Harbour seals at Horns Reef before, during and after construction of Horns Rev Offshore Wind Farm

Final report to Vattenfall A/S

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Foreword

This report presents results and conclusions from studies of harbour seals in the Danish Wadden Sea using satellite telemetry and addresses the possible impact of Horns Rev Offshore Wind Farm on the seals.

The study is part of a large demonstration project on offshore wind farms. The monitoring programme has covered all important aspects of environmental impact of the wind farm at Horns Reef as well as a second offshore wind farm in the southwestern Baltic (Nysted Offshore Wind Farm). The present report can thus be read on its own, providing results and conclusions of the harbour seal studies at Horns Rev Offshore Wind Farm, but should be seen as a part of a larger conglomerate of studies on benthos, epifauna, fish, birds and other marine mammals at two different locations.

This report, together with all other reports of the monitoring program, can be found on the website of the Horns Rev Offshore Wind Farm: www.hornsrev.dk.

An overview of the entire monitoring programme will be published separately in connection with the “Offshore Wind Farms and the Environment” conference 27-29 November to take place in Copenhagen, 27-29 November 2006, organised by the Danish Energy Authority.

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Summary

Horns Rev offshore wind farm was constructed on Horns Reef in the northern German Bight in 2002. As part of a large environmental monitoring program 21 harbour seals were caught in the period 2002-2005 on the island Rømø and equipped with satellite transmitters. In addition to satellite transmitters, 21 seals were equipped with a sophisticated datalogger in a cooperation with the University of Kiel. These loggers are capable of collecting high resolution information on the diving behaviour and movement of the seals. The loggers fall of the animals after a couple of months. To get the data the loggers have to be retrieved from the coast, where they wash up. At present, 7 of the deployed loggers have been retrieved.

The primary aim of the investigations was uncovering the importance of Horns Reef as foraging area for harbour seals from the Danish Wadden Sea. A secondary aim was to determine whether seals were present in the wind farm after construction and whether their behaviour was affected by the presence of the turbines.

Foraging of harbour seals from the Wadden Sea

The study has documented that harbour seals from the island Rømø are foraging primarily outside the Wadden Sea in the period September to July. Individual seals appear to have strong preference for smaller, confined areas, which they will return to again and again on their foraging trips. The combined picture of many seals however, shows a more or less even distribution of seals primarily in an area from Rømø out to approximately 100 km from shore, stretching from Holmslands Klit in north to south of the Danish-German border. Similar results have been found in telemetry studies in Germany and the Netherlands and confirm that the entire eastern part of the German Bight is the primary foraging habitat for harbour seals from the International Wadden Sea. Horns Reef and thus also the wind farm is located in the centre of the foraging area of the seals from Rømø and the area is thus of importance to the seals. Nothing seems to indicate however, that the reef or the wind farm area is of greater importance than the surrounding areas.

Effects of construction and operation of the wind farm

The accuracy of the positions retrieved from satellite transmitters and dataloggers turned out to be insufficient to conclude with certainty on the degree to which construction of the wind farm has affected the seals. However, it is close to certain that one or more of the tagged seals were inside the wind farm area during the period the transmitters were active. Visual observations from ship surveys, conducted as part of the monitoring program on harbour porpoises, supports this, as seals were observed inside the wind farm area in numbers not readily different from the surrounding waters. An exception from this was the construction period in spring and summer 2002, where very few seals were observed inside and in the immediate surroundings of the wind farm. Seals were most likely staying away from the construction site due to the very high levels of underwater noise generated by the pile driving operations and the associated mitigation.

Underwater noise from the turbines appears to be the only potential negative source of impact of practical relevance. The scale of this impact is considered to be marginal, based on measurements of the emitted noise from the turbines and compared to the other sources of underwater noise in the area, caused by e.g. ship traffic. It is believed that the artificial reef formed on the foundations and scour protection potentially will benefit the seals in the area through an increase in food availability.

Dansk resumé

Horns Rev Havmøllepark blev bygget på Horns Rev ud for Blåvands Huk i 2002. Som en del af et omfattende overvågningsprogram af effekter på havmiljøet blev 21 spættede sæler fra Rømø udstyret med satellitsendere i årene 2002-2005. Senderne gjorde det muligt at følge sælernes bevægelser og fødesøgning over flere måneder. Desuden blev 21 sæler i samarbejde med Kiels Universitet udstyret med en avanceret datalogger, der kan gemme detaljeret information om sælernes dykkeadfærd og bevægelser. Dataloggerne falder af sælerne efter et par måneder og skal genfindes (skyllet op på stranden) for at få adgang til dataene. I skrivende stund er 7 dataloggere genfundet.

Det primære formål med undersøgelserne var at afdække betydningen af Horns Rev som fødesøgningsområde for spættede sæler fra Det danske Vadehav. Et sekundært mål var at afgøre hvorvidt sæler opholdt sig i mølleparken efter den blev taget i brug og hvorvidt deres adfærd i og omkring mølleparken er påvirket af møllerne.

Fødesøgning hos spættet sæl i Vadehavet

Undersøgelsen dokumenterer at spættede sæler fra Rømø i perioden september til juni primært finder deres føde uden for Vadehavet. De enkelte sæler synes ofte at have præference for mindre, afgrænsede områder, som de vender tilbage til igen og igen. Det samlede billede viser en nogenlunde jævn fordeling af sælernes positioner hovedsageligt i et område fra Holmslands Klit til syd for den Dansk-tyske grænse og ud i en afstand af ca. 100 km fra kysten. Tilsvarende resultater er fundet i tyske og hollandske undersøgelser og bekræfter at hele den østlige del af Tyske Bugt er det vigtigste fødesøgningsområde for spættede sæler fra Det internationale Vadehav.

Horns Rev og dermed også Horns Rev havmøllepark ligger midt i fødesøgningsområdet for sælerne fra Rømø og området er således af betydning for sælerne. Der er imidlertid ikke noget, der tyder på at revet eller mølleområdet skulle være af større betydning end de omliggende områder.

Effekter af konstruktion og drift af møllepark

Nøjagtigheden af de positioner satellitsenderne og dataloggerne leverede, viste sig ikke at være tilstrækkelig høj til med sikkerhed at kunne konkludere i hvilket omfang mølleparken har påvirket sælerne i området. Det er dog overvejende sandsynligt at en eller flere af de mærkede sæler har været inde i mølleparken i den periode senderne har været aktive. Visuelle observationer fra skib, indsamlet i forbindelse med overvågning af marsvin i området, understøtter dette, idet der blev observeret sæler i mølleparken i et antal ikke umiddelbart forskelligt fra hvad der blev set udenfor. Undtaget fra dette billede er konstruktionsperioden i foråret og sommeren 2002, hvor meget få sæler blev set inde i og umiddelbart uden for mølleområdet. Det er overvejende sandsynligt at sælerne holdt sig væk fra området i denne periode på grund af de meget høje lydtryk der fremkom ved nedramning af stålfundamenter i havbunden og de til ramningerne knyttede afværgeforanstaltninger.

Af negative påvirkninger af sælerne efter ibrugtagning af møllerne skønnes undervandsstøj at være den eneste af praktisk betydning. Omfanget af denne påvirkning skønnes at være minimal, baseret på målinger af støjen i mølleparken, sammenholdt med den øvrige undervandsstøj i området forårsaget af skibstrafik mm. Til gengæld skønnes det kunstige rev, der dannes på fundamenterne at kunne bidrage positivt, idet fødeudbuddet for sælerne sandsynligvis øges inde i mølleparken.

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).

1.1 Horns Reef and the Wadden Sea

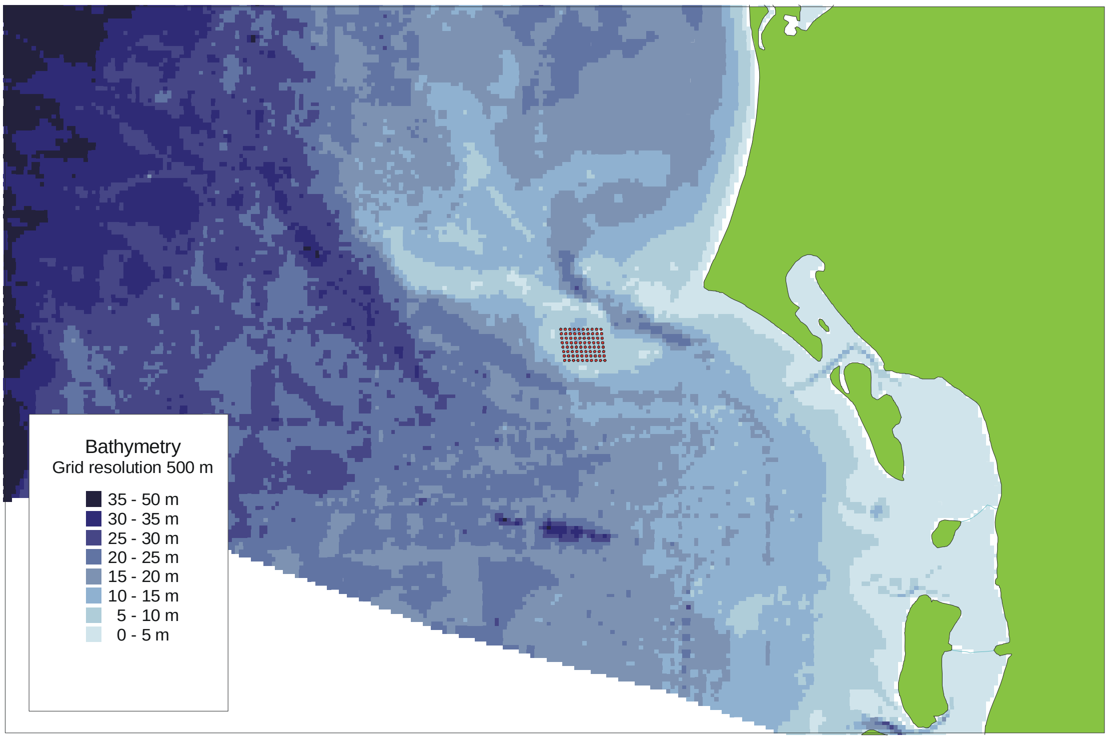


Figure 1. Bathymetry of Horns Reef and adjacent waters. Individual turbines of Horns Rev Offshore Wind Farm are indicated with dots. The wind farm is located on the eastern part of the outer reef, which is separated from the inner reef by the deep channel "Slugen".

Horns Reef forms the north-eastern border of the German Bight and 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 reef consists of an outer and an inner part, different in origin and separated by a 20 m deep channel – Slugen. 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 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).

1.1.1 Hydrography

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 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).

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.

1.1.2 Human activities

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

In addition to fishing vessels in the area 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

Figure 3. Aerial photo of Horns Rev Offshore Wind Farm. Photo: S. Tougaard.

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 550 m between neighbouring turbines. All turbines are connected by a 36 kV grid of cables buried in the bottom (Figure 4). 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.

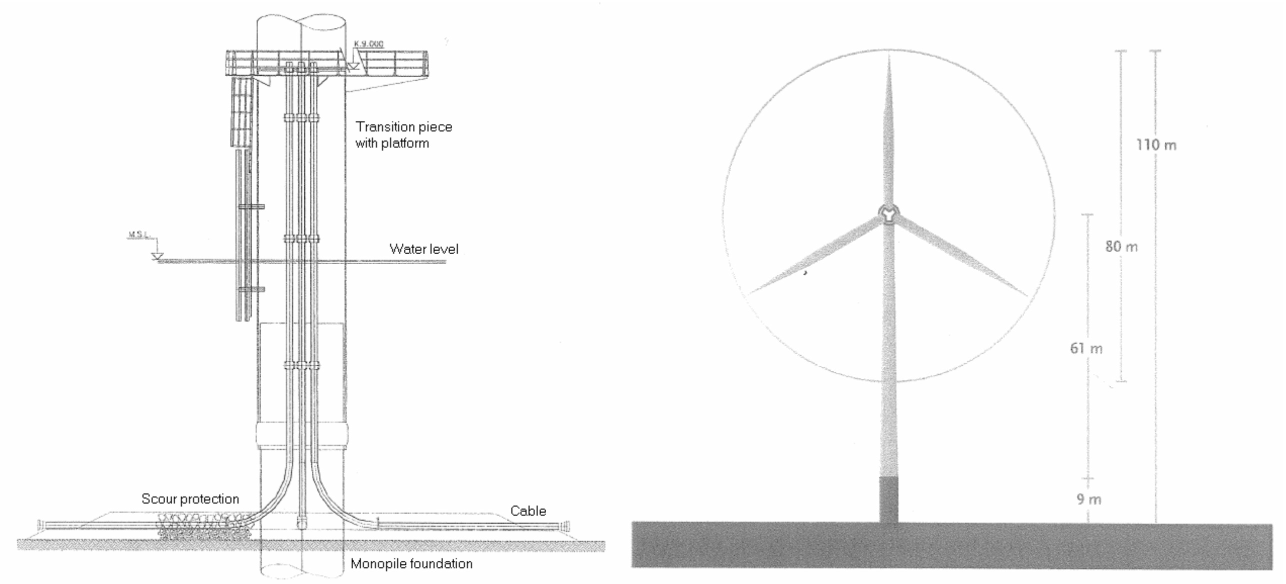


Figure 4. Dimensions of turbines and foundations. Left: foundation with scour protection and , transition piece with platform. Right: dimensions of turbine.

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 5, 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 5, right).

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. 10 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.

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

Figure 5 Left: Pile driving from the jack-up rig ”Buzzard”. Right: mounting of wings from the jack-up “Ocean Ady”. Photos : Vattenfall A/S.

1.3 Seals at Horns Reef and the Wadden Sea

Harbour seal (*Phoca vitulina*) is the most common seal species in the Wadden Sea and German Bight and also in the Horns Reef area. In recent years two groups of grey seals (*Halichoerus gryphus*) has established themselves in the Dutch and German Wadden Sea (Härkönen *et al.* 2006a). Increasing numbers of grey seals has been observed in the Danish Wadden Sea and this may lead to breeding individuals in the near future. Although all investigations under the current monitoring program has dealt with harbour seals, most of the discussion will be pertinent to grey seals as well and only when this is not the case will grey seals be discussed separately.

Figure 6. Harbour seals hauled out at Langli Sand, with the city of Hjerting (north of Esbjerg) in the background. The haulout bank is on the north side of Grådyb, the deep channel leading into Esbjerg harbour. Photo S. Tougaard.

1.3.1 Reproduction

The Danish Wadden Sea is the only breeding area for harbour seals on the Danish west coast and also the only area where harbours seals haul out regularly in larger numbers. The only true haulout site outside the Wadden Sea is close to shore at Blåvands Huk, where up to 50 seals have been counted at the same time.

During the summer months harbour seals depend on access to undisturbed haulout sites. They give birth to the pups in late June, followed by a 3-4 week period of suckling, which must take place on land. Breeding and suckling takes place on smaller, isolated sand banks in the inner Wadden Sea.

Mating occurs immediately after weaning of the pup, followed by a gradual movement to the high sands along the western edge of the Wadden Sea (Bollert, Koresand, Langlisand etc.), where moulting occurs.

1.3.2 Foraging ecology

Previously, up to the 1990'ties, it was assumed that seals were common in the Wadden Sea because it offered good foraging for the seals. With VHF-transmitter taggings in the 1990'ties however, it became clear that the North Sea plays a much larger role for foraging than previously believed (Nørgaard 1996 and 1.3.4.1 below). Very few studies are available on feeding biology of harbour seals from the Wadden Sea, but it is clear also from other studies (e.g. Pierce *et al.* 1991; Andersen *et al.* 2004) that harbour seals are opportunists with respect to prey and that their prey items to a large degree is a reflection of the local species distribution. It is assumed that bottom dwelling fish, with plaice (*Pleuronectes platessa*) as the most important species, forms the bulk of prey items of harbour seals from the Wadden Sea area.

1.3.3 Sensory physiology

Seals are semi-aquatic animals and their senses are thus adapted both to a life in water and on land.

1.3.3.1 Vision

Seals have good vision, both in air and water, with variation from species to species in terms of the degree to which the eyes are adapted to water. The lens is adapted to underwater vision and focusing in air is believed to be possible due to the slit-formed pupil (when contracted), which results in a large depth of focus (Fobes and Smock 1981).

As all other pinnipeds (and cetaceans) the harbour seal is considered to be functionally colour blind (Peich *et al.* 2001). They have very few cones in the retina and all of these are of the same (blue) type (Newman and Robinson 2005).

The sensitivity of the eyes is high, enhanced by the presence of a *tapetum* behind the retina and seals are probably able to orient visually even at great depth (Levenson and Schusterman 1999).

1.3.3.2 Hearing

Seals have ears well adapted to an aquatic life. These adaptations include a cavernous tissue in the middle ear which allows for balancing the increased pressure on the eardrum when the animal dives (Møhl 1967) and also a separate pathway for sound to the middle ear in water. The audiogram of harbour seals shows good underwater hearing in the range from a few hundred Hz to about 50 kHz (Figure 7, left)

The critical bandwidth of harbour seal hearing decreases with frequency, at least in the range 2.5 kHz to 30 kHz where it has been measured (Figure 7, right). The critical bandwidth is (among other) a measure of the sensitivity to masking by noise. Noise which falls within the critical bandwidth around a given tone stimulus of constant frequency is able to mask the tone (i.e. cause an elevation of the detection threshold) whereas noise that falls outside the critical band has no or only little effect on the detection of the tone. Small critical bandwidths thus indicate little sensitivity to noise interference, whereas broader critical bands indicate larger sensitivity to noise.

Nothing is known on the hearing of grey seals, although it is probably fair to assume that it is not dramatically different from harbour seal hearing.

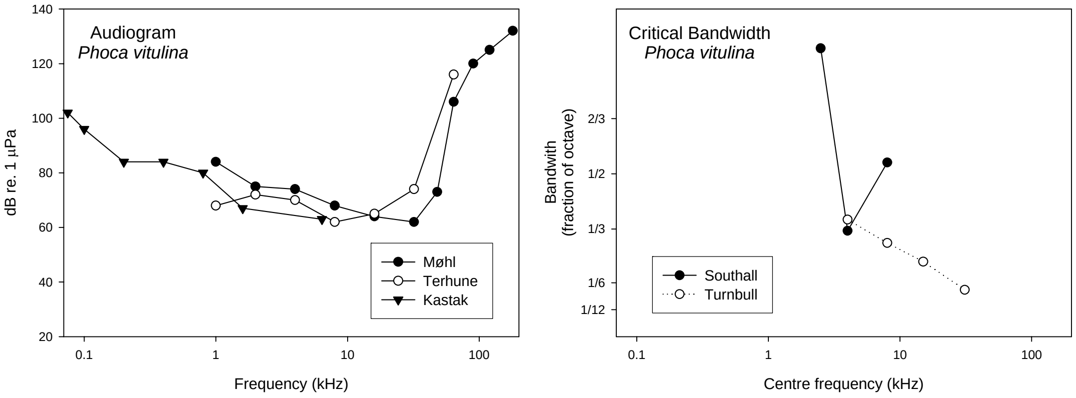


Figure 7. Left: audiograms of three harbour seals, showing threshold of hearing under quiet conditions at frequencies in the range from 80 Hz to 150 kHz. Data from Møhl (1968); Terhune and Turnbull (1995); Kastak and Schusterman (1998). Note that thresholds are measured in dB re. 1 μPa and thus cannot be compared with dB SPL of human audiology, which is referenced to 20 μPa. Right: critical bandwidth of harbour seals, expressed as fraction of an octave. Data from Southall *et al.* (2001) and Turnbull and Terhune (1990).

1.3.3.3 Touch/vibration

Seals have very well developed whiskers (vibrissae) and the follicles are highly vascularised and with a large number of attached sensory nerves (Dykes 1975). Behavioural experiments have shown that the whiskers of seals are extraordinary sensitive to particle movement in the water (Denhardt *et al.* 1998) and it is within practical possibilities that seals can detect the vortices and eddies left behind in the wake of a swimming fish, even several minutes after the fish has passed (Denhardt *et al.* 2001). It can thus be conjectured that the whiskers play as large a role as the eyes, if not larger, in terms of locating prey. This is especially true at great depth, at night and when visibility in general is low.

Figure 8 Grey seal with mystacial whiskers around the mouth and supraotic whiskers above the eyes. Photo S. Tougaard.

1.3.3.4 Electro- and magnetoreception

Many bony fish and cartilaginous fish have very good electroreceptive capabilities and can sense extremely weak electric fields generated by e.g. muscles of their prey. Sharks and rays are known for their ability to locate prey solely by electroreception (Kalmijn 1982). Marine mammals on the other hand are not known to have specialised electroreceptive cells and has not been shown to be capable of detecting the weak fluctuations in the electric field that electroreceptive fish can.

