EFFECTS OF LARGER TURBINES FOR THE OFFSHORE WIND FARM AT KRIEGER'S FLAK, SWEDEN

Assessment of impact on marine mammals

Scientific Report from DCE – Danish Centre for Environment and Energy No. 286 2018

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Data sheet

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Abstract: Construction and operation of an offshore wind farm on the Swedish part of Kriegers Flak has been assessed with respect to potential impacts on marine mammals. Underwater noise is assumed the main source of potential impact from construction, in particular percussive piling of turbine foundations. Impact was modelled by estimating the cumulated sound exposure for marine mammals near the construction site and by assessing disturbance to animals in time and space. Provided that adequate mitigation measures are adopted, such as use of deterring sounds prior to pile driving and reduction of radiated noise the construction is not considered to have long-term impact on the abundance or population development of marine mammals in the area. Likewise is the operation of the wind farm considered to be without significant long-term impact on marine mammals.

Keywords: Offshore renewables, pile driving, underwater noise, harbour porpoises, harbour seals, grey seals

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Contents

Summary

Construction and operation of an offshore wind farm on the Swedish part of Kriegers Flak has been assessed with respect to impacts on marine mammals, in the context of an application to increase the size of turbines in the wind farm, compared to the original Environmental Impact Assessment from 2004.

Abundance of marine mammals

Two species of seals, harbour seal (*Phoca vitulina,* knubbsäl) and grey seal (*Halichoerus grypus*, gråsäl) are abundant in the waters around Kriegers Flak. Both populations are in favourable conservation status.

One cetacean, the harbour porpoise (*Phocoena phocoena*, tumlare) inhabits the waters around Kriegers Flak. The area is a mixing zone between two populations. The by far largest number of porpoises in the area are believed to belong to the Danish Belt Seas population, which is in favourable conservation status. A smaller number of porpoises, in particular during winter months, are believed to belong to the critically endangered population in the Baltic Proper.

Sensitivity to impact

Underwater noise is likely to be a main source of potential impact from wind-farm construction, in particular percussive piling of foundations. Percussive pile driving is known to generate very high sound pressures, likely capable of inflicting permanent damage to the hearing of seals and porpoises and has been shown to cause behavioural disturbances at distances of tens of km from the pile driving site.

Various mitigation measures are available, including use of deterring devices, soft-start and reduction of radiated noise by means of for example air bubble curtains.

Magnitude of impact was assessed for direct damage (acoustic trauma), hearing loss (permanent threshold shift, PTS), disturbance of behaviour and masking. Hearing loss was assessed by considering total cumulated sound exposure levels (SELcum) over the duration expected for piling of one foundation (4.5 hours), taking movements of the animals into consideration and applying appropriate auditory frequency weighting to the acoustic measurements. Disturbance of behaviour was assessed by applying reaction distances from observational studies at other wind farm construction projects.

Impact from construction

Noise exposure from pile driving was modelled in a worst-case scenario. This scenario included the largest monopiles under investigation for the project (15 m pile diameter) and worst-case assumptions regarding location of the turbine foundation and sound propagation properties of the surrounding waters (upward-refracting sound speed profile). This scenario included standard practice of deployment of a deterring device and soft-start procedure as mitigation against damage to marine mammal hearing.

It is considered unlikely that marine mammals will be exposed to sound pressures likely to cause acoustic trauma.

Under this scenario, it is expected that seals and porpoises close to the pile-driving site will be exposed to levels capable of inflicting smaller amounts of permanent hearing loss. This hearing loss is assessed to have a **minor** impact on the populations of harbour seals, grey seals and porpoises from the Danish Belt Sea population. In a precautionary assessment, the impact on the critically endangered Baltic Proper population of porpoises is assessed to be **moderate** during winter months and **minor** during summer months. The difference in assessments is due to the seemingly very low likelihood of encountering porpoises from the Baltic Proper population around Kriegers Flak during summer.

Pile driving is also likely to cause disturbances to the natural behaviour of both seals and porpoises. The magnitude of this disturbance was assessed by relating the expected area of disturbance to the total area where the different species are regularly encountered. The largest impact from disturbance is expected for harbour seals and Baltic Proper porpoises in winter, where the impact is assessed to be **moderate**. The impact on grey seals and Belt Sea porpoises is assessed to be **minor** and for Baltic Proper porpoises in summer impact is assessed to be **negligible**, due to the very low likelihood of encountering porpoises from this population during summer.

Impacts can be reduced by reducing the radiated noise from the pile driving. This was investigated by modelling the noise impact by application of a bubble curtain, currently considered best available technology for reduction of noise radiation. The bubble curtain is expected to reduce the broadband source level of the piling by at least 5.5 dB and frequency weighted levels even more. Such a reduction in radiated noise means that permanent hearing loss is not expected to occur in neither seals, nor porpoises, and impact from hearing loss is thus assessed to be **negligible** on all populations.

Reduction of radiated noise from piling is also predicted to reduce both impact ranges and duration of the disturbance of behaviour. Impact from disturbance of behaviour is thus assessed to be **minor** for all populations, except for Baltic Proper porpoises in summer, where it is assessed as **negligible**, due to the low likelihood of encountering these animals.

It is considered unlikely that pile driving noise will be capable of masking sounds relevant to porpoises to any noticeable degree and the magnitude of this impact on porpoises was thus assessed as **negligible**.

There is a possibility that communication sounds from both grey seals and harbour seals can be masked by pile driving noise, but as this communication is only expected to take place close to haul out sites (primarily at Falsterbo), the possible masking is considered to be small and impact assessed as **minor**.

Cumulative effects of simultaneous pile driving at one or more currently planned offshore wind farms in the area are considered negligible.

Impact from operation

No negative effects of the wind farm is predicted once in operation and the effect is thus assessed as negligible, based on studies of effects of operating offshore wind farms on seals and porpoises. The cumulative effect of adding an additional offshore wind farm to already existing offshore wind farms in the area is likewise considered **negligible**.

Impact on Natura2000 areas

It is considered likely that the adjacent Natura2000 area Sydvästskånes Udsjövatten will be impacted during construction of the wind farm. Disturbance from pile driving is estimated to make 27% of the habitat area inaccessible to seals and porpoises (computed in both time and space) during the period where pile driving takes place, and is assessed to constitute a **major** impact. Application of mitigation measures to reduce the emitted noise during pile driving, such as bubble curtains, is estimated capable of reducing the habitat loss to 2.5%, and the disturbance in that case is assessed to constitute a **minor** impact.

Impact on Sydvästskånes Udsjövatten during operation of the wind farm is assessed as **negligible**, as are the impacts of both construction and operation on the remaining Natura2000 areas in Swedish, Danish and German waters.

1. Background

Vattenfall AB, Sweden has previously obtained a permission from the Swedish authorities to build and operate an offshore wind farm on Kriegers Flak in the Western Baltic. This permission was granted in 2006, extended in 2015 and will currently expire in 2018. As part of an application for a renewal of the permission, including the option to use larger turbines, an update of the impact assessment was requested by the Swedish authorities in the light of new knowledge and the designation of an adjacent Natura 2000 area.

The present report was commissioned by Vattenfall Vindkraft AB, Sweden. It serves as a background report for the updated environmental impact assessment (EIA), with specific focus on possible impact on marine mammals by construction and operation of the wind farm. The main need for a revision of the EIA has arisen due to a wish to use larger turbines than in the original proposal, made possible by the technical development in turbine design. Larger turbines require larger foundations, which again are likely to generate higher noise levels during installation. On the beneficial side is that larger turbines mean that fewer turbines are needed and thus fewer foundations need to be installed. The original design thus included 128 turbines, which is anticipated to be reduced to somewhere between 32 and 76 turbines, depending on the turbine size (between 8.4 MW and 20 MW). Furthermore, the knowledge about impact of construction and operation of offshore wind farms, in particular with respect to underwater noise, has increased substantially over the last ten years, as has also the knowledge about the distribution and sensitivity of marine mammals in the area. The assessment presented in this report thus replaces the previous assessment of impact on marine mammals with respect to underwater noise.

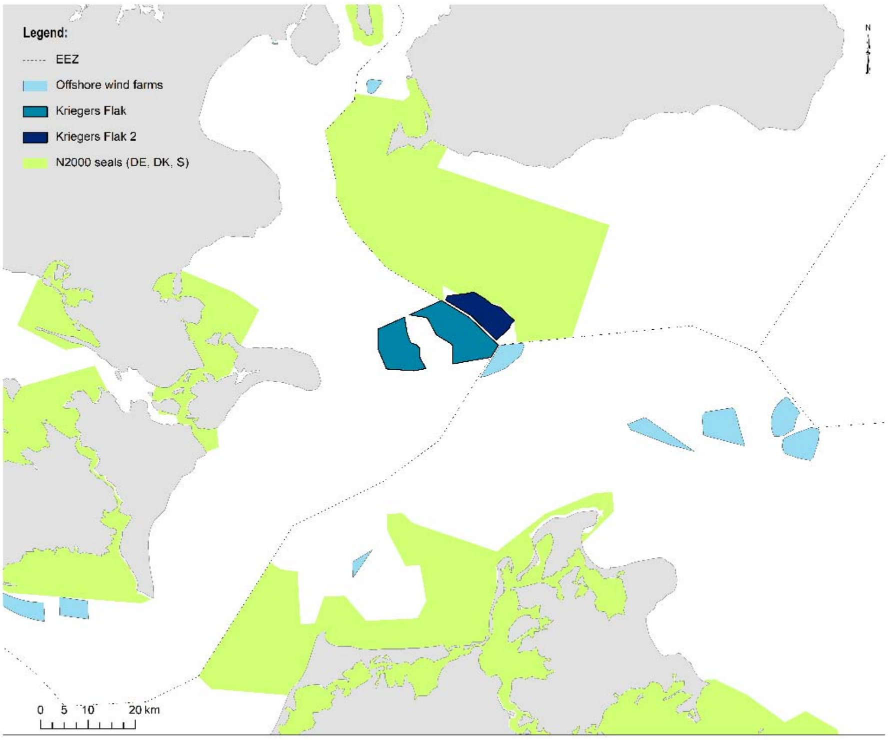

Figure 1.1. Map of the waters surrounding Kriegers Flak, with the location of the proposed wind farm Swedish Kriegers Flak, together with already existing and projected wind farms. Green polygons indicate Natura2000 areas where marine mammals are part of the basis for designation.

1.1 The Swedish Kriegers Flak Offshore Wind Farm

The location of the wind farm is Kriegers Flak, a shallow bank in the entrance to the Baltic Proper, located where the economic exclusive zones (EEZ's) of Sweden, Denmark and Germany meet (Figure 1.1). At present, one wind farm, German Kriegers Flak (Baltic II), is already fully commissioned and in operation. In addition, construction of a 600 MW wind farm, Danish Kriegers Flak, has started on the Danish part and is scheduled to be fully commissioned in 2021.

Thorough descriptions of the area can be found in the original EIA for the wind farm (Sweden Offshore Wind AB 2004) as well as in the EIA for the Danish Kriegers Flak wind farm (Dietz *et al.* 2015). In brief, the core of the bank is an outcrop of a very thick layer of mesozoic chalk (exposed above water at Møns Klint and on Rügen), overlaid by sand and gravel. The shallowest part of the bank is around 17 m deep, located in the Danish part, gently sloping down to about 25 m, followed by a steep drop down to more than 40 m in the surrounding waters (Figure 1.2).

