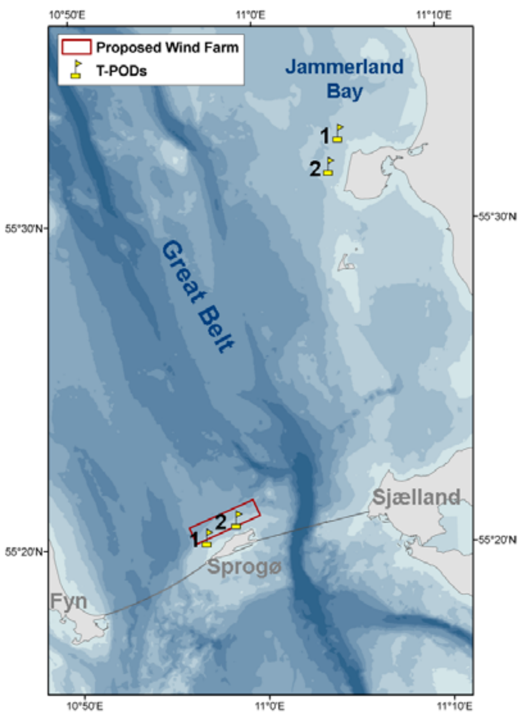

Figure 4.1. Layout of monitoring stations. Two stations within the wind farm ("impact") north of Sprogø are termed Sprogø West (SP_W - 1) and Sprogø East (SP_E - 2) and two reference stations off Reersø are termed Jammerland North (JM_N -1) and Jammerland South (JM_S - 2).

4.1 T-PODs

The passive acoustic dataloggers used in the study were T-PODs. The T-POD or POrpoise Detector is a small self-contained data-logger that logs echolocation clicks from harbour porpoises and other cetaceans and is developed by Nick Tregenza (Chelonia, UK). It is programmable and can be set to specifically detect and record the echolocation signals from harbour porpoises. The T-POD consists of a hydrophone, an amplifier, a number of band-pass filters and a data-logger that logs echolocation click-activity. It processes the recorded signals in real-time and only logs time and duration of clicks fulfilling a number of acoustic criteria set by the user. These criteria relate to click-length (duration), frequency distribution and intensity, and are set to match the specific characteristics of echolocation-clicks. The T-POD relies on the highly stereotypical nature of porpoise sonar signals. These are unique in being very short (50-150 microseconds) and containing virtually no energy below 100 kHz. The main part of the energy is in a narrow band between 120-150 kHz, which makes the signals ideal for automatic detection. Most other sounds in the sea, with the important exception of echosounders and boat sonars, are characterised by being either more broadband (energy distributed over a wider frequency range), longer in duration, with peak energy at lower frequencies or combinations of the three.

The actual detection of porpoise signals is performed by comparing signal energy in a narrow filter centred at 130 kHz with another narrow filter centred at 90 kHz. Any signal, which has substantially more energy in the high filter relative to the low filter, is highly likely to be either a porpoise or a man-made sound (echosounder or boat sonar). Some spurious clicks of undetermined origin (such as background noise and cavitation sounds from high-speed propellers) may also be recorded. These, as well as boat sonars and echosounders are filtered out off-line in software, by analysing intervals between subsequent clicks. Porpoise click trains are recognisable by a gradual change of click intervals throughout a click sequence, whereas boat sonars and echosounders have highly regular repetition rates (almost constant click intervals). Clicks of other origins tend to occur at random, thus with highly irregular intervals.

The T-POD operates with six separate and individually programmable channels. To maximise the chance to detect harbour porpoises during this study, all channels had identical settings (Table 4.1). All T-PODs used were version 3 and all were individually calibrated and had detection threshold adjusted (parameter "sensitivity") to obtain comparable detection thresholds. Calibration was conducted in accordance with Kyhn *et al.* 2008 and thresholds of T-PODs matched to each other.

Table 4.1. ***T-POD filter settings used during deployments.***

Parameter	value
A filter: frequency (kHz)	130
B filter: frequency (kHz)	90
Ratio: A/B	5
A filter: Q (kHz) / integration time	short
B filter: Q (kHz) / integration time	long
Sens½1itivity:	Individually adjusted
Max number of clicks / scan:	no limit
Minimum click duration: (µS)	30

Each of the six channels of the T-POD records sequentially for 9 seconds, with 6 seconds per minute assigned for change between channels. This gives an overall duty cycle of 90% (54 seconds per minute), 15% for individual channels (9 seconds per minute). The number of clicks per minute (see below) per minute was calculated as the sum of these 6 channels, adjusted by a factor of 60/54 corresponding to the actual active period of T-POD monitoring.

In order to minimise data storage requirements only the onset time of clicks and their duration are logged. This is done with a resolution of 10 µs. The absolute accuracy of the timing (time since deployment) is considerably less, due to drift in the T-PODs clock during deployment (up to a few minutes per month). This drift however, is only of concern when comparing records from two T-PODs deployed simultaneously. Clicks shorter than 30 µs and sounds longer than 2550 µs were discarded.

Comparison of T-POD recordings with simultaneous visual tracking of porpoises with theodolite show that the effective detection distance is between 100 and 200 meters with a maximum detection distance of 3-500m (Tougaard 2008; Kyhn *et al.* 2011).

4.2 Deployment and service

T-PODs were deployed about 2 m above the sea bed by means of anchors and surface markers (Figure 4.2). The large buoys were deployed and recovered from a larger boat (either the VTS-service vessel from the Great Belt Bridge or a fishing vessel from Korsør), while service of the instruments were done either from the VTS-vessel or NERI's own, smaller boat "Hanne". Instruments were deployed in late spring all years and serviced with regular intervals (1-2 months) until late fall, where stations were recovered for the winter. Deployment periods for the three years were: baseline period: Apr 2008 – September 2008, construction period: July 2009 – November 2009 and post-construction period, denoted operation period: April 2010 – November 2010.

4.3 Comparison of T-PODs during deployment

Seven different T-PODs have been deployed at four different positions: two positions were located in the putative impact area (SP_E and SP_W) and two positions were located in a reference area (JM_N and JM_S). One T-POD (POD282) was used for monitoring at both JM_N and JM_S, but at both positions there were extended periods (>2 months) where POD282 monitoring was duplicated with other T-PODs. POD282 and POD338 were deployed simultaneously at JM_S (2 July 2008 – 9 September 2008), and POD282 and POD374 were deployed simultaneously at JM_N (10 August 2010 – 18 October 2010). These periods with duplicate monitoring allowed for assessing differences between T-PODs. The time series obtained from the T-POD signals contain some gaps where the T-PODs have not been deployed or specific T-PODs have not been operating properly due to various reasons.

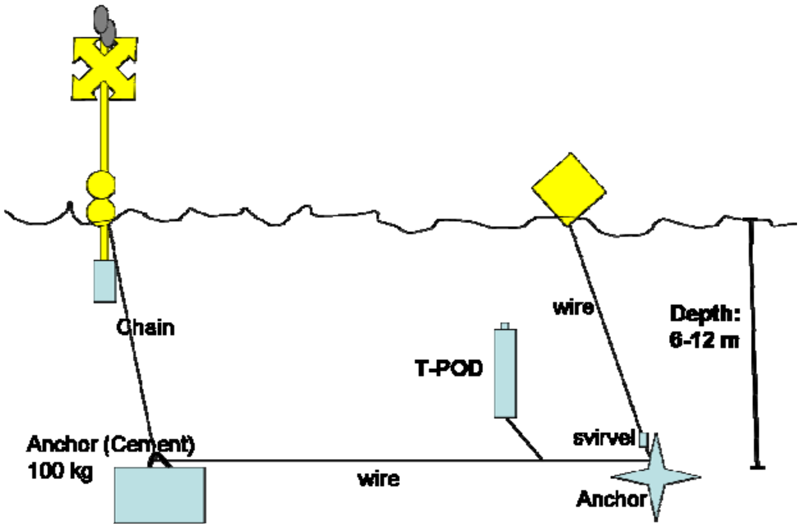

Figure 4.2. Schematic drawing of deployment setup. A heavy buoy and anchor block is placed permanently on the position. The T-POD is deployed next to a secondary, smaller anchor and buoy, which can be retrieved and serviced from a small boat.