Magnetoreception or the ability to detect changes in the earth’s magnetic field and/or determine the north/south direction has not been convincingly demonstrated in any marine mammal. This however, does not mean that they cannot perceive magnetic stimuli, as these abilities have proved very difficult to demonstrate in vertebrates in general (Wiltschko and Wiltschko 1996), with several species of migrating birds as the most notable exception. This sensory modality is not nearly as well understood as the other modalities (vision, hearing, smell, electroreception etc.) and it thus is unclear how common this ability is in vertebrates in general. Thus, so far it remains open whether seals have magnetoreceptive capabilities or not and it is not even safe to conclude whether we *a priori* should expect them to have this ability or not (i.e. whether the sense is the normal condition for vertebrates or it is a specialisation).

1.3.4 Population size and development

The harbour seals in the Danish Wadden Sea are considered part of a common population in the International Wadden Sea, stretching from Den Helder in the Netherlands to Blåvandshuk in Denmark (Reijnders *et al.* 1997).

The Danish Wadden Sea population of harbour seals has increased with about 12% every year since hunting was completely abolished in 1976 (Trilateral Seal Expert

Group 2002). Only exceptions were the 1988 and 2002 phocine distemper virus epizootic (Härkönen *et al.* 2006b). In 1988 estimated half of the Danish population was killed (Reinders et al. 1997). From 1989 and onwards the population has increased again with the same rate as before the epizootic, until 2002 where a new outbreak of the same virus reduced the numbers with 47% (Härkönen *et al.* 2006b). The population in August 2002 (before the second epizootic) is estimated to have been 3.450 in the Danish Wadden Sea and 25.000 in the international Wadden Sea (Trilateral Seal Expert Group 2002). After the second epizootic the population has increased and in 2005 2650 harbour seals were counted in the Danish Wadden Sea and 18.500 in the entire International Wadden Sea (Figure 10).

Figure 9. Harbour seal haul out banks in the Danish Wadden Sea. Circles indicate number of hauled out animals counted on an aerial survey conducted on August 14th 2002, i.e. immediately after the construction period. Red square indicates wind farm area.

1.3.4.1 Previous VHF and satellite transmitter studies

In a previous study, conducted from November 1990 to October 1993, 48 harbour seals on Rømø were equipped with VHF-transmitters (Nørgaard 1996). This study showed that 56% of the tagged seals remained connected to the same haul out bank where they were caught and tagged (Bollertsand, Koresand or Lammelægger). Ten percent moved to banks in Schleswig-Holstein (about 75 km away) and a single animal was found in Niedersachsen, German Wadden Sea (about

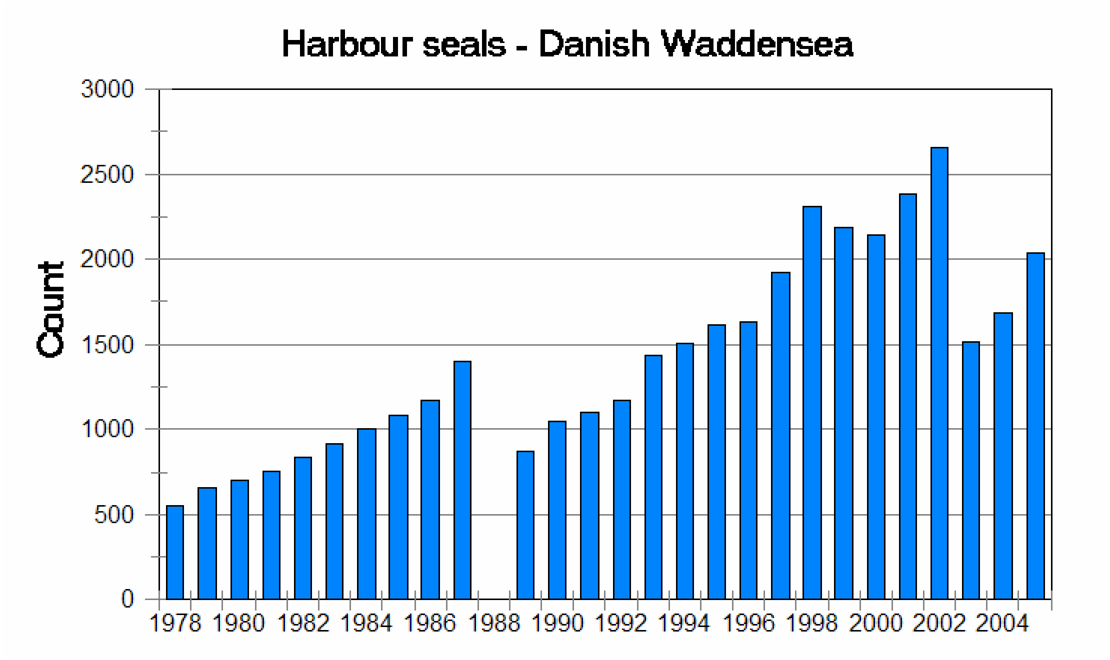


Figure 10. Development in the population of harbour seals in the Danish Wadden Sea from 1978 until present. Columns show number of seals counted on land from aerial surveys in August. The declines from 1987 to 1989 and from 2002 to 2003 were due to epidemics of phocine distemper virus. Source: Abt *et al.* (2005).

150 km away). The rest remained on banks within a radius of 25 km from the bank where they were tagged (Nørgaard 1996).The range of the VHF-transmitters was limited to 50 km. In winter (October 24th to February 21st) the seals spent 31% of the time outside the receiving range, compared to 7% in summer (February 21st to October 24th). On average they spent 8 days at a time outside receiving range during winter, with a maximum period of 31 days, compared to a maximum of 6 days in summer. Seals also spent significantly more time on land in summer (27%) compared to winter (14%). No correlation between amount of time outside receiving range and sex or age of animals was found. In 96% of the cases, the direction taken by the seals when they left the receiving range was NW, i.e. the direction of the Horns Reef area.

In 2002 10 harbour seals were equipped with satellite transmitters as part of the monitoring program of the wind farm in order to study their offshore behaviour and in particular their use of the Horns Reef area. These results are described in Tougaard *et al.* (2003b) as well as below. In brief they showed that harbour seals venture out much further into the North Sea than previously believed (up to 300 km from haulout sites) and that there is a regular exchange between populations in Denmark, Germany and the Netherlands.

1.3.5 Grey seals

The maximum number of grey seals counted in the Danish Wadden Sea on the same day is 7 (Tougaard, unpublished) so the species is presently to be considered an infrequent visitor. However, the population of grey seals in Germany and the Netherlands has increased substantially since 1980 and a total of 1,800 grey seals were counted in 2005. If this development continues, it is expected that more grey seals will frequent the Danish Wadden Sea in the coming years and that perhaps a breeding population may be established.

1.3.6 Status of protection

The seals in the International Wadden Sea are protected under the trilateral Seal agreement under the Bonn Convention from 1991. This agreement obliges the three countries (Denmark, Germany and the Netherlands) to “closely cooperate in achieving and maintaining a favourable conservation status for the common seal population in the Wadden Sea”. In the context of this agreement a *Conservation and management plan for the Wadden Sea seal population* has been adopted. The latest management plan is for the period 2002-2006 and is to be revised every four years.

The entire Danish Wadden Sea is furthermore protected as a habitat area for both harbour seals and grey seals under the European Union Habitats Directive.

Hunting of seals in Denmark was abolished in 1977 and although it is possible to obtain permission to shoot seals in connection to fishing gear, such permits has not been issued in the Danish Wadden Sea.

1.4 Scope of investigations and possible effects

The ultimate question in the context of offshore wind farms and marine mammals is whether the construction and operation has an effect (positive or negative) on the population size and if this is the case whether this effect is acceptable or not. Seals, that must spend a significant amount of time on land, can be counted with reasonable accuracy from aerial surveys (see section 1.3.4 above) and changes in population size can thus be followed from year to year. Construction of a single offshore wind farm at Horns Reef, even if cause of severe negative impact on the seals in the area, is however, unlikely to affect the population to a degree measurable from annual haul out counts. The population of harbour seals in the Danish Wadden Sea is large which means that an effect of the wind farm should likewise be large in order to be visible. Furthermore, the population is also growing at a high rate (Abt *et al.* (2005) and section 1.3.4.) and even if a decrease in growth rate is observed, this effect is not easily attributable to the wind farm, as growth rates are often density dependent and thus not expected to remain constant. To address the issue of impact from offshore wind farms on seals one must break the effect up into individual components and address these individually. An overview of significant factors, their potential effect on seals and ultimate impact on the population is shown in Figure 11. Effects are divided into negative (red) and positive (green). The factors, their potential severity and how they can be addressed are discussed below.

1.4.1 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 seals 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.

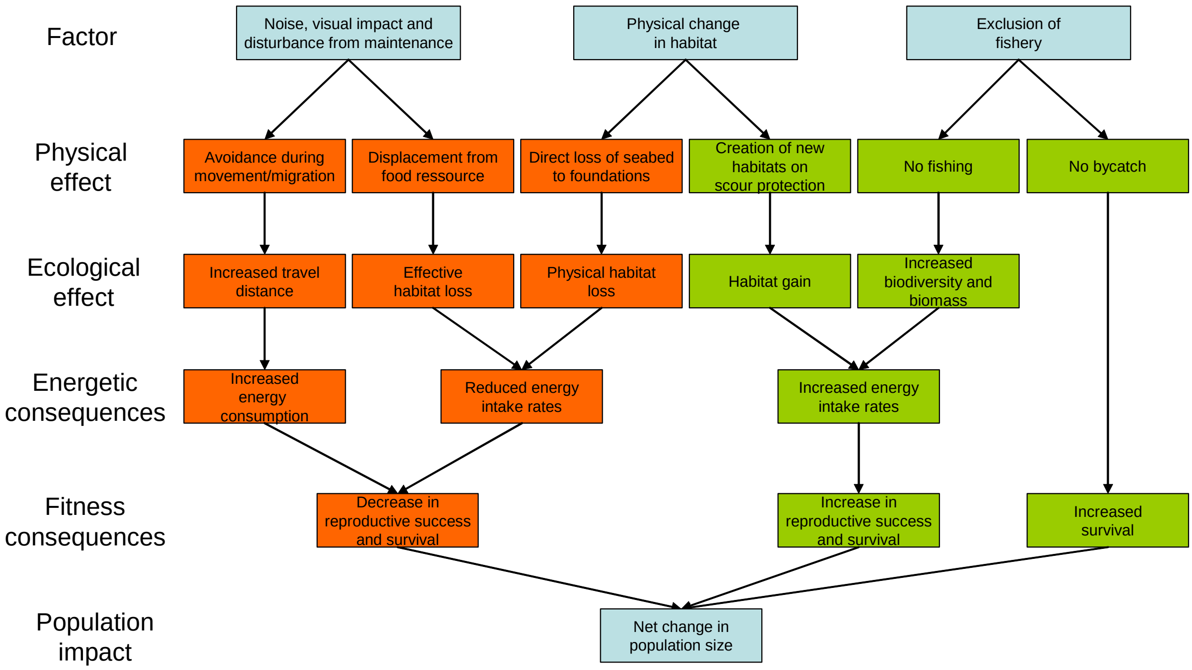


Figure 11. Schematic overview of potential effects of a wind farm on seals, showing how the individual factors may have a positive or negative impact on the animals, with ultimately leads to effects at the population level. Negative effects are shown in red and positive effects in green. Adapted from Fox *et al.* (2004).

1.4.1.1 Noise from pile driving

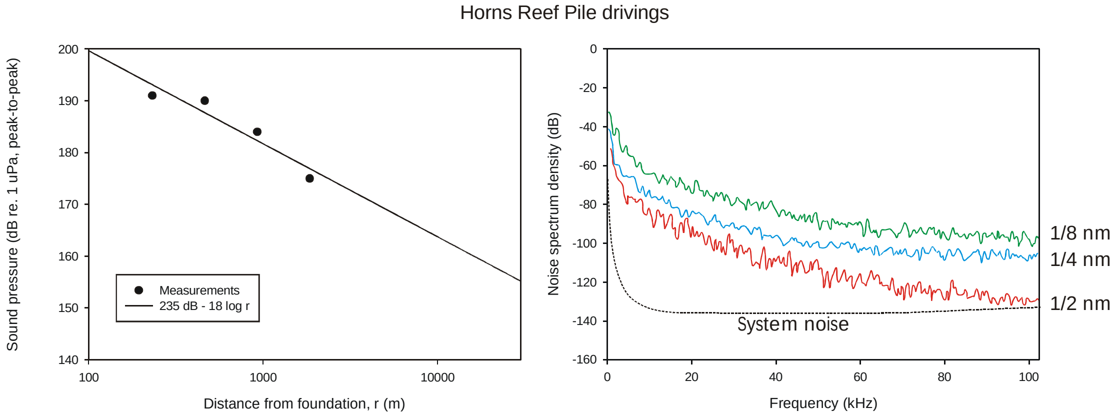


Figure 12. Sounds from piling at Horns Rev offshore wind farm. Left: sound pressure levels measured at various distances from the construction site and best fitting straight line. Right: Power spectra of piling sounds at three different distances from the construction site (1/8, ¼ and ½ nautical mile, 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 12 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 seals or 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).

It is difficult to extrapolate sound levels out to greater distances, but levels are nevertheless so high that they should be clearly audible to seals at distances of tens of kilometres and thus also potentially able to interfere with their behaviour.

1.4.1.2 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. For further details on types of sounds etc. see Tougaard *et al.* (2006).

1.4.2 Physical presence of turbines and service activities

The construction and operation of the turbines creates changes in the physical environment which may themselves be negative or at best neutral to the seals. In addition they may have secondary effects which can be both positive and negative.

1.4.2.1 Visual impact

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 seals from the area. Based on the general behaviour of seals, being investigative and often seen close to ships and inside harbours, this possibility seems unlikely. If anything, the turbines are likely to serve as visual landmarks and thus aid in navigation for the seals.

Figure 13. Row of turbines seen from a point close to sea level. Photo Vattenfall A/S.

1.4.2.2 Noise from turbines

Noise radiated from the turbine foundations into the water during normal operation could potentially have an effect on seals. Figure 14 shows measurements of underwater turbine noise from a single turbine in Horns Rev offshore wind farm. The noise 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 based on measurements comparable to those from Horns Rev indicate that seals are able to hear individual turbines at distances up to several hundred meters or under ideal conditions perhaps several kilometres (Henriksen 2001). The most critical parameter when determining theoretical detection distances is the transmission loss (Madsen *et al.* 2006). Transmission loss was not measured by Betke (2006), but measurements from Ingemansson Technology AB (2003) at Utgrunden, recalculated by Madsen *et al.* (2006) indicate a transmission loss of 30 dB per 10-fold increase in distance.

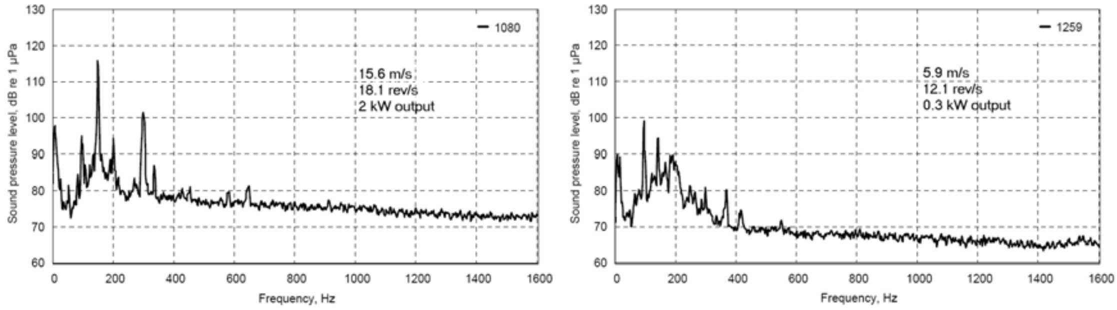


Figure 14. Measurements of noise from turbine in Horns Rev Offshore Wind Farm running close to maximum power rating (left) and at low level (right). Measurements were made with a Reson TC4032 hydrophone mounted 2.5 m above the seafloor 87 meters from the turbine foundation and recorded on an MP3 recorder 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).

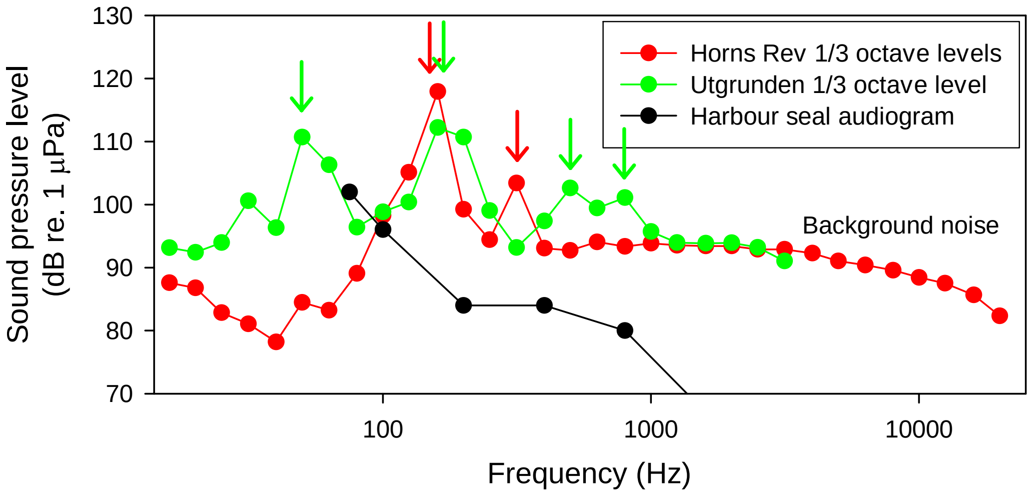


Figure 15. Average 1/3 octave spectrum, normalised to a distance of 100 m from Horns Rev together with similar measurement from Utgrunden offshore wind farm. Red line indicate hearing threshold of harbour seal. Noise spectra from Betke (2006), audiogram from Kastak *et al.* (1999). Arrows indicate the 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 seals 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, as long as the noise does not directly interfere with their activity. 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 unlikely that it will mask sounds of importance to the seals to any significant degree. Harbour seals communicate by underwater sounds, but are not very vocal and are mainly known to vocalise in connection with mating. The mating calls contain most of their energy at frequencies higher than the turbine noise (Bjørgesæter *et al.* 2004) and are thus not readily masked by the turbine noise, even if the seals should choose to vocalise very close to the turbine foundations. There could be other sounds of significance, such as from potential prey, which contains significant energy at lower frequencies and thus potentially could be masked by the turbine noise. Many fish, such as the sea scorpion and gurnard are known to communicate with low frequency sound and seals could potentially eavesdrop on this communication in order to find prey and it cannot be ruled out completely that masking could be relevant to this potential interaction. However, if relevant, it will only be very close to the turbines.

1.4.2.3 Other factors

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. Eltra calculated the size of the magnetic field from the sea cable connecting Nysted Offshore Wind Farm to land 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), which should be compared to the natural magnetic field in Denmark of 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.

Although seals cannot use olfaction underwater, 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 seals 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 seals are released from the turbine towers after completion.

1.4.3 Changes in habitat

The construction of an offshore wind farm on hard sandy bottom as on Horns Reef will inevitably cause the habitat to change. 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 seals however, as it comprises a loss of not more than 500 m^2 per turbine or 0.02% of the total area of the wind farm (20 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 16) and create an artificial reef. These will in turn attract fish and crustaceans and thus increase the biodiversity in the area and increase the potential prey available to the seals. Leonhard and Pedersen (2006) have thus estimated that an increase in biomass on the turbine foundations by 150% relative to the original biomass in the seabed now covered by the foundations. In other words, changes in the habitat caused by the wind farm are, if anything, likely to have a beneficial effect on seals and were not targeted as a specific issue in the monitoring program.

Figure 16. Scour protection boulders photographed in 2004 (two years after construction), with sea anemones, common starfish (*Asteria rubens*), an edible crab (*Cancer pagurus*) and Goldsinny-wrasse (*Ctenolabrus rupestris*). Photo: Bio/Consult A/S.

1.4.4 Exclusion of fishery

For reasons of safety (to fishermen, service work and installations) no commercial fishery is allowed in the wind farm. Seals are occasionally bycaught in fishing gear (monofilament gillnets and bottom trawls) but the extent of the problem is unknown. Due to the small size of the wind farm and the fact that fishery with bottom set gill nets did not occur in the area before 2002, the reduction in bycatch due to exclusion of fishery is probably minimal.

