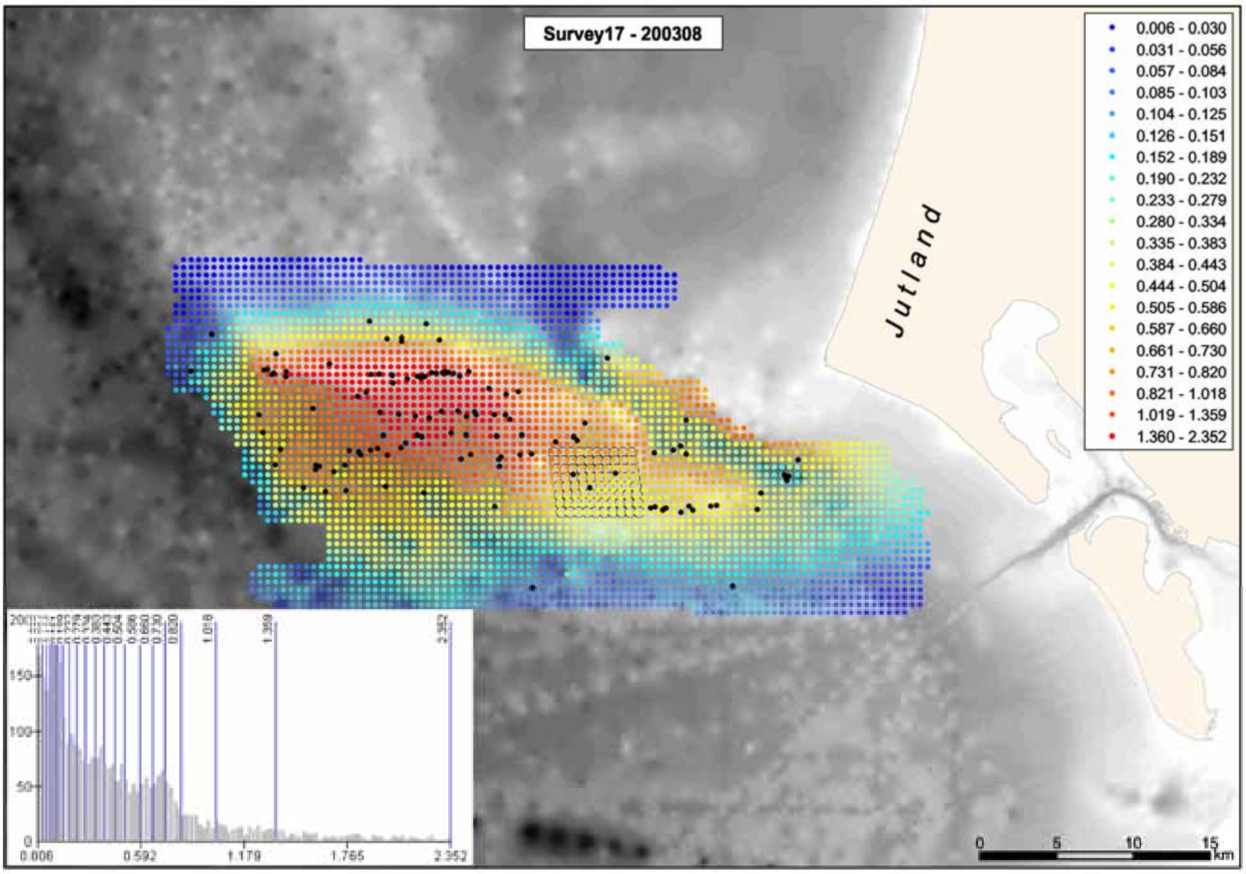
Harbour Porpoises on Horns Reef
Effects of the Horns Reef Wind Farm

Final Report to Vattenfall A/S



Jakob Tougaard
Jacob Carstensen
Mary S. Wisz
Martin Jespersen
Jonas Teilmann
Nikolaj Ilsted Bech
National Environmental Research Institute, Roskilde

Henrik Skov
DHI Water and Environment, Hørsholm

NERI Commissioned Report

Roskilde, Denmark, November 2006

Foreword

This report is the final report in a series of annual reports from the porpoise monitoring programme at Horns Reef in the Danish North Sea. Monitoring commenced in 1999 in connection to the planning and approval of the largest offshore wind farm in the world: Horns Rev Offshore Wind Farm, which was later constructed in 2002.

It has been our aim that this final report should stand on its own, avoiding extensive references to previous reports. This should be to the benefit of new readers and also provide a better overview of the results of the entire monitoring programme, extending from before construction to the present day operating wind farm. The cost is of course a relatively large overlap with previous reports especially in the introductory and methods sections.

The porpoise monitoring programme has resulted in a tremendous advance in the methodologies used to study abundance and behaviour of porpoises on a fine scale and this development is clearly reflected in the different reports. Details on this development should be found in the previous reports but in terms of results and conclusions on effects of the wind farm the present report replaces previous reports, as only this report contains results from analysing the entire dataset collected.

The monitoring at Horns Reef was developed in parallel with a monitoring program on porpoises in connection with construction of Nysted Offshore Wind Farm in 2003. There are only few references to this work in the present report, as a direct comparison of the two studies is presented elsewhere in a separate report (Teilmann *et al.* 2006).

Table of Contents

Summary

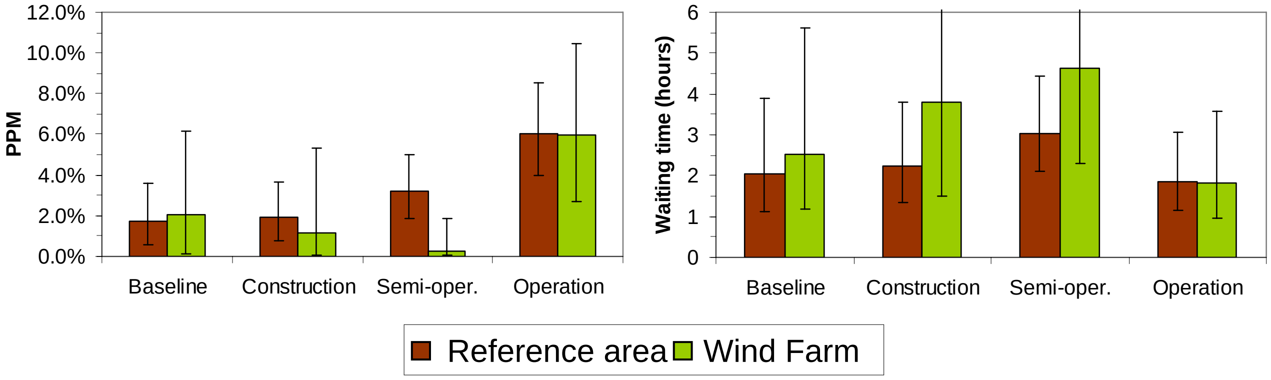
The monitoring program on harbour porpoises at Horns Rev Offshore Wind Farm in the Danish North Sea, initiated in 1999, has now come to an end with collection of final data in 2005 and spring 2006. Seven years of surveys and five years of acoustic recordings of harbour porpoises on Horns Reef have resulted in a unique set of data documenting effects of the construction and operation of one of the world's two largest offshore wind farms.

Horns Reef is a shallow reef consisting entirely of sand and with a complex hydrography. The reef and adjacent areas are important habitats for harbour porpoises. The occurrence of porpoises, as documented by visual surveys from ship and airplane as well as with acoustic dataloggers mounted on the seabed, is patchy in both space and time. There is thus a large variation between visual surveys in the number of animals observed and where they are observed. In general the wind farm area seems to be as important to the porpoises as the rest of the reef.

Effects of wind farm

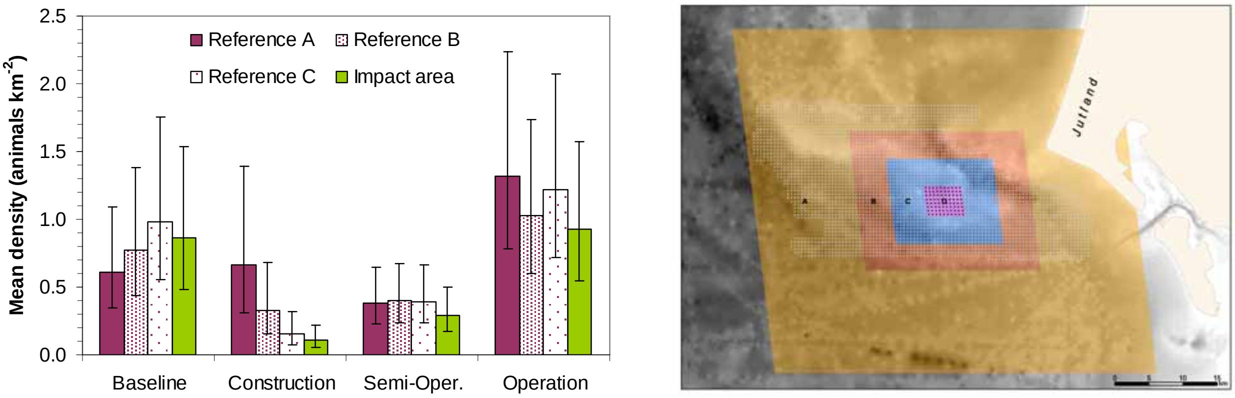
The current dataset, which covers time before, during and after construction of Horns Rev Offshore Wind Farm, indicates a weak negative general effect from the construction and semi-operation on porpoises, with more specific effects linked to pile driving activities. No effects were observed from the operating wind farm.

Acoustic recordings (with T-PODs) did not show any significant change in abundance in the wind farm area as a whole during construction (see figure below). However, there was a significant difference between semi-operation (when intensive maintenance work too place) and operation, measured on the indicator porpoise-positive-minutes (PPM). PPM reached the lowest mean value in the entire monitoring period during semi-operation. Porpoise acoustic activity was higher in the operation phase than during baseline, but this was the case both in the wind farm and in the surrounding reference areas.



Mean values for porpoise positive minutes (PPM, equal to the fraction of a day where porpoises could be detected) and waiting time between porpoise encounters, recorded by acoustic dataloggers (T-PODs) placed inside Horns Rev Offshore Wind Farm and in nearby reference areas. Values are separated into four periods: baseline, construction, semi-operation, and operation. Semi-operation covers a period following construction, where intensive maintenance and service operations occurred and the turbines thus were not operating at full capacity. Error bars indicate 95% confidence limits for the mean values.

Conclusions from the ship surveys point in the same direction as the acoustic data, i.e. a weak negative and local effect of the wind farm during construction but otherwise no significant changes (see figure below). Also ship survey data indicate more porpoises in the area as a whole during the operational period than for any other of the periods, baseline included.



Estimated mean densities of porpoises for combinations of the four areas shown on the map and the four time periods, based on observations from ship surveys conducted throughout the entire period from 1999 to 2005. Error bars show the 95% confidence intervals for the estimated mean densities. Note the gradient in density towards wind farm during construction.

Specific effects of construction

Although the design of the monitoring program was only aimed at detecting general effects of the construction and operation of the wind farm on porpoise abundance, it was nevertheless possible to document specific effects of a single activity: pile drivings. The T-POD data indicate that porpoises left the entire Horns Reef area in response to the loud impulse sound generated by the pile driving operation. After a period of 6-8 hours, activity returned to levels normal for the construction period as a whole.

Responses of porpoises to the construction and operation of Horns Rev Offshore Wind Farm thus lies within what was anticipated in the Environmental Impact Assessment: a partial displacement during construction and return to baseline activity during normal operation.

Dansk Resumé

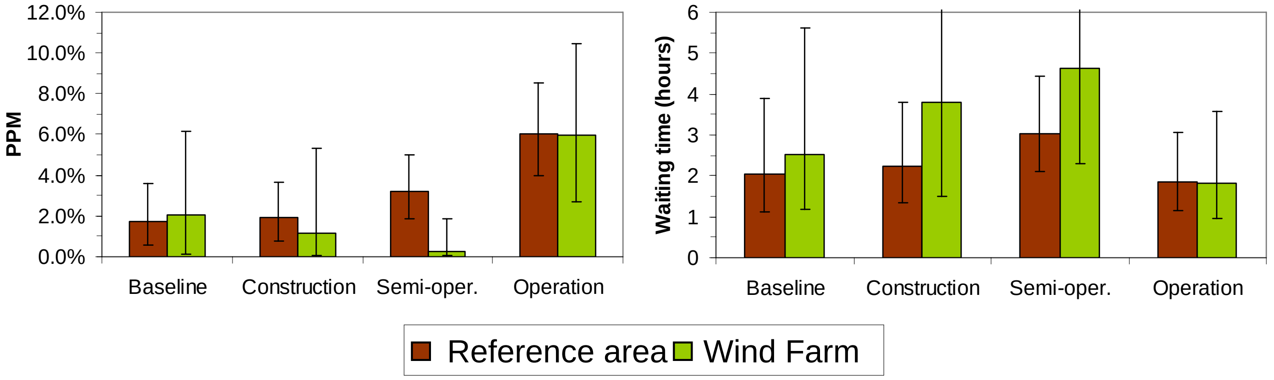
Med indsamling af data i 2005 og foråret 2006 er overvågningsprogrammet for marsvin (*Phocoena phocoena*) omkring Horns Rev havmøllepark, påbegyndt i 1999, nu afsluttet i sin nuværende form. Gennem de seneste syv år er linietranssekttællinger blevet gennemført og akustiske registreringer af marsvin er gennemført gennem de seneste fem år. Dette unikke datamateriale dokumenterer effekter af konstruktion og drift af en af verdens største havmølleparker.

Horns Rev er et lavvandet sandrev med en kompliceret hydrografi. Revet og omliggende områder er vigtige biotoper for marsvin. Forekomsten af marsvin er dokumenteret gennem linietranssekttællinger fra skib og fly, såvel som gennem registrering af marsvins orienteringslyde ved hjælp af automatiske dataloggere monteret på havbunden. Disse data viser at forekomsten af marsvin er ujævn både i tid og rum, med stor variation fra tælling til tælling af hvor mange dyr der observeres og hvor på revet de ses. Der er ikke basis for at konkludere at havmølleparken er hverken mere eller mindre betydningsfuld for marsvinene end de øvrige dele af ydre Horns Rev.

Effekter af havmølleparken

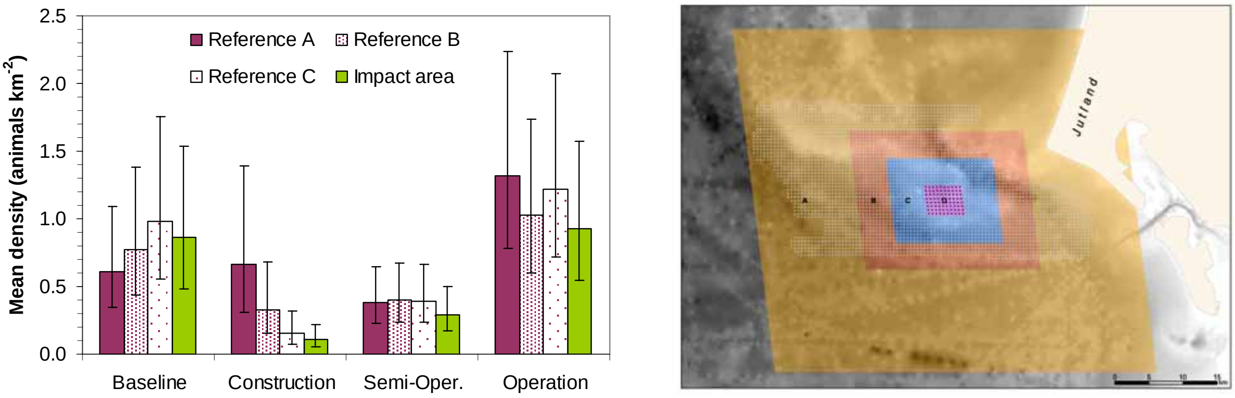
Det foreliggende datamateriale, som dækker en periode fra før byggeriet (baseline), over konstruktion til driftsfase af Horns Rev havmøllepark, indikerer en svag negativ, generel effekt på marsvin af konstruktionen, med mere specifikke reaktioner til nedramning af møllefundamenter. Der blev ikke set effekter på marsvin af mølleparken i drift.

Akustiske registreringer (med T-PODs) viste ikke nogen signifikant ændring i tilstedeværelsen af marsvin i mølleparken som helhed under konstruktionen (se figuren nedenfor). Den eneste signifikante forskel mellem perioderne var mellem semi-drift og drift; indikatoren marsvine-positive minutter (PPM) nåede det laveste niveau for hele undersøgelsen under semi-driftperioden. Den akustiske aktivitet af marsvinene var højere i driftsfasen end under baseline-målingerne før byggeriet begyndte, men uden signifikante forskydninger mellem havmølleparken og de omliggende referenceområder.



Gennemsnitlige værdier for marsvine-positive minutter (PPM, svarende til den %-del af døgnet hvor marsvin kan høres) og ventetid mellem besøg af marsvin ved de akustiske dataloggere (T-POD), som var placeret inde i Horns Rev Havmøllepark og udenfor i nærliggende referenceområder. Værdierne er opdelt på fire perioder: baseline, konstruktion, semi-drift og drift. Semi-drift dækker en periode efter konstruktionen hvor omfattende servicearbejde foregik på møllerne og parken derfor ikke var i fuld drift. Lodrette streger angiver 95% konfidensintervaller.

Konklusionerne fra skibstællingerne peger i samme retning som de akustiske data: en svag negativ og lokal effekt af havmølleparken under byggeriet, og derudover ingen signifikante ændringer i fordelingen af marsvin (se nedenstående figur). Skibstællingerne peger ligeledes på tilstedeværelsen af flere dyr på revet som helhed i driftsfasen, set i forhold til perioden før byggeriet begyndte.



Gennemsnitlige tætheder af marsvin fra rumlige modeller af marsvineudbredelsen i og omkring Horns Rev Havmøllepark. Tæthederne er baseret på visuelle observationer fra skib. Lodrette streger angiver 95% konfidensintervaller. Bemærk gradienten i tæthed mod havmølleparken under konstruktionen.

Specifikke effekter af byggeriet

Selvom overvågningsprogrammet oprindeligt kun var designet til at påvise generelle effekter af byggeri og drift af havmølleparken på tilstedeværelsen af marsvin viste det sig imidlertid muligt at dokumentere specifikke effekter knyttet til en enkelt aktivitet: nedramning af møllefundamenter. T-POD data indikerer at marsvinene forlod hele Horns Rev området som reaktion på de kraftige lydtryk genereret ved ramningsoperationerne. Efter en periode på i gennemsnit 6-8 timer vendte aktivitetsniveauet af marsvinene tilbage til normalniveauet for byggeperioden som helhed.

Reaktionerne hos marsvin på byggeri og drift af Horns Rev havmøllepark ligger således indenfor det, der blev beskrevet som sandsynligt i Miljøkonsekvensvurderingen (VVM'en), der gik forud for byggeriet: en nedgang i tilstedeværelsen af marsvin under byggeriet, efterfulgt af tilbagevenden til normalniveauer for aktivitet i løbet af driftsfasen.

1 Introduction

In 1996 in the wake of the Kyoto summit the Danish government passed an action plan for energy: Energi 21, in which it was decided to establish 5,500 MW of wind power in Denmark before 2030, 4,000 MW of which was to be established as large scale offshore wind farms. This decision was followed by action in 1998 where the Minister for Environment and Energy commissioned the Danish power companies to establish 750 MW of offshore wind power in Danish waters as a demonstration project (Anon. 2005). The aim of the project was twofold: to test the feasibility and economy of large scale offshore wind power and address potential negative effects on the marine environment by establishment of an ambitious environmental monitoring program (Anon. 2002b). After a change in government in 2001 the ambitions of the demonstration project were reduced to two wind farms (a total power of 318 MW,) one at Horns Reef off the Danish west coast (Horns Rev Offshore Wind Farm) and one in Femar Belt at the entrance to the Baltic (Nysted Offshore Wind Farm). Horns Reef Offshore Wind Farm, which was constructed by Elsam A/S on Horns Reef in the Danish North Sea in 2002 and put into operation on 18th of December 2002, is the largest offshore wind farm in the world. This report describes results of the monitoring program on harbour porpoises on Horns Reef, conducted in the period from 1999 to 2005.

1.1 Horns Reef

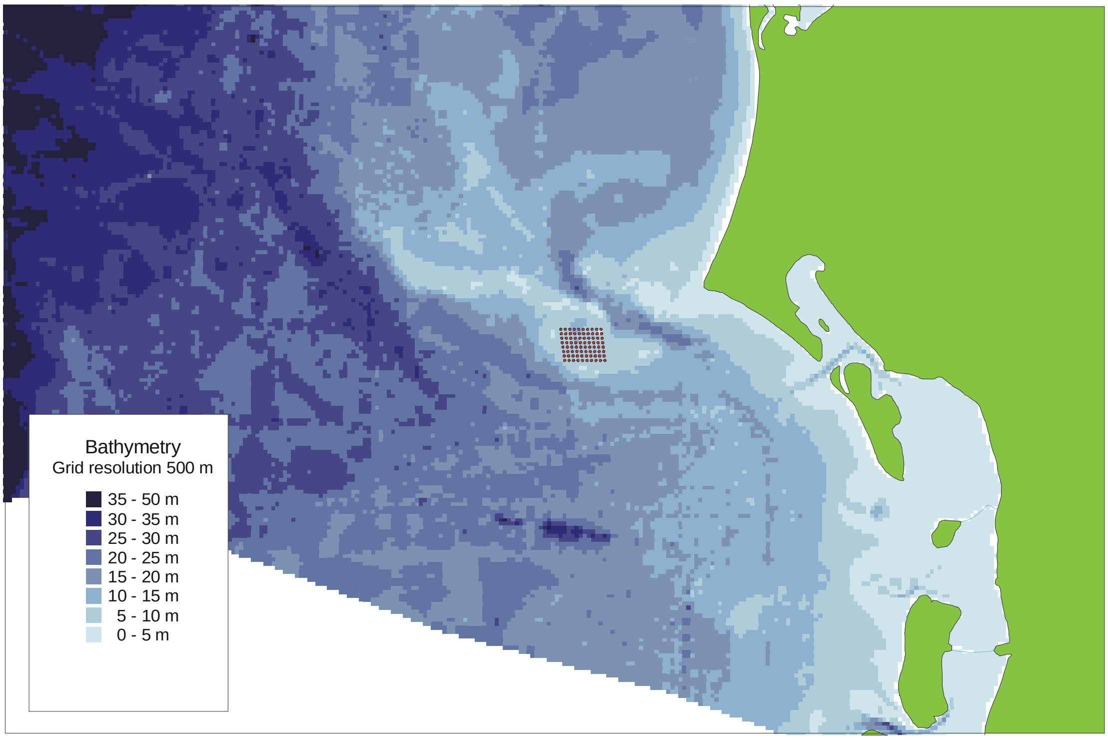


Figure 1 **Bathymetry of Horns Reef and adjacent waters. Individual turbines of Horns Rev Offshore Wind Farm are indicated with dots. The wind farm is located on the eastern part of the outer reef, which is separated from the inner reef by the deep channel “Slugen”.**

Horns Reef stretches westward about 40 km out from Blåvands Huk into the North Sea. The reef has played and continues to play a central role in forming the coastline at Blåvands Huk and Skallingen. The reef is the northernmost “stronghold” responsible for creation of the long chains of islands which borders the Wadden Sea, with the next "stronghold" being the glacial moraine on the German island of Sylt.

The Horns Reef area is hydrodynamically very complex. The area is dominated by a coastal current with general northward direction (the Jutland coastal current), driven by the tide and the large outflux of freshwater from the large rivers into the Wadden Sea (with Elbe and the Rhine as the two largest). A frontal system is created along the outer edge of the Wadden Sea up to the level of Horns Reef, in which the less saline water from the rivers is mixed into the more saline North Sea water (Figure 2).

Figure 2. **Satellite image of the northern Wadden Sea and Horns Reef. The reef is visible below the surface as blue-green shadows. Note the complex eddies caused by the mixing of less saline water from the rivers into the more saline North Sea water. Source: International Wadden Sea Secretariat.**

The reef consists of an outer and an inner part, different in origin and separated by a 20 m deep channel – Slugen (Figure 3). The inner reef east of Slugen consists of a large number of shallow sand barriers and sand banks, more or less continuous with Blåvands Huk itself and formed by deposition of sand by the coastal currents in the time since the area was flooded by the sea about 1000 years ago (Leth *et al.* 2004).

The tidal amplitude is about 1.2 meters to the south of Horns Reef, but the reef acts to dampen the oscillations and the tide is significantly weaker on the north side. This dampening drives the often very strong currents in the area, mainly up through Slugen. Due to this strong current, the edges of the inner and outer reef towards Slugen are extremely steep. The outer reef, with the five shallows Cancer (pronounced "Canger"), Vyl, Munk, Tuxen and Vovov, is a large deposition of gravel and sand, formed within the last 8.000 years on top of remains from the Eem interglacial period or the Saale glacial period. The bank stretches northwards about 25 km from Vovov (Leth *et al.* 2004).

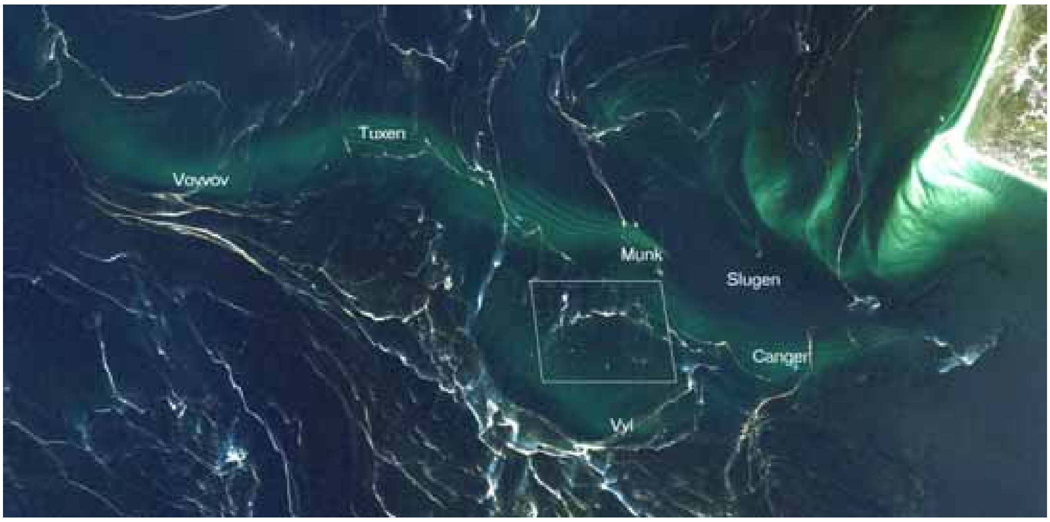


Figure 3 **Satellite image of Horns Reef with the shallow areas visible as light green contours. Horns Rev I Offshore Wind Farm indicated by trapezoid. Subsection of picture in Figure 2. Courtesy of the International Wadden Sea Secretariat.**

1.1.1 Human activities

Horns Reef and the plains south of the reef have traditionally been important to fishery and are still home to several types of fishery. This is primarily sand eel (*Ammodytes* spp.) fishery with bottom trawls and shrimp beam trawling. Previously there was also a large Danish purse seine fishery in the area, but this has now completely disappeared. In addition, shellfish fishery for *Spisula* occasionally occurs.

Besides fishing vessels a significant traffic of smaller and larger ships occur to and from Esbjerg harbour (bulk carriers with coal, supplies for offshore oil fields, as well as various cargo shipping). Large ships pass south of the reef, whereas smaller coasters coming from the north use the deep channel “Slugen”. Most parts of the outer reef are so shallow that only small ships can pass (draught less than 3-4 meters) and as navigation is difficult around these shallow areas only fishing vessels and other ships with a particular need to enter these areas (e.g. service ships to the wind farm and survey ships for the monitoring programs) are found on the reef itself.

No recreational boat traffic is present in the outer reef area.

1.2 Horns Rev Offshore Wind Farm

Horns Rev Offshore wind farm was constructed in 2002 and consists of 80 Vestas V80-2 offshore wind turbines, each with a nominal power output of 2 MW. It is placed in shallow water (depth 6.5-13.5 m) at the south-eastern part of the outer reef (Figure 1). Distance from Blåvands Huk to the closest turbine is approx. 14 km.

The turbines are three-winged with a wingspan of 80 m and the nacelle (containing gearbox and generators) is placed 70 m above mean sea level on a steel tower. Turbine towers are placed on steel monopile foundations. Each foundation consists of a transition piece (with maintenance platform etc.) on top of a 4 m diameter steel monopile which extend approximately 25 m into the seabed (Figure 4). A scour protection of large rocky boulders is placed on the bottom around the monopile foundations and extending approximately 10 m out from the foundation.

The 80 turbines are placed in ten rows of eight turbines, with 560 m between neighbouring turbines. All turbines are connected by a 36 kV grid of cables buried in the bottom. The cable connections converge on a separate transformer platform placed just outside the wind farm to the north east. From the transformer platform the main cable runs east across Slugen and ashore at Oksby south of Blåvands Huk where it is connected to the main grid.

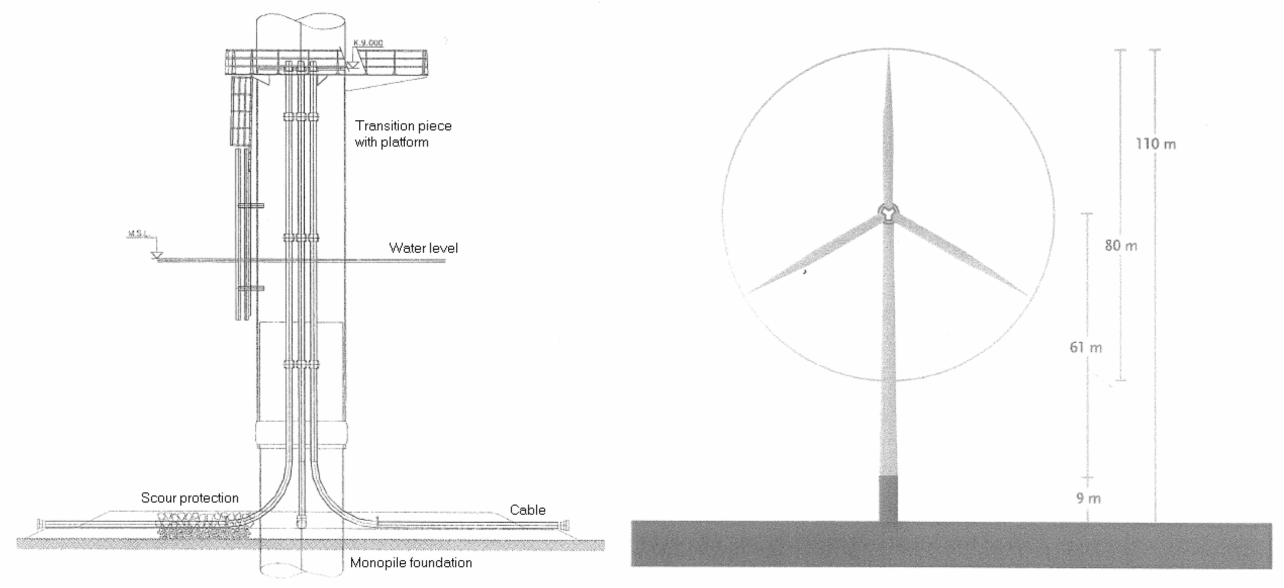


Figure 4 **Dimensions of turbines and foundations. Left: foundation with scour protection and transition piece with platform. Right: dimensions of turbine.**

1.2.1 Construction

Construction began in March 2002 with deposition of filter material (small boulders) on the individual positions. The role of the filter material was to reduce suspension of bottom material during subsequent piling of foundations. Foundations were driven into the seabed from a jack-up rig (Buzzard) with a large hydraulic hammer (*Figure 6*, left), an operation which took from less than one hour up to several hours per foundation, depending on bottom conditions. A transition piece, serving as platform for the turbine tower was mounted on top of the monopile and following this the tower, nacelle and wings were mounted (*Figure 6*, right).

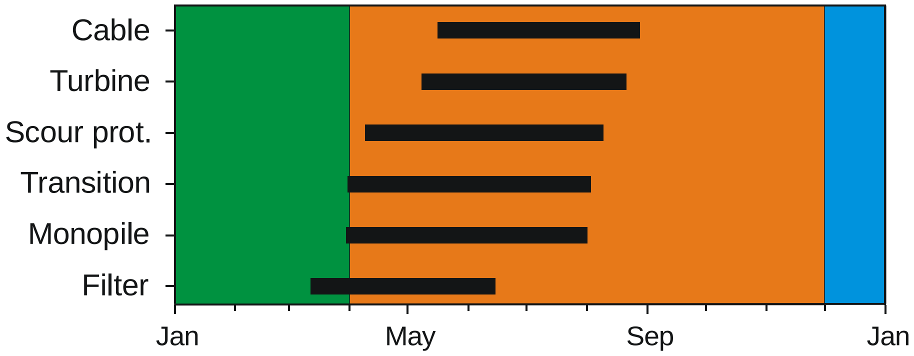


Figure 5 **Timeline of main construction events in 2002. Green, orange and blue rectangles indicate baseline, construction and operational period, respectively, as defined in this report (see methods section for details).**

Figure 6 **Left: Pile driving from the jack-up rig ”Buzzard”. Right: mounting of wings from the jack-up “Ocean Addy”. Photos : Vattenfall A/S.**

Cables connecting the individual turbines and connecting the turbines with the transformer platform were burrowed in the seabed and finally a scour protection, in the form of large boulder rocks was deposited on the seabed around each monopile. This scour protection extends out to approx 25 m from the turbine foundation (Figure 4). All operations were conducted in parallel and by the end of August 2002 all turbines were mounted and cables connected (Figure 5).

The wind farm was officially put into operation on December 8th 2002.

1.3 Scope of investigations

The ultimate question in the context of offshore wind farms and marine mammals is whether the construction and operation of these have a net impact (positive or negative) on the population size in the area and if this is the case whether this change in population size is acceptable or not. In the end, the latter question is political rather than biological and will not be discussed here.

Even if the ultimate goal may be to address impact at the population level, this is rarely possible for a number of reasons, e.g. the population range is not defined and the population area is in any case much larger than the study area. Instead it is useful to address the issue through an overview of the significant factors affecting the porpoises and their ultimate impact on the population (*Figure 7*). Effects are divided into negative (red) and positive (green). The net effect is thus broken up into a number of individual contributions from different factors that can be assessed individually. The focus of the study is thus the proximate question of whether the abundance and behaviour of porpoises is affected by construction and operation of an offshore wind farm and the ultimate question of impact at population level will only be touched upon in the discussion.

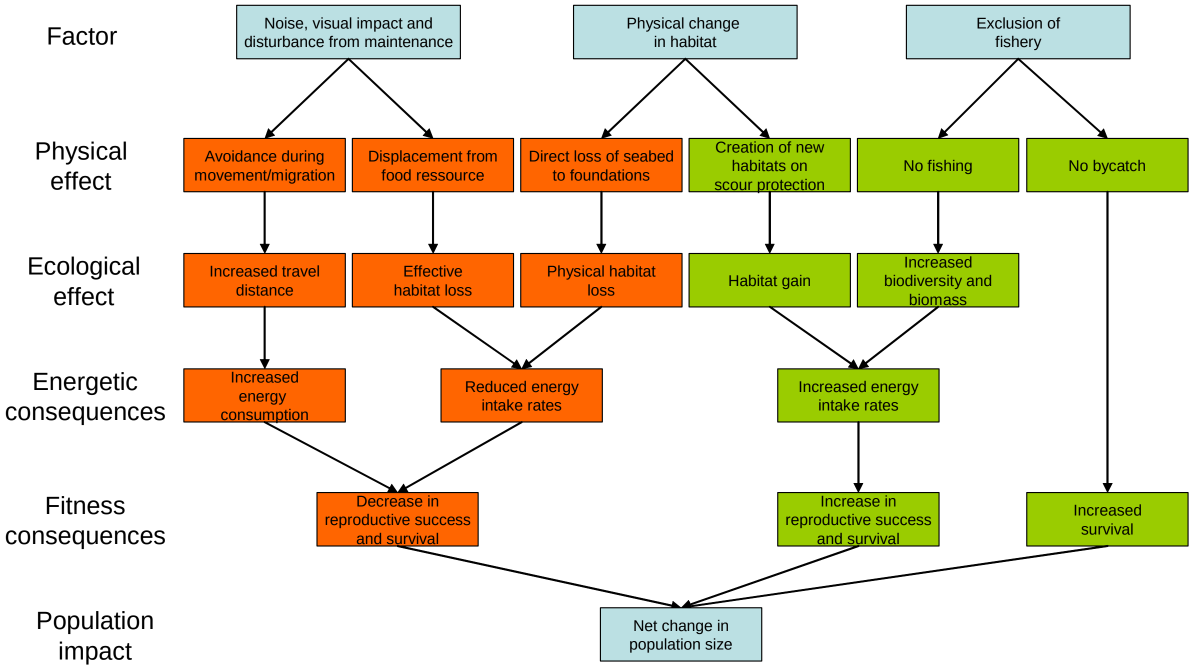


Figure 7 **Potential effects of offshore wind farms on harbour porpoises. Factors with negative effect are shown in red, factors with positive effects are shown in green. Adapted from Fox *et al.* (2004).**

1.3.1 Underwater noise and other changes to the physical environment

The construction and operation of the turbines creates changes in the physical environment which may influence the porpoises directly. It is thus possible that the physical presence of the turbines has a negative effect on porpoises, i.e. that porpoises will be reluctant to enter an area with new large structures such as the turbine foundations and be deterred by the rotating wings. Such effects are very difficult to assess experimentally and no studies have demonstrated such effects in any marine mammal. Most concern has surrounded possible effects of underwater noise from construction activities and also from operating turbines, but also visual appearance has been suggested as a factor potentially affecting porpoises.

1.3.1.1 Noise from operating wind turbines

Noise radiated from the turbine foundations into the water could potentially have an effect on porpoises. The noise from the turbines in Horns Rev is comparable to what has been measured from other turbines (see e.g. Wahlberg and Westerberg 2005). The noise is characterised by not being very loud, with all energy at very low frequencies and with pronounced peaks in the spectrum. Calculations and field experiments indicate that harbour porpoises are able to hear individual turbines at distances up to about hundred meters (Henriksen 2001). These calculations however, are based on a 1/3 octave filter bank model and as mentioned above (section 1.4.3), there is recent experimental evidence showing that this assumption does not hold for porpoises (Popov *et al.* 2006). At present, it is thus difficult to estimate the range at which the turbines are audible to the porpoises, although the generally low levels of noise emitted, combined with the relatively poor hearing abilities of porpoises at low frequencies makes it unlikely that they should be audible beyond a few hundred meters at best. Figure 10 shows noise from a single 1.4 MW turbine at Utgrunden Wind Farm (Ingemansson Technology AB 2003), the noisiest turbine measured to date. Absolute third-octave levels measured at 83 meters distance from the turbine foundation are low, with a maximum of 126 dB re 1 µPa at 180 Hz, measured at a wind speed of 13 m/s. This level roughly coincides with the extrapolated audiogram of the porpoise, indicating that it should be just audible to a porpoise 83 m from the turbine, where the measurement was made. A second, smaller peak around 800 Hz is present in the turbine noise. This peak is considerably above threshold level for the porpoise at 800 Hz and 10-15 dB above background noise level, and should be clearly audible to the animal at 83 meters. The distance at which this peak disappears below the background noise can be calculated given knowledge of the transmission loss in the waters around the turbine. Measurements from Ingemansson (2003), recalculated by Madsen *et al.* (2006) indicate a transmission loss of 30 dB per 10-fold increase in distance. Using this value, the peak at 800 Hz reaches the background noise level at a distance of 260 m from the turbine.

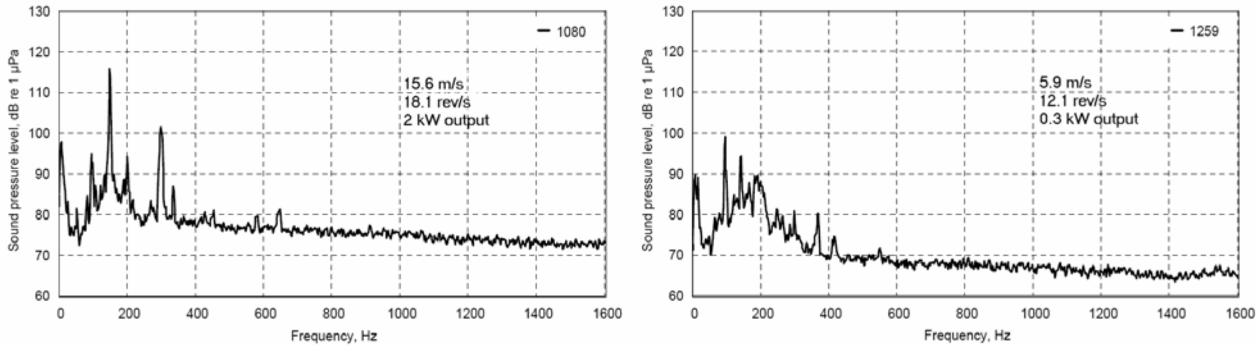


Figure 8 **Measurements of noise from turbine in Horns Rev Offshore Wind Farm running close to maximum power rating (left) and at low level (right). Measurements were made with a Reson TC4032 hydrophone mounted 2.5 m above the seafloor 87 meters from the turbine foundation and recorded on an MP3 recorder 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).**

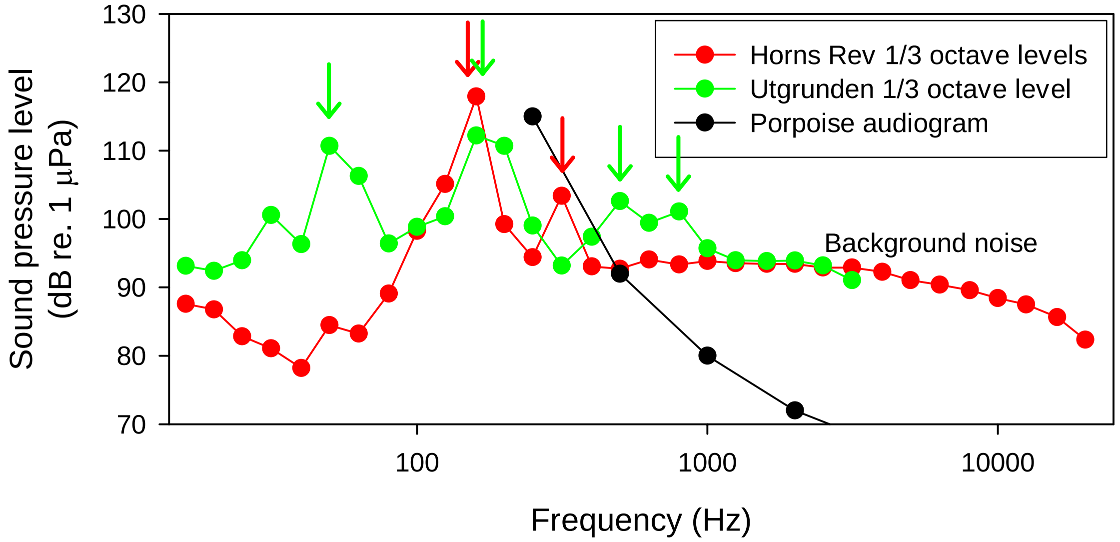


Figure 9 **Average 1/3 octave spectrum, normalised to a distance of 100 m from Horns Rev together with similar measurement from Utgrunden offshore wind farm. Red line indicate hearing threshold of harbour seal. Noise spectra from Betke (2006), audiogram from Kastelein** ***et al.*** **(2002). Arrows indicate the prominent peaks in the spectrum where the turbine noise exceeds the background noise. Noise above 800 Hz and 1250 Hz for Horns Rev and Utgrunden respectively, is background noise unrelated to the turbine noise.**

When it comes to reactions of the porpoises to the noise, we are left with qualified guessing. Sound pressure levels where behavioural reactions are observed are likely to be considerably higher than levels of audibility and may vary considerably from individual to individual. A high dependence on context is also likely, as animals engaged in important activities, such as feeding or mating, may be more tolerant to increased noise levels. The extent of the zone of responsiveness (sensu Richardson *et al.* 1995) is thus likely to be considerably smaller than the zone of audibility and reactions may thus be expected to occur only in the very vicinity of the turbine foundations.

Besides being a disturbing factor in itself, noise has the potential to interfere with detection of other sounds, known as masking. This may occur when there is an overlap between the frequency ranges of the noise and the sound in question. The low frequency emphasis of the turbine noise makes it very unlikely that it will mask any sounds of importance to the porpoises under any conditions. The echolocation signals of porpoises contain virtually no energy below 100 kHz and are thus completely outside the frequency range of the turbine noise. There may be other sounds, such as from potential prey, which contains significant energy at lower frequencies and thus potentially could be masked by the turbine noise. However, it is well established that the audiogram of a particular animal reflects the frequency content of the sounds of importance to the particular animal. Porpoises have poor low frequency hearing, poorer than e.g. seals and considerably poorer than low frequency hearing specialists, such as fish. Thus, by this indirect inference, it seems unlikely that they listen for sounds below 1 kHz on a regular basis and any masking by the turbine noise in this frequency range is thus unlikely to be significant to harbour porpoises.

1.3.1.2 Noise from service and maintenance activities

The third potentially disturbing factor is service operations on the turbines, where small, fast boats commute between land and the wind farm, as well as between the wind turbines. In situations where seas are too rough for the boats to moor at the turbines or fast access is needed the turbines are accessed from helicopter.

Small fast boats are known to be very noisy especially at cruising speeds above 15 knots (Richardson et al., 1995, Erbe 2002) and the pure presence of these boats are likely to have a deterring effect on harbour porpoises. In contrast to the noise from the turbines, the boat noise is of intermittent nature and overall disturbance will depend on the duration of each visit and intervals between visits.

The effects of boat traffic on presence of harbour porpoises are poorly documented and while there is a general agreement that porpoises will evade individual fast motor vessels, there is no basis for concluding that high boat traffic levels in general correlate with low abundance of porpoises. Some of the highest densities of porpoises in inner Danish waters are in fact found in the most heavily trafficked areas, Storebælt and Lillebælt (Kinze *et al.* 2003; Teilmann *et al.* 2004).

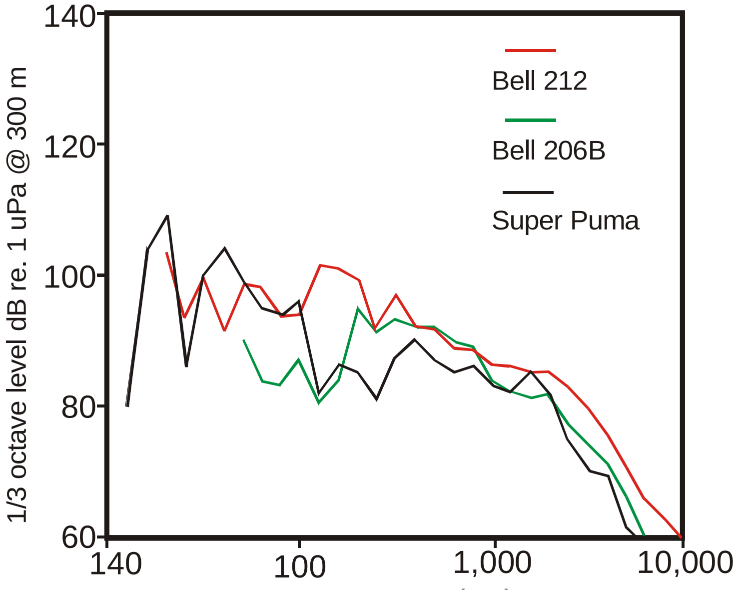


Figure 10 **Underwater spectra from helicopters flying overhead 300 m above the water surface, expressed as 1/3 octave levels. From Richardson *et al.* (1995)**

Helicopters are very noisy, but as they never get very close to the water surface and most of the sound is reflected from the surface, the noise that enters the water is limited. *Figure 10* shows noise spectra from passing helicopters measured in the water below. If compared to *Figure 9* it can be seen that the noise levels generated by a helicopter 300 m above the water surface is comparable to the noise from the operating turbines.

During hoisting operations where service personnel is hoisted to or from the turbine nacelle the helicopter will hover in a height of about 100 m above the water, which will mean that noise levels can be expected to be approximately 10 dB higher than in *Figure 10*. These levels are low by any standard and since they are comparatively rare events and intermittent of nature they may deter porpoises from the immediate vicinity of the turbine for a short while but are unlikely to represent any significant impact.

1.3.1.3 Disturbance from construction activities

The construction of the wind farm constitutes a major disturbance to the local environment. The seabed is disturbed due to the pile driving activities, burrowing of cables and establishment of scour protection and the noise level is significantly elevated due to noise from ships and activities. Disturbance of the seabed is unlikely to affect the porpoises directly, but could have an influence through displacement of their prey. The largest impact is likely to come from construction activities directly and of these the most severe impact is likely to have been pile driving operations.

1.3.1.4 Noise from pile driving

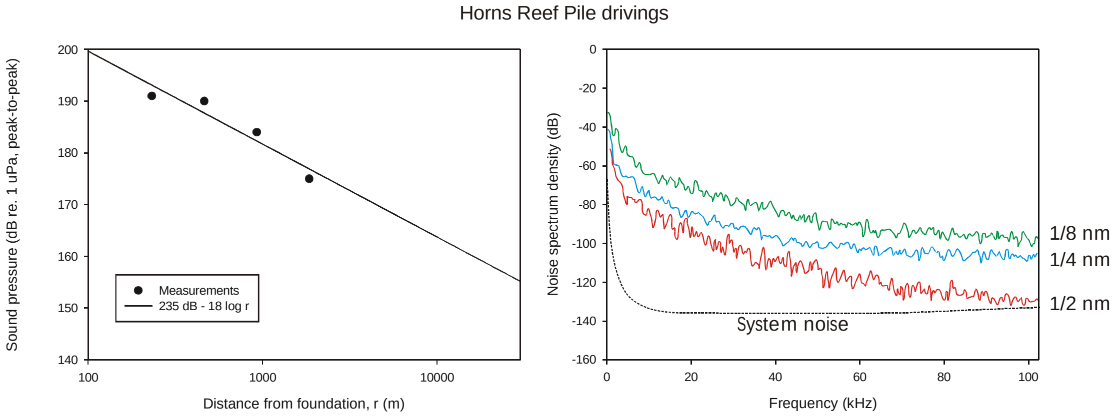


Figure 11 **Sounds from piling at Horns Rev offshore wind farm. Left: sound pressure levels measured at various distances from the construction site and best fitting straight line. Right: Power spectra of piling sounds at three different distances from the construction site (1/8, ¼ and ½ nautical mile, respectively). Data courtesy of Elsam A/S (Anon. 2002a).**

Pile drivings, by which steel monopiles are driven into the seabed with a large hydraulic hammer, generates very high sound pressures. Figure 11 shows measurements made in Horns Rev offshore wind farm during piling of one foundation. Sound levels are high, about 190 dB re 1 μPa several hundred meters form the construction site and with a best fit of attenuation of 18 dB per 10 times increase in distance this translates into a source level of 235 dB re 1 μPa at 1 m distance. Although such high sound pressures are unlikely to have been present close to the monopile due to near field effects, the levels are nevertheless sufficiently high to raise concern that porpoises present close to the foundation during piling may suffer temporary or permanent damage to their hearing. For this reason mitigation measures were also taken (see below).

Most energy of the pile driving sounds is at low frequencies, where especially porpoises and to a lesser degree seals have poor hearing. It is nevertheless evident from the spectra in *Figure 11*, that there is energy present in the signals well into the range of best hearing for porpoises (up to 100 kHz and possible beyond). Although it is difficult to extrapolate sound levels out to greater distances, the high levels and the presence of significant energy at high frequencies would predict the sounds to be clearly audible to porpoises and thus also potentially able to interfere with their behaviour at distances of tens of kilometres and possibly more.

Mitigation procedures

In order to protect seals and porpoises against being exposed to excessive and harmful sound pressures close to the pile driving site either a ramp up procedure was employed or acoustic deterring devices were deployed. The ramp up procedure meant that gradually increasing force was used in the first series of blows to each monopile, leading to an incremental increase in sound pressure, designed to deter any seals or porpoises from the construction site. This procedure was used on the first few pile drivings, but was later replaced by deterring devices. These devices, an Aquamark100 porpoise pinger and a Lofitek seal scarer were deployed prior to piling, at the time when the jack-up rig was anchored. These devices were considered efficient to deter seals and porpoises out to safe distances.

1.3.1.5 Electromagnetic fields

Any cable carrying current will generate an electromagnetic field. The magnetic part of this field adds to the natural magnetic field of the earth and has thus the potential to interfere with magnetic orientation in the vicinity of the cable.

The cables at Horns Rev Offshore Wind Farm consist of three conductors carrying three phases of alternating current (AC) at 36 kV. Each conductor generates its own alternating field and in theory the three fields should cancel out. Due to the geometry of the cable they do not cancel out completely, but the total field is nevertheless considerably weaker than from a single conductor cable. The size of the magnetic field from the sea cable connecting Nysted Offshore Wind Farm to land has been calculated to approximately 5 µT on the sea bottom one meter above the cable when the wind farm runs at maximal capacity (cable carrying 600 A, Eltra 2000). The natural magnetic field in Denmark is approximately 45 µT

These small disturbances to the local geomagnetic field are irrelevant for marine mammal navigation, even if this is based on magnetoreception, as disturbances are small and extremely local around the cable.

1.3.1.6 Chemicals in the water

Although porpoises have no sense of smell, they can nevertheless still taste the water, when opening the mouth and their eyes are continuously exposed to whatever dissolved irritants there may be in the water. Such chemical pollution, annoying or even harmful to the animals could potentially be present during construction, although not likely. Most relevant is probably oilspills, but none such has been reported and even if minor spills occurred, their effect would have been transient, due to the strong currents in the area.

It seems unlikely that any substances which could affect porpoises are released from the turbine towers after completion.

1.3.1.7 Visual appearance

Figure 12 **Turbines on Horns Reef seen from a point close to sea level (during maintenance, where turbines were stopped). Seastate 4-5 Beaufort. Photo: Vattenfall A/S.**

The foundations below water and the turbines above water represents a change to the visual scene of the area and it could be hypothesized that this could deter porpoises from the area.

The visual appearance underwater is likely to be minimal, if existing at all in the operating wind farm. Underwater parts of the foundation and scour protection quickly become overgrown with algae and epifauna and thus visually resembles other reef-like structures in the sea.