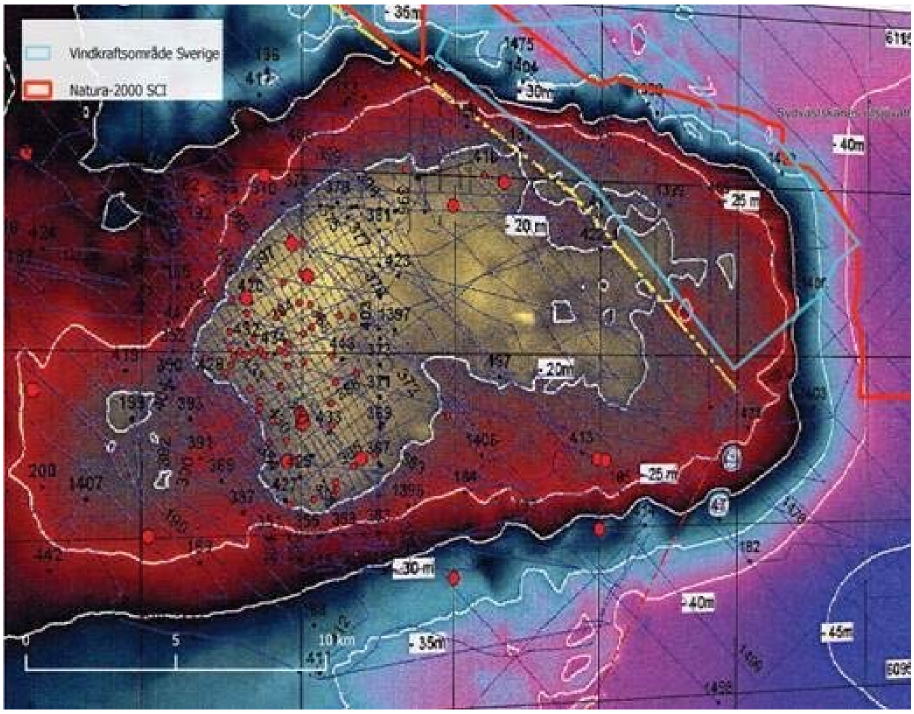

Figure 1.2. Overview of Kriegers Flak with indication of depth contours with 5 m intervals. The yellow line marks the border between the Swedish and Danish EEZ, blue polygon is the Swedish Kriegers Flak wind farm and red is the border of the Natura2000 area. Modified from Sweden Offshore Wind AB (2004)

The layout of the wind farm, i.e. the size and number of turbines and their exact positions have not been decided yet and neither have the details about choice of foundation type and method of installation. The final number of turbines depends on the size of the individual turbines and is expected to be between 32 and 76 turbines. The following assessment is thus based on worst-case assumptions regarding the type, size and location of foundations with respect to underwater noise generation.

2. Marine mammals relevant to the project

Three species of marine mammals occur regularly in the Western Baltic: harbour porpoise (*Phocoena phocoena*), harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*). All three species are protected under the EU habitats directive and listed on Annex 2, mandating member states to designate protected areas for these species as part of the Natura2000 network. Harbour porpoises are also listed on Annex 4, implying strict protection everywhere the species occur.

Several other species of cetaceans are occasionally observed in the Western Baltic, including different species of dolphins and baleen whales. Although all these species are listed in Annex 4 of the Habitats Directive, they occur so infrequently and unpredictably that they have been excluded from this assessment.

2.1 Harbour porpoise (tumlare)

The harbour porpoise is the smallest, but also the most numerous cetacean in Europe. It is widely but unevenly distributed throughout European waters. The distribution is presumably linked to the distribution of prey (e.g. Sveegaard *et al.* 2012), which in turn is linked to parameters such as hydrography and bathymetry (Gilles *et al.* 2011).

2.1.1 Subpopulations in the Baltic

Morphological and genetic studies (Wiemann *et al.* 2010, Galatius *et al.* 2012, Lah *et al.* 2016) have aimed at elucidating the population structure of porpoises in the Baltic and adjacent waters. All studies are consistent with the idea of three separate subpopulations: one in the Baltic Proper, a second in the western Baltic, the Danish Straits and southern Kattegat (henceforth called the Belt Sea population), and a third in Skagerrak and the North Sea. These studies were however not able to determine exact borders between the populations, likely because of overlap between the populations.

Until the first half of the 20th century, harbour porpoises were widely distributed in the entire Baltic Sea, but a dramatic decline has been observed within the last 50-100 years. Until recently, little was known about the distribution and status in the Baltic Proper (Skora *et al.* 1988, Andersen *et al.* 2001, Koschinski 2002). The severe decline of the harbour porpoise population in the Baltic Proper makes it the smallest population of harbour porpoises in the world (ASCOBANS 2002) and it is now listed as “critically endangered” by the International Union for Conservation of Nature (IUCN). In 2016, the SAMBAH project using extensive static acoustic monitoring estimated the remaining number of porpoises in the Baltic Proper to be approx. 500 (95% CI 80-1,100) (SAMBAH 2016). The critically endangered status of this very small subpopulation is in stark contrast to the Belt Sea population. This population is assessed by IUCN as “least concern” (together with all other porpoise populations in the Atlantic Ocean) and numbers are estimated to be in the tens of thousands (Sveegaard *et al.* 2015b).

The distribution of the two subpopulations of the Baltic Proper and the Belt Seas overlap in the waters west of Bornholm, i.e. in the area where Kriegers Flak is located. This overlap is of particular importance for the wind farm project, as the assessment of impact depends on the conservation status of the populations. The overlap was examined by re-examining genetic data, as well as data from satellite tracked porpoises (Sveegaard *et al.* 2011) and passive acoustic monitoring (subset of data from SAMBAH) (Sveegaard *et al.* 2015a). During summer months (May-Sept) a clear decreasing gradient in porpoise density was observed east of 13.5° eastern longitude, indicating that only few porpoises from the more abundant Belt Sea population cross this line (Figure 2.1).

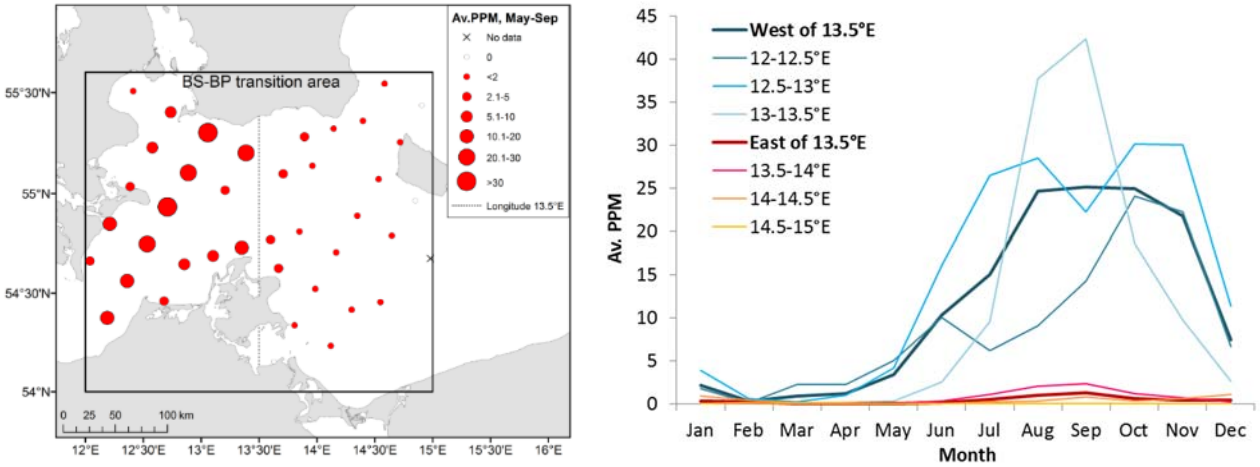

Figure 2.1. Left panel: map of the transition zone between the Belt Sea and Baltic Sea populations, with SAMBAH acoustic stations shown with red dots. The vertical line indicates 13.5° longitude, which has been suggested as a separation between management areas of the two populations. Right panel: the average number of minutes with porpoise detections per day. Each line shows the monthly variation in half-degree longitude increments over the area shown in the left panel. From Sveegaard *et al.* (2015a).

The porpoise detections from the SAMBAH project were analysed as Porpoise Positive Seconds per day (PPS) and split into two seasons (**Figure 2.2**). In the summer period, the data were further divided into the two population groups. Division in the SAMBAH analysis was made with a line running east of Bornholm and was made for practical reasons. As the number of animals in the western part is many times larger than in the Baltic Proper, the coloured contours have been made with two different colour scales. During the breeding period in summer, porpoises in the Baltic Proper concentrate around the shallow Midsjö Banks south of Gotland and Öland and there is a clear drop in density outwards from this area, consistent with the notion of an isolated breeding population in the Baltic proper. The porpoises of the Baltic Proper are more widespread in winter, and were detected as far north as the coast off southwestern Finland. Porpoises from the Belt Sea population are restricted to the waters west of 13.5 eastern longitude, i.e. roughly around and west of Kriegers Flak, with fewer animals in the winter months, but generally much higher densities than in the Baltic proper.

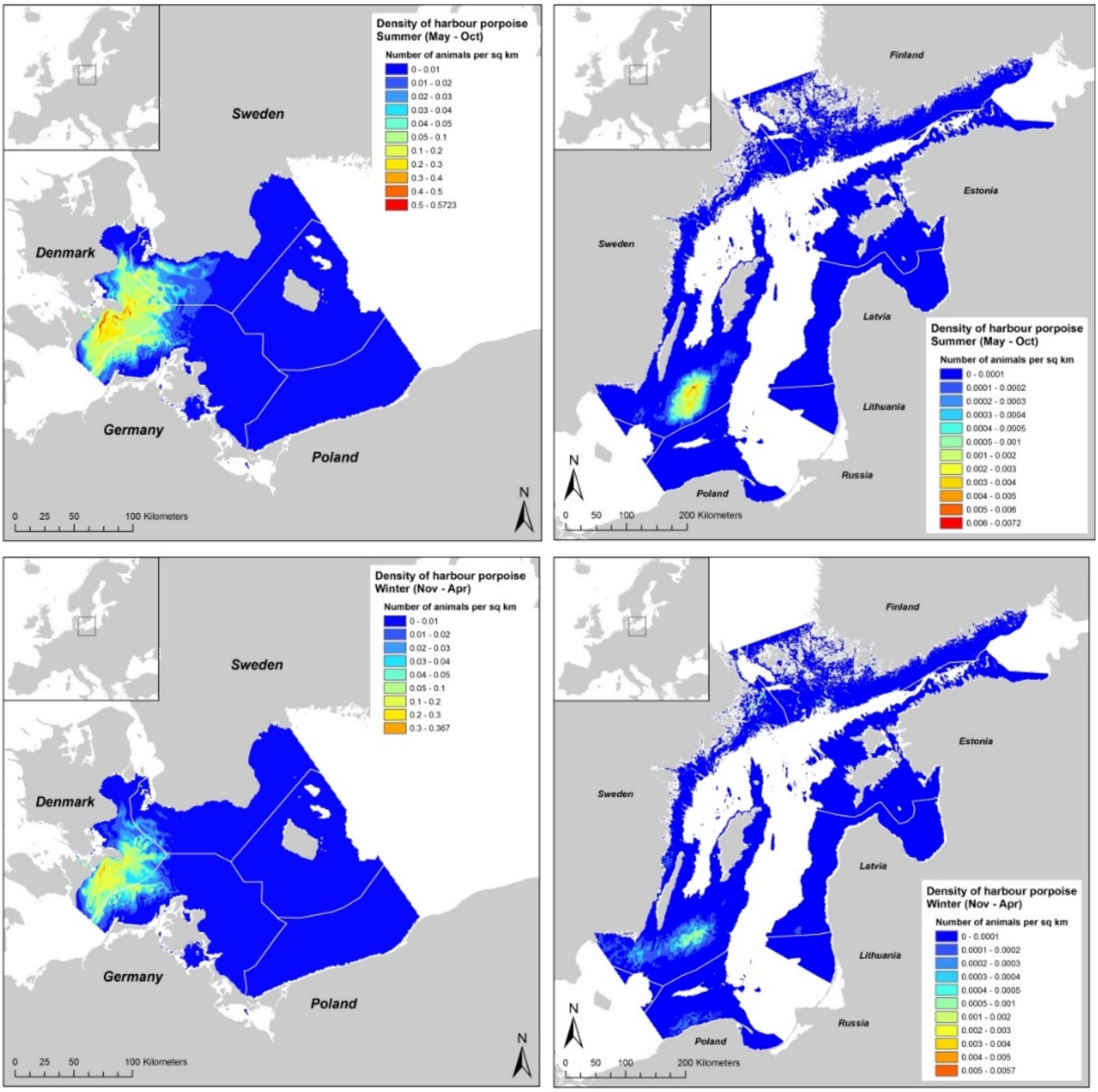

Figure 2.2. Predicted density of porpoises (in number of animals per km^2) for each season and for the southwestern and north-eastern part of the study area, respectively. Kriegers Flak is located west of Bornholm, in the area where the Swedish, Danish and German EEZs meet. From SAMBAH (2016).