A more likely beneficial effect of banning fishery is the greater availability of prey to the seals and likely also an increase in diversity of prey (see above). These changes in the fish community are difficult to assess, both for technical reasons and because they are overlaid by the probably more dramatic changes in the fish community caused by the introduction of hard substrates (see also above).

1.5 Assessing the effects

The focus of the monitoring program has primarily been on potential negative effects of the wind farm in operation and in summary, these effects all relate to the seals use of the wind farm area. If seals, for one or the other reason are deterred (completely or partially) by the presence of the turbines, this may lead to increased travel distances and an effective loss of habitat. Methodologically, these effects are very difficult to assess however. Seals are notoriously difficult to study at sea. They spend most of their time submerged and are mostly seen solitary at sea. They are very difficult to observe at the surface, except under very good conditions (Beaufort sea state 0-2) and species determination in the field is often difficult, even for trained observers. For these reasons dedicated surveys from ship or airplane are not well suited for seals at sea (however, see e.g Leopold *et al.* 1997), as sighting rates are low and little can be inferred about their foraging behaviour from surface observations.

It is thus not feasible to design a monitoring program where the distribution of seals inside and outside the wind farm area is determined directly by surveys, as has been done for harbour porpoises and birds and neither is it possible to monitor the behaviour of seals as they approach the wind farm, as has been done with migrating birds.

No automatic detection system, equivalent of the T-POD datalogger used to monitor harbour porpoises (Carstensen *et al.* 2006) has been constructed for seals and as seals do not vocalize in the same regular fashion as harbour porpoises, this type of monitoring is not very useful in the context of monitoring and impact assessment.

Thus, the only direct method to assess the effects of the wind farm is through studies of individual seals by equipping them with instruments for tracking their behaviour and movement.

1.5.1 Telemetry in the study of habitat use

Telemetry is not without limitations. Unless a large number of animals are tagged, the information collected is inherently biased towards individuals and first conclusions are often of the type: “Animal A did this, whereas animal B did something else”. If a high variation in behaviour among individuals is present, one must be very careful about extrapolating results from a few individuals to the population as a whole. We may, by equipping one animal with sophisticated equipment, gain detailed information about its behaviour during hundreds of dives, but in a strict sense, this information only relates to this particular individual and cannot be used to infer about the behaviour of the population (pseudoreplication). Thus, if we tag 10 individuals and collect data from now thousands of dives, our sample size is still only 10. This fundamental limitation to the conclusions of telemetry studies will be evident in the following and should be kept in mind whenever judging the results.

1.5.2 Evolution of the project

At the time it was decided to build Horns Rev offshore wind farm, limited knowledge on foraging behaviour of harbour seals from the Wadden Sea was available. VHF-telemetry studies had shown, as described above (section 1.3.4.1), that the seals spend considerable time outside the Wadden Sea, especially outside the summer months. Furthermore, even though it could not be established where the seals tagged on Rømø foraged most intensively (due to limitations in the VHF-systems), there were clear indications that Horns Reef could be central to the seals. Thus, the main objective in the first satellite tracking study was to verify this, i.e. answer the fundamental question whether Horns Reef is a significant habitat for harbour seals or not (Tougaard *et al.* 2003b).

The first study showed that harbour seals forage extensively further offshore than previously thought and that not so much the reef area itself, but the entire offshore area west of the Wadden Sea was important as foraging habitat. Due approval of the project being delayed the seals were tagged very close to the start of the construction and data were thus collected mainly during the construction period. A stratification of the data into the three periods: baseline, construction and operation, was thus adopted in the data analysis.

After Horns Rev wind farm was constructed focus in the seal monitoring changed towards effects of the wind farm. It was clear that effects on seals would be small, if present at all and the central questions were whether seals would enter the wind farm after construction and if they did, whether their behaviour inside the wind farm was affected by the turbines being present. Answering this type of questions requires spatial accuracy on a scale not currently possible with normal satellite transmitters and new methods had to be found. A development of a tag containing a GPS-receiver was initiated and a prototype was constructed. This prototype did not function properly and the cooperation with the developing company was discontinued (Tougaard and Tougaard 2004).

In parallel with this a different system had been developed at University of Kiel. This system, a datalogger (described in the Methods section) originally developed for penguins and later adapted for seals, is capable of determining accurate positions based on dead reckoning from information on measured swimming speed and direction (Wilson and Wilson 1988). However, the positioning routine was not considered sufficiently accurate to allow conclusions to be drawn on a scale relevant for the wind farm. It was thus decided to combine the two systems, i.e. add a satellite transmitter to the datalogger.

1.6 Hypotheses

The primary hypothesis to be tested in the study was thus the indication that Horns Reef and thus also the wind farm area plays a central role for foraging harbour seals from the Danish Wadden Sea. Secondarily it was the aim to establish whether operation of the wind farm has had an effect on the foraging behaviour of harbour seals in the Horns Reef area, i.e. whether they spend more or less time in the wind farm area, compared to the surrounding waters.

1.7 Links to other monitoring programs

The monitoring project on seals has been coordinated with similar projects on seals at Nysted Offshore Wind Farm. The settings of the two projects are very different however, as Nysted offshore wind farm is located very close to an important haulout site and effects on haulout behaviour thus formed a central part of that project. A combined description of the two programmes and comparison of results and conclusions is covered in a separate report.

2 Methods

Several systems of telemetry equipment and dataloggers are available for the study of marine mammals. At the time of the first part of the present study in 2002 there were three main options: VHF-transmitters, satellite transmitters and data storage tags. Of these the satellite transmitters seemed the best option. VHF transmitters were disregarded due to their limited transmission range and difficulties involved in accurate positioning at sea and data storage tags were at that time not able to return reliable positions from sea. Thus, even though the accuracy in positioning of satellite linked systems is often not very high (see discussion below) and the amount of additional data on dive behaviour etc. which can be transmitted is very limited, it was nevertheless the best option available.

2.1 The Argos system

Satellite transmitters rely on the telemetry and positioning system provided by Service Argos Receivers are placed on US National Atmospheric and Ocean Administration (NOAA) weather satellites. The five satellites operate in sun-synchronous, polar orbits and over the North Sea one or more satellites will be visible on the sky approx. 30% of the time.

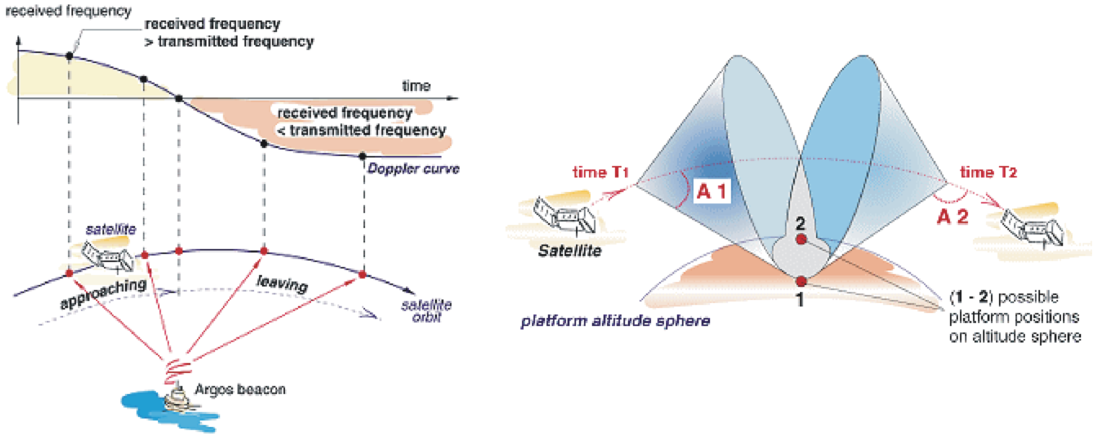


Figure 17. Principle of positioning with the Argos system. Depending on the speed of the satellite in relation to the transmitter, the received signal is Doppler-shifted in frequency (left). This can be converted into a bearing and from two bearings the position of the transmitter can be found. Source: Service Argos.

Two uplinks from the transmitter during a single satellite passage are needed to establish the position of the tagged animal (Figure 17). Better accuracy can be obtained if more than two uplinks are received on a single pass and locations are assigned by ARGOS into 7 location classes: 3, 2, 1, 0, A, B and Z. The first four classes are based on at least four uplinks in which case there is one or more additional degrees of freedom available to estimate the precision of the location. Locations classified A and B are based on 3 and 2 uplinks, respectively and the precision can not be assessed from the Doppler shift measurements alone. The last position class, Z is reserved for positions, which fail to converge in the positioning algorithm and should always be discarded.

A transmitter on a diving animal, transmitting only one uplink at each surfacing will produce few positions of location class 0-3, as the probability of receiving 4 uplinks or more during a 10-minute passage is small. It is thus to be expected that most positions at sea will be of location class A and B. White and Sjöberg (2002) demonstrated that the average precision of 0 and A class positions from a grey seal at sea was better than 5 km, whereas the average precision for B class positions were close to 50 km. Class 0, A and B positions need not be discarded, but their accuracy needs to be evaluated by other means. This is usually done by comparing with previous and subsequent positions and assessing whether it is probable that the animal could move the distance to the point in question in the available time between positions. Vincent *et al.* (2002) not only estimated the accuracy of all location classes in a study on captive swimming grey seals, they also showed that appropriate filtering can increase precision for class 0, A and B positions considerably (Table 1).

Table 1. Precision of Argos location classes as provided by Service Argos (left column) and empirically determined accuracy, after filtering (centre and left columns). Precision is given as 68% percentiles, equal to the standard deviation under the assumption that errors are normally distributed around the true position. See text for details on filtering. Empirical data from Vincent *et al.* (2002).

Location Class	Service Argos Longitude and Lattitude	Vincent *et al.* 2002 Longitude (m)	Vincent *et al.* 2002 Lattitude (m)
3	150	300	160
2	350	500	260
1	1000	1000	430
0	-	3000	1900
A	-	900	700
B	-	4800	3200

2.1.1 Wildlife computers SDR-T16 and SPOT2/SPOT4

Three different satellite transmitters were used, all manufactured by Wildlife Computers Inc., Seattle, USA. The SDR-T16 unit is equipped a pressure transducer and thus is capable of recording dive depth information, whereas SPOT2 and SPOT4 transmitters only provide indirect information on dive behaviour through measurements of water temperature and submersion times.

All three types transmit radio signals to the Service Argos satellite system with regular intervals (every 45 sec. at sea and 90 sec. when hauled out) when the transmitter is clear of the water.

Transmission time is limited by battery life, which differs among types and batteries used. SDR-T16 units were equipped with four M1-cells, SPOT2 units had one C-cell and SPOT4 units had 2 AA-cells. This corresponds to nominal 30.000, 90.000 and 60.000 transmissions per unit, respectively.

To optimize performance the units were programmed not to transmit during night hours (22.00-3.00) where satellite coverage was poor.

After moulting and the transmitter had been shed, one SDR-T16 unit was recovered on the beach by a tourist and was refitted with new batteries and redeployed.

Figure 18. Wildlife Computers SPOT4 (left) and SDR-T16 (right) satellite transmitter mounted on the head of two harbour seals. Antenna faces backwards and electronics and batteries are visible through the translucent plastic moulding. Photos S. Tougaard.

2.2 Datalogger

The datalogger, developed by Rory Wilson and co-workers at University of Kiel, consists of several separate units, which together continuously records a number of parameters relevant to the movement of the tagged animal. Most important are pressure (depth), speed, pitch, roll and 3D compass orientation. Also the environmental parameters such as temperature and light level are recorded. All measurements are recorded with 5 second intervals. Some deployments also included mounting of an IMASEN-unit (inter-mandibular-angle-sensor), capable of detecting whenever the seal opened its mouth. IMASEN data were not used in this study.

Figure 19. Datalogger ready to be deployed. The red hard foam flotation which contains all electronics is placed inside a neoprene "backpack", which is glued to the back of the animal at seven points along the edge. To the left is the cable to the IMASEN-device, which is mounted on the head of the animal. Antenna in the rear end of logger (right) belongs to the integral Argos transmitter. Photo: S. Tougaard.

All electronics are housed in a moulded shell of high buoyancy (Figure 19) which acts as float for the detached unit (see below). Included in the unit is a Wildlife Computers

SPOT4 transmitter. However, only few locations were obtained at sea since these transmitters were placed on the back and therefore often submerged when the seals surface to breathe.

The unit was housed in a neoprene “backpack” glued to the fur on the back of the animals with epoxy glue. After a predetermined delay of about 2 months a release mechanism was automatically exerted and the unit released from the “backpack”. As the units float, they would eventually wash up on coast where they in many cases have been found and returned to either the Fisheries and Maritime Museum or the University of Kiel.

2.3 Capture and tagging

A total of 36 harbour seals were caught between January 2002 and November 2005. Of these 21 were equipped with satellite transmitters and 23 with dataloggers. Eight animals were equipped with both an Argos transmitter on the head and a datalogger on the back. Data on the individual seals are shown in Appendix C. Seals were caught on haul-out sites on the northern tip of the island Rømø or adjacent sand banks (Bollert Sand, 55°12,73"N 08°30,84"E, Koresand, 55°13,36"N 08°29,85"E and Sønderbanke, 55°12,88"N 08°28,39"E). If not caught on Bollert, they were transported there, tagged and released.

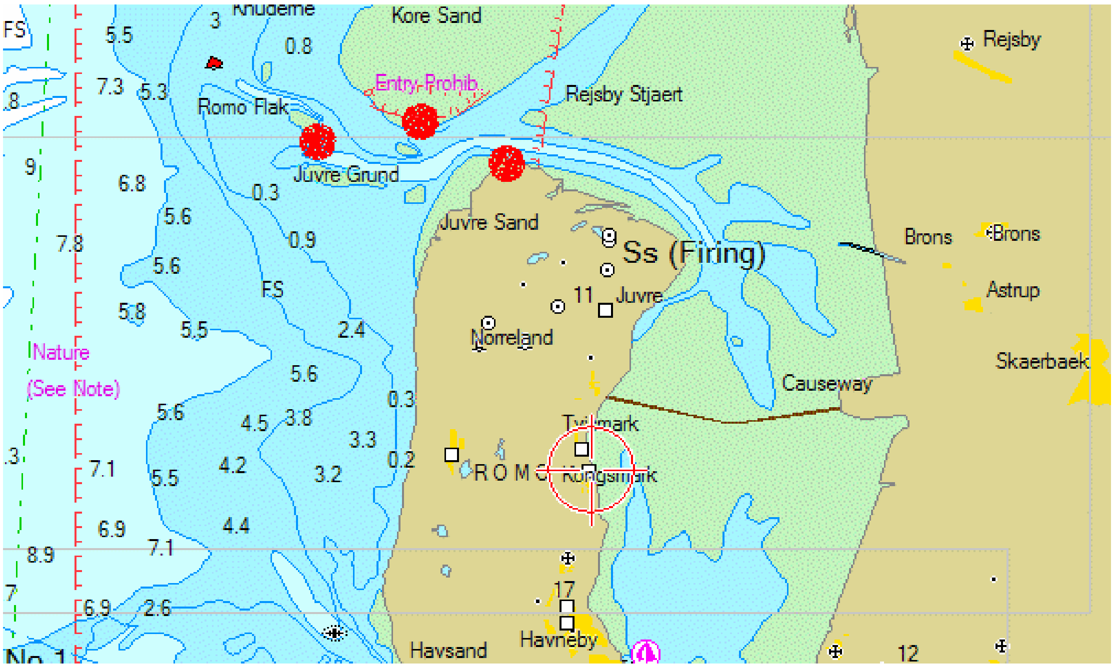


Figure 20. Northern part of Rømø with the Juvre Dyb tidal area and the capture sites indicated by red dots.

The seals were approached by the rescue vessel from Havneby, Rømø. This boat is equipped with two strong hydro jet engines, which enables fast sailing in very shallow waters. The lack of propellers furthermore minimizes the risk of injury should a seal accidentally come too close to the boat and eliminates the risk of entangling gear in propellers.

Figure 21 Capture and tagging. Photos S. Tougaard.

The boat approached the seals close and parallel to the coast until the point where the seals fled into the water. The seals generally remained in the immediate vicinity of the bank and one man was put on shore with the tail end of a long net (100m long, 6m high, 100 mm mesh size). The boat then drove in an arc along the beach and around the seals, encircling a substantial number of animals with the net. The other end of the net was taken ashore and the entire net hauled up on the beach including the caught seals (Figure 21, left). The required number of seals were taken from the net and strapped to stretchers for mounting of transmitters. Any remaining animals were released.

The transmitters were glued to the fur on top of the head of the animals with fast hardening two-component epoxy glue (Araldite 2012). Prior to attachment the fur was

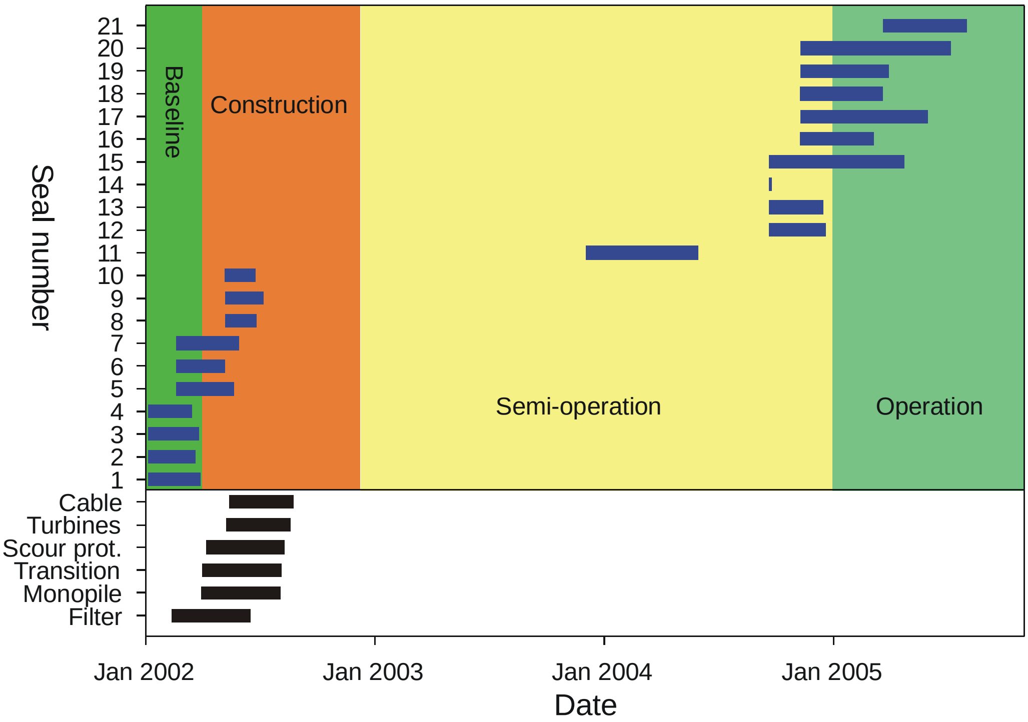


Figure 22. Timeline of deployments of Argos transmitters and their transmission time. The main construction events in 2002 are indicated below the deployments. Green, orange, light yellow and light green indicate baseline, construction, semi-operation and operational period, respectively, as defined in this report. Semi-operation refers to a period with extensive maintenance work on the turbines, where the wind farm thus was operating well below nominal capacity. No separation between semi-operation and operation has been made in the analysis of the seal data.

thoroughly washed with water, acetone and alcohol and dried with hairdryer. After hardening, which took up to 20 minutes due to the low air temperature, the seals were released.

The dataloggers were contained in a neoprene bag, which was glued onto the back of the seals with epoxy glue (see picture on front cover). On some of the seals an IMASEN sensor was glued to the upper side of the head, just behind the nostrils and with a permanent magnet glued to the underside of the lower jaw. The IMASEN sensor was connected to the datalogger through a thin, flexible cable, which was attached along the way to the back with small gaze strips glued into the fur.

Dataloggers were retrieved when washed up on the beach along the German and Danish coast. Several units were located through the positions received from Service Argos from the transmitter imbedded in the logger (Figure 23).

Figure 23. Datalogger found on the dam to Rømø in 2006. This logger was deployed on November 26th. 2005. It was found 100 m from the positions provided by the Argos transmitter. Photo: S. Tougaard.

2.4 Filtering of ARGOS positions

Argos positions were filtered in order to remove positions that were unrealistic. This filtering is based on the methods described by McConnell *et al.* (1992) and Keating (1994) and considers both the distance between subsequent positions and the change in direction from one pair of positions to the following pair. The first filter calculates the mean swimming speed between pairs of positions and removes positions which cause unrealistically high swimming speed. A cut-off speed of 5 km/h was used in this filter. The second filter considers the angle between the straight line from position A to position B and the straight line between position B and position C. If position B is very far from the true position of the seal, this angle is likely to be very small, i.e. it appears that the animal has moved from one area to another area and then immediately back to the first position. See Douglas (2003) for details.