In air, the 100 m high turbines with their rotating wings represent a major change to the visual scene (*Figure 12*), but it is unclear if and how this may affect porpoises. Porpoise vision is poor in air (see 1.4.4 below) and they are not known to orient in relation to structures above water. In calm weather and sunshine the rotating wings will generate patterns of large moving shadows, which will penetrate into the water. Fish are known to react strongly to shadows cast on the surface (presumably they associate it with piscivorous birds), but reactions have not been described for porpoises or dolphins. In any case this phenomenon will only occur in sunshine and calm winds, where the sea is sufficiently calm for the shadows to penetrate into the water (sea state 0-1 Beaufort); yet sufficient wind must be present for the turbines to rotate. Such conditions are rarely seen on Horns Reef for prolonged periods.

1.3.2 Changes in habitat

The construction of an offshore wind farm on hard sandy bottom as on Horns Reef will inevitably cause changes to the habitat. First of all is the direct loss of habitat to foundations and scour protection. This is unquestionable negative to the organisms inhabiting the sandy seabed. This loss is unlikely to be of any significance to the porpoises however, as it comprises a loss of not more than 500 m^2 per turbine or considerably less than 0.01% of the total area of the wind farm (27.5 km^2). Such a small loss is unlikely to affect the productivity and biodiversity of the remaining sandy bottom in the wind farm. Furthermore the loss in productivity is likely to be more than balanced by the introduction of new hard substrates (foundation tower and scour protection), which inevitably will be colonised by algae and filter feeding epifauna (see Figure 13) and create an artificial reef (Petersen and Malm 2006). These will in turn attract fish and crustaceans and thus increase the biodiversity in the area and increase the potential prey available to the top predators like porpoises. Thus, changes in the habitat caused by the wind farm are, if anything, likely to have a beneficial effect on porpoises and were not targeted as a specific issue in the monitoring program.

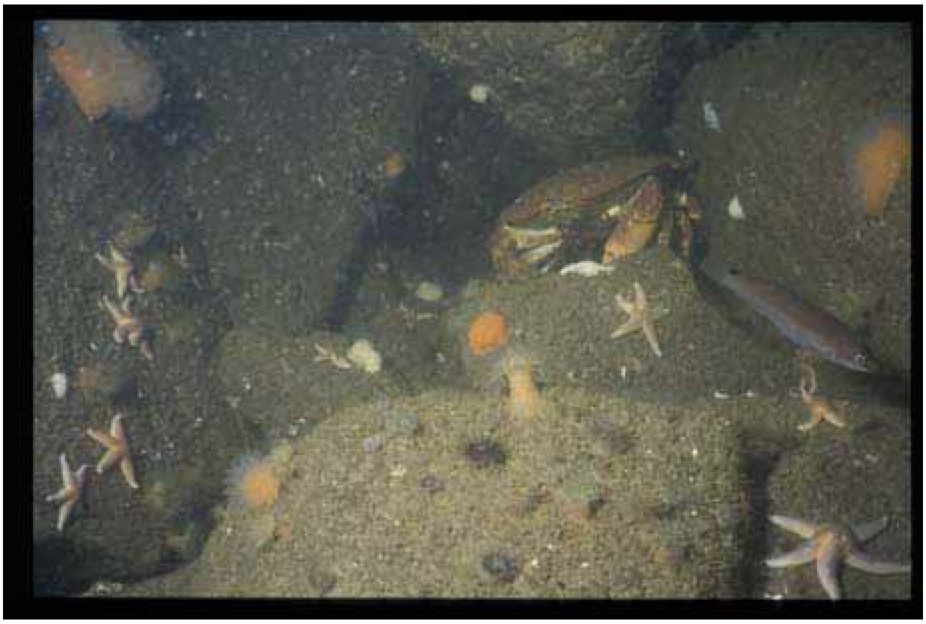


Figure 13 **Scour protection boulders photographed in 2004 (two years after construction), with sea anemones (***Metridium senile***), dead men's fingers (***Alcyonium digitatum***), common starfish (***Asteria rubens***), an edible crab (***Cancer pagurus***) and goldsinny-wrasse (***Ctenolabrus rupestris***). Photo: Bio/Consult A/S.**

1.3.3 Exclusion of fishery

For reasons of safety (to fishermen and installations) no commercial fishery is allowed in the wind farm. This may benefit porpoises directly due to a reduction of bycatch, which is by far the largest anthropogenic cause of increased mortality in porpoises in the North Sea (Vinther and Larsen 2004). Due to the small size of the wind farm and the fact that no fishery with bottom set gill nets occurred in the area before 2002, the reduction in bycatch due to exclusion of fishery is probably minimal.

A second, and perhaps more beneficial effect of restrictions in fishery is the greater availability of prey to the porpoises and likely also an increase in diversity of prey. These changes in the fish community are difficult to assess both for technical reasons and because they add on top of changes in the fish community caused by the introduction of hard substrates.

1.4 Harbour porpoises in the North Sea and on Horns Reef

The harbour porpoise (*Phocoena phocoena*) is one of the smallest odontocetes (toothed whales) and the only cetacean (whale), which breeds in inner Danish waters (Figure 14). Harbour porpoises are distributed throughout the entire North Sea, with exception of the English Channel and high densities are found in the German Bight. According to the SCANS survey conducted in 1994, there are estimated 260.000 porpoises in the North Sea (Hammond et al. 2002; Hammond et al. 1995).

Little is known about the fine-scale distribution of porpoises and what factors governs this distribution. Several studies have indicated the presence of a north-south gradient in porpoise densities along the German Wadden Sea (Benke *et al.* 1998; Sonntag *et al.* 1999). High densities are found in the area west of Sylt, where a high number of females with calves have also been observedSonntag *et al.* 1999). Baseline observations on Horns Reef showed that harbour porpoises are abundant in the Horns Reef area, including the area now occupied by the wind farm. It has been suggested that harbour porpoises in the German Bight area are associated with the estuarine frontal system of the area (see section 1.1 above). It is known that piscivorous birds often associate with estuarine frontal systems, such as has been shown for divers (*Gavia* sp.) in the German Bight (Skov and Prins 2001). A recent study from the Bay of Fundy, Canada (Johnston *et al.* 2005), where porpoises were tagged with satellite transmitters and tracked showed a strong association of tagged porpoises with hydrographical fronts and eddies formed by the strong tide. A concurrent series of line transect surveys in the frontal areas with very high densities of porpoises supported the conclusion of an aggregation to the front. A very strong correlation in abundance with tide was also observed in the line transect data, with more than five times as many porpoises observed at high tide compared to low tide Johnston *et al.* 2005). As similar complex hydrographical features (fronts and eddies) are present in the Horns Reef area, it is likely that they also play a major role in determining the fine-scale distribution of porpoises in the area, including the wind farm.

Figure 14 **Two harbour porpoises at the surface. Photo: Jonas Teilmann.**

It is unlikely that porpoises respond to the gradients in salinity per se. These gradients are comparatively weak and without physiological consequences for the animals. The gradients and frontal systems however, are important for concentrating nutrients and plankton and porpoises probably respond to an increased concentration of prey, which again aggregate in the frontal regions due to the higher production and / or availability of planktonic prey.

1.4.1 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 calves in early summer. The calves begin suckling immediately after birth and feed by their mother until March the following year and possibly longer. As porpoise cows most often give birth every year, this period can last 12 months at most. The females can conceive when they are 3 or 4 years old (Kinze *et al.* 2003). If she does not conceive or loose her calf, a porpoise cow must wait until the next year before she can conceive again (Read 1990). Changes in food resources may influence the reproduction of porpoises. The only information that exists on breeding harbour porpoises in Danish waters, are sightings of calves. Calves seem to be sighted throughout their range and there may not be any particular breeding areas (Hammond *et al.* 1995; Kinze *et al.* 2003). However, satellite tracking of adult females show that they may have preference for some areas (Teilmann *et al.* 2004).

1.4.2 Foraging ecology

The preferred food sources of harbour porpoises in Danish waters comprise a large variety of fishes: herring (*Clupea harengus*), mackerel (*Scomber scombrus*), cod (*Gadus morhua*), saithe (*Pollacius virens*), plaice (*Pleuronectes platessa*), flounder (*Platichtyes flesus*), goby (*Gobius niger*), sandeel (*Ammodytes spp.*), garfish (*Belone belone*) and eelpout (*Zoarces viviparus*), (Börjesson and Berggren 2003). The daily food intake per adult harbour porpoise is about 1.75kg consisting mainly of fishes of up to 20-25cm in length with a preference for fat fishes like herring, mackerel, eelpout and small individuals of different cod species (Börjesson and Berggren 2003).

Between 1985 and 1990, the stomach contents of 21 harbour porpoises from the southern part of the Belt Seas and the western part of the Baltic Sea were studied. Herring made up 36% while cod made up 41% and eelpout 10% of the fish weight eaten (Börjesson & Berggren 1995). In another study a large proportion of gobies were found in the stomach of porpoises in the Baltic Sea, in particular in smaller individuals (Lick 1993). No exact information exists on the stomach contents of harbour porpoises from Horns Reef, but it is likely that their food preferences reflect the available prey of suitable size, i.e. sandeel (Ammodytes sp.), herring (Clupea harengus), sprat (Clupea sprattus) and perhaps small Gadoids (codfish).

1.4.3 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 click (130 kHz peak frequency, 50-100 µs duration; Møhl and Andersen 1973; Teilmann *et al.* 2002b) 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.* 2006; Akamatsu *et al.* 2005).

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). Odontocete inner ears have anatomical specialisations for ultrasonic hearing, such as high thickness to width ratios of the basal (high-frequency) part of the basilar membrane, supplemented by additional stiffening elements along the cochlear duct (Ketten 2000).

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 increases slowly with about 20 dB per decade for lower frequencies and increases steeply at high frequencies. In general, smaller species like the harbour porpoise have higher upper limits of hearing, around 150 kHz (Andersen 1970; Kastelein *et al.* 2002) than larger species.

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. The bandwidth of the auditory filters differs somewhat among species and with frequency within the same species. A general approximation for mammals however, is that the bandwidth is 1/3 octave throughout the hearing range of the animal. 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. A recent study on porpoises (*Phocoena phocoena* and *Neophocoena phocaenoides*) however, has revealed that their filter bank is differently organised than the normal for mammals and that they closely approach a constant bandwidth filter bank (Popov *et al.* 2006). This new information has important implications for the discussion of possible effects of underwater noise from wind turbines, as discussed in this report. As Popov *et al.* (2006) did not measure filter bandwidths below 20 kHz (i.e. not in the range where turbine noise is) and as the standard mammalian constant Q model does not fit the data, there is uncertainty as to the extent low frequency noise affects the hearing of porpoises.

1.4.4 Vision

Cetaceans have good vision, although odontocetes compared to other mammals have small eyes in relation to their body size. 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. Movement however, such as from rotating turbine wings, should be clearly visible to porpoises, even in air.

Odontocetes, like mysticetes and also seals, are functionally colour blind (Peich *et al.* 2001).

1.4.5 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 cannot be ruled out 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 the weak conclusion is that it remains a possibility that odontocetes, including the porpoise have a magnetic sense, but there is no experimental data to support it.

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. Although marine mammals seems like good candidates for electroreception, as they like sharks live and find their prey in often dark and murky waters, there is so far nothing that supports this. In contrast to the case for magnetic sense, this absence of evidence should be taken more conclusively. Electroreceptive sensory cells are well known from animals with electric sense and among other features have a characteristic morphology and often special and easily recognisable support structures attached to them, such as the Lorenzinian ampullae of cartilaginous fish (Bullock and Heiligenberg 1986). No cells with this special morphology and support structures have been identified in any cetacean and it thus seems unlikely that they are sensitive to weak electric fields, or even able to perceive them.

1.5 Hypotheses regarding effects

In the Environmental Impact Assessment (EIA, Tougaard *et al.* 2000) conducted prior to permission to build the park was granted, two main predictions regarding effects on harbour porpoises were stated:

Activities during construction would create disturbance in the area, mainly in the form of underwater noise, increased ship and boat traffic and disturbance to the bottom sediment. All these factors would likely cause porpoises to leave the wind farm area partly or totally during construction.

Operation and normal maintenance activities in the completed wind farm would not cause significant disturbance to the porpoises and porpoise abundance on the reef as a whole would return to within 25% of baseline levels.

Thus the main focus of the monitoring program has been to document changes in abundance of porpoises on Horns Reef in the period from before construction to well into the operational period. A secondary aim has been to attempt identification of individual factors which are likely to be responsible for any changes in abundance observed.

1.6 Links to other monitoring programs

The porpoise monitoring programme on Horns Reef is one part of the environmental monitoring programme at Nysted and Horns Rev offshore wind farms. Ship surveys were only conducted on a regular basis at Horns Reef, due to the higher abundance of porpoises here, compared to the area around Nysted Offshore Wind Farm, but the acoustic monitoring programme was developed in parallel with the porpoise monitoring program at Nysted Offshore Wind Farm. This report does not deal with specific comparisons of results of the two programs, as this is done in a separate report. Aerial surveys at Horns Reef were conducted as part of the bird monitoring programme, but are included in the present study for completeness. Many of the issues relevant for porpoises and addressed in this report are general for marine mammals and although the experimental methods differ, many of the same questions discussed in this report has also been addressed for harbour seals during the seal monitoring programme (Tougaard *et al.* 2006b).

2 Materials and Methods

The overall strategy of the porpoise monitoring program has been to combine methods with high spatial resolution (line transect surveys) with methods with high temporal resolution (autonomous acoustic dataloggers). The spatial distribution of porpoises in and around the wind farm area was mapped by line transect surveys throughout the Horns Reef and adjacent waters, which provides high-resolution snapshots of porpoise distribution at fixed points in time. The temporal occurrence of porpoises was monitored by acoustic dataloggers (T-PODs), which yields continuous records of porpoise echolocation activity at fixed points in space.

2.1 General description – the BACI test

The presence and distribution of porpoises on Horns Reef varies tremendously on an almost day to day basis. The factors underlying these changes are not well known but it is probably fair to assume that the changes somehow reflect the abundance and availability of prey. These are in turn likely influenced by factors such as bathymetry, sediment type, time of year, time of day, tidal cycle and hydrographical features. For visual surveys additional factors such as conditions of observation and differences among observers may add variation from survey to survey. For acoustic dataloggers differences among T-PODs will also add to the variation. Controlling for the effects of these factors in an analysis of the data is not trivial. Various attempts have been made in previous reports and in the current report a spatial model is developed which allows for some of these factors to be included in the analysis of the ship survey data.

However, the key question of the study is whether there is a differential effect of the wind farm, i.e. are fewer animals observed inside the wind farm and close to it, *relative* to the surrounding areas. Answering this is accomplished through a BACI-approach (Before-After-Control-Impact), where the presence of animals inside an impact area is compared to the presence of animals in one or more reference areas nearby (*Figure 22*). The reference areas need not be identical to the impact area in all respects other than the wind farm, as long as the natural variation in the two areas is similar and correlated. The test does not assess changes in absolute numbers, but changes in the difference between impact and reference areas. A significant negative BACI effect thus indicates that fewer animals were observed in the impact area than expected from the animals observed in the reference areas.

The use of the BACI-design means that for survey data we need not worry too much about the survey to survey variation, as we compare sighting rates (or more specifically modelled animal densities) between wind farm and reference areas on a survey to survey basis, corresponding to a paired test. In the same manner we need not worry about systematic differences between T-POD stations and variation across the year etc., as we compare animal abundance in the wind farm with reference areas on a day by day basis in a manner again similar to a paired test.

2.2 Ship surveys

Surveys were conducted from a number of different ships, ranging from small to medium sized trawlers such as M/S Christoffer (*Figure 15*) to the former light buoy handling ship “M/S Søløven”. Surveys were only initiated whenever the weather forecast predicted calm seas and observations were only conducted in seastate 3 Beaufort and below.

Figure 15 **"M/S Søløven", former ship of the Royal Danish Administration of Navigation and Hydrography, now rigged for survey work and related activities. Observations were conducted on the "monkey island" on top of the bridge.**

Transect layout consisted of lines oriented east-west and covered an area of approx. 800 km2. The entire part of the outer reef above the 10 m depth contour was included as was the deep channel Slugen and the deeper areas north and south of the reef. The very shallow inner reef was not covered (Figure 16). Two different general layouts were used. The general layout consisted of about 500 km of transect lines (incl. transport from line to line) and could be completed in two days in the summer. During construction a reduced layout was used, which covered only the core parts of the reef and permitted completion of surveys within one day. Additional lines north and south of the general layout were sailed during baseline, but not included in the analysis.

Observations were made from the roof of the bridge. Three observers were continuously searching for porpoises and seals. During baseline and construction also bird observations were recorded. Two observers scanned each a 90 degree sector (0-90 degrees and 270-360 degrees relative to the ships midline, respectively). These two observers used handheld binoculars (8x40) most of the time. The task of the third observer was divided into two. Approximately half the time was spent looking forward along the centreline using binoculars in order to maximise detection probability on the line. The remaining time was spent observing with naked eye for animals in the vicinity of the ship. This was done because animals close to the ship are easily overlooked when searching with binoculars. In addition, the third observer kept the written observation log for all three observers.

Whenever animals were observed the bearing and distance from the ship to the animals was estimated. A horizontal angle board and different devices for measuring small vertical angles were used (calliper or variant hereof). These devices allowed measurement of the distance between line to the visible horizon and line to observation at 50 cm distance from the observer's eye. This can then be translated into an angle and together with knowledge of the eye height above water translated into distance to observation (Pihl and Frikke 1992).

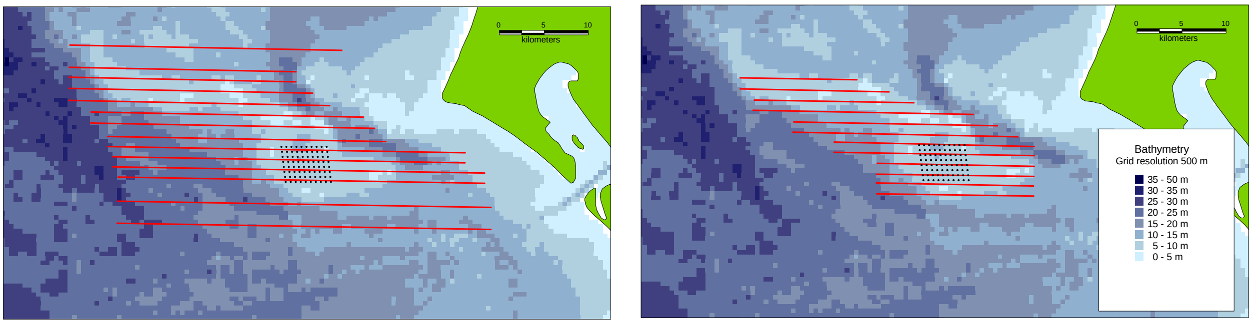


Figure 16 **Transect layouts. During baseline, semi-operation and operation the lines in the left map were used. During baseline and part of semi-operation the lines were surveyed sequentially. During the rest of semi-operation and operation every other line was surveyed on day one and the remaining lines on the second day of the survey. During construction a reduced layout was used, which enabled completion of all lines in one day (right map). Additional lines to the north and south were surveyed during baseline, but these data were not included in the analysis.**

Observers, which had no previous experience with line transect sampling, were trained as a fourth observer on their first survey, before they could serve as regular observers.

Each observation was recorded with time, distance and bearing and number of animals observed. The observer who first saw the animals was also recorded, as well as whether they were first seen with or without binoculars. This information was recorded to allow for subsequent analysis of differences between observers and evaluation of search strategies.

The position of the ship was recorded from GPS, either manually or by transferring the track log to a computer. The temperature and salinity of the surrounding water was sampled continuously during surveys (WTW 340 conductivity meter). A temperature and salinity probe was placed in a bucket into which the ship's fire hose was pouring water. Depth of the samples was approximately 3 meter (depth of the intake to the pump. Measurements were sampled at regular intervals, either manually or through a serial port connection to a notebook PC. The clock of the PC was adjusted to follow GPS-time and measurements could thus subsequently be assigned to geographical positions.

2.2.1 Spatial modelling

This spatial modelling analysis consisted of two steps. In the first step detection functions were fitted to the sighting data from the surveys, and the second step we modelled the estimated counts of porpoise sightings in segments along the transect line as a function of environmental predictor variables.

Line transect distance sampling methods (Buckland *et al.* 2001) allow for conversion of observations along transect lines into densities (animals per unit area). Details on application of the methods to the survey data can be found in Appendix A. Briefly, the density of porpoises can be estimated for individual segments along the track line as a function of the number of animals observed in the segment, and factors shown to influence their detectability. The densities along the trackline can then be correlated with environmental factors (bathymetry, distance to coast, surface temperature and salinity etc.). If sufficiently strong correlations are found these will allow for a modelling of the distribution of porpoises, i.e. an interpolation of predicted densities to the areas between lines and (with great caution) also extrapolation to areas outside the surveyed area and to days where surveys were not conducted and with other hydrographical situations.

Detection functions

As a first step in the spatial modelling process we computed detection functions for all the 4 groups of surveys (baseline, construction, semi-operation and operation). According to the date the survey was conducted, we pooled each survey that contained at least 30 observations: baseline 5 surveys, construction 3 surveys, semi-operation 7 surveys, and operation 5 surveys.

Using the sightings information in the surveys, we modelled the probability of detecting a porpoise as a function of perpendicular distance, 2 explanatory variables proposed to influence porpoise detectability, and a key function (either hazard rate or half normal). The 2 explanatory variables included sea state, and the survey's id-number. Sea state was treated as an ordinal categorical variable ranging from 0-3. Survey ID was a categorical variable which carried combined information regarding the season of the survey, observers and ship. To determine which of these explanatory variables and key function were needed, we selected the most parsimonious detection function model from a suite of candidate models based on AIC model selection.

For all detection function analyses, we assumed that the probability of detecting an animal on the trackline (g(0)) was 1, which is likely to be too high. For relative comparisons however, as described below, the exact value of g(0) is not critical, as long as it is constant. We used the Mark Recapture Distance Sampling analysis engine in Program Distance 5.0, as this is the only software that allows us to extract the detection probability estimates for individual sightings based on multiple covariates (e.g. sea state and survey id) as were needed for spatial modelling.

Spatial modelling count model

We first modelled the estimated counts of porpoises in each 500 m grid cell in the study area as a function of a number of predictor variables, including spatial coordinates (easting and northing), salinity, temperature, tide and bathymetry using generalised additive mixed models (GAMM). However, we found that these explained too little of the variation in the data to be useful, so we switched to generalised additive models (GAM) (see below).

Predictor variables

In our previous report we evaluated the fit of GAM spatial models built with dynamic predictors derived from simulations of hydrologic conditions during two surveys carried out in 2004. These explanatory variables summarised hourly spatial means and ranges in salinity, temperature, and vertical speed. According to our model evaluation criteria, the resulting models fitted the data poorly, and had limited explanatory power. The August model explained only 7% of the deviance. We considered this explanatory power to be insufficient and instead derived our own dynamic explanatory variables based on CTD data recorded on the ship concurrent with observations. We thus used the following explanatory predictor variables: salinity, temperature, tide.

Salinity and Temperature

We derived these predictors from CTD data collected during the surveys (see section 2.2 above). The CTD data only represent salinity and temperature along the path of the ship. To approximate salinity and temperature at the time during the survey, we interpolated their values between the track lines using the linear interpolation tool in ArcGIS. We then extracted the average values of salinity and temperature within each 500 * 500 meter segment along the trackline, and used this in model building and later in prediction to 500* 500 meter grid cells. For some surveys, mechanical failures in the CTD equipment, or problems with interpolating salinity values between the track lines, prevented the inclusion of the salinity data in spatial modelling. Thus, we did not include salinity in our analyses of surveys 1-3, 7, 16, 17 and 19.

Tide

A previous analysis of T-POD data (Tougaard *et al.* 2005) indicated a relationship between porpoise occurrence and tidal cycle. Therefore, we included tide as an explanatory predictor in spatial modelling. The tide data were obtained from a measuring station at Esbjerg Harbour, where water level is recorded every 20 minutes. Data from 1999 through April 2004 are from the harbour and data from May 2004 and onwards from the measuring station at the entrance to the harbour (Grådyb Barre). Each porpoise observation on the surveys was assigned a value for tidal cycle equal to the ratio of time since last high tide to time of observation divided by the total duration of the time between the two high tides surrounding the observation. Thus values close to 0 and 1 corresponds to sightings made at high tide, whereas values close to 0.5 correspond to sightings at low tide.

Bathymetry

Bathymetry was collected from an interpolated grid (resolution 500m x 500m) based on measurements form the Royal Danish Administration of Navigation and Hydrography.

GAMM and GAM

To determine whether a single spatial model could be used for each survey group (baseline, pile driving, semi operation and construction) we used GAMM (Generalised Additive Mixed Modelling). As with GAM (Generalized Additive Models), these models allow us to model the estimated number of sightings per segment of transect line as a function of a suite of explanatory predictors. However GAMM offers the possibility to model the variability between surveys using a combination of fixed and random effects. When the results of GAMM indicated low explanatory power due to difficulties in modelling variability between surveys (baseline models explained less than 2% of the variation in the data), we opted to build GAM models for each survey individually. We applied the ‘count model’ of Hedley *et al.* 1999) to model the trend in spatial distribution of harbour porpoises at Horns Reef. The response variable was the estimated number of individual porpoise sightings in segment i, $\hat{N}_i$, estimated using the Horvitz-Thompson estimator (Horvitz and Thompson 1954):

$$\hat{N}_i = \sum_{j=1}^{n_i} \frac{s_{ij}}{\int \hat{g}_{ij}(x,z)\,\pi(x)\,dx}, \qquad i = 1,\ldots,v$$

,

where n_i is the number of groups detected in segment i, s_{ij} is the observed number of porpoises in group j in segment i, $\int \hat{g}_{ij}(x,z)\pi(x)dx$ is its estimated probability of detection assuming that the probability density function (pdf) of perpendicular distances, x, is uniform with respect to the survey tracklines (and is obtained from the fitted model for the detection function), z being its covariate attributes (used in the detection function model), and v is the total number of segments. In this analysis, each segment was 500m long.

A generalized additive model (GAM) with spatially referenced covariates was used to model the response, with the following general formulation:

$$E\left[\hat{N}_i\right] = \exp\left[\ln(a_i) + \beta_0 + \sum_{k=1}^{q} f_k(z_{ik})\right], \qquad i = 1,\ldots,v$$

Here a_i is an offset that corresponds to the area of the i^{th} segment. β_0 denotes the intercept, and the f_k are one-dimensional smooth functions (cubic smoothing splines) of the q spatial covariates z.

Spatial coordinates were also considered for inclusion in the model. A log link was used, as was a quasi binomial family.

Apart from the grid co-ordinates X and Y, available spatial covariates were: salinity, temperature, position in tidal cycle, and bathymetry Model selection was carried out using F-test model selection criteria with a probability threshold of 0.05, as implemented in the GAM interface package GRASP 2.5 (Lehmann *et al.* 2002) within R. We estimated the fit of our models by computing the proportion of deviance explained (D^2) by each selected model.

2.2.2 BACI analysis of porpoise densities

Mean densities of porpoises were calculated for 20 cruises over 4 different areas, representing the impact area (wind farm with a 280 m margin around) and three reference areas with a gradient from the wind farm (reference C: outside the impact area extending 5 km to the East and West and 4 km to the North and South, reference B: outside reference C extending additional 5 km to the East and West and 4 km to the North and South, and reference A: remaining area outside reference B, see *Figure 17*). The 20 cruises represented 4 distinct periods: Baseline (cruise 1, 2, 3, 4, and 5), Construction (cruise 7, 8, and 11), Semi-operation (cruise 16, 17, 18, 19, 21, and 22) and Operation (cruise 23, 24a, 24b, 25, 26, and 27).

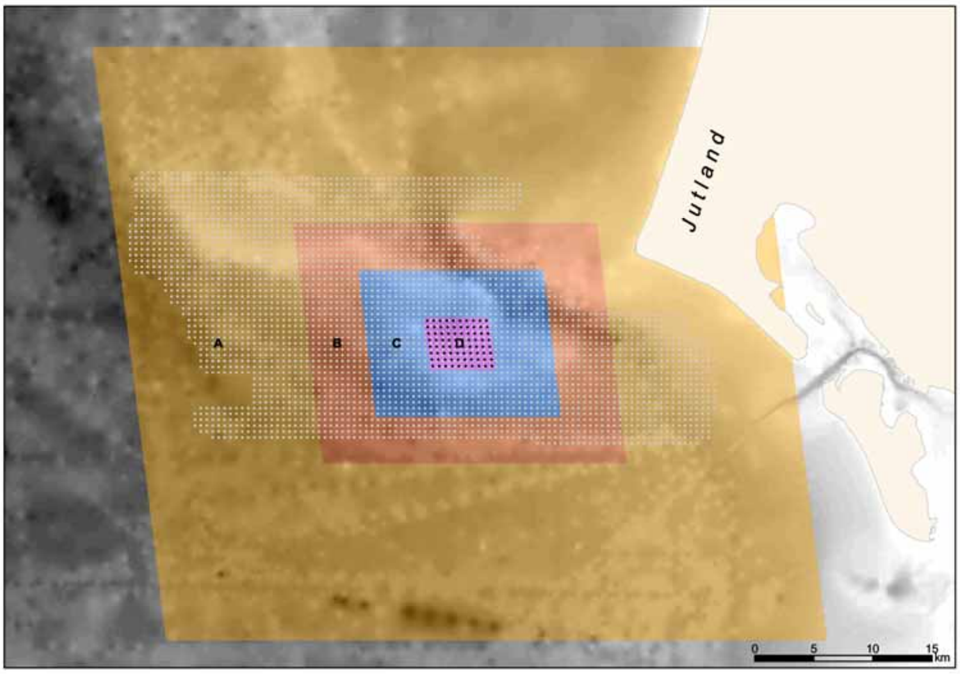


Figure 17 **Zones used for statistical test of impact. Only the parts of the four zones within the surveyed area (indicated by white dots) were included in the analysis. Each white dot represents one grid cell of the spatial model. Black dots indicate individual turbines.**

Estimated mean densities were obtained for each area in each cruise, and it was assumed that there was a structural temporal trend in the mean density over the entire study area. Therefore, observations were paired by cruises and relative changes between the areas were investigated by the following model for the log-transformed mean density

$$\ln(Dijk) = area_i + period_j + area_i \times period_j + cruise_k(period_j) + e_{ijk}$$

where $area_i$ and $period_j$ both have 4 levels to describe variations between impact, reference A, B and C, and between baseline, construction, semi-operation and operation, respectively. The interaction $area_i \times period_j$ describes relative changes between areas and periods at all levels combined. $cruise_k(period_j)$ describes temporal variations between cruises and e_{ijk} is the residual variation. The overall BACI effect (significance of $area_i \times period_j$) has 9 degrees of freedom to describe variations between all combinations of area and period, however, BACI test were also constructed as contrast to examine relative changes between combinations of two periods and two areas, a total of 18 contrasts.

2.3 Aerial surveys

Aerial surveys were conducted in connection to the bird impact study (Petersen 2005). Details on survey methods should be found in Petersen 2005). Briefly, the survey area, approximately 1,800 km² was surveyed along 30 north-south oriented tracklines (*Figure 18*) with a highwinged, twin-engine Partenavia P-68 Observer (altitude 76 m (250 feet), cruising speed approximately 185 km/t (100 knots)). Two experienced observers each covered one side of the aircraft. Flight track data was recorded continuously from a differential GPS and together with a temporal accuracy of the observations of generally within four seconds, this translates into a positional accuracy on the longitudinal axis within 200 m. Surveys were not initiated when wind speed exceeded 6 m/s.

Few porpoises were sighted on most of the surveys and as only 7 surveys, of which none were during construction, had more than 30 sightings, spatial modelling was not attempted on the data.

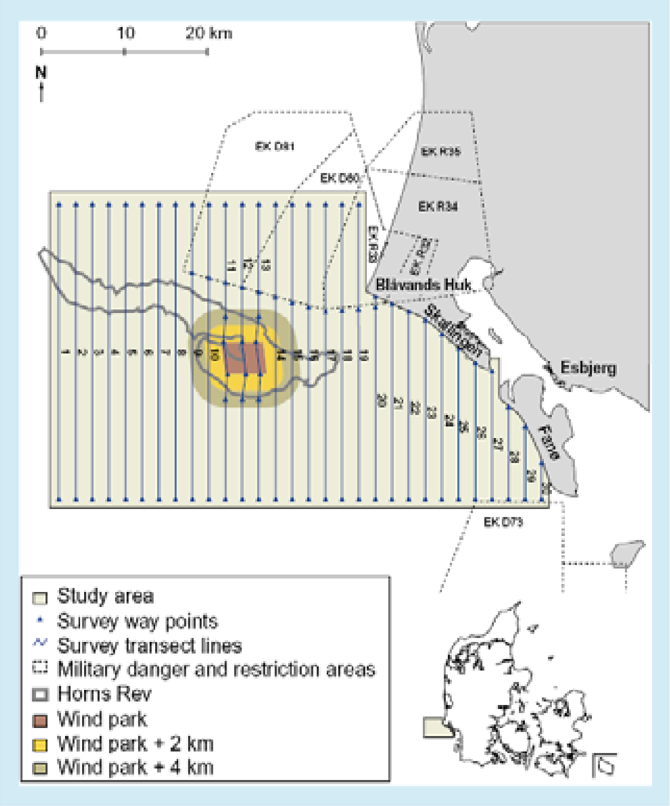


Figure 18 **Survey layout for aerial surveys. See Petersen (2005) for details.**

2.4 Acoustic dataloggers (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. 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 (e.g. Teilmann *et al.* 2001). See also Carstensen *et al.* (2006).

The T-POD consists of a hydrophone, an amplifier, two 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 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.

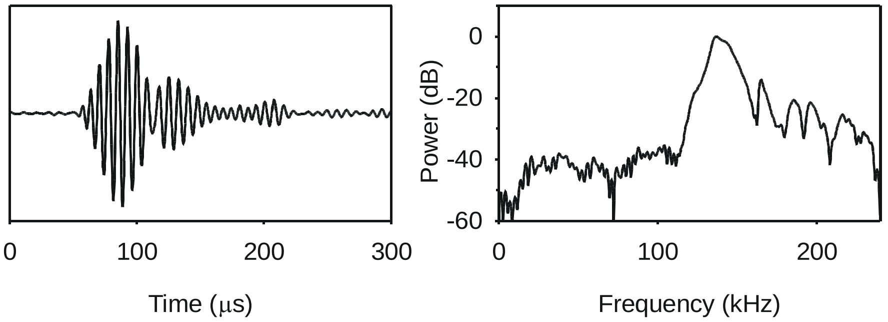


Figure 19 **Porpoise click time signal (left) and power spectrum (right). There is virtually no energy present below 100 kHz (the curve below 100 kHz represents background noise of the recording).**

The 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 (Figure 19). 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 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 substantial 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 a man-made sound (echosounder or boat sonar).

Some clicks of undetermined origin (e.g. 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 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 origin tend to occur at random, thus with highly irregular intervals.

Comparison of T-POD recordings with visual observations of porpoises in the waters around the T-POD indicate a maximum detection distance of 250 m, with an effective detection radius of about 75 m for version 1 and 100 m for version 3 (Tougaard, unpublished).

No other cetacean regularly found in the North Sea has sonar signals that can be confused with porpoise signals. Dolphins (with the exception of the genus *Cephalorhynchus*, which does not occur in European waters) use broadband sonar clicks, i.e. energy distributed over a wide frequency range, from below 20 kHz to above 150 kHz (Au 1993). It is thus highly unlikely that they will trigger the T-POD, when settings are adjusted to detect porpoises.

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. All channels used in this study had identical settings (*Table 1*). In the earliest deployments channel 1 was adjusted to monitor ship activity, but the data were not usable and are excluded from further analysis.

All T-PODs recorded porpoise clicks on channels 2-6 (5 in total) and the average click intensity per minute was calculated as the sum of these 5 channels, adjusted by a factor of 60/45 corresponding to the actual active period of T-POD monitoring.

Table 1 **T-POD filter settings used at Horns Reef**

Setting	Version 1	Version 3
A filter frequency	130 kHz	130 kHz
B filter frequency	90 kHz	90 kHz
Ratio A/B>	5	5
A filter sharpness (Q)	10	low
B filter sharpness (Q)	18	high
Minimum intensity	0	6

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), 15% for individual channels (9 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 (time since deployment) is much less, due to drift in the T-PODs clock during deployment (a few minutes per month). This drift however, is only of concern when comparing records from two T-PODs deployed simultaneously. Clicks shorter than 50 µs and sounds longer than 2550 µs were discarded.

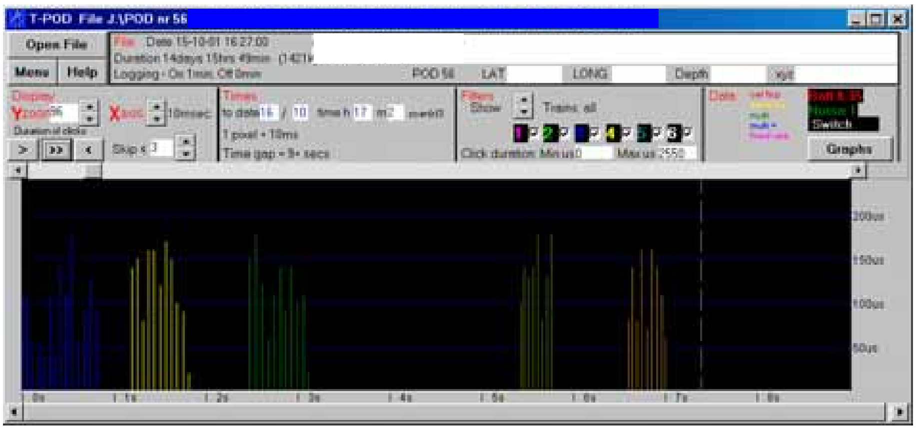
The hydrophone of the T-POD has a resonance frequency of 120 kHz and is cylindrical and thus in principle omnidirectional (equally sensitive at all angles of incidence) in the horizontal plane. T-PODs are insensitive to temperature changes within the normal operating range between 3ºC and 25ºC, except from a reduction in battery life at lower temperatures. Battery-voltage does not influence sensitivity as the electronics in the T-POD receive a stable voltage until the battery is drained below 5.1 V, where the electronics turn off.

Version 1 T-PODs is equipped with 8 MB RAM and version 3 T-PODs with either 32 MB or 128 MB RAM. Both are powered with 49.5Ah, 7.2V lithium batteries (6 3.6V D-cells), which gives a maxi-

Figure 20 **An open T-POD connected to a computer. The hydrophone can be seen as a small attachment in the lower end of the T-POD. A prefabricated 6xD-cell LiIon battery pack is seen behind the T-POD.**

mum logging period of about 60 days. A 20 MHz CPU operates data handling. The memory will normally be filled in 2-4 month depending on echolocation activity and software settings.

A parallel cable to a PC downloads data from the T-POD in the field for storage and analysis (Figure 20). Data can be analysed with the T-POD.exe program used for communicating with the T-POD, or exported to any spreadsheet software for further analysis. Figure 21 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, echo sounder 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.



Date 15-10-01 16:27:00
Duration 14days 15hrs 49min
Logging - On 1min, Off 0min
POD 56
Trains all
1 pixel = 10ms
Time gap = 9+ secs
Skip < 3
Click duration: Min us 0 Max us 2550

Figure 21 **Screen snapshot from the T-POD.exe software. Five 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.**

2.4.1 Deployment of T-PODs

The first T-PODs were deployed at Horns Reef in July 2001, and this report presents data collected from the T-PODs onwards to the end of 2005 where the data collection ended. The time series obtained from the T-POD signals contain larger and smaller gaps due to technical and logistical problems connected to the T-POD design and the difficulties surrounding any type of field work in a heavily exposed area such as Horns Reef. These difficulties mean that time series at the different positions within the investigation area are combined from recordings with different T-PODs, because gear has been lost and T-PODs occasionally were moved from one position to another.

Due to loss of old T-PODs with internal transducers, newer T-PODs versions with an external transducer were introduced in 2003 and 2004 (T-PODs numbered 161, 224, 226, 270 and 282). Specifically, the T-POD with id 270 is a version 1 that had an external transducer installed, and T-POD with id 11 which was refitted with new version 3 electronics but maintained the internal transducer. This implies that two different types of transducers have been in use at Horns Reef and moreover, that two T-PODs are hybrids in the sense that parts of the T-PODs were replaced.

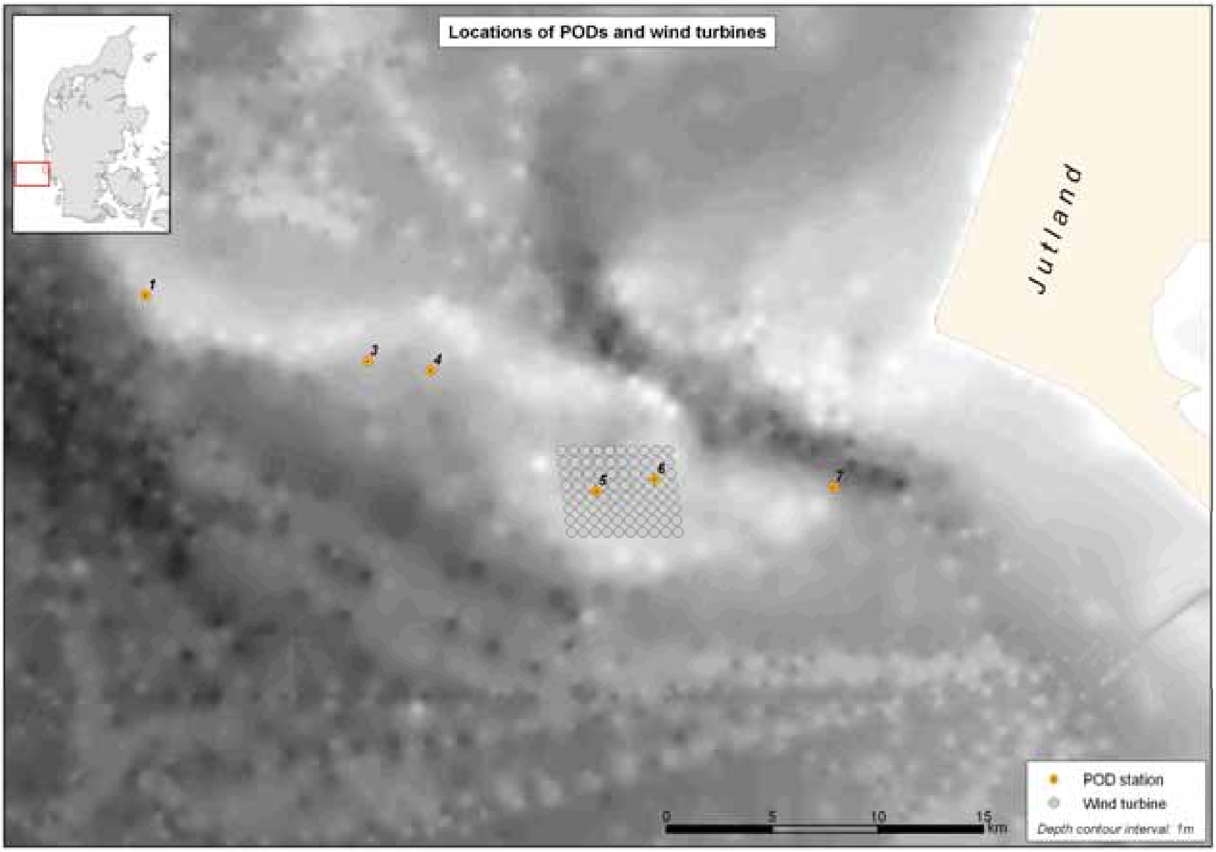


Figure 22 **Study area with individual turbines indicated with open circles and positions of the six T-POD measuring stations (see methods section). Depth indicated by shades of grey: shallow areas in white. Original layout consisted of eight stations, but station 2 and station 8 were removed during the program and are not included in the analysis.**

Monitoring at Pos. 8 (Slugen) was stopped after the baseline study due to loss of T-PODs, low porpoise echolocation activity and a seasonal variation different from the other positions (Tougaard *et al.* 2003). Consequently, these data were excluded from further analysis.

The time series were partitioned into four phases: 1) a baseline from July 1st 2001 to March 3rd 2002, 2) a construction period from March 4th 2002 to December 18th 2002, and 3) a semi-operational phase December 18th 2002 to December 31st 2004, and an operational period from January 1st to December 31st 2005 where the monitoring program was terminated in its present form.

2.4.2 Indicators from T-POD signals

T-POD data were analysed in the same manner as previously reported (Skov *et al.* 2002; Teilmann *et al.* 2001; Carstensen *et al.* 2006). Four indicators were extracted from T-POD signals, based on the logged number of clicks per 1-minute interval. This signal, denoted xt, consists of many observations of zero (periods with no clicks) and relatively few observations with click recordings. The click number per minute was aggregated into daily observations of:

$$\text{Click frequency} = \frac{\text{Number of minutes with clicks}}{\text{Total number of minutes}} = \frac{N\{x_t > 0\}}{N_{total}} \qquad (2\text{-}1)$$

$$\text{Click intensity} = \frac{1}{N\{x_t > 0\}} \sum_{x_t>0} x_t \qquad (2\text{-}2)$$

Another approach to analysis was to consider recorded clicks as the outcome of a point process, i.e. separate events occurring within the monitored time span. We considered xt 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 sequences consisting of both minutes with and without clicks. Such short sequences were considered to belong to the same encounter. We decided to use a silent period of at least 10 minutes to separate two different encounters from each other. This threshold value was determined from graphical investigation of different time series of xt. Thus, two click recordings separated by a 9-minute silent period would still be part of the same encounter. The conversion resulted in two new indicators for porpoise echolocation activity:

Encounter duration = Number of minutes between two silent periods longer than 10 minutes

Waiting time = Number of minutes in a silent period lasting more than 10 minutes

The definitions imply that waiting time has a natural lower bound of 10 minutes, as well as the possibility of encounters potentially including periods with zero clicks between periods with clicks spaced less than 9 minutes apart. Encounter duration and waiting times were computed from data from each T-POD deployment. Consequently, each deployment resulted in one more observation of encounter duration, since the silent periods at the 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.

2.4.3 Interpretation and statistical modelling

The four indicators vary according to presence and behaviour of porpoises in the vicinity of the T-PODs. The indicators daily frequency and waiting time between encounters are indicative of porpoise presence. A higher daily frequency and a lower average waiting time between encounters compared to another T-POD recording is indicative of a relative higher abundance of porpoises. Daily intensity and average encounter duration are little affected by the number of animals in the area. Instead they provide information on the acoustic behaviour of porpoises, when these are present. The exact interpretation of these two indicators is difficult, as no behavioural observations concurrent with T-POD recordings are available. A high average intensity means that more clicks are recorded, whenever animals are close to the T-POD. This could simply be a reflection of the animals physically being closer to the T-POD, or it could be caused by the animals actually emitting more clicks. The latter would be the case for foraging animals, or animals actively investigating objects close to the T-POD. A high average encounter duration is likely to be caused by animals spending more time in the area close to the T-POD, again indicating a higher interest in the area (caused by food or something else).

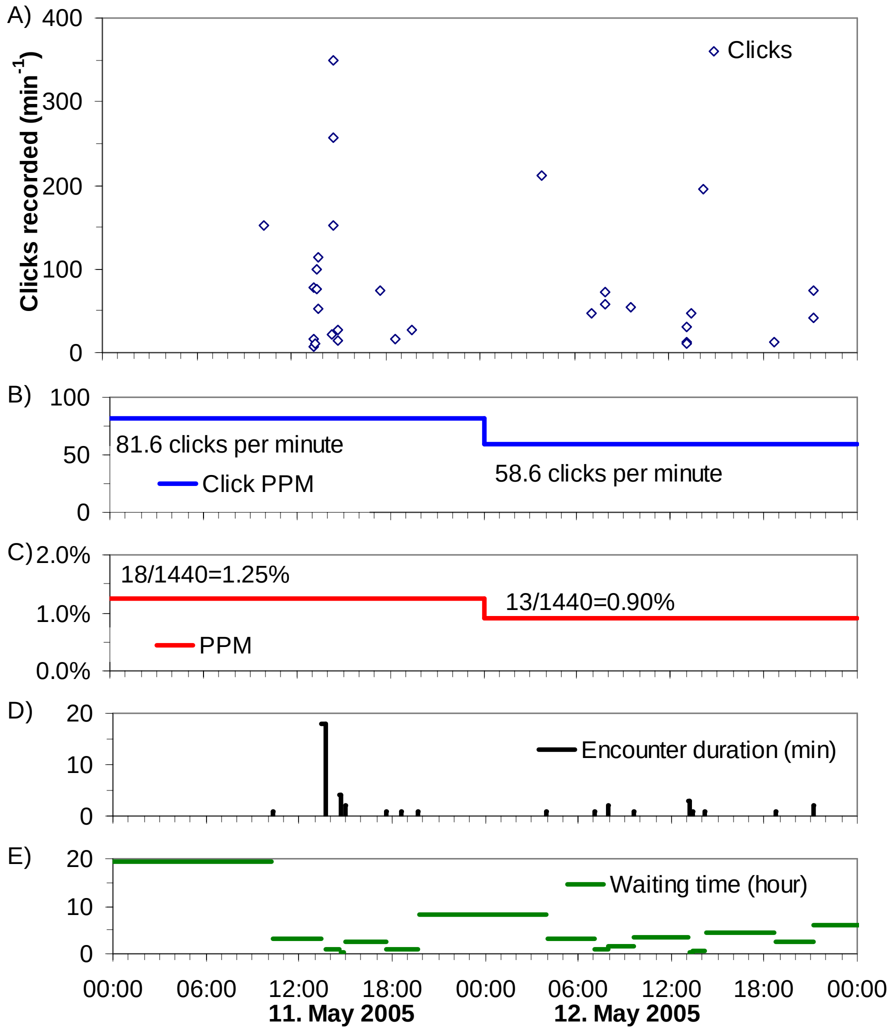


Figure 23. **Calculation of the 4 indicators (B-E) from clicks (A) exemplified using two randomly chosen days at station Imp. W inside the wind farm. The values for clicks/PPM (B) and PPM (C) for the two days are listed above the lines. Encounters (D) are shown as vertical lines fat the time of occurrence with a length equal to the duration of the encounter in minutes. Waiting times (E) are shown as vertical lines between two encounters with a level showing the duration in hours.**

The four indicators were assumed to be potentially affected by the following factors Area (inside wind farm or reference position), Podnr(area station) (differences among different T-PODs deployed at the same station), Period (baseline, construction or operation), Area×Period (BACI effect, describing different response to impact in wind farm and reference areas in the three periods), Month (variation across the year), transducer (internal or external hydrophone on T-POD) and podtype(transducer) (version 1or version 3 electronics).

Variations in the indicators, after appropriate transformation (see appendix B), were assumed Normal-distributed with a mean value described by the equation:

$$\mu = area + station(area) + month + period + area \times period + transducer + podtype(transducer) \qquad (2\text{-}3)$$

Besides answering general questions on differences between wind farm area and reference areas, seasonal variation, variation among T-PODs etc., the main purpose of the analysis is to address differential changes in abundance and behaviour of porpoises in the wind farm area during construction and operation. Thus, the BACI-test addresses whether a decrease (or increase) in porpoise abundance in the wind farm e.g. during construction is higher than what can be expected based on changes observed concurrently in the reference areas.

Further details on the statistical analysis of T-POD data can be found in Appendix B – Statistical analysis of T-POD data.

3 Results

The results are divided into separate analyses of survey data and acoustic monitoring

3.1 Line transect surveys - ship

Table 2 **List of all line transect surveys conducted, with indication of effort (km sailed) and number of animals observed.**

	Start	End	Ship	Survey days	Porpoise groups	Porpoises total	Km sailed	groups/km	Anim/km
Baseline	24-04-1999	03-05-1999	Gorm	3	33	62	569	0.058	0.109
	24-08-1999	30-08-1999	Gorm	3	92	194	520	0.177	0.373
	11-11-1999	15-11-1999	Esvagt Dana	3	29	55	463	0.063	0.119
	23-02-2000		Esvagt Delta	1	186	410	174	1.068	2.355
	23-07-2000	25-07-2000	Pip	3	54	90	396	0.136	0.227
	12-08-2000	14-08-2000	Esvagt Dana	3	92	222	474	0.194	0.468
	15-08-2001	18-08-2001	Alice Bekker	3	83	151	496	0.167	0.304
	21-08-2001	22-08-2001	Alice Bekker	2	132	321	409	0.323	0.784
Construction	12-03-2002		M/S Alice Becker	1	11	13	156	0.071	0.083
	23-03-2002	24-03-2002	M/S Gitte Iversen	2	40	53	235	0.171	0.226
	20-04-2002	21-04-2002	M/S Gitte Iversen	2	32	66	336	0.095	0.196
	08-06-2002	09-06-2002	M/S Christoffer	2	4	4	114	0.035	0.035
	28-07-2002		M/S Gitte Iversen	1	54	143	245	0.220	0.584
	08-08-2002		M/S Christoffer	1	96	306	262	0.366	1.168
Semi-operation	12-02-2003	13-02-2003	M/S Christoffer	2	13	23	260	0.050	0.088
	18-03-2003		M/S Christoffer	1	12	15	166	0.072	0.090
	23-07-2003	24-07-2003	M/S Christoffer	2	55	109	435	0.126	0.251
	06-08-2003	07-08-2003	M/S Christoffer	2	124	285	403	0.308	0.707
	09-08-2003	10-08-2003	M/S Christoffer	2	82	259	366	0.224	0.708
	17-10-2003	18-10-2003	M/S Christoffer	2	131	422	315	0.416	1.340
	19-02-2004	20-02-2004	Christoffer	2	12	22	279	0.043	0.079
	26-04-2004	27-04-2004	Christoffer	2	42	83	268	0.157	0.310
	02-08-2004	03-08-2004	Christoffer	2	65	124	378	0.172	0.328
Operation	23-06-2005	24-06-2005	Søløven	2	135	259	427	0.316	0.607
	30-06-2005	01-07-2005	Søløven	2	89	170	420	0.212	0.405
	18-08-2005	21-08-2005	Søløven	3	246	777	409	0.601	1.900
	15-10-2005	16-10-2005	Juli-Ane	2	30	54	203	0.148	0.266
	22-11-2005	23-11-2005	Søløven	2	29	53	237	0.122	0.224
	13-03-2006	14-03-2006	Alice Bekker	2	4	5	167	0.024	0.030
	23-04-2006	24-04-2006	Alice Bekker	2	6	9	332	0.018	0.027

Eight surveys were conducted during the baseline period (before 1st of March 2002), six were conducted during construction (1 April-8 August 2002), nine were conducted during semi-operation (18 December 2002 and 31 October 2004) and seven were conducted during the Operation period (1 November 2004 – April 2006).