4.4 Indicators from T-POD signals

In line with previous studies (Carstensen *et al.* 2006; Tougaard *et al.* 2006b; Scheidat *et al.* 2009) four indicators were extracted from T-POD signals having a constant frequency of 1 minute. This signal, denoted x_t, described the recorded number of 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

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

Click PPM = $$\text{Click intensity} = \frac{1}{N\{x_t > 0\}} \sum_{x_t > 0} x_t$$

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

Another approach 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 minutes with clicks and minutes without clicks. Such short-term sequences were considered to belong to the same encounter although there were also silent periods (minutes without clicks) within the sequence. In line with previous studies a silent period of 10 minutes was used to define two encounters as being separate from each other. Thus, two click recordings separated by a 9 minute silent period would still be part of the same encounter. A schematic example is shown in Figure 4.3. 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

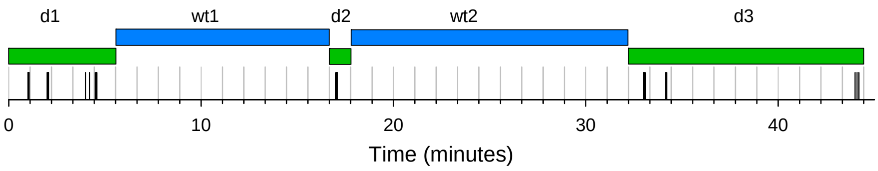

Figure 4.3. Schematic illustration of encounter durations (green) and waiting times (blue) for a sequence of click trains.

This implied that waiting times had a natural lower bound of 10 minutes on average, as the definition and way the waiting time was computed allowed for some minimum intervals to be as low as slightly above 9 minutes. Encounters also potentially include periods (minutes) with no clicks, as long as there were no more than 9 such silent minutes in a row.

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, and therefore not used. 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.

4.5 Models for indicators

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 (3 fixed and 2 random) and combinations thereof:

- *Area* (fixed factor having 2 levels) describes the spatial variation between reference and impact (wind farm) area.

- *Station(area)* (random factor having 4 levels) describes the station-specific variation within the two areas.

- *Period* (fixed factor having 3 levels) describing the difference between the baseline, construction and operation periods.

- *Month* (fixed factor having 8 levels) describes the seasonal variation by means of monthly values (April – November).

- *Podid* (random factor having 7 levels) describes the random variation between different T-PODs.

There were three main factors (*area, period* and *month*) that were partially replicated. *Area* was spatially replicated by having two monitoring locations (*station(area)*) within each area. *Period* represented 3 different modes of potential perturbation as well as 3 different years, and consequently differences between periods and years were indistinguishable. *Month* was replicated at all 8 levels with July, August and September included in all periods and the other months monitored in two of the three periods. Given that *period* and interannual variation between years could not be separated a fully crossed design of the three main factors could not be analysed. This implied that the interaction *period*×*month* as well as *period*×*month*×*area* could not be tested, because there was no replication of the seasonal pattern within any of the different periods. Thus, for the BACI analysis it is only possible to test for a general change between period and area (*period*×*area*), whereas it is not possible to test if there were significant changes in seasonal patterns between the impact and reference area across the three periods. Since both *area* and *month* were replicated, differences in the seasonal pattern (*area*×*month*) between the two areas could be tested. Thus, variations in the echolocation indicators μ_{ijk},, after appropriate transformation, were assumed normal-distributed with a mean value described by the equation:

$$\mu_{ijk} = area_i + period_j + area_i \times period_j + month_k + area_i \times month_k \quad (1)$$

Random effects of the model included variation between T-PODs (*podid*), variation between stations within each area (*station(area)*) and the interaction of station with period (*station(area)*×*period*) and month (*station(area)*×*month*). Finally, the two interactions that could not be tested as fixed effects (*period*×*month* and *period*×*month*×*area*) were included as random effect.

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 4.2). 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 4.2. 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-transformation 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 Eq. (1) were multiplicative on the original scale. This meant that for example 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 Eq. (1) was tested using F-test (type III SS) for the normal distribution (SAS Institute 2003).

Marginal means for the different factors of the model were calculated and back-transformed to mean values on the original scale. Most important, the factor $area_i \times period_j$, also referred to as the BACI effect, described step-wise changes (between baseline, construction and operation) in the impact area different from that in the reference area, but this effect was further broken down by means of formulation of contrasts (on the parameter estimates) into 1) change between baseline and construction, 2) change between baseline and operation, and 3) change between construction and operation. Here exemplified with change from baseline to construction:

$$\text{BACI contrast} = \text{E}[\text{Imp, construct}] - \text{E}[\text{Imp, baseline}] - \text{E}[\text{Ref, construct}] + \text{E}[\text{Ref, baseline}] \qquad (2)$$

For log-transformed indicators such contrasts can be interpreted by calculating

$$\exp(\text{BACI contrast}) = \frac{\text{E}[\text{Imp, construct}]}{\text{E}[\text{Imp, baseline}]} \cdot \frac{\text{E}[\text{Ref, baseline}]}{\text{E}[\text{Ref, construct}]} \qquad (3)$$

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 for any two selected periods.

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. However, fixed main factors (*area*, *period* and *month*) as well as the BACI factor (*area*×*period*) were not removed by backward elimination in order to assess their individual level of significance. The final models, after eliminating all non-significant factors, are presented in the results only.

Harbour porpoises north of Sprogø. Photo Signe Sveegaard.

5 Results

A total of 1565 stationdays of data was collected, distributed over the four stations in the two areas (wind farm and reference area), see Table 5.1.

5.1 Data collected

Table 5.1. Individual deployments and amount of data collected.

Station	POD ID	Data start	Data stop	Days
Sprogø W	339	25-04-2008	02-06-2008	38
Sprogø W	335	02-07-2008	09-09-2008	69
Sprogø W	335	02-07-2009	24-11-2009	145
Sprogø W	335	20-04-2010	02-10-2010	165
Sprogø E	341	14-04-2008	02-06-2008	49
Sprogø E	341	02-07-2008	09-09-2008	69
Sprogø E	341	21-08-2009	24-11-2009	95
Sprogø E	341	20-04-2010	10-08-2010	112
Sprogø E	341	06-09-2010	27-10-2010	51
Jammerland N	337	25-04-2008	02-06-2008	38
Jammerland N	282	21-08-2009	29-09-2009	39
Jammerland N	282	10-08-2010	18-10-2010	69
Jammerland N	374	18-10-2010	10-11-2010	21
Jammerland S	338	14-04-2008	02-06-2008	49
Jammerland S	338	02-07-2008	09-09-2008	69
Jammerland S	338	02-07-2009	23-11-2009	144
Jammerland S	338	20-04-2010	18-10-2010	181

5.2 Descriptive statistics – click PPM and PPM

Clicks per PPM and PPM were calculated from recordings of the deployed T-PODs, minute by minute (Figure 5.1 and Table 5.2.). There was a total of 1565 days with T-POD monitoring data with an almost even distribution between baseline (n=464), construction (n=425), and operation (n=676), as well as between impact area (n=760) and reference area (n=805). The numbers of deployment days were also comparable across the 4 positions ranging from 244 at JM_N, 382 at SP_E, 423 at SP_W, and 516 at JM_S. There were only 1539 daily values of click PPM, i.e. number of days with click recordings, because 26 days (~1.3%) of the deployment days were without any detected clicks. Temporal variations and variation between positions and PODs were relatively smaller for Click PPM compared to PPM (Table 5.2.). For the three periods and the 4 positions the coefficients of variation varied between 38% and 71% for click PPM and between 54% and 139% for PPM.