2.5 Habitat use - presence/absence data

After filtering it was assumed that errors on latitude and longitude were normally distributed according to a bivariate Gaussian distribution (Vincent *et al.* 2002). The bivariate Gaussian distribution has the parameters μ_x and μ_y (mean error on longitude and latitude, respectively), σ_x and σ_y (standard deviation of errors) and ρ (correlation between errors on longitude and latitude). We further assumed that errors on longitude and lattitude were uncorrelated ($\rho = 0$) and that mean errors were zero (no systematic bias in observed positions towards any particular direction).

The probability that the true position associated with a given observed position is located inside a given rectangle was assumed to depend on the distance between the observed position and the centre of the rectangle as well as the size of the rectangle. The probability is calculated on the basis of the cumulated bivariate Gaussian distribution. The combined probability that at least one true position is located inside a given square, $P(n_A > 0)$ is calculated by combining the probabilities that at least one of the observations inside the square or in one of the adjacent squares truly belongs inside the square in question.

$$P(n_A > 0) = 1 - P(n_A = 0) = 1 - \prod_{i=1}^{N}(1 - P(v_i \in A))$$

$P(n_A > 0)$ is thus given as 1 minus the probability that no uplinks originated from the square A. This probability is again calculated from the product of the N probabilities that each of the N positions did *not* originate in the particular square, 1- $P(v_i \in \mathrm{A})$. v_i is thus the i^{th} position of the dataset, which contains a total of N positions and n_A is the number of true positions inside square A.

A second parameter that can be associated with each UTM-square and which can be of interest in this context is the most likely number of true positions inside the square, $E(n_A)$. This is given as the sum of the individual probabilities associated with individual observations:

$$E(n_A) = \sum_{i=1}^{N} P(v_i \in A)$$

Thus $E(n_A)$ is found for square A as the sum of the individual probabilities that the *i'th* position v_i truly belongs in the square, summed over all N positions of the dataset. $E(n_A)$ thus represents the expected number of positions in the square.

2.6 Habitat use – time

A quantitative assessment of habitat use was performed by computing the time spent in 10x10 km grid cells, based on Argos positions. Based on all filtered positions an interpolated track was made for each seal. A position for every 10 minutes was calculated under the assumption that the animal moved in a straight line with constant speed between positions. A grand mean across all seals was calculated for each cell:

$$\text{Mean time spent in } cell_{i,j} = \frac{\sum_{N\ seals} 10 \cdot n_{\text{positions in } cell_{i,j}}}{\sum_{N\ seals} \text{Transmitting days}}$$

This grand mean expresses the average time (in minutes) spend in a particular cell per day per tagged seal and is thus a measure of the importance of that particular 10x10 km square.

The analysis was separated into baseline, construction and operation period.

2.7 Positioning and dive data from dataloggers

In this exploratory study only a limited amount of information was extracted from the dataloggers. This information included individual tracks reconstructed on the basis of movement information (speed and direction of movement from the 3D-magnetic compass). The integral Argos transmitter mainly provided positions from when the seals were hauled out. From these positions (i.e. start and end of a single fouraging track) and the data on speed and direction the entire track could be reconstructed by dead reckoning. This was done using custom software.

Dive data was extracted from the pressure transducer recordings.

See e.g. Wilson (2004) for an introduction to the datalogger and examples of applications to the study of penguins.

2.8 Visual observations

Line transect surveys from ship were conducted regularly in the area in order to monitor harbour porpoises in and around the wind farm (Tougaard *et al.* 2006). Seals were consistently observed on these surveys, although never in large numbers. These observations have been included in this report for completeness, although the data material is not large enough to warrant detailed analysis.

Observations were made by three trained observers, sitting or standing on top of the bridge of the ship and scanning the waters in front of the ship with a combination of naked eye and binoculars (8-10 times magnification). The ship was moving along east-west oriented line transects with a speed of approximately 10 knots.

Whenever a seal was observed the time, angle and distance to the animal was noted. Positions were logged continuously with a GPS. See Tougaard *et al.* (2006) for details on individual surveys.

Observations were assigned to the three periods: baseline, construction and operation. Due to the low number of seal sightings per survey, the dataset was considered inappropriate for application of distance sampling methods (Buckland *et al.* 2001) as could be done with the more numerous porpoise sightings. Instead a simple calculation of average rate of sightings per transect km was computed for 4x4 km squares.

3 Results

A very large body of data has been collected and a wealth of information on foraging behaviour of harbour seals has been gained. In order to restrict the discussion focus will nevertheless remain on the offshore wind farm in the following, with some general comments. The results fall into two groups, those collected in 2002 and described previously (Tougaard *et al.* 2003b) and those collected in subsequent years (2004-2005). Selected relevant data from the German dataloggers will also be presented.

3.1 Movement

Filtered positions from all seals are shown in Figure 24, separated into data from 2002 and data from 2003-2005. There are both similarities and marked differences between the two datasets. The haulout patterns are very similar, with a concentration on the haulout bank where animals were tagged (Bollert) and the bank Langjord, the next major haulout bank north of Bollert. In both groups several animals spent considerable time at Langli Sand, the northernmost haulout site in the Wadden Sea and on the sandbanks around Föhr and Amrum in Schleswig-Holstein. A remarkable similarity in the two datasets is that one seal in 2002 and one seal in 2005 both relocated to the southern part of the Dutch Wadden Sea, around the islands of Terchelling and Vlieland.

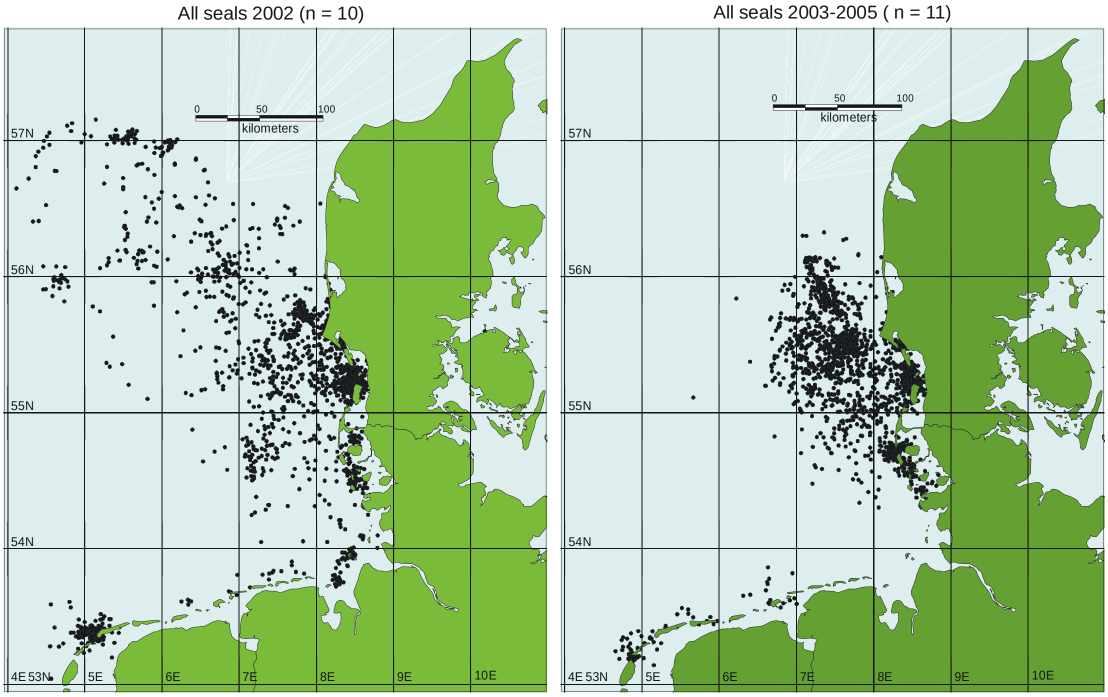


Figure 24. All ARGOS positions (after filtering) from seals tagged in 2002, covering baseline and construction (left) and seals tagged in 2003-2005 after completion of wind farm (right). Each dot represents one position from one seal. Maps with tracks of all individual seals can be found in Appendix A.

The most remarkable difference between 2002 and 2003-2005 positions is the longer distance travelled offshore in 2002, where three individuals (all pups from the previous summer) moved 200-300 km offshore on several foraging trips. All animals in 2003-2005 (including 3 pups from the previous summer) remained within 100 km from shore. With the exception of the very long trips in 2002, the areas frequented by the seals are overlapping, covering an area from around Holmslands Klit 50 km north of Horns Reef down to Amrum and out to a distance of approx. 100 km offshore. With the exception of the two animals in the Netherlands, there is a clear general orientation towards north-west in the foraging trips by the seals.

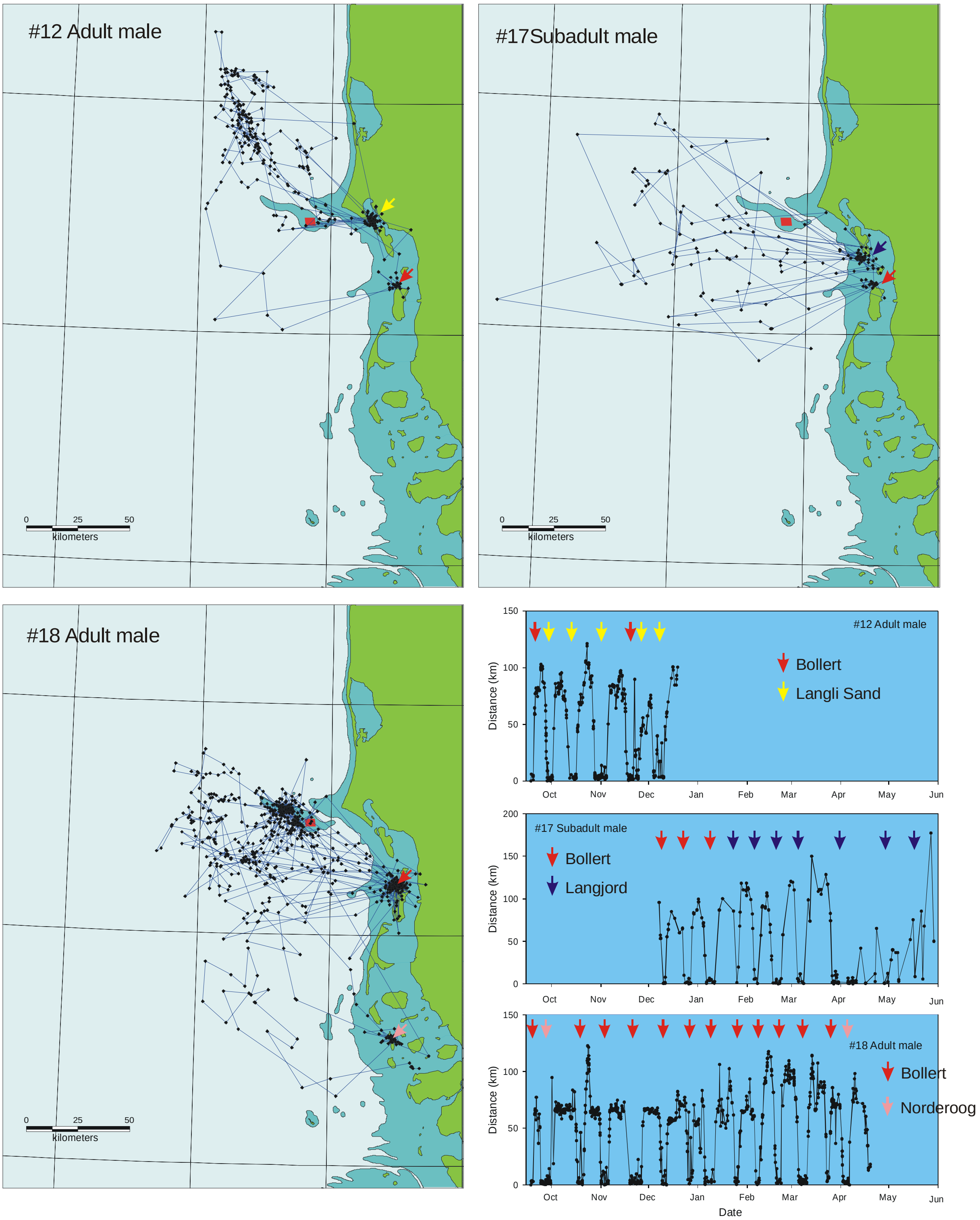


Figure 25. Tracks from three different seals tagged in 2004. Maps show filtered Argos positions connected with straight lines. Graphs in lower right corner show distance to haulout site. Haulouts are indicated by arrows coloured according to site. Blue-grey shading indicate 10 m depth contour and the wind farm is indicated as a red trapezoid.

Three examples of tracks from individual seals are shown in Figure 25, all selected because of relevance to discussion of Horns Rev offshore wind farm. Tracks from all 21 tagged seals can be found in Appendix A.

When looking at the maps, the tree animals behaved very differently in the period their tags were transmitting. Animal #12 spent almost all offshore time in the area north of Horns Reef and in Slugen, the deep channel separating the inner and outer reef. Animal #17 in contrast, distributed its foraging activities over a much wider area, both north, west and south of the reef. Animal #15 falls in between the other two seals, with time spent over a broad area southwest of the reef, together with a long period of very focused foraging at the central part of the outer reef (around the shallow area "Tuxen"). When looking at time budgets for the three seals, they were nevertheless strikingly similar in behaviour (lower right panel in Figure 25). They spent 1-2 weeks at sea, 50-100 km from the haulout site, returned for up to one week of haulout and then took off on a new foraging trip. All three animals returned to Bollert for haulout at least once after tagging and did not use more than one other haulout site in the period. The most noteworthy deviation from this regular pattern of haulout and foraging is animal #17 from April and onwards, where foraging trips becomes increasingly irregular. This can be due to poorer performance of the transmitter at sea towards the end of its lifetime, but is nevertheless consistent with pattern seen from other tagged seals, where foraging trips becomes shorter in time and smaller in distance to haulout in late spring and over the summer.

3.2 *Habitat use – presence/absence*

Overall results of the analysis based on the precision of Argos positions are shown as maps in Figure 26, and the results relevant for discussing the importance of Horns Reef are shown as maps in Figure 27 and Figure 28.

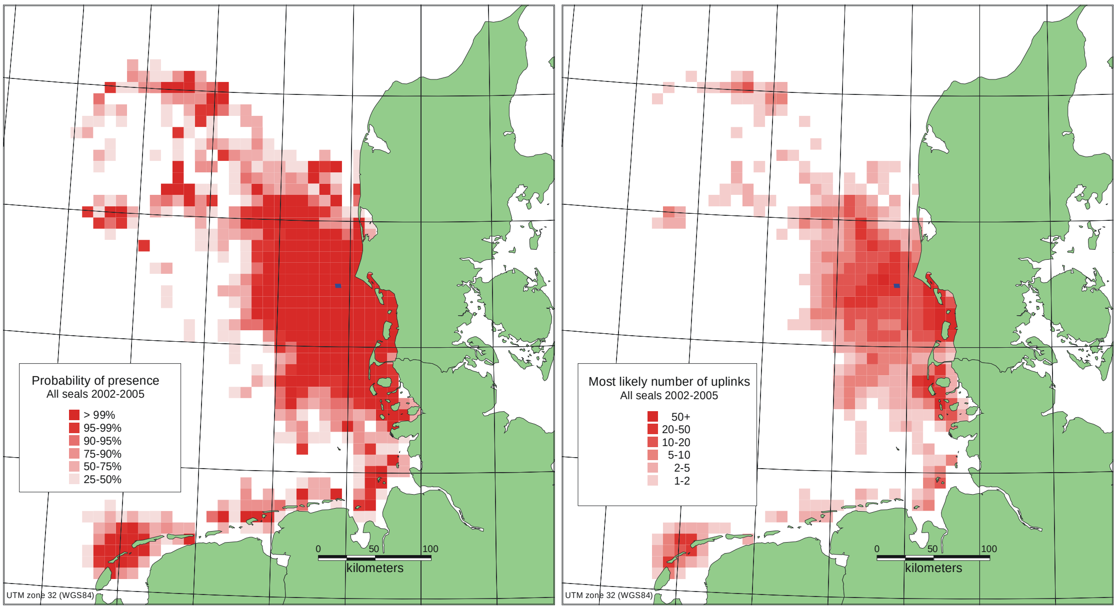


Figure 26. Analysis of presence based on filtered Argos positions from all 21 seals analysed in 10x10 km squares. Left map shows probability of presence, i.e. the probability that at least one uplink originated in the particular 10x10 km square. Right map shows the most likely number of uplinks from individual 10x10 km squares. Horns Rev offshore wind farm is shown as a small blue trapezoid.

The overall pattern in uplink distribution shows a clear concentration in animal presence in an area centred on Horns Reef and with a radius of 50-100 km to the north, west and south. All 10x10 km squares in this area were visited at least once and within a radius of 50 km out from the outer reef most 10x10 km squares were visited 10 times or more by transmitting seals. A very high number of transmissions are found in the squares containing the main haulout sites, but also the central part of the outer reef (around the shallow “Tuxen”) contains more than 50 positions. Most of the latter are due to a single individual, animal #18, which spent considerable time in this area (see Figure 25).

Data were also analysed at higher resolution (4x4 km squares) in the area around Horns Reef (Figure 27 and Figure 28). These maps show a scattered presence around the reef and the wind farm during baseline and construction periods and a more consistent presence during operation of the wind farm. No correction has been made to adjust for the unequal number of animals and positions in the three periods, with the majority of the data falling into the operational period (roughly four times as many days with data as in baseline and construction periods). This bias should be taken into account when comparing the maps. Common for all three periods was a strong presence around the haulout sites Langli Sand, Langjord and especially Bollert, but also that offshore presence of the seals concentrate in localised areas. These areas differ between periods and likely reflect differences between individual seals.

3.3 Habitat use - time

The previous analysis is very conservative in the sense that it is restricted to a highlight of areas which with a high degree of confidence was visited by tagged seals. This analysis is inherently vulnerable to bias introduces by unbalanced datasets, i.e. unequal number of positions in the different periods and from the different animals. An alternative and less restrictive analysis was performed on interpolated tracks and results are presented as maps in Figure 29. These maps express the amount of time spent in 10x10 km squares, averaged over all seals and over all periods where data were collected. These maps are more consistent across the three periods and show a clustering of activity around the outer reef, in line with the previous maps.

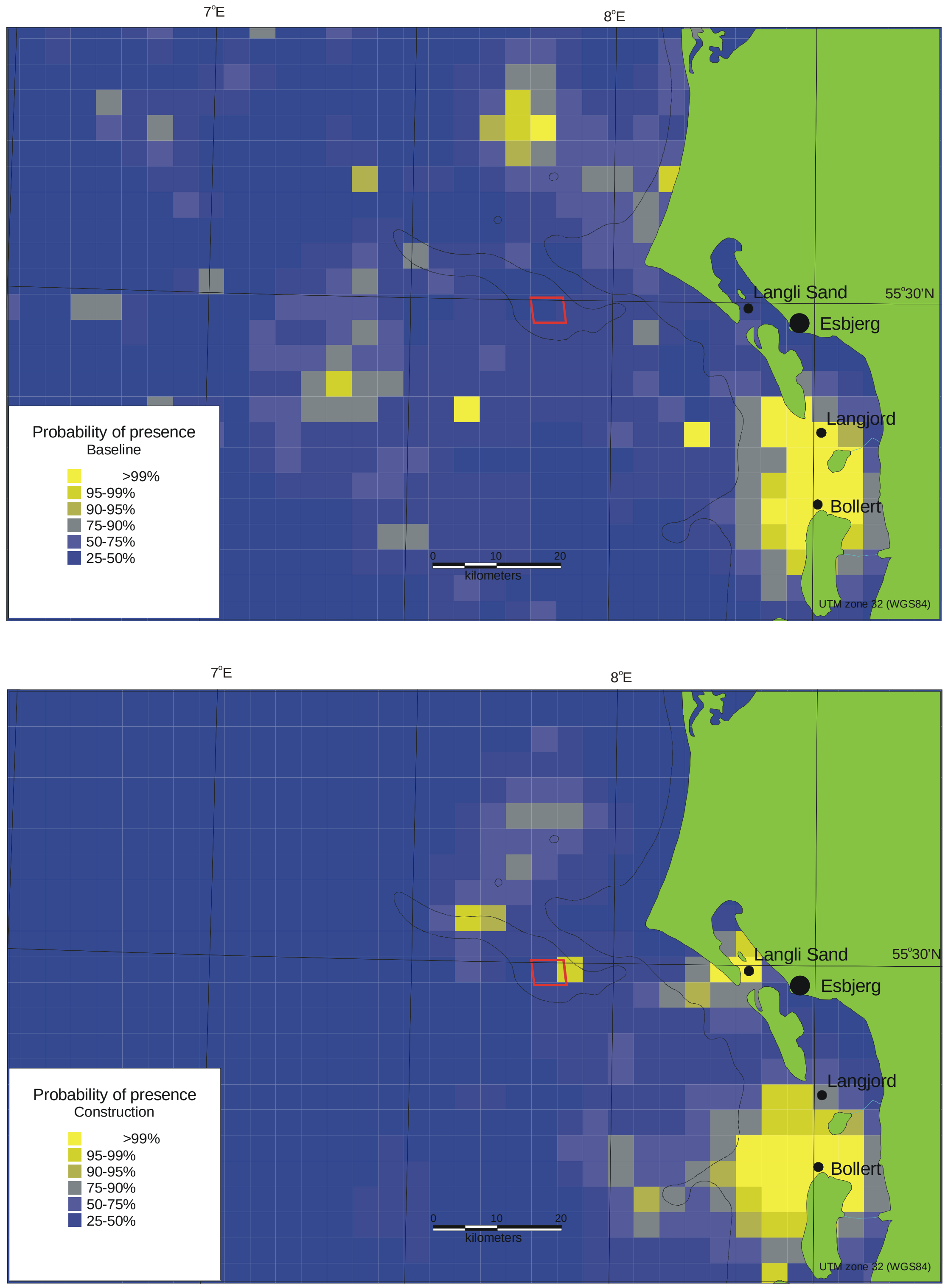


Figure 27. Probability of presence of tagged seals, based on filtered Argos positions and analysed in 4x4 km squares. The analysis was performed on positions from baseline, construction and operation periods separately (upper left map, lower left map and upper right map, respectively) and on all positions combined (lower right map). Wind farm is shown as red trapezoid and 10 m depth contour as solid black lines. Main haulout sites are indicated on maps.