Of the 30 surveys conducted, 20 surveys recorded at least 30 porpoise sightings, and were analysed in spatial modelling. Data from all surveys are included as maps in Appendix C.

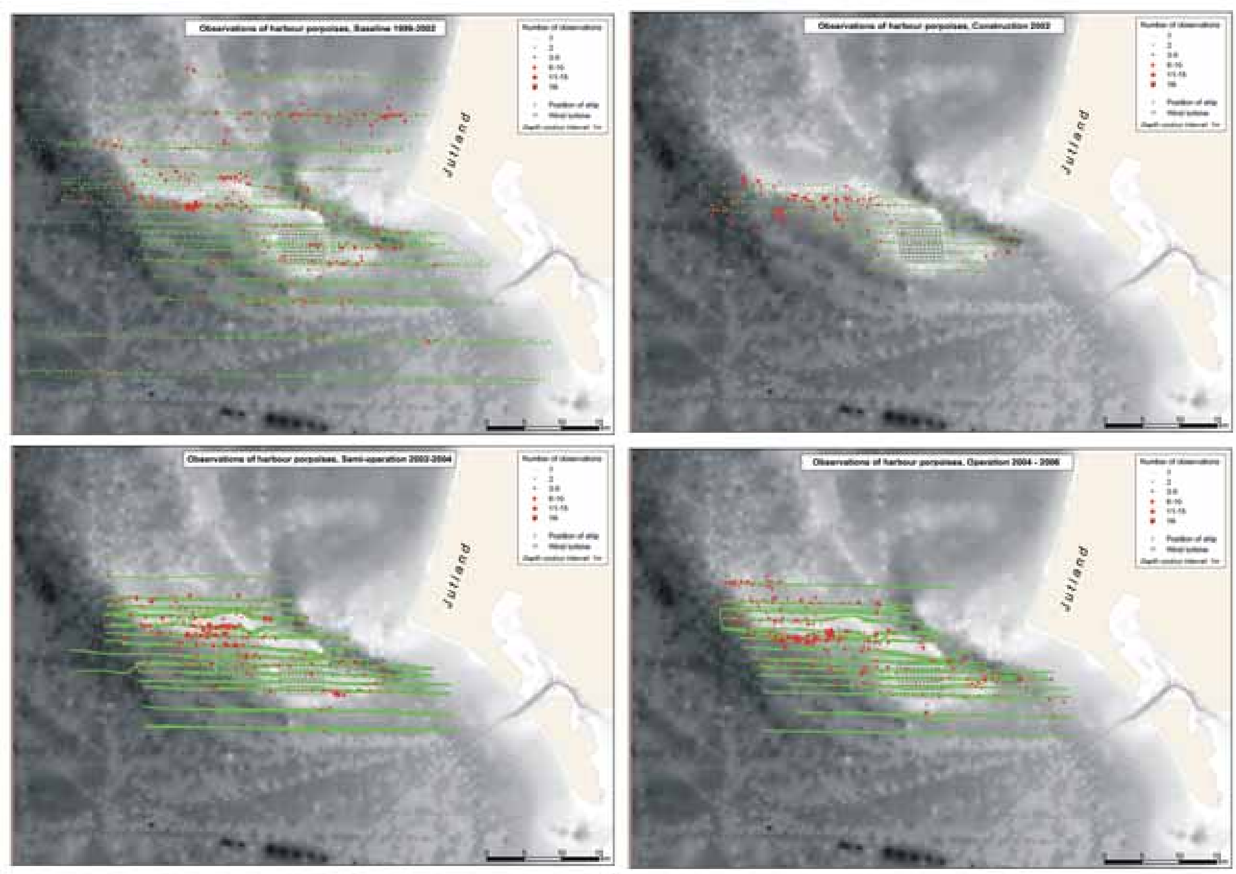


Figure 24 **Maps showing all sightings on ship surveys, separated into the four periods: baseline, construction, semi-operation and operation. Red dots represent sightings of groups of porpoises, with dot size indicating group size. Green lines indicate transect lines sailed.**

There was a considerable variation in number of porpoises observed from survey to survey and across the year. On average, most porpoises were seen in the late summer and few were seen in the winter months (*Figure 25*). One survey in February during baseline (out of three in total in February) had the highest sighting rate of all surveys, however.

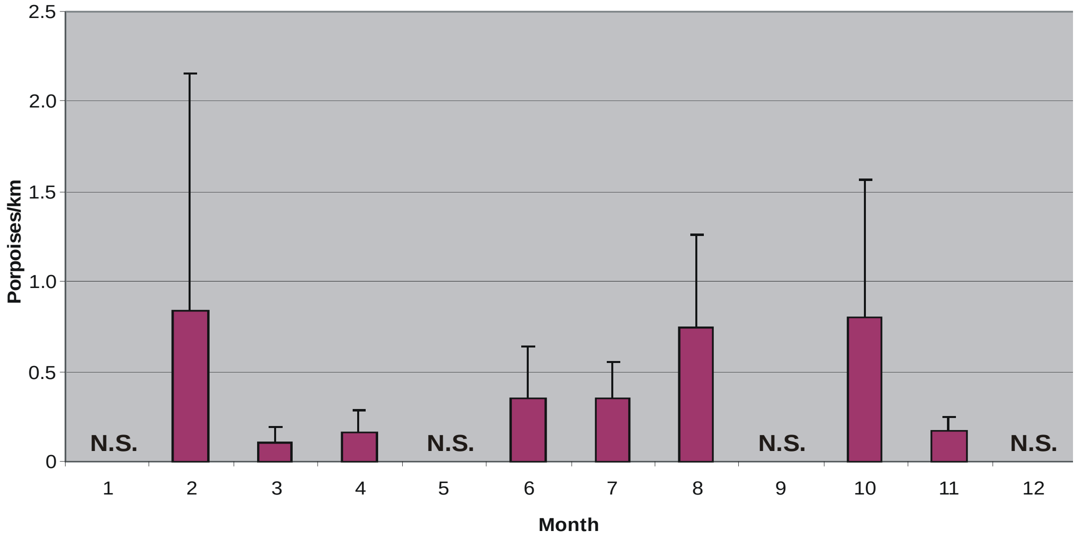


Figure 25 **Average number of porpoises sighted per km sailed on ship surveys, separated according to survey months. Number of surveys per month between two and nine. Error bars indicate standard deviation. N.S. indicate that no surveys were conducted in that particular month..**

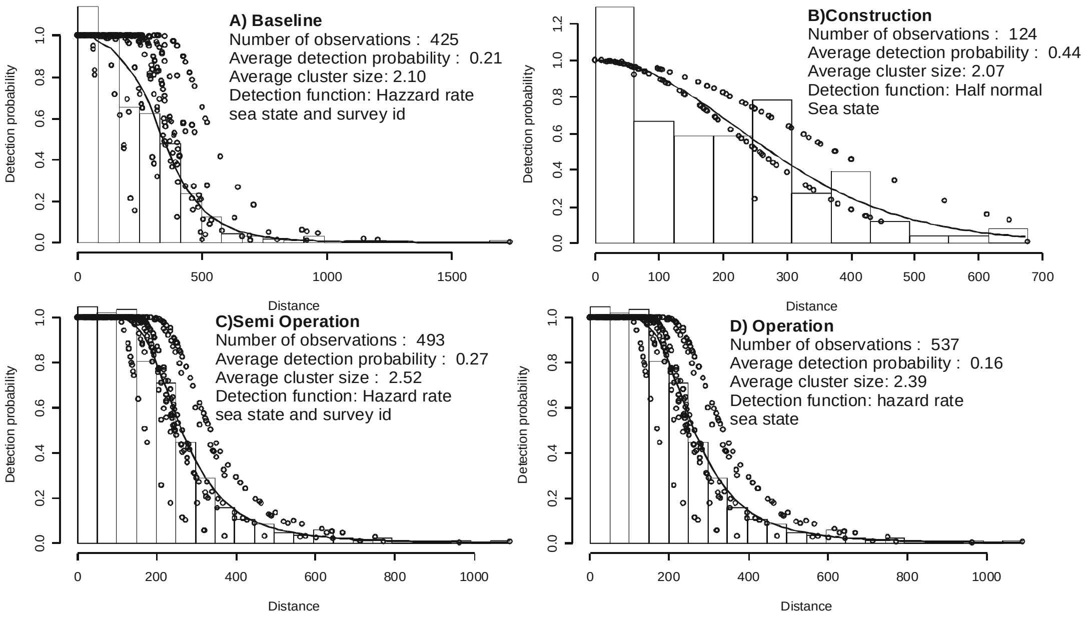


Figure 26 **Average detection functions for the four periods of the study. Indicated for each period are additional variables with explanatory power on the detection function. Note the different x-axes.**

3.1.1 Detection functions

Figure 26 shows average detection functions for the four periods. Sea state was selected as an important detection function covariate in all four groups of surveys (baseline, pile driving, semi-operation, and operation). Survey ID was selected as an important covariate only in baseline and semi-operation surveys. However, in all 4 survey periods, both sea state and survey id were supported only slightly less by the data, as indicated by delta AIC values less than 2, i.e. the model performed only marginally better by inclusion of the variables Average effective strip half-width was approximately 300 m for all surveys. Average cluster size was lowest during construction (2.07) and highest during the semi-operation period (2.52) .

3.1.2 GAM count model

Based on forward-backward stepwise selection based on F-test criteria, the most parsimonious GAM models were selected for each survey with more than 30 observations. Various combinations of tidal phase, salinity, temperature and bathymetry were selected as significant predictors in each of the surveys (Table 3). In all but one survey at least one geographical variable (easting or northing) was selected as significant. The proportion of total deviance explained by the models ranged from 14% (survey 23) to 49% (survey 11 and 26).

Table 3 Results of GAM model selection for all analysed surveys. Indicated for each survey is the p-value for each of the tested predictors. Correlation and D^2 expresses goodness of fit of model predictions to data. n/a = data not available ns = not significant at 0.05 or below.

Period	ID	Date (YY/MM)	Easting	Northing	Tidal phase	salinity	temperature	bathymetry	correlation	D^2
Baseline	1	99/09	0.00003	0.00002	0.00000	n/a	0.00729	0.00009	0.546	0.296
	2	00/07	0.00005	0.00001	ns	n/a	ns	0.00008	0.419	0.275
	3	00/08	0.00195	0.00533	0.00266	n/a	0.01677	ns	0.382	0.292
	4	01/08	0.00009	0.00000	ns	ns	0.00007	ns	0.433	0.268
	5	01/08		0.01498	0.01462	0.03228	0.00000	0.03154	0.514	0.383
Construction	7	02/03	0.00001	0.00004	ns	n/a	ns	ns	0.370	0.212
	8	02/04	0.00099	0.00041	ns	0.04111	ns	ns	0.446	0.342
	11	02/07	0.00546	0.00891	ns	0.00002	ns	0.00070	0.638	0.492
Semioperation	16	03/07	ns	ns	0.00002	n/a	0.00000	ns	0.270	0.187
	17	03/08	0.00006	0.00000	ns	n/a	ns	0.03028	0.321	0.154
	18	03/08	0.00027	0.00000	ns	ns	0.00203	0.00017	0.553	0.309
	19	03/10	0.00052	0.00000	ns	n/a	ns	ns	0.398	0.264
	21	04/04	0.00392	ns	0.00571	0.00251	0.00051	ns	0.414	0.285
	22	04/08	ns	0.00000	ns	0.00012	0.00335	ns	0.359	0.227
Operation	23	05/06	0.00882	0.00000	0.00008	ns	ns	0.03637	0.295	0.138
	24a	05/06	0.00001	ns	0.00089	ns	0.00137	ns	0.348	0.238
	24b	05/07	0.00002	ns	ns	ns	0.00105	ns	0.288	0.202
	25	05/08	0.00000	0.00000	0.02555	0.00016	0.00806	0.03312	0.563	0.399
	26	05/10	0.00004	ns	0.00002	0.00000	0.00004		0.599	0.484
	27	05/11	0.00001	0.00000	0.00000	n/a	0.00000	0.00170	0.562	0.463

The relationship between porpoise density and each predictor shifted between surveys, with response shapes showing increasing, decreasing, or complex relationships. One example is shown in *Figure 27*, were response curves for significant predictor variables (F-test P< 0.05) from survey 18 are pictured. In this case, the significant variables were easting, northing, temperature and bathymetry (water depth). In this example there were peaks in densities at intermediate values of easting and northing, indicating that observations were aggregated towards the centre of the survey area. A positive correlation was found with temperature and a negative correlation with bathymetry, indicating that observations were predominantly in warmer, shallower areas of the survey area. Response curves for all modelled surveys are shown in Appendix D.

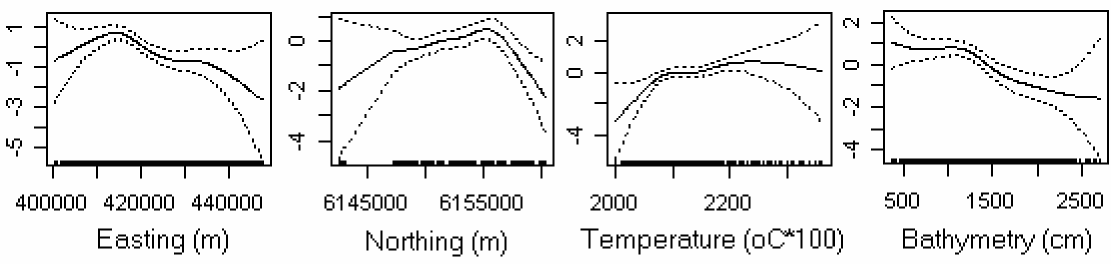


Figure 27 **Example of significant correlations with predictor variables from survey 18. Significant variables were easting, northing, temperature and bathymetry. Y axis represents porpoise density in normalised units (prior to back-transformation). Dotted lines indicate 95% confidence intervals. Overall explained variance was 31%.**

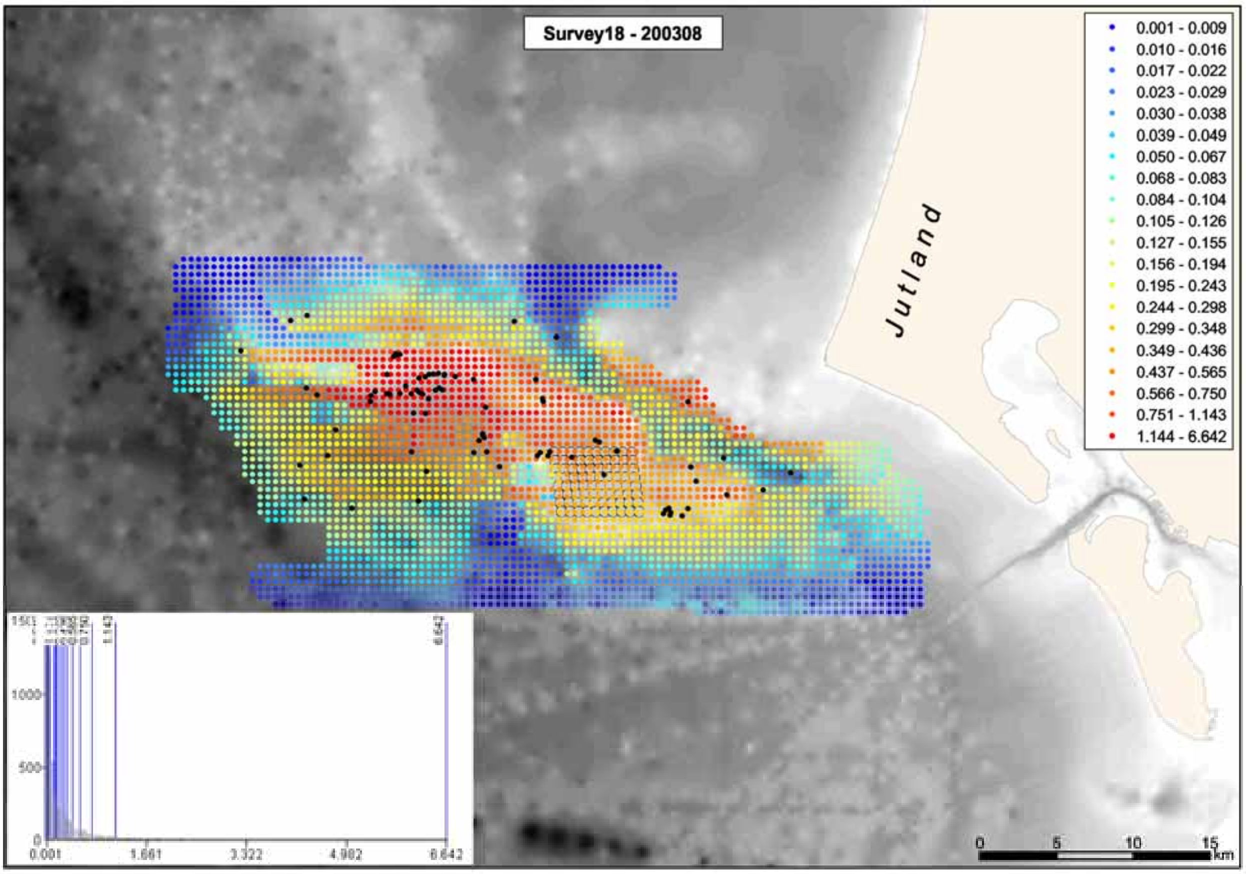


Figure 28 **Map of predicted density of porpoises during survey 18 (semi-operation), based on the correlations shown in** *Figure 27*. **Red areas indicate high porpoise density and blue areas low density. Unit in legend is porpoises/km^2. Black dots indicate actual observations of porpoises on the survey. Insert lower left shows distribution of densities across all grid cells in the survey area (dotted area in map), with porpoise density on x-axis and number of grid cells on y-axis.**

Using the selected model and GIS maps of covariates we generated a spatial prediction of porpoise density ofr each survey. One example is shown in *Figure 28*, based on the response functions in *Figure 27*. Highest densities on this survey were predicted in the central part of the outer reef and along the eastern edge of Slugen, with densities dropping towards deeper areas to the north, west and south. Predicted maps from all modelled surveys are shown in appendix D.

No consistent pattern was observed in the correlations across surveys. There was a high variation in what parameters came out significant and the direction of the predicted responses. There were thus no clear patterns in the distribution, neither seen across all surveys or from period to period.

3.1.3 BACI analysis on densities from surveys

The analysis of the density model showed significant variations between the four periods ($F_{3,48}$=20.50; p<0.0001) and significant variation between cruises ($F_{16,48}$=20.50; p=0.0325), whereas variations between areas ($F_{3,48}$=2.04; p=0.1203) and the overall interaction between area and period ($F_{9,48}$=1.53; p=0.1651) were not significant. The estimated mean densities for the different combinations of area and period indicated similar levels for all 4 areas in all periods except the construction period, where a declining gradient from the outer reference area to the impact area was observed (*Figure 29*).

Table 4 shows tests of contrasts from the BACI-analysis, where the impact area (wind farm) was compared to each of the three reference areas individually, instead of the mean, as in the general BACI-analysis. Significant changes between periods were only observed when comparing the impact area with the outer reference area and only the construction period differed. The significant contrasts showed a decline in mean density (factor of 8.8) from baseline to construction in the impact area relative to reference area A. From construction to semi-operation the mean density increased (factor of 4.8) in the impact area relative to reference area A, whereas there was a relative increase (factor of 4.4) from construction to operation. The highest densities were observed in the operation period, followed by baseline, semi-operation and construction period having the lowest density (*Figure 29*). In other words, there was a significant decline in the density of porpoises inside the wind farm during construction, when compared to the reference area furthest away from the wind farm.

Table 4: **Test of contrasts from the BACI analysis for combinations of periods (baseline, construction, semi-operation, and operation) and area (reference A, B, C versus impact). Significant contrasts (*p*<0.05) are highlighted in bold.**

BACI contrast		Impact area versus		
Period 1	Period 2	Reference A	Reference B	Reference C
Baseline	Construction	**0.0024**	0.0767	0.7469
Baseline	Semi-operation	0.2889	0.4700	0.7750
Baseline	Operation	0.2226	0.7114	0.7991
Construction	Semi-operation	**0.0211**	0.2192	0.9293
Construction	Operation	**0.0294**	0.1277	0.9081
Semi-operation	Operation	0.8647	0.7104	0.9738

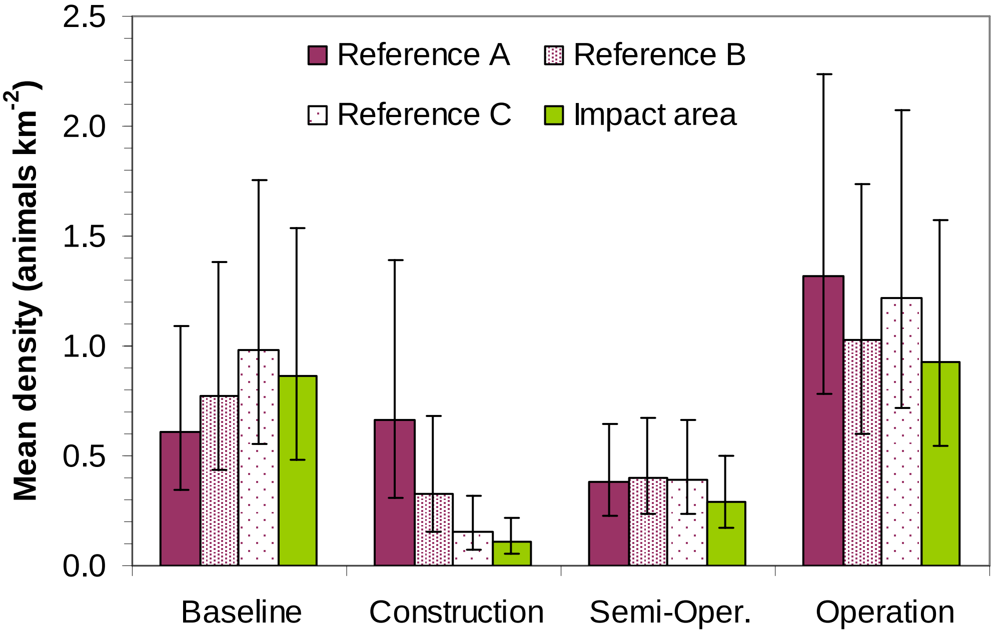


Figure 29 **Estimated mean densities for combinations of the 4 areas and 4 periods. Error bars show the 95% confidence intervals for the estimated mean densities.**

3.2 Line transect surveys – aerial

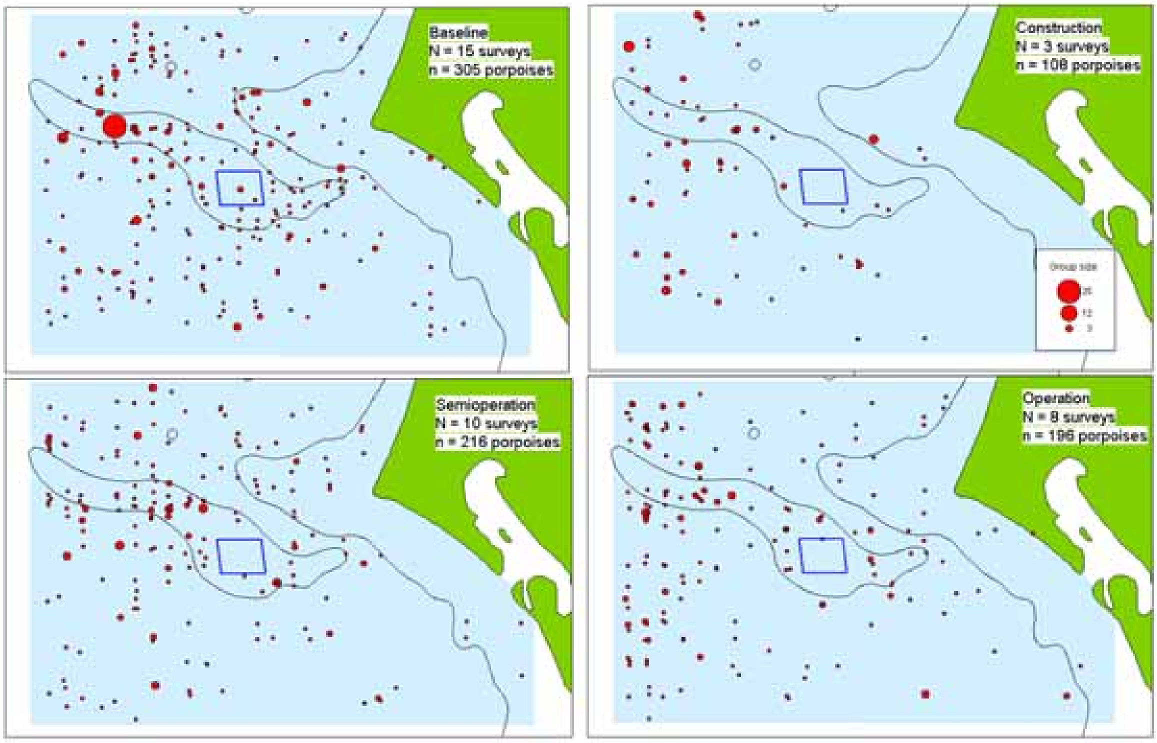


Figure 30 **Maps showing porpoise sightings on aerial surveys, separated into baseline, construction, semi-operation and operation periods. Blue area indicates extent of survey area.**

In total 36 aerial surveys were conducted from 1999 to 2006. On average 23 porpoises were observed per survey, evenly distributed over the four periods (baseline, construction, semi-operation and operation). Average group size was 1.27 and only 7 surveys had 30 sightings or more and consequently no spatial modelling was performed on the data. Figure 30 shows all sightings divided into the four periods. Three sightings were made within the wind farm area, two during baseline and one during operation, too little to justify statistical testing of differences between periods. Although not statistically tested, the aerial observations appear to be more evenly distributed over the survey area than the ship observations (compare maps in *Figure 24* and *Figure 30*).As in the ship survey data there was a large survey to survey variation (lowest count per survey 2 sightings, highest count 74 sightings). The variation across months of the year was consistent however, displaying a peak in late summer and very few sightings during winter months (*Figure 31*).

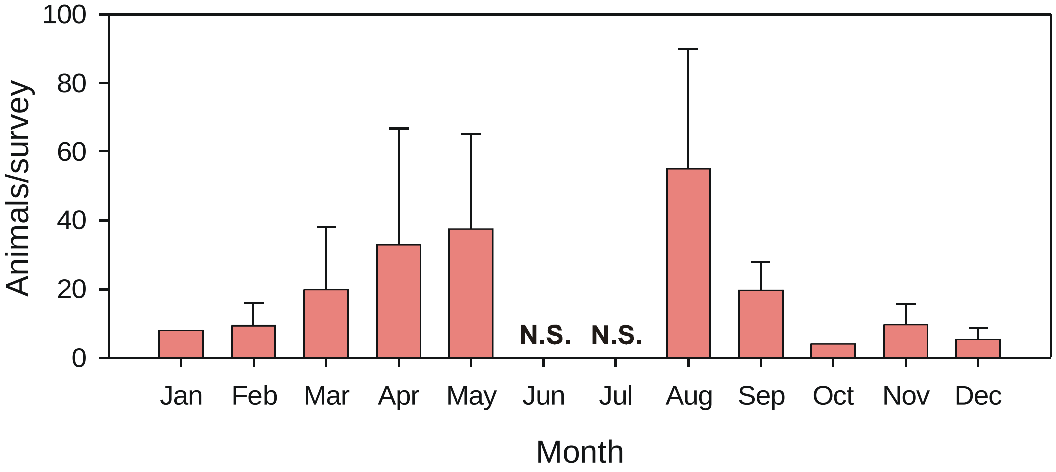


Figure 31 **Annual variation in porpoise sightings on aerial surveys. Mean over all surveys across all periods from 1999 to 2006. Between one and six surveys per month. No surveys were conducted in June or July, indicated by N.S. Error bars indicate standard deviation.**

3.3 Acoustic dataloggers

Deployments of T-PODs at Horns Reef and data obtained through the entire monitoring period are shown in *Table 5*.

From July 10th 2001 to December 26th 2005, 20 different T-PODs (10 version 1 and 10 version 3) were deployed in the impact and reference area. Five of the 6 channels for these T-PODs were configured for recording porpoise clicks. The 4 indicators were calculated from time series of the average number of clicks over a 1 minute cycle covering these 5 channels. An example of indicator calculation is shown in *Figure 23*. The total number of observations and time series plots of the 4 indicators for all 6 stations covering the entire period are given in Appendix F. There were a total of 3.35 million 1-minute recordings out of which 182,534 minutes were positive (~5.5%).

Calculating indicator observations from the 1-minute recordings resulted in 2231 values of clicks/PPM, 2305 PPM and over 36000 single encounters and waiting times. These dates were unevenly distributed between stations (Appendix F). There were relatively few successful deployments in the baseline period (187 days) and construction period (294 days) periods compared to the semi-operation and operation periods (975 and 849 days, respectively). These days of deployments resulted in 1690, 2638, 10817 and 21191 encounters during the baseline, construction, semi-operation and operation periods, respectively. Due to the large amount of encounters and the complexity of the model, encounter duration and waiting times were aggregated to daily values by averaging before the BACI analysis.

Monthly averages for the wind farm and reference area were of similar magnitude and partly showed the same trend through the entire study period (Figure 32A). Daily PPM also showed similar levels in the two areas except for the operation period when the high echolocation activity recorded at Pos. 3 resulted in high PPM levels for the reference area (Figure 32B). Similar results were observed for encounter duration, which were also relatively longer in the operation period at Pos. 3 (Figure 32C). Average waiting times were typically about 2 hours during baseline, construction and semi-operation in both areas, but were lower in the operation period (Figure 32D).

Table 5 **Overview of deployments of T-PODs, separated on years and stations and number of days with usable data. Stations 2 and 8 were removed from analysis, due to the low amount of data. These stations are also removed from the calculation of overall efficiency of data collection at the bottom of the table.**

Station		2001	2002	2003	2004	2005	Grand Total
1	Days with data	36	132	57	66	63	354
	Deployment days	184	277	246	168	126	1001
2	Days with data		0				0
	Deployment days		25				25
3	Days with data	25	23	8	73	249	378
	Deployment days	155	227	94	98	284	858
4	Days with data		0	4	17	64	85
	Deployment days		96	94	98	64	352
5	Days with data	47	11	172	88	312	630
	Deployment days	113	250	328	168	317	1176
6	Days with data	94	30	31	0	48	203
	Deployment days	234	263	277	70	228	1072
7	Days with data	0	130	259	157	102	648
	Deployment days	95	220	304	168	181	968
8	Days with data	63					63
	Deployment days	232					232
Total days with data		265	326	531	401	838	2361
Total deployment days		1013	1358	1343	770	1200	5684
Available days*		1050	1636	1636	652	1636	6610
Deployment %*		74.4	81.5	82.1	118.1	73.3	82.1
Data/deployment %*		25.9	24.5	39.5	52.1	69.8	42.3
Data/Total %*		19.2	19.9	32.5	61.5	51.2	34.8

3.3.1 Wind farm relative to reference area

Nine of the 20 T-PODs used in the entire study were deployed in the impact area (Pos. 5 and 6) and 13 T-PODs were deployed in the reference area (Pos. 1, 3, 4 and 7). Two T-PODs were deployed in both impact and reference areas. During the baseline and construction periods all T-PODs were version 1 with internal transducer, but these were gradually replaced during the semi-operation and operation periods with version 3 with external transducer. Moreover, two T-PODs were modified versions (POD11 and POD270). Although the monitoring program suffered substantial losses of data leading to a highly unbalanced dataset, the deployments were overlapping and the factors of the BACI analysis were not confounded. Particularly, the monitoring activities in 2005 improved the estimation of the common seasonal variation imposed to all years of the study period.

Initially the BACI analysis was carried out with all 7 fixed factors of the model, but pod-type(transducer) was not significant for any of the four indicators (p=0.3216 for daily click PPM, p=0.5965 for daily PPM, p=0.5174 for encounter duration and p=0.3273 for waiting time) and the model was therefore reduced by taking this factor out and re-examine the model, i.e. no systematic variation in T-PODs across version.

The T-POD specific variation (random effect) was significant for three out of the four indicators (p=0.0158 for click PPM, p=0.0050 for PPM, p=01194 for encounter duration, and p=0.0203 for waiting time), whereas the transducer type (internal/external) was significant relative to the ran dom residual and T-POD specific variation for waiting time only (*Table 6*). Moreover, there were significant correlations between successive observations (p<0.0001 for all indicators). The fixed factors of the model mainly indicated significant temporal variations for all indicators (*Table 6*).

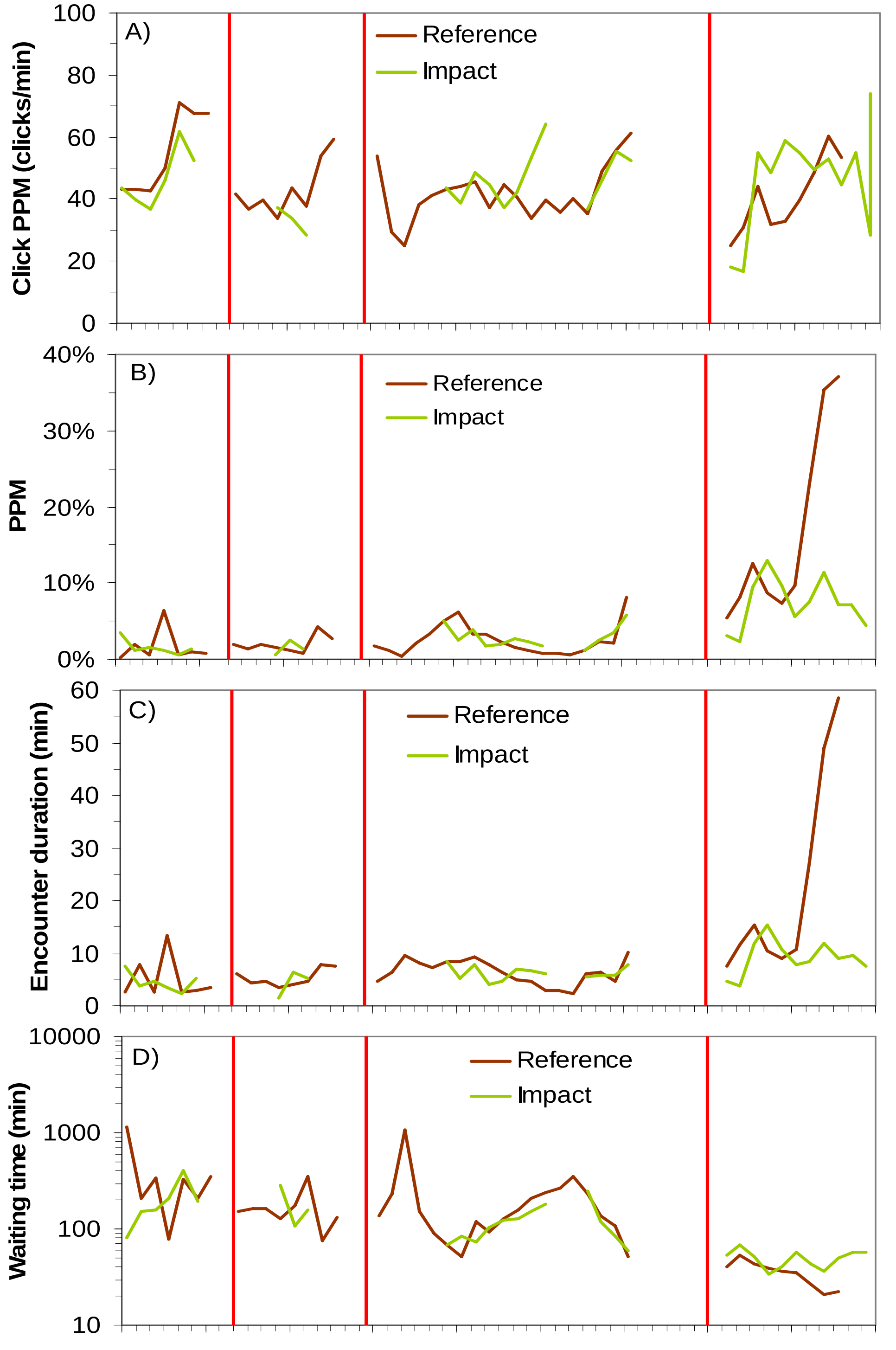


Figure 32 **Monthly averages of the 4 indicators for the control and reference area. Note the log-scale on the y-axis for waiting time.**

Spatial variation between the two areas was significant for encounter duration only, with encounter being 53% longer in the reference area throughout the entire period (*Table 6*). There was no significant variation between stations within the two areas for any of the four indicators. All four indicators had a significant seasonal variation and significant variation between periods, but only for daily PPM were the period variations different between areas (*Area×period*).

Table 6 **Test of fixed factors in the model for the four indicators of porpoise echolocation activity. Significant factors (p<0.05) are highlighted in bold.**

	Test for fixed factors in model					
Indicator variable	*Area*	*Station (area)*	*Period*	*Month*	*Area×period (BACI-effect)*	*Transducer*
Daily clicks / PPM	0.0740	0.2896	**0.0050**	**<0.0001**	0.2201	0.4260
Daily PPM	0.2700	0.5652	**<0.0001**	**<0.0001**	**0.0013**	0.1362
Encounter duration	**0.0283**	0.1417	**0.0453**	**0.0259**	0.9473	0.0890
Waiting time	0.2683	0.7950	**0.0116**	**0.0002**	0.6824	0.0368

The clicks / PPM means over the entire period were 43.1 and 36.2 clicks per minute for the reference and impact area, respectively (*Figure 33*). Click PPM was highest during baseline (50.8 clicks per minute) decreasing to levels between 34 and 40 clicks per minute thereafter. The higher clicks / PPM in the reference area was persistent throughout the entire study period, and therefore no significant change occurred for *area×period*. However, the BACI contrasts revealed a relative increase of 31% in click PPM in the impact area from semi-operation to operation (*Table 7*). This significant contrast was caused by a 34% decrease in click PPM in the reference area, whereas click PPM remained at the same level from semi-operation to operation. There was no relative change between the two areas from baseline to operation.

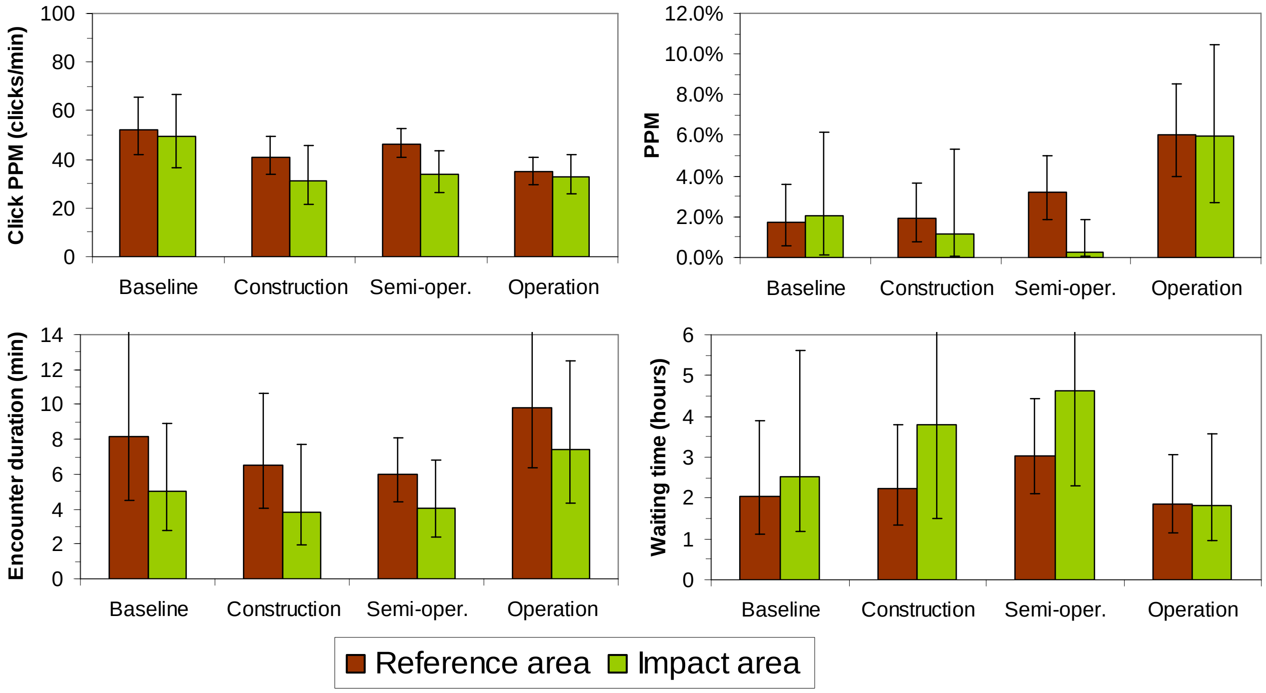


Figure 33 **Mean values for combinations of area and period back-transformed to the original scale for combinations of the two areas (control and impact, combined and separately) and the four periods (baseline, construction, semi-operation, and operation). Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in** *station* **and** *month* **have been accounted for by calculating marginal means.**

The daily PPM was slightly higher in the impact area during the baseline period (mean of 29.9 minutes with porpoise clicks per day compared to25.3 in the reference area), whereas PPM was higher in the reference area in the following periods (*Figure 33*). Daily PPM was particularly low in the impact area during the semi-operation period (mean of 4.1 minutes with clicks). PPM levels for both areas combined were comparable for the baseline, construction, and semi-operation periods (20-28 minutes with clicks), but during the operation period PPM increased to 86 and 87 in the impact and reference area, respectively. Although there were some gradual shifts in PPM between the two areas in the first three periods, only the relative change from semi-operation to operation was significant (*Table 7*). Thus, although PPM increased by 87% from semi-operation to operation in the reference area, the increase in the impact area was much larger (factor of 21). There was no relative change between the two areas from baseline to operation.

Table 7 **Test of contrasts from the BACI analysis for combinations of periods (baseline, construction, semi-operation, and operation). Significant contrasts (p<0.05) are highlighted in bold.**

BACI contrast		Significance of contrasts for indicators			
Period 1	Period 2	Click PPM	PPM	Encounter duration	Waiting time
Baseline	Construction	0.3880	0.5639	0.9372	0.5992
Baseline	Semi-operation	0.2708	0.0838	0.8389	0.7452
Baseline	Operation	0.9553	0.8652	0.6441	0.6957
Construction	Semi-operation	0.8461	0.2694	0.7817	0.8540
Construction	Operation	0.3614	0.6943	0.5994	0.3781
Semi-operation	Operation	**0.0496**	**<0.0001**	0.7715	0.3044

Mean encounter durations were consistently higher in the reference area (7.5 minutes) than in the impact area (4.9 minutes) (*Table 6*). Levels slowly declined from 6.4 minutes to 4.9 minutes during baseline, construction and semi-operation, but increased to a mean of 8.5 minutes during operation (*Figure 33*). The trends were comparable in the two areas. There was no relative change between the two areas from baseline to operation.

For all four period the mean waiting times were 2.3 and 3.0 hours in the reference and impact area, respectively. Waiting times were longer in the impact area for all periods except the operation period (*Figure 33*). Mean waiting times were 2.3 hours during baseline increasing to 2.9 and 3.7 hours during construction and semi-operation, and then decreasing to 1.8 hours during operation. The trends were comparable for the two areas with no significant relative shifts in the mean levels between periods (*Table 7*). There was no relative change between the two areas from baseline to operation.

All indicators had a significant seasonal variation (*Table 6* and Figure 34). The estimated seasonal variation was used to compare the different periods such that observations were compared across the same months. Mean click PPM varied from 24 to 49 clicks per minute with the lowest values in February and March. Mean PPM were low in January-March (ca. 0.6-1.1%) peaking in September with a mean of 3.1%. Encounter duration was similarly low during January-March (means between 4.4 and 5.3 minutes), whereas it varied from 6.4 to 9.9 minutes for the rest of the year with the longest encounters in September. Mean waiting times were longest in January (2.3 hours), gradually decreasing to less than 1 hour in September and then increasing again towards the end of the year. In general, there was a pronounced seasonal pattern with the lowest echolocation activity during winter and high echolocation activity during late summer.

3.3.2 Diurnal patterns in encounter distribution

Encounters mark points in time when environmental conditions seem to favour the presence of harbour porpoises. In the following the distribution of encounters during the day as well as for wind speed is investigated for the different areas and periods.

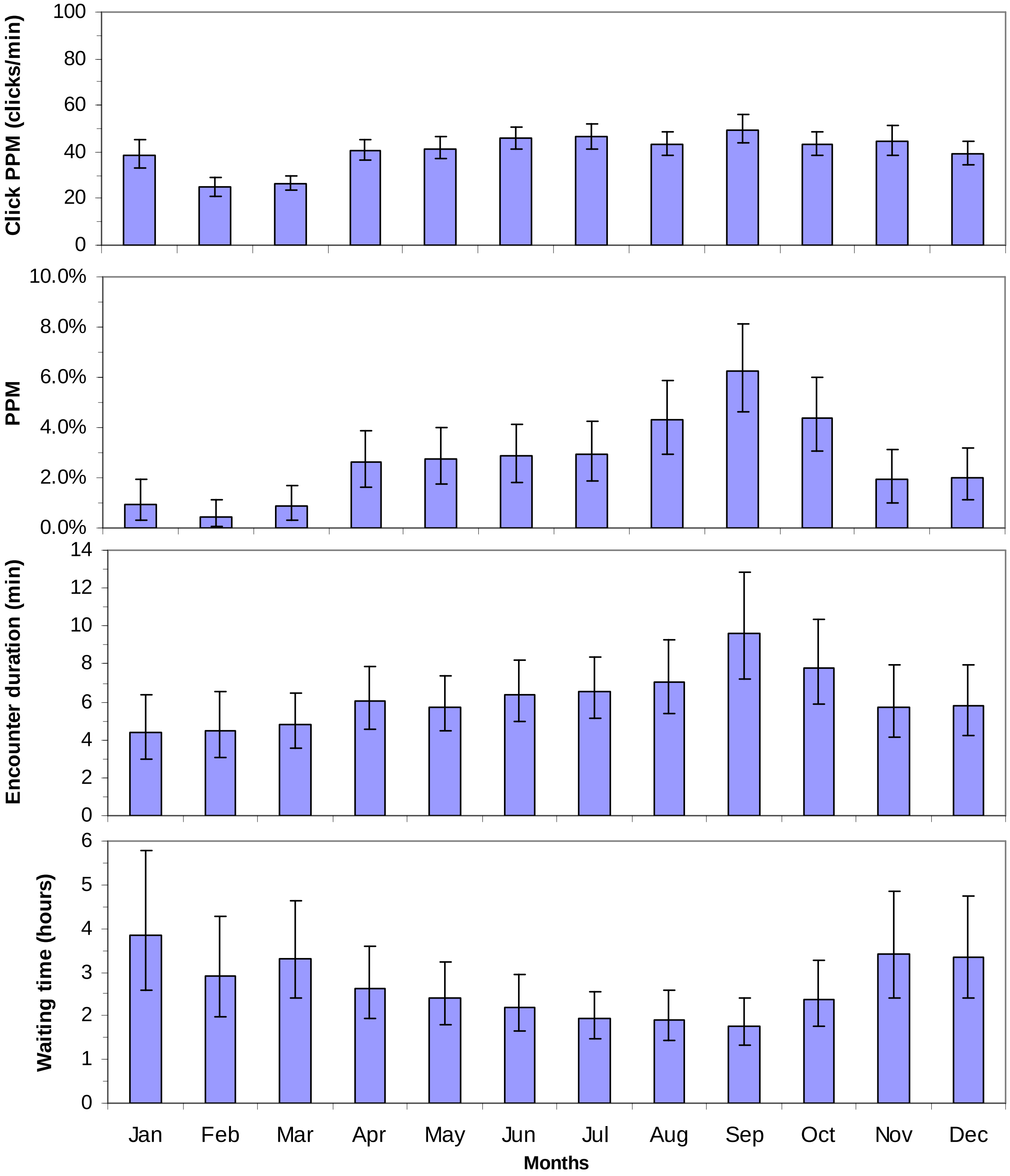


Figure 34 **Seasonal means for the four indicators after back-transformation. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in *area, station, period* and *area×period* have been accounted for by calculating marginal means.**

During baseline significant and similar diurnal patterns with most encounters during daytime were observed for the reference and impact area (*Figure 35*). This pattern did not change during construction in the reference area, whereas the number of encounters in the impact area was rather limited. A pronounced diurnal pattern with most encounters during daytime was seen in the reference area during semi-operation, which was in contrast to the diurnal pattern in the impact area with most encounters night-time. During operation a uniform distribution of encounters was found in both areas (*Figure 35*). The T-PODs were logging continuously for long periods and the different hours of the day were therefore monitored equally well.

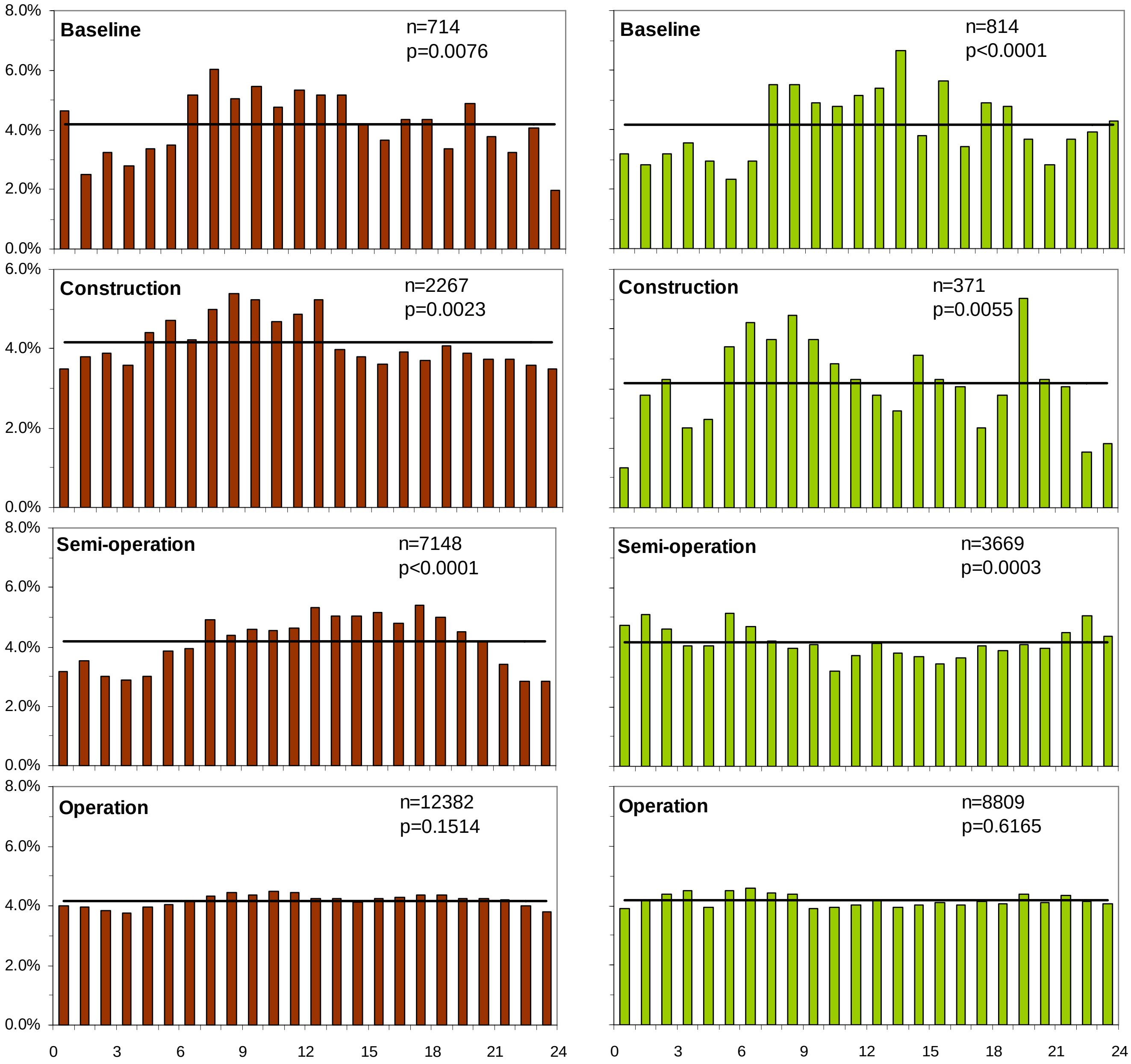


Figure 35 **Distribution of encounters over the day in the reference area (left panel) and impact area (right panel) for the four periods. For each graph n=number of encounters and p=probability of equal distribution over all hours of the day. Vertical lines show the uniform distribution of encounters for comparison.**

Testing differences between the reference and impact areas for each single month of monitoring, there were 6 months (1 from baseline and 5 from semi-operation) with significantly different diurnal patterns. Those months with the most encounters (>500) showed a typical diurnal pattern with most encounter during daytime in the reference area, whereas most encounters were observed during night-time in the impact area (*Figure 36*).