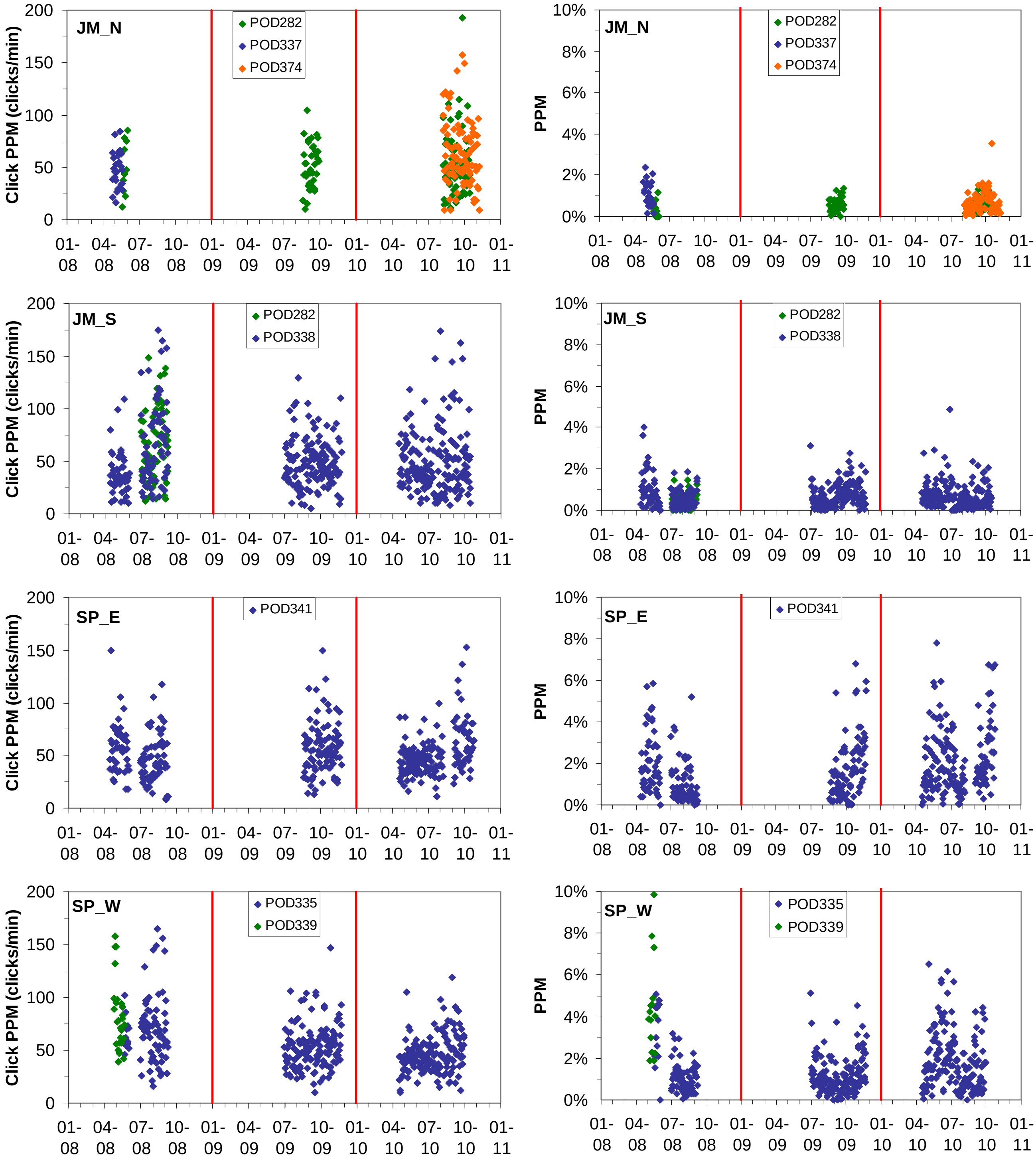

Figure 5.1. Click PPM (left panel) and PPM (right panel) extracted from T-POD data collected at Sprogø and Jammerlandsbugten during baseline (2008), construction (2009) and operation (2010). Different symbols and colours mark observations derived from different T-PODs. A few click PPM estimates (3 observations) and PPM estimates (12 observations all at SP_W) exceeded the plotting range (not shown).

There was no clearly visible and repeatable seasonable pattern during the three periods, neither for click PPM nor for PPM (Figure 5.1). The first two months of monitoring at SP_W (April-May 2008) were characterised by exceptionally high PPM (all 12 observations outside the plotting range in Figure 5.1) and a high click PPM for April 2008 as well. The T-POD deployed at this station (POD339) had frequent click recordings with a PPM above 10% for 11 consecutive days (from 25 April to 5 May 2008), but the appearance of clicks were not unusual and the T-POD (POD335) that replaced POD339 also had frequent clicks in May and June 2008 (Figure 5.1), suggesting that SP_W could have been the scene for high porpoise echolocation activity in spring 2008.

Table 5.2. Statistics of the two daily indicators monitored in the baseline, construction and operation periods at Sprogø and Jammerlandsbugten. 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	Position	Click PPM (clicks/minute)					PPM (%)				
			N	Min	Median	Mean	Max	N	Min	Median	Mean	Max
Baseline	Reference	JM_N	37	12.2	47.5	48.2	85.4	41	0	0.76	0.86	2.36
		JM_S	185	10.0	49.4	58.0	174.4	191	0	0.42	0.60	4.03
	Impact	SP_E	119	8.3	46.7	50.2	150.0	121	0	0.90	1.43	5.83
		SP_W	110	15.6	69.5	72.8	165.0	111	0	1.46	3.33	20.28
Construction	Reference	JM_N	39	10.0	48.2	50.8	104.1	40	0	0.56	0.60	1.35
		JM_S	140	5.6	43.5	48.5	128.9	143	0	0.63	0.75	3.11
	Impact	SP_E	94	12.8	54.0	56.6	149.3	96	0	1.42	1.69	6.81
		SP_W	144	10.0	52.1	53.7	147.3	146	0	0.90	1.18	5.11
Operation	Reference	JM_N	163	8.9	51.7	58.6	193.2	163	0.01	0.56	0.66	3.54
		JM_S	179	8.3	41.4	51.9	290.5	182	0	0.56	0.71	4.86
	Impact	SP_E	164	11.1	48.0	53.8	440.0	165	0	1.60	2.09	7.78
		SP_W	165	10.0	43.9	45.9	119.1	166	0	1.56	1.83	6.53

The average PPM was lower during the construction period (1.09% vs. 1.49% and 1.31% in the baseline and operation period, respectively), whereas click PPM averages were similar across the three periods. This general tendency was also observed across the four stations. Average click PPM ranged from 53.2 to 55.7 clicks/min, whereas average PPM was almost 3 times higher in the impact area (1.8-2.0%) than in the reference area (0.7%). However, due to a potential seasonal variation combined with differences in the months covered by the monitoring at the different stations, the statistics given in Table 5.2 cannot be implicitly compared without resolving all the different sources of variation. These different sources of variation will be partitioned out in the statistical analysis of the daily indicator observations (below).