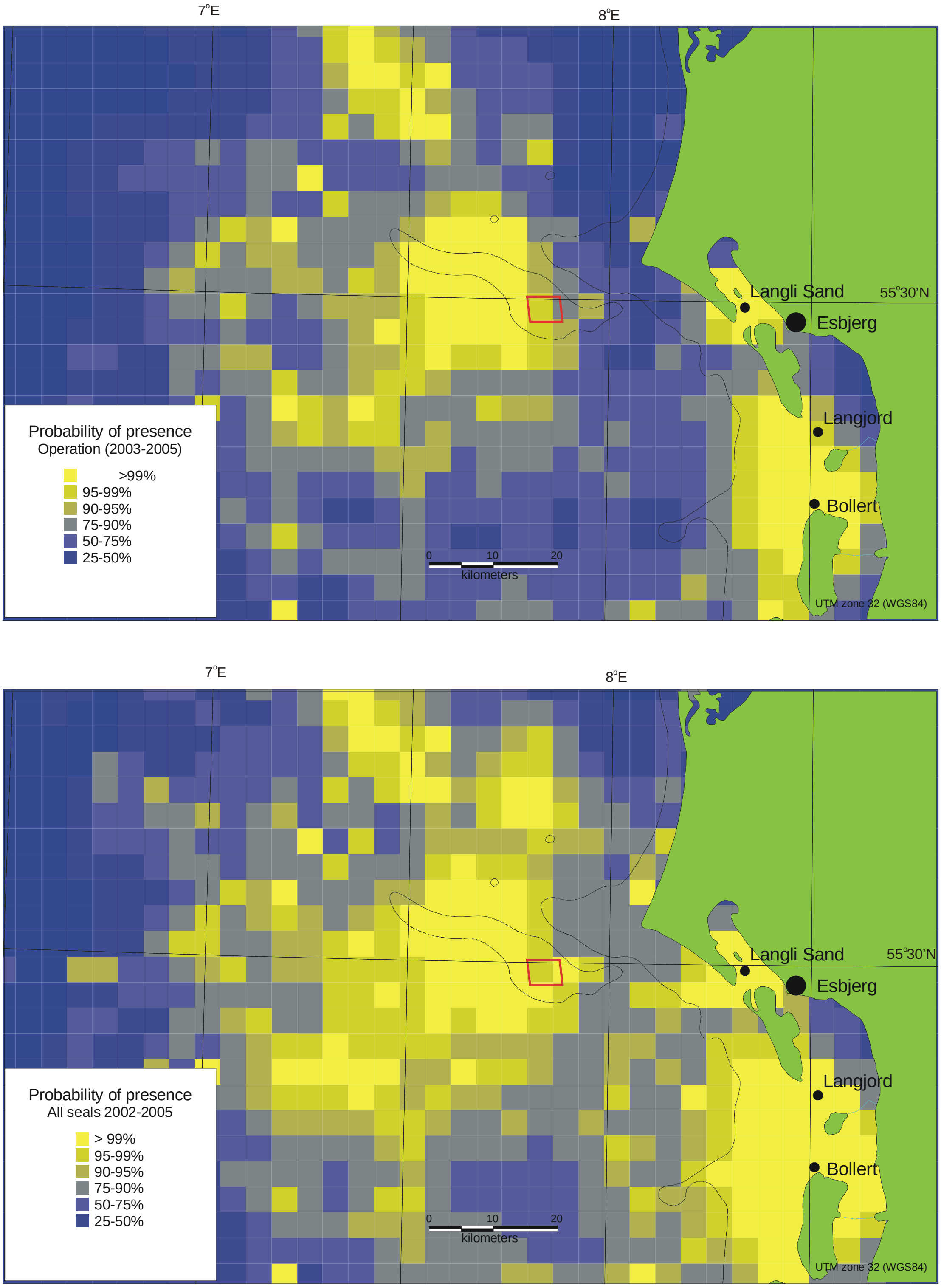


Figure 27 cont.

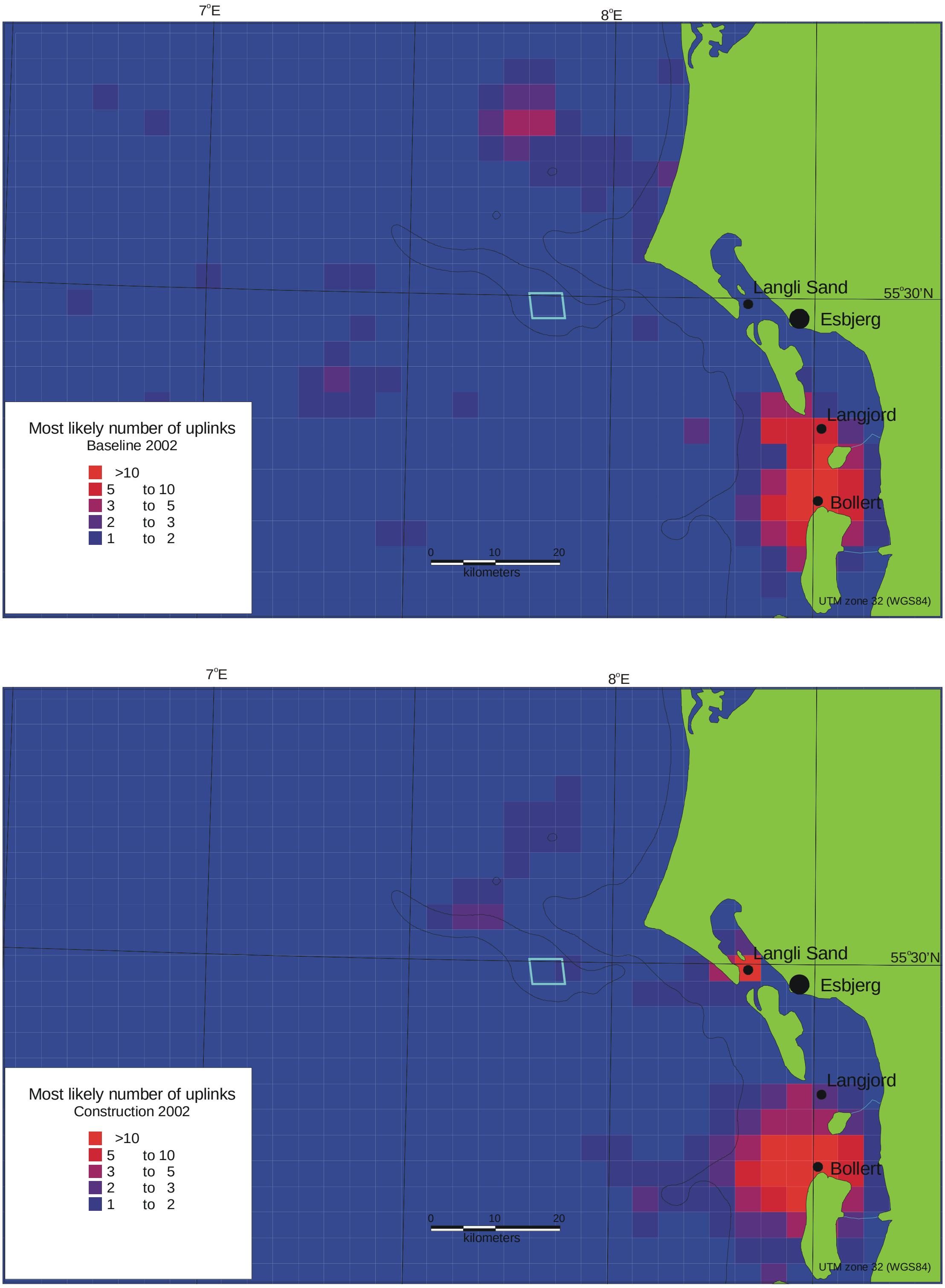
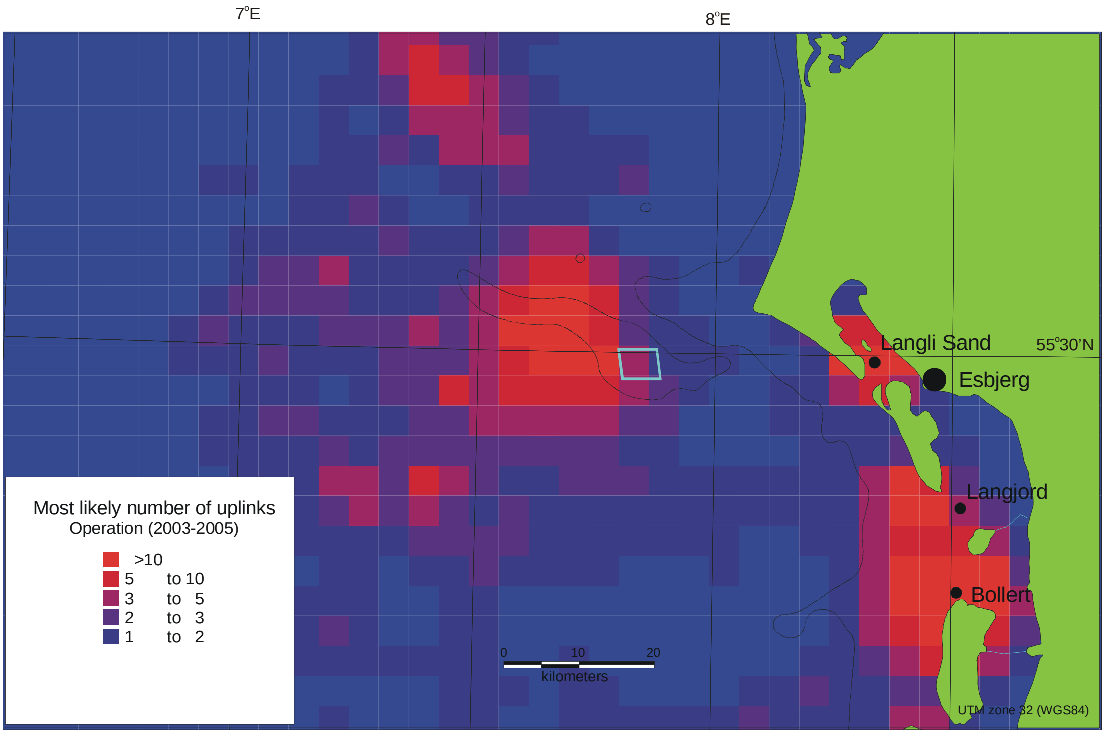


Figure 28. Most likely number of uplinks from tagged seals, based on filtered Argos positions and analysed in 4x4 km squares. The analysis was performed on positions from baseline, construction and operation periods separately (upper left map, lower left map and upper right map, respectively) and on all positions combined (lower right map). Wind farm is shown as blue trapezoid and 10 m depth contour as solid black lines. Main haulout sites are indicated on maps.



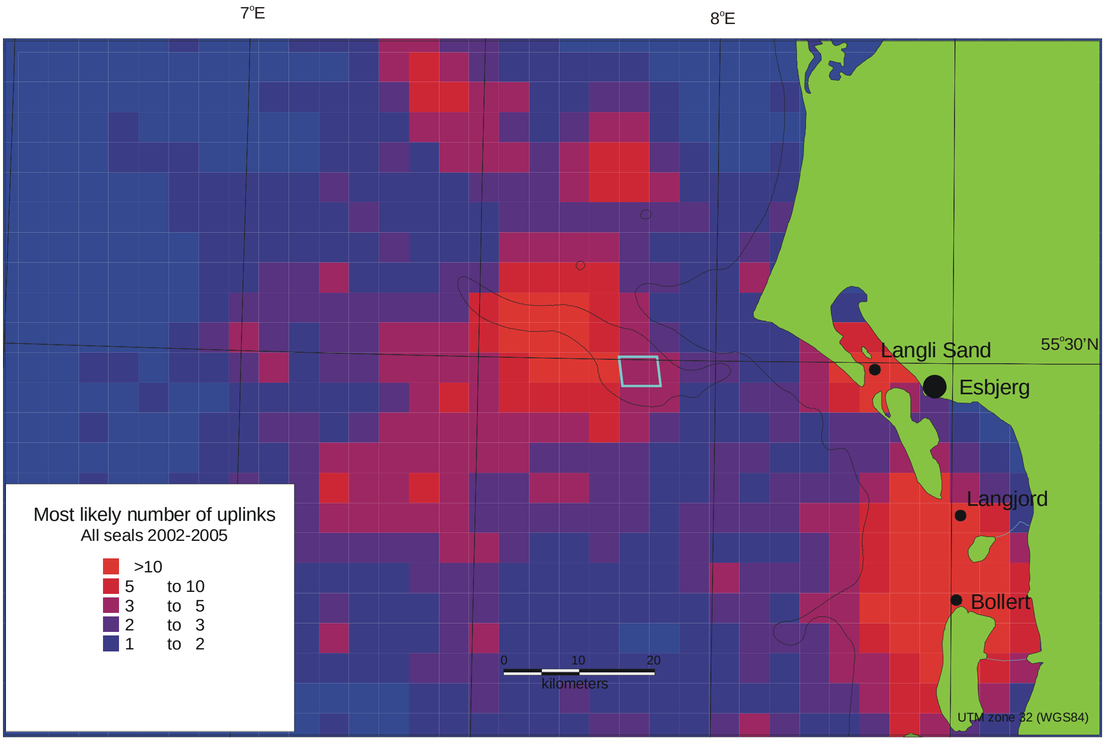


Figure 28 cont.

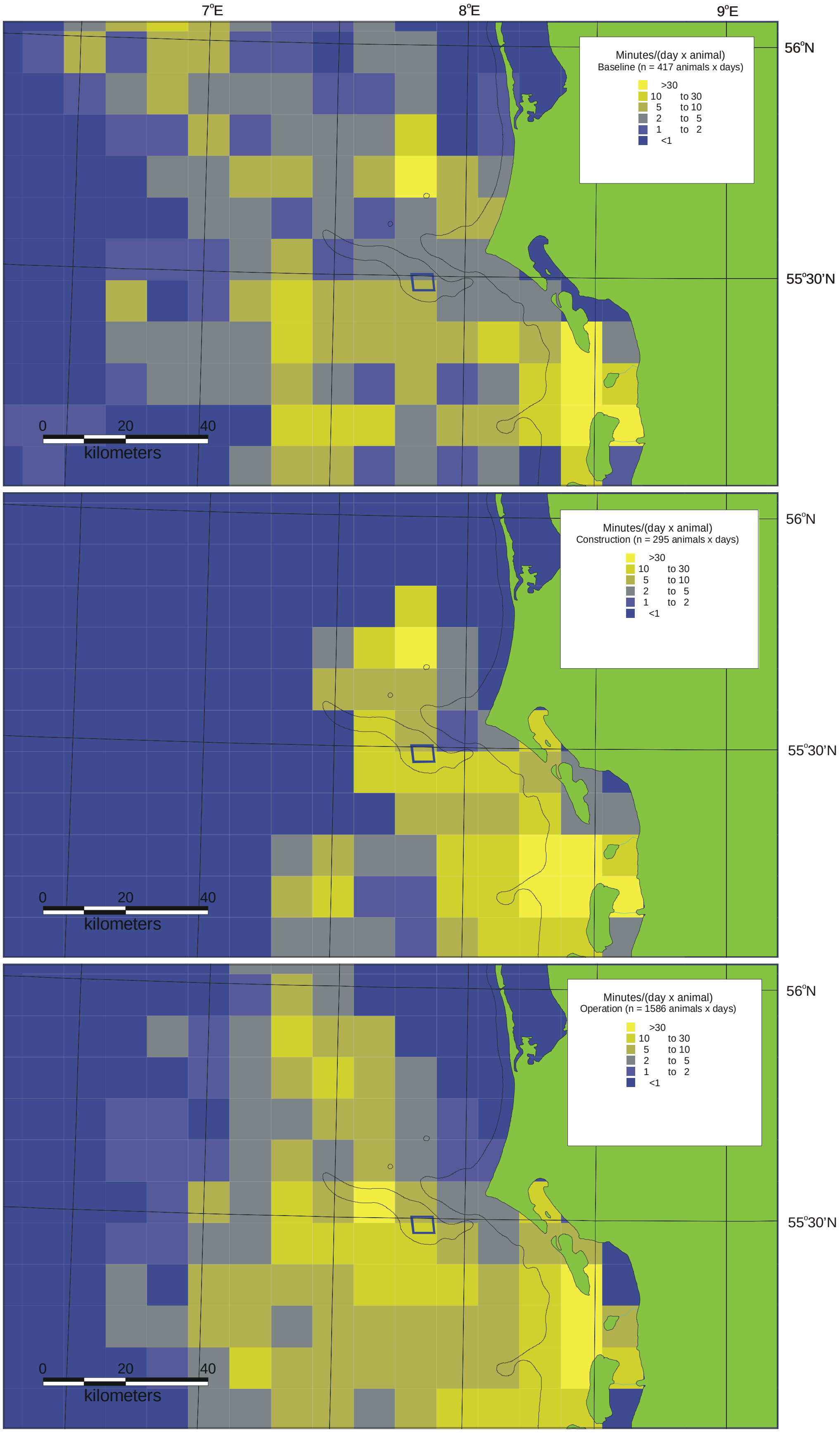


Figure 29. Analysis of time spent in 10x10 km squares, based on linear interpolated tracks between filtered Argos positions. Each value represents the average time (in minutes) spent per day per seal in each of the 10x10 km squares. Analysis was performed separately for positions from baseline, construction and operational period.

3.4 Datalogger data

Twenty-three seals were equipped with dataloggers of which seven have been recovered at the time of this report and of these data from four has been analysed. Only one of these four seals spent considerable time in the area around Horns Reef and appears to have passed through the wind farm on two occasions. Data from this seal were selected for further analysis and is presented below. The seal, an adult male tagged in April 2004, made 11 trips out from Bollert during the 94 days the datalogger was collecting data. Four examples of tracks are shown in Figure 30 and all 11 tracks are shown in Appendix B.