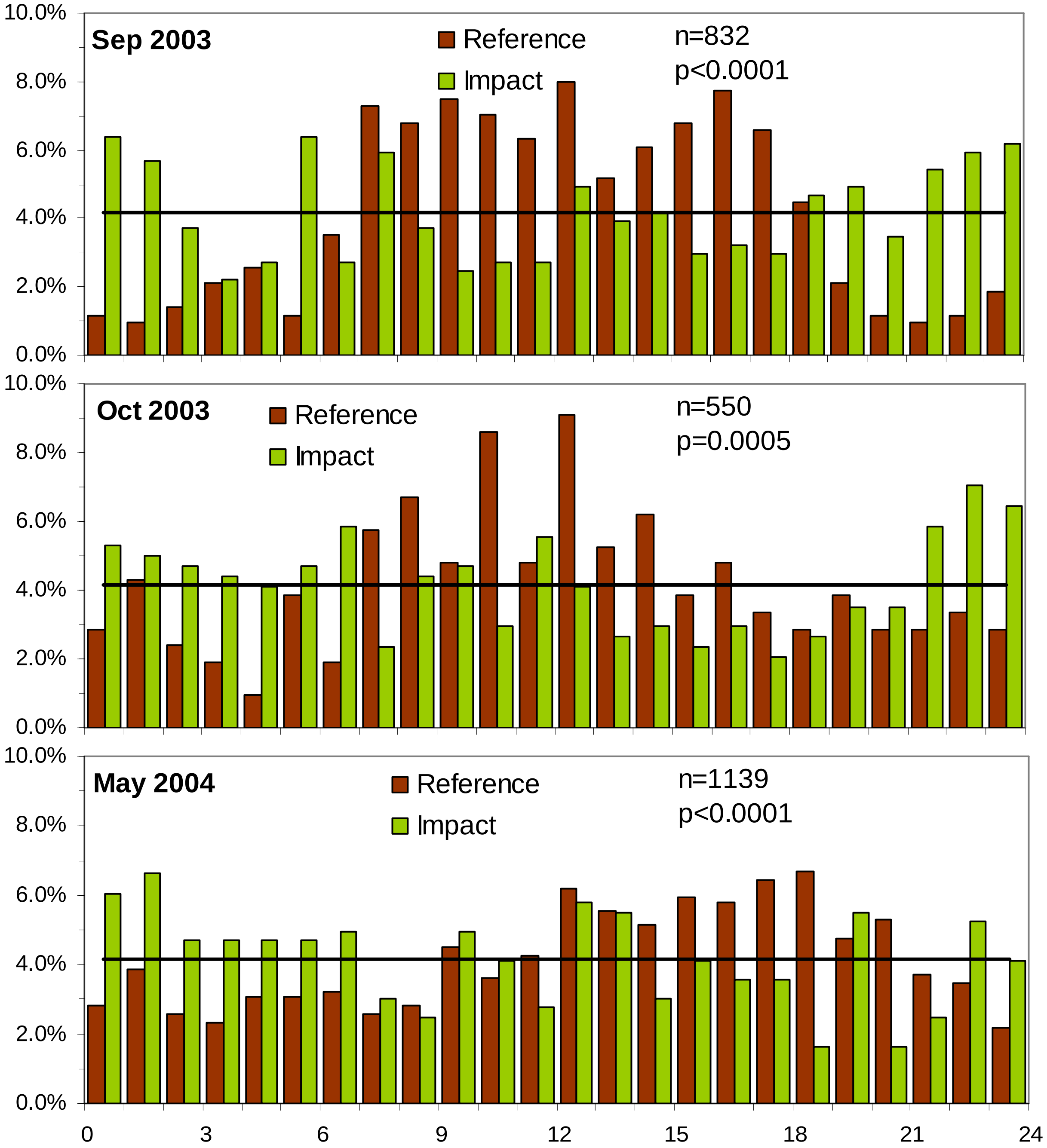


Figure 36 **Encounter distribution for specific months with >500 encounters and significantly different diurnal patterns between reference and impact area. n is the total number of encounters and p is the probability that the two distributions are equal. All data from semi-operation period.**

3.3.3 Effect of pile driving activities

Between March 30th and August 1st 2002, the period with pile driving operations, three T-PODs were logging harbour porpoise echolocation activity. Pile driving typically lasted 1-2 hours per foundation and the waiting time associated with each pile driving was identified. The waiting time after pile driving had ceased were significantly longer (p<0.0001 for all three positions) than all other waiting times in the same period (Figure 37). Mean waiting times increased from 2.9 to 8.0 hours at Pos. 1., from 1.9 to 5.6 hours at Pos. 6, and from 2.5 to 8.1 hours at Pos. 7. The increase in waiting time was longer than the average time used for pile driving and not specific to the impact area only. Most noteworthy is that the magnitude of the response did not diminish with distance from the construction site.

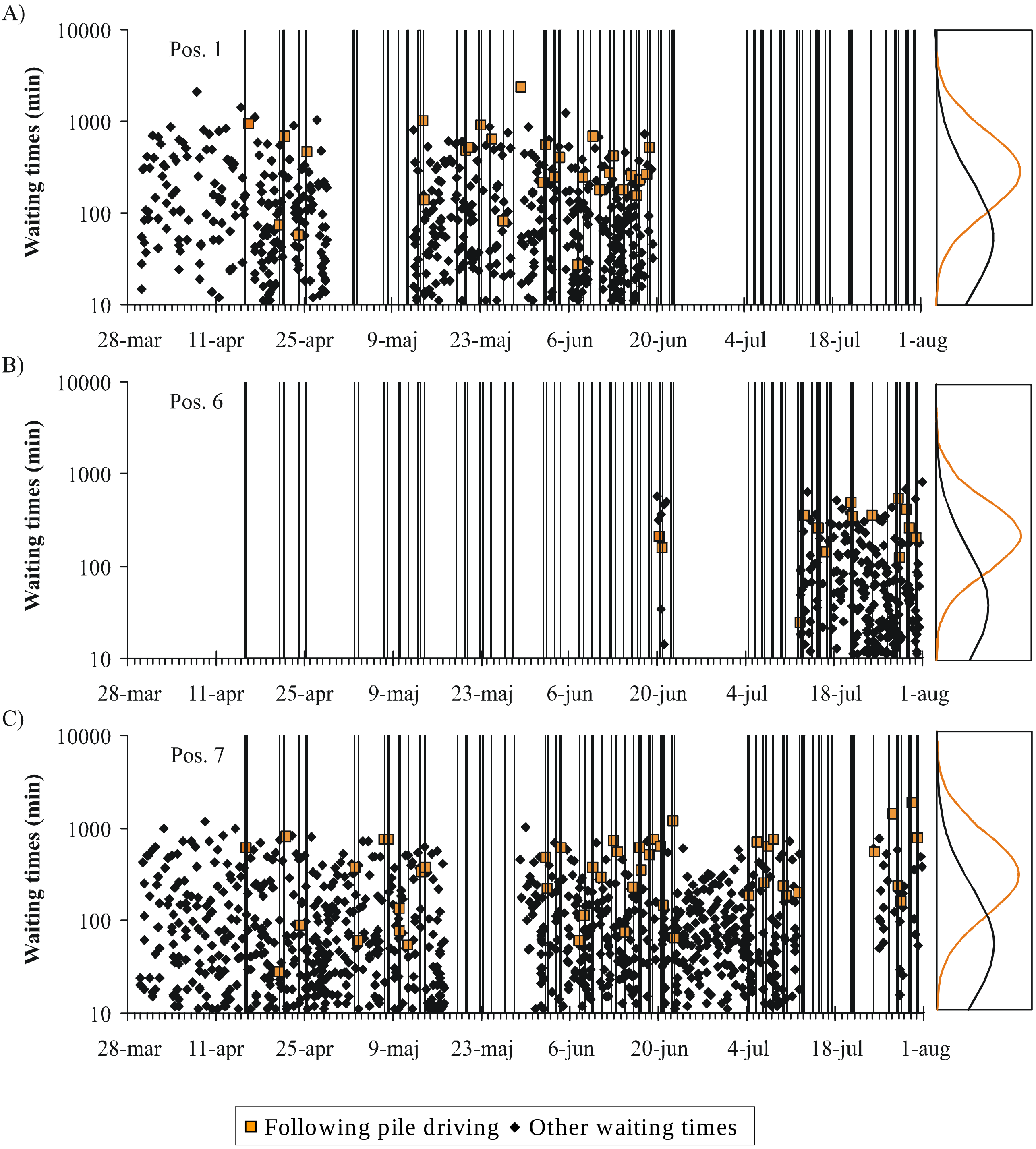


Figure 37 **Waiting times (symbols) at the three stations in the period of pile driving activity at Horns Reef. Note the logarithmic scale. The timing of the pile driving activities is indicated by vertical lines. For 12 turbine positions the exact time of pile driving activities was not known. The distribution of waiting times following pile drivings and outside pile drivings are shown to the right with orange and black, respectively.**

3.3.4 Echolocation activity in relation to wind

The wind distribution when encounters were logged by the T-PODs deviated significantly from the overall wind distribution for all periods and areas with more encounters recorded during windy conditions (*Figure 38*). This pattern was most pronounced during baseline in both areas. In general, winds <6 m s^{-1} had fewer encounters, winds between 6 and 10 m s^{-1} had similar encounter distributions, and winds above 10 m s^{-1} gave more encounters.

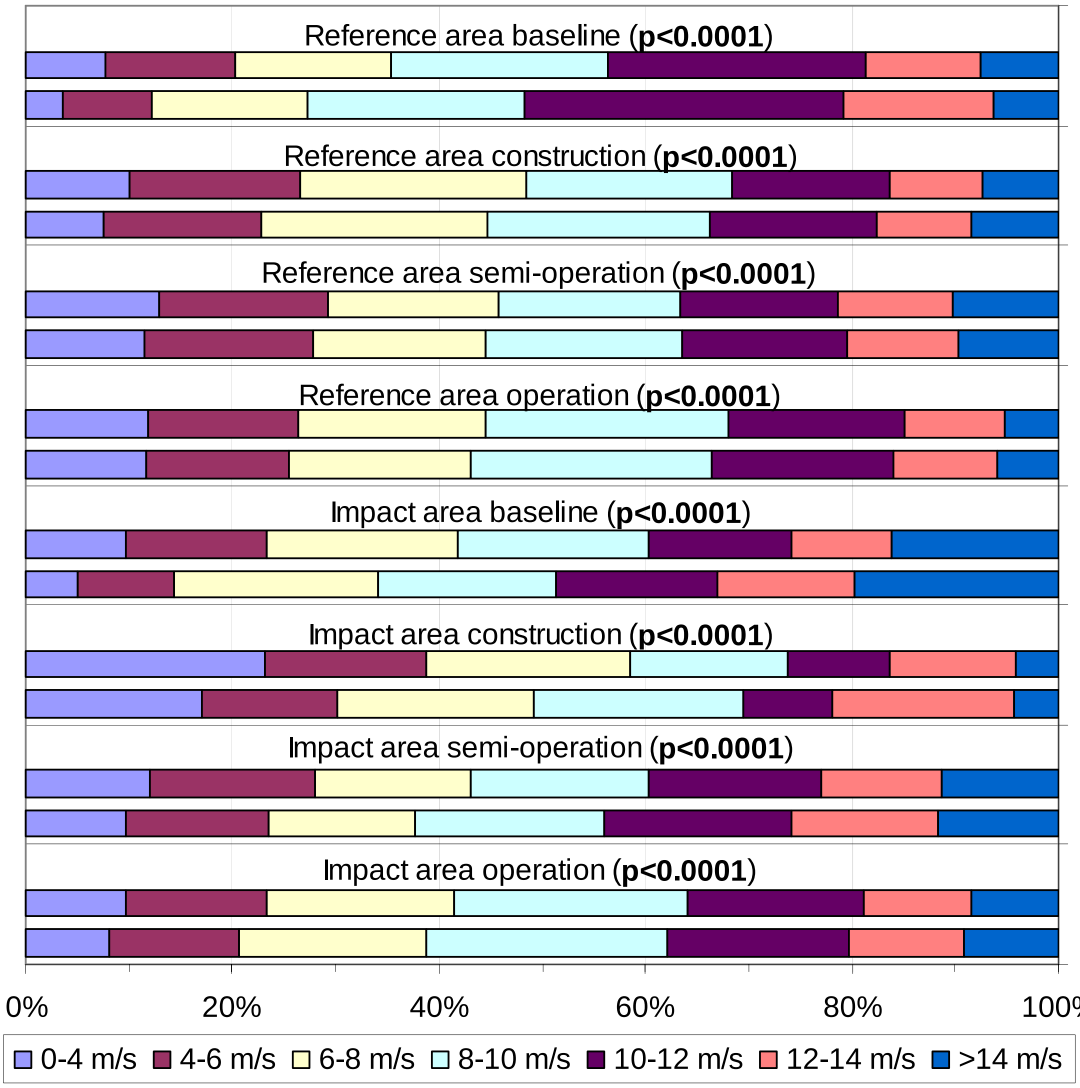


Figure 38 **Distribution of wind speed in general (top) and for encounters (bottom) for each area and period. Probabilities for testing if the wind distribution during encounters is equal to the overall wind distribution are given in parentheses.**

The potential covariation of the indicators to wind was investigated from time series of wind speed, obtained from the wind gauge located in the wind farm area. Daily averages of the wind speed were combined with daily click PPM and PPM. Encounter duration was combined with the average wind during the specific hour of the encounter. Waiting times were not combined with the wind data, since it was difficult to characterise wind speed with a single number for long silent periods. Moreover, averaging wind speed over long periods has an adverse effect resulting in average values for wind only, i.e. long waiting times (several days) will be associated with average wind conditions. Including wind as an additional variable (including *area×period×wind* as a covariate) it was investigated if the echolocation activity was related to wind speed and if the relationship differed between areas and periods. The wind speed was partitioned into 7 different categories (0-4 m s^{-1}, 4-6 m s^{-1}, 6-8 m s^{-1}, 8-10 m s^{-1}, 10-12 m s^{-1}, 12-14 m s^{-1}, and >14 m s^{-1}).

There was a significant effect of wind (*area×period×wind)* on click PPM (p<0.0.0001), PPM (p<0.0.0001), and encounter duration (p=0.0193). The effect of wind on echolocation indicators were most pronounced in the reference area, whereas there was a significant effect of wind in the impact area for click PPM only (*Table 8*). In the reference area when the effect of wind was significant, echolocation activity typically increased with wind speed up to 10-12 m s^{-1} and then declined (*Figure 39*). In the impact area the two periods with significant effect of wind both showed an increasing echolocation activity with wind speed (data not shown). There were no similarities in the wind speed relationships between the two areas.

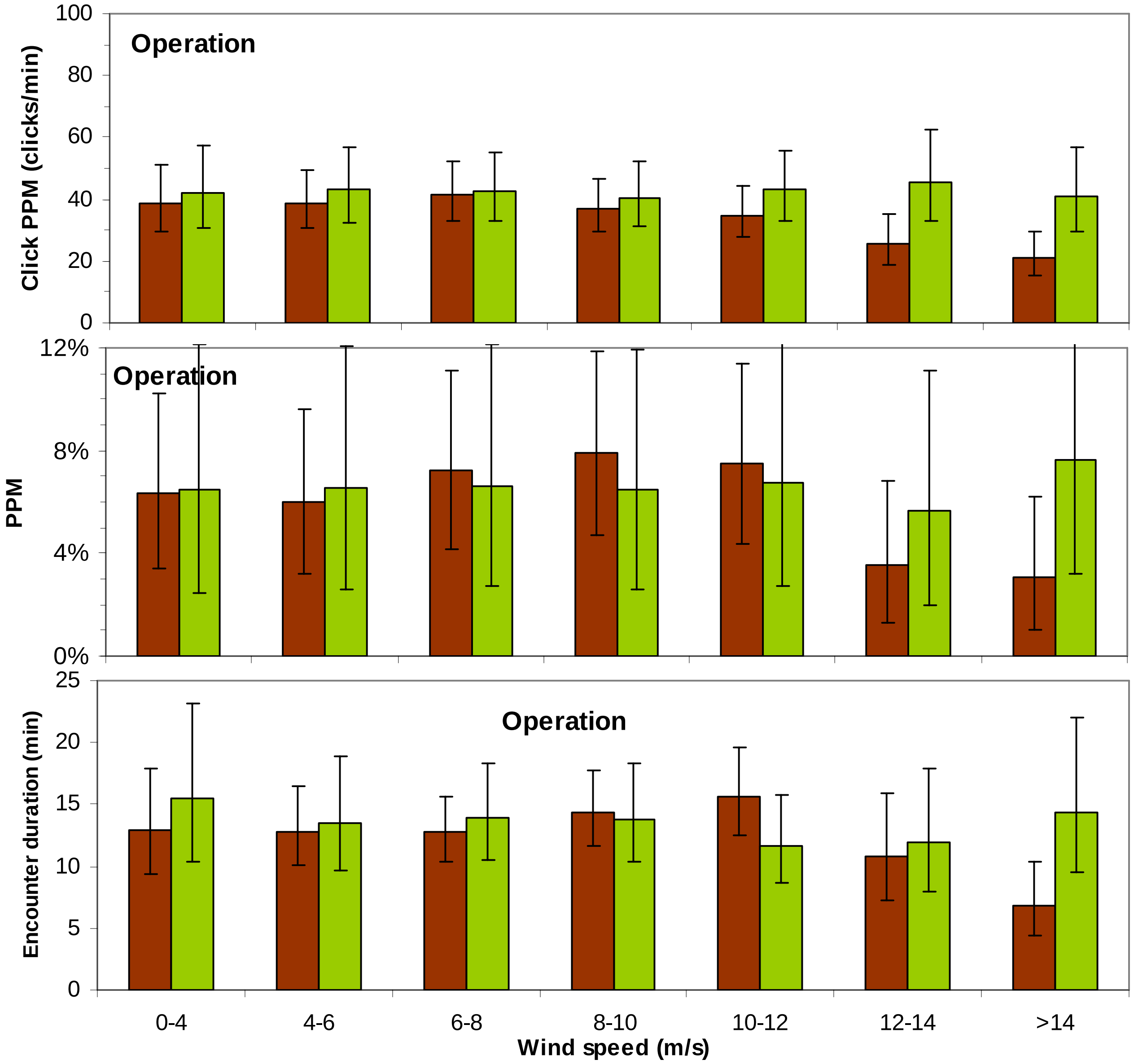


Figure 39 **Distribution of daily click PPM, daily PPM and encounter duration for different wind speeds in the reference and impact areas during the operation period. Error bars indicate 95% confidence limits for the mean values. Variations caused by differences in area, station, period, month and area×period have been accounted for by calculating marginal means.**

Table 8 **Test for wind-specific relationship of click frequency and encounter duration for different periods and areas. Significant relationships (*p*<0.05) are highlighted in bold.**

Period	Reference area			Impact area		
	Click PPM	PPM	Encounter duration	Click PPM	PPM	Encounter duration
Baseline	0.9203	**0.0239**	0.1345	**0.0006**	0.1296	0.2513
Construction	**0.0050**	0.2584	0.8974	0.0581	0.4625	0.7541
Semi-operation	**0.0036**	0.1342	**0.0074**	**0.0385**	0.0611	0.2191
Operation	**<0.0001**	**<0.0001**	**0.0056**	0.9745	0.7273	0.7407

4 Discussion

The monitoring program at Horns Rev Offshore Wind Farm, initiated in 1999 has come to an end, with collection of final data in 2005 and spring 2006. Seven years of surveys and five years of acoustic recordings have provided a unique data material on porpoise abundance and distribution around Horns Reef. The outline of the following is first a general discussion of porpoise abundance on Horns Reef, followed by a specific discussion of the documented effects of constructing and operating Horns Rev Offshore Wind Farm on the porpoises.

4.1 Natural patterns in distribution and abundance

Horns Reef is an important area for harbour porpoises. This is evidenced by the high number of animals that can be observed on visual surveys. Mean density outside the winter months is about 1 porpoise/km2, well above the SCANS I estimate from 1994 of 0.1 porpoise/km2 for the central North Sea and 0.3 porpoises/km2 for the German Bight (Hammond *et al.* 2002). The occurrence of porpoises on Horns Reef is not stable however. Although there is a general tendency for fewer animals to be sighted on surveys outside summer, very high number has occurred on surveys in both October and February. High numbers are consistently observed during summer months however.

A similar annual pattern was observed in the T-POD data, with a peak in activity in late summer and lowest activity in mid-winter.

Horns Reef is bathymetrically and hydrodynamically very complex. Based on the spatial modelling no patterns in the distribution of porpoises were consistent from survey to survey. Moreover, the importance of the various hydrographic variables, and the shape of their relationship to porpoise densities shifted from survey to survey. Neither could strong and stable patterns of association with hydrographical parameters be found. Nevertheless, the relationships to these predictors were significant, although they are clearly not simple. The porpoises will likely be associated with available prey but since there was no systematic observation of fishes concurrent with the ship survey, such relations can not be investigated in the present study. If animals are associated with the mixing zone between the estuarine water masses and the more saline North Sea water, this relationship is not strong and probably confounded by the fact that the mixing does not necessarily occur along a frontal zone running north to south along the coast, but in a highly complex system of meanders and eddies (see satellite photo in *Figure 2*). Our previous spatial models which included hydrodynamic variables and spatial coordinates were only able to explain on average about 7% of the variation (Tougaard *et al.* 2005). In the current models considerable higher proportions of the variance has been explained, possibly due to the combination of static and dynamic predictors, including bathymetry, salinity and temperature from CTD measurements and tide, together with spatial coordinates. The frequent significance of the spatial coordinates suggests that the distribution of porpoises in the survey area is not random, but grouped according to some other, unknown factors. Whatever these factors are, they seem to change from survey to survey, as correlations with position changes from survey to survey. This more than anything probably reflects that porpoises move around in the area in response to movement or changes in availability of their prey and that these movements are only indirectly coupled to hydrographic scenarios.

The ship survey data contain most of the observations around the shallower areas of the reef and in some years particular associations with the most shallow parts, especially “Tuxen” has been observed. The same pattern is seen in the aerial survey data, although not as prominent. The aerial surveys clearly demonstrate that porpoises can be found everywhere in the survey area.

4.2 Effects of the wind farm

Construction was expected to be the main cause of disturbance, as was already anticipated in the EIA (Tougaard *et al.* 2000), whereas effects of operation were expected to be weak. There is even the possibility that the net effect on porpoises could be positive, due to the beneficial effects of the artificial reef effect of the foundations and scour protection Petersen and Malm (2006).

The current dataset, which covers time before, during and after construction of Horns Rev Offshore Wind Farm, indicates a weak general effect of construction on porpoises, with more specific effects linked to pile driving activities. There are no indications in the data of an effect of operation of the wind farm on harbour porpoises.

T-POD data did not show any significant decrease in abundance in the wind farm area as a whole during construction. The only significant difference between periods was between semi-operation and operation, measured on the indicator porpoise-positive-minutes (PPM). PPM reached the lowest mean value in the entire monitoring period during semi-operation. Strong conclusions should not be based on this observation however, as there are relatively large gaps in the time series of T-POD recordings, especially during baseline and construction. The loss and replacement of T-PODs has resulted in a somewhat inconsistent data set, where 20 T-PODs have been deployed during different periods with only small temporal overlap. In fact, the loss of data has been so large that the T-POD specific variation could not be determined independently, and consequently the T-POD specific variation was reduced to variations between transducer type and hybrid versions. The most important issue in this context is that monitoring data in the impact area during construction is available from only one T-POD (id 39), due to equipment failure. The BACI-test thus relies on these data and especially that the sensitivity of this T-POD was comparable to the other T-PODs. It is known from other studies (Tougaard et al., 2005) that the T-POD specific variation can be important, particularly for indicators PPM and waiting time. The sensitivity of T-POD no. 39 was compared to the sensitivity of other T-PODs used on Horns Reef (no. 36, 37, 38 and 40; Teilmann *et al.* 2002a) and this particular T-POD did in fact have a higher sensitivity than the other T-PODs tested, at least at one angle of incidence. It thus remains a possibility that a small decrease in porpoise abundance inside the wind farm during construction was counterbalanced by this T-POD's somewhat higher sensitivity.

Although echolocation activity appeared related to wind speed this did not affect the BACI analysis. Average daily wind speed observations for days with deployment at the different stations were analysed by means of the same model used in the BACI analysis. This analysis showed that the only systematic wind effect for days of deployment was the seasonal variation (*month*: p=0.0233), whereas neither the overall BACI effect (*area×period*: p=0.4273) nor any of the BACI contrasts (p between 0.0994 and 0.9048) were significant. This shows that wind conditions were comparable between days of deployment in different areas, periods and combinations of these. Consequently, if there is a cause- effect of wind on echolocation activity this will only affect the estimated seasonal variation in echolocation activity such that this is a combined effect of seasonal variations in wind conditions and harbour porpoise density. The relative changes in echolocation activity between areas and periods are most likely not affected by changing wind conditions.

Conclusions from the ship surveys are not strong, yet are consistent with the T-POD results. Ship survey data indicate a weak negative and local effect of the wind farm during construction but otherwise no dramatic changes. It is noteworthy that both T-POD data and ship survey data indicate more porpoises in the area as a whole during the operational period than for any other of the periods, baseline included. The two datasets are completely independent and thus when put together strengthen the conclusions considerably: a weak decrease in abundance during construction and semi-operation and no or insignificant changes in the distribution between wind farm and reference areas in the operating wind farm, when seen relative to the baseline period.

4.2.1 Specific effects of construction

Although the design of the monitoring program was only aimed at detecting overall effects of the construction and operation of the wind farm on porpoises, it nevertheless turned out to be possible to document effects of a single activity: pile drivings. The T-POD data indicate that porpoises left the entire Horns Reef area, or at least changed their acoustic behaviour in response to the impulse sound generated by the piling operation. After a period of 6-8 hours, activity returned to levels normal for the construction period as a whole. There are two important conclusions from this. The most significant aspect of the reaction observed is that no spatial gradient in response was observed with exposure level. In other words the response was equally strong at the westernmost tip of Horns Reef (T-POD station 1) as it was inside the construction area (T-POD station 6). We thus cannot extrapolate reactions and in that way estimate the extent of the area affected by the pile drivings, but only say that it covers at least an area with a radius of 25 km (distance from wind farm area to T-POD station 1) and likely considerably more. The second conclusion regards the duration of the response, which seems to be relatively short, considering the magnitude of the impact. It is remarkable that porpoises apparently return to normal behaviour within 6-8 hours following an impact capable of affecting an area of at least 600 km^2. One possible explanation to this relatively fast recovery is that the presence of porpoises on Horns Reef is highly dynamic and that the animals returning may not be the same animals that were deterred from the area during piling.

Knowledge about the response of individual animals to the pile driving sounds is crucial to the understanding of the true impact of the pile drivings on the porpoises at Horns Reef. It is thus important to understand whether individuals, who leave the area due to the sound of the pile driving, are merely annoyed and return to normal behaviour after a short lag time, or they are deterred from the area for a much longer period and simply replaced by other animals. In the latter case the impact of the pilings could be considerably more severe than the figures suggest on immediate inspection.

If we consider the effect of pile drivings from a habitat point of view we can estimate the impact. There were 80 foundations, which were piled over a period of 5 months. Each piling took on average 70 minutes and if we assume that animals disappeared immediately at onset of piling and remained outside range of the T-PODs for 7 hours on average, this corresponds to 640 hours out of 5 months or 17% of the time during construction. This must be considered a significant disturbance to the area. It is noteworthy however, that this large reduction in presence of porpoises on the reef is not reflected in the T-POD recordings when these are seen as a whole over the entire construction period suggesting any effect of construction activities in-between pile drivings to be marginal.

4.2.1.1 Mitigations

Evaluation of the effectiveness of mitigation in connection with pile drivings was not incorporated into the design of the study program and is in any case difficult to assess experimentally. What is sensible to ask is whether the pingers and seal scarer engaged prior to onset of piling were sufficiently intense to deter any porpoises (and seals) out to safe distances and also whether the effects observed in the waiting time analysis may represent a response to the mitigation rather than the piling itself. The answer to the first question is likely yes. Although there is much controversy connected to determination of safe limits of sound exposure to marine mammals, there is common consensus that sound pressures below 160 dB re. 1 μPa are unlikely to represent any danger and that sound pressures above 180 dB re 1 μPa (190 dB re 1 μPa for seals) may represent a risk to the hearing of the animals (National Research Council 2003). Levels in this range were measured during pile driving at distances of 1000 m and closer to the foundation. Pingers have been shown to deter porpoises out to distances of a few hundred meters (Koschinski and Culik 1997), which will provide some protection. The seal scarer operates with a considerably higher sound pressure and as it is audible to not only seals but also porpoises should be able to deter the animals even further away. From various studies on effects of pingers it is not clear what features of the sounds the animals react to. In fact it seems that porpoises react negatively to almost any novel sound of sufficient intensity, as several very different types of signals has been used in pingers (ranging from 10 kHz pure tone beeps to highly complex frequency modulated sweeps in the ultrasonic range), all with good success. This has been shown in experiments with animals in captivity (e.g. Teilmann *et al.* 2005) and full scale fishing trials (e.g. Larsen 1998, Trippel *et al.* 1999). On the other hand, the sound level of the seal scarer is considerably weaker than the sound pressure from the pile drivings (source levels of 210 dB re 1 μPa versus 235 dB re 1 μPa) and it is unlikely that the reactions seen at station 1, 20 km from the construction site were caused by the seal scarer. Thus even though a reaction to the pingers and seal scarers were likely (and desired), the reaction reflected in the increased waiting time following pile drivings should most certainly be attributed to the impact sounds from the pilings.

4.2.2 Specific effects of operation

In contrast to what has been observed at Nysted Offshore Wind Farm (Tougaard *et al.* 2006a) there are no indications in the current dataset from Horns Reef of porpoises avoiding the wind farm area when the turbines at Horns Rev are in normal operation. This conclusion is supported by independent measurements with T-PODs placed inside and immediately outside the wind farm in 2005 (Blew *et al.* 2006). These data does not indicate any gradient in porpoise abundance across the outer edge of the wind farm.

4.2.2.1 Noise from turbines in operation

It is unquestionable that turbines in offshore wind farms generate underwater noise (Betke 2006, see also *Figure 8*). The levels however, are weak by any standard (see discussion by Madsen *et al.* 2006) and any effects on marine mammals must necessarily be local, i.e. within hundreds of meters from the turbine foundations (the situation may be quite different for fish however; see Wahlberg and Westerberg 2005). The measurements from Horns Rev Offshore Wind Farm (Betke 2006) demonstrate that these turbines generate noise of intensity and with a spectral content well in line with what has been measured from other offshore turbines. Based on the general conclusion of the monitoring program at Horns Rev, i.e. no detectable effect on abundance of porpoises in the operating wind farm, the underwater noise from the turbines is not considered to impact the porpoises. As conditions may be different in other locations (more noisy turbines or more quiet background) this conclusion should not uncritically be extended to other wind farms. However, as pointed out by Madsen *et al.* (2006) the potential impact of turbine noise should never be judged on its own, but always seen in relation to other natural or anthropogenic noise sources in the local environment. Most important in this respect is noise from shipping and leisure boat traffic, which in many areas may far surpass the turbine noise, except in the immediate vicinity of the foundations.

4.2.3 Cumulative effects

Cumulative effects, here restricted to combined effects of two or more factors (e.g. individual wind farms) larger than the simple sum of the individual effects. As there (currently) is only one wind farm on Horns Reef it is difficult to address this issue through anything but theoretical considerations. The main reason why two or more wind farms could cause a combined impact larger than the sum of the individual wind farms could be through formation of barriers to the movement of animals. This requires that porpoises avoid the wind farms, at least to some degree, and as the present data does not seem to indicate this is the case on Horns Reef, the creation of strong barrier effects seems at present not likely. It will be possible to address the issue experimentally in the near future however, as permission has been given to the construction of a second offshore wind farm on Horns Reef of similar proportions as the present Horns Rev Offshore Wind Farm

During construction consideration of cumulative effects is important. If construction of one wind farm the size of Horns Rev Offshore Wind Farm is capable of strongly affecting porpoises in an area of 600 km^2 and possibly much more for roughly 17% of the construction time, it can quickly become problematic if two or more wind farms are constructed close to each other at the same time. At the current speed of development this is not an issue, but if all plans for e.g. wind farms in the German Bight are realised within a short time span, this issue should be addressed.

However, in this context it is important also to include other sources of loud impulse sounds, which in this respect includes other types of piling for other purposes (offshore oil and gas development and sheet pilings at harbours etc.). The impact of pile driving is not unique to offshore wind farms and other installations and operations utilising this techniques should be included in any assessment of impact from offshore wind farms and these activities should be covered by the same restrictions as the offshore wind farms, if such were to be implemented in the future.

4.3 Methodological considerations for future studies

The monitoring programme was initiated with the field work in connection with the EIA (Tougaard *et al.* 2000) and later developed into the current programme. Although there were some predictions in the EIA with respect to what reactions could be expected from the porpoises, no-one had ever undertaken monitoring of porpoises on this scale before and new methods had to be invented. Developing methods along the way in a long term monitoring program is not optimal as the perhaps most important aspect of such a monitoring is that data can be compared throughout the entire period. The methods which we have ended up using in this final analysis thus represents a compromise between using the newest and best methods available on one hand and maintaining comparability with the data collected early in the program. E.g. even though there could be good reasons for switching from ship to aerial surveys, the former was maintained in order to avoid the difficulties in having to compare datasets collected from different platforms. For the T-POD study, the work in Horns Rev Offshore Wind Farm (together with Nysted Offshore Wind Farm) has been pioneering, as the T-POD was just developed at the time the programme started.

The rather severe technical and logistical difficulties encountered in the beginning of the T-POD monitoring program underlines the great importance of initiating a monitoring program well in advance of the expected impact. This is not only in order to collect a long baseline series, which is essential to later analyses, but also to allow for some loss of data due to unforeseen difficulties and / or changes in design of the study, following collection of the first data.

However, despite the difficulties encountered in the present study, the fundamental BACI-design has proved to be remarkably robust and have provided the answers the program was designed to deliver. The fact that two independent methods were used concurrently (ship surveys and T-PODs) have compensated for some of the uncertainties that each of the two methods have on their own.

Conclusion

In order to conclude it is useful to go back to the beginning of the monitoring program, which was conceived together with conduction of the Environmental Impact Assessment (EIA). The EIA for Horns Rev on porpoises stated that: "*The harbour porpoises are expected to react on disturbances during the construction phase by moving out of the construction area. The animals are expected to become accustomed to the conditions during operation, except during larger service operations*" (Tougaard *et al.* 2000).

In broad terms this turned out to be what happened: A weak negative reaction during construction and semi-operation, with return to baseline situation during normal operation of the wind farm.

Acknowledgements

A large number of people and institutions have been involved in the project and all deserve credit for their contributions. Special thanks go to the skilled skippers and crews on the survey ships: M/S Alice Bekker, F/V Gitte Iversen, M/S Gorm, M/S Esvagt Dana, M/S Esvagt Delta, M/S Christoffer, F/V Juli-Anne, M/S Søløven, and F/V Pip. Jenny Knudsen, Foga A/S Esbjerg, who took care of the often difficult and frustrating task of matching our schedules with ship availability and not the least weather forecasts, also deserves a particular acknowledgement. About 30 different observes participated on the survey. All are thanked; none mentioned by name - none forgotten.

Ole Lindbjerg, Christian Mikkelsen and Steen Andersen, Elsam Engineering A/S are thanked for servicing of T-PODs at Horns Reef. Oluf D. Henriksen played a central role in developing the T-POD monitoring program and Bjarne Bekker, Esbjerg played an important role in developing better mooring and deployment systems for the T-PODs. Nick Tregenza, Chelonia, U.K. is thanked for endless help and advice on setup of T-PODs and analysis of data and Peter Mikkelsen is thanked for database wizardry.

Jette Kjær and Jesper Kyed Larsen, Vattenfall A/S and Steffen Andersen, Dong Energy, together with the rest of the environmental group and the International Expert Panel are all thanked for valuable and constructive discussions and feedback at all stages in the program.

The monitoring program was financed by the Public Service Obligation (PSO) through contracts with Vattenfall A/S.

References

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle. In: *Internatinal Symposium on Information Theory* (eds. Petran, B. N. and Csàaki, F.), pp. 267-281. Budapest: Akadèemiai Kiadi.

Akamatsu, T., Dietz, R., Miller, L. A., Naito, Y., Siebert, U., Teilmann, J., Tougaard, J., Wang, D., and Wang, K. (2006). Comparison of echolocation behavior between coastal oceanic and riverine porpoises. *Deep-Sea Research Part II* **Subm.**.

Akamatsu, T., Wang, D., Wang, X., and Naito, Y. (2005). Biosonar behaviour of free-ranging porpoises. *Proc.R.Soc.Lond.B* **272**, 797-801.

Andersen, S. (1970). Auditory sensitivity of the Harbour Porpoise *Phocoena phocoena*. *Investigations on Cetacea* **2**, 255-258.

Anon. (2002a) Horns Reef - Noise in the sea during pile driving of a turbine foundation. Fredericia, Denmark, Report from Tech-Wise A/S. p. -4.

Anon. (2002b) Review report: The Danish offshore wind farm demonstration project - Environmental impact assessment and monitoring. SEAS Wind Energy Centre. pp. 1-41.

Anon. (2005).Offshore wind power - Danish experiences and solutions pp. 1-32. Copenhagen: Danish Energy Authority.

Au, W. W. L. (1993).The sonar of dolphins New York: Springer-Verlag.

Benke, H., Siebert, U., Lick, R., Bandomir, B., and Weiss, R. (1998). The current status of harbour porpoises (*Phocoena phocoena*) in German waters. *Arch.Fish.Mar.Res.* **46**, 97-123.

Betke, K. (2006) Measurement of underwater noise emitted by an offshore wind turbine at Horns Rev. Oldenburg, Germany, Institut für technishe und angewandte Physik GmbH. pp. 1-19.

Blew, J., Diederichs, A., Grünkorn, T., Hoffmann, M., and Nehls, G. (2006) Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms at Horns Rev, North Sea and Nysted, Baltic Sea, in Denmark. Status report 2005 to the Environmental Group. Hamburg, BioConsult SH.

Börjesson, P. and Berggren, P. (2003). Diet of harbour porpoises in the Kattegat and Skagerrak Seas: Accounting for individual variation and sample size. *Mar.Mamm.Sci.* **19**, 38-58.

Brill, R. L., Moore, P. W. B., and Dankiewicz, L. A. (2001). Assessment of dolphin (*Tursiops truncatus*) auditory sensitivity and hearing loss using jaw phones. *J.Acoust.Soc.Am.* **109**, 1717-1722.

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L., and Thomas, L. (2001).Introduction to distance sampling. Estimating abundance of biological populations Oxford University Press.

Bullock, T. H. and Heiligenberg, W. (1986).Electroreception Wiley & Sons.

Burnham, K. P. and Anderson, D. R. (2002).Model selection and inference: A practical information-theoretic approach 2nd ed. New York: Springer.

Carstensen, J., Henriksen, O. D., and Teilmann, J. (2006). Impacts on harbour porpoises from offshore wind farm construction: Acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). *Mar.Ecol.Prog.Ser.* **in press**.

Chatfield, C. (1984).The analysis of time series - an introduction 3 ed. Lonon: Chapman and Hall.

Eltra. (2000) Beregning og måling af magnetfelter omkring kabler og vindmøller. Internt notat 2000-238. 2000.

Erbe, C. (2002). Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. *Mar.Mamm.Sci.* **18**, 394-418.

Fox, T., Desholm, M., Kahlert, J., Petersen, I. K., Kjær, T., and Clausager, I. Summarising the findings of bird studies in relation to the offshore wind farms at Nysted and Horns Rev. Talk given at the Offshore Wind Farms Conference, Billund, Denmark 21-22 Sept. 2004. 2004.

Green, R. H. (1979).Sampling design and statistical methods for environmental biologists New York: Wiley.

Hammond, P. S., Benke, H., Berggren, P., Borchers, D. L., Buckland, S. T., Collet, A., Heide-Jørgensen, M-P., Heimlich-Boran, S., Hiby, A. R., Leopold, M. F., and Øien, N. (1995) Distribution and abundance of the harbour porpoise and other small cetaceans in the North Sea and adjacent waters. Final report Life 92-2/UK/027. p. -240.

Hammond, P. S., Berggren, P., Benke, H., Borchers, D. L., Collet, A., Heide-Jørgensen, M.-P., Heimlich, S., Hiby, A. R., Leopold, M. F., and Øien, N. (2002). Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters. *J.Appl.Ecol.* **39**, 361-376.

Hedley, S. L., Buckland, S. T., and Borchers, D. L. (1999). Spatial modelling from line transect data. *J.Cetacean.Res.Manage.* **1**, 255-264.

Hedley, S. L., Buckland, S. T., and Borchers, D. L. (2004). Spatial distance sampling models. In . . In: *Advanced Distance Sampling: Estimating abundance of biological populations* (eds. Buckland, S. T. *et al.*), pp. 48-70. New York: Oxford University Press.

Henriksen, O. D. (2001) Noise from offshore wind turbines - effects on porpoises and seals. -110. 2001. University of Southern Denmark.

Horvitz, D. G. and Thompson, D. J. (1954). A generalization of sampling without replacement from a finite universe. *J.Am.Stat.Assoc.* **47**, 663-685.

Ingemansson Technology AB. (2003) Utgrunden off-shore wind farm - Measurements of underwater noise. Report 11-00329-03012700. Göteborg, Sweden.

Johnston, D. W., Westgate, A. J., and Read, A. J. (2005). Effects of fine-scale oceanographic features on the distribution and movements of harbour porpoises *Phocoena phocoena* in the Bay of Fundy. *Mar.Ecol.Prog.Ser.* **295**, 279-293.

Kastelein, R. A., Bunskoek, P., Hagedoorn, M., Au, W. W. L., and Haan, D. d. (2002). Audiogram of a harbor porpoise (*Phocoena phocoena*) measured with narrow-band frequency modulated signals. *J.Acoust.Soc.Am.* **112**, 334-344.

Ketten, D. R. (2000). Cetacean ears. In: *Hearing by whales and dolphins* (eds. Au, W. W. L., Popper, A. N., and Fay, R. R.), pp. 43-108. New York: Springer.

Kinze, C. C., Jensen, T., and Skov, R. (2003) Focus på hvaler i Danmark 2000-2002. Tougaard, S. Esbjerg, Denmark, Fisheries and Maritime Museum. Biological Papers No. 2,

Koschinski, S. and Culik, B. (1997). Deterring harbour porpoises from gillnets: observed reactions to passive reflectors and pingers. *Rep.Int.Whal.Commn.* **47**, 659-668.

Larsen, F. (1998) Effekten af akustiske alarmer på bifangst af marsvin i garn. Charlottenlund, Danmarks Fiskeriundersgelser. DFU-Rapport nr. 44-97,

Lehmann, A., Overton, J. M., and Leathwick, J. R. (2002). GRASP: Generalized regression analysis and spatial predictions, Ecological Modelling, 157: 189-207. *Ecological Modelling* **157**, 189-207.

Leth, J. O., Larsen, B., and Anthony, D. (2004). Sediment distribution and transport in the shallow coastal waters along the west coast of Denmark. *GEUS bulletin* **4**, 41-44.

Littell, R. C., Milliken, G. A., Stroup, W. W., and Wolfinger, R. D. (1996) SAS System for mixed models. Cary, NC., SAS Institute Inc.

Madsen, P. T., Wahlberg, M., Tougaard, J., Lucke, K., and Tyack, P. L. (2006). Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. *Mar.Ecol.Prog.Ser.* **309**, 279-295.

McCullagh, P. and Nelder, J. A. (1989).Generalized linear models 2nd. ed. Boca Raton, Florida: Chapman & Hall/CRC Press.

Møhl, B. and Andersen, S. (1973). Echolocation: high-frequency component in the click of the harbour porpoise (*Phocena ph. L.*). *J.Acoust.Soc.Am.* **54**, 1368-1372.

Møhl, B., Au, W. W. L., Pawloski, D. A., and Nachtigall, P. E. (1999). Dolphin hearing: Relative sensitivity as a function of point of application of a contact sound source in the jaw and head region. *J.Acoust.Soc.Am.* **105**, 3421-3424.

National Research Council (2003).Ocean noise and marine mammals Washington, D.C.: The National Academies Press.

Norris, K. S. (1964). Some problems of echolocation in cetaceans. In: *Marine bioacoustics* (ed. Tavolga, W. N.), pp. 316-336. New York: Pergamon Press.

Pearl, D. L. and Fenton, M. B. (1996). Can echolocation calls provide information about group identity in the little brown bat (*Myotis lucifugus*)? *Can.J.Zool.* **74**, 2184-2192.

Peich, L., Behrmann, G., and Kröger, R. H. H. (2001). For whales and seals the ocean is not blue: a visual pigment loss in marine mammals. *Eur.J.Neurosci.* **13**, 1520-1528.

Petersen, I. K. (2005) Bird numbers and distributions in the Horns Rev offshore wind farm area. Annual status report 2004 to Elsam Engineering A/S. Kalø, NERI.

Petersen, J. K. and Malm, T. (2006). Offshore windmill farms: Threats to or possibilities for the marine environment. *Ambio* **35**, 75-80.

Pihl, S. and Frikke, J. (1992). Counting birds from aeroplanes. In: *Manual for Aeroplne and ship surveys of waterfowl and seabirds. IWRB spec. Publ. 19* (eds. Komdeur, J., Bertelsen, J., and Cracknell, G.), pp. 8-23. Slimbridge, UK: Ministry of the Environment, National Environmental Research Institute.

Popov, V. V., Supin, A. Y., Wang, D., and Wang, K. (2006). Nonconstant quality of auditory filters in the porpoises, *Phocoena phocoena* and *Neophocoena phocaenoides* (Cetacea, Phocoenidae). *J.Acoust.Soc.Am.* **119**, 3173-3180.

Proske, U. and Gregory, E. (2003). Electrolocation in the platypus - some speculations. *Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology* **136**, 821-825.

Read, A. J. (1990). Reproductive seasonality in Harbor porpoises, *Phocoena phocoena* (L.), from the Bay of Fundy (Canada). *Can.J.Zool.* **68**, 284-288.

Richardson, W. J., Greene, C. R., Malme, C. I., and Thomson, D. H. (1995).Marine mammals and noise San Diego: Academic Press.

Rohlf, F. J. and Sokal, R. R. (1981).Statistical tables 2nd. ed. San Fransico: W.H.Freeman & Co.

SAS Institute (2003).SAS/STAT User's guide, version 8.2 Cary, North Carolina: SAS Instititute.

Searle, S. R., Speed, F. M., and Milliken, G. A. (1980). Populations marginal means in the linear model: An alternative to least squares means. *The American Statistician* **34**, 216-221.

Skov, H. and Prins, E. (2001). Impact of estuarine fronts on the dispersal of piscivorous birds in the German Bight. *Mar.Ecol.Prog.Ser.* **214**, 279-287.

Skov, H., Teilmann, J., Henriksen, O. D., and Carstensen, J. (2002) Investigations of harbour porpoises at the planned site for wind turbines at Horns Reef. Technical report to Techwise A/S. Copenhagen, Ornis Consult A/S. p. -45.

Sonntag, R. P., Benke, H., Hiby, A. R., Lick, R., and Adelung, D. (1999). Identification of the first harbour porpoise (*Phocoena phocoena*) calving ground in the North Sea. *Journal of Sea Research* **41**, 225-232.

Sørensen, T. B. and Kinze, C. C. (1994). Reproduction and reproductive seasonality in Danish harbour porpoises, *Phocoena phocoena*. *Ophelia* **39**, 159-176.

Teilmann, J., Dietz, R., Larsen, F., Deportes, G., Geertsen, B. M., Andersen, L. W., Aastrup, P., Hansen, J. R., and Buholzer, L. (2004) Satellitsporing af marsvin in danske og tilstødende farvande. Faglig rapport fra DMU, nr. 484. Roskilde, Denmark, NERI.

Teilmann, J., Henriksen, O. D., and Carstensen, J. (2001) Porpoise detectors (PODs) as a tool to study potential effects of offshore wind farm on harbour porpoises at Rødsand. Roskilde, Denmark, NERI. p. -41.

Teilmann, J., Henriksen, O. D., Carstensen, J., and Skov, H. (2002a) Monitoring effects of offshore windfarms on harbour porpoises using PODs (porpoise detectors). Technical report to SEAS A/S. Roskilde, Denmark, NERI.

Teilmann, J., Miller, L. A., Kirketerp, T., Kastelein, R., Madsen, P. T., Nielsen, B. K., and Au, W. W. L. (2002b). Characteristics of echolocation signals used by a harbour porpoise (*Phocoena phocoena*) in a target detection experiment. *Aquat.Mamm.* **28**, 275-284.

Teilmann, J., Tougaard, J., Miller, L. A., Kirketerp, T., Hansen, K., and Brando, S. (2005) Reactions of captive harbor porpoises (*Phocoena phocoena*) to pinger-like sounds. Marine Mammal Science . 2005.

Teilmann, J., Tougaard, J. and Carstensen, J. (2006) Summary report on harbour porpoise monitoring around Nysted and Horns Rev Offshore Wind Farms. NERI technical report to Energi E2 A/S and Vattenfall A/S. Roskilde, Denmark.

Thomas, L., Laake, J. L., Strindberg, S., Marques, F. F. C., Buckland, S. T., Borchers, D. L., Anderson, D. R., Burnham, K. P., Hedley, S. L., Pollard, J. H., and Bishop, J. R. B. (2003) Distance 4.1. Release 2. University of St.Andrews, U.K., Research Unit for Wildlife Population Assessment .

Tougaard, J., Carstensen, J., Bech, N. I., and Teilmann, J. (2006a) Final report on the effect of Nysted Offshore Wind Farm on harbour porpoises. Annual report to EnergiE2. Roskilde, Denmark, NERI.

Tougaard, J., Carstensen, J., Henriksen, O. D., Skov, H., and Teilmann, J. (2003) Short-term effects of the construction of wind turbines on harbour porpoises at Horns Reef. Roskilde, Denmark, Hedeselskabet. Technical report to Techwise A/S. HME/362-02662, p. -72.

Tougaard, J., Carstensen, J., Wisz, M. S., Teilmann, J., Bech, N. I., Skov, H., and Henriksen, O. D. (2005) Harbour Porpoises on Horns Reef - Effects of the Horns Reef Wind Farm. Annual Status Report 2004 to Elsam Engineering A/S. Roskilde, Denmark, NERI.

Tougaard, J., Tougaard, S., Jensen, R. C., Jensen, T., Adelung, D., Liebsch, N., and Müller, G. (2006b) Harbour seals on Horns Reef before, during and after construction of Horns Rev Offshore WInd Farm. Final report to Elsam Engineering A/S. Esbjerg, Denmark, Fisheries and Maritime Museum.

Tougaard, S., Skov, H., and Kinze, C. C. (2000) Investigation of marine mammals in relation to the establishment of a marine wind farm on Horns Reef. Esbjerg, Denmark, Fisheries and Maritime Museum. p. -34.

Trippel, E. A., Strong, M. B., Terhune, J. M., and Conway, J. D. (1999). Mitigation of harbour porpoise (*phocoena phocoena*) by-catch in the gillnet fishery in the lower Bay of Fundy. *Can.J.Fish.Aquat.Sci.* **56**, 113-123.

Vinther, M. and Larsen, F. (2004). Updated estimates of harbour porpoise by-catch in the danish bottom set gillnet fishery. *J.Cetacean.Res.Manage.* **6**, 19-24.

Wahlberg, M. and Westerberg, H. (2005). Hearing in fish and their reactions to sounds from offshore wind farms. *Mar.Ecol.Prog.Ser.* **288**, 295-309.

Wiltschko, R. and Wiltschko, W. (1996). Magnetorception: Why is conditioning so seldom successful? *NW* **83**, 241-247.

Appendix A - Distance sampling and spatial modelling

Line-transect distance sampling methods allow researchers to estimate the abundance of animals in a surveyed area, even though many animals in that area have not been detected Hammond *et al.* 1995; Buckland *et al.* 2001. In these methods, the number of animals observed along a transect line is recorded, along with the perpendicular distance of these observations to the transect line. It is assumed that all animals on the transect line will be detected, but animals further away from the transect line are more likely to be missed. Thus, if we plot the number of observations versus distance from the transect line, we can fit a detection function to the data using a number of statistical methods. This function assumes that the probability of observing an animal on the transect line is 1.0, but decreases with distance from the transect line, and is the central theme in distance sampling methods. These functions are flexible, and can incorporate information on a number of factors that might also influence the probability of detecting an object and the resulting estimates of animal abundance. Examples of such factors include seastate (fewer animals may be observed in rough waters than in calmer sea conditions), observer (some observers see more animals than others)., and cluster size (large pods may be easier to observe at greater distances than smaller pods).

We computed detection functions for each of the surveys. When sample size was sufficient to do so, various combinations of other explanatory variables, in addition to perpendicular distances, were included to compute detection functions. These other explanatory variables included seastate and cluster size (number of individuals in an observed pod).

Selecting the most parsimonious detection function

Based on standard methods (Buckland *et al.* 2001), we selected the most parsimonious of these detection functions using Akaike's Information Criterion (AIC).

$$\mathrm{AIC} = -2\log_e(\ell(\theta\,|\mathrm{data})) + 2K$$

where loge(ℓ(θ|data)) is the value of the maximised log-likelihood over the estimated parameters given the data and the model, and K is the number of parameters in a candidate model. Information-theoretic methods of model selection rely on the calculation of the Akaike Information Criteria (AIC,Akaike 1973) as a model selection tool. Within a set of candidate models, such as each of our possible detection functions, models with relatively low AIC values are the most parsimonious and strike a balance between bias and variance of model predictions. AIC is a measure of the relative Kullback-Leibler information lost in using candidate model i to approximate truth j.

For each of the candidate models, we calculate AIC and then rescale these values to calculate AIC differences (Δi), so that the model having the lowest AIC (or AICc) value has a Δi value of 0, i.e.

$$(\Delta_i). = \mathrm{AIC}_i - \min(\mathrm{AIC})$$

where AICi is the AIC (or AICc) value of the i'th model, and min(AIC) is the AIC (or AICc) value of the model with the lowest AIC (or AICc) value. Thus, the model with a (Δi) = 0 is the Kullback-Leibler best approximating model in the candidate set. The larger the value of (Δi), the less plausible is the fitted model i as being the best approximating candidate model. Typically, models with (Δi) values between zero and two have strong support. Models with (Δi) values between two and ten have some support decreasing to essentially no support where (Δi) exceeds than ten (Burnham and Anderson 2002).

From the Akaike differences (Δi), we derive the Akaike weights (wi) for each of the r candidate models.

$$w_i = \frac{\exp\left(-\frac{1}{2}\Delta_i\right)}{\sum_{r=1}^{R}\exp\left(-\frac{1}{2}\Delta_i\right)}$$

Akaike weights (wi) approximate the probability that a given candidate model will be the Kullback-Leibler best model (best approximating model in the set of candidate models) if the analysis was repeated on a different sample drawn from the population. These weights are scaled between zero and one, and represent the evidence for a particular model as a proportion of the total evidence supporting all of the models. Therefore, all Akaike weights sum to one, and a model with a Akaike weight of 0.9 is expected to be the Kullback-Leibler best model in 90% of all possible samples. The candidate model with the largest Akaike weight is the most parsimonious model and has the most support among the specified candidate models, given the data.

Calculation of detection functions, ESWs and animal abundances were all performed by the software package Distance ver. 5.0 (Thomas *et al.* 2003).

Spatial Modelling

An extension of distance sampling methods allows researchers to estimate the number of objects observed along segments of the transect line, and model these as a function of environmental explanatory covariates (Hedley *et al.* 2004; Hedley *et al.* 1999). These methods allow us to infer whether the number of animals observed in a given area varies as a function of environmental covariates such as bathymetry, tidal phase, or distance to wind farm. These methods also allow us to predict the number of porpoises in places we have not surveyed, most importantly in this context to the areas between survey lines.