The management border of the Belt Sea population is supported by satellite tracking of 94 porpoises during the years 1997-2015, incidentally live caught in pound nets, and equipped with satellite transmitters (**Figure 2.3**). Individual animals were tracked for up to 522 days. All animals were caught in Danish waters within the proposed management area for the Belt Sea population (Kattegat, Belt Seas or Western Baltic) (Sveegaard *et al.* 2015a). The satellite-tracked porpoises spent most of the time in the western part of the area, with a steep gradient towards the east, across Kriegers Flak in summer, which was less pronounced, but still present in winter (Figure 2.3).

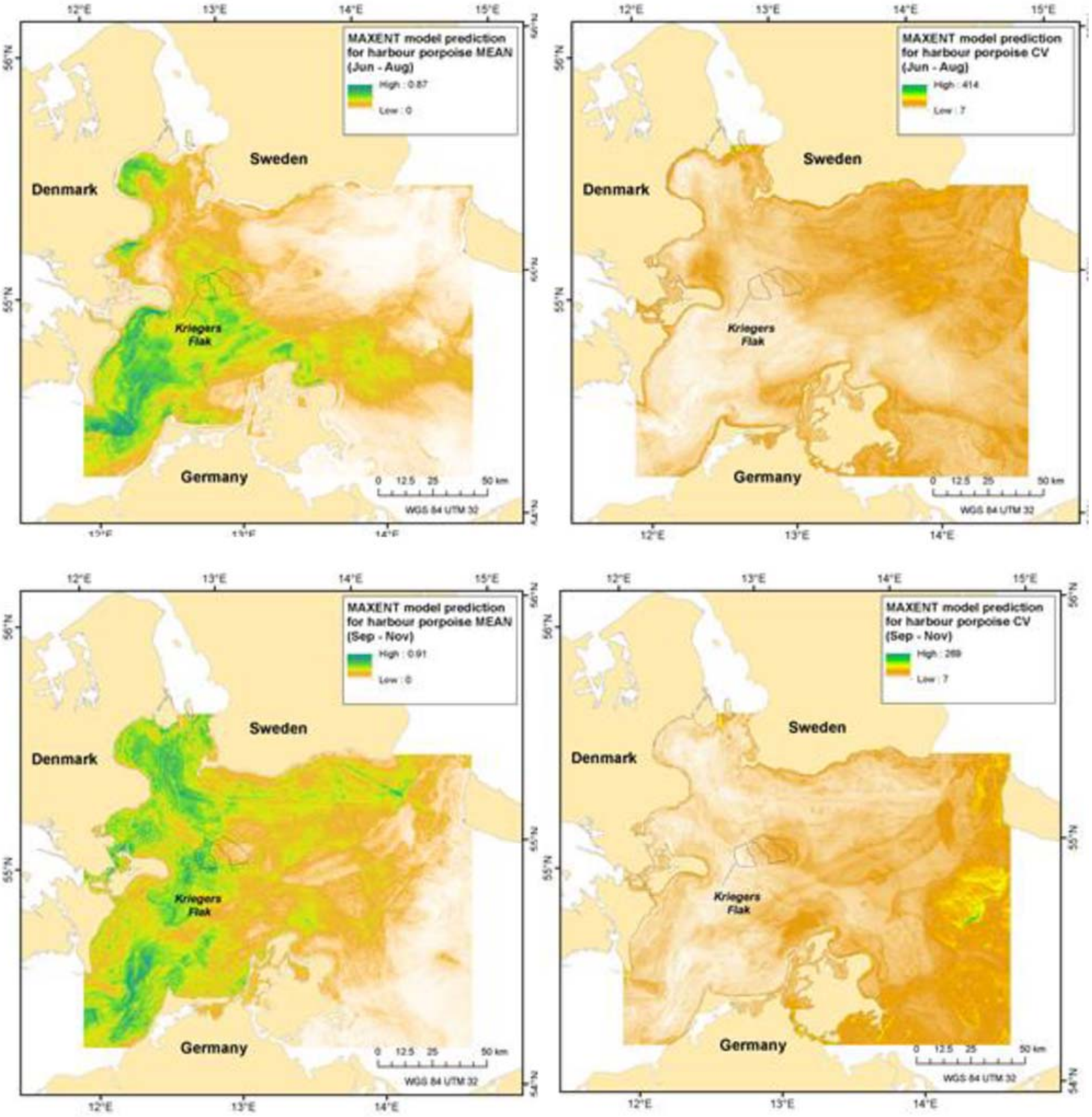

Figure 2.3. Mean prediction of the "probability of presence of harbour porpoise" based on satellite derived positions of porpoises. Top is summer months, bottom is winter months. Right maps show the uncertainty of the prediction expressed by the coefficient of variation (CV). From Dietz *et al.* (2015).

Two conclusions can be drawn from these results. First of all is that porpoises are abundant in the waters around Kriegers Flak, with summer densities on average around 0.1 porpoise/km^2, but secondly that almost all of the porpoises encountered, especially in the summer months, are likely to belong to the Belt Sea population, which is in favourable conservation status. In the winter months, animals from the critically endangered Baltic Proper population are more spread out and observed in low densities in the waters along the coast of Blekinge. This supports a westward migration in autumn, as has been suggested previously, based on passive acoustic data collected along the German coast (Verfuss *et al.* 2007). This means that the probability of encountering porpoises from the Baltic Proper population around Kriegers Flak is likely increased during winter. However, also in winter the Baltic Proper porpoises are outnumbered in the waters around Kriegers Flak by porpoises from the Belt Sea population.

Based on the results of the SAMBAH monitoring(SAMBAH 2016, Carlén *et al.* 2018), as well as satellite tracked porpoises from the Belt Sea population, a recent assessment of important habitats for porpoises in Swedish waters was conducted (Carlström & Carlen 2016). The overall results are shown in the form of a map in Figure 2.4.

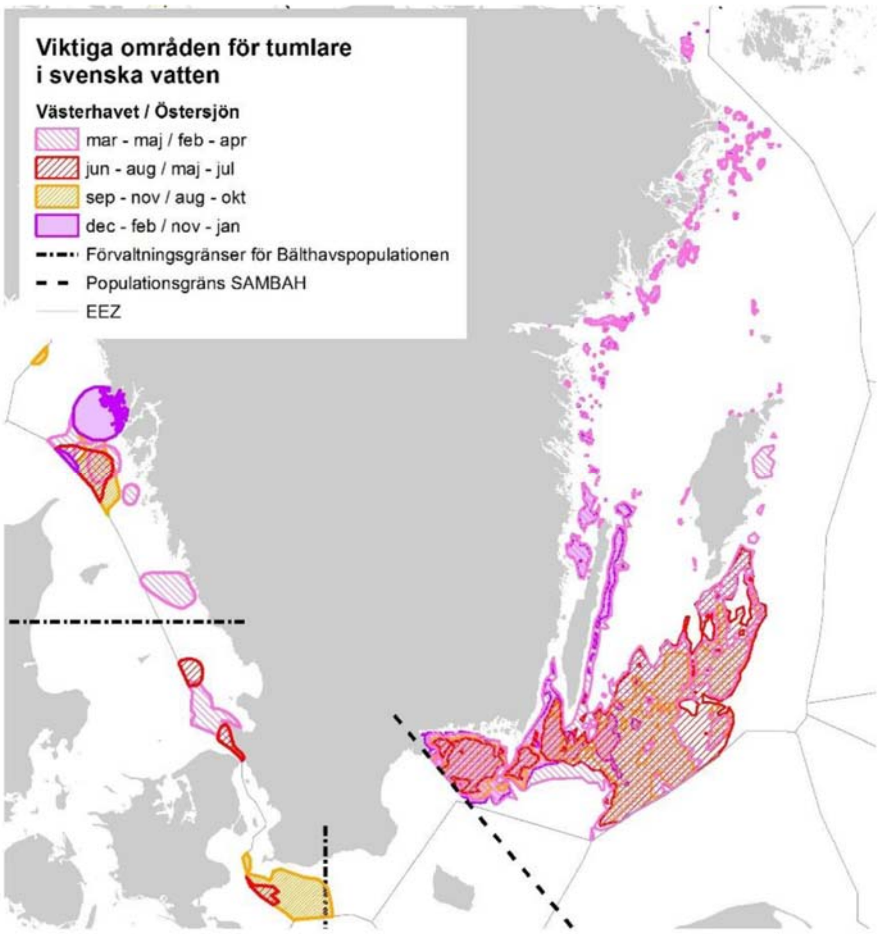

Figure 2.4. Areas in Swedish waters considered of special importance to harbour porpoises – separated into three management units, northern Kattegat, Belt Seas and Baltic Proper. Indicated is also the separation line between the Baltic Properpopulation and the Belt Sea population used for abundance estimates in the SAMBAH project. From Carlström and Carlen (2016).

This assessment highlights the waters south of Skåne and around Falsterbo as being of particular importance for the Belt Sea population, with a locally more western presence during summer months (red area) and more spread out presence in the winter months (yellow area). Areas identified as being of special importance to the Baltic Proper population are exclusively located east of Bornholm.

2.2 Harbour seal (knubbsäl)

Harbour seals are abundant in the Danish Straits and Kattegat, with the exception of waters south of Fyn, and their abundance extend along the coast of Skåne and Blekinge into the Baltic. Based on molecular data and satellite telemetry, the harbour seals in the Baltic region have been split into three management units or sub-populations, among which there is at least partial reproductive isolation: one in southern Kalmarsund, a second in the southwestern Baltic, and a third in Kattegat (Goodman 1998, Härkönen *et al.* 2006, Olsen *et al.* 2014). Tagging studies have shown limited movements of harbour seals (e.g. Dietz *et al.* 2015) and no or limited exchange between colonies separated by more than approx. 100 km (Härkönen *et al.* 1999).

Haul-out sites (also called colonies) in the Baltic are only found in southern Kalmarsund and in the southwestern Baltic concentrated around the Rødsand sand bar, Aunø Fjord in South Sjælland, Falsterbo and Saltholm in the Sound. The Kalmarsund population comprises around 1,000 individuals (HELCOM 2015) and the southwestern population around 1,500 individuals (Sveegaard *et al.* 2015b).

The knowledge on abundance and density of seals is extensive with respect to the locations of the haul-out sites, but very limited when it comes to their use of the surrounding waters, especially in the Kalmarsund region. In the western part of the Baltic, 10 harbour seals have been tagged with GPS transmitters at Falsterbo, Sweden, in 2012 (Figure 2.5). Even though no seals were observed inside the wind farm area, they were observed close by and given the low sample size (10 tagged animals), it must be concluded that it is very likely to encounter harbour seals from Falsterbo in the wind farm area.