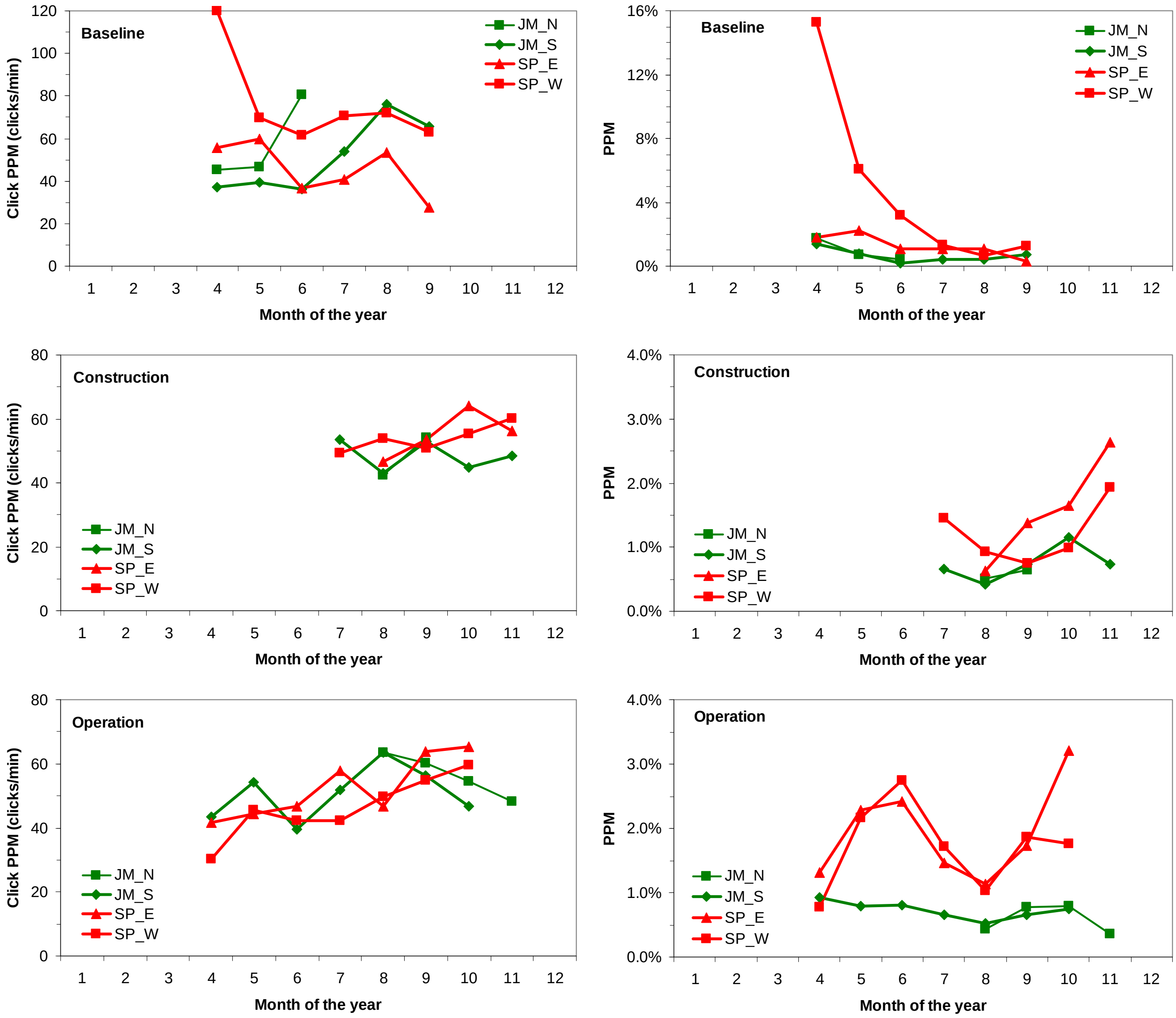

Figure 5.2. Monthly averages of Click PPM (left panel) and PPM (right panel) for the 4 stations during baseline, construction and operation periods. The two stations in the impact area (SP_E and SP_W) are red coloured, whereas the two stations in the reference area (JM_N and JM_S) are coloured green. Note the scaling difference for both Click PPM and PPM during baseline.

5.3 Descriptive statistics – encounter duration and waiting time

Encounter duration (n=11705) and waiting time between encounters (n=11682) were calculated from the POD data (Figure 5.3. and Table 5.3). Despite longer T-POD deployment in the reference area there were more encounters in the impact area (n=7670) than in the reference area (n=4035), indicating an overall higher acoustic activity at Sprogø. The number of encounters ranged from 1276 at JM_N, 2759 at JM_S, 3541 at SP_E to 4129 at SP_W, which may suggest a general spatial gradient from east to west given the comparable amount of deployment days at the four stations. The number of encounters were similar for the baseline (n=3330) and construction (n=2983) periods, but substantially higher during the operation period (n=5392).

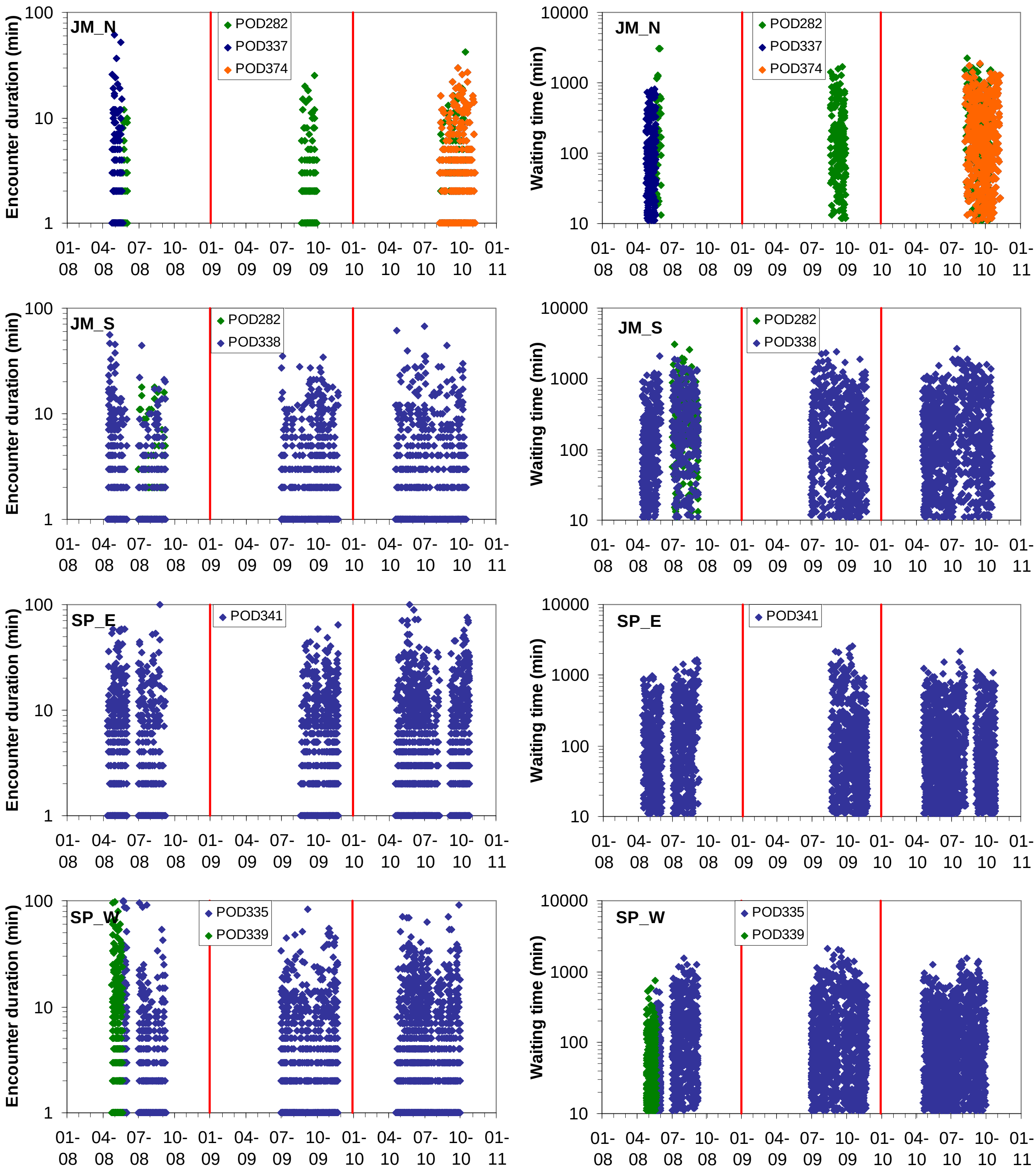

Figure 5.3. Encounter duration (left panel) and waiting time (right panel) extracted from T-POD data collected at Sprogø and Jammerlandsbugten during baseline (2008), construction (2009) and operation (2010). Different colours mark observations derived from different T-PODs. Note the log-scale on the y-axis.

Encounter durations were typically just 1-2 minutes with a mean of 3-6 minutes, but could be exceeding 8 hours during the intense echolocation period at SP_W in spring 2008 (Table 5.3). Waiting times were typically about 2 hours but could exceed 2 days (Table 5.3). For the 3 periods and 4 positions the relative variation in encounter duration (CV=131-353%) and waiting time (115-186%) were larger than for PPM and click PPM, however, there were also approximately seven times as many observations. Both duration and waiting time distributions were strongly skewed to the right with mean values substantially higher than medians (Figure 5.3. and Table 5.3).

Table 5.3. Statistics of encounters and waiting times monitored in the baseline, construction and operation periods at Sprogø and Jammerlandsbugten.