Response

For each survey, we divided the transect line into segments each with length = 500m. We then counted the number of animals observed in each segment along the transect line. These counts formed the response for a generalised additive model (see above).

The Count Model

The count model approach follows that of (Hedley *et al.* 2004). First, we divided each transect line into T small contiguous segments and summed the number of observations within each segment j. We then modelled the counts of animals observed within a particular segment as

$$E\left[n_j\right] = \exp\left[\log_e(2lj\hat{\mu}) + \beta_0 + \sum_{k}^{K}\beta_k z_{jk}\right], j = 1,...T.$$

where $E\left[n_j\right]$ is the expected number of animals observed in segment j, $\log_e(2l_j\hat{\mu})$ is the logarithm of the effective area of each segment, lj is the length of segment j, and $\hat{\mu}$ is the effective strip half-width which in our case is constant across all segments. The term $\log_e(2l_j\hat{\mu})$ entered into the GLM or GAM model as an offset term, while $\beta_0 + \sum_k \beta_k z_{jk}$ are parameters to be estimated by GLM or GAM with a Poisson error structure. Among these, β_0 is the intercept of the GML or GAM model, β_k is the parameter estimate for spatial covariate zk,. and K is the number of spatial covariates in the model.

Appendix B – Statistical analysis of T-POD data

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:

- *Area* (2 levels) describes the spatial variation between control and impact area.
- *Station (area)* (6 levels) describing the station-specific variation nested within the two areas.
- *podnr(area station)* describes the T-POD specific variation for the three stations where the equipment was replaced
- *Period* (3 levels) describing the stepwise changes in the activity level during the baseline, the construction and post construction period.
- *Area× Period* (6 levels) describing differences in the 3 periods between the control and impact area.
- *Month* (12 levels) describes the seasonal variation by means of monthly values.

It was not possible to include a T-POD specific variation, instead two factors were included to account for variations in T-POD types.

- *transducer* (two levels) describing hydrophone type (internal vs. external)
- *podtype(transducer)* (two levels) describing differences of the two hybrid T-PODs.

All factors in the model were fixed effects. Variations in the indicators, after appropriate transformation, were assumed Normal-distributed with a mean value described by the equation:

$$\mu = area + station(area) + month + period + area \times period + transducer + podtype(transducer) \quad (1)$$

The factor area× period, also referred to as the BACI effect, described a step-wise change 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. BACI effects, each having 1 numerator degree of freedom, for the relative change for the two areas between baseline and construction, between baseline and operation, and between construction and operation were also calculated explicitly as contrasts of the marginal means in the model and for example,

$$\exp(\text{BACI contrast}) = \frac{E[\text{Impact, construction}]}{E[\text{Impact, baseline}]} \cdot \frac{E[\text{Reference, baseline}]}{E[\text{Reference, construction}]} \quad (2)$$

i.e. the exponential of the contrast described 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 baseline and operation as well as between construction and operation.

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. Thus, this model included an extension to the general linear theory (e.g. McCullagh and Nelder 1989) by mixing fixed and random effects.

Transformations, distributions and back-transformations were selected separately for the different indicators by investigating the statistical properties of data (Table 9). 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 9 List of transformation, distributions and back-transformation employed on the four indicators for harbour porpoise echolocation activity.

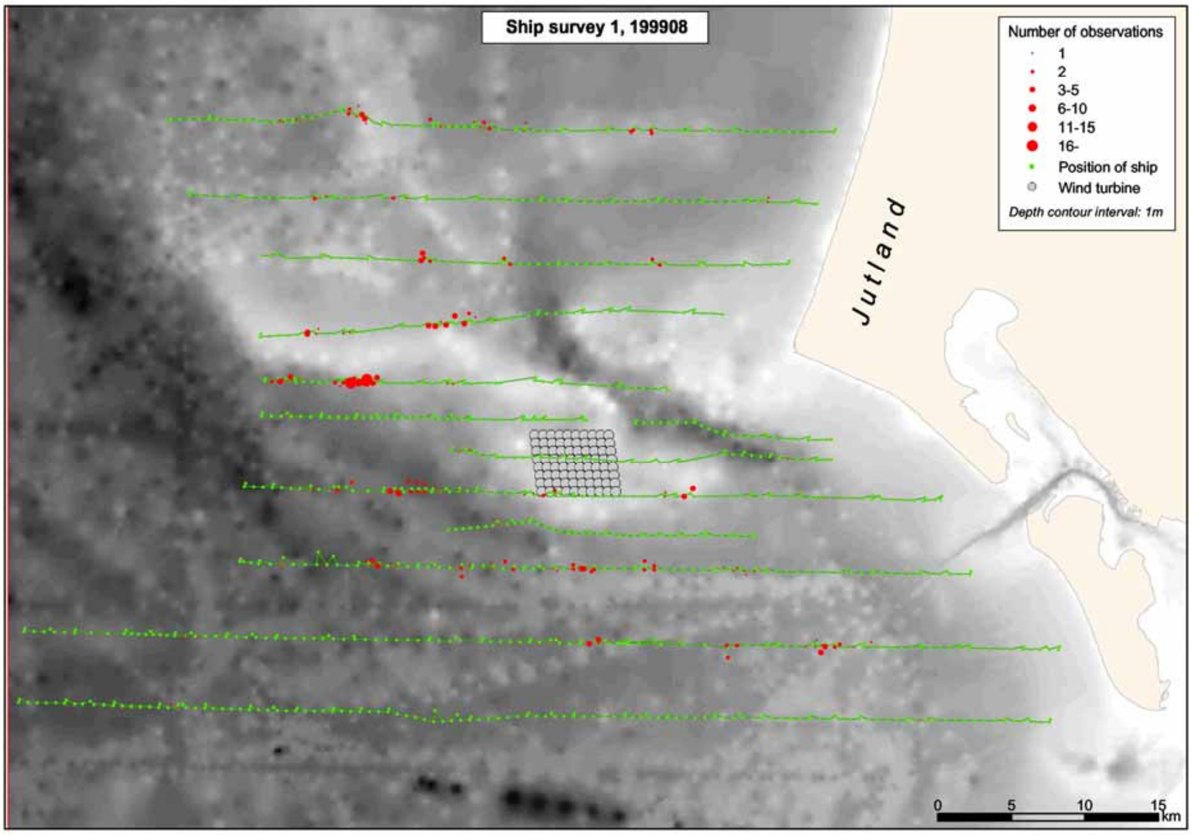
Indicator	Transformation	Distribution	Back-transformation
Daily intensity	Logarithmic – log(y)	Normal	$\exp(\mu+\sigma^2/2)$▫
Daily frequency	Angular – $\sin^{-1}(\sqrt{y})$	Normal	Table 6 Rohlf and Sokal 1981
Encounter duration	Logarithmic – log(y)	Normal	$\exp(\mu+\sigma^2/2)$▫
Waiting time	Logarithmic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

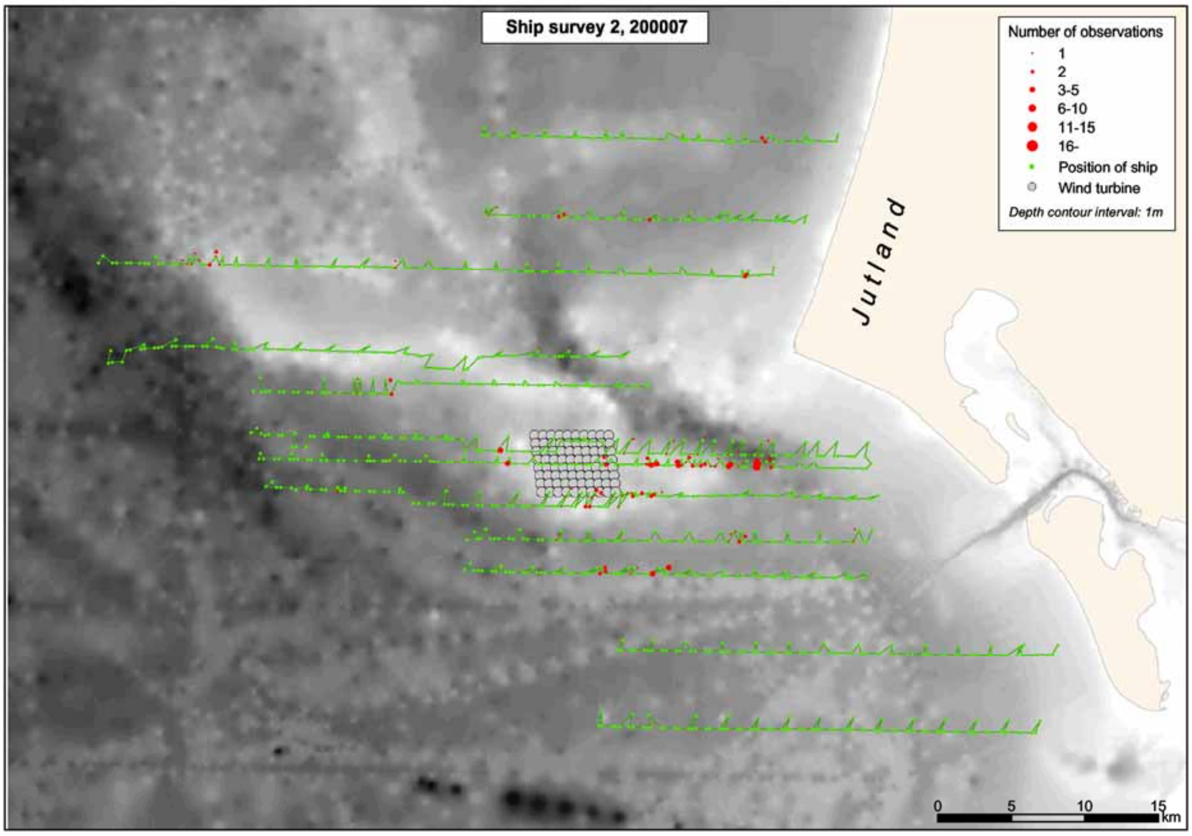
▫The back-transformation of the logarithmic transformation can be found in e.g. McCullagh and Nelder 1989), p. 285.

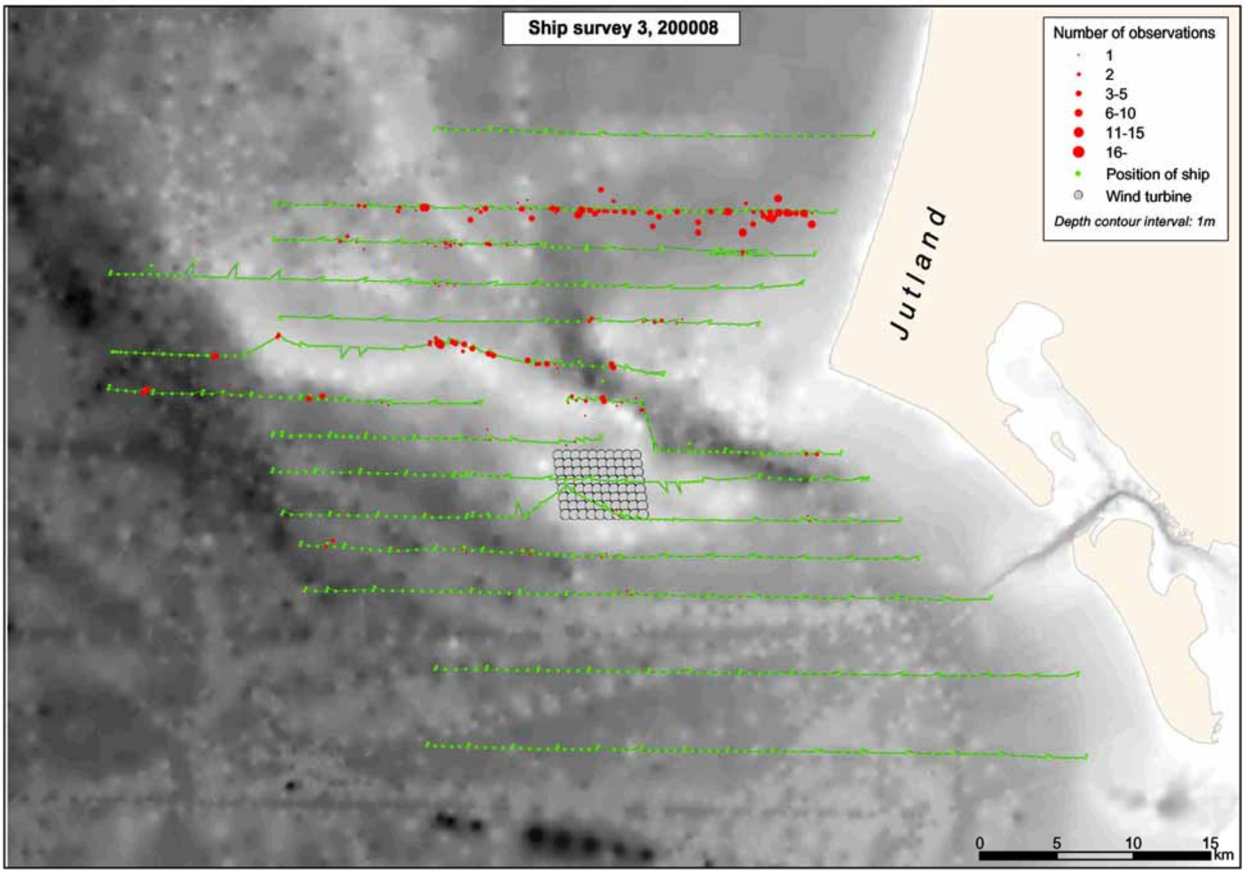
Waiting times has a natural lower bound of 10 minutes imposed by the encounter definition, and we therefore subtracted 10 minutes from these observations before taking the logarithm in order to derive a more typical lognormal distribution. Applying the log-transformation had the implication that additive factors as described in (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 models (McCullagh and Nelder 1989), and the significance of the different factors in (1) was tested using F-test (type III SS) for the normal distribution (SAS Institute 2003). The normal distribution was chosen for encounter duration as opposed to the Gamma distribution used in Tougaard *et al.* 2003) in order to employ a covariance structure describing temporal correlation in the observations.

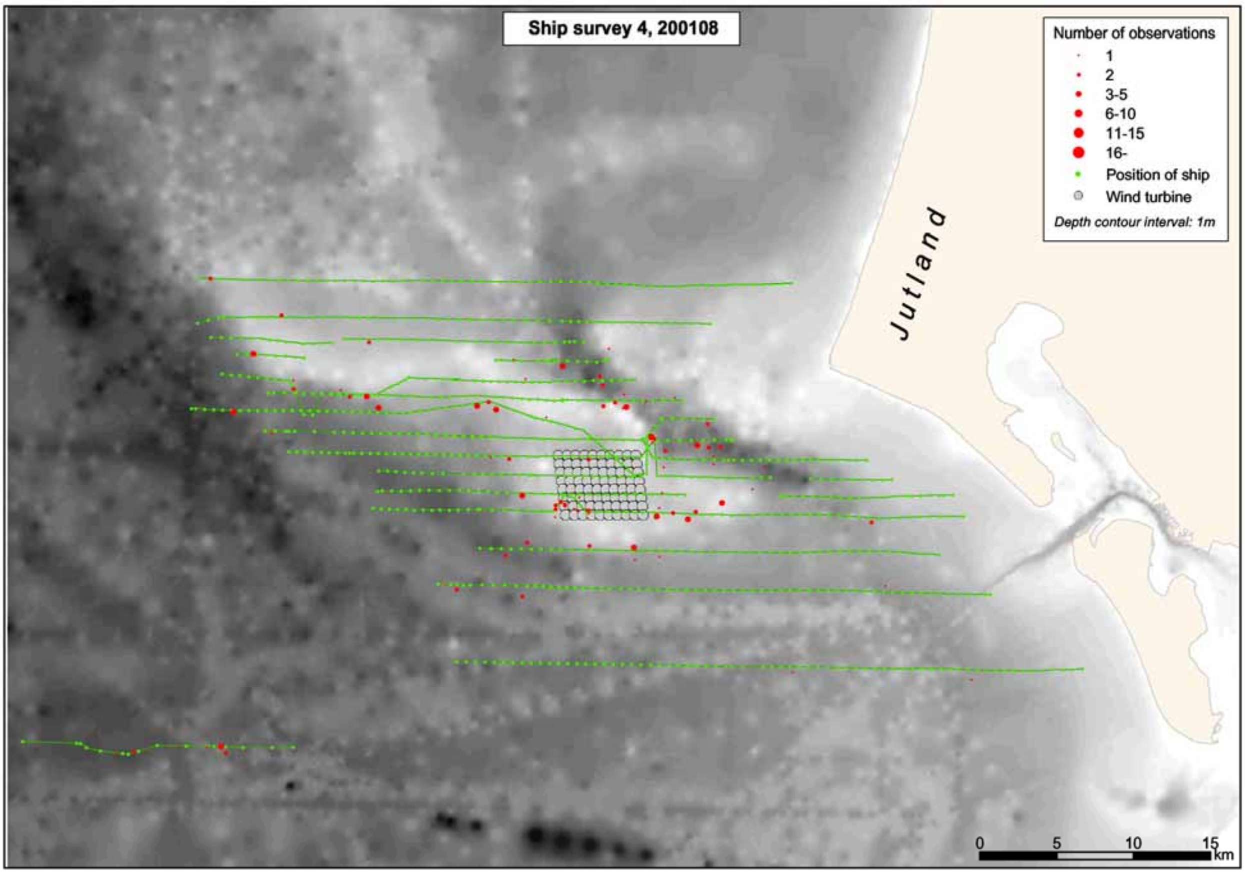
The statistical analyses were carried out within the framework of mixed linear models (Littell *et al.* 1996) by means of PROC MIXED in the SAS system. Statistical testing for fixed effects (F-test with Satterthwaite approximation for denominator degrees of freedom) and random effects (Wald Z) were carried out at a 5% significance level (Pearl and Fenton 1996). The F-test for fixed effects was partial, i.e. taking all other factors of the model into account.