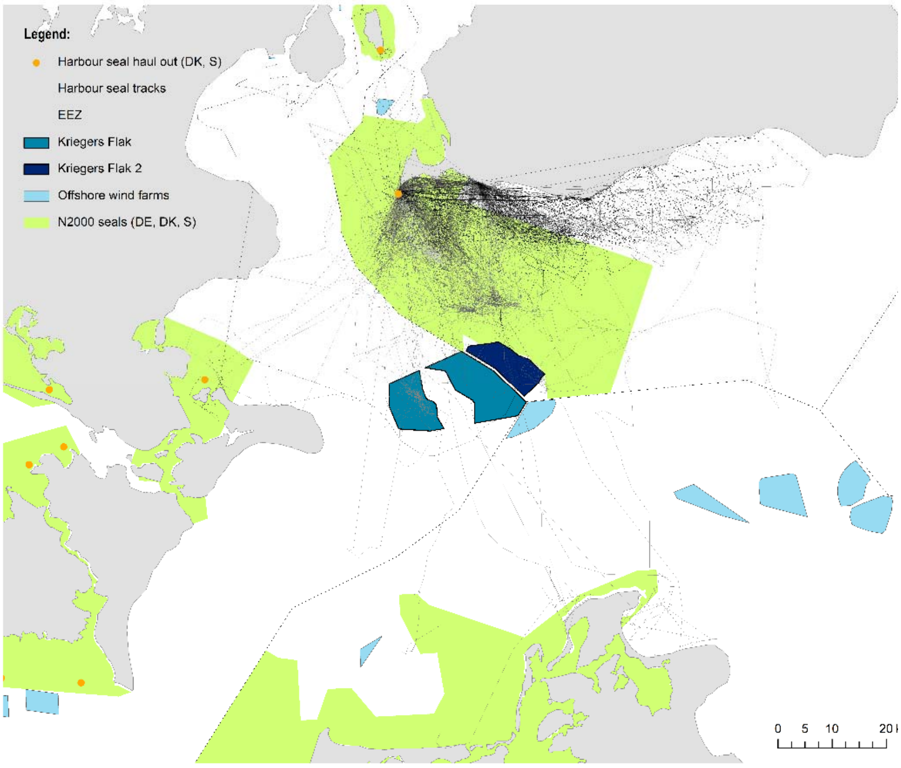

Figure 2.5. GPS derived positions of 10 harbour seals caught and tagged on Falsterbo. Indicated are also existing and projected offshore wind farms and Natura2000 areas. Source DCE/AU Bioscience.

2.3 Grey seal (gråsäl)

The grey seal is currently the most abundant seal species in the Baltic. Around 1900, the grey seal population had a size of 80-100,000 individuals while in the 1970s it was down to about 4,000 because of hunting and pollution (Harding & Härkonen 1999). Abundance based on photo-identification of individuals in 2000 yielded an estimate of 15,600 individuals while an aerial survey in 2004 found 17,640 grey seals on land (Hiby *et al.* 2006). With an annual population increase of 7.9% and correction for seals in the water, which are not counted during the surveys, it is believed that the total population in the Baltic in 2014 was above 40,000, based on 32,200 counted seals (HELCOM 2015).

The Baltic grey seals are distributed from the northernmost part of the Bothnian Bay to the southwestern Baltic. Generally, during the breeding period, the seals haul-out on drift ice in the Gulf of Riga, the Gulf of Finland, the Northern Baltic Proper and the Bothnian Bay or on the rocks in the northwestern Baltic. Graves *et al.* (2008) and Fietz *et al.* (2016) found clear genetic differentiation between the Baltic and North Sea grey seals.

The area around Kriegers Flak holds a major grey seal haul-out at Falsterbo, and further away at Rødsand, Ertholmene near Christiansø and Utklippan. Satellite tracking of grey seals has shown that this species moves over long distances in the Baltic Sea and most tagged grey seals from the southern Baltic Sea have moved far into the Baltic Proper (Dietz *et al.* 2015). See Figure 2.6. A tagged female from Rødsand in the Danish Baltic was observed with a pup in Estonia and observed back at Rødsand a month later. This indicates seasonal migrations that are closely related with the requirements for feeding and site fidelity for breeding area, where grey seals travel up to 380 km from the tagging site (Dietz *et al.* 2015). Typically, however, they feed more locally, foraging just offshore and adopting a regular pattern of travelling between local feeding sites and preferred haul-outs (Sjöberg & Ball 2000, Oksanen *et al.* 2014).

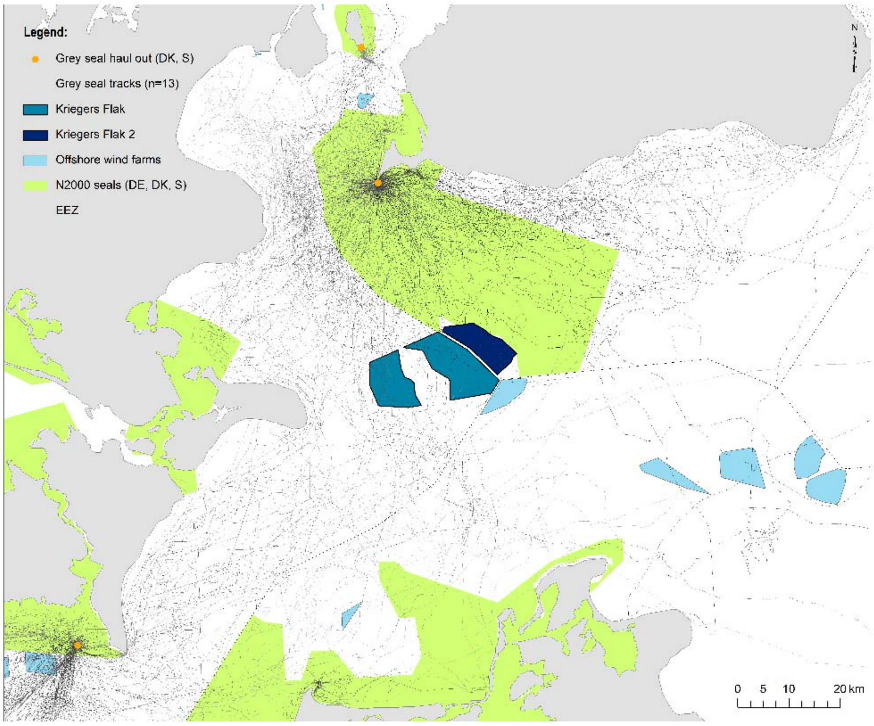

Figure 2.6. Movement of grey seals caught and tagged with satellite transmitters at Rødsand and Falsterbo. Shown are also existing and planned offshore wind farms and Natura2000 areas. Source DCE/AU Bioscience.

2.4 Protected areas

A number of areas have been designated as Natura2000 areas in order to offer increased protection of seals and porpoises. These areas are shown on the map in Figure 1.1 and listed in Table 2.1.

Table 2.1. List of relevant Natura2000 areas in the waters around Kriegers Flak.

Name	Country	Species
Falsterbohalvön	Sweden	Harbour and grey seals
Sydvästskånes Udsjövatten	Sweden	Harbour seal, grey seal, harbour porpoise
Kadetrinne	Germany	Harbour seal, grey seal, harbour porpoise
Darßer Schwelle	Germany	Harbour seal, grey seal, harbour porpoise
Darß	Germany	Harbour seal, grey seal, harbour porpoise
Plantagenetgrund	Germany	Harbour seal, grey seal, harbour porpoise
Recknitz estuary and Zingst peninsula	Germany	Harbour seal, grey seal
Westrügen inlet and Hiddensee	Germany	Harbour seal, grey seal, harbour porpoise
Libben, cliffs, Wittow and Arkona stone reefs	Germany	Harbour seal, grey seal, harbour porpoise
Nordrügen inlet	Germany	Harbour seal
The sea between Præstø Fjord and Grønsund	Denmark	Harbour seal

Of particular interest is the newly (2017) designated Natura2000 area Sydvästskånes Udsjövatten. This area covers 115 km^2, surrounding the Swedish Kriegers flak wind farm area within the Swedish EEZ and extending northwards, where it borders directly with the Natura2000 area Falsterbohalvön. A clear correspondence between the designated Natura2000 area and the areas identified as important by Carlström and Carlen (2016) is evident (compare with **Figure 2.4**). No management plan is available for Sydvästskånes Udsjövatten, but the basis for designation includes the following description:

"The north-western part of the area is of particular importance for overwintering and resting for different species of ducks. In the winter months, the area is probably used by both the Baltic and the Belt Sea populations of harbour porpoises. Only porpoises from the Belt Sea population are likely to be present in the summer months. Harbour- and grey seals are present". (source: http://skyddadnatur.naturvardsverket.se/ translated from Swedish).

Central for the assessment of impact of the Swedish Kriegers Flak offshore wind farm is thus the possibility of encountering animals belonging to the critically endangered Baltic Proper harbour porpoise population, especially in winter months. The information available from the SAMBAH project (**Figure 2.2**) shows that such encounters are not unlikely, but the assessment made by Carlström and Carlen (2016) does not identify the waters around Kriegers flak as being of special importance to this population of porpoises, but identify it as such for the Belt Sea porpoises).

3. Primer on underwater acoustics

Underwater acoustics differ from aerial acoustics in a number of important ways. The much higher density of water means that the speed of sound is higher (about 1500 m / s vs. about 340 m / s in air), which also means that the wavelength is about five times larger in water compared to air. However, more important is that the dissipative loss experienced as the sound waves propagate through water is much smaller in water than in air. This means that whereas even very loud noise in air rarely is audible beyond some few kilometres from the source, underwater sound may be detectable hundreds or even thousands of km from the source, in particular for the low frequencies and in deep oceans. Even in shallow waters, the noise from pile driving is readily detectable above ambient noise beyond distances of 100 km from the pile driving.

A second consequence of the high density of water is that any air to water interface, such as the sea surface, or air bubbles in the water (or inside an animal) will reflect the sound almost completely, whereas underwater sound passes almost unattenuated through most biological tissue, as the density of this is almost equal to that of water.

A third consequence of the high density of water is that because water is almost incompressible it is easier to create high pressures in water than in air. In air, a larger fraction of the acoustic energy relates to the periodic movement of the medium (the so-called particle motion) than to the generation of pressure. Two signals of the same acoustic energy, one in air and the other in water, will differ dramatically with respect to associated pressure and particle motion. In air, the particle motion will be much higher than in water, and the pressure will be much smaller. For these reasons, it is difficult to compare measures of signal magnitude in air and water (i.e. to determine which of the two is the loudest), as one has to be very specific as to what is compared: energy, pressure or particle motion. This error is likely to be the most common error relating to impact of underwater noise on marine mammals.

3.1 Sound pressure and energy

Sound is pressure fluctuations and can be characterised by the time-varying deviation from the ambient pressure, p(t), These pressure deviations are measured in Pascal (Pa). Often, this is converted into a sound pressure level on the logarithmic dB-scale:

Equation 3.1

$$L = 20 \log_{10}(\frac{p}{p_0})$$

Where p_0 is the reference pressure, by convention 1 µPa for underwater sound. The unit of sound pressure level is thus dB re. 1 µPa (read dB relative to 1 microPascal).

Because of the difference in density of air and water, as described above, the pressures generated by applying the same acoustic energy to water is much higher than in air. This means, that dB values for underwater sounds tend to be considerably larger than what one is accustomed to in air, which can give the false impression of immensely high noise levels. In general, dB values for sound measured in water cannot be compared to dB values on the well-known scale for sound in air. Instead, the sound pressure levels of underwater sounds should only be compared to other underwater sounds. Some reference points for comparison are given in Table 3.1.

Table 3.1. Typical sound pressure levels of various biological and man-made sources.

	Source level at 1 meters distance
Explosion of 100 g TNT	275 dB re. 1 µPa
Echolocation click of sperm whale	235 dB re. 1 µPa
Commercial echosounder	220 dB re. 1 µPa
Echolocation click of harbour porpoise	190 dB re. 1 µPa
Blue whale call	180 dB re. 1 µPa
Harbour seal mating call	145 dB re. 1 µPa
Natural background noise in shallow waters on a calm day	100 dB re. 1 µPa

The energy, E, of a sound of duration, t, is measured in Joule / m^2 and can be computed from the pressure signal as[1]:

Equation 3.2

$$E = \frac{\int p(t)^2 dt}{\rho c}$$

Where ρc, known as the acoustic impedance, is the product of the density of water, ρ, and the sound speed, c. More commonly used in relation to impact assessments, however, is the sound exposure level (SEL), expressed in dB as:

Equation 3.3

$$SEL = L_{E,p} = 10 \log \int_0^\tau \frac{p^2(t)}{p_0^2} dt$$

Where p(t) is the instantaneous pressure at time t of a signal of duration τ and p_0 is the reference pressure (1 µPa, in water). The unit of SEL is thus dB re. $1 \mu Pa^2 s$. By use of this reference, the acoustic impedance of Equation 3.2 cancels out in the calculations, and can be conveniently ignored. It is possible to show that this unit is indeed a unit of energy, being proportional to J / m^2 by means of a constant depending on the acoustic impedance of water.