Period	Area	Position	Encounter duration (minutes)					Waiting time (minutes)				
			N	Min	Median	Mean	Max	N	Min	Median	Mean	Max
Baseline	Reference	JM_N	286	1	1	3.68	61	284	11	89	187	3040
		JM_S	917	1	1	3.19	56	914	11	154	290	3021
	Impact	SP_E	945	1	1	5.60	100	943	11	87	173	1630
		SP_W	1182	1	1	9.00	515	1178	11	54	120	1540
Construction	Reference	JM_N	211	1	1	2.55	25	210	12	135	266	1676
		JM_S	841	1	1	3.05	35	839	11	114	239	2425
	Impact	SP_E	831	1	2	5.91	65	830	11	55	158	2542
		SP_W	1100	1	1	4.42	84	1098	11	74	185	2135
Operation	Reference	JM_N	779	1	1	3.32	42	777	11	164	294	2243
		JM_S	1001	1	1	3.39	68	1000	11	123	257	2678
	Impact	SP_E	1765	1	2	6.08	121	1763	11	54	126	2157
		SP_W	1847	1	1	4.84	134	1846	11	56	123	1554

There appeared to be a distinctive seasonal pattern for waiting times that increased from April to August during the baseline and operation periods, followed by a decrease from August to October during the construction and operation periods (Figure 5.4). A seasonal pattern for encounter duration was not visually apparent.

Encounters were on average longer during baseline (6.0 min) than during construction (4.3 min) and operation (4.8 min). Average waiting times were comparable ranging from 174 minutes during operation, 188 minutes during baseline to 198 minutes during construction.

Spatial differences were also apparent from the observations (Figure 5.4 and Table 5.3). Encounters in the reference area (mean of 3.2 min) were almost half the encounter duration observed in the impact area (mean of 5.9 min). Similarly, waiting times were on average almost twice as long in the reference area (~4.4 hours) than in the impact area (~2.4 hours). Due to the potential seasonal variation combined with differences in the months covered by the monitoring the statistics given in Figure 5.4 cannot be implicitly compared without resolving all the different sources of variation. These different sources of variation will be partitioned out in the statistical analysis of the encounter statistics (below).

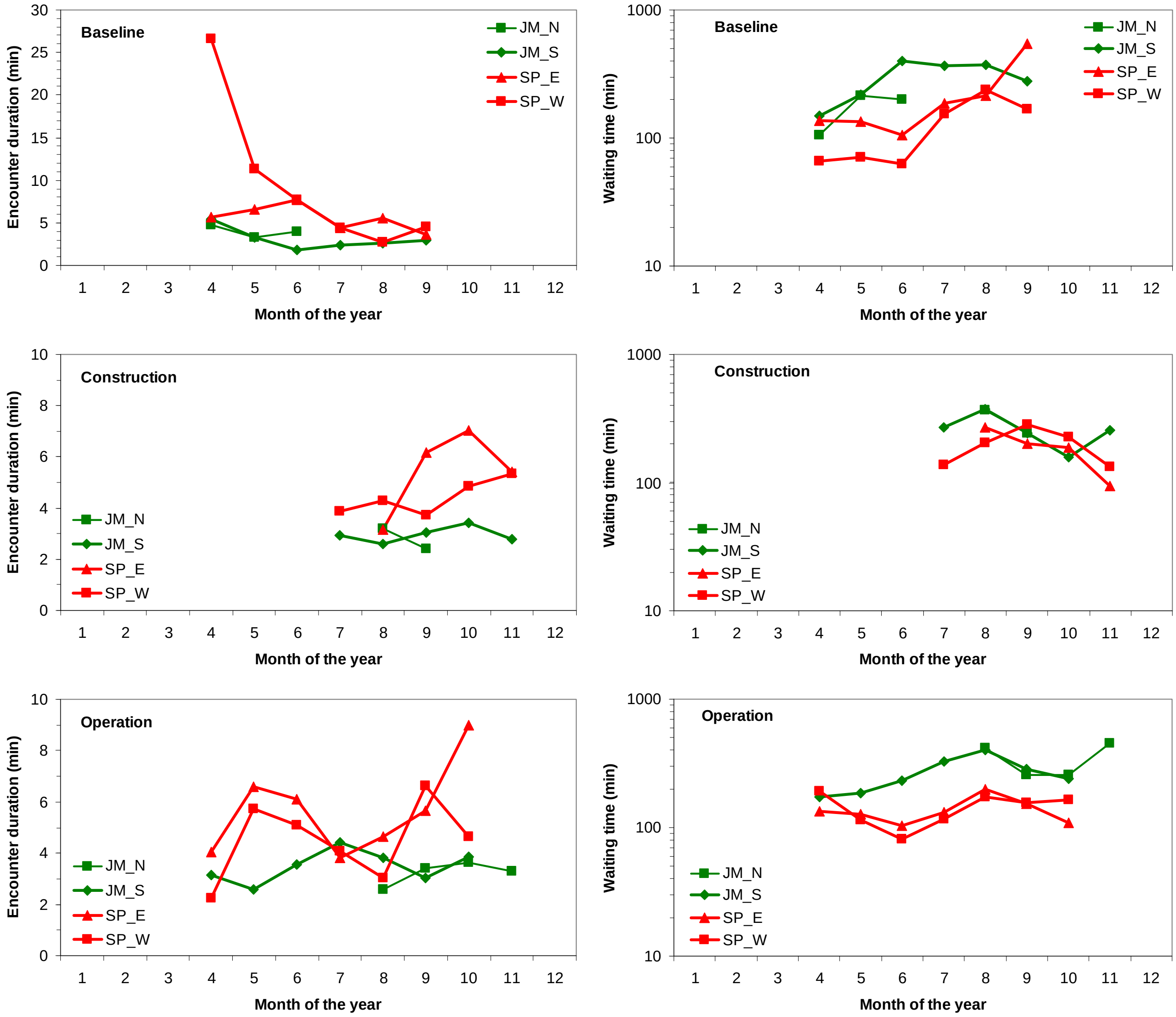

Figure 5.4. Monthly averages of encounter duration (left panel) and waiting time (right panel) for the 4 stations during baseline, construction and operation periods. The two stations in the impact area (SP_E and SP_W) are red coloured, whereas the two stations in the reference area (JM_N and JM_S) are coloured green. Note the scaling difference for encounter duration during baseline

5.4 BACI analysis

The model for spatial-temporal variation (Eq. 1) including random factors and an ARMA(1,1) correlation structure was computed for the 4 indicators. The ARMA(1,1) correlations structure was significant for all indicators, except for click PPM where it was reduced to an AR(1) correlation structure. For none of the four indicators the T-POD specific random variation was found significant. Most of the random factors were insignificant and removed from the models with the exception of *area*×*period*×*month* for PPM and waiting time, and *period*×*month* for click PPM, suggesting that there was some random variation in the seasonal pattern of echolocation activity over the three years and this even differed between the two areas for PPM.

The fixed factor *area*×*month* was significant for encounter duration only, suggesting that the seasonal pattern of echolocation activity was mostly common across the two areas (Table 5.4). This significant effect is most likely due to relatively longer encounters during autumn in the impact area combined with almost similar encounter durations during summer months (Figure 5.5). The overall seasonal pattern was significant for PPM and waiting time (Table 5.4), showing higher echolocation activity in spring and autumn and less echolocation activity during summer months (Figure 5.5).

Table 5.4. Significance testing of fixed effects in Eq. (1) for the four indicators after removing non-significant effects (excluding main and BACI effects).

Fixed effects	**Click PPM**			**PPM**		
	DFs	F	P	DFs	F	P
area	1, 20.4	2.88	0.1047	1, 34.3	33.70	<0.0001
period	2, 21.2	1.99	0.1611	2, 36.5	0.06	0.9454
area×period	2, 20.5	0.35	0.7058	2, 34.4	1.12	0.3367
month	7, 21.6	0.90	0.5219	7, 166.3	2.17	0.0393
area×month						
Fixed effects	**Encounter duration**			**Waiting time**		
	DFs	F	P	DFs	F	P
area	1, 707.8	121.20	<0.0001	1, 19.6	62.35	<0.0001
period	2, 8.7	0.38	0.6956	2, 20.7	0.90	0.4203
area×period	2, 702.3	0.52	0.5932	2, 19.5	0.95	0.4031
month	7, 708.0	1.52	0.1579	7, 20.3	5.44	0.0013
area×month	7, 708.2	5.96	<0.0001			