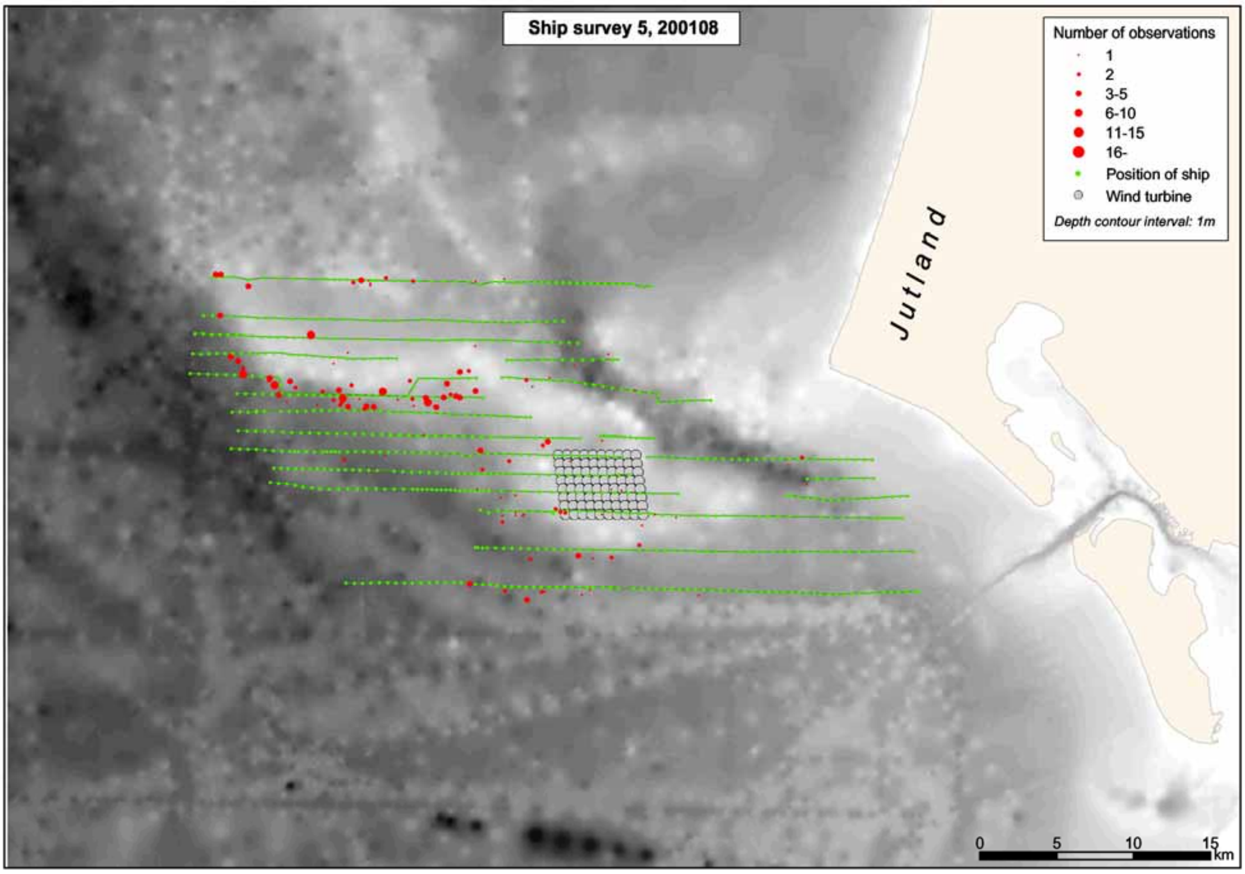
Appendix C - Individual ship surveys

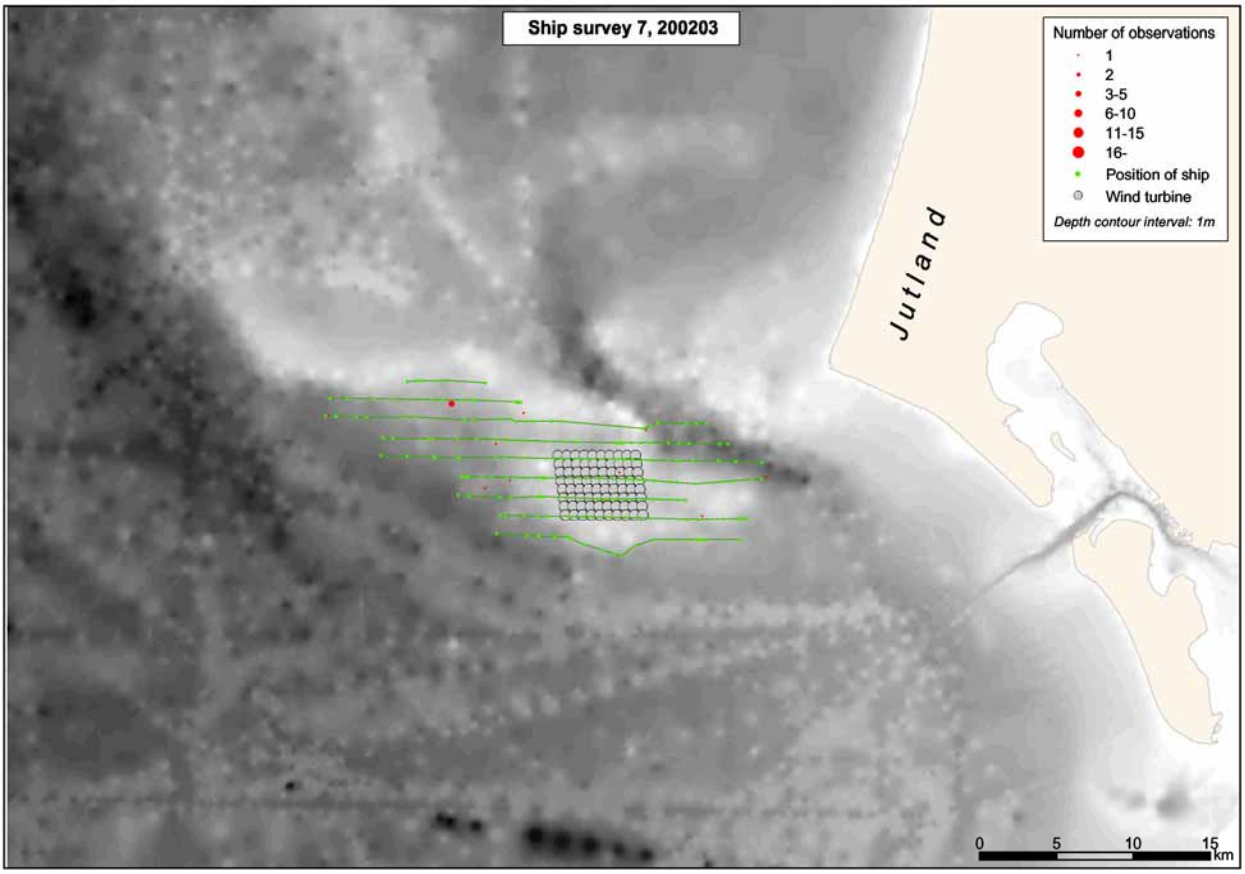


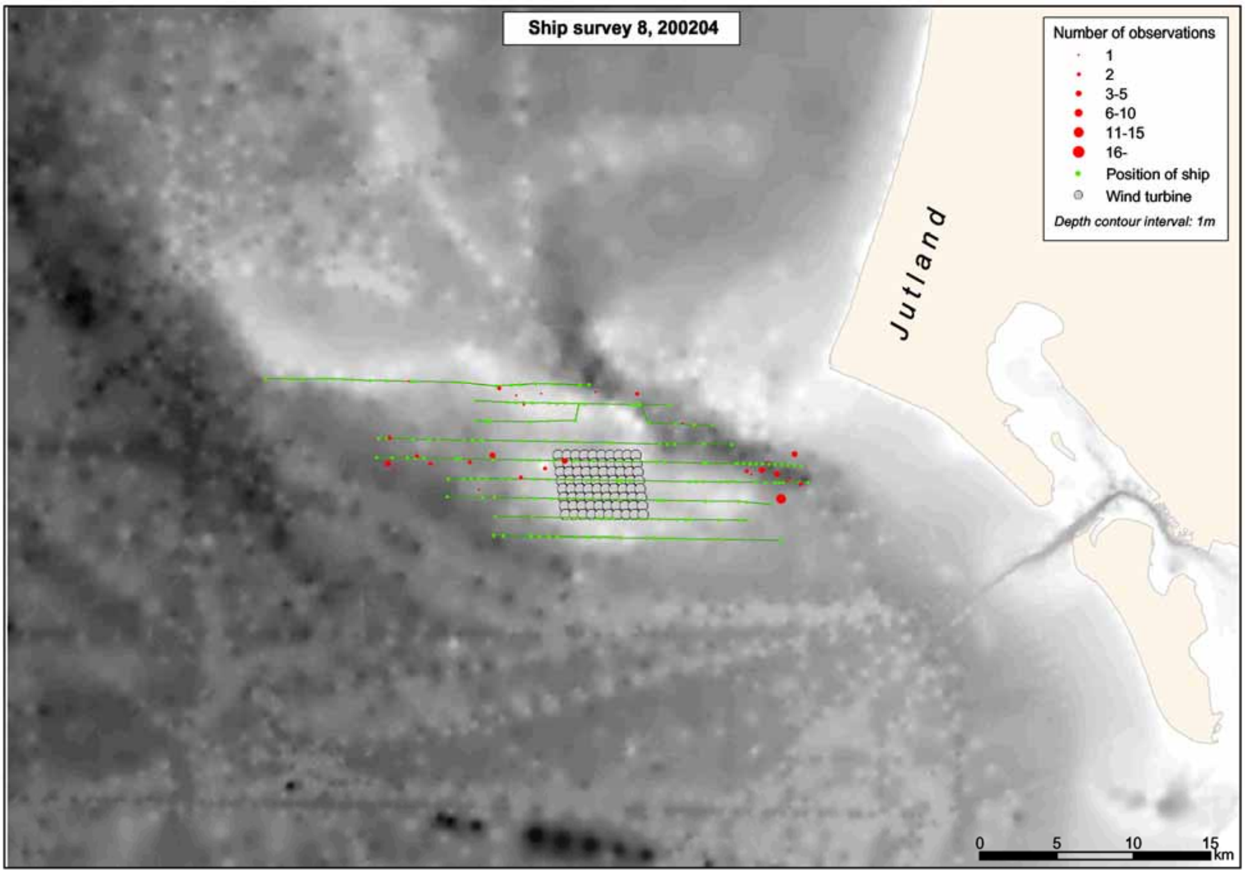


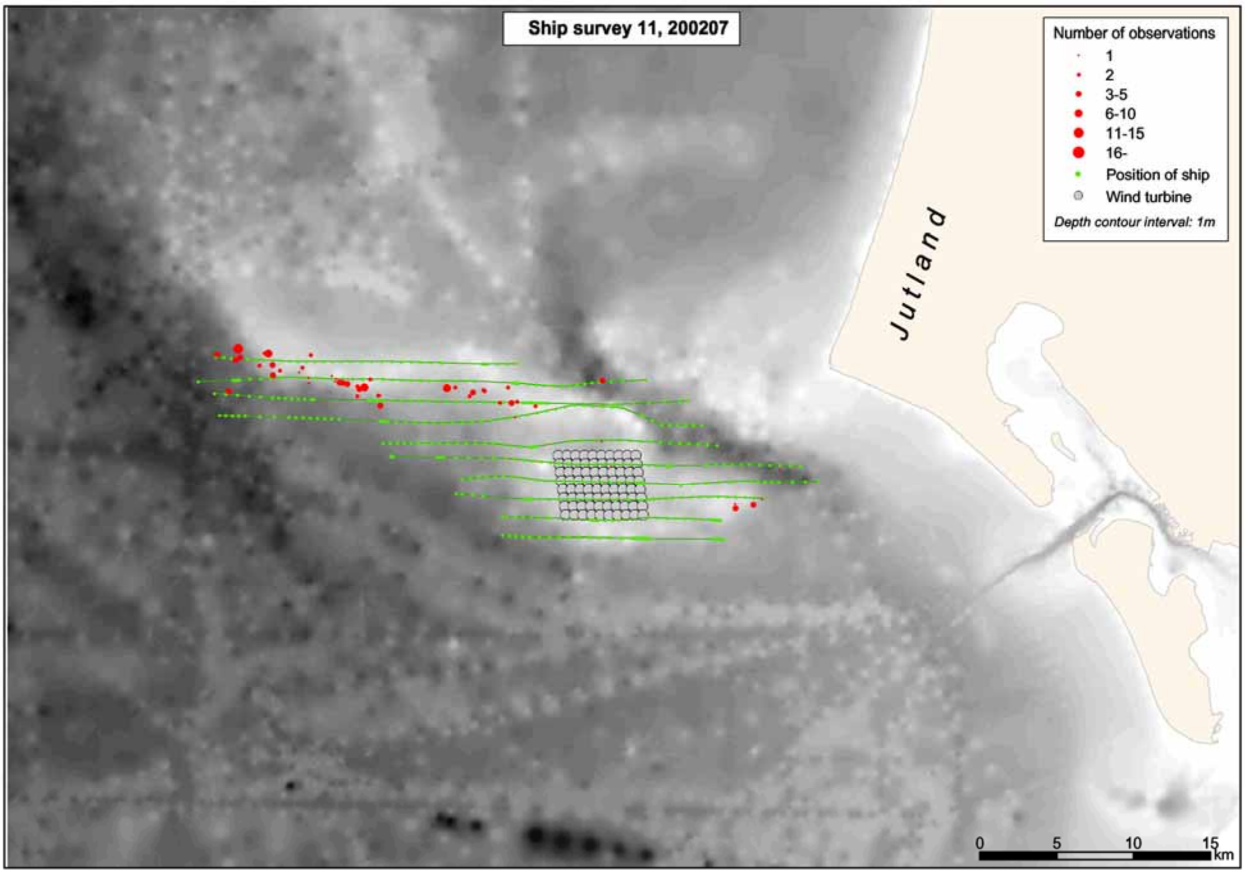

Ship survey 3, 200008
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

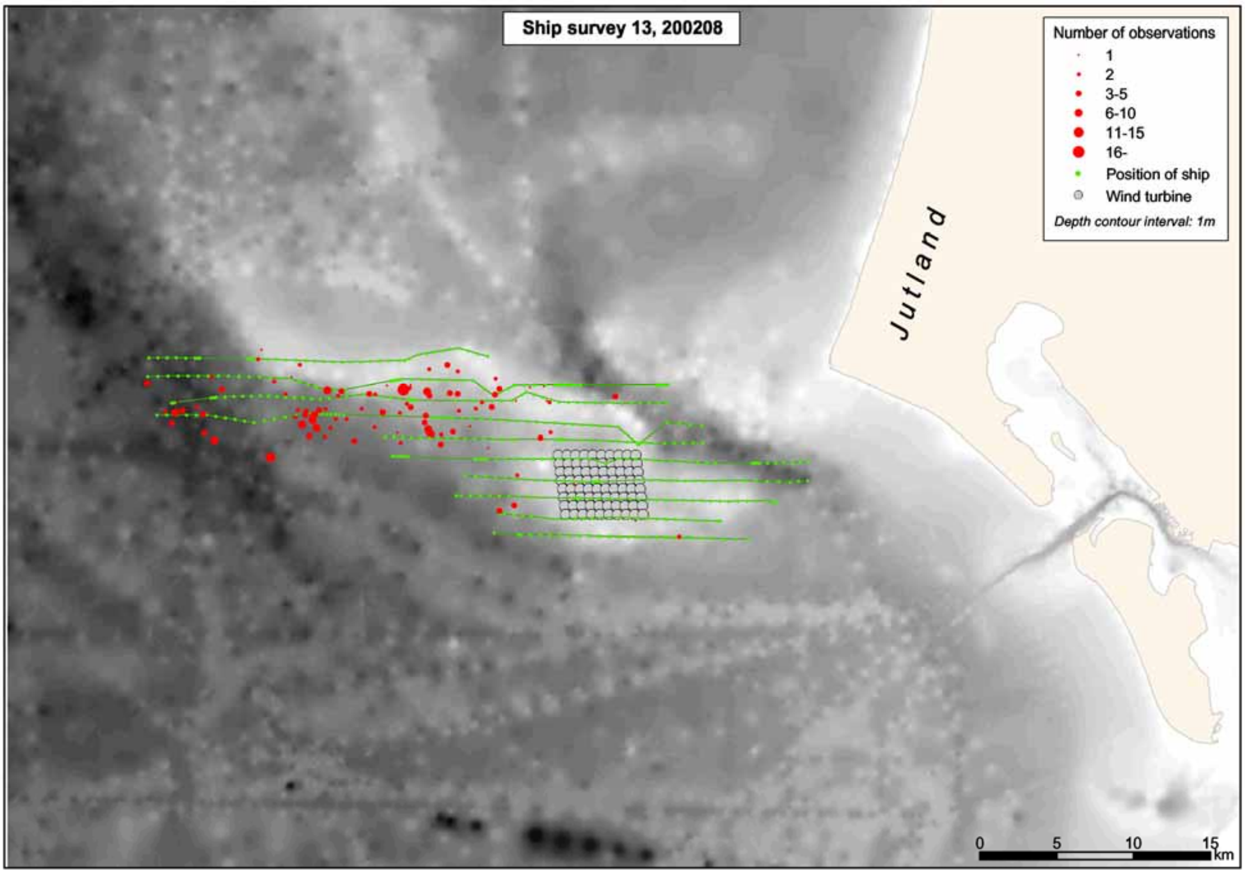

Ship survey 4, 200108
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

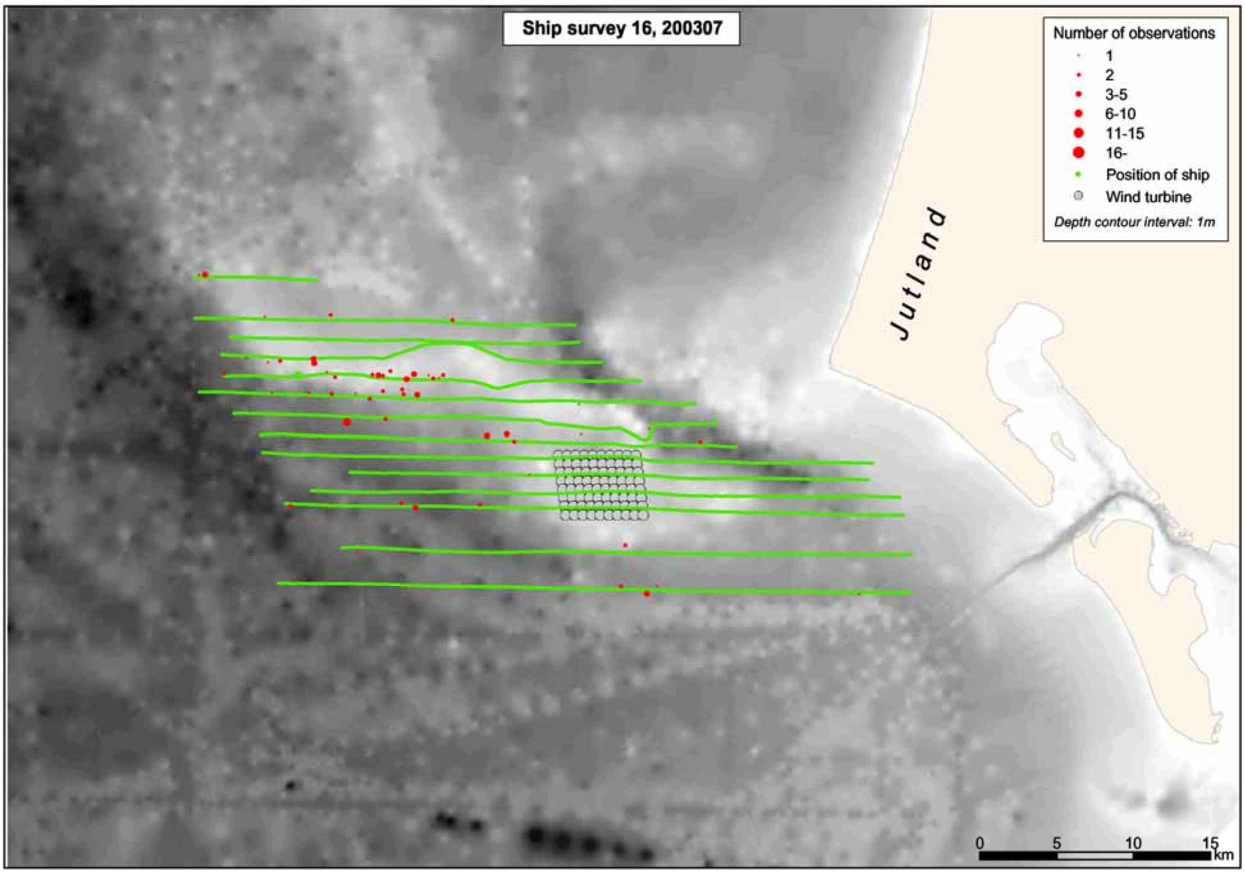

Ship survey 5, 200108
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

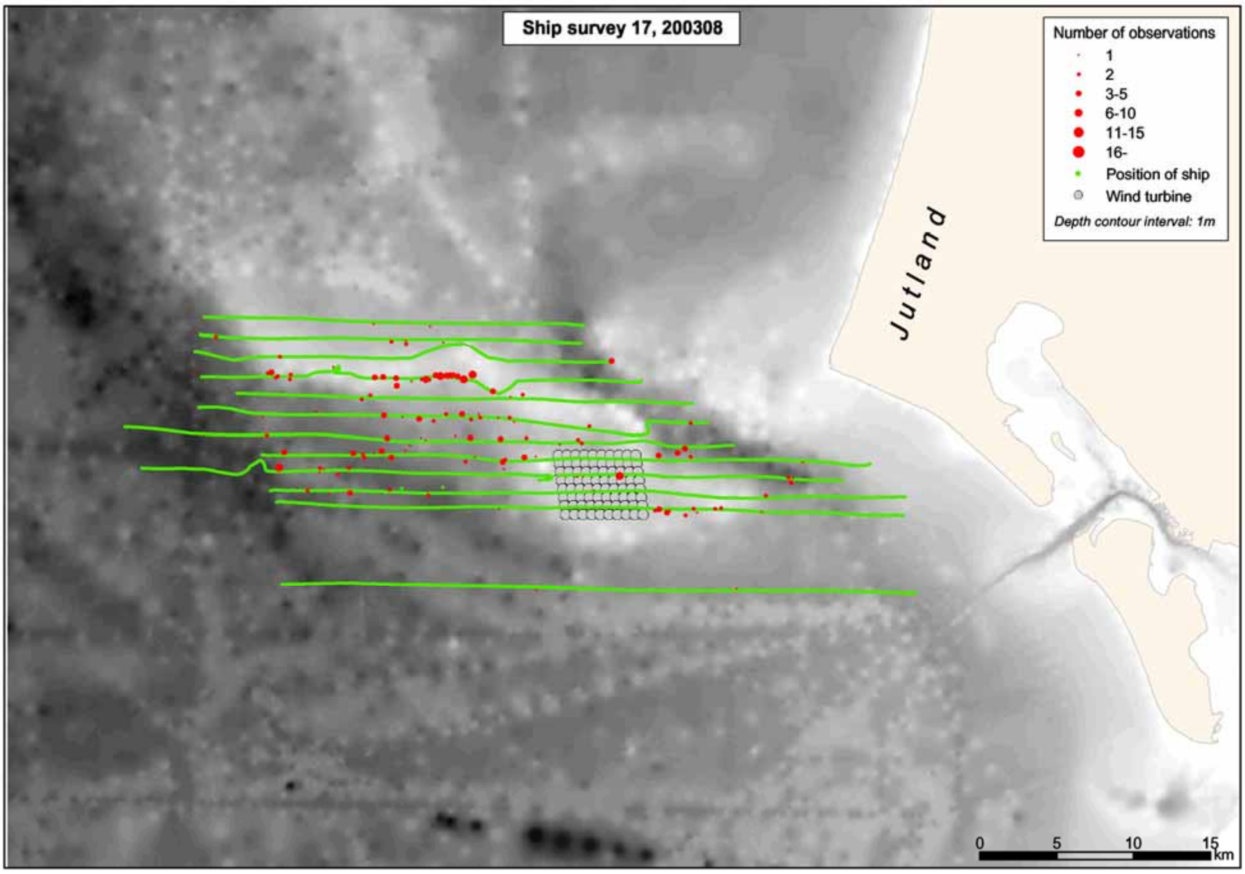

Ship survey 7, 200203
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

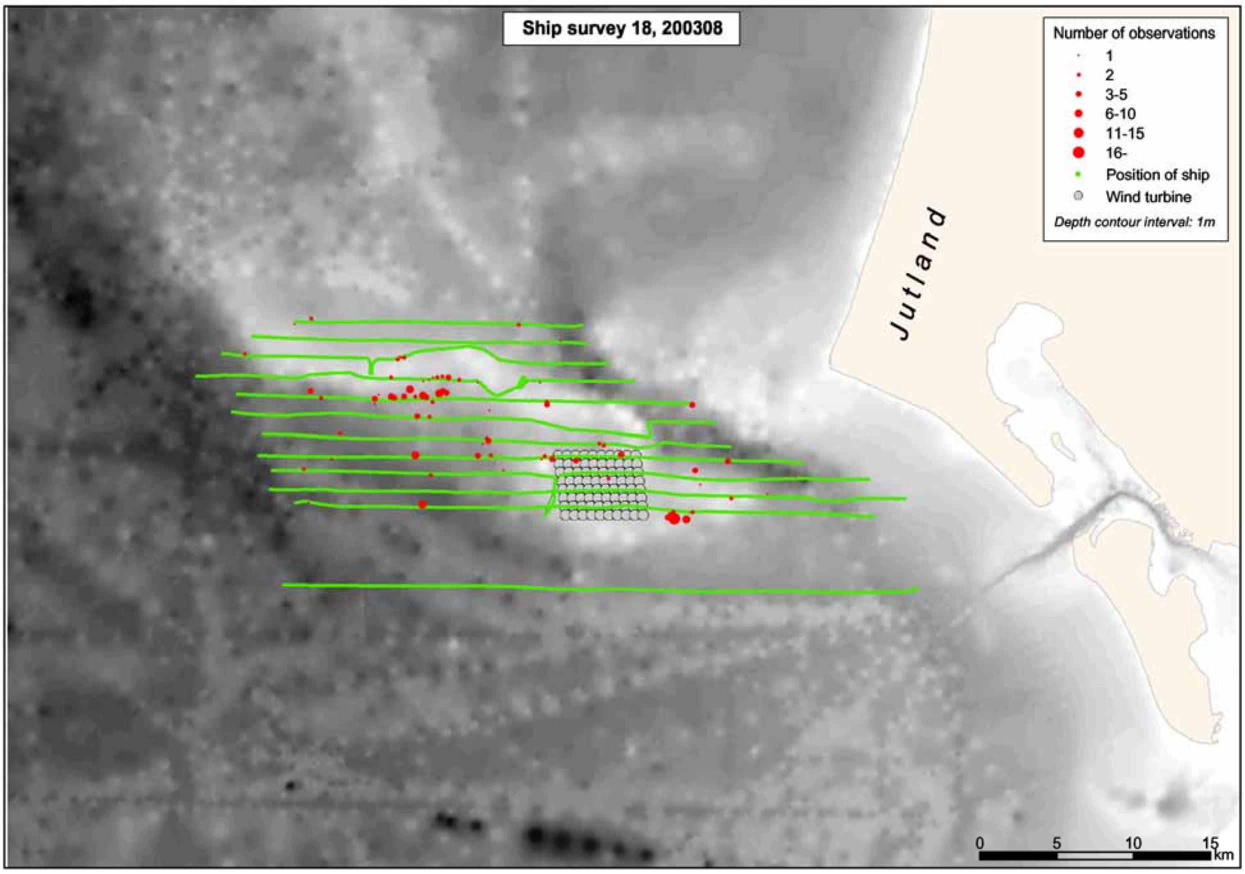

Ship survey 8, 200204
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

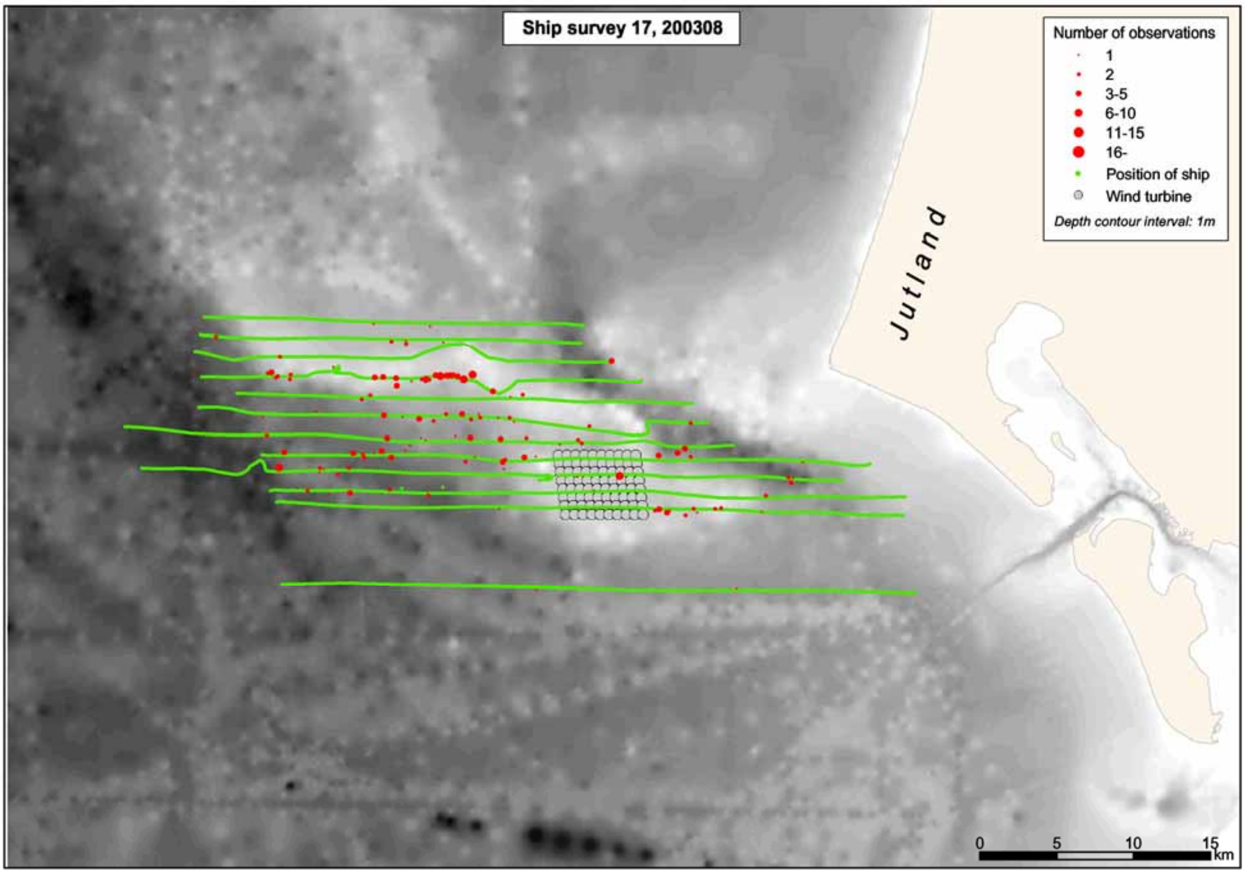

Ship survey 11, 200207
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

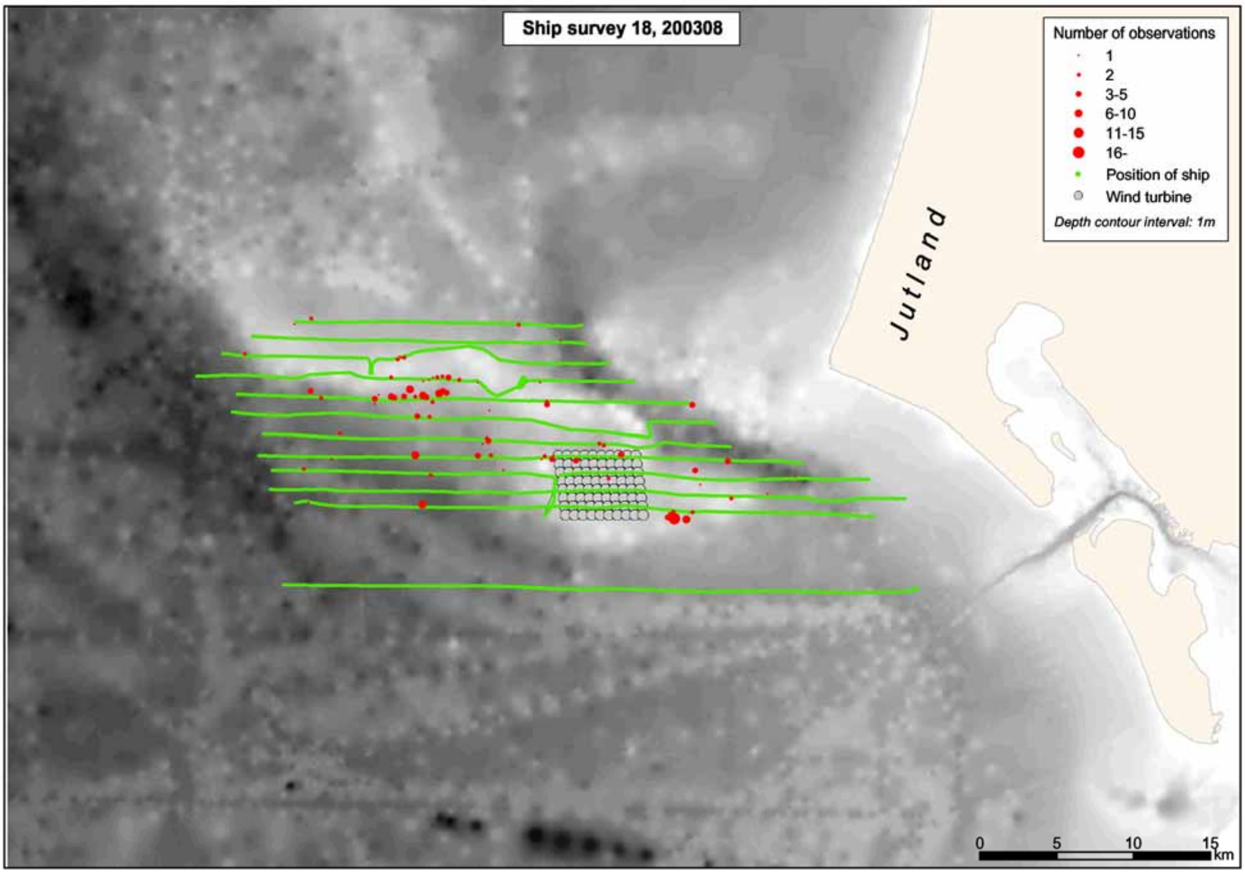

Ship survey 13, 200208
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

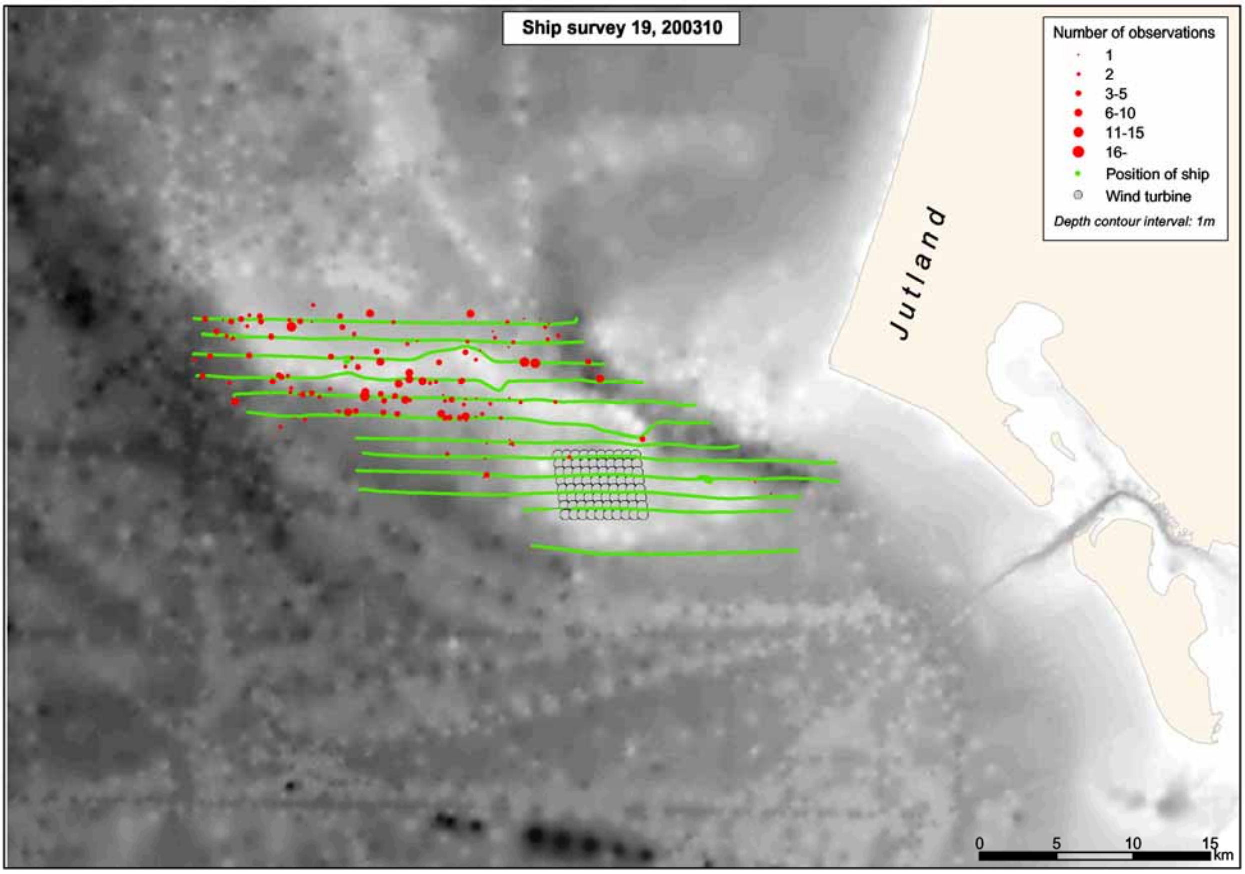

Ship survey 16, 200307
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

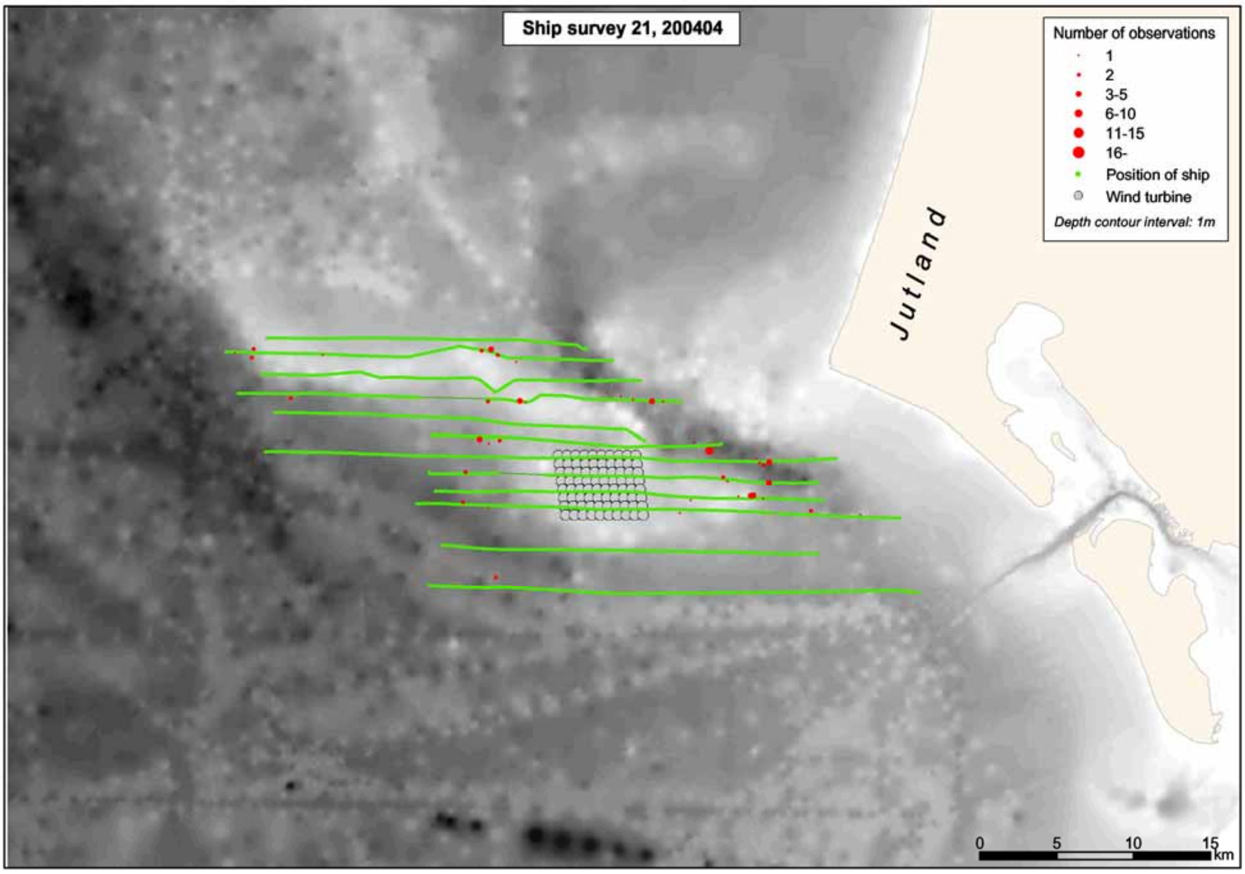

Ship survey 17, 200308
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

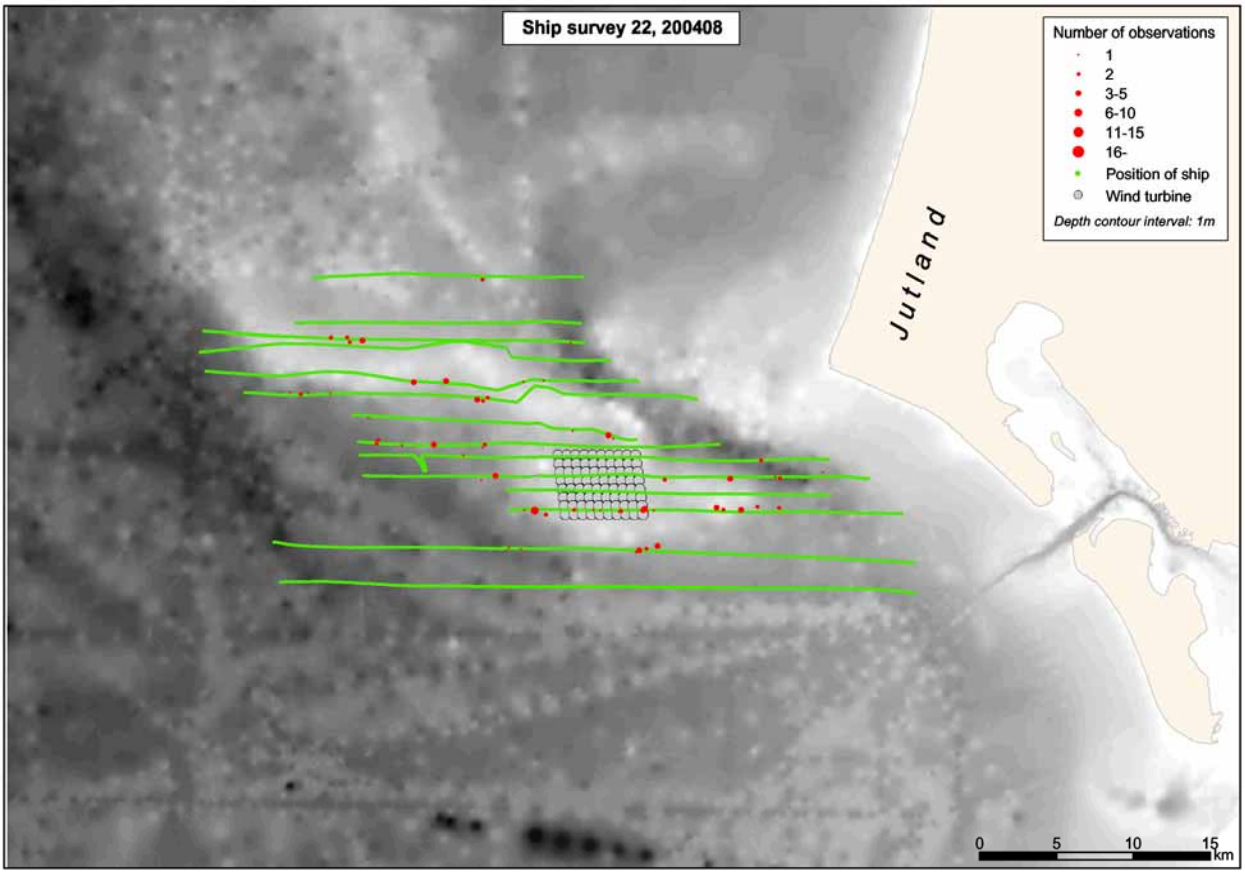

Ship survey 18, 200308
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

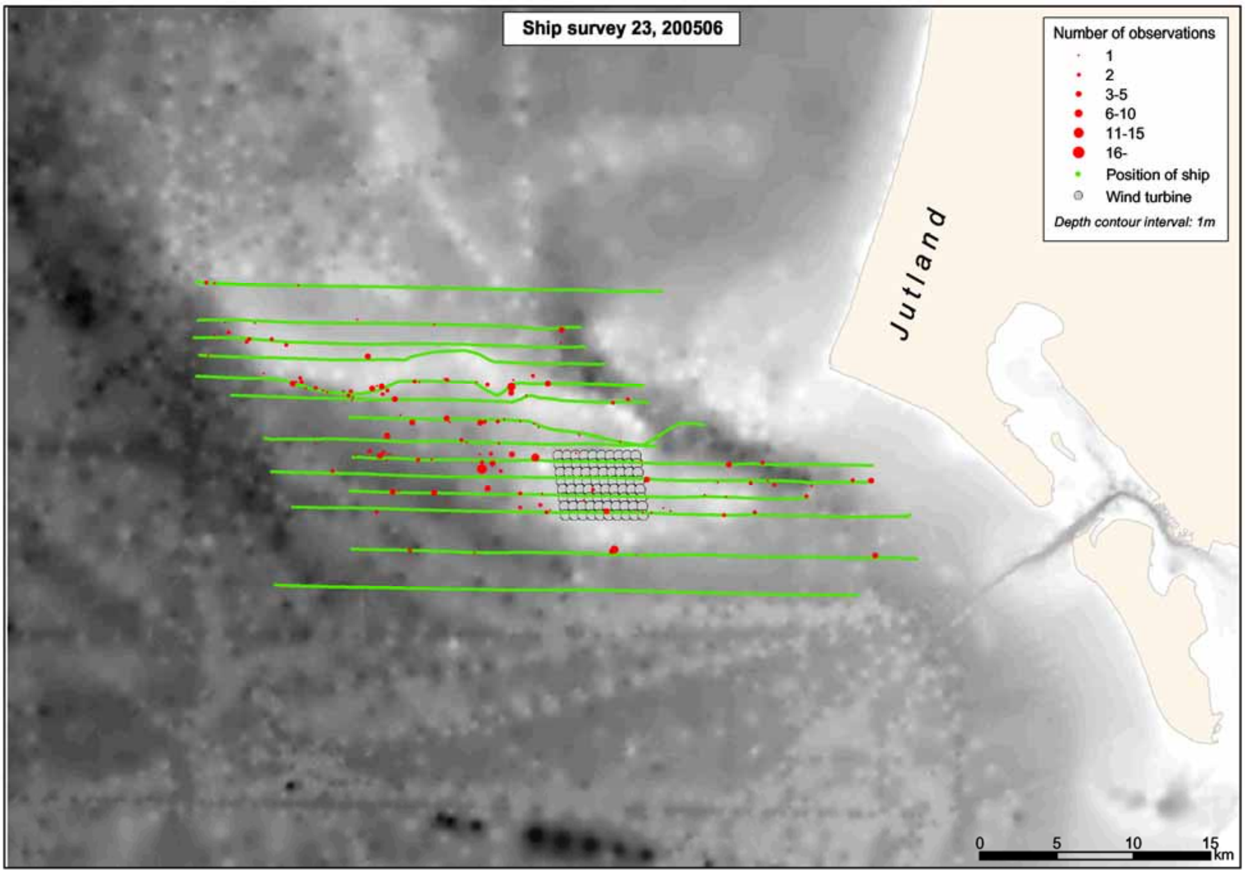

Ship survey 17, 200308
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

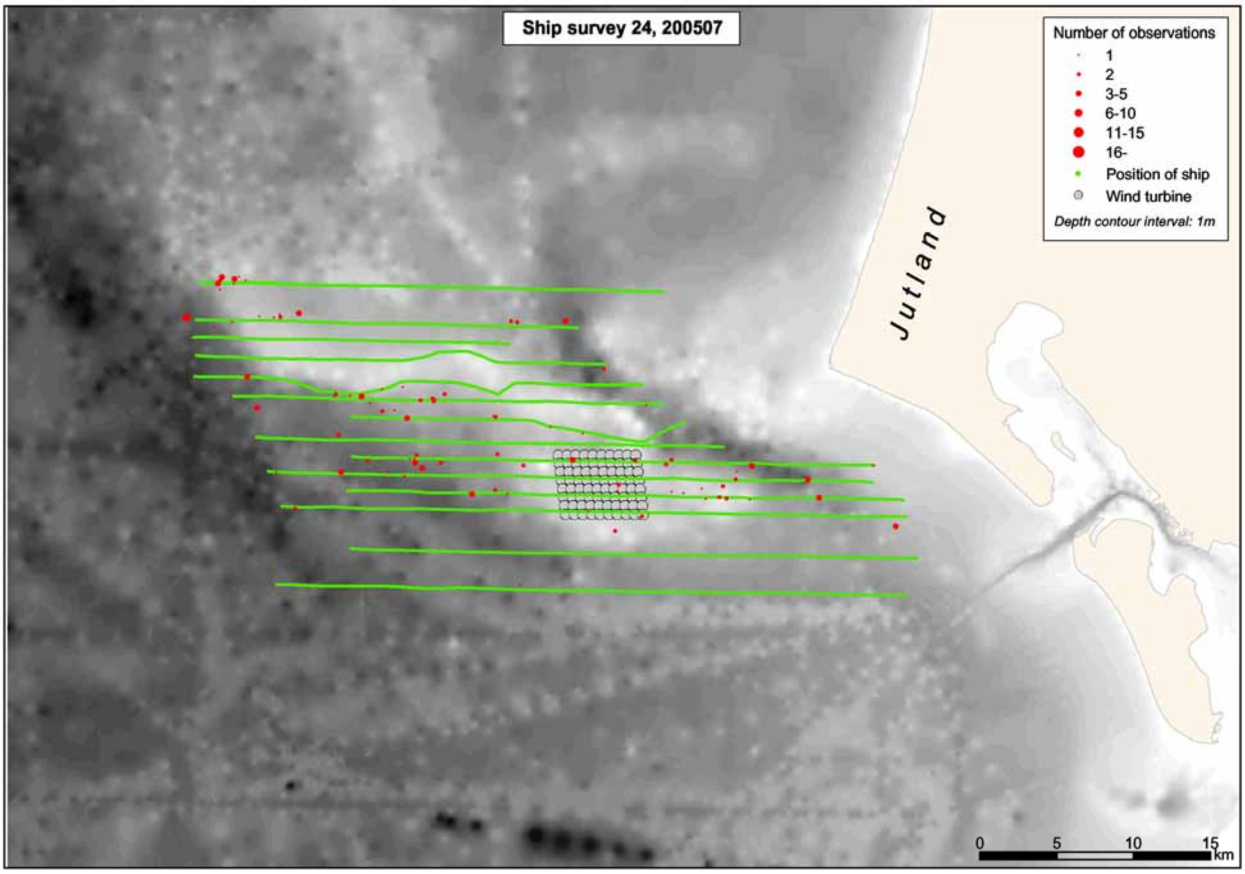

Ship survey 18, 200308
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

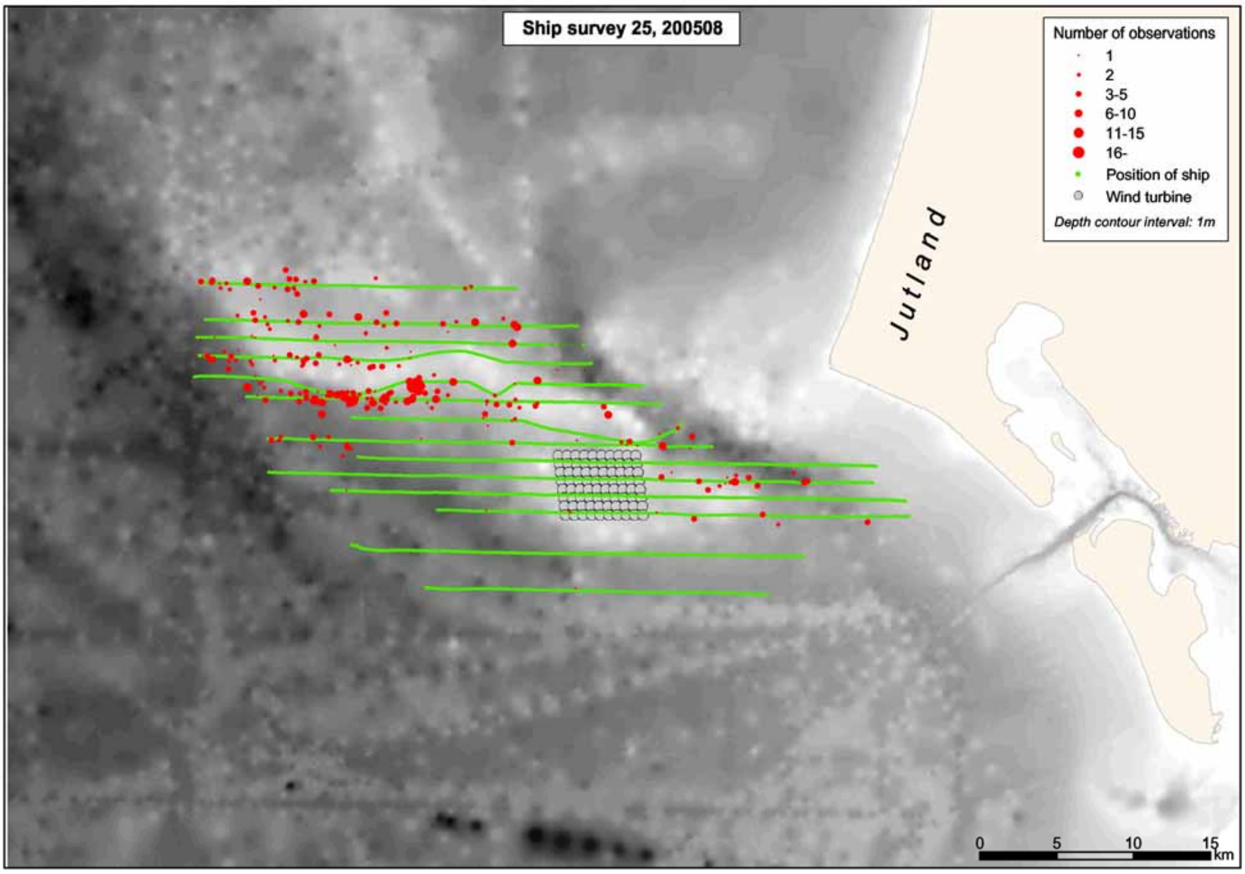

Ship survey 19, 200310
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

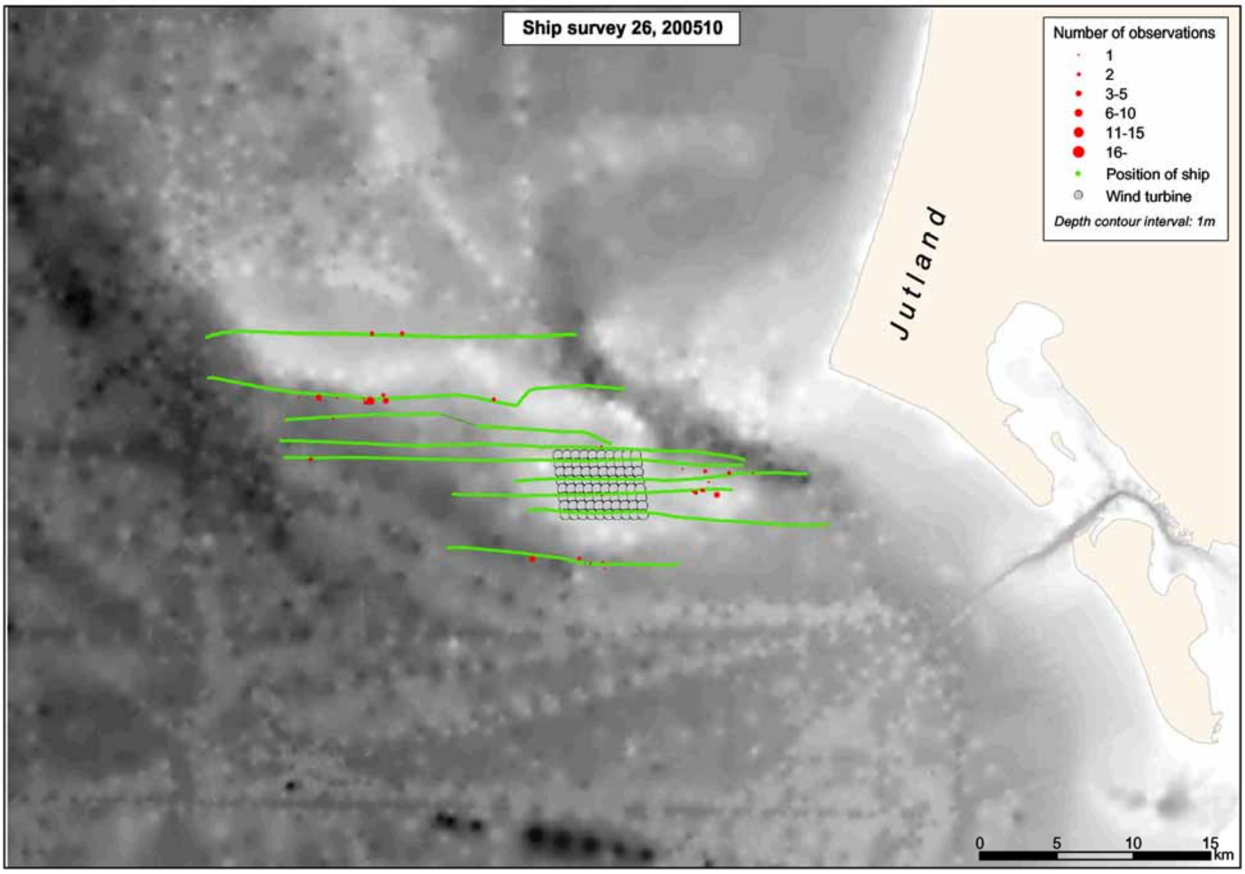

Ship survey 21, 200404
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

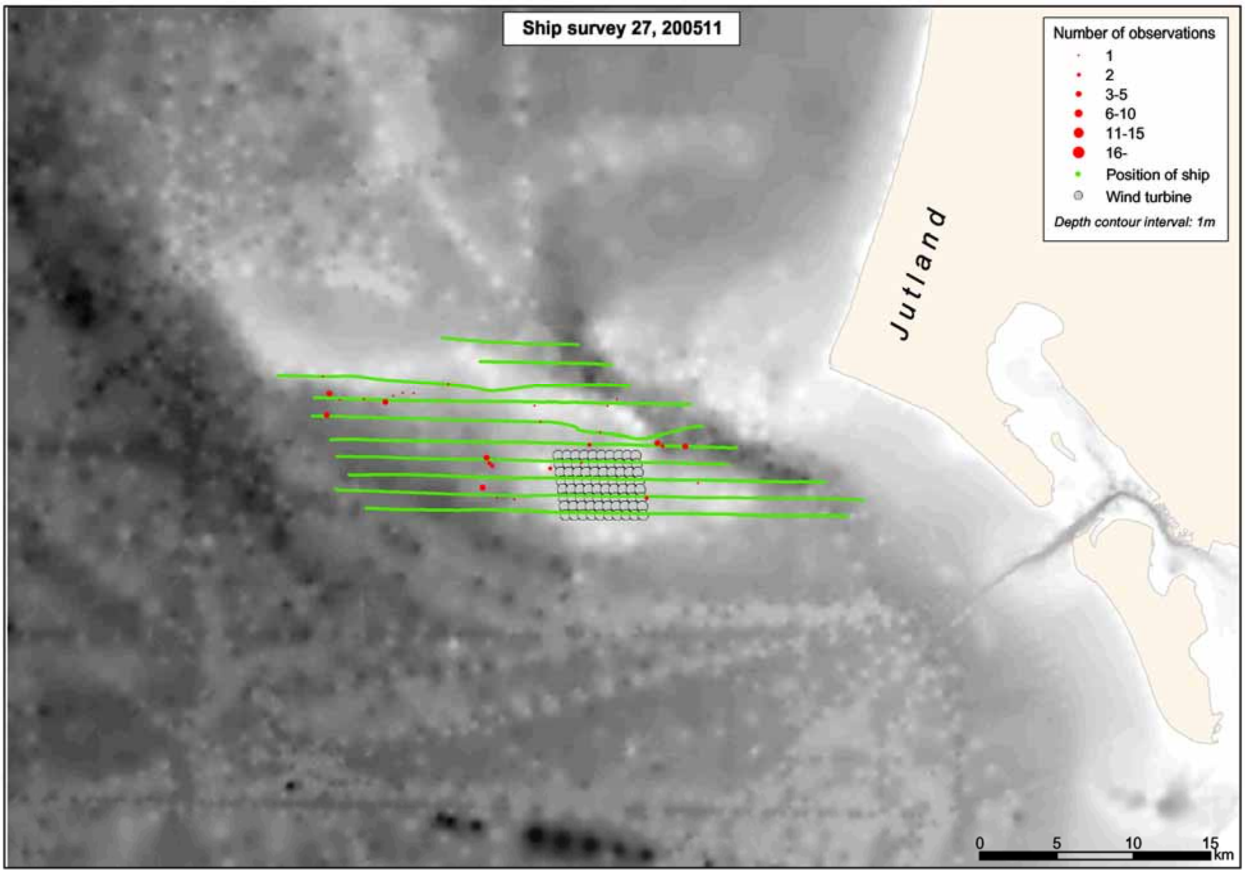

Ship survey 22, 200408
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

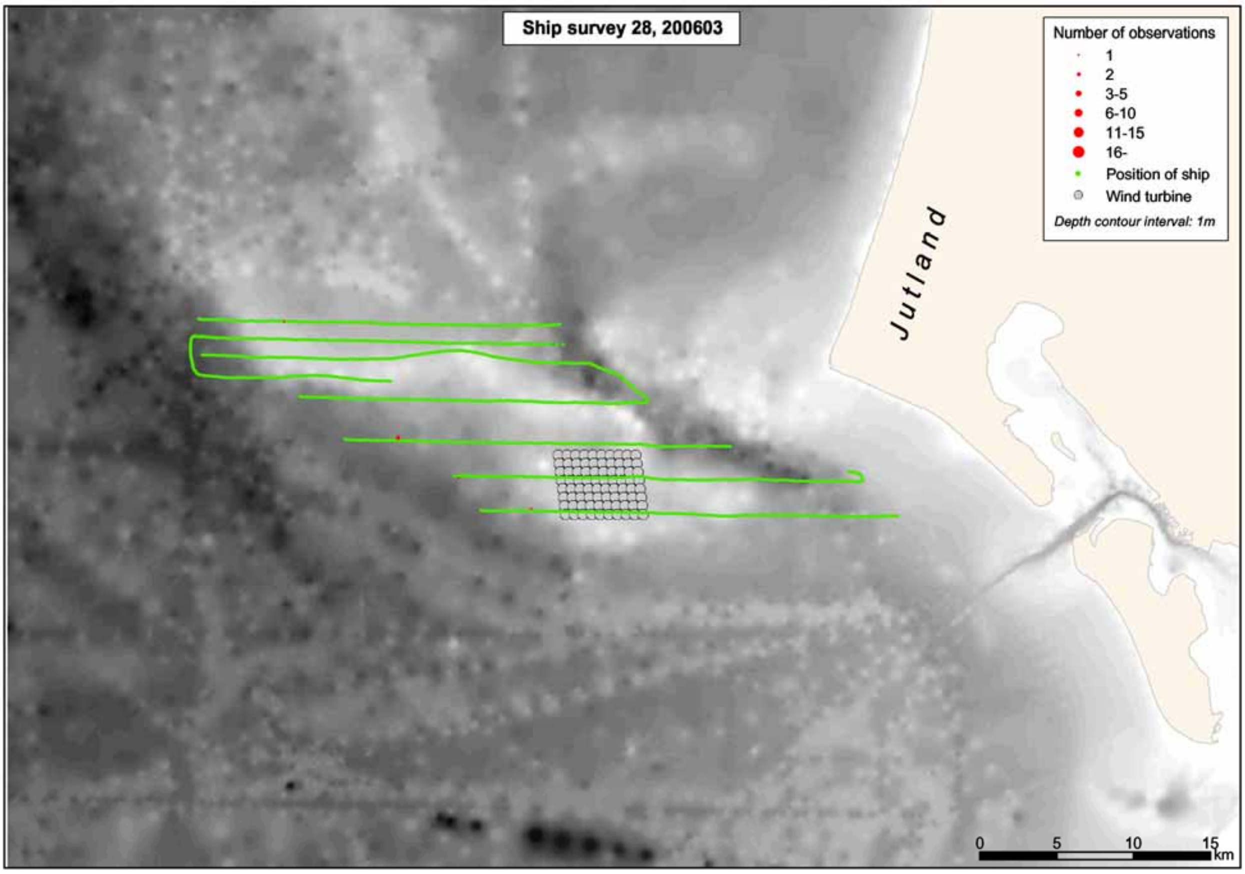

Ship survey 23, 200506
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

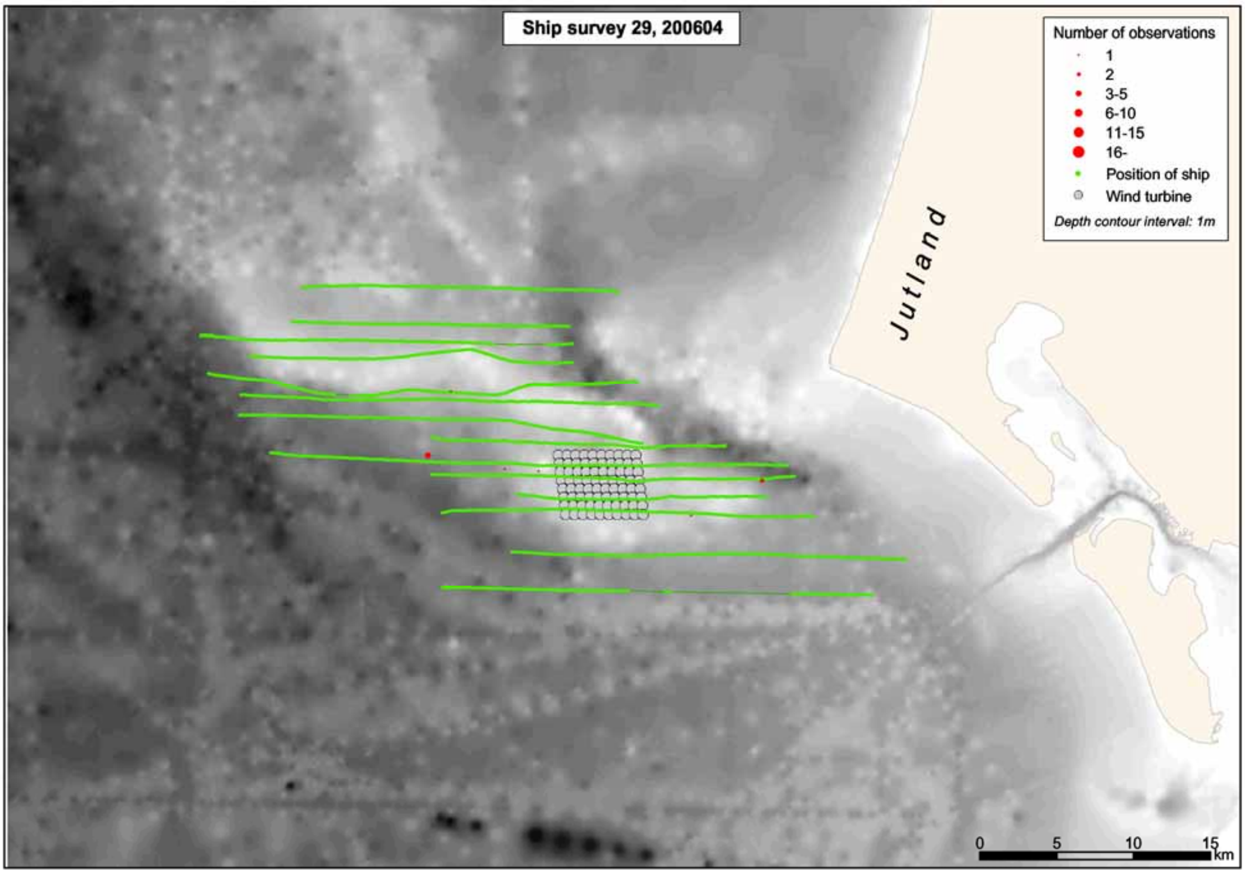

Ship survey 24, 200507
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km


Ship survey 25, 200508
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

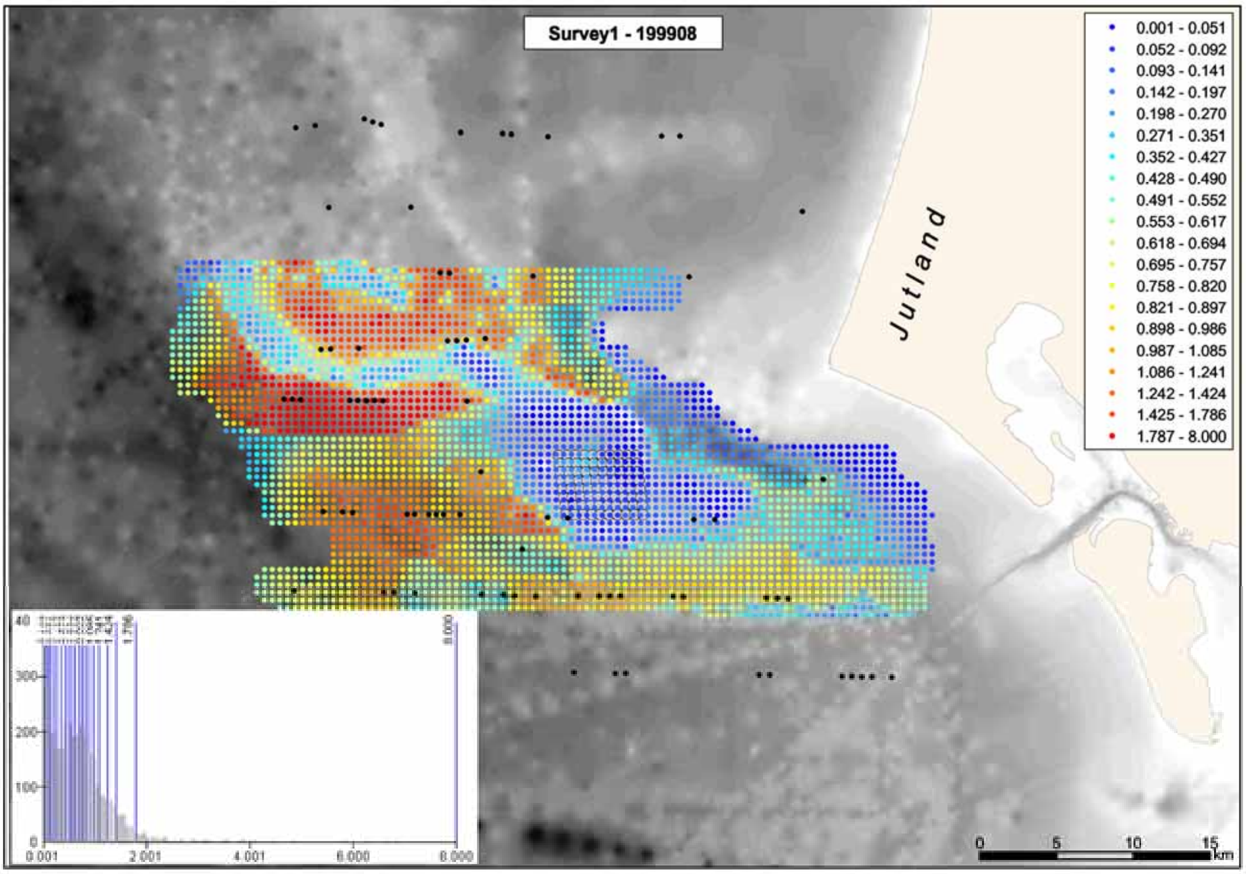

Ship survey 26, 200510
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

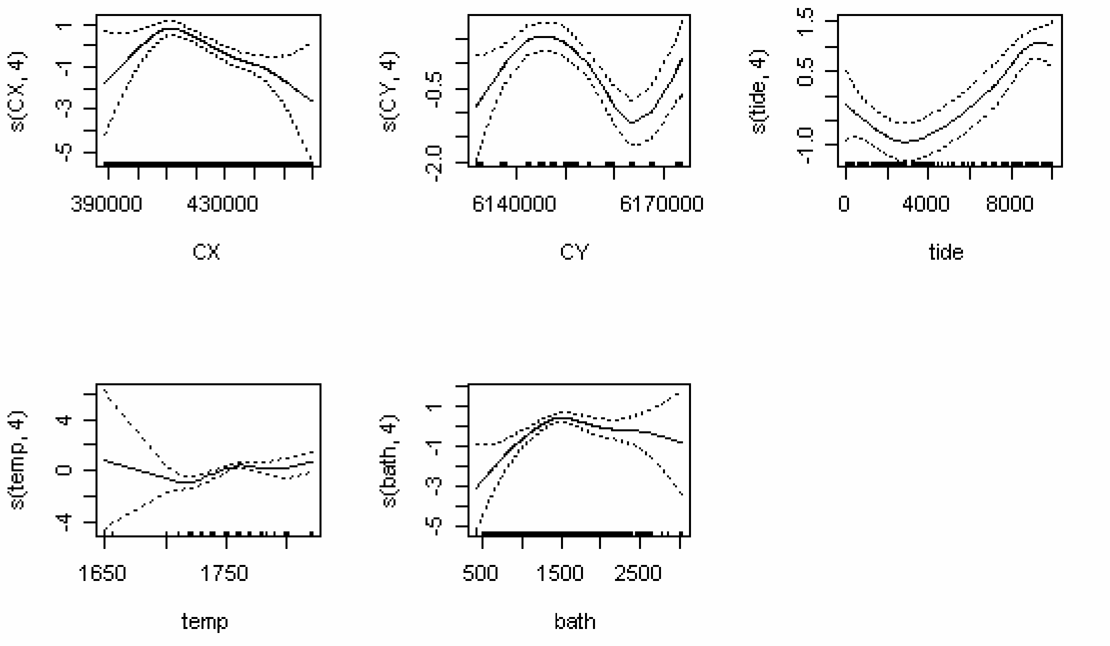

Ship survey 27, 200511
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

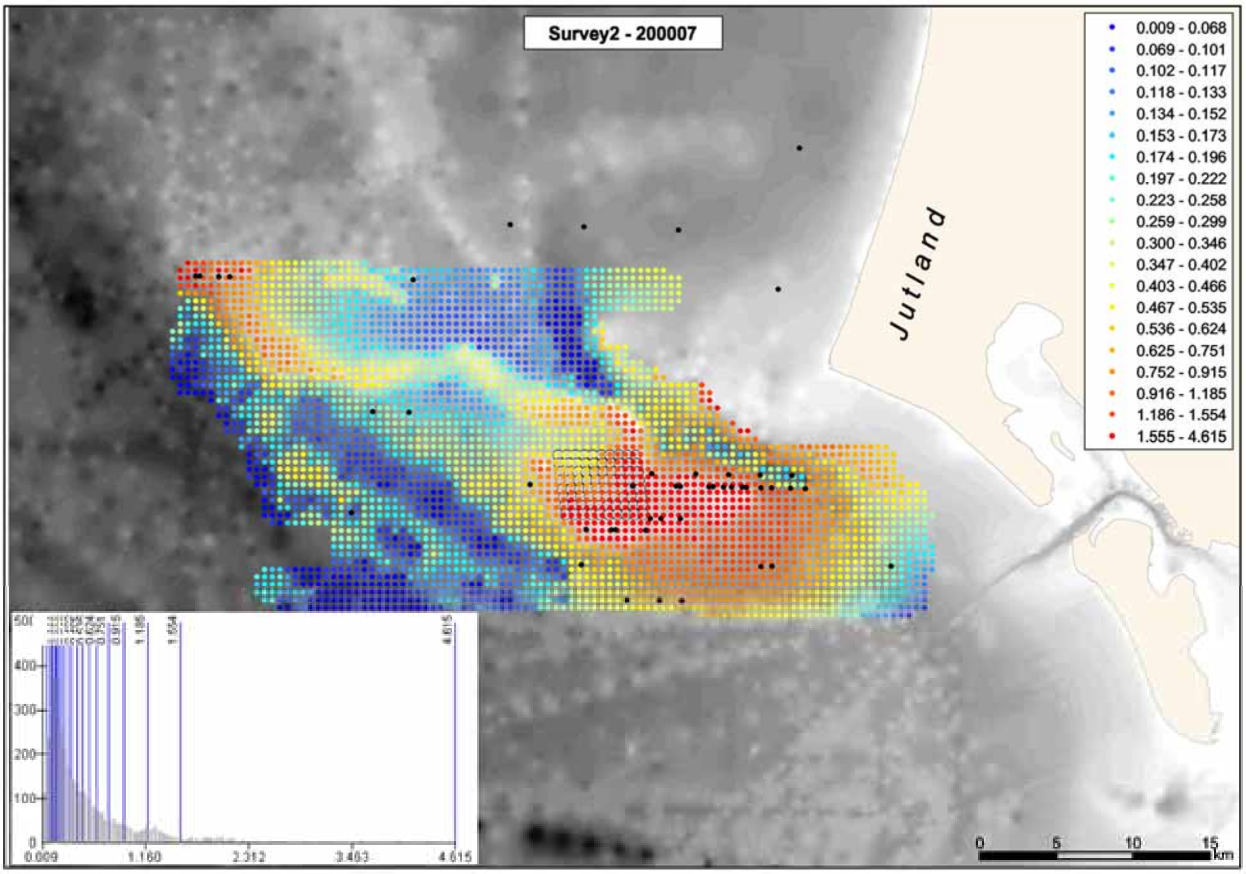

Ship survey 28, 200603
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

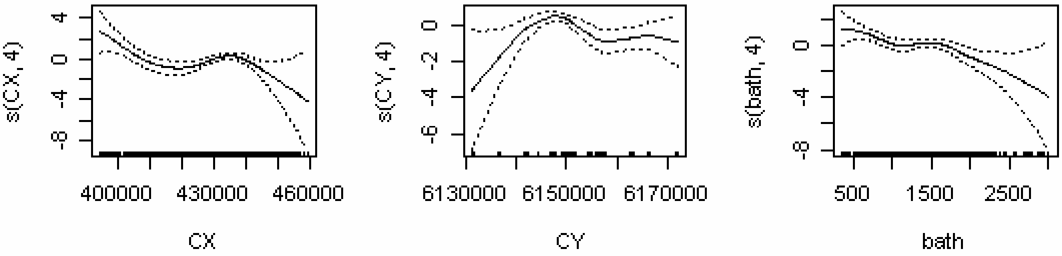

Ship survey 29, 200604
Number of observations
1
2
3-5
6-10
11-15
16-
Position of ship
Wind turbine
Depth contour interval: 1m
Jutland
0
5
10
15
km

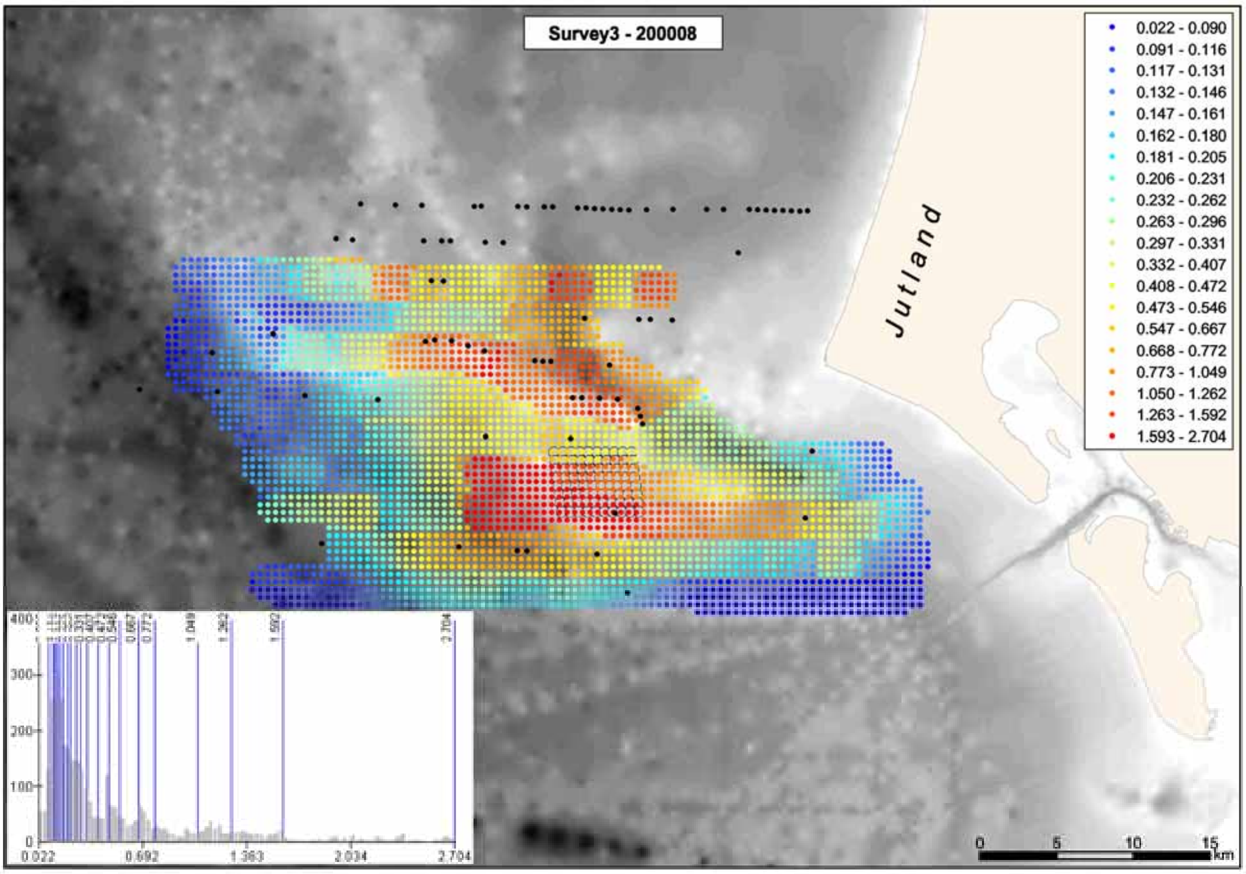
Appendix D – Spatial modelling

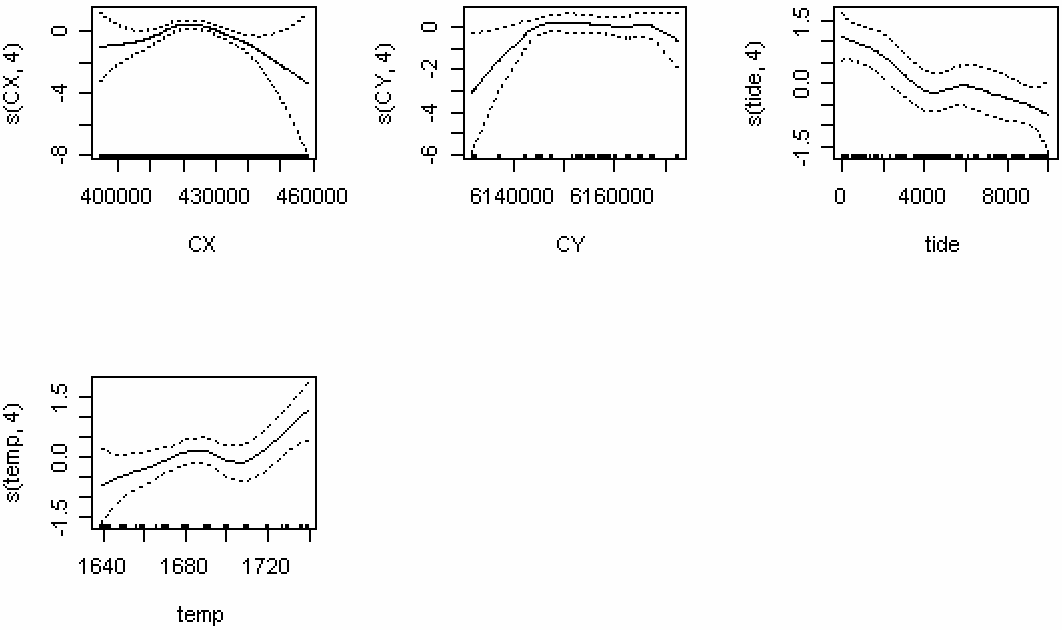


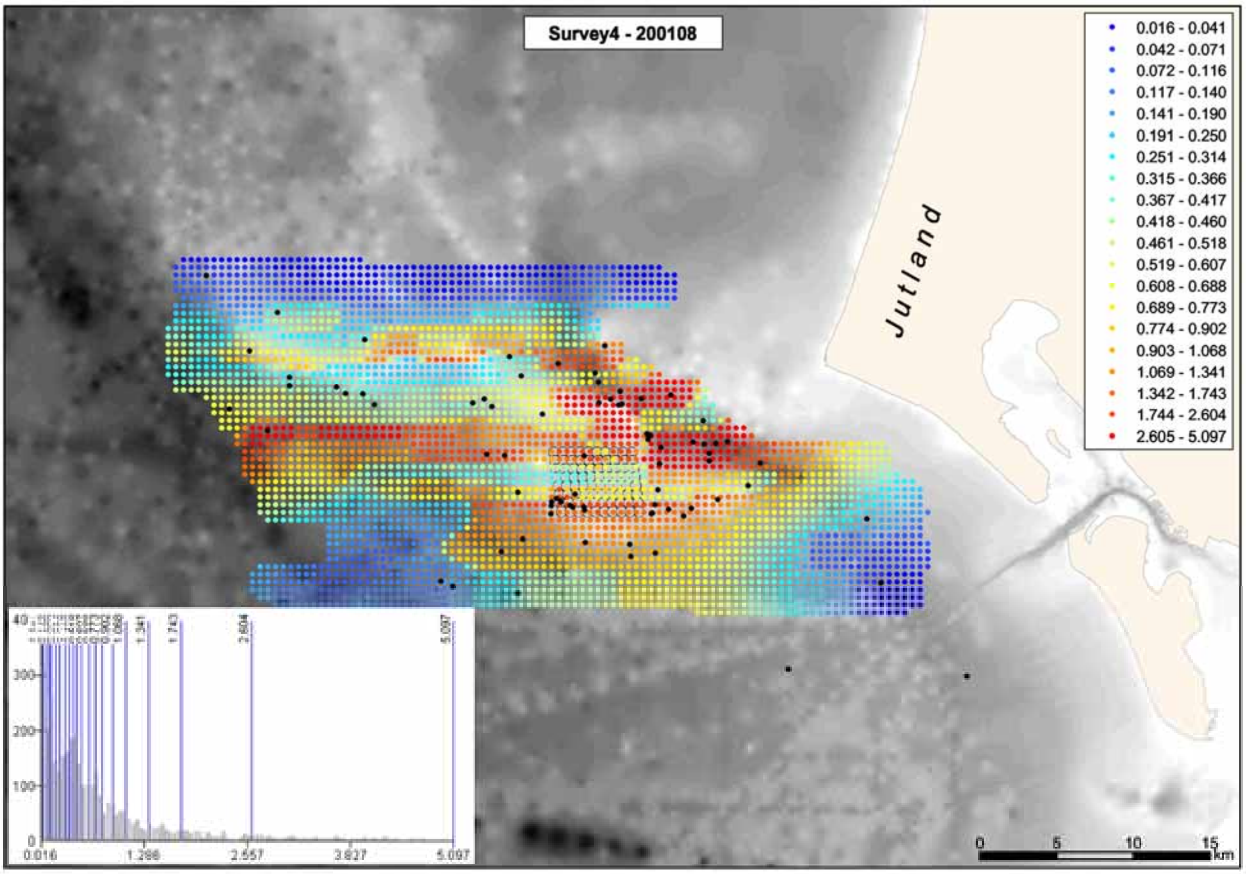


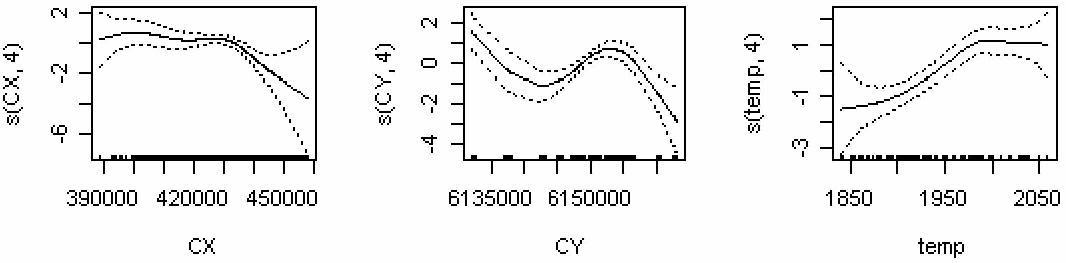

Survey2 - 200007
Jutland
0.009 - 0.068
0.069 - 0.101
0.102 - 0.117
0.118 - 0.133
0.134 - 0.152
0.153 - 0.173
0.174 - 0.196
0.197 - 0.222
0.223 - 0.258
0.259 - 0.299
0.300 - 0.346
0.347 - 0.402
0.403 - 0.466
0.467 - 0.535
0.536 - 0.624
0.625 - 0.751
0.752 - 0.915
0.916 - 1.185
1.186 - 1.554
1.555 - 4.615
0.009
1.160
2.312
3.463
4.615
0
100
200
300
400
0
5
10
15
km