Note that the units of sound pressure level (dB re. 1 µPa) and sound exposure level (dB re. 1 $\mu Pa^2 s$) are different, as they express two entirely different physical properties (pressure vs. energy). Thus, they cannot be compared. Note also that other references may occur in the literature as well. Comparison of non-comparable dB-values is likely to be the second-most important source of errors in assessment of underwater noise (comparison between air and water being the first, cf. above).

3.2 Frequency spectra

The distribution of energy in a sound signal across frequencies can be analysed and displayed in different ways. A very common and useful way to display the frequency distribution is by the power density spectrum, which is the amplitude spectrum of the Fourier transformed time signal (see for example Bloomfield 1976). Short signals can be transformed directly, whereas longer signals must be cut into smaller parts and averaged after transformation (by

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[1] Strictly speaking, this equation is only valid for a plane, propagating sound wave, i.e. not too close to the source and not in a confined space. It is a good approximation as long as one is more than several times the wavelength away from the source and in water deeper than a few times the wavelength.

what is referred to as a Welch average, Welch 1967). The power density spectrum is usually normalised to 1 Hz analysis bandwidth, which gives the y-axis a unit of dB re. 1 µPa^2/Hz.

A common alternative to the power density spectrum, where analysis band is constant, is to use analysis bands where the ratio of bandwidth to centre frequency is constant (so-called constant-Q filter bank). Commonly used filter bandwidth are 1/3 octave and 1/1 octave. It is beyond the point of this report to go in details about pros and cons of the different frequency spectra. The only important point in this context is to note that spectra calculated with different methods cannot be compared directly, but must be properly transformed to adjust for the different analysis bandwidths. Converting a 1/3-octave band level to spectrum density level can be done by the following relation:

Equation 3.4

$$\boldsymbol{L_{1Hz} = L_{\frac{1}{3}octave} - 10\log_{10}(0.23f_c)}$$

Where f_c is the centre frequency of the 1/3-octave band, $L_{1/3octave}$.

In a similar way, the levels of a 1/1-octave band spectrum can be converted to spectrum density levels by:

Equation 3.5

$$\boldsymbol{L_{1Hz} = L_{1\,octave} - 10\log_{10}(0.70f_c)}$$

3.3 Source level and transmission loss

In its most simple form, sound pressures decrease with increasing distance to the source. This is primarily due to two factors: geometrical spreading, where the initial acoustic energy is spread over an increasingly larger surface, as the sound propagates away in all directions from the source; and absorption, the gradual and inevitable loss of energy as heat as the sound moves through the water. In practice, a large number of additional factors influence the propagation of sound away from a sound source, which is the reason why one has to rely on more complex modelling tools to predict sound levels away from the source, as done in Appendix 1. In a generalized form, however, sound propagation can be understood from this simple equation:

Equation 3.6

$$\boldsymbol{RL(r) = SL(1m) - TL(r)}$$

Which states that the received level (RL) at some distance, r, from the source (measured in metres) equals the level at the reference distance 1 m (known as the source level, SL) minus the transmission loss TL, which is what is lost going from 1 m to distance r, for whatever reason. Often, it is not meaningful to think of the source level as an actual sound level which can be measured 1 m from the source. This is certainly the case for pile driving. A monopile is clearly not a point source, but has a diameter and length well above 1 m. Thus, it does not make sense to speak about an actual source level 1 m from the monopile. The term *point source equivalent source level* is thus more appropriate and it should be understood as the back-calculated source level of an equivalent point source with the same far field characteristics as the monopile source. SL thus carries no information about actual sound levels near the monopile but can (and is) nevertheless be used to predict sound levels at distances of some hundred meters and beyond by means of appropriate transmission loss models. The source level is thus a fundamental input parameter to modelling of transmission loss.

4. Sensitivity of marine mammals to noise

Marine mammals rely heavily on underwater hearing for orientation, navigation and communication underwater. Consequently, they have very good underwater hearing and are sensitive to noise, as a disturbing factor and, if sufficiently loud, also by directly inflicting injury to the animals.

4.1 Hearing in marine mammals

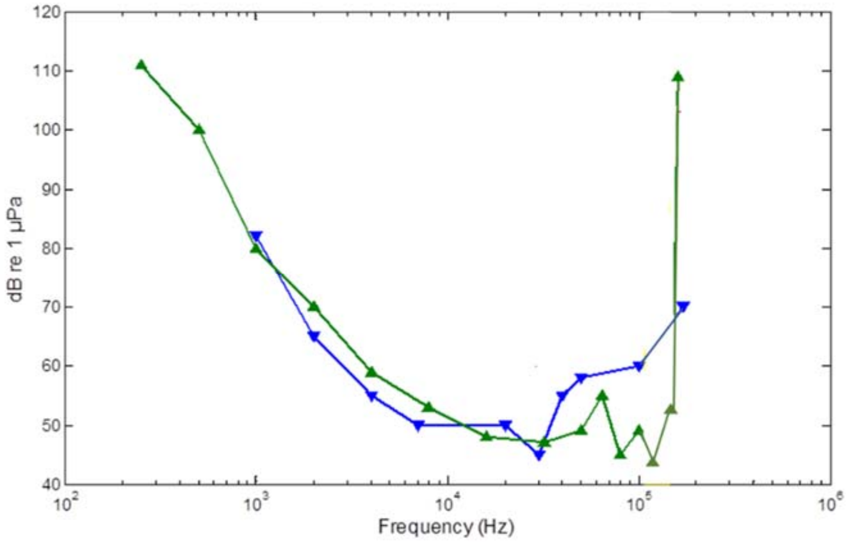
Marine mammals have good underwater hearing, as seen in their audiograms, which expresses the hearing threshold at different frequencies.

4.1.1 Porpoises

Porpoises, like all toothed whales (Odontocetes), have good underwater hearing and use sound actively for navigation and prey capture (echolocation). Harbour porpoises produce short, ultrasonic clicks (130 kHz peak frequency, 50-100 µs duration (Møhl & Andersen 1973, Kyhn *et al.* 2013); and are able to orient and find prey in complete darkness. Data from porpoises tagged with acoustic data loggers indicate that they use their echolocation almost continuously (Akamatsu *et al.* 2007, Linnenschmidt *et al.* 2013, Wisniewska *et al.* 2016).

Harbour porpoise hearing is very sensitive and covers a broad frequency range (Figure 4.1). Best hearing is in the frequency range between about 10 kHz to around 160 kHz.

Figure 4.1. Audiograms for harbour porpoises modified from Kastelein *et al.* (2010a)) (green) and Andersen (1970) (blue). The audiogram shows the hearing threshold, i.e. the minimum audible level as a function of frequency. Best sensitivity (lowest threshold) is in the range 10-160 kHz.



4.1.2 Seals

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 a separate bone conduction pathway for sound transmission 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 4.2). No audiogram is available for grey seals, but given their close taxonomic relationship and similar ear anatomy, it is a reasonable first assumption that their hearing is comparable to harbour seal hearing.

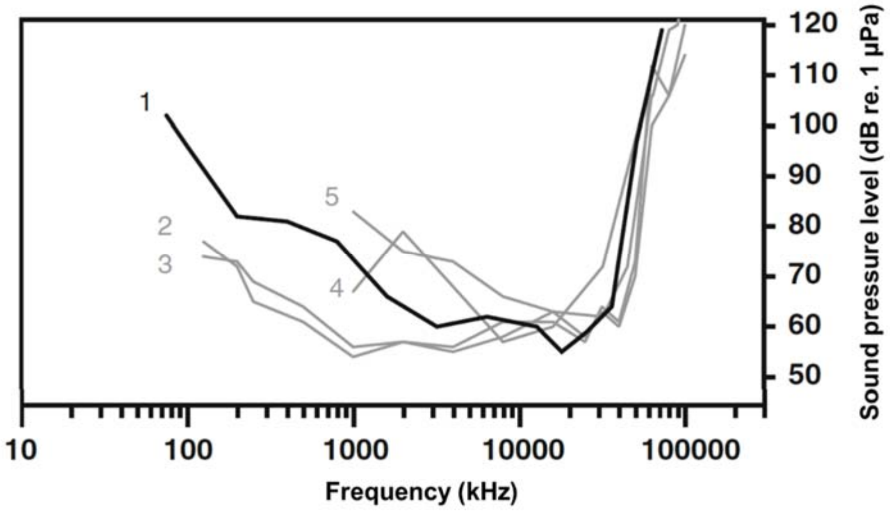


Figure 4.2. Audiograms for harbour seals. Numbers refer to different studies. 1: Reichmuth *et al.* (2013), 2+3: (Kastelein *et al.* 2009), 4: (Terhune 1988), and 5: Møhl (1968), From Reichmuth *et al.* (2013).

4.2 Acoustic trauma

Very loud, impulsive sound is capable of inflicting direct damage to biological tissue (acoustic trauma). There is some uncertainty with respect to the physical entity responsible for the damage, i.e. whether a very large peak pressure (measured in Pascal) in itself is damaging, or whether it is the differential acceleration of tissues with different density, in which case the acoustic impulse (measured in Pascal· seconds) is the appropriate measure. There is limited information about blast injuries in marine mammals, but it is assumed that the sensitivity of smaller marine mammals, such as seals and porpoises, is comparable to the sensitivity of human divers, as the lung volume is believed to be a major factor determining vulnerability (Yelverton *et al.* 1973). A recent review of blast injury on human divers (Lance *et al.* 2015) indicate a 10% risk of survivable injury at an exposure to 30 Pa· s, or a corresponding peak pressure of at least 226 dB re 1 µPa.

4.3 Noise induced hearing loss

It is generally accepted that the inner ear is the organ most sensitive to acoustic injury in marine mammals. This implies that injury to the auditory system will occur at lower sound levels than injuries to other tissues (Southall *et al.* 2007). Noise induced threshold shifts are in the same way accepted as precautionary proxies for more widespread injuries to the auditory system. A noise induced threshold shift is a temporary or permanent reduction in hearing sensitivity following exposure to loud noise (for example commonly experienced by humans as a temporarily reduced hearing after a rock concert). Temporary threshold shifts (TTS) disappear after some time, how long depending on the severity of the impact. Small amounts of TTS will disappear in a matter of minutes, extending to hours or even days for very large TTS. A schematic illustration of the time course of TTS is shown in Figure 4.3. The amount of TTS immediately after end of the noise exposure is referred to as initial TTS. It expresses the amount by which the hearing threshold is elevated and is measured in dB. The larger the initial TTS, the longer the recovery period.

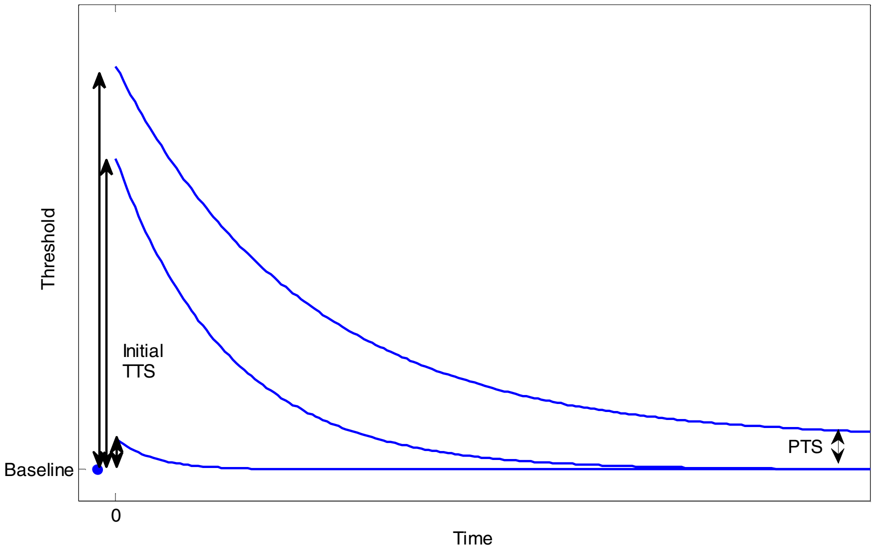


Figure 4.3. Schematic illustration of the time course in recovery of TTS. Zero on the time axis is the end of the noise. The threshold returns gradually to baseline level, except for very large amounts of initial TTS where a smaller, permanent shift (PTS) may persist. As the figure is schematic, there are no scales on the axes. Time axis is usually measured in hours to days, whereas the threshold shift is measured in tens of dB. From Skjellerup *et al.* (2015)

At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a smaller or larger amount of permanent threshold shift (PTS, see Figure 5.1). This permanent threshold shift is a result of damage to the sensory cells in the inner ear (Kujawa & Liberman 2009). An initial TTS of 40 dB or higher is generally considered to constitute a significantly increased risk of generating a PTS (reviewed in National Marine Fisheries Service 2016). It is well known from humans and terrestrial animals that lower levels of TTS, if induced repeatedly, also may lead to PTS (Kujawa & Liberman 2009).