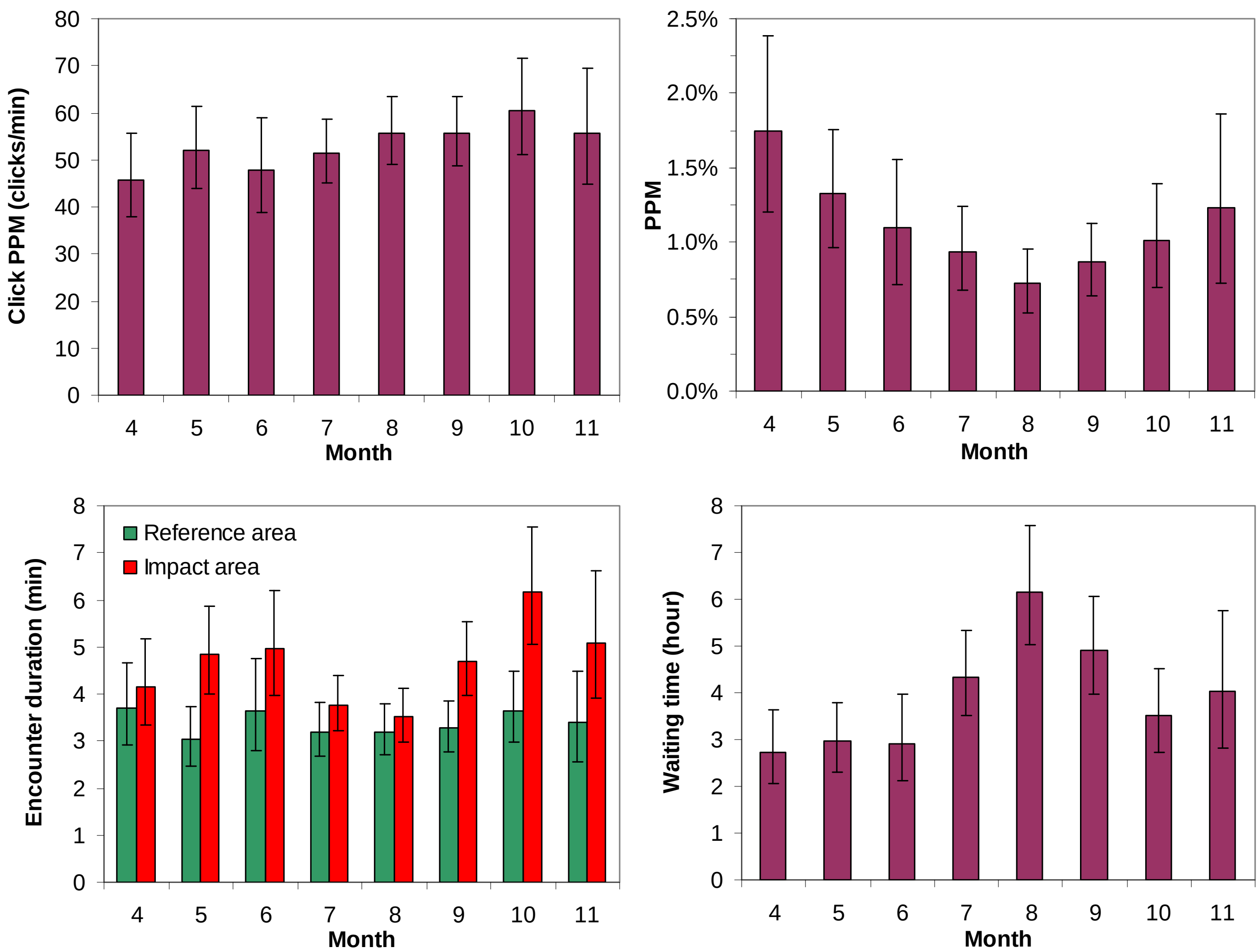

Figure 5.5. Monthly means for the four indicators over the entire area for click PPM, PPM and waiting time. For encounter duration the area-specific seasonal variation is shown because this effect was significant (Table 5.4). Error bars indicate 95% confidence limits for the mean values.

For click PPM the difference between reference area (57.2 clicks/min) and impact area (63.0 clicks/min) was small and insignificant, whereas there was a significant difference between areas for the other indicators. PPM was significantly higher in the impact area (1.62%) than in the reference area (0.68%). Encounter durations were more than 1 minute longer in the impact area (4.58 minutes vs. 3.38 minutes) and mean waiting times were twice as long in the reference area (5.4 hours) than in the impact area (2.7 hours). The station-specific variation within the two areas was not significant for any of the four indicators.

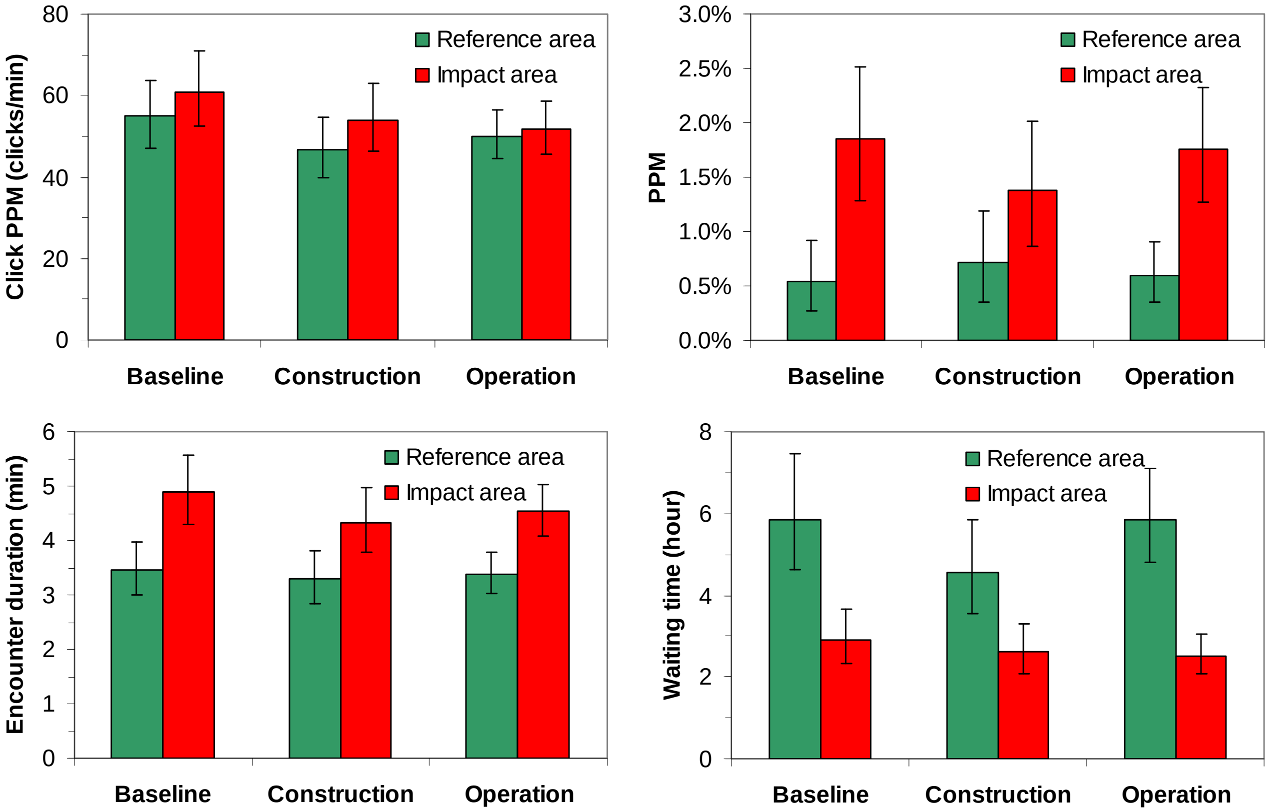

Figure 5.6. Mean values for combinations of area and period back-transformed to the original scale for combinations of the two areas and three periods. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in months of monitoring across the different periods and areas have been accounted for by calculating marginal means.

There was no significant change between the three periods for any of the four indicators (Table 5.4). Mean values for click PPM varied between 57 and 66 clicks/min, with the highest value during baseline. PPM gradually increased from the baseline (1.07%) to the operation period (1.13%). Mean encounter duration ranged from 3.8 to 4.1 minutes, whereas waiting times were shortest during construction (3.46 hours), slightly longer during operation (3.84 hours) and longest during baseline (4.14 hours). There was no overall shift in echolocation activity between the two areas across the three periods (*area*×*period* not significant for any of the four indicators in Table 5.4). This means that the difference between the impact area and reference area was maintained for all three periods (Figure 5.6).