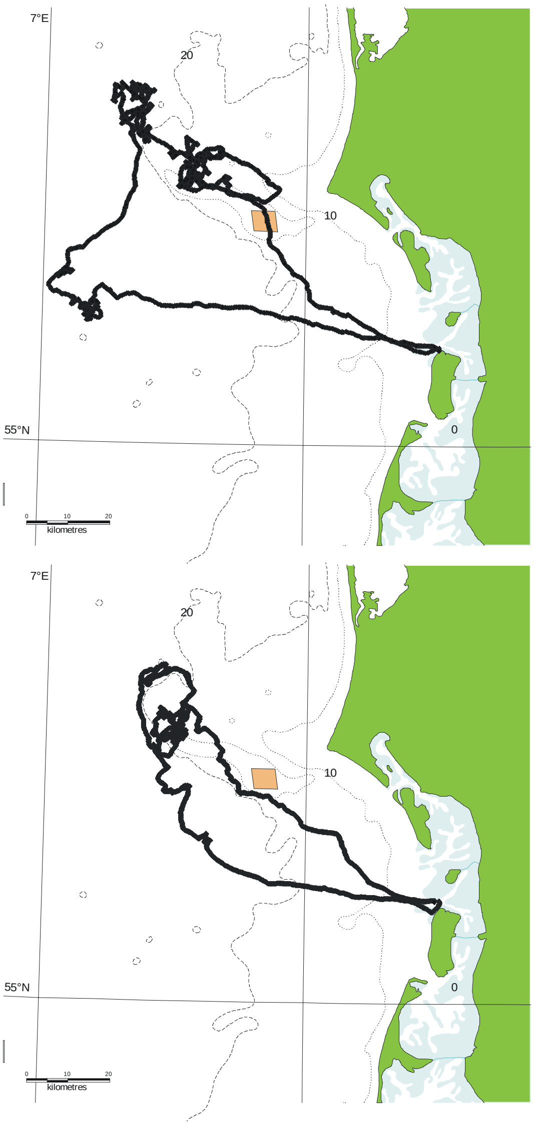


Figure 30. Four examples of foraging trips made by an adult male harbour seal tagged on Bollert in April 2004. Wind farm is shown as red trapezoid. Dotted and broken lines represent 10 m and 20 m depth contours, respectively.

This particular individual spent considerable time in especially the northern Horns Reef area, as seen in the tracks in Figure 30. Two example of dive behaviour are shown in Figure 31 and Figure 32.

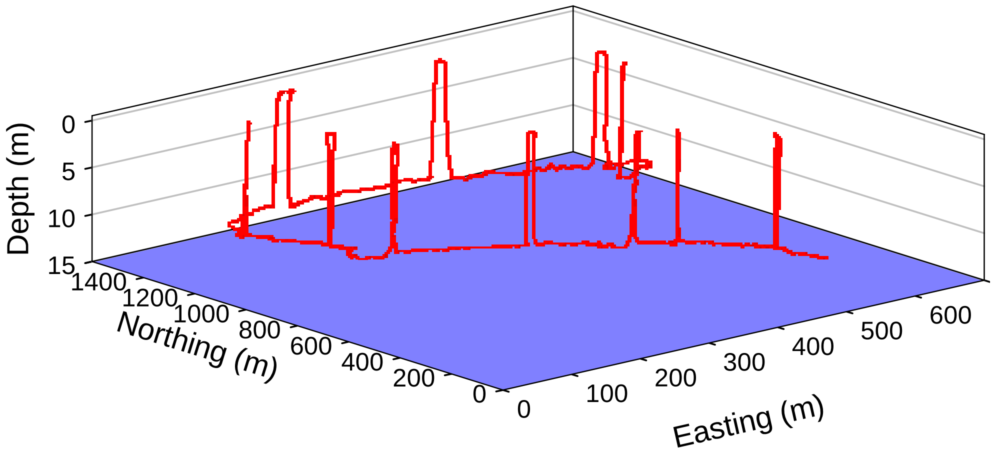


Figure 31. 3D reconstruction of dive behaviour during presumed foraging. The swimming path of the animal over the course of about 45 minutes is shown with the red line. Note that the scale of the depth axis is different from the horizontal axes.

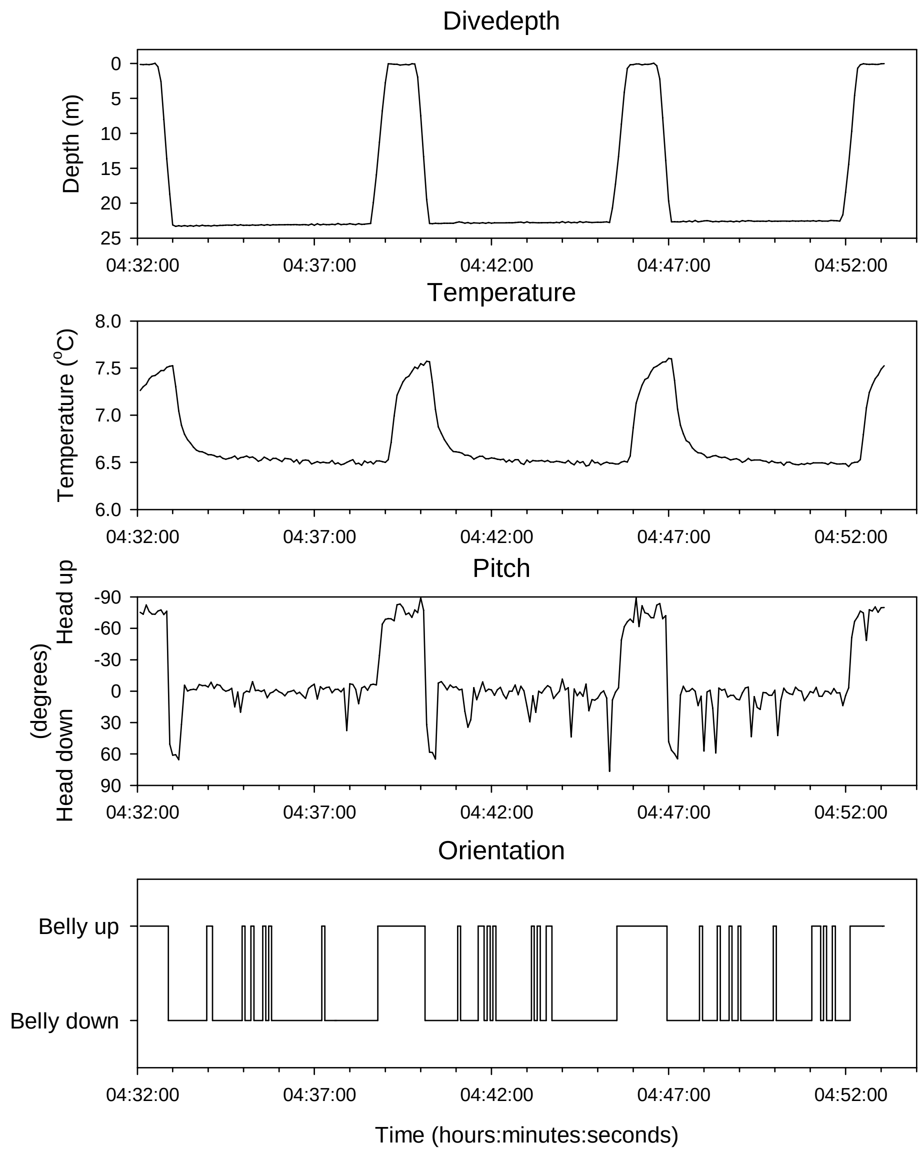


Figure 32. Measurements from datalogger recorded during 21 minutes when the seal was foraging in an area north of the outer part of Horns Reef. Top trace shows dive depth, next trace shows temperature (low-pass filtered due to the time constant of the thermistor, third trace shows pitch and bottom trace shows orientation of the animal.

Two tracks pass through the wind farm area. Dive data from one of the tracks is shown in Figure 33 together with bathymetry of the wind farm at the positions from the datalogger. It is immediately evident that the two do not correspond. The seal thus could not have been inside the wind farm during this period, even through the positions tell so. Assuming that the seal dives to the bottom in all dives, which is substantiated by the gradual change in dive depth over the track, we can conclude that the seal moved from a relatively shallow area out over a steep edge and into deeper water. Towards the end of the track the seal dives to more than 25 m. The combination of a steep edge and deep water is found several places further to the east of the wind farm around Slugen and it thus appears likely that the track is displaced several kilometres to the southwest from the true track.

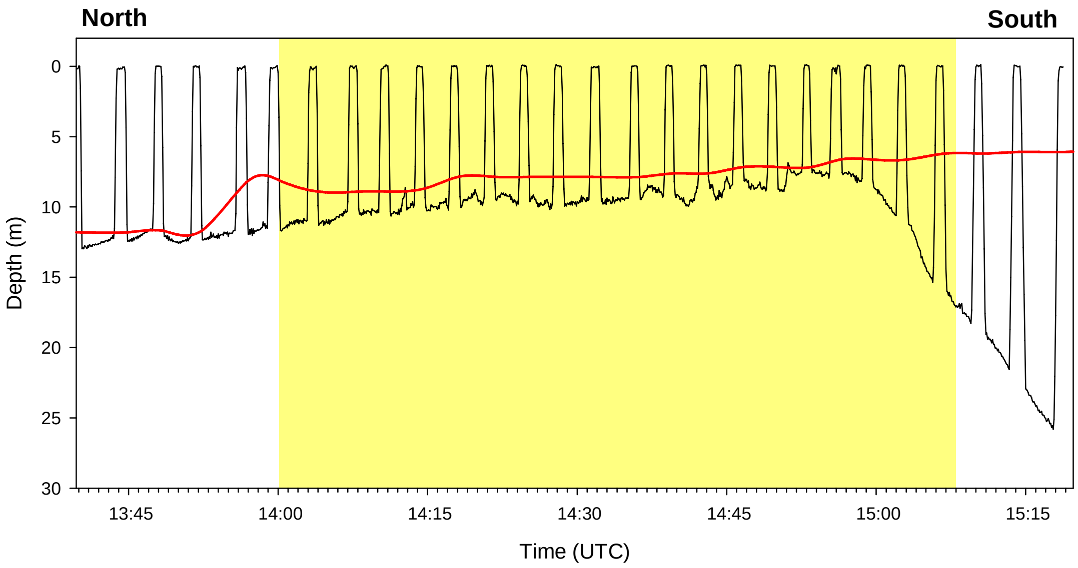


Figure 33. Dive pattern of harbour seal with datalogger in the period where it swam through the wind farm from north to south, according to the map (Figure 30, upper left). The yellow area indicates the time where the seal allegedly was in the wind farm. The red line indicates the water depth at the corresponding positions.

This relatively large inaccuracy in positioning by the dead reckoning algorithm means that conclusions cannot be drawn on the scale of the wind farm. If one of the two tracks apparently passing through the wind farm on the map can be shown definitely not to have done so, then one or more of the other tracks passing around the wind farm may as well have passed right through. Thus, as is the case for Argos positions, the accuracy of location is not sufficiently large we must resort to averaging over several tracks, under the assumption that errors will even out in the resulting mean.

All 11 foraging trips are combined in the maps in Figure 34. All four parameters calculated - number of dives, total dive time, total time at bottom and number of (presumed) feeding wiggles; show a clear concentration in a small area about 10 km north of Vovov. Although this particular individual moved over a large area on its foraging trips, it nevertheless has a clear preference for an area of rather limited size.

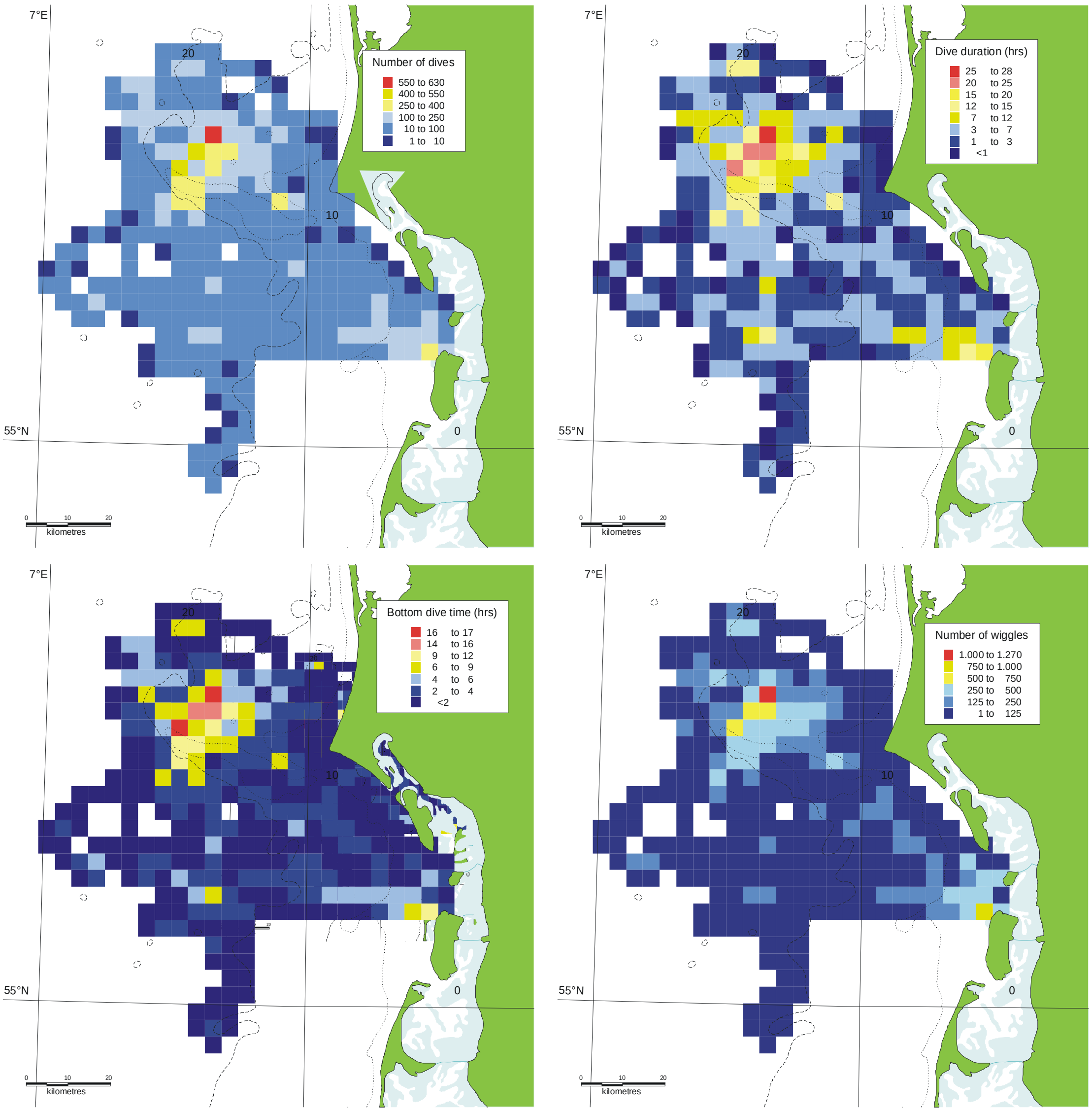


Figure 34. Analysis of dives made by the same individual as in Figure 30. Maps show data from all 11 foraging trips, aggregated into 10x10 km squares. Upper left shows total number of dives per 10 x 10 km square, upper right shows summed time spent diving in each square, lower left shows summed time spent at the bottom in each square and lower right shows number of wiggles counted per square.

3.4.1 Visual observations

Seals were seen consistently on almost all surveys, but always in low numbers, only in few cases more than 10 per day. Determination of species is difficult at sea, and especially young grey seals can easily be mistaken for harbour seals. However, as no adult grey seals were observed, it is assumed that all observations are harbour seals. The sightings are shown in Figure 35, normalised by effort. The central parts of the outer reef and the wind farm were covered well in all three periods, whereas the adjacent areas were covered to different degrees. Due to the low number of sightings and large variation in observations from survey to survey, no statistical test of differences in distribution has been attempted and the maps are presented as a supplement only.

During baseline surveys seal sightings were scattered over the survey area, with several well-surveyed areas without sightings. This is in contrast to surveys during construction and operation, where seals were observed in almost all of the well-surveyed squares.

The highest number of seals per unit effort was observed during construction, with lower numbers during operation. This is likely to be fully or partly explained by the development of the seal population in general. In autumn 2002 (i.e. following completion of most surveys) there was an outbreak of phocine distemper virus, which killed approximately half of the population and although the population has recovered well in the following years, the population is still not up to the level it was in summer 2002.

During construction there were fewer observations of seals in the vicinity of the wind farm, although animals were observed inside the construction area. None of these observations were on days with pile drivings, however (data not shown).

After end of construction seals were observed evenly distributed over the central parts of the outer reef, including inside the wind farm.

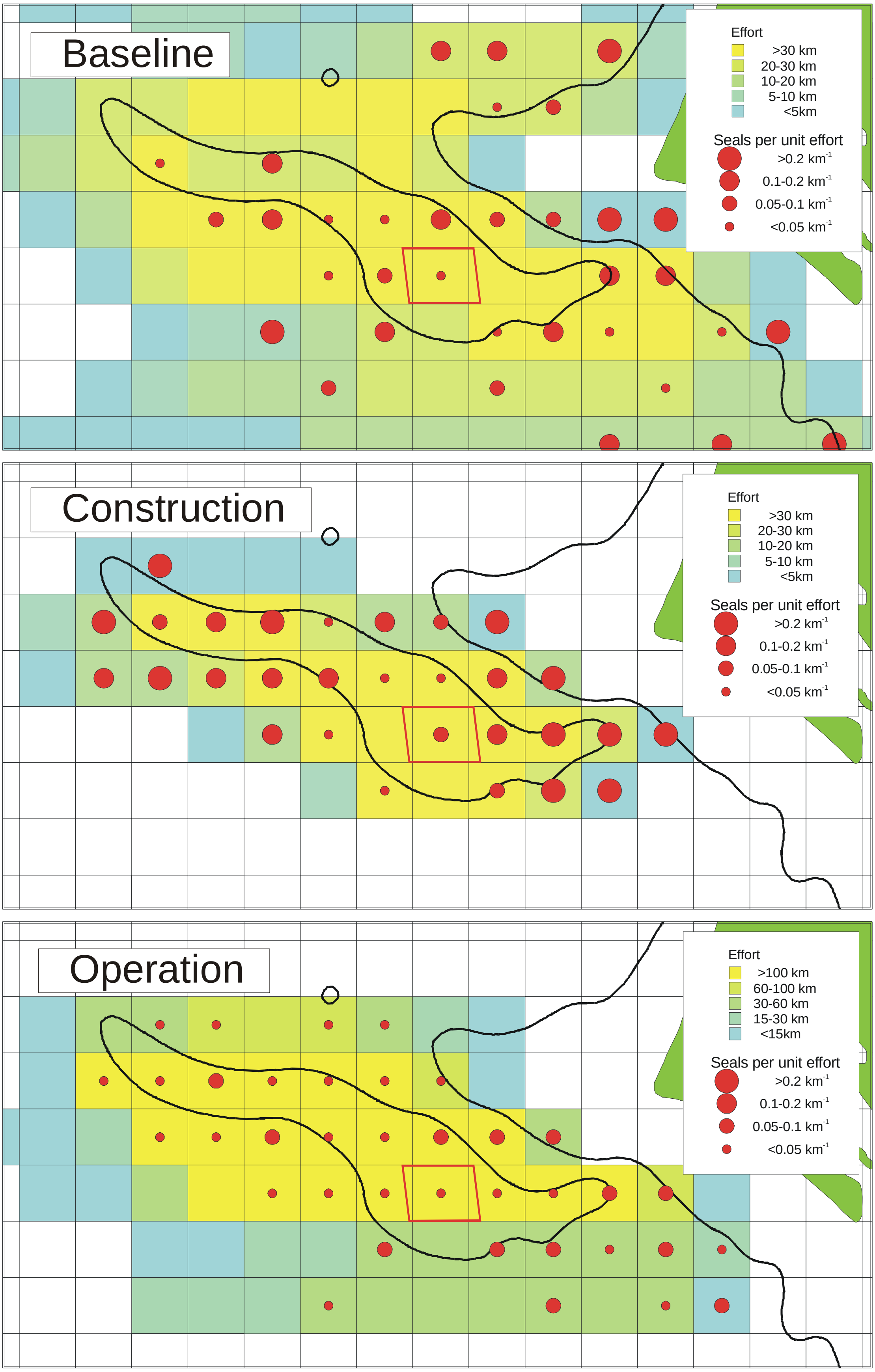


Figure 35 Seal sightings normalized by effort (kilometres of trackline sailed in each 4x4 km square). Note that effort scales differ. Solid black line indicate 10 m depth contour. Wind farm area is indicated by red trapezoid.

4 Discussion

This discussion falls into two parts, matching the two main questions raised in the introduction: How important is Horns Reef to harbour seals from Rømø and has the seals' use of the area changed after construction of the wind farm?