4.3.1 Relationship between TTS and PTS

Thresholds for inducing TTS and PTS are thus central for assessment of risk of auditory injury. Deriving such thresholds has been the subject of a large effort from many sides (see reviews by Southall *et al.* 2007, Finneran 2015). No current consensus on general thresholds for TTS and PTS can be said to exist. Matters are simplified somewhat, however, if one restricts to only one type of sound, such as pile driving noise and limits the discussion to only species for which sufficient data is available. In this way, extrapolation across species and sound sources is limited. A comparatively large effort has gone into investigating TTS caused by low frequency noise, including that from pile driving, in small cetaceans, such as harbour porpoises, bottlenose dolphins and belugas (*Delphinapterus leucas*). TTS is in general localised to frequencies around and immediately above the frequency range of the noise inducing the TTS (often referred to as the fatiguing noise). This means that TTS induced by low frequency noise typically only affects the hearing at low frequencies (Kastelein *et al.* 2013b).

As PTS thresholds for ethical reasons cannot be measured by direct experiments, the agreed approach to estimate thresholds for PTS is by extrapolation from TTS thresholds to the noise exposure predicted to induce 40-50 dB of TTS and thus a significant risk of PTS. This extrapolation, however, is not trivial, as it is complicated by the fact that the relationship between exposure and amount of initial TTS is not proportional (see review by Finneran 2015). Thus, one dB of added noise above the threshold for inducing TTS can induce more than one dB of additional TTS (see Figure 4.4). Note how the choice of slope has a very large influence on the estimated threshold for PTS. In Figure 4.4 the estimated PTS threshold is anywhere between 17 dB above the TTS threshold (red curve, 3 dB of TTS per added dB of noise) and 50 dB above the TTS threshold (blue curve, 1 dB of TTS per added dB of noise). The slope of the TTS growth-curve differs from experiment to experiment and slopes as high as 4 dB of TTS per dB of additional noise has been observed in a harbour porpoise (Lucke *et al.* 2009).

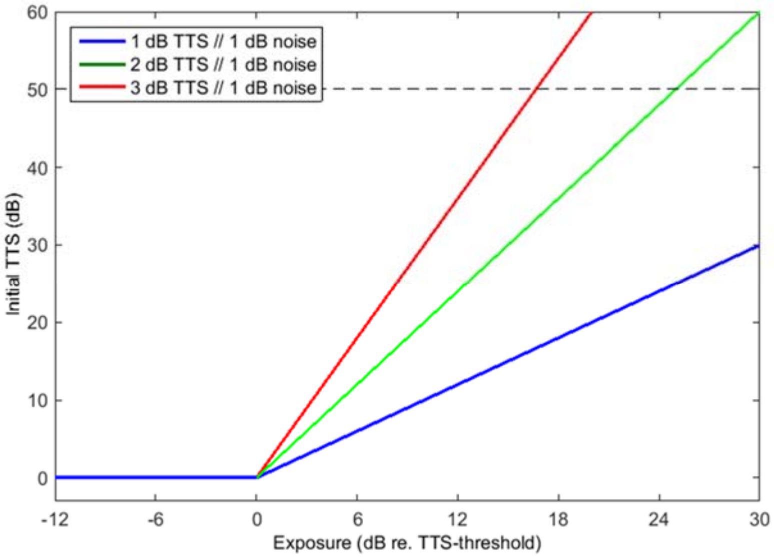


Figure 4.4. Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicate threshold for inducing PTS, assumed in this figure to be at 50 dB initial TTS. From Skjellerup et al. (2015).

Two additional aspects of TTS and PTS are of central importance in assessments. The first aspect is the question of how to account for mismatch between the dominant frequency of a noise and the frequency range of best hearing for the animals, which leads to the issue of frequency weighting, discussed below (4.3.2). The second aspect is the cumulative nature of TTS / PTS. It is well known that the duration of exposures and the duty cycle (proportion of time during an exposure where the sound is on during intermittent exposures, such as pile driving) has a large influence on the amount of TTS / PTS induced, and thus must be factored into the threshold somehow (discussed in 4.3.2 below) .

4.3.2 Frequency dependence and auditory weighting

Animals do not hear equally well at all frequencies. Substantial uncertainty is connected to the question of how this fact should be incorporated into assessing risk of inflicting TTS and PTS. For humans, where an enormous empirical evidence is available in the form of thousands of patients with known noise exposure and measured hearing loss, the consensus is that weighting with a curve roughly resembling the inverted audiogram, the so-called dBA-weighting, provides the best overall prediction of risk of injury (see Houser *et al.* 2017 for an extensive review). The situation for marine mammals is much less fortuitous, as very few instances of hearing loss have been documented and the noise exposure history of these animals were in most cases unknown. See, however, Kastak *et al.* (2008) and Kastelein *et al.* (2013a) for notable exceptions.

Southall *et al.* (2007) proposed that frequencies should be weighted with a broad weighting function (M-weighting) which only excludes energy at very low and very high frequencies, well outside the range of best hearing for the animals. Separate weighting functions were developed for different groups of marine mammals, grouped according to their known or presumed hearing abilities. A substantial amount of experimental evidence has become available since the review by Southall et al. (2007) and consensus appears to lead in the direction of more restrictive weighting functions based on the inversed audiogram (Tougaard *et al.* 2015, National Marine Fisheries Service 2016).

In line with the original proposal of Southall et al. (2007), separate curves have been derived for different groups of marine mammals (Figure 4.5). Five groups were defined, two for seals and three for cetaceans. Of the two seal curves, one for true (phocid) seals and one for eared (otariid) seals, only the first (phocids) is relevant, as it includes both harbour and grey seal. The three cetacean groups are defined on the basis of their (presumed) hearing abilities: low-frequency (LF) cetaceans include all the baleen whales, high-frequency (HF) cetaceans comprises the so-called narrow-band high-frequency species (see for example Madsen *et al.* 2005), which includes the harbour porpoises. The remaining odontocetes are grouped in the mid-frequency (MF) cetaceans group.

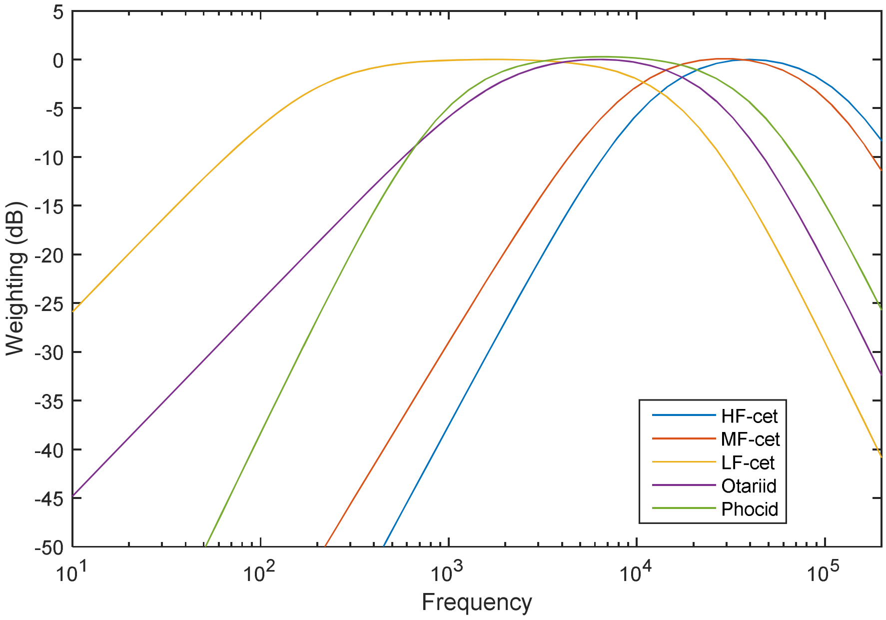


Figure 4.5. Frequency weighting curves proposed by National Marine Fisheries Service (2016).

4.3.3 Equal energy hypothesis and cumulative SEL

A substantial effort has gone into quantifying sound levels required to elicit TTS in marine mammals. The initial experiments were primarily conducted on bottlenose dolphins, belugas and California sea lions (*Zalophus californianus*) (all reviewed by Southall *et al.* 2007), but recently also a large number of results are available from other species, most notably harbour porpoises (see comprehensive review by Finneran 2015). The initial recommendations of Southall *et al.* (2007) reflected an uncertainty as to what single acoustic parameter best correlated with amount of TTS induced and resulted in a dual criterion: one expressed as instantaneous peak pressure and another as acoustic energy of the sound (integral of pressure squared over time, see below). In the reviews of Tougaard *et al.* (2015) and Finneran (2015) this uncertainty is no longer present and it is generally accepted that everything else being equal the amount of TTS correlates better with the acoustic energy than with the peak pressure. The acoustic energy is most often expressed as the sound exposure level (SEL), given as Equation 3.3 above. SEL equals the time integral of the sound intensity. For a signal of constant intensity and duration, the energy thus simply equals the duration times the intensity. Figure 4.6 illustrates four signals, which all have the same energy and thus according to the equal energy hypothesis should have the same ability to induce TTS.

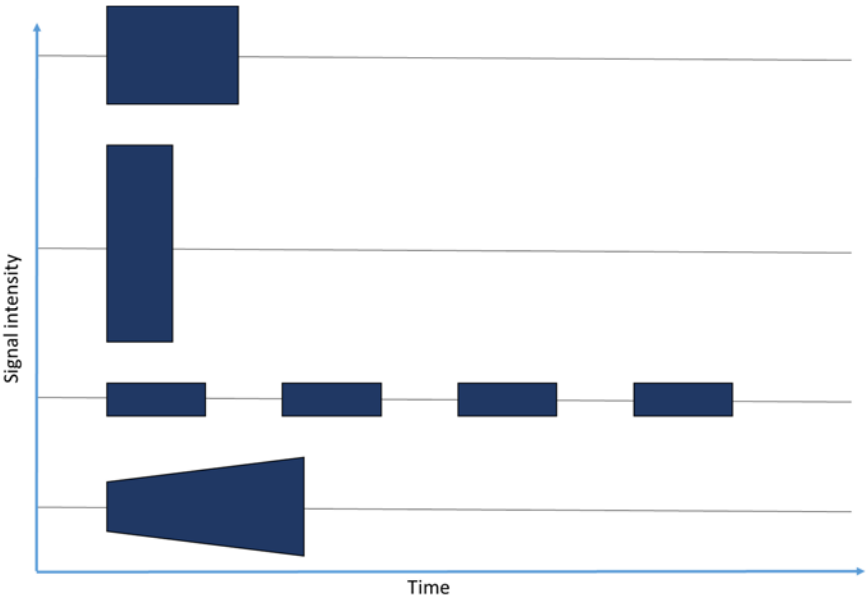


Figure 4.6. The equal energy hypothesis implies that all four examples of signals shown to the right have the same ability to induce TTS, as they are of equal energy (the areas of the four signals are the same).

The signal energy should be cumulated up to some upper limit. This limit is debated. In human audiometry it is customary to use 24 hours, in conjunction with the sensible assumption that people are often exposed to loud noise during their workday and then spend the night resting in a quiet place. This assumption is less relevant for marine mammals, but the 24 h maximum was also applied in a precautionary approach by Southall *et al.* (2007) and retained by National Marine Fisheries Service (2016), stressing that it is likely to be very conservative (in the sense that it leads to overprotection). An experiment with harbour porpoises (Kastelein *et al.* 2016) indicate that the integration time should be at least several hours. For pile driving it is thus reasonable to use the entire duration of a pile driving event (i.e. piling of one foundation), which may last several hours, but not include the time between installations, as the completely dominating source of acoustic energy is from the pile driving strikes. Also, as the turnaround time (time from start of pile driving at one foundation to start on the next foundation) is almost always more than 24 hours, the energy is not integrated from one foundation to the next.