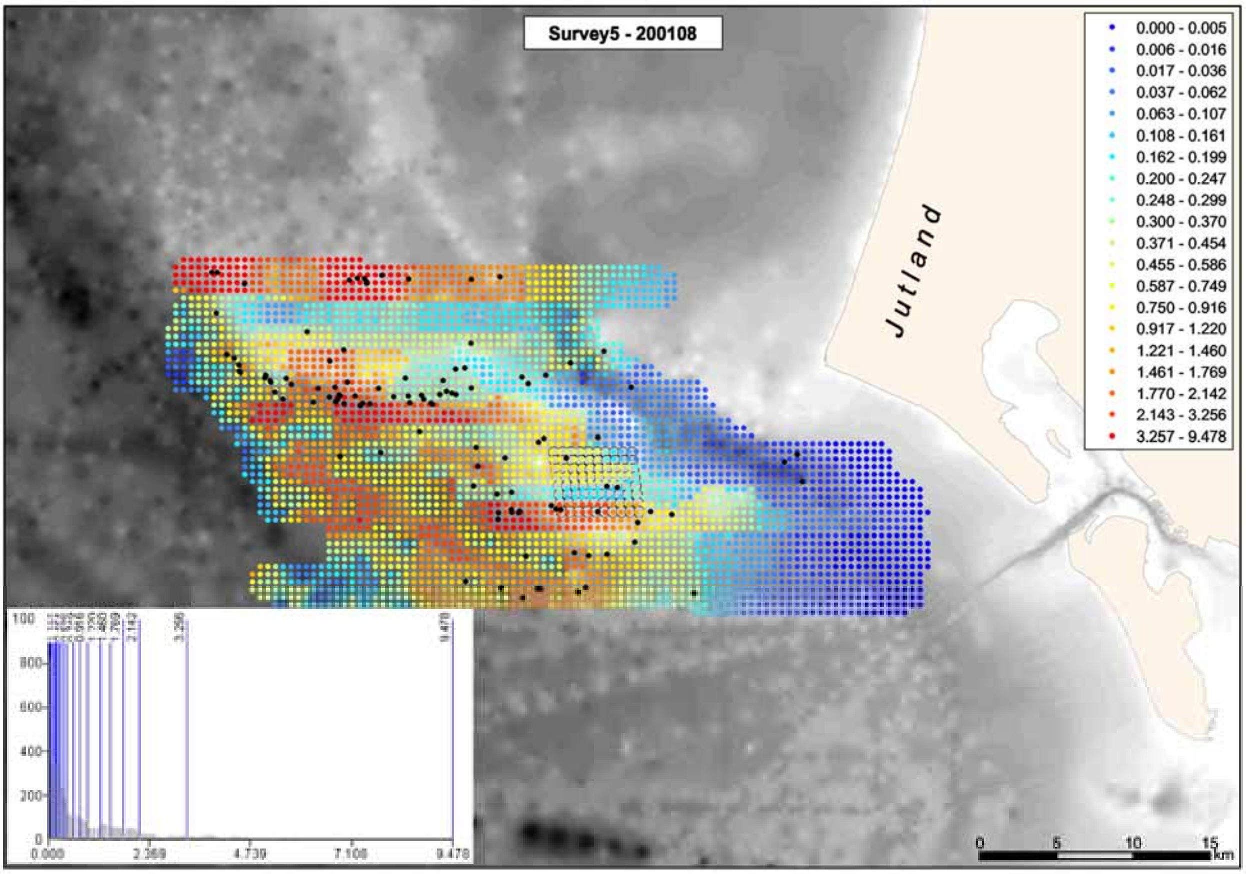

s(CX,4)
CX
400000
430000
460000
s(CY,4)
CY
6130000
6150000
6170000
s(bath,4)
bath
500
1500
2500

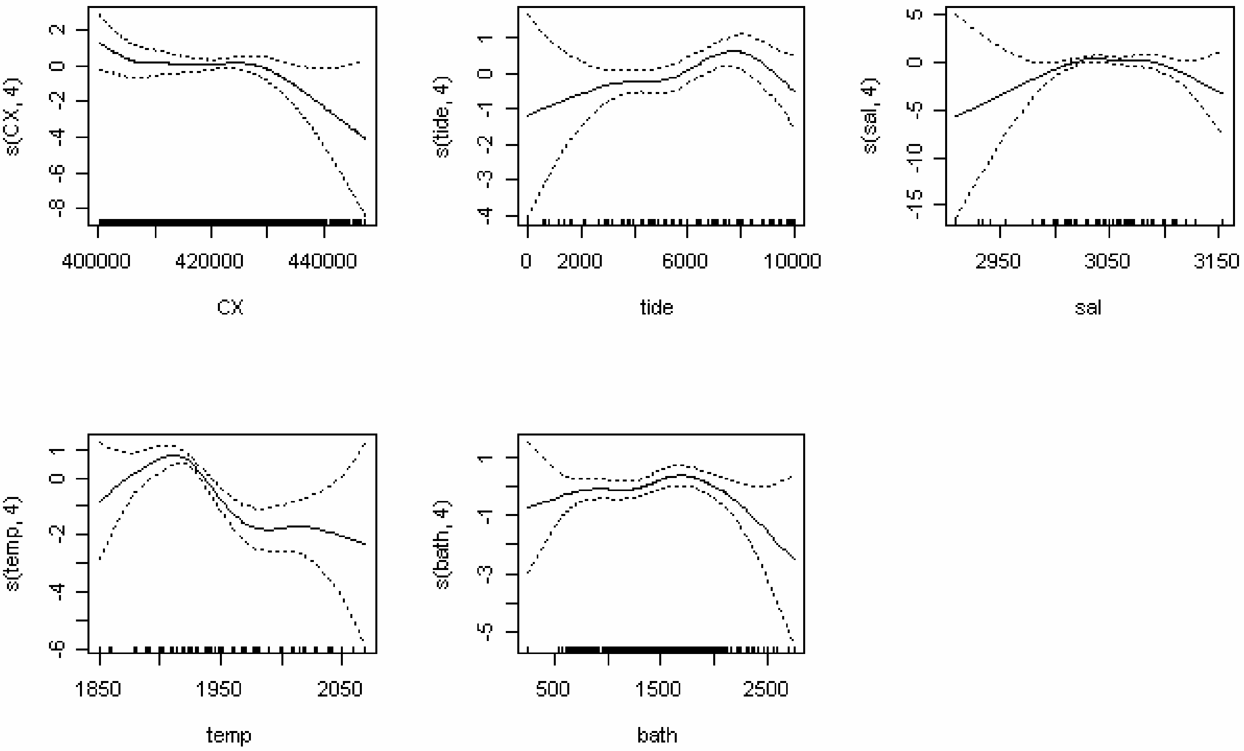

Survey3 - 200008
0.022 - 0.090
0.091 - 0.116
0.117 - 0.131
0.132 - 0.146
0.147 - 0.161
0.162 - 0.180
0.181 - 0.205
0.206 - 0.231
0.232 - 0.262
0.263 - 0.296
0.297 - 0.331
0.332 - 0.407
0.408 - 0.472
0.473 - 0.546
0.547 - 0.667
0.668 - 0.772
0.773 - 1.049
1.050 - 1.262
1.263 - 1.592
1.593 - 2.704
Jutland
400
300
200
100
0
0.022
0.692
1.363
2.034
2.704
0
5
10
15
km

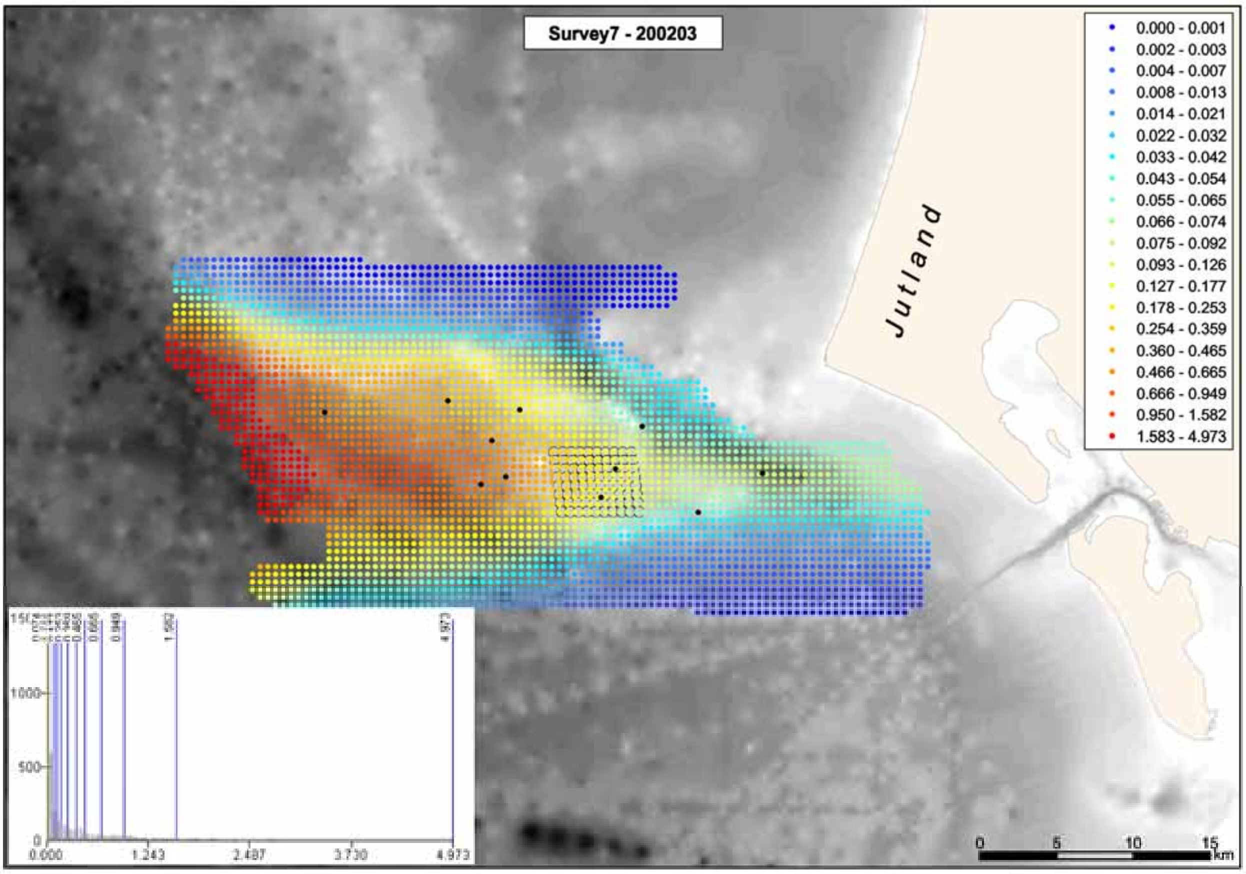

s(CX, 4)
0
-4
-8
400000
430000
460000
CX
s(CY, 4)
0
-2
-4
-6
6140000
6160000
CY
s(tide, 4)
1.5
0.0
-1.5
0
4000
8000
tide
s(temp, 4)
1.5
0.0
-1.5
1640
1680
1720
temp

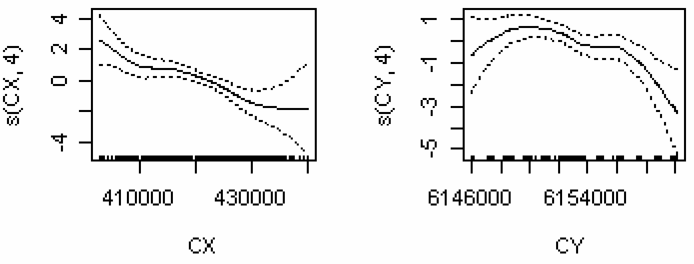

Survey4 - 200108
Jutland
0.016 - 0.041
0.042 - 0.071
0.072 - 0.116
0.117 - 0.140
0.141 - 0.190
0.191 - 0.250
0.251 - 0.314
0.315 - 0.366
0.367 - 0.417
0.418 - 0.460
0.461 - 0.518
0.519 - 0.607
0.608 - 0.688
0.689 - 0.773
0.774 - 0.902
0.903 - 1.068
1.069 - 1.341
1.342 - 1.743
1.744 - 2.604
2.605 - 5.097
0.016
1.286
2.557
3.827
5.097
0
100
200
300
400
1.068
1.341
1.743
2.604
5.097
0
5
10
15
km

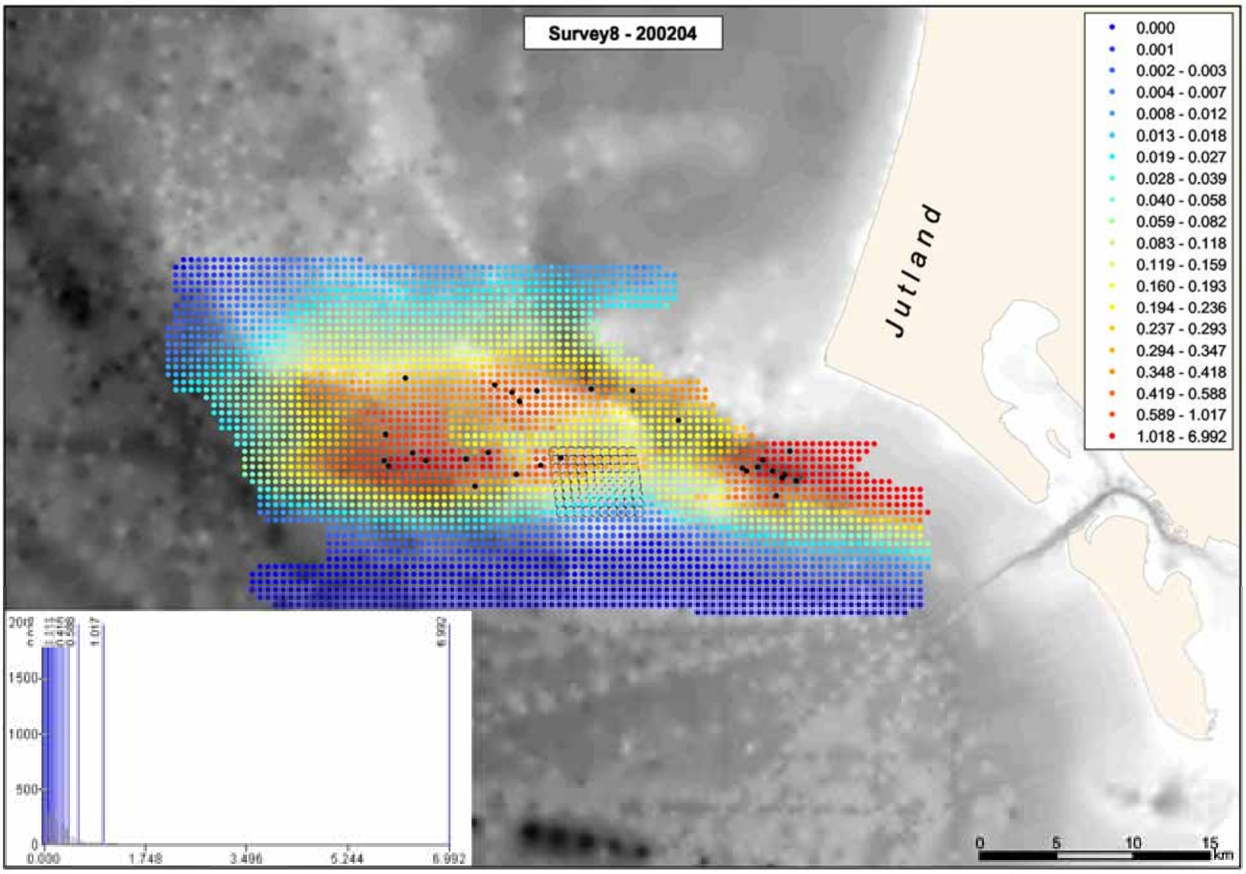

s(CX, 4)
2
-2
-6
390000
420000
450000
CX
s(CY, 4)
2
0
-2
-4
6135000
6150000
CY
s(temp, 4)
1
-1
-3
1850
1950
2050
temp

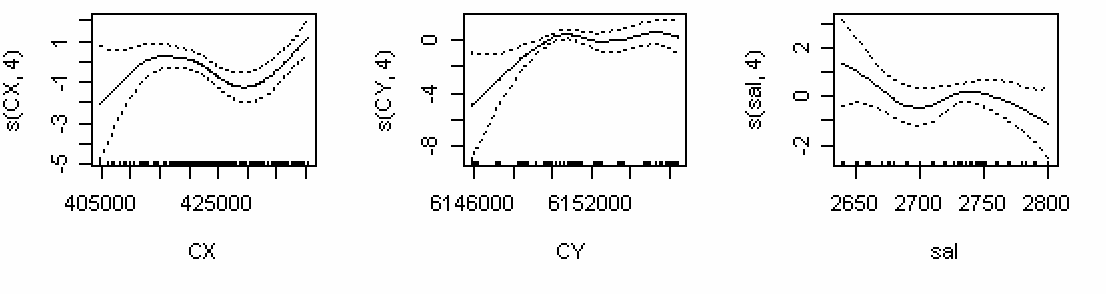

Survey5 - 200108
Jutland
0.000 - 0.005
0.006 - 0.016
0.017 - 0.036
0.037 - 0.062
0.063 - 0.107
0.108 - 0.161
0.162 - 0.199
0.200 - 0.247
0.248 - 0.299
0.300 - 0.370
0.371 - 0.454
0.455 - 0.586
0.587 - 0.749
0.750 - 0.916
0.917 - 1.220
1.221 - 1.460
1.461 - 1.769
1.770 - 2.142
2.143 - 3.256
3.257 - 9.478
0.000
2.369
4.739
7.108
9.478
0
200
400
600
800
100
0 5 10 15 km

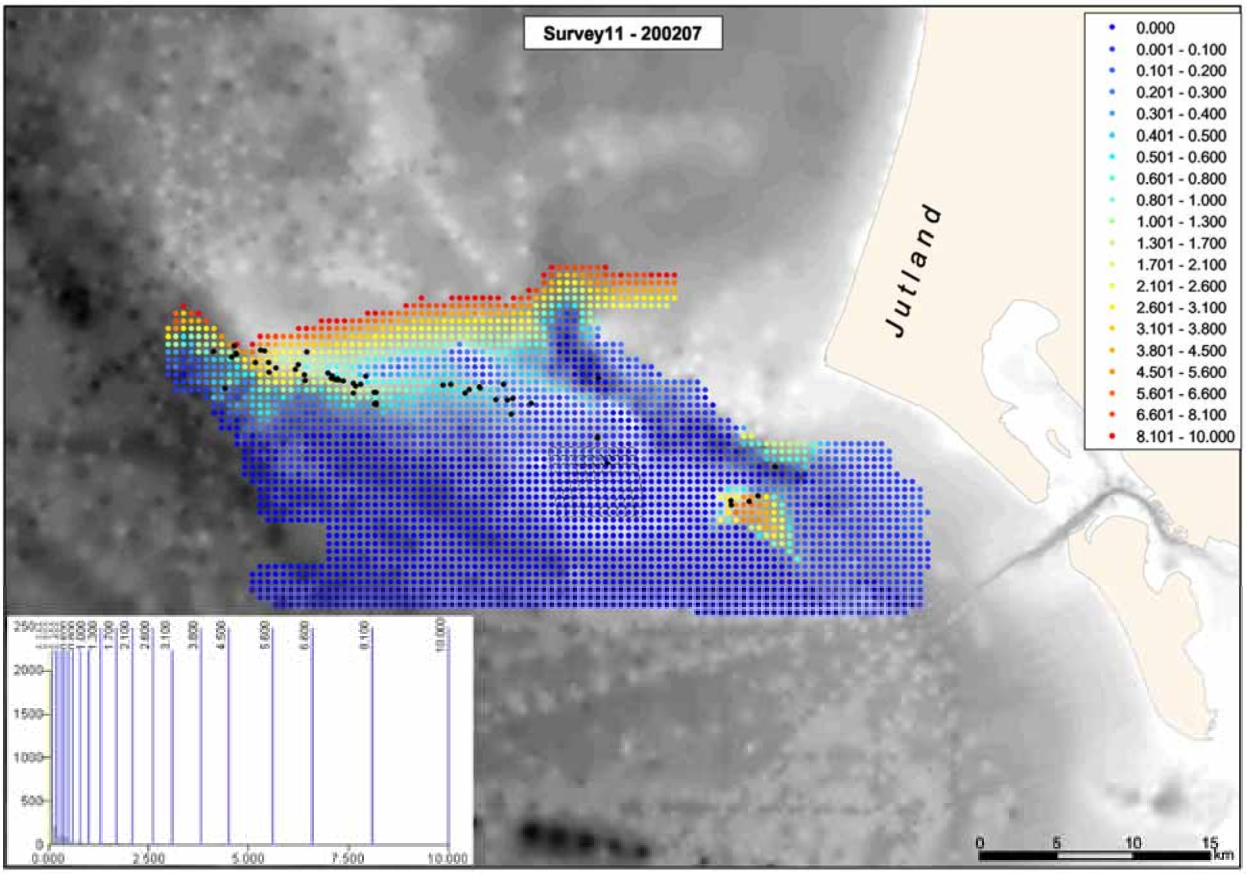

s(CX, 4)
CX
400000
420000
440000
s(tide, 4)
tide
0
2000
6000
10000
s(sal, 4)
sal
2950
3050
3150
s(temp, 4)
temp
1850
1950
2050
s(bath, 4)
bath
500
1500
2500

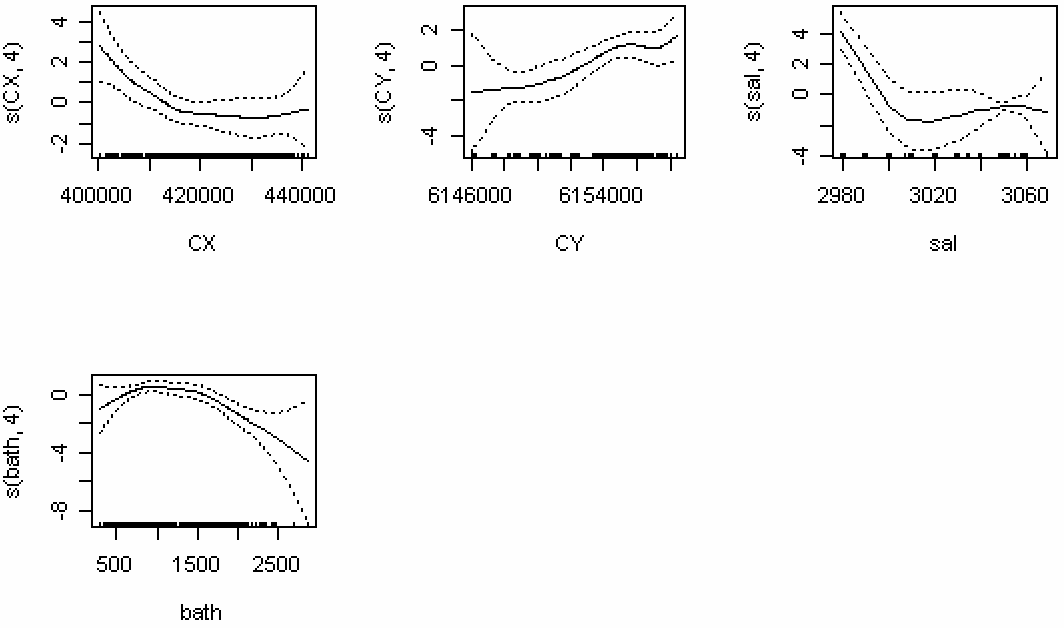

Survey7 - 200203
Jutland
0.000 - 0.001
0.002 - 0.003
0.004 - 0.007
0.008 - 0.013
0.014 - 0.021
0.022 - 0.032
0.033 - 0.042
0.043 - 0.054
0.055 - 0.065
0.066 - 0.074
0.075 - 0.092
0.093 - 0.126
0.127 - 0.177
0.178 - 0.253
0.254 - 0.359
0.360 - 0.465
0.466 - 0.665
0.666 - 0.949
0.950 - 1.582
1.583 - 4.973
1500
1000
500
0
0.000
1.243
2.487
3.730
4.973
0.665
0.949
1.582
4.973
0
5
10
15
km

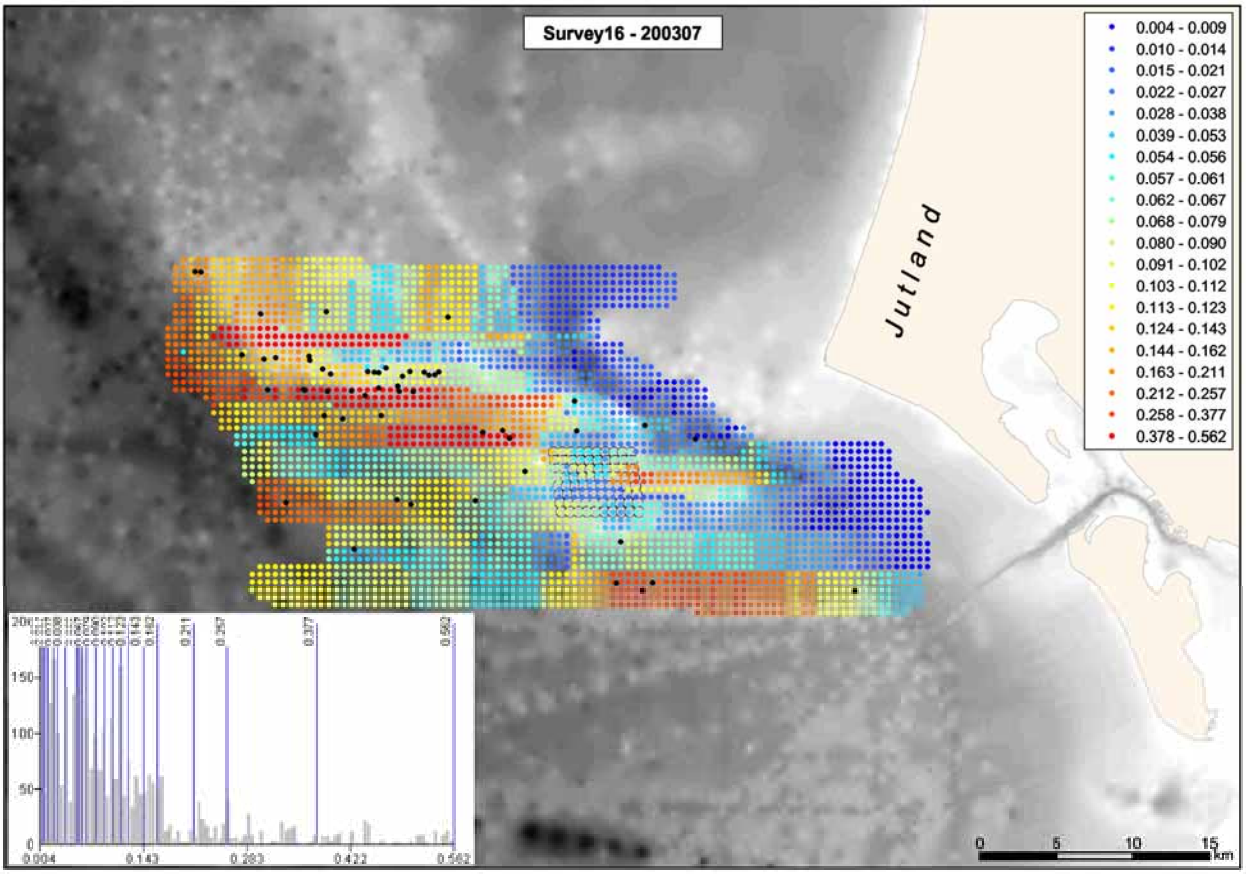

s(CX,4)
4
2
0
-4
410000
430000
CX
s(CY,4)
1
-1
-3
-5
6146000
6154000
CY

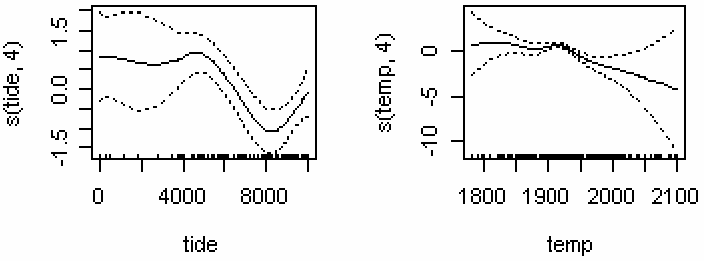

Survey8 - 200204
0.000
0.001
0.002 - 0.003
0.004 - 0.007
0.008 - 0.012
0.013 - 0.018
0.019 - 0.027
0.028 - 0.039
0.040 - 0.058
0.059 - 0.082
0.083 - 0.118
0.119 - 0.159
0.160 - 0.193
0.194 - 0.236
0.237 - 0.293
0.294 - 0.347
0.348 - 0.418
0.419 - 0.588
0.589 - 1.017
1.018 - 6.992
Jutland
2000
1500
1000
500
0
0.000
1.748
3.496
5.244
6.992
1.017
0
5
10
15
km

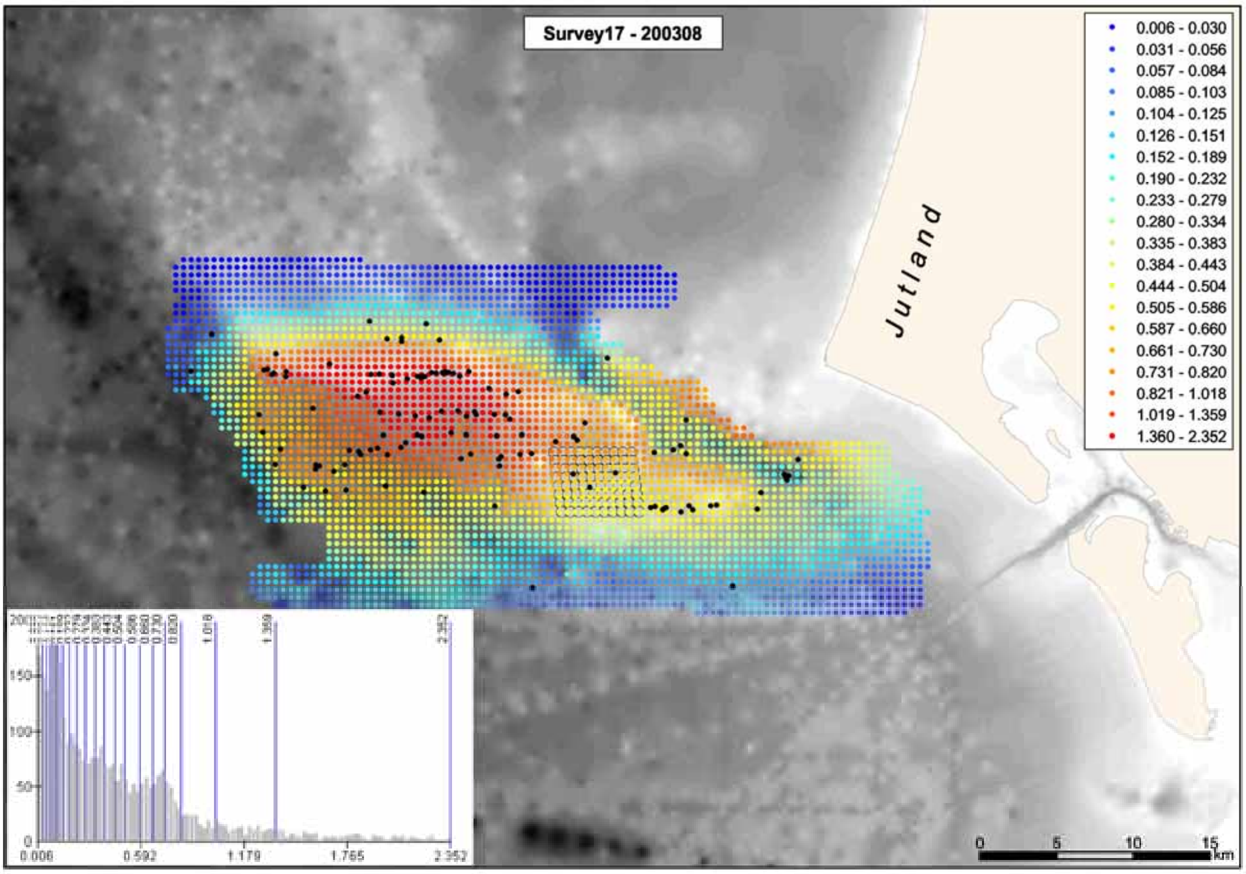

s(CX, 4)
1
-1
-3
-5
405000
425000
CX
s(CY, 4)
0
-4
-8
6146000
6152000
CY
s(sal, 4)
2
0
-2
2650
2700
2750
2800
sal

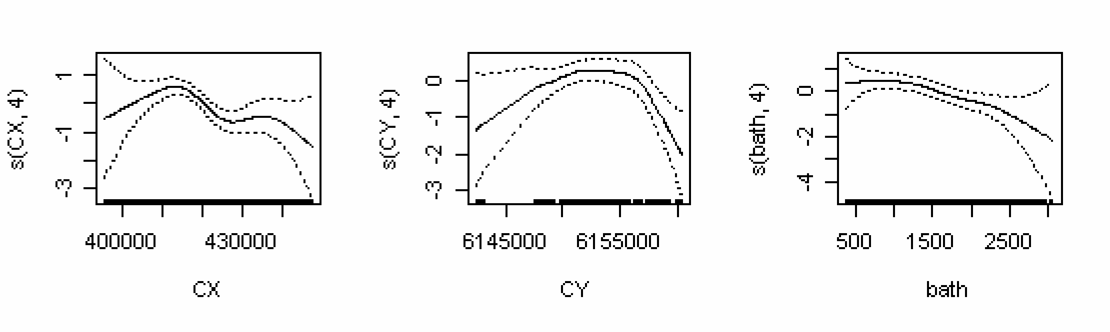

Survey11 - 200207
0.000
0.001 - 0.100
0.101 - 0.200
0.201 - 0.300
0.301 - 0.400
0.401 - 0.500
0.501 - 0.600
0.601 - 0.800
0.801 - 1.000
1.001 - 1.300
1.301 - 1.700
1.701 - 2.100
2.101 - 2.600
2.601 - 3.100
3.101 - 3.800
3.801 - 4.500
4.501 - 5.600
5.601 - 6.600
6.601 - 8.100
8.101 - 10.000
Jutland
2000
1500
1000
500
0
0.000
2.500
5.000
7.500
10.000
0
5
10
15
km

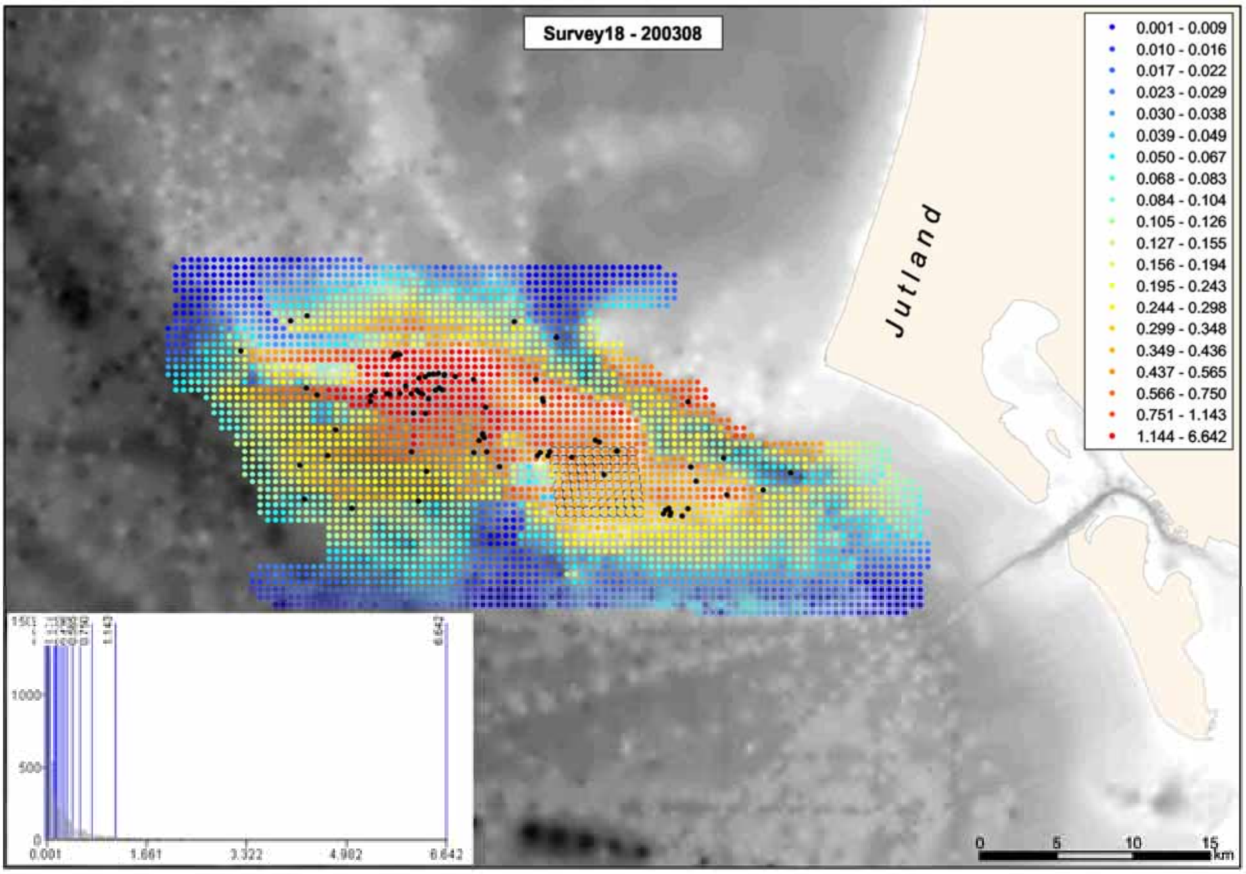

s(CX, 4)
4
2
0
-2
400000
420000
440000
CX
s(CY, 4)
2
0
-4
6146000
6154000
CY
s(sal, 4)
4
2
0
-4
2980
3020
3060
sal
s(bath, 4)
0
-4
-8
500
1500
2500
bath

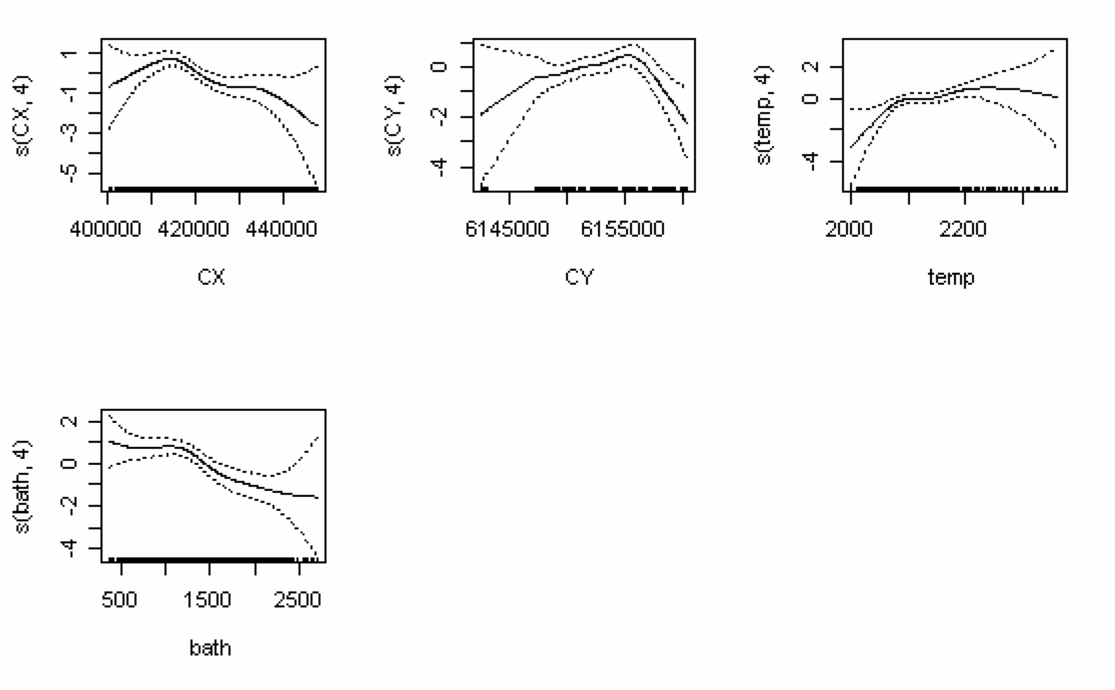

Survey16 - 200307
0.004 - 0.009
0.010 - 0.014
0.015 - 0.021
0.022 - 0.027
0.028 - 0.038
0.039 - 0.053
0.054 - 0.056
0.057 - 0.061
0.062 - 0.067
0.068 - 0.079
0.080 - 0.090
0.091 - 0.102
0.103 - 0.112
0.113 - 0.123
0.124 - 0.143
0.144 - 0.162
0.163 - 0.211
0.212 - 0.257
0.258 - 0.377
0.378 - 0.562
Jutland
0.211
0.257
0.377
0.562
200
150
100
50
0
0.004
0.143
0.283
0.422
0.562
0
5
10
15
km

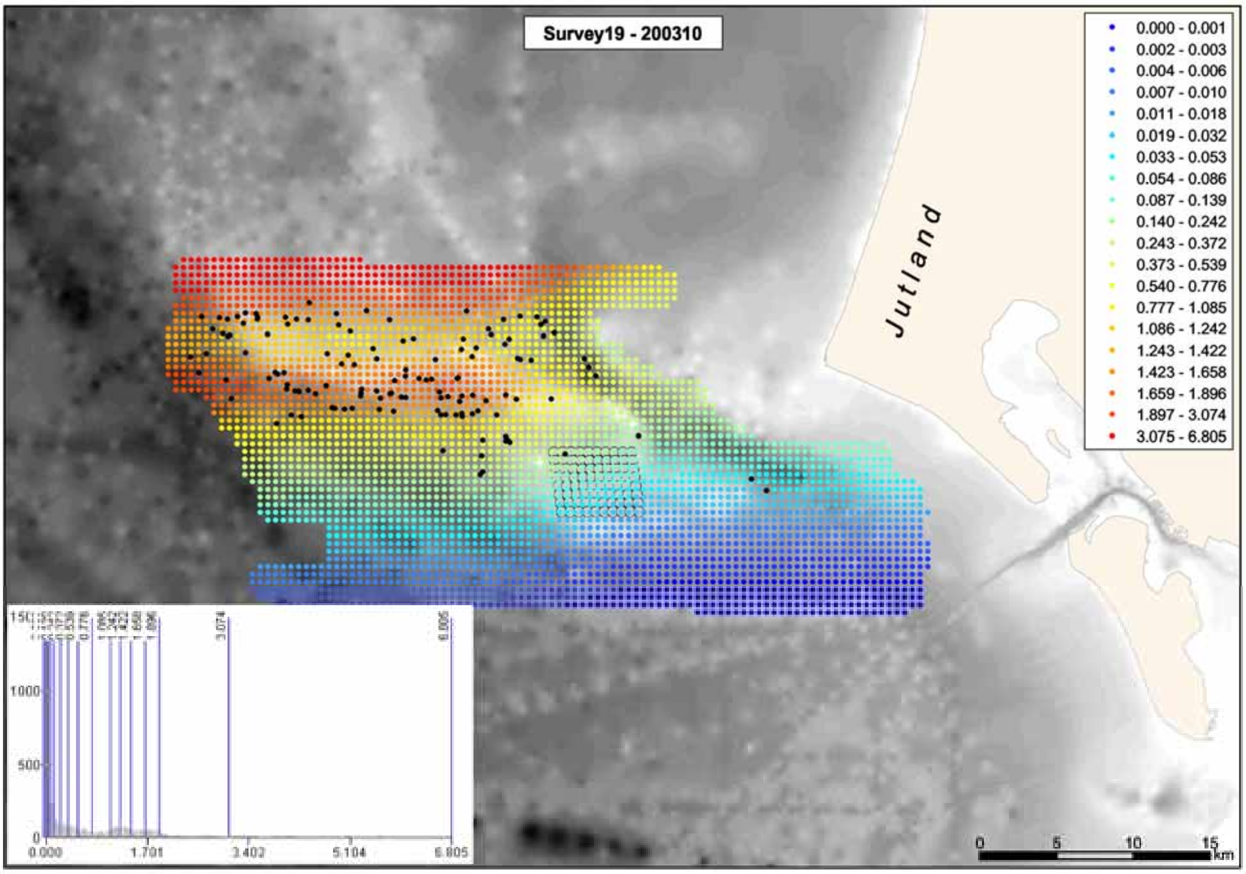

s(tide, 4)
1.5
0.0
-1.5
0
4000
8000
tide
s(temp, 4)
0
-5
-10
1800
1900
2000
2100
temp

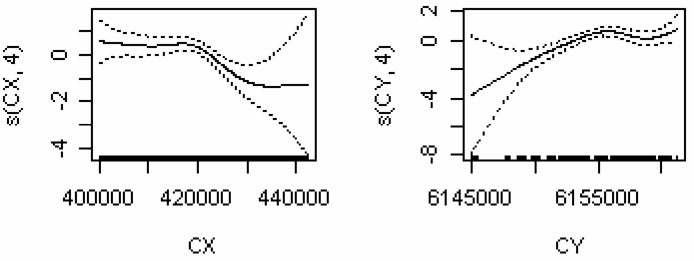

Survey17 - 200308
Jutland
0.006 - 0.030
0.031 - 0.056
0.057 - 0.084
0.085 - 0.103
0.104 - 0.125
0.126 - 0.151
0.152 - 0.189
0.190 - 0.232
0.233 - 0.279
0.280 - 0.334
0.335 - 0.383
0.384 - 0.443
0.444 - 0.504
0.505 - 0.586
0.587 - 0.660
0.661 - 0.730
0.731 - 0.820
0.821 - 1.018
1.019 - 1.359
1.360 - 2.352
200
150
100
50
0
0.006
0.592
1.179
1.765
2.352
1.018
1.359
0
5
10
15
km

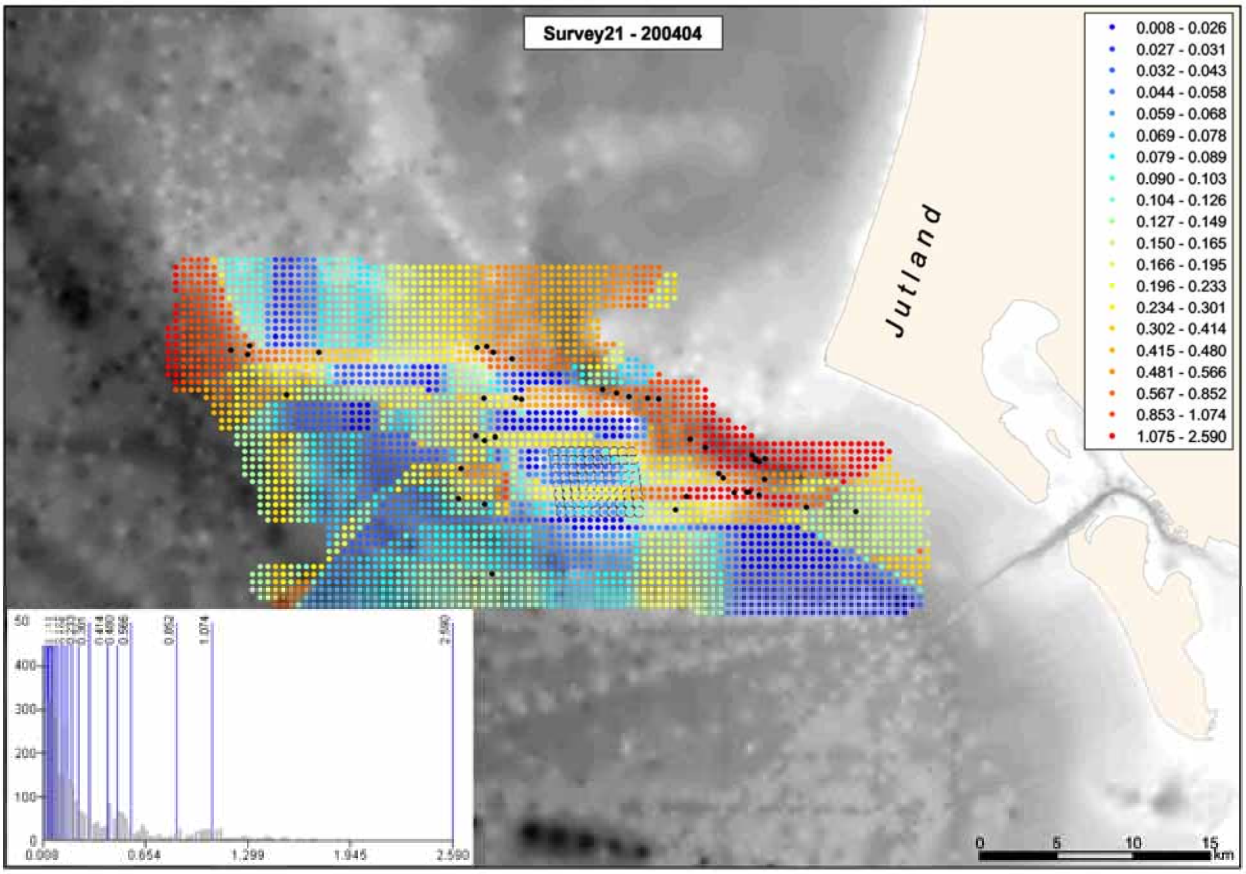

s(CX, 4)
1
-1
-3
400000
430000
CX
s(CY, 4)
0
-1
-2
-3
6145000
6155000
CY
s(bath, 4)
0
-2
-4
500
1500
2500
bath

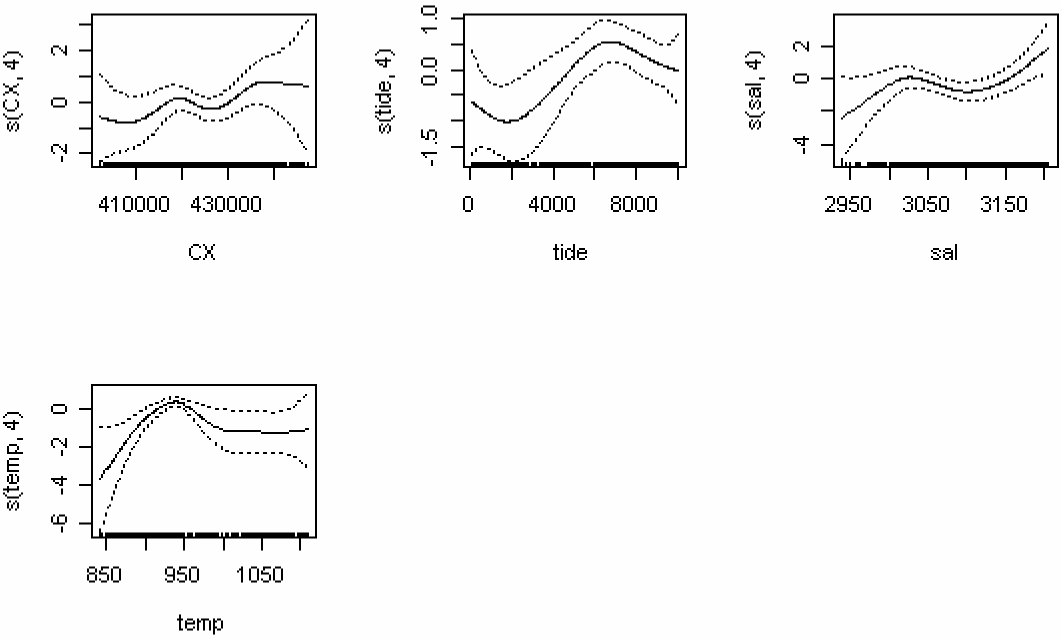

Survey18 - 200308
0.001 - 0.009
0.010 - 0.016
0.017 - 0.022
0.023 - 0.029
0.030 - 0.038
0.039 - 0.049
0.050 - 0.067
0.068 - 0.083
0.084 - 0.104
0.105 - 0.126
0.127 - 0.155
0.156 - 0.194
0.195 - 0.243
0.244 - 0.298
0.299 - 0.348
0.349 - 0.436
0.437 - 0.565
0.566 - 0.750
0.751 - 1.143
1.144 - 6.642
Jutland
1000
500
0
0.001
1.661
3.322
4.982
6.642
0
5
10
15
km

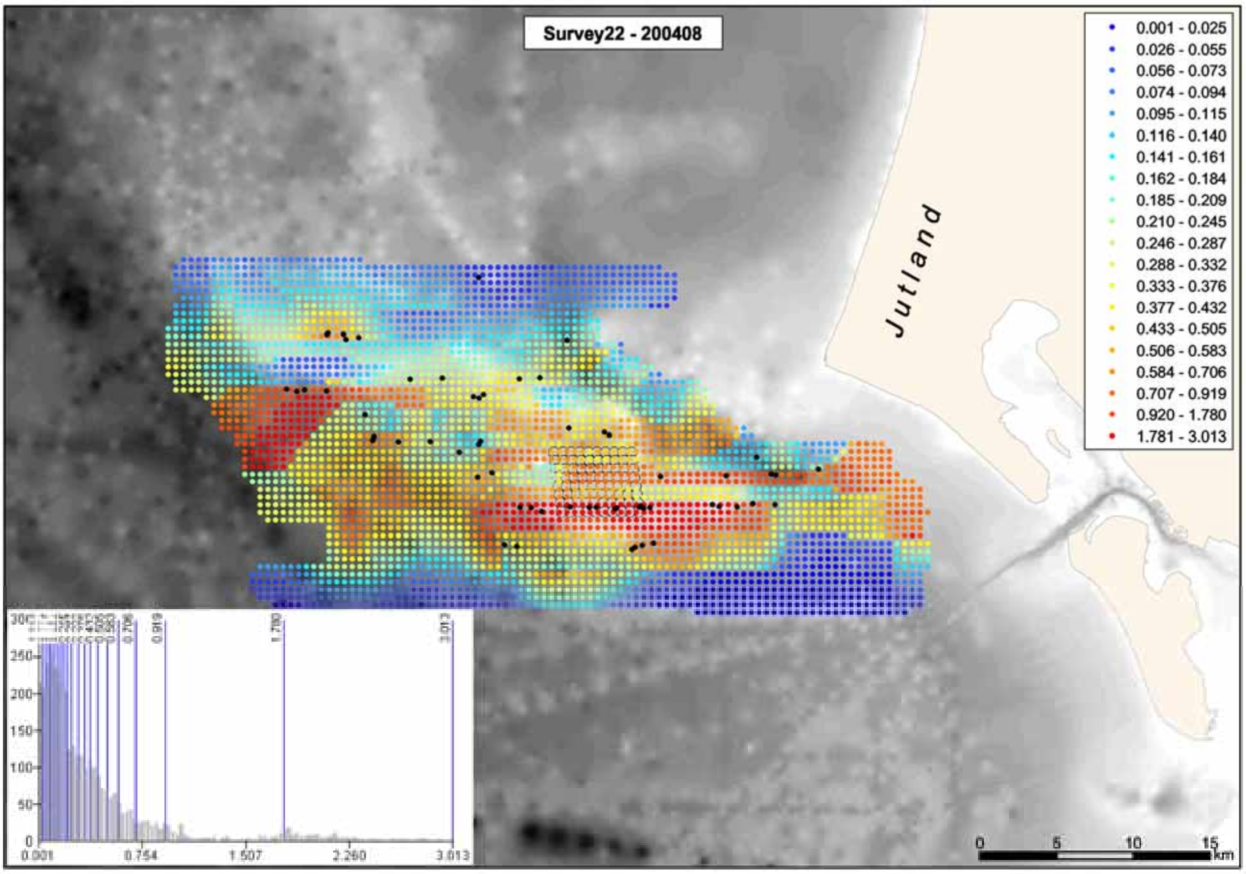

s(CX, 4)
1
-1
-3
-5
400000
420000
440000
CX
s(CY, 4)
0
-2
-4
6145000
6155000
CY
s(temp, 4)
2
0
-4
2000
2200
temp
s(bath, 4)
2
0
-2
-4
500
1500
2500
bath