5.5 T-POD field intercalibration

During baseline there were simultaneous deployment of two T-PODs at stations JM_N and JM_S. To assess differences between T-PODs, click PPM and PPM were compared during the two periods of simultaneous deployment by means of a type II regression that assumes uncertainty on both regression variables (x and y variables). 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 test employed in the BACI model (Eq. 1), because the daily indicators from the two different T-POD types are paired such that short-term temporal variation (day-to-day variation) is accounted for.

There were 68 full days of simultaneous deployment in both periods, although 5 days at JM_S with no clicks recorded resulted in 63 click PPM observations only. There was a good agreement between the T-PODs for click PPM, both periods having a slope not significantly different from 1. Re-estimating the model, after fixing the slope to 1, resulted in intercepts for both periods significantly different from zero. Since these intercepts were estimated on log-transformed data, this corresponds to POD374 recording 22% more clicks than POD282 at JM_N and POD228 recording 14% more clicks than POD282 at JM_S (Figure 5.7). Similar results were observed for PPM. The intercepts of the angular-transformed observations were not significantly different from 0 and the regression lines were therefore forced to intercept at 0. Re-estimating the models with fixed intercepts at 0 resulted in slopes significantly different from 1, corresponding to 12% higher PPM for POD374 and 8% higher PPM for POD338 relative to POD282. Thus, differences between T-PODs appear to be a relative sensitivity issue, i.e. proportional to the indicator.

It was also assessed whether this sensitivity changed over the course of the two periods with duplicate deployments by adding a trend factor to the model. This analysis would reveal if the systematic difference between T-PODs was constant with time. However, the trend factor was not significant ($P>0.05$) for any combination of the daily indicators and periods. Thus, differences in T-POD sensitivity was most likely constant over the duration of the study.

Finally, it might be surprising that the field intercalibration test documented significant differences between T-PODs, whereas the impact assessment analysis (BACI analysis) yielded a non-significant random variation across T-PODs. For the log-transformed click PPM the residual variance was 0.26, and for the two intercalibration regressions the residual variances were 0.15 and 0.28 for JM_N and JM_S, respectively. For the angular-transformed PPM the residual variance was 0.0025, and for the two intercalibration regressions the residual variances were 0.0001 and 0.0002 for JM_N and JM_S, respectively. Hence, the T-POD specific variation was similar or lower than residual variation for click PPM and substantially lower for PPM. This relatively low variation between T-PODs is most likely the reason for the non-significant random factor in the BACI analysis.

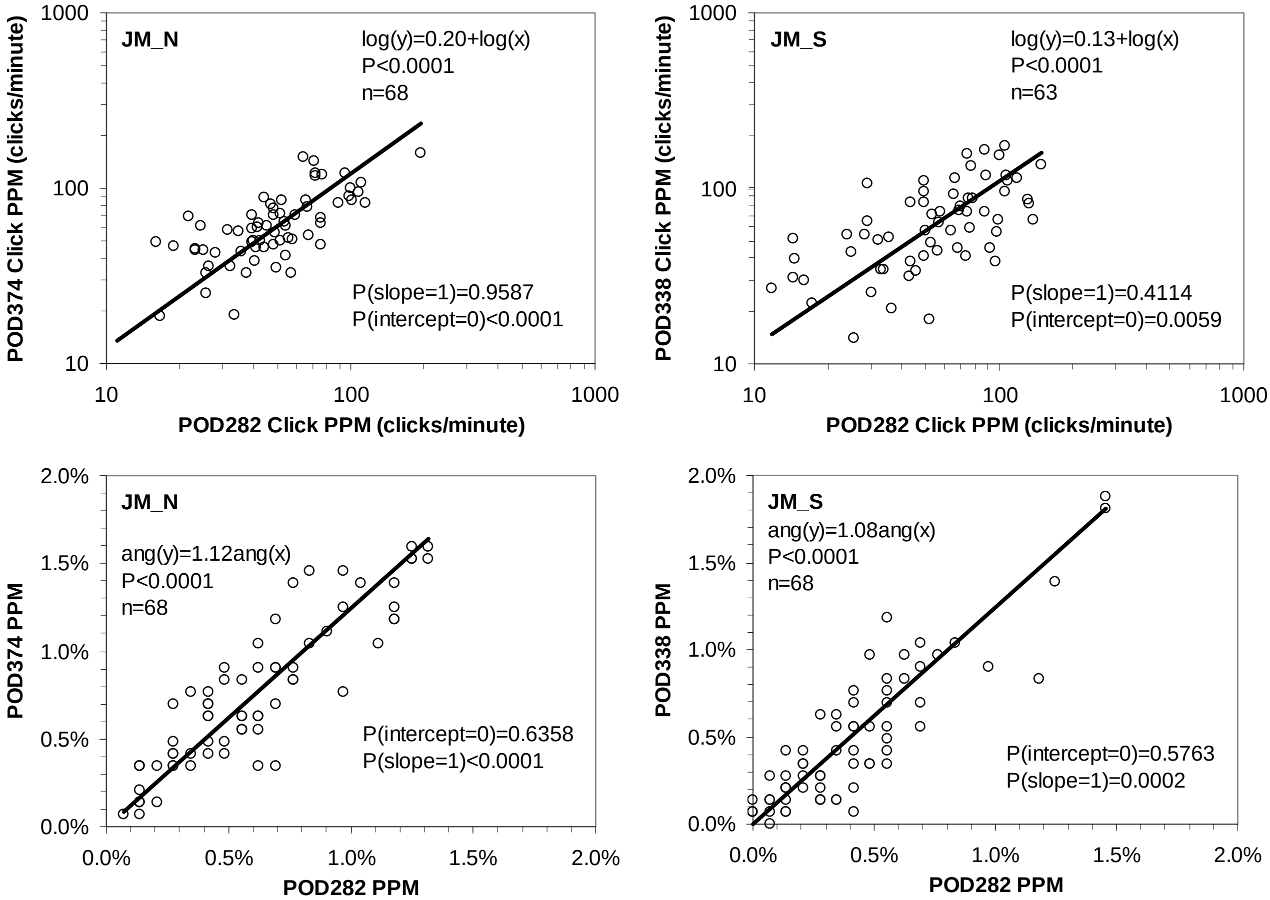

Figure 5.7. Intercalibration of T-PODs deployed simultaneously at JM_N (10 August 2010 – 18 October 2010) and JM_S (2 July 2008 – 9 September 2008) by means of the daily indicators, click PPM and PPM. Regressions were carried out on transformed variables (see Materials and methods) but are shown using the back-transformations.

6 Discussion

The data demonstrated a large and stable abundance of porpoises in the northern Great Belt, consistent with previous studies, such as aerial surveys (Heide-Jørgensen *et al.* 1993), satellite telemetry (Sveegaard *et al.* 2011b) and towed acoustic arrays (Sveegaard *et al.* 2011a). There were thus only 26 station days out of 1565 (1.7%) without any detections and median waiting time between encounters ranged from 54 minutes to 164 minutes.

6.1 Variation between areas, stations T-PODs and with season

There were statistically significant differences between the wind farm (impact) area and the control area. Thus, on average the PPM was about twice as high in the wind farm area compared to the reference area and waiting time likewise almost half of what it was in the reference area. Encounter duration was also significantly longer in the wind farm area, but only with about 20%. Clicks per PPM was not significantly different in the two areas. These results suggest a higher abundance of porpoises in the wind farm area, indicated by higher PPM and shorter waiting time, whereas the acoustic behaviour is not very different between the two areas, indicated by only a small difference in encounter duration and no difference in clicks per PPM.

There was a similar large and significant variation in PPM and waiting time with season (month), where a minimum in PPM and corresponding maximum in waiting time was seen in August. No significant seasonal effect was seen on the indicators clicks per PPM and encounter duration. The seasonal pattern was similar for wind farm area and reference area for all indicators except waiting time, where a small minimum in July and August was not present in the control data. All together the seasonal data indicate that there was a general lower abundance of porpoise in the northern Great Belt during the summer months, compared to spring and autumn, whereas their acoustic activity remained unchanged with season. No data were available for the winter months.