4.3.4 TTS and PTS thresholds for harbour porpoises

At the time of completion of the review by Southall et al. (2008) no experimental data was available on TTS in harbour porpoises or any other HF-cetacean and a threshold had to be extrapolated from data on TTS in bottlenose dolphins and beluga whales. This has changed dramatically and harbour porpoise is now one of the best-studied species when it comes to TTS. See Finneran (2015) and Tougaard *et al.* (2015) for recent reviews.

A pivotal study is Lucke *et al.* (2009), which showed that TTS could be induced in a harbour porpoise by exposure to a single pulse from an airgun at a received unweighted (broadband) sound exposure level of 154 dB re. 1 µPa²s (see note[2]). This threshold has been the foundation of legislation regarding

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[2] There is some variation in this threshold, depending on authors and values between 152 and 155 can be found in different sources. The variation is due to different definitions of TTS-threshold, ranging from lowest level where a threshold elevation, no matter how small, can be reliably detected, to a more conservative definition of the

pile driving in for example Germany (German Federal Ministry for the Environment and Nuclear Safety 2013) and has thus been instrumental in driving the development of effective sound attenuation devices (see 4.6.2 below). However, not all authors are comfortable with extending a threshold derived from a single, loud pulse to a very long sequence of weaker, repeated pulses. A later study (Kastelein *et al.* 2015) thus measured TTS in a porpoise after exposure to a 1 hour sequence of pile driving pulses and reported a considerably higher threshold at 180 dB re. 1 µPa^{2}s, unweighted and cumulated over all pulses (SELcum). A range of experiments supports the conclusion that thresholds for single pulses, intermittent pulses / noise, and continuous noise cannot be compared directly and thus that the simple assumption that total noise SEL determines the TTS induced (the equal energy hypothesis described above) cannot explain all variation seen in experimental results. Other studies with longer sounds in the low frequency range (1-4 kHz; Kastelein *et al.* 2012, Kastelein *et al.* 2013b, Kastelein *et al.* 2014) have thus resulted in significantly higher thresholds than the threshold of Lucke *et al.* (2009). There is yet no full understanding of this difference between single, short impulses and longer signals, but it could be related to the recent demonstration of a rapid reduction in hearing sensitivity in dolphins after being conditioned to a loud noise by a warning signal (Nachtigall & Supin 2014). This could explain why the noise exposure experienced by the inner ear to a single transient noise could be significantly higher than to a longer noise or a repeated series of pulses, as the animal, upon perceiving the first part of the noise, consciously or unconsciously reduces the sensitivity of the ear. Functionally, this is to some degree equivalent to the stapedial reflex of terrestrial mammals, which contracts the stapedius muscle in the middle ear when a loud and potentially damaging sound is heard, but it is unknown how this mechanism works in cetaceans.

Another problem rooted in ignoring the repetitive pulses of a real pile driving, is the cumulative impact of many, closely spaced pulses. Finneran *et al.* (2010) showed in an experiment with single noise pulses, repeated noise pulses and continuous noise that the amount of TTS induced by repeated pulses is higher than the TTS caused by a single pulse, demonstrating that impact is accumulating across pulses (Figure 4.7). However, the TTS induced by the multiple pulses was less than the TTS induced by a continuous noise signal with the same total energy as the pulse train, demonstrating that there is some recovery from TTS between pulses, or that the sensitivity of the ear is reduced deliberately by the animal upon receiving the first few pulses.

Based on a comprehensive review of the entire literature on TTS and PTS in marine mammals, guidance on thresholds have recently been provided in the US (National Marine Fisheries Service 2016). All measurements of TTS in marine mammals were combined with all available information on auditory sensitivity in marine mammals (audiograms) to create appropriate frequency weighting curves and TTS-growth curves. An example of such a curve, based on data from porpoises, is shown in Figure 4.8.

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exposure required to elevate the threshold 6 dB above average baseline level. These differences are without practical significance.

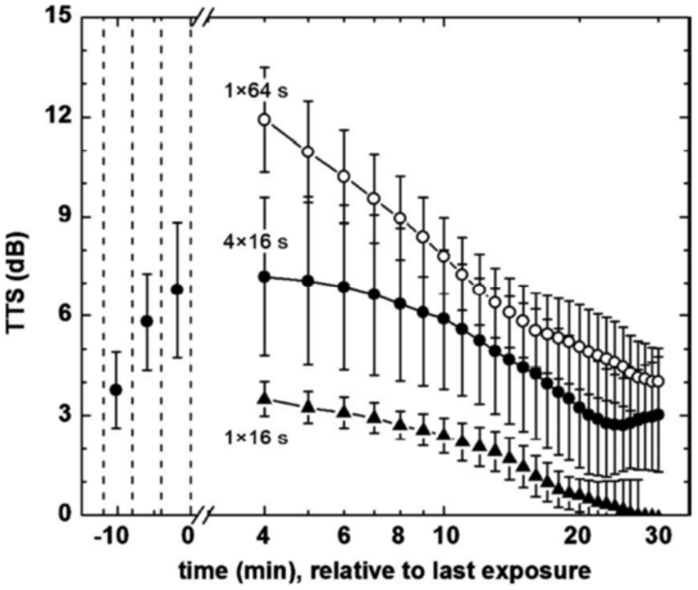

Figure 4.7. TTS in a bottlenose dolphin after exposure to either one 16 s pulse (triangles), four 16 s pulses (closed circles) or one 64 s pulse (open circles). From Finneran *et al.* (2010).

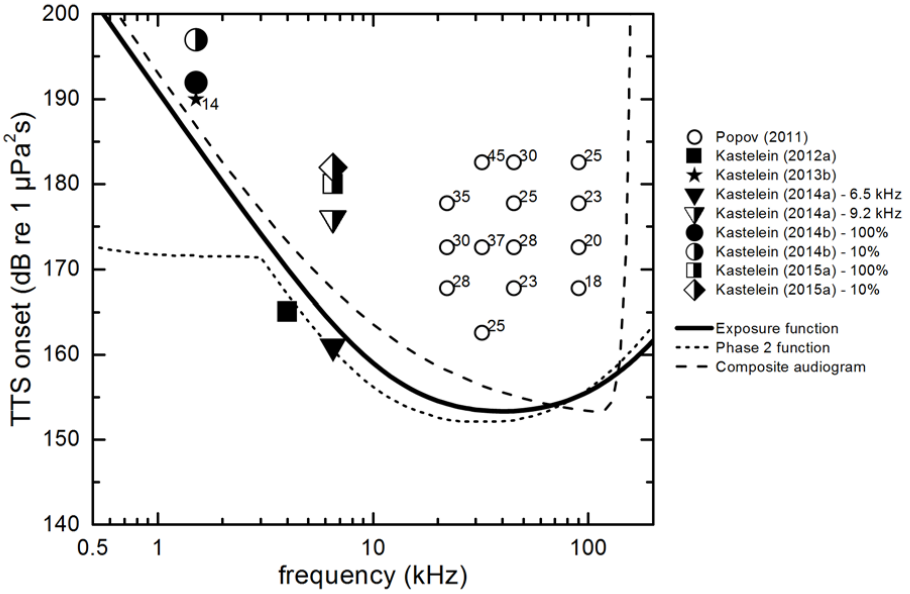

Figure 4.8. Results of all TTS studies conducted before 2016 with non-impulsive sounds on harbour porpoises. Open symbols were obtained with electrophysiolgical methods (ABR), closed and semi-closed symbols with behavioural methods. Numbers indicate the amount of TTS induced (in dB) for data points not representing thresholds. Solid line indicate the HF-cetacean weighting function. From National Marine Fisheries Service (2016).

Weighted onset TTS thresholds were derived for each species group for impulsive sounds and non-impulse sounds, respectively and from the TTS-growth functions onset PTS thresholds were estimated as the sound exposure level required to elicit 40 dB of TTS, which was considered indicative of a significantly increased risk of developing PTS. PTS thresholds were extrapolated from TTS thresholds by fitting TTS-growth curves (similar to the idealised curves shown in Figure 4.4) to the experimental data. Two different sets of thresholds were derived: one set for impulsive sounds (Based on the single data point by Lucke *et al.* 2009) and another for non-impulsive sounds based on the data shown in Figure 4.8. The distinction between impulsive and non-impulsive sounds relates to the observation also discussed above that a single, short and loud noise pulse may be more damaging than longer, continuous noise of the same sound exposure level. The distinction between impulsive and non-impulsive sounds is not clear, however. Typical characteristics of impulsive noise include short duration, broad frequency spectrum and most importantly a steep rise-time. Transients generated by underwater explosions clearly qualify as impulsive sounds, whereas it is debatable whether pile driving noise falls in one or the other category. Pile driving noise pulses are comparatively short, but do not have very steep rise times and although they contain energy at very high frequencies close to the source, they still have a pronounced low-frequency emphasis. Both sets of thresholds are given in Table 4.1. They are expressed as weighted and cumulated SEL over 24 hours ($L_{E,p,w,24\,h}$).

Table 4.1. Weighted thresholds for TTS and PTS for high-frequency hearing cetaceans, which includes harbour porpoises. From National Marine Fisheries Service (2016).

Type of noise	TTS-threshold	PTS-threshold
Impulsive noise	140 dB re. 1 µPa^{2}s	155 dB re. 1 µPa^{2}s
Non-impulsive noise	153 dB re. 1 µPa^{2}s	173 dB re. 1 µPa^{2}s

These thresholds are weighted and thus not directly comparable to the thresholds suggested by a recent Swedish review (Andersson *et al.* 2016). The suggested threshold for TTS in that review is 175 dB re. 1 µPa^{2}s, unweighted and is based on the work of a Danish working group (Skjellerup *et al.* 2015, Skjellerup & Tougaard 2016), who again based their recommendations on a precautionary interpretation of the results of Kastelein *et al.* (2015). This experiment, which was mentioned, but not included in the analysis presented by National Marine Fisheries Service (2016), measured TTS in porpoises induced by exposure to playback of real pile driving sounds for 1 hour at a total SEL of 180 dB re. 1 µPa^{2}s[3]. This level is unweighted and thus not directly comparable to the guidance thresholds reported by National Marine Fisheries Service (2016). However, Tougaard and Dähne (2017) derived a weighted level of the threshold from (Kastelein *et al.* 2015) (see Figure 4.9) of 140 dB re. 1 µPa^{2}s. This value happens to be identical to the TTS threshold for impulsive noise derived by National Marine Fisheries Service (2016) (Table 4.1), adding additional support to both the threshold value itself and the frequency weighting procedure. The thresholds of National Marine Fisheries Service (2016) (Table 4.1) were thus adapted for this assessment.

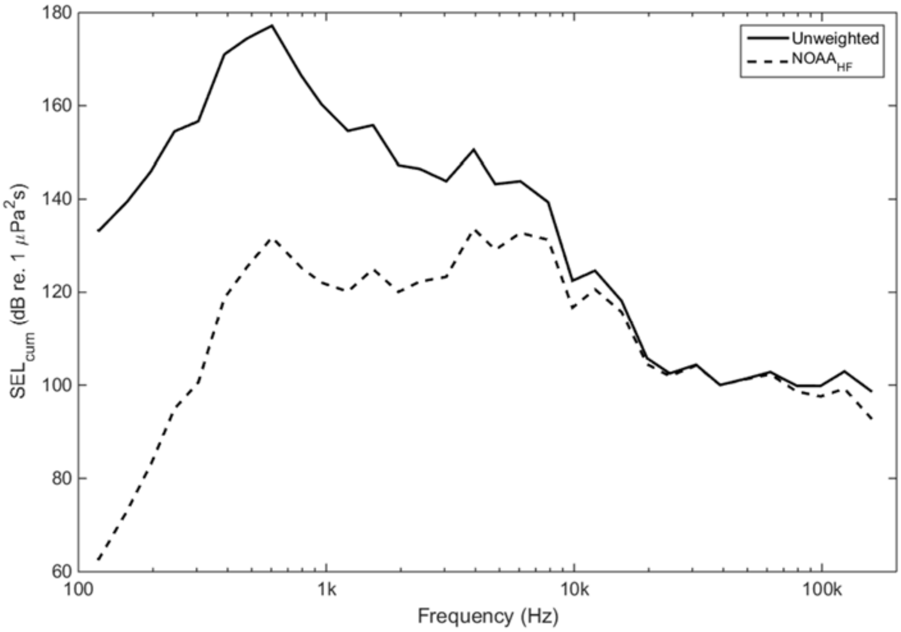

Figure 4.9. Third-octave spectrum of the stimulus used by Kastelein *et al.* (2015), adjusted to a total SELcum of 180 dB re. 1 µPa^{2}s (solid line) and the same spectrum weighted with the HF-cetacean weighting function of National Marine Fisheries Service (2016). Modified from Tougaard and Dähne (2017).