4.1 Importance of Horns Reef area

When this study was initiated in 2002 it was believed that the harbour seal was a strictly coastal species. Based on VHF-transmitter data it was assumed that the shallow areas of Horns Reef played a central role in foraging for the harbour seals from the Danish Wadden Sea. Both views were not supported after the results of the 10 first satellite transmitters were analysed (Tougaard *et al.* 2003b). The revised view on the foraging behaviour of harbour seals from Rømø has been substantiated by the addition of considerable more data from 2003-2005. It is clear that whereas the foraging of individual seals may be concentrated in relatively small areas, which the individual seal may return to again and again, the combined data from all seals show that they distribute more or less evenly over a very large area. Horns Reef proper (area above 10 m depth contour) is thus not of particular importance to seals when compared to the area from the reef and northwards up to Holmslands Klit. Also the area south of the reef, extending down to the German island of Sylt is of importance to the seals from Rømø. If we combine the data from Danish seals with data from Germany and the Netherlands the outline of a continuous foraging area emerges, stretching all the way down to north of the Rhine delta (Figure 36). The general north-western orientation of foraging trips of the seals from Rømø cannot be found in the other datasets, but the map is clearly suggestive of an explanation to this. The coastline of the Wadden Sea is concave and a very large number of seals inhabiting the central Wadden Sea area share a rather limited body of water in the German Bight for foraging. This forces the outer populations in Denmark and the Netherlands to orient outwards from the central German Bight area, towards north-west and south-west, respectively.

All three pups tagged in 2002 ventured beyond the central foraging habitat identified above and into the central North Sea. This behaviour is remarkable, as none of the pups tagged in 2004 showed the same behaviour, although their transmitters were active during the same time of the year (winter). No clear explanation can be given to this difference. However, one noteworthy difference between the two periods is the dramatic decline in the seal population that occurred in the fall of 2002, due to the second phocine distemper virus outbreak (Figure 10). Although the population is recovering well from this decline, the population was nevertheless still lower in 2005 than in 2002 and it could be speculated that the difference seen in the behaviour of the pups is related to this difference in population size. It is commonly seen in many animals that the young animals are those displaced farthest from the core habitat. What the mechanism behind such a displacement should be in the case of seals at sea is not easily understood, but the general results nevertheless clearly suggest that they are more or less evenly distributed over a very large area when offshore. As there were clearly more animals in the population in 2002 compared to 2004, the extent of the distribution range could thus have been larger in 2002, although the core habitat clearly seems to have been identical in both years. No pups were tagged in the German and Dutch studies, so these datasets cannot be used to test that hypothesis. Another possible explanation to the large foraging trips made by the pups in 2002 is that changes in the distribution of prey items have occurred. Sand eels (*Ammodytes* sp.) are thought to be important in the diet of harbour seals (Pierce *et al.* 1990) and the areas frequented by the pups in 2002 were areas that also supported intense sand eel fishery (Jensen *et al.* 2004). This fishery has diminished dramatically since 2002 due to overfishing and this decrease in sand eel populations could also explain why no animals from 2003-2005 went as far into the North Sea as the pups in 2002.

4.2 Effects of wind farm

Conclusive results regarding effects of the wind farm on harbour seals were not obtained. This is not the same as concluding that no effects are present, but due to limitations in the methods used, the effects would have had to be very strong in order to be detectable in the data. A short discussion of the possible effects outlined in the introduction will follow below, with comments to what can be concluded from the data.

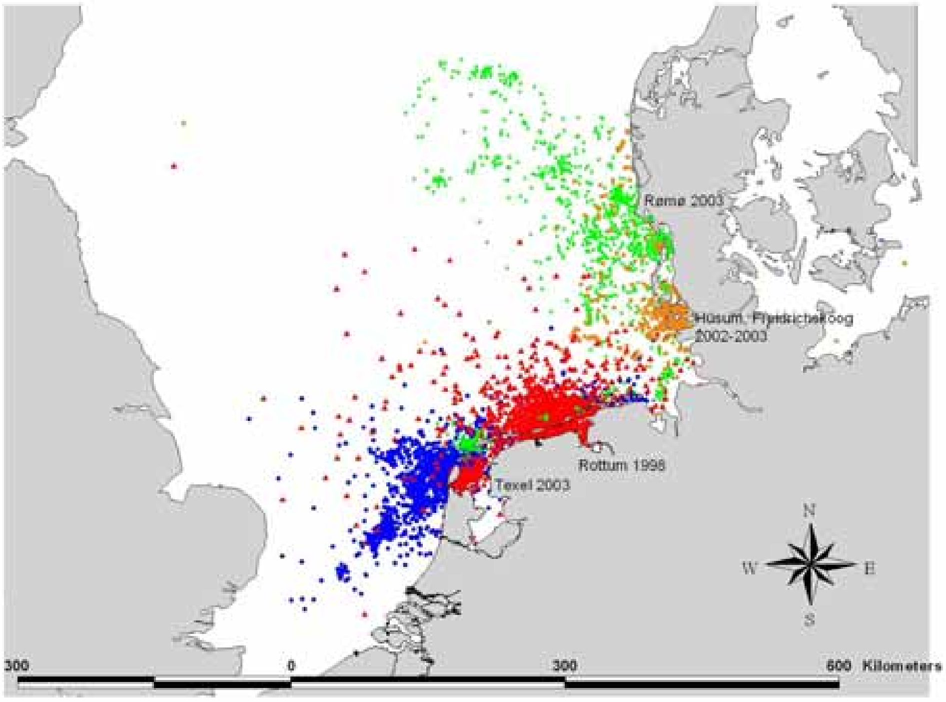


Figure 36. Satellite transmitter positions from seals tagged in 1998-2003 in the Netherlands (blue), Niedersachsen (red), Schleswig-Holstein (yellow) and Denmark (green). The map gives a good impression of the area of particular importance to harbour seals from the Wadden Sea: An area stretching from Holmslands Klit in north almost to the Rhine delta in the south and extending approximately 100 km offshore. Note that only Danish seals from 2002 are included. From Reijnders *et al.* 2005).

4.2.1 Construction

Construction was anticipated to cause a significant disturbance to the seals in the local area of the construction site (Impact assessment, Tougaard *et al.* 2000). The satellite tracks in this period however, show no sign of a deterring effect of the construction at the scale of tens of kilometres, which is the accuracy of the satellite positioning. At least one of the tagged seals was immediately outside the wind farm and possibly inside the wind farm during construction, but as the tagged seals in general spent very little time in the Horns Reef area during both baseline and construction periods, it cannot be concluded whether fewer than expected seals were inside or close to the construction site during construction. Sighting data from harbour porpoise surveys however, do seem to indicate an effect of the construction. During surveys in the construction period 5 seals were observed, all of which were seen in the very first part of construction, where activity levels still were not up to full. More significant is that of the 5 seals, 2 were seen on a survey prior to the first pile driving and the remaining 3 seals were all seen on the same day, which was in a short period without pile drivings. Thus, as shown already for harbour porpoises (Tougaard *et al.* 2003a; Carstensen *et al.* 2006) pile drivings may affect seals as well.

As described in the introduction and in Tougaard *et al.* (2006), pile driving of steel monopiles generate very high sound pressures and this activity is predicted to be the largest single source of disturbance to marine mammals. It was to be expected that seals and porpoises would avoid the area close to the construction site during pile driving. For porpoises the effect of pile drivings on the acoustic behaviour has been shown to extend out to at least 25 km from the construction site (Tougaard *et al.* 2003a). As the hearing of seals is better than harbour porpoises in the lower frequency range where most energy is present in the pile driving sounds, the seals are able to hear the sounds at least as far away as the porpoises. There is a general belief that seals are more tolerant to loud impulse sounds, such as airgun pulses than porpoises and other odontocetes (National Research Council 2003) although there is limited data to support this claim. One study at Northstar Island, Alaska showed that ringed seals did not react dramatically to pile driving sounds of received levels at least 150 dB re. 1 μPa in the water around the island (Blackwell *et al.* 2004). However, 150 dB re 1 μPa is the level predicted to have been present in a distance of more than 20 km from the construction site, based on extrapolation of the measurements made at Horns Rev offshore wind farm and assuming a transmission loss of 18 dB per 10 times increase in distance (Figure 12).

Sound pressures of the seal scarer and porpoise pingers were considerably lower than the pile driving sounds (Tougaard *et al.* 2006), yet likely to have been sufficiently intense to deter seals from the immediate vicinity of the construction site and hence have protected the animals from temporary or permanent damage to their hearing.

4.2.2 Operation

No negative effects of the wind farm were observed after it was put into normal operation, but as was the case for the construction period, the inherent limitations of satellite telemetry means that any effect would have had to be large in order to be detected. Based on the analysis of potential negative impacts of the wind farm made in the introduction it is concluded that these are unlikely to have a significant effect on the seals. This is supported by the visual sightings, where no effect was apparent. On the contrary, it is believed that the positive effects due to the artificial reef effect and exclusion of fishery may more than counteract any negative effects, and could lead to a net positive effect of the wind farm on the seals.

Seals were clearly present inside the wind farm area in the operational period, evidenced both from satellite telemetry data and visual observations on surveys. Unfortunately the limitations of both the satellite transmitters and the dataloggers, in terms of inaccurate positioning at the scale relevant for the wind farm means that no conclusions can be drawn regarding effects of the wind farm on behaviour of individual seals.

4.2.2.1 Noise from turbines in operation

As outlined in the introduction the noise from operating turbines has been focus of much attention in connection to marine mammals. However, turbine sounds measured so far and including the measurements from Horns Rev are low by any standard. Although they may be audible to seals at distances of many kilometers under ideal conditions (Madsen *et al.* 2006), this may not by itself mean that animals are disturbed by the sounds at these distances. As conditions are most often less than ideal (sea state zero is far from the typical condition at Horns Reef), the zone of audibility is likewise in most cases also reduced.

Noise from operating turbines, such as the noise measured in Horns Rev wind farm should not be dismissed as a potential impact on harbour seals, but a sense of proportion is called for in any evaluation of possible impact. By this is meant that any impact from the turbines should be compared to other anthropogenic impact in the same area. Shipping traffic in the German Bight as a whole is among the highest in the world and around Horns Reef there is also considerable traffic, going to and from Esbjerg harbour, along the coast at the outer edge of the reef, as well as commercial fishing vessels on the reef area itself. Depending on assumptions on transmission loss, the ships may be audible at significantly larger distances than the turbines (Madsen *et al.* 2006), and are thus likely to represent the strongest impact on whatever marine mammals may be in the area.

4.3 Cumulative effects

Even if a negative effect of Horns Rev wind farm on seals is present, it is nevertheless likely to be insignificant in relation to the entire population in the area, simply due to the small size of the wind farm compared to the area used by the seals. However, this does not mean that construction of future wind farms in the region should occur without considering possible effects on seals. Small effects may be cumulative in a non-straightforward manner, meaning that several wind farms combined could cause a larger impact than a simple addition of individual effects would predict.

Based on the general picture drawn above, namely that the seals distribute evenly over a very large area and in general are little affected by the presence of the wind farm, the exact location for one or more additional wind farms is not an issue of strong concern.

One issue which must be addressed in relation to coming wind farms is the question of barrier effects. If seals are reluctant to swim through the wind farms, even if some seals will do it and some even may forage in the wind farm, this will in general lead to longer travelling routes to and from foraging areas and hence larger energy expenditure. At this point this possibility is entirely hypothetical, as we have no indications that seals avoid the wind farm, at least to some degree, but on the other hand neither do we have proof that they do not react to the wind farm.

Cumulative effects of construction work is an issue of some concern. Although we do not have estimates of the range at which seals were affected by construction work, this range may well be measured in tens of kilometres, as was the case for harbour porpoises. This means that construction of a single wind farm may affect an area of several hundred square kilometres, which may be significant, but still acceptable, considering the large area otherwise available to the seals. If however, several wind farms are constructed at the same time in the same region, as current plans for development of offshore wind power indicate, cumulative effects could be significant.

In this case it is necessary to consider whether local populations of seals are excluded from a significant part of their foraging habitat during construction, either directly or through barrier effects of several construction sites operating simultaneously. Coordination of construction activities across wind farms is called for in this case in the likely event that several new wind farms are to be constructed in the German Bight area within the same time period.

4.4 Methodological considerations for future studies

As discussed in the introduction and methods sections telemetry and dataloggers are not ideal for studies of the kind conducted here. Nevertheless, they seem to be the only real option, when it comes to studying seals. When evaluating the outcome of the current project one can conclude that the first aim, determination of general foraging habitat of the seals was fulfilled with success by means of the satellite transmitters. When it comes to the second aim, assessing effects of the wind farm on behaviour of individuals we knew from the beginning that a good portion of luck was required. Neither the satellite transmitters, nor the dataloggers have the desired spatial accuracy to deliver firm conclusions on whether animals were inside or near the wind farm. The idea of combining the two systems has so far not paid off, however. Of the few dataloggers retrieved from double tagged individuals, none contained data from the Horns Reef area and most of the remaining dataloggers have still not been retrieved and may never be.

Fortunately if a similar study was to be designed today, several new and very promising developments have been made in recent years, most significantly the development of the Fastloc GPS-receiver. This small GPS-unit has the capacity to determine an accurate position based on a brief “look” at the sky of only 10 ms. This means that a very accurate position can be acquired every time an animal surfaces. In addition, the short acquisition time increases the lifetime of the batteries considerably. The inclusion of a Fastloc unit into the datalogger would solve the inherent problem of large scale inaccuracy of the dead reckoning algorithm. The only remaining issue is relying on luck that a sufficient number of animals come near the relevant area and that their dataloggers are retrieved.

5 Conclusion

Through the satellite telemetry data we can conclude that Horns Reef plays an important role as foraging area for harbour seals from Rømø, but on the other side it is also clear that the area is only part of a large continuous area of importance, stretching from Holmslands Klit north of the reef to the German/Danish border and extending out about 100 km from the coast. From the relatively coarse resolution analysis no particular areas within this region appear to be significantly more important to the seals than the rest of the area.

Horns Rev offshore Wind Farm is placed within this area of special importance to harbour seals, but as this area is very large compared to the area of the wind farm the location is not in itself problematic.

When it comes to local effects of the wind farm on seals no effects were observed, e.g. in the form of avoidance when seals swam towards the wind farm or altered dive behaviour inside the wind farm compared to outside. However, the accuracy of the positions received or calculated for the seals was not sufficiently high to safely identify when the tagged seals in fact were inside or outside the wind farm. From visual observations in connection with harbour porpoise surveys it is nevertheless clear that seals were present inside the wind farm and in numbers not markedly different from the adjacent areas. Thus, if the wind farm has an effect (negative or positive) on the seals this effect is not very large. Based on general knowledge to the feeding biology of harbour seals it is expected that the creation of new habitats around the foundations (artificial reefs) and the exclusion of fishery from the wind farm will, if anything, have a beneficial effect on the seals.

Assessing effects of construction of the wind farm was not a primary goal of the monitoring program and telemetry data cannot support strong conclusions on this question. However, from the survey data, there is indication of an effect of pile drivings on the distribution of seals on the reef, with no observations inside the wind farm and a few km from the wind farm on days with pile drivings. This is consistent with observations on harbour porpoises and is readily explained by the very high underwater sound pressures generated by the pile drivings.

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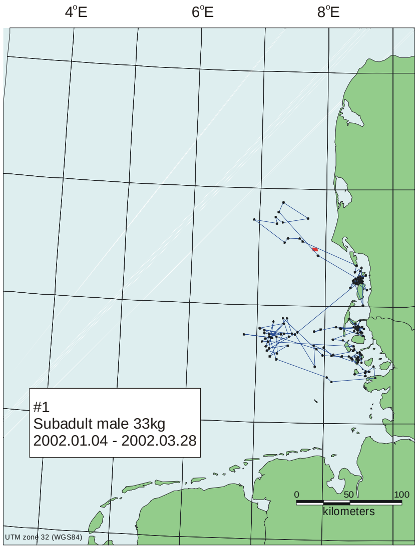
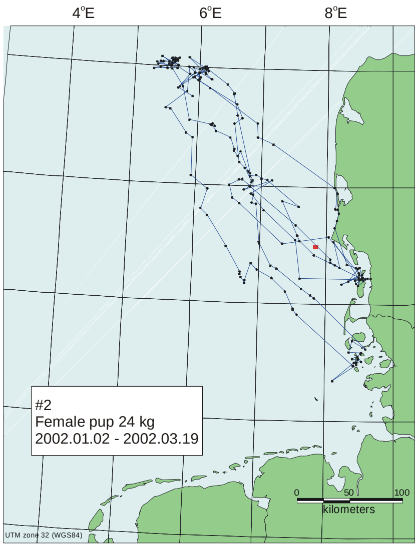
Appendix A Individual Argos tracks

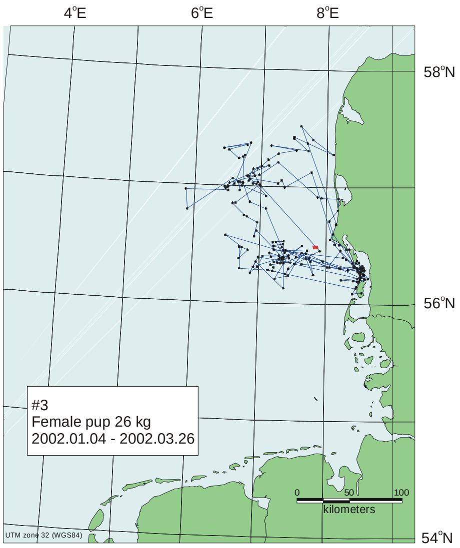
Tracks of all seals tagged with Argos transmitters (Wildlife Computers SPOT2/4 and SDR-T16), based on filtered Argos positions. Further details on the animals can be found in table 2.



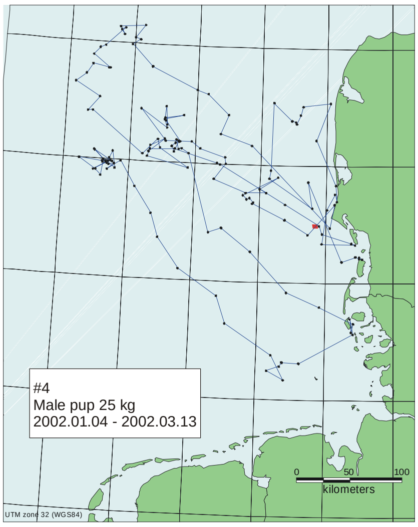
#1
Subadult male 33kg
2002.01.04 - 2002.03.28



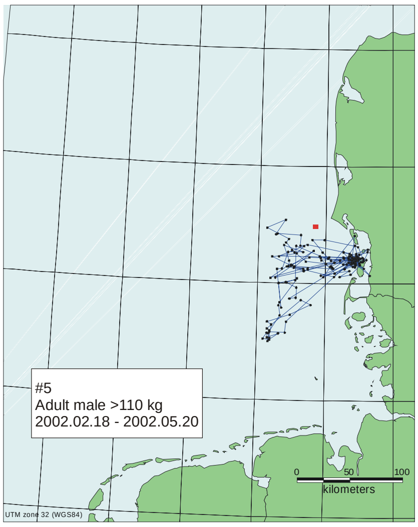
#2
Female pup 24 kg
2002.01.02 - 2002.03.19



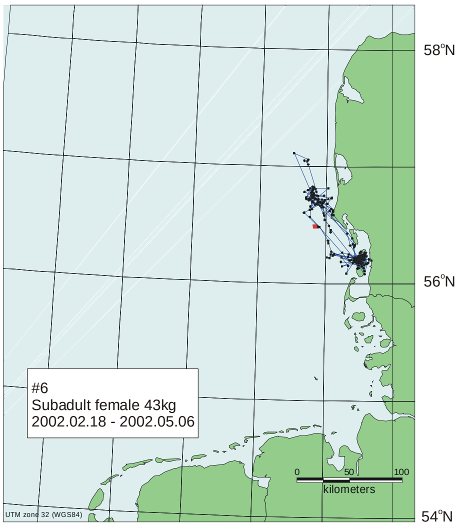
#3
Female pup 26 kg
2002.01.04 - 2002.03.26



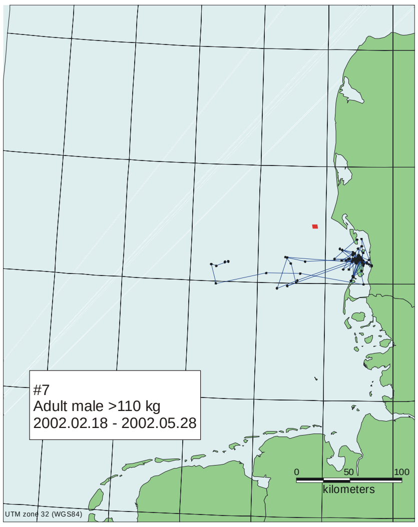
#4
Male pup 25 kg
2002.01.04 - 2002.03.13