The BACI analysis could not detect significant differences between T-PODs or between monitoring stations within areas (impact or control), but a direct comparison between T-PODs deployed in tandem on the same station could show systematic differences in sensitivity. However, although significant, the variation among T-PODs was so low that it did not contribute significantly to the variation in the BACI analysis. In other words, even though the T-PODs were different in sensitivity, despite being individually calibrated, these differences were small compared to the differences observed between areas and across seasons.

6.2 Effects of the wind farm

The BACI analysis did not show any significant BACI-effect (factor *area* x *period*), which indicates that there were no significant changes from year to year (co-varying with baseline, construction and operation) which could not be explained by overall changes of abundance of porpoises in the entire study area (northern Great Belt). In other words, the construction and operation of the wind farm did not have any impact on porpoises measureable by the T-PODs in the design used. This is in contrast to other studies (Nysted, Carstensen *et al.* 2006; Horns Reef I, Tougaard *et al.* 2006b; Tougaard *et al.* 2009a; and Horns Reef II, Brandt *et al.* 2011) and the expectations from the Impact Assessment (Sveegaard *et al.* 2008), where it was anticipated that porpoises would be displaced from the construction site during construction and return again to the wind farm after a shorter or longer delay. The lack of significant effects can be due to several, not mutually exclusive factors

- Insufficient statistical power. If insufficient data is collected, then the statistical power (β) may be so low that it is not possible to reject the null-hypothesis (in this case that the wind farm has no effect), even though an effect is there (Type II error). This is unlikely to be the case in the present dataset, as a very large amount of data was collected and fairly evenly distributed across stations and monitoring years. Furthermore, it was possible to demonstrate clearly significant differences between the impact and control areas and demonstrate a strong seasonality in the acoustic activity of porpoises. No attempt has been made at actually estimating the power (β), as this is not a straightforward task for analyses of the type conducted.

- The small size of the wind farm. The wind farm consists of only 7 turbines, in contrast to the 72 turbines or more at the three other wind farms studied. The construction period was thus significantly shorter and everything else being equal, impact likely to be significantly smaller.

- The layout of the wind farm. The 7 turbines are placed on a line, as opposed to the three larger wind farms where turbines are placed in a more or less regular grid. Thus, in contrast to the larger wind farms it is not meaningful to talk about being "inside the wind farm", compared to being "outside the wind farm" and animals thus cannot end in a spot where they are surrounded by turbines and/or jack-up rigs and working vessels. Noisy activities may not be as disturbing for the animals if these at all times have a clear "route of escape" away from the disturbance.

- Absence of noisy activities during construction. The three other wind farms where negative effects were seen during construction all included very noisy activities during construction. On Horns Reef (I + II) steel monopile foundations were driven hydraulically into the seabed, which is known to generate excessive levels of noise, capable of displacing porpoises up to at least 20 km from the piling site (Tougaard *et al.* 2009a; Brandt *et al.* 2011). At Nysted, even though gravitational foundations were used, a large number of steel sheet piles were driven into the seabed as reinforcement of one particular foundation, which also displaced porpoises from the area (Carstensen *et al.* 2006).

- High levels of ship traffic in the area. The Great Belt is a very busy waterway, with hundreds of merchant ships passing every day, a high level of leisure boat traffic and also bottom trawling taking place. This could both mean that porpoises in the area are generally habituated to high levels of disturbance and that noise levels are so high in the first place that audibility of extra noise sources (vessels during construction and turbine noise during operation) is reduced and hence have little effect.

- Prior history of a large construction activity in the area. In the period 1988-1998, i.e. 11 years before construction of the wind farm the Great Belt Connection) was constructed. This was a much larger operation, extending over 10 years and involved a lot of the same activities as construction of the wind farm, such as dredging and placement of foundations on the seabed, only on a much larger scale. Although the lifetime of porpoises on average is likely to be below 10 years (Read and Hohn 1995), there may well be animals around which thus have prior experience with (and hence easily habituated to) construction activities.

- Importance of the area. Animals, including porpoises are likely to balance nuisance or even danger to gain and thus if the central Great Belt is very important to porpoises (indicated by the high abundance of animals) they may be tolerating more disturbance than elsewhere, simply because they gain more by remaining in the area despite the disturbance than they would by moving somewhere else where conditions were less profitable.

Thus, dismissing the first possibility of insufficient statistical power it remains that the disturbance inevitably caused by the construction activities had only a limited spatial extend and did not interfere with the presence of porpoises at the two measuring stations located about 500 m from the nearest turbine. Thus, although there clearly must have been an impact (porpoises are unlikely to remain in the very close vicinity of for example an operating dredger), this impact was likely of a very limited nature and not detectable in the overall mean indicators analysed.

However, given that the level of disturbing activities is considerable in the area even before construction began, there is risk of confusing "no disturbance" with a disturbance that took place even before construction began. Given that the level of disturbing activities was high in the area in the first place; this could have caused the more sensitive animals to permanently vacate the area. This means that the animals left are the more tolerant ones, likely to better habituate to new sources of disturbance added (Bejder *et al.* 2009). This effect is subtle and difficult to deal with. However, the consequence is that even though the construction of the wind farm in this particular place did not cause additional disturbance, construction of a similar wind farm in another area with other sources of disturbance could well cause an effect.

Finally, one should not dismiss positive effects of building an offshore wind farm. A higher abundance of porpoises inside a wind farm compared to baseline levels has been documented in one case in the Dutch North Sea (Egmond aan Zee, Scheidat *et al.* 2009). The reason behind the increase in abundance could not be determined, but at least two possibilities present themselves. The first is an increase in prey availability, due to the increased biological production on the turbine foundations and increased biodiversity following introduction of hard substrates to the otherwise barren sand bottom (Petersen and Malm 2006; Leonhard and Pedersen 2006). The other is a refuge effect, where the porpoises can find shelter inside the wind farm from other, even more disturbing activities outside the wind farm. The latter is likely to be the case for the Egmond aan Zee offshore wind farm, as it is located in an area of the North Sea with extremely high levels of shipping traffic and very heavy beam trawling. There may be similar positive effects from the 7 turbines at Sprogø, but due to the much smaller size of the wind farm and comparatively much lower level of disturbance outside the wind farm area, such positive effects, if present, are unlikely to have a magnitude where they are measureable.

6.3 Impact of the wind farm on the habitat area

Sprogø offshore wind farm is located in the very centre of a Natura2000 area designated for porpoises and it is thus well worth considering the impact of the wind farm on the specially protected area. It is an ongoing and relevant discussion whether construction works such as offshore wind farms are compatible with the objectives of Natura2000 areas. From the results presented and the discussion above it is evident that at least in the present case, there seems not to be a conflict between the objective of maintaining an attractive habitat for porpoises and construction of the wind farm. However, generalisation of this result should only be made with great caution to other, future wind farms and preferably coupled with new studies. A number of points, paralleling the bullets above, should be kept in mind:

- Sprogø Offshore Wind Farm is a very small wind farm (7 turbines)

- Gravitational foundations were used and no sheet piling took place during construction

- There is heavy ship traffic and a high ambient noise level in the area

- At least some of the older animals may have had prior experience with large construction works (construction of the Great Belt Connection).

- The high level of other sources of disturbance in the area may have caused a pseudo-habituation by removal of the skittish and more sensitive animal prior to impact (construction).

6.4 Limitations of the study

The present study was designed with almost the minimal design possible, i.e. one control area, one impact area, two stations within each area and only one year of data for each of the three study periods (baseline, construction and operation). In spite of this, the statistical power is considered high and conclusions regarding lack of general effects are robust. There are clear limitations to the study, however.

First of all the minimal design, with only one year of data from each of the three periods did not allow for a separation of effects of construction and operation from year to year differences not related to the wind farm.

Secondly, and more important is that analyses of PPM and clicks per PPM were performed on daily averages, aggregated again into monthly means. This means that limited information is available about effects occurring on a finer time scale than 1 day and it is thus possible that the construction and/or operation could have caused changes to for example diel patterns in abundance. However, such changes are likely to show up in the two other indicators (encounter duration and waiting time), as changes in diel patterns are likely to also cause changes to the distribution of waiting times and encounter durations.

Thirdly, as also mentioned above, did the fact that measuring stations were placed some distance away from the turbines mean that more local effects closer to construction activities and perhaps operating turbines most certainly were overlooked. The spatial extent of these local effects is likely to be very small however.

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