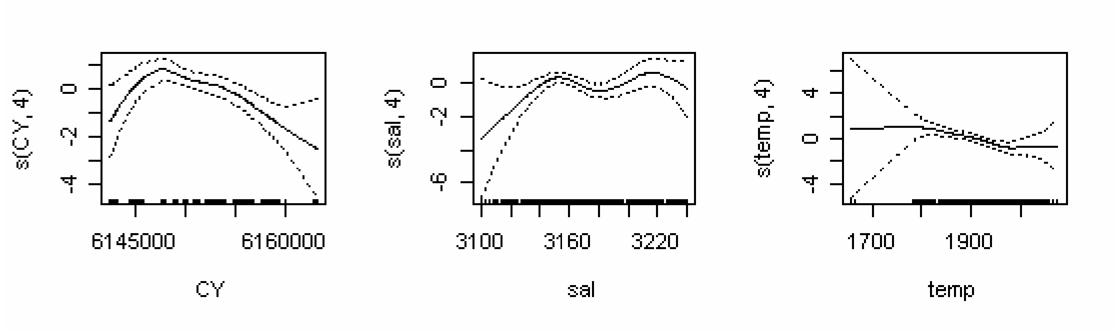

Survey19 - 200310
● 0.000 - 0.001
● 0.002 - 0.003
● 0.004 - 0.006
● 0.007 - 0.010
● 0.011 - 0.018
● 0.019 - 0.032
● 0.033 - 0.053
● 0.054 - 0.086
● 0.087 - 0.139
● 0.140 - 0.242
● 0.243 - 0.372
● 0.373 - 0.539
● 0.540 - 0.776
● 0.777 - 1.085
● 1.086 - 1.242
● 1.243 - 1.422
● 1.423 - 1.658
● 1.659 - 1.896
● 1.897 - 3.074
● 3.075 - 6.805
Jutland
1000
500
0
0.000
1.701
3.402
5.104
6.805
3.074
0
5
10
15
km

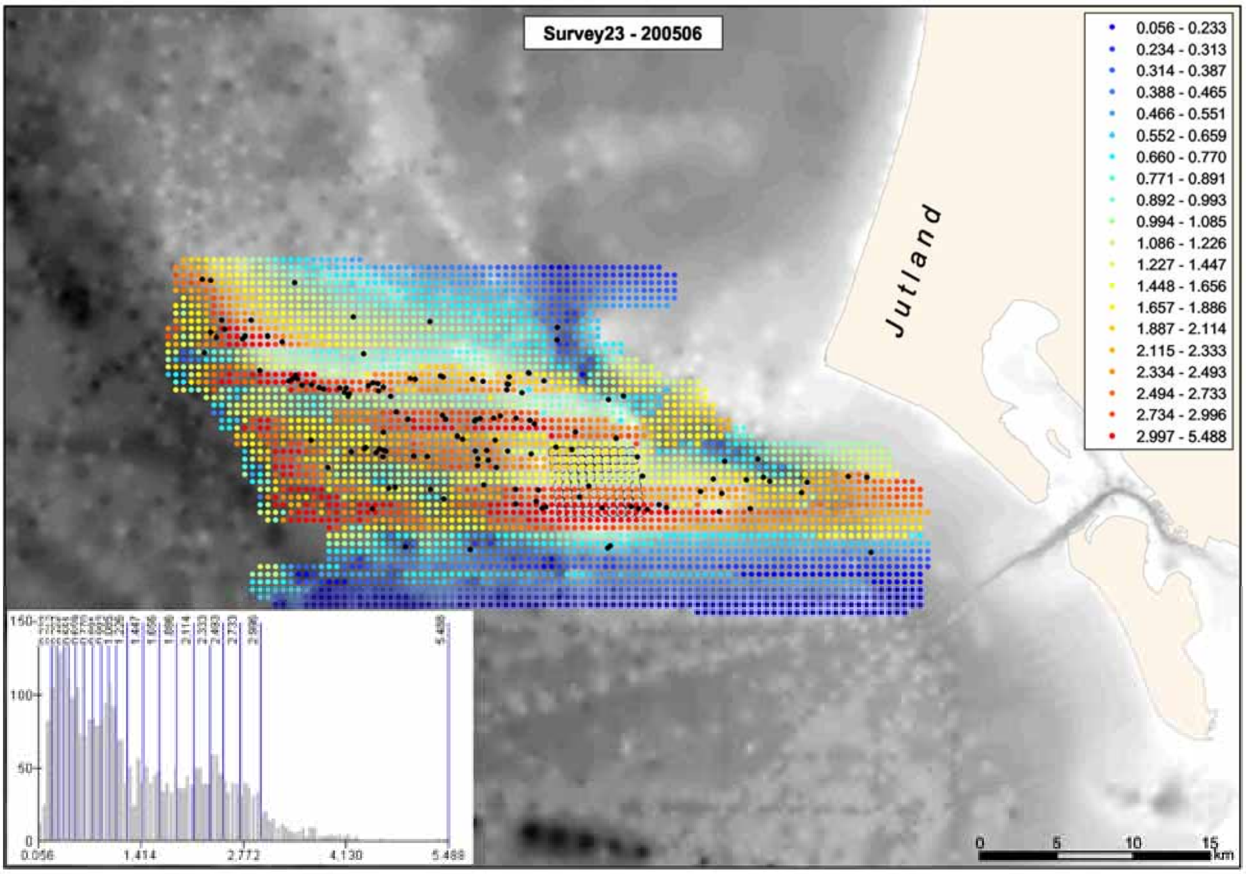

s(CX, 4)
0
-2
-4
400000
420000
440000
CX
s(CY, 4)
2
0
-4
-8
6145000
6155000
CY

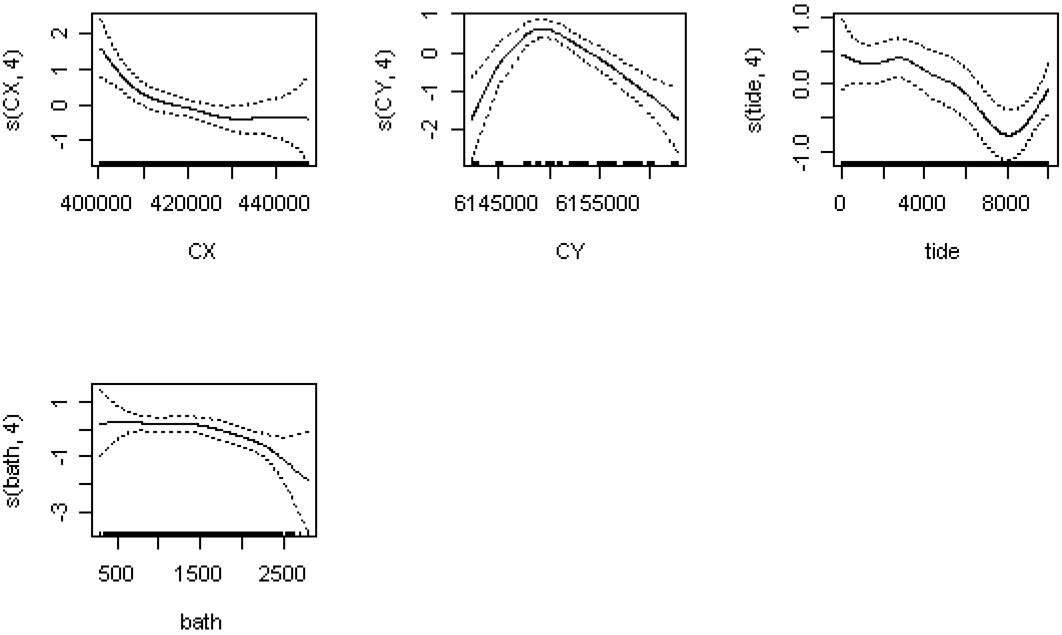

Survey21 - 200404
0.008 - 0.026
0.027 - 0.031
0.032 - 0.043
0.044 - 0.058
0.059 - 0.068
0.069 - 0.078
0.079 - 0.089
0.090 - 0.103
0.104 - 0.126
0.127 - 0.149
0.150 - 0.165
0.166 - 0.195
0.196 - 0.233
0.234 - 0.301
0.302 - 0.414
0.415 - 0.480
0.481 - 0.566
0.567 - 0.852
0.853 - 1.074
1.075 - 2.590
Jutland
0.414
0.480
0.566
0.852
1.074
2.590
400
300
200
100
0
0.008
0.654
1.299
1.945
2.590
0
5
10
15
km

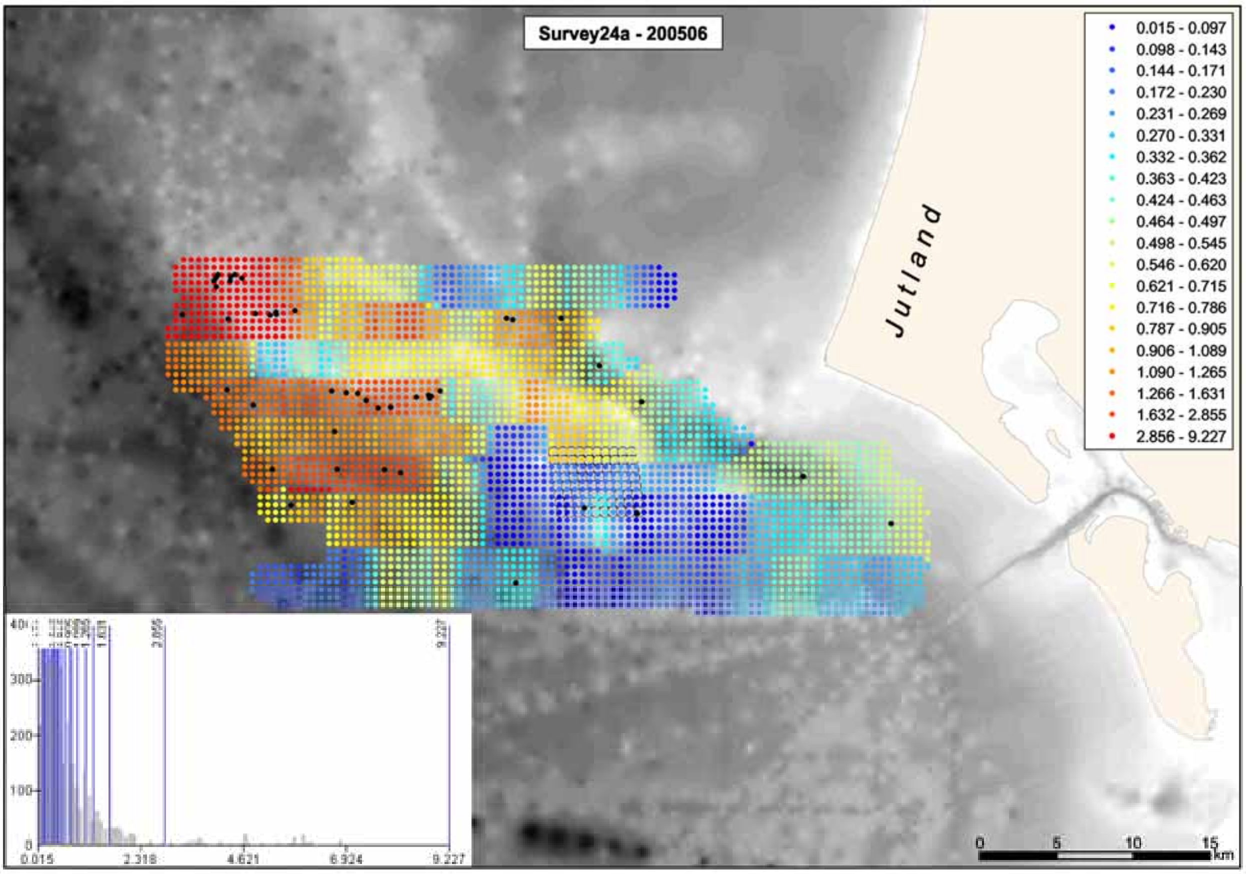

s(CX, 4)
2
0
-2
410000
430000
CX
s(tide, 4)
1.0
0.0
-1.5
0
4000
8000
tide
s(sal, 4)
2
0
-4
2950
3050
3150
sal
s(temp, 4)
0
-2
-4
-6
850
950
1050
temp

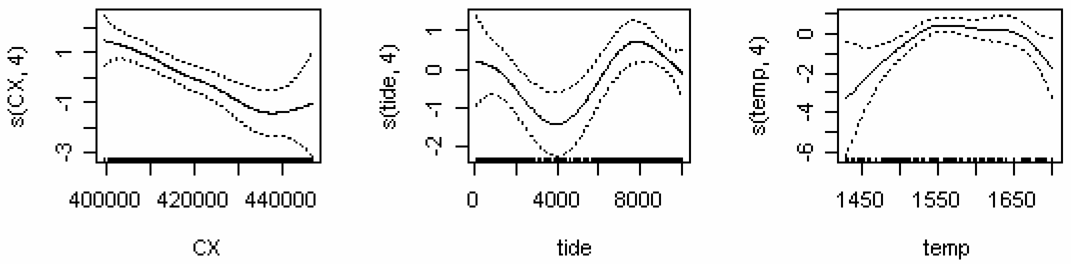

Survey22 - 200408
Jutland
0.001 - 0.025
0.026 - 0.055
0.056 - 0.073
0.074 - 0.094
0.095 - 0.115
0.116 - 0.140
0.141 - 0.161
0.162 - 0.184
0.185 - 0.209
0.210 - 0.245
0.246 - 0.287
0.288 - 0.332
0.333 - 0.376
0.377 - 0.432
0.433 - 0.505
0.506 - 0.583
0.584 - 0.706
0.707 - 0.919
0.920 - 1.780
1.781 - 3.013
0.706
0.919
1.780
3.013
250
200
150
100
50
0
0.001
0.754
1.507
2.260
3.013
0
5
10
15
km

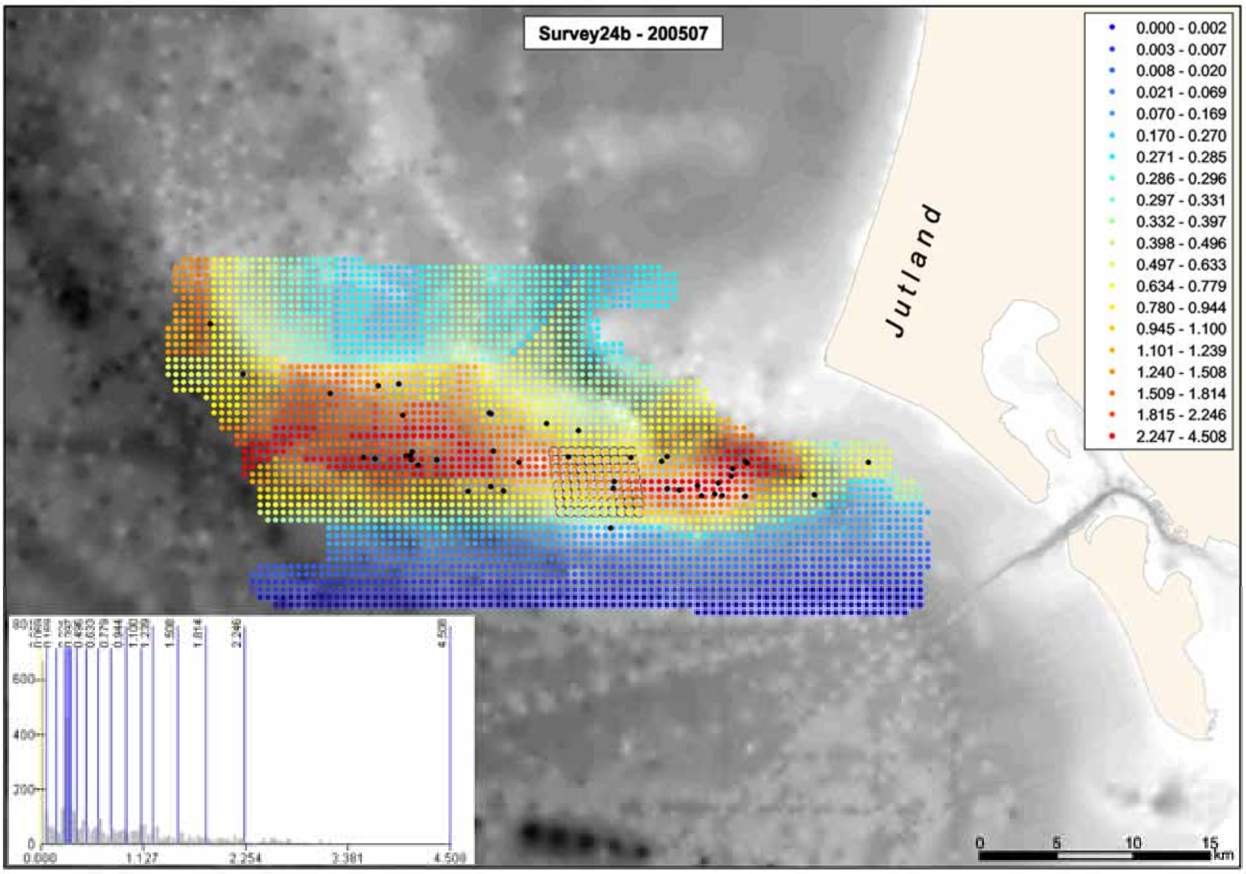

s(CY, 4)
0
-2
-4
6145000
6160000
CY
s(sal, 4)
0
-2
-6
3100
3160
3220
sal
s(temp, 4)
4
0
-4
1700
1900
temp

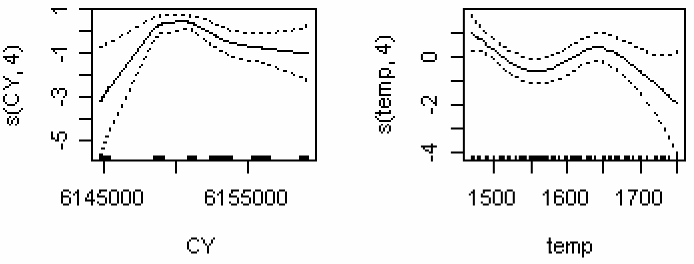

Survey23 - 200506
0.056 - 0.233
0.234 - 0.313
0.314 - 0.387
0.388 - 0.465
0.466 - 0.551
0.552 - 0.659
0.660 - 0.770
0.771 - 0.891
0.892 - 0.993
0.994 - 1.085
1.086 - 1.226
1.227 - 1.447
1.448 - 1.656
1.657 - 1.886
1.887 - 2.114
2.115 - 2.333
2.334 - 2.493
2.494 - 2.733
2.734 - 2.996
2.997 - 5.488
Jutland
150
100
50
0
0.056
1.414
2.772
4.130
5.488
0
5
10
15
km

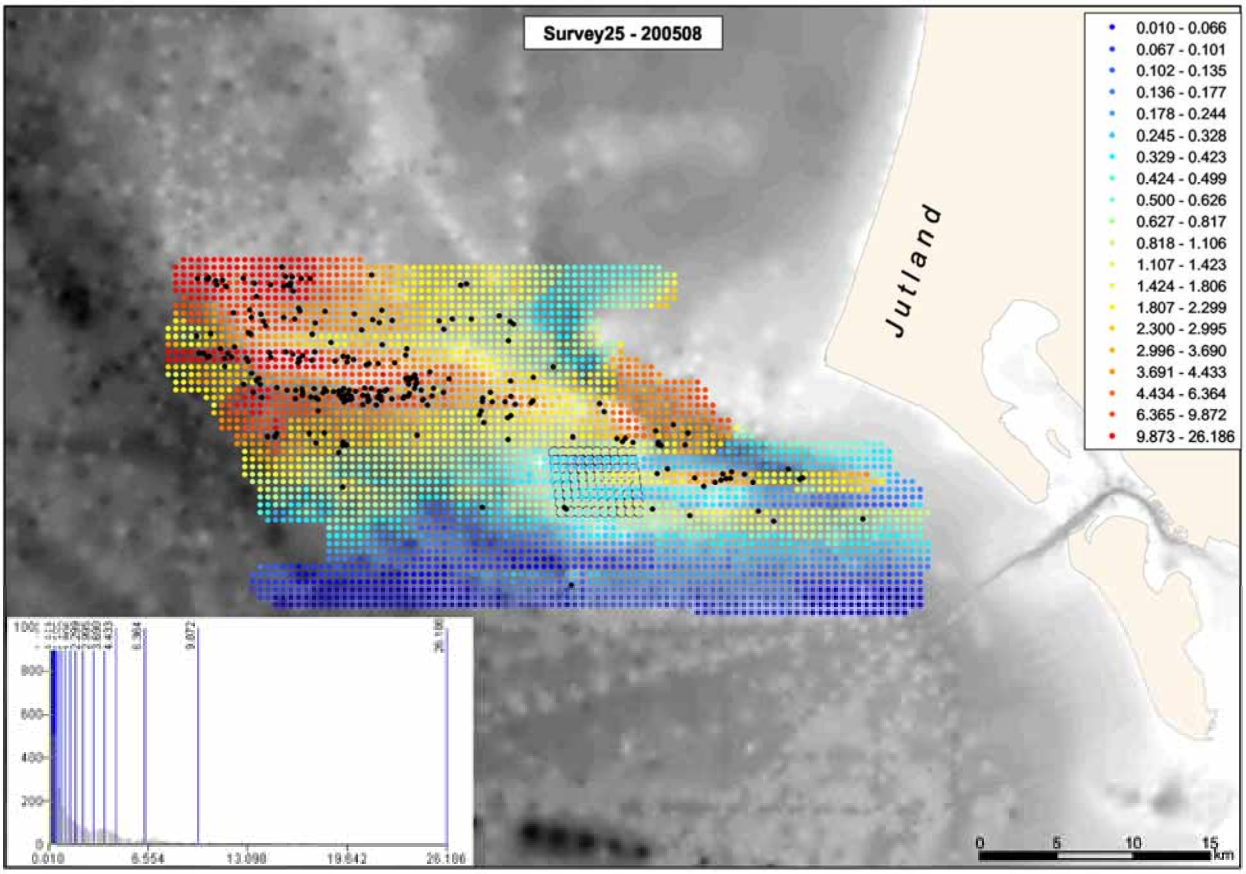

s(CX, 4)
-1
0
1
2
400000
420000
440000
CX
s(CY, 4)
-2
-1
0
1
6145000
6155000
CY
s(tide, 4)
-1.0
0.0
1.0
0
4000
8000
tide
s(bath, 4)
-3
-1
1
500
1500
2500
bath

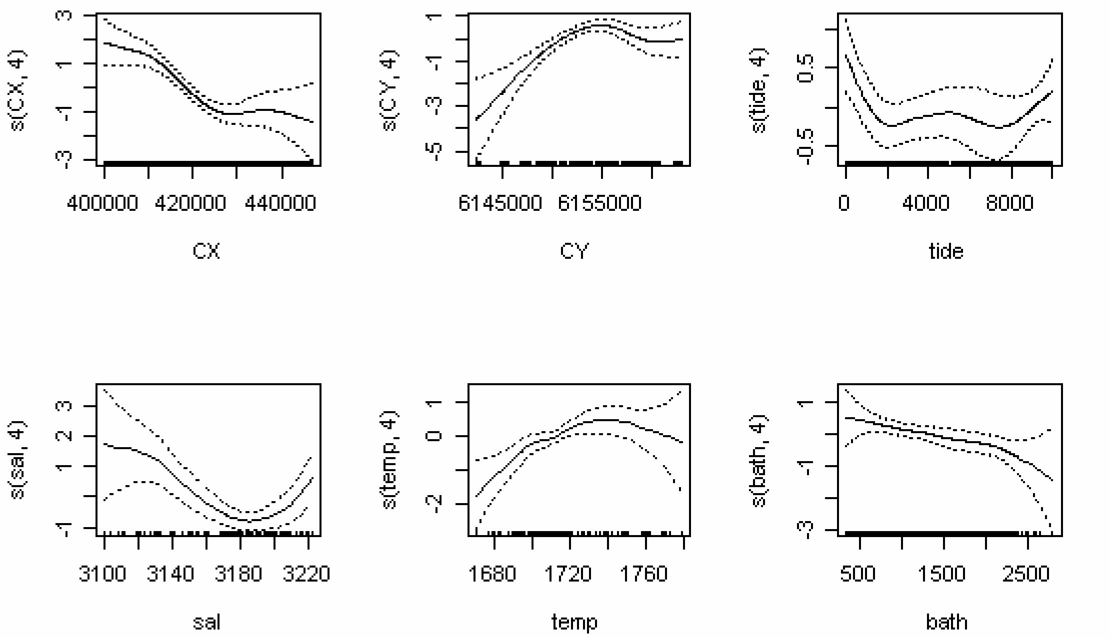

Survey24a - 200506
0.015 - 0.097
0.098 - 0.143
0.144 - 0.171
0.172 - 0.230
0.231 - 0.269
0.270 - 0.331
0.332 - 0.362
0.363 - 0.423
0.424 - 0.463
0.464 - 0.497
0.498 - 0.545
0.546 - 0.620
0.621 - 0.715
0.716 - 0.786
0.787 - 0.905
0.906 - 1.089
1.090 - 1.265
1.266 - 1.631
1.632 - 2.855
2.856 - 9.227
Jutland
400
300
200
100
0
0.015
2.318
4.621
6.924
9.227
2.855
9.227
0
5
10
15
km

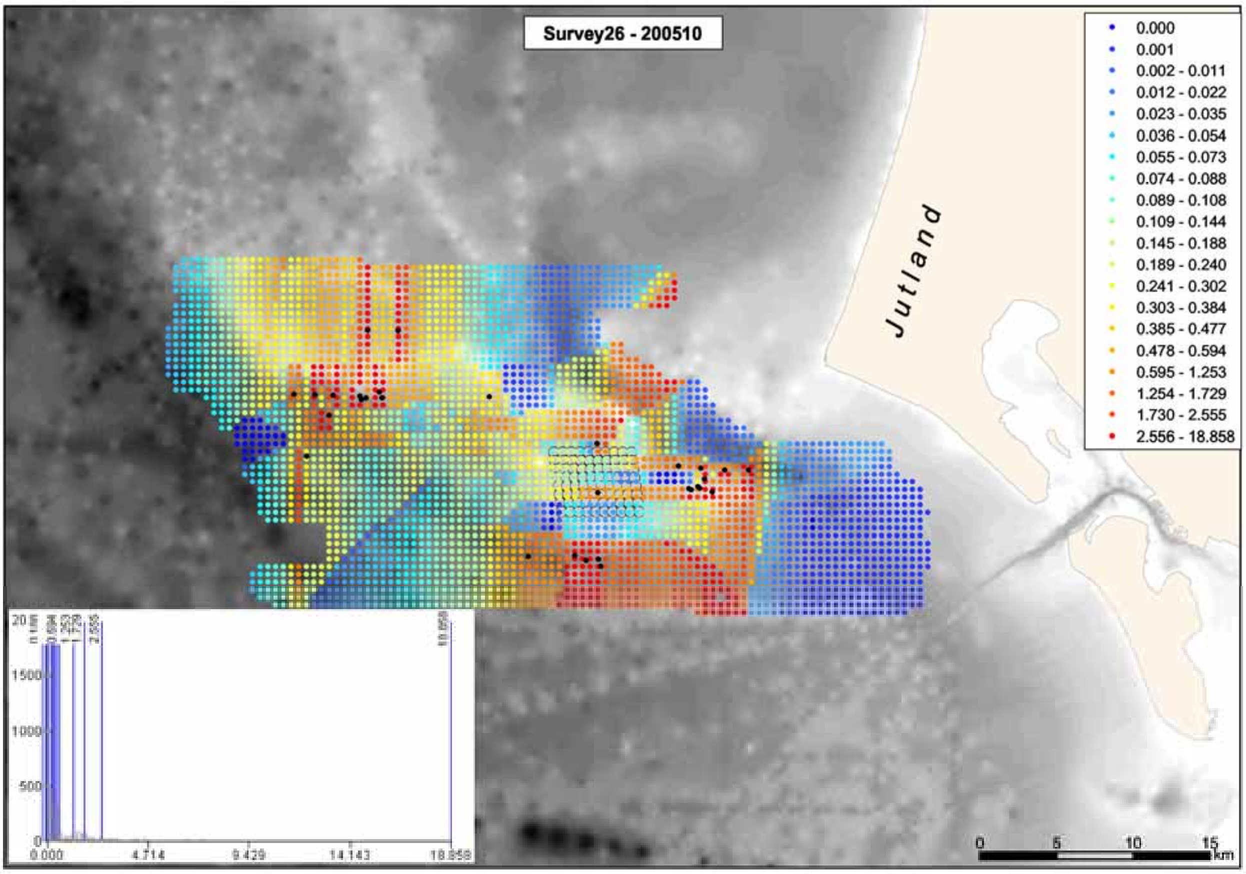

s(CX, 4)
1
-1
-3
400000
420000
440000
CX
s(tide, 4)
1
0
-1
-2
0
4000
8000
tide
s(temp, 4)
0
-2
-4
-6
1450
1550
1650
temp

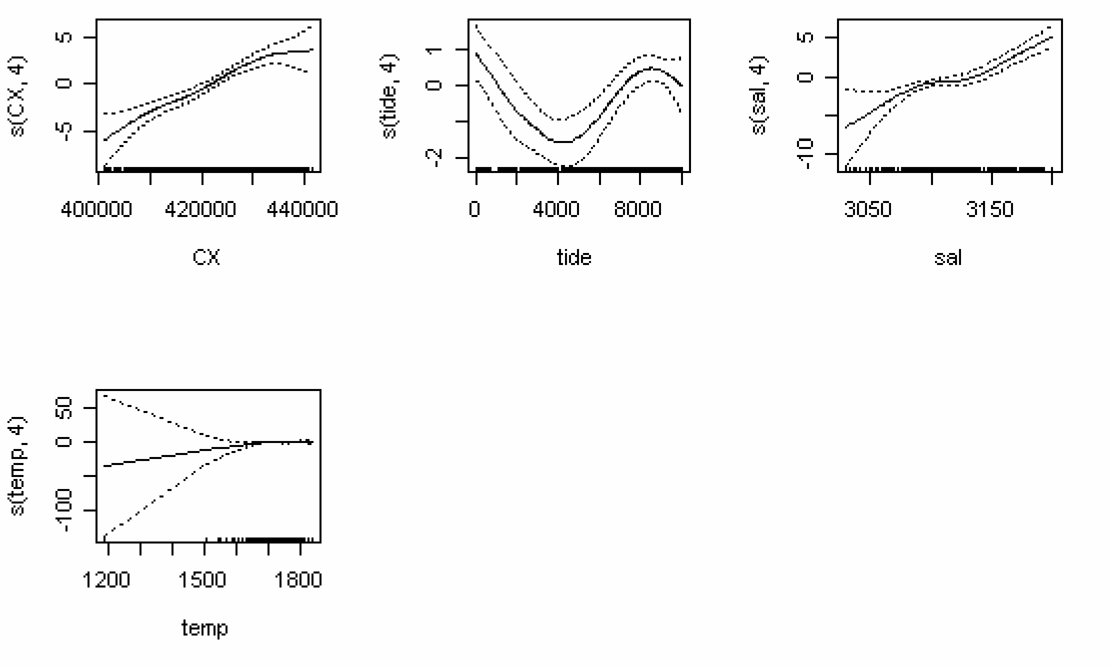

Survey24b - 200507
0.000 - 0.002
0.003 - 0.007
0.008 - 0.020
0.021 - 0.069
0.070 - 0.169
0.170 - 0.270
0.271 - 0.285
0.286 - 0.296
0.297 - 0.331
0.332 - 0.397
0.398 - 0.496
0.497 - 0.633
0.634 - 0.779
0.780 - 0.944
0.945 - 1.100
1.101 - 1.239
1.240 - 1.508
1.509 - 1.814
1.815 - 2.246
2.247 - 4.508
Jutland
0
5
10
15
km
600
400
200
0
0.000
1.127
2.254
3.381
4.508
0.633
0.779
0.944
1.100
1.239
1.508
1.814
2.246
4.508

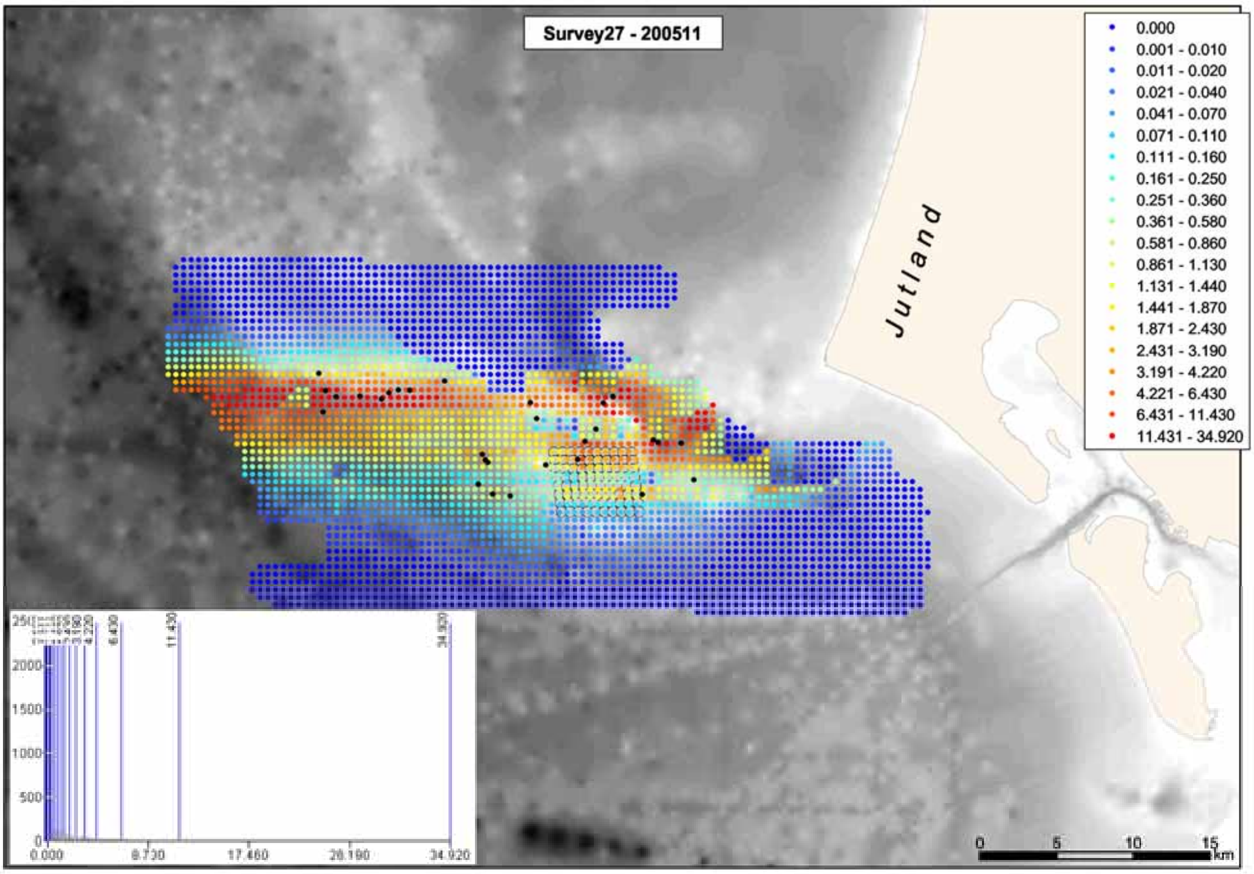

s(CY,4)
1
-1
-3
-5
6145000
6155000
CY
s(temp,4)
0
-2
-4
1500
1600
1700
temp

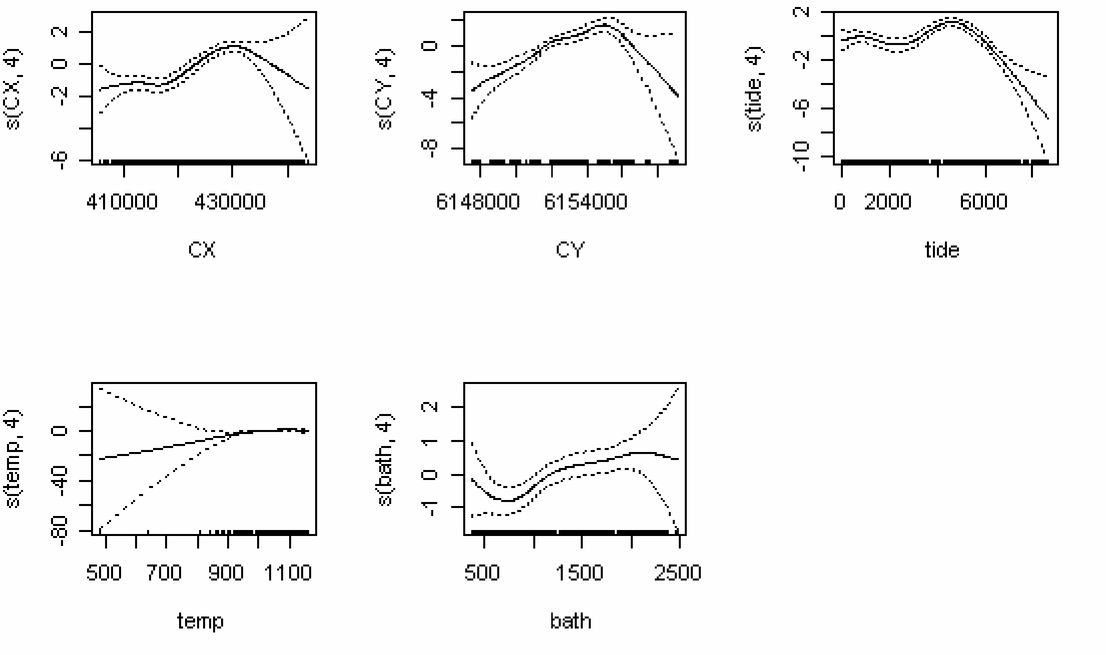

Survey25 - 200508
0.010 - 0.066
0.067 - 0.101
0.102 - 0.135
0.136 - 0.177
0.178 - 0.244
0.245 - 0.328
0.329 - 0.423
0.424 - 0.499
0.500 - 0.626
0.627 - 0.817
0.818 - 1.106
1.107 - 1.423
1.424 - 1.806
1.807 - 2.299
2.300 - 2.995
2.996 - 3.690
3.691 - 4.433
4.434 - 6.364
6.365 - 9.872
9.873 - 26.186
Jutland
1000
800
600
400
200
0
0.010
6.554
13.098
19.642
26.186
6.364
9.872
0
5
10
15
km


s(CX,4)
3
1
-1
-3
400000
420000
440000
CX
s(CY,4)
1
-1
-3
-5
6145000
6155000
CY
s(tide,4)
0.5
-0.5
0
4000
8000
tide
s(sal,4)
3
2
1
-1
3100
3140
3180
3220
sal
s(temp,4)
1
0
-2
1680
1720
1760
temp
s(bath,4)
1
-1
-3
500
1500
2500
bath


Survey26 - 200510
0.000
0.001
0.002 - 0.011
0.012 - 0.022
0.023 - 0.035
0.036 - 0.054
0.055 - 0.073
0.074 - 0.088
0.089 - 0.108
0.109 - 0.144
0.145 - 0.188
0.189 - 0.240
0.241 - 0.302
0.303 - 0.384
0.385 - 0.477
0.478 - 0.594
0.595 - 1.253
1.254 - 1.729
1.730 - 2.555
2.556 - 18.858
Jutland
2000
1500
1000
500
0
0.000
4.714
9.429
14.143
18.858
0
5
10
15
km


s(CX, 4)
5
0
-5
400000
420000
440000
CX
s(tide, 4)
1
0
-2
0
4000
8000
tide
s(sal, 4)
5
0
-10
3050
3150
sal
s(temp, 4)
50
0
-100
1200
1500
1800
temp


Survey27 - 200511
0.000
0.001 - 0.010
0.011 - 0.020
0.021 - 0.040
0.041 - 0.070
0.071 - 0.110
0.111 - 0.160
0.161 - 0.250
0.251 - 0.360
0.361 - 0.580
0.581 - 0.860
0.861 - 1.130
1.131 - 1.440
1.441 - 1.870
1.871 - 2.430
2.431 - 3.190
3.191 - 4.220
4.221 - 6.430
6.431 - 11.430
11.431 - 34.920
Jutland
0
5
10
15
km
2000
1500
1000
500
0
0.000
8.730
17.460
26.190
34.920
4.220
6.430
11.430
34.920


s(CX, 4)
CX
410000
430000
s(CY, 4)
CY
6148000
6154000
s(tide, 4)
tide
0
2000
6000
s(temp, 4)
temp
500
700
900
1100
s(bath, 4)
bath
500
1500
2500

Appendix E - Aerial surveys

Table 10 All aerial surveys with indication of number of porpoises sighted.

Date	Count	groups	groupsize
19990803	52	18	2.89
19990903	29	24	1.21
19991112	9	9	1.00
20000217	19	15	1.27
20000221	14	12	1.17
20000319	8	6	1.33
20000427	80	74	1.08
20000821	8	7	1.14
20001006	4	4	1.00
20001222	4	3	1.33
20010209	3	3	1.00
20010320	20	18	1.11
20010421	10	9	1.11
20010822	37	25	1.48
20020107	8	7	1.14
20020312	7	6	1.17
20020409	6	6	1.00
20020808	95	60	1.58
20030213	2	2	1.00
20030316	54	42	1.29
20030423	58	49	1.18
20030905	16	11	1.45
20031204	9	7	1.29
20031230	3	3	1.00
20040229	8	7	1.14
20040326	34	30	1.13
20040510	18	17	1.06
20040909	14	12	1.17
20050308	3	3	1.00
20050309	13	11	1.18
20050402	10	9	1.11
20050514	57	48	1.19
20050817	83	66	1.26
20051118	16	14	1.14
20051119	4	3	1.33
20060202	10	8	1.25
Total	825	648	1.27

Appendix F – T-POD indicators

All data collected since the start of the T-POD monitoring program in 2001 are shown in figures on the following pages. Summaries of data from individual T-PODs and stations, separated into periods (baseline, construction, semi-operation and operation) are presented in Table D1.

Table D1: Number of observations for the 4 indicators derived from deployments of 13 different T-PODs at the 6 stations in the wind farm (Pos. 5 and 6) and in the reference area (Pos. 1, 3, 4 and 7).

Station	Period	Pod #	Daily indicators		Encounter indicators	
			Click PPM	PPM	Encounters	Waiting times
Pos. 5	Baseline	36	46	49	313	310
	Construction	39	9	10	50	49
	Semi-operation	226	84	84	1110	1108
		270	178	180	2128	2127
	Operation	335	310	313	7535	7530
	Entire period		627	636	11136	11124
Pos. 6	Baseline	36	3	3	27	26
		40	63	67	474	468
	Construction	39	31	31	321	313
	Semi-operation	161	31	33	431	428
	Operation	161	24	24	664	662
		236	7	7	121	121
		342	21	21	489	488
	Entire period		180	186	2527	2506
Impact all	Entire period		807	822	13663	13630
Pos. 1	Baseline	37	38	39	339	335
	Construction	15	19	19	117	116
		37	85	88	682	680
	Semi-operation	37	65	66	307	306
		224	84	84	1004	1000
	Operation	341	64	65	1638	1635
	Entire period		355	361	4087	4072
Pos. 3	Baseline	38	26	29	375	372
	Construction	20	13	13	243	242
	Semi-operation	20	9	9	80	81
		37	46	70	170	168
	Operation	334	250	250	6718	6709
	Entire period		344	371	7586	7572
Pos. 4	Semi-operation	22	8	8	73	72
		226	18	18	100	99
	Operation	342	65	65	1491	1489
	Entire period		91	91	1664	1660
Pos. 7	Construction	45	127	133	1225	1222
	Semi-operation	11	331	351	3899	3890
		282	72	72	1515	1513
	Operation year 3	282	104	104	2535	2532
	Entire period		634	660	9174	9157
Reference all	Entire period		1424	1483	22511	22461
All data			2231	2305	36174	36091

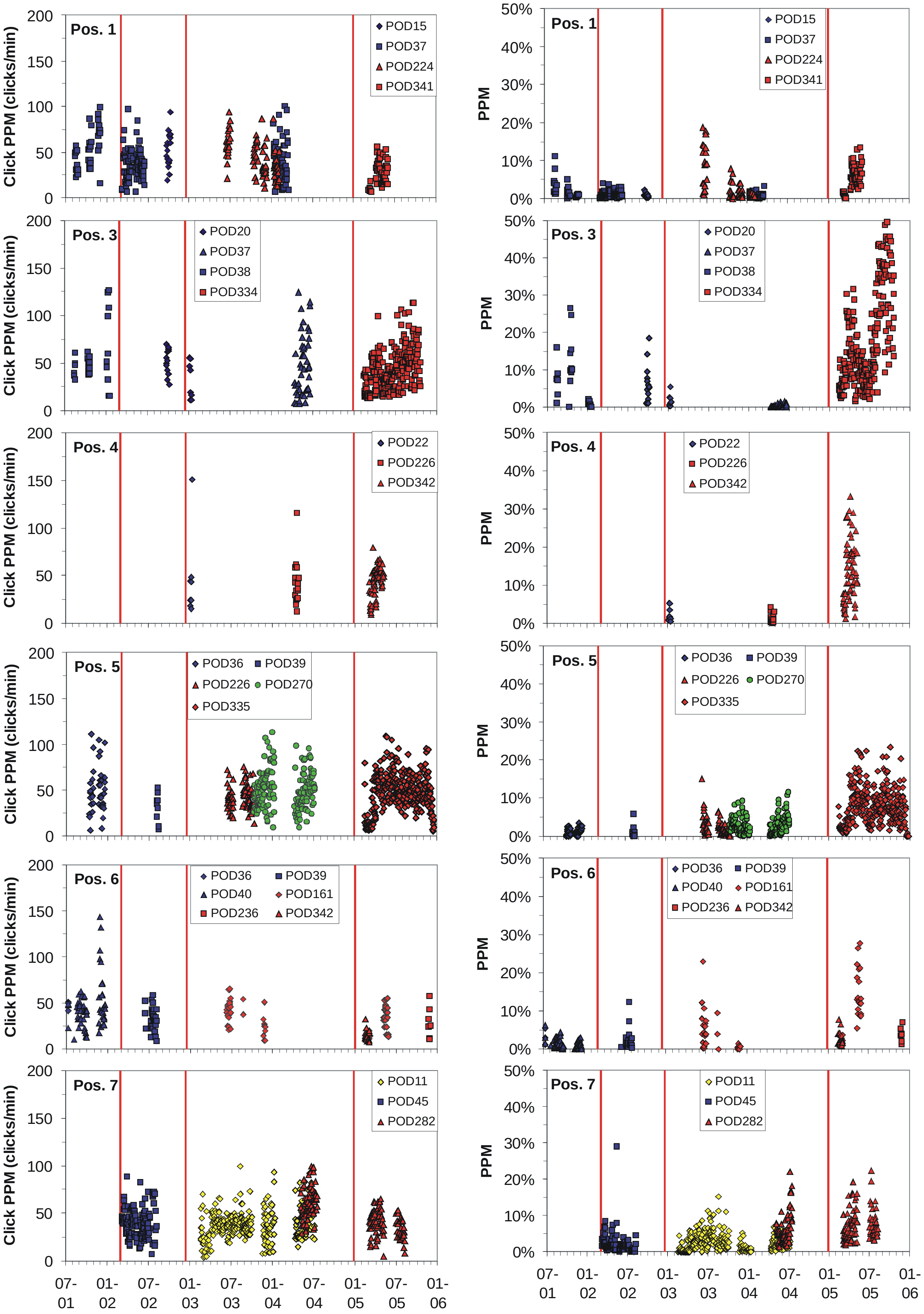

Pos. 1
POD15
POD37
POD224
POD341
Pos. 3
POD20
POD37
POD38
POD334
Pos. 4
POD22
POD226
POD342
Pos. 5
POD36
POD39
POD226
POD270
POD335
Pos. 6
POD36
POD39
POD40
POD161
POD236
POD342
Pos. 7
POD11
POD45
POD282
Click PPM (clicks/min)
0
50
100
150
200
PPM
0%
10%
20%
30%
40%
50%
07-01
01-02
07-02
01-03
07-03
01-04
07-04
01-05
07-05
01-06

Figure F.1: Daily click intensity (left panel) and click frequency (right panel) extracted from T-POD data collected at Horns Reef from July 10th 2001 to December 26th 2005. Different symbols mark observations derived from different T-PODs, and different colours indicate the use of different types of T-POD. The three vertical lines show the different periods used for the assessment. Two click PPM and ten PPM exceeded the plotting range (not shown).

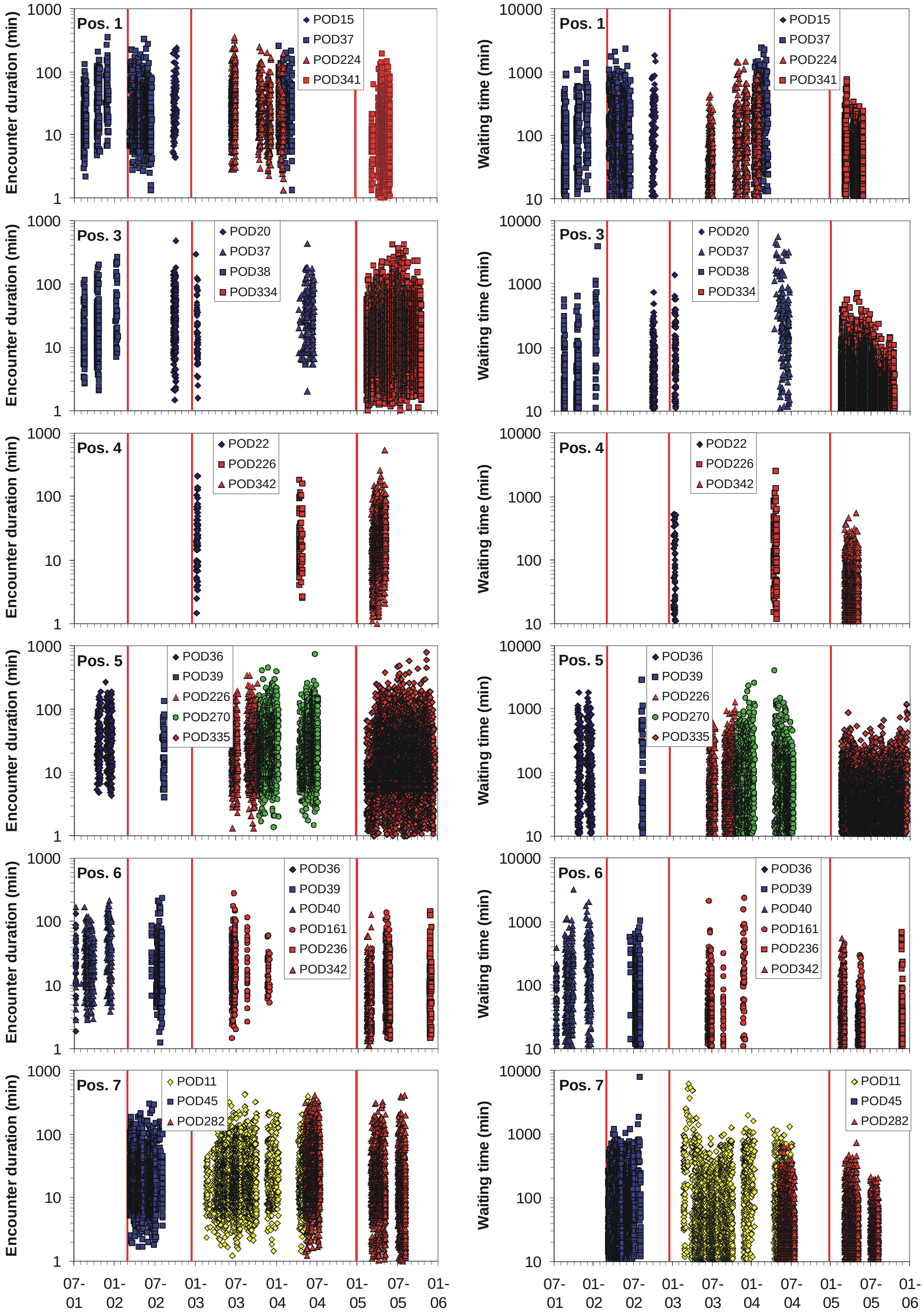

Pos. 1
POD15
POD37
POD224
POD341
Pos. 3
POD20
POD37
POD38
POD334
Pos. 4
POD22
POD226
POD342
Pos. 5
POD36
POD39
POD226
POD270
POD335
Pos. 6
POD36
POD39
POD40
POD161
POD236
POD342
Pos. 7
POD11
POD45
POD282
Encounter duration (min)
Waiting time (min)
1
10
100
1000
10000
07-01
01-02
07-02
01-03
07-03
01-04
07-04
01-05
07-05
01-06

Figure F.2: Encounter duration (left panel) and waiting time (right panel) extracted from T-POD data collected at Horns Reef from July 10th 2001 to December 26th 2005. Different symbols mark observations derived from different T-PODs, and different colours indicate the use of different types of T-POD. The three vertical lines show the different periods used for the assessment. One encounter and one waiting time exceeded the plotting range (not shown). Note the log-scale on the y-axis.