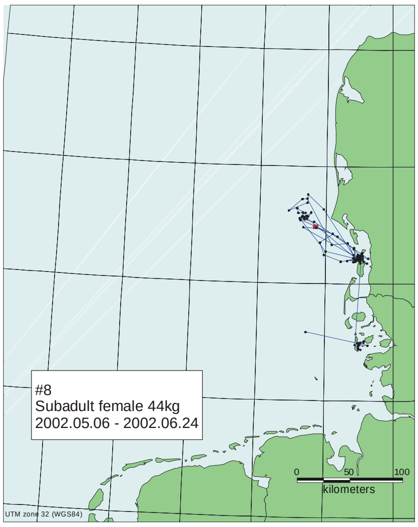
#5
Adult male >110 kg
2002.02.18 - 2002.05.20



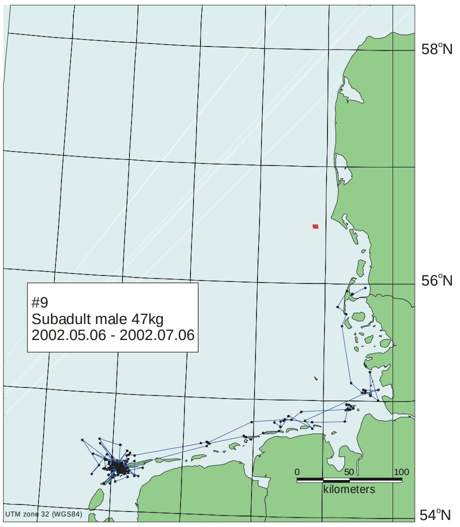
#6
Subadult female 43kg
2002.02.18 - 2002.05.06



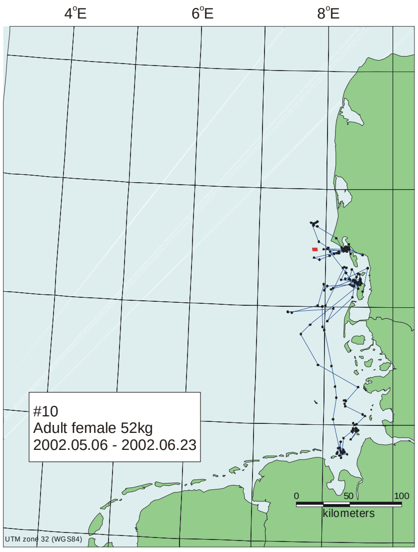
#7
Adult male >110 kg
2002.02.18 - 2002.05.28

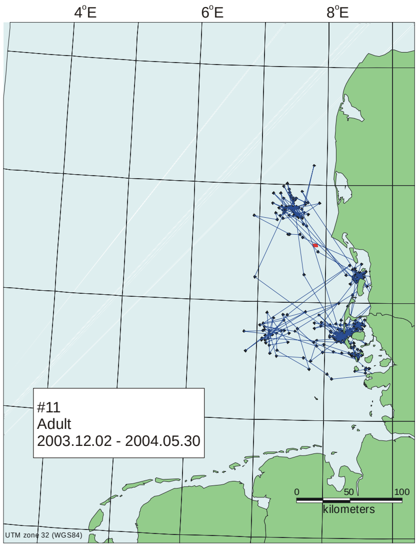


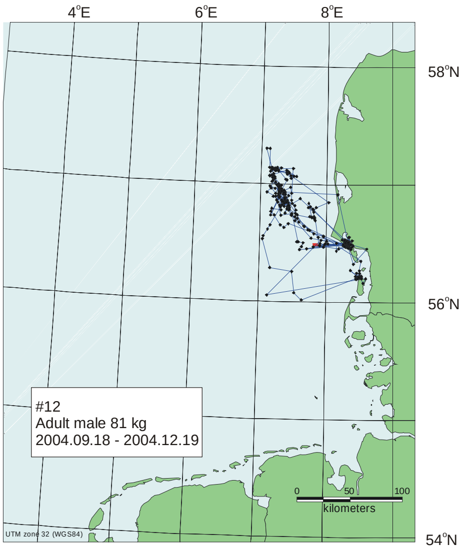
#8
Subadult female 44kg
2002.05.06 - 2002.06.24

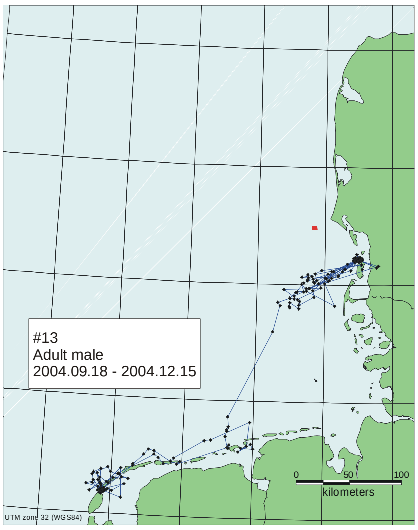


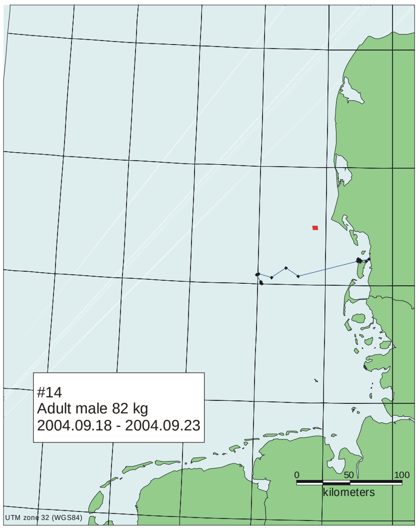
#9
Subadult male 47kg
2002.05.06 - 2002.07.06

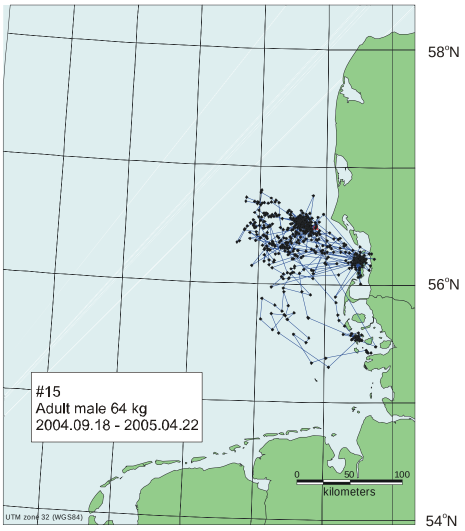

4°E
6°E
8°E
#10
Adult female 52kg
2002.05.06 - 2002.06.23
0
50
100
kilometers
UTM zone 32 (WGS84)

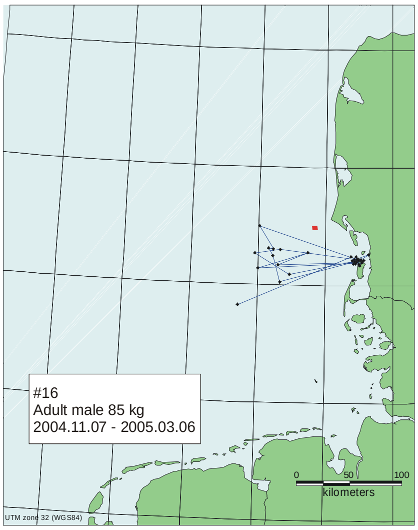

4°E
6°E
8°E
#11
Adult
2003.12.02 - 2004.05.30
0
50
100
kilometers
UTM zone 32 (WGS84)

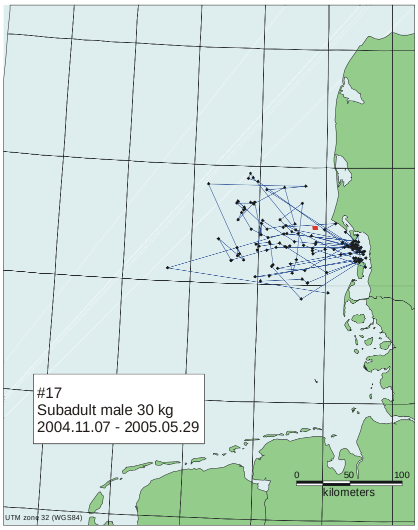

4°E
6°E
8°E
58°N
56°N
54°N
#12
Adult male 81 kg
2004.09.18 - 2004.12.19
0
50
100
kilometers
UTM zone 32 (WGS84)

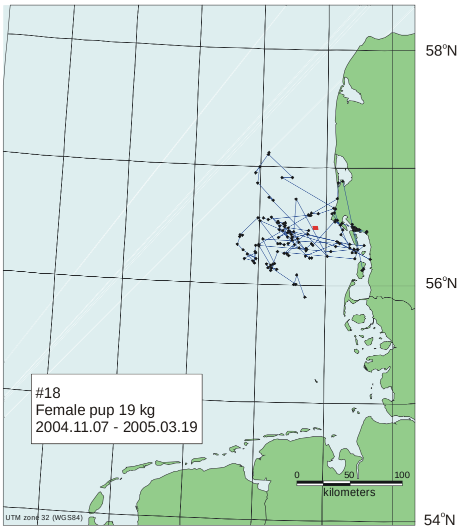

#13
Adult male
2004.09.18 - 2004.12.15
0
50
100
kilometers
UTM zone 32 (WGS84)

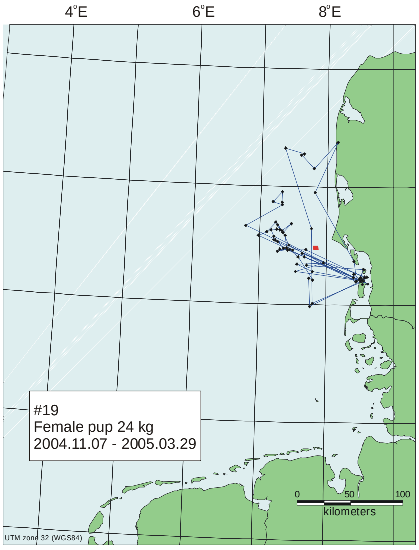

#14
Adult male 82 kg
2004.09.18 - 2004.09.23
0
50
100
kilometers
UTM zone 32 (WGS84)

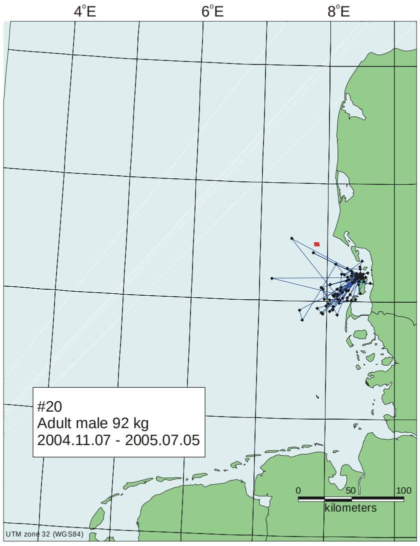

58°N
56°N
54°N
#15
Adult male 64 kg
2004.09.18 - 2005.04.22
0
50
100
kilometers
UTM zone 32 (WGS84)

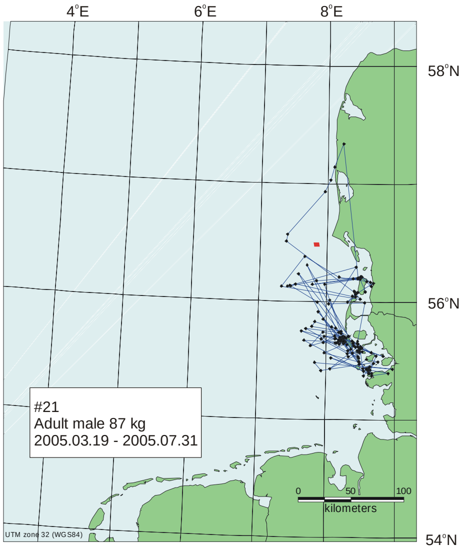

#16
Adult male 85 kg
2004.11.07 - 2005.03.06
0
50
100
kilometers
UTM zone 32 (WGS84)


#17
Subadult male 30 kg
2004.11.07 - 2005.05.29
0
50
100
kilometers
UTM zone 32 (WGS84)


58°N
56°N
54°N
#18
Female pup 19 kg
2004.11.07 - 2005.03.19
0
50
100
kilometers
UTM zone 32 (WGS84)

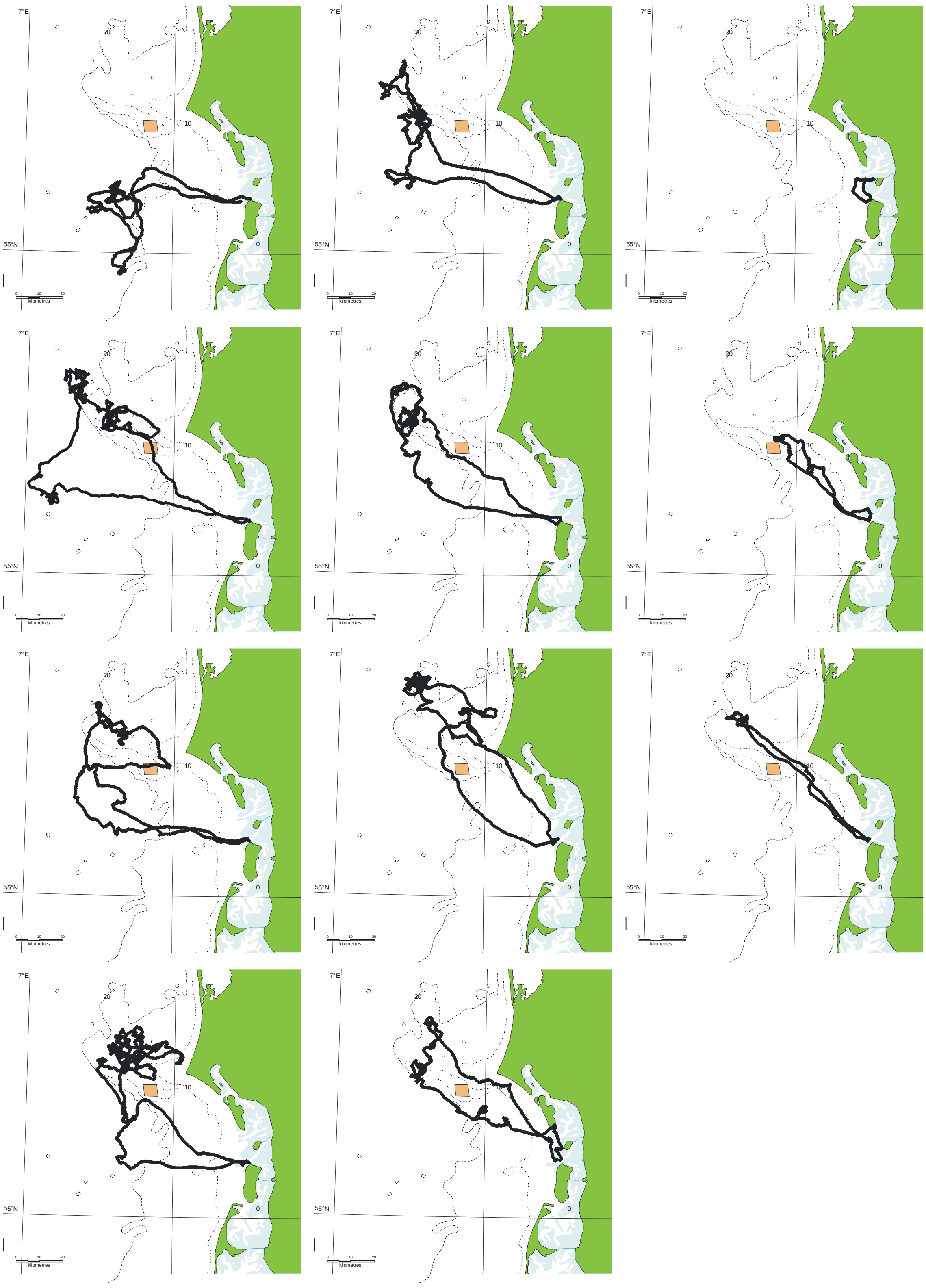

4°E
6°E
8°E
#19
Female pup 24 kg
2004.11.07 - 2005.03.29
0
50
100
kilometers
UTM zone 32 (WGS84)


4°E
6°E
8°E
#20
Adult male 92 kg
2004.11.07 - 2005.07.05
0
50
100
kilometers
UTM zone 32 (WGS84)


4°E
6°E
8°E
58°N
56°N
54°N
#21
Adult male 87 kg
2005.03.19 - 2005.07.31
0
50
100
kilometers
UTM zone 32 (WGS84)

Appendix B Individual tracks from datalogger

Foraging trips made by an adult male harbour seal tagged on Bollert in April 2004. Wind farm is shown as red trapezoid. Dotted and broken lines represent 10 m and 20 m depth contours, respectively.



Appendix C Details on individual seals

Date	Locality	Sex	Age class	Length (cm)	Weight (kg)	Elsam ID	ARGOS type	PTT no.	Last uplink date	Days	Logger ID	FTZ ID	Rec.	Last logger date	Days
04-01-2002	Bollert	M	sub.ad	128	33	1	SDR-T16	8372	28-03-2002	84					
04-01-2002	Bollert	F	pup	92	24	2	SDR-T16	8373	19-03-2002	75					
04-01-2002	Bollert	F	Pup	95	26	3	SDR-T16	8374	25-03-2002	81					
04-01-2002	Bollert	M	pup	97	25	4	SDR-T16	8375	13-03-2002	69					
18-02-2002	Bollert	M	Ad	149	>110 kg	5	SDR-T16	8376	20-05-2002	92					
18-02-2002	Bollert	F	sub.ad	122	43	6	SDR-T16	8377	06-05-2002	78					
18-02-2002	Bollert	M	Ad	143	>110 kg	7	SDR-T16	8378	28-05-2002	100					
06-05-2002	Koresand	F	sub.ad	119	44	8	SDR-T16	8379	24-06-2002	50					
06-05-2002	Koresand	M	sub.ad	122	47	9	SDR-T16	8380	06-07-2002	62					
06-05-2002	Koresand	F	sub.ad	133	52	10	SDR-T16	8381	23-06-2002	49					
02-12-2003	Bollert	F	Ad	165		11	SDR-T16	8372	30-05-2004	179	12.03-1	Pv2474			
02-12-2003	Bollert	M	Ad	173							12.03-2	Pv2475			
13-04-2004	Koresand	M	Ad	170	85						04.04-1	Pv 2509			
13-04-2004	Koresand	M	Ad	170	86						04.04-2	Pv 2510	X	16-07-2004	94
13-04-2004	Koresand	M	Ad	172	95						04.04-3	Pv 2508			
18-09-2004	Koresand	M	Ad	180	81	12	Spot 2	17758	19-12-2004	92	09.04-2	Pv 2710			
18-09-2004	Koresand	M	Ad	148		13	Spot 2	17764	15-12-2004	88	09.04-3	Pv 2701	X	16-10-2004	28
18-09-2004	Koresand	M	Ad	175	82	14	Spot 2	17565	23-09-2004	5	09.04-4	Pv 2706			
18-09-2004	Koresand	M	Ad	149	64	15	Spot 2	17776	22-04-2005	216	09.04-1	Pv 2707	X	22-09-2004	4
18-09-2004	Koresand	M	Ad	155	66						09.04-5	Pv 2705	X	25-11-2004	68
18-09-2004	Koresand	M	Ad	173	69						09.04-6	Pv 2704	X	23-11-2004	66
07-11-2004	Koresand	M	Ad	154	85	16	Spot 4	8376	06-03-2005	119	11.04-8	no ID			
07-11-2004	Koresand	M	Pup	101	30	17	Spot 4	8378	29-05-2005	203					
07-11-2004	Koresand	F	Pup	92	19	18	Spot 4	8377	19-03-2005	132					
07-11-2004	Koresand	F	Pup	94	24	19	Spot 4	8375	29-03-2005	142					
07-11-2004	Sønderbanke	M	Ad	150	92	20	Spot 4	8373	05-07-2005	240	11.04-3	no ID			
19-03-2005	Bollert	M	Ad	157	83						03.05-1	Pv 2875			
19-03-2005	Bollert	M	Ad	166	81						03.05-2	Pv 2868			
19-03-2005	Bollert	M	Ad	175	96						03.05-3	Pv 2872	X	06-06-2005	79
19-03-2005	Bollert	M	Ad	172	87	21	Spot 4	8374	31-07-2005	134	03.05-4	Pv 2873			
19-03-2005	Bollert	M	Ad	178	91						03.05-5	Pv 2870			
19-03-2005	Bollert	M	Ad	170	91						03.05-6	Pv 2869			
19-03-2005	Bollert	M	Ad	168	104						03.05-7	Pv 2874			
19-03-2005	Bollert	M	Ad	184	105						03.05-8	Pv 2871			