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[3] Cumulating acoustic energy across several pulses is commonly referred to as cumulated SEL, or SEL$_{cum}$.

4.3.5 TTS and PTS thresholds for seals

Southall et al. (2007) estimated TTS and PTS thresholds for seals in general, but these estimates were based on data from bottlenose dolphins, beluga and California sea lions. However, since 2007 actual measurements from harbour seals have become available.

PTS was induced due to an experimental error by Kastak *et al.* (2008), where a harbour seal was exposed to a 60 s tone at 4.1 kHz at a total SEL of 202 dB re. 1 µPa^{2}s. This means that an actual measurement is available. In fact, a second experiment (in a different facility and on a different animal) produced a very strong TTS (44 dB) by accident by exposure to 60 minutes of 4 kHz octave band noise at a SEL of 199 dB re. 1 µPa^{2}s (Kastelein *et al.* 2013a). The level of TTS is considered to have been very close to inducing PTS.

A number of experiments have determined TTS in harbour seals for various types of noise of shorter and longer duration, summarized by Finneran (2015) and evaluated by National Marine Fisheries Service (2016) with the same methods as described for porpoise thresholds. The guidelines recommend the thresholds given in Table 4.2, expressed as phocid-weighted cumulated SEL over maximum 24 hours. As for HF-cetaceans, two sets are available, one set for impulsive noise and one set for non-impulsive noise.

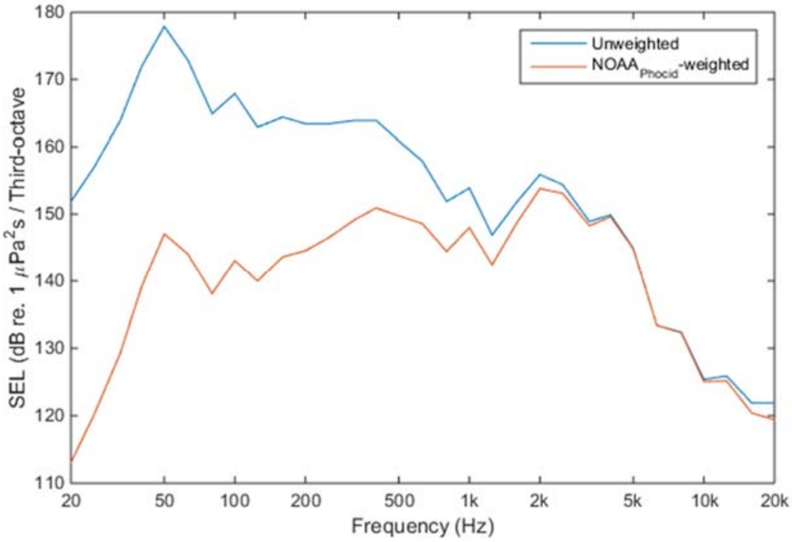
Table 4.2. Weighted thresholds for TTS and PTS in phocid seals. From National Marine Fisheries Service (2016).

Type of noise	TTS-threshold	PTS-threshold
Impulsive noise	170 dB	185 dB
Non-impulsive noise	181 dB	201 dB

Experiments on a ringed seal (*Pusa hispida*) and a spotted seal (*Phoca largha*) exposed them to air gun pulses at SEL up to a maximum of 181 dB re. 1 µPa^{2}s (unweighted), but did not induce TTS in any of the seals (Reichmuth *et al.* 2016). Figure 4.10 shows the third-octave spectrum of the most powerful air-gun signal used by Reichmuth *et al.* (2016), adjusted on the Y-axis to a total SEL of 181 dB re. 1 µPa^{2}s for the unweighted signal (obtained as the sum of all third-octave bins: $10\log_{10}(\sum 10^{L_{third-octave}/10})$). In the same way the $\mathrm{NOAA}_{\mathrm{phocid}}$-weighted SEL could be found as the sum of the weighted third-octave bins, equal to 162 dB re. 1 µPa^{2}s. This level, clearly below the threshold for TTS, is thus consistent with the impulsive noise threshold derived by National Marine Fisheries Service (2016) (Table 4.2).

There are no results available from grey seals and results from California sea lions (Finneran *et al.* 2003) are considered less likely to be representative for grey seals than the harbour seal data. Consequently, the results from harbour seals should be considered valid for grey seals, until actual data may become available.

Figure 4.10. Third-octave spectrum of the loudest airgun pulse used by Reichmuth *et al.* (2016), both as unweighted (blue) and NOAA$_{\text{phocid}}$-weighted (red).



4.3.6 Consequences of TTS and PTS for the animals

The long-term effects of various degrees of temporary or permanent hearing loss on survival and reproductive success of marine mammals is unknown. It is thus difficult to assess how these impacts may affect the population of seals and porpoises. Intuitively, as PTS is graded, there should be a lower level, below which the hearing loss is so small that it is without long-term consequences for the animal. This is supported by the observation that also dolphins seem to experience natural, age-related hearing loss (presybycusis; Ridgway & Carder 1997, Houser & Finneran 2006, Li *et al.* 2013). Large hearing losses, however, will inevitably affect the ability of the animal to carry out its normal range of behaviours and hence cause a decrease in fitness. Although this may not directly lead to the death of the individual, it may reduce the life span and reproductive success of the animal.

TTS and PTS primarily affects hearing around and immediately above the frequency range of the fatiguing noise. In a study with playback of pile driving sounds to harbour porpoises, the TTS developed at 4 kHz and 8 kHz, but not at 16 kHz or 128 kHz (Kastelein *et al.* 2015). This means that any TTS induced by pile driving is unlikely to affect the echolocation abilities of porpoises, but TTS could potentially affect detection ranges for communication sounds and acoustic cues from the environment. As seals use low frequency calls for communication (see for example Van Parijs *et al.* 2001, Sabinsky *et al.* 2017), the impact of permanent low-frequency hearing loss could potentially be larger in seals than in porpoises.

In general, however, there is very limited knowledge on the natural variation in hearing abilities of wild dolphins and seals (however, see Houser & Finneran 2006) and how hearing loss may affect the fitness of the animals.

4.4 Disturbance of behaviour

Permanent or temporary damage to marine mammal hearing may not necessarily be the most detrimental effect of noise. Noise levels below the TTS threshold may affect and alter the behaviour of animals, which can carry implications for the long-term survival and reproductive success of individual animals, and thereby ultimately on the population status (National Research Council 2003). See Figure 4.11. Effects can occur directly from severe reactions as for example panic or fleeing (negative phonotaxis), by which there is an increased risk of direct mortality due to for example bycatch in gill nets or separation of dependent calves from mothers. More common, however, is probably less severe effects where animals are displaced from habitats, or their foraging or mating behaviour disrupted due to noise (as demonstrated by Wisniewska *et al.* 2018).

However, at present, the knowledge about how immediate, short-term behavioural changes translate into population level effects is very incomplete and inference from exposures to population level is extremely difficult. Conceptually, it is not difficult to envision that the effect of repeated disturbances to animals will reduce the time available to whatever behaviours important for the short- and long-term survival of the animals, such as feeding, mating and nursing offspring. Quantifying these relationships can be very difficult, as the individual disturbance only in extreme cases will produce a measurable effect in itself. Separation between mother and dependent calf / pup with loss of the offspring as a result is one notable exception. Most of the time, the disturbance will likely only mean that a little less food is consumed, a little less milk transferred to the calf / pup, and perhaps loss of a mating opportunity. These impacts are cumulative, however, and repeated disturbances will therefore add up and at some point effects will become measurable. This has been referred to as the “death by a thousand cuts” (Todd 2016).

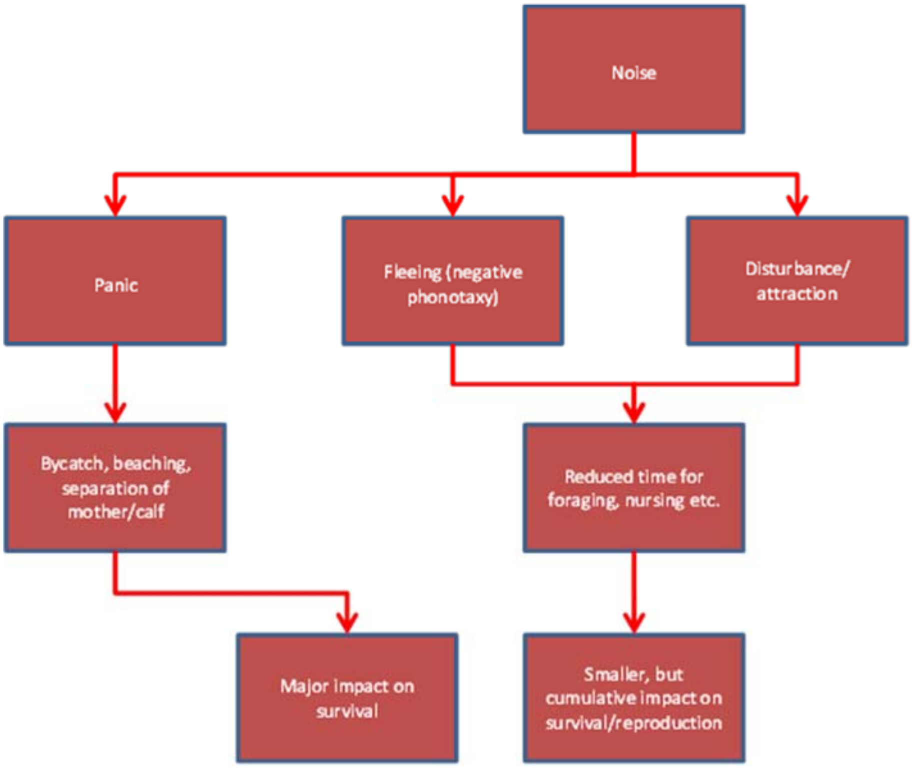


Figure 4.11. Schematic illustration of mechanisms by which noise-induced changes to behaviour can lead to effects on short-term and long-term survival and reproduction (fitness) in marine mammals. From Skjellerup et al. (2015).

Although quantitative models are under development to allow a better understanding of the link between behavioural disturbances and population developments, such as the agent-based DEPONS model for porpoises (Nabe-Nielsen *et al.* 2018), such models have not been developed for the waters and populations around Kriegers Flak. The limiting factor is the lack of accurate knowledge on the abundance and behaviour of marine mammals and details in their reaction towards acoustic disturbance. For the time being, we are thus limited to describing reaction thresholds and spatial and temporal extents of the zone of impact.

4.4.1 Behavioural effects of pile driving noise on porpoises

The reaction of porpoises to pile driving has been studied during construction of several wind farms. Initially all pilings were performed unattenuated, i.e. without any attenuation in the form of for example air bubble curtains (see section 4.6.2). Irrespective of the size of the monopiles, the results showed displacement and / or disturbance of the behaviour of porpoises out to distances of at least 20 km from the piling site (Tougaard *et al.* 2009a, Brandt *et al.* 2011, Dähne *et al.* 2013, Haelters *et al.* 2015). A single illustrative example, from the German wind farm Alpha Ventus, is shown in Figure 4.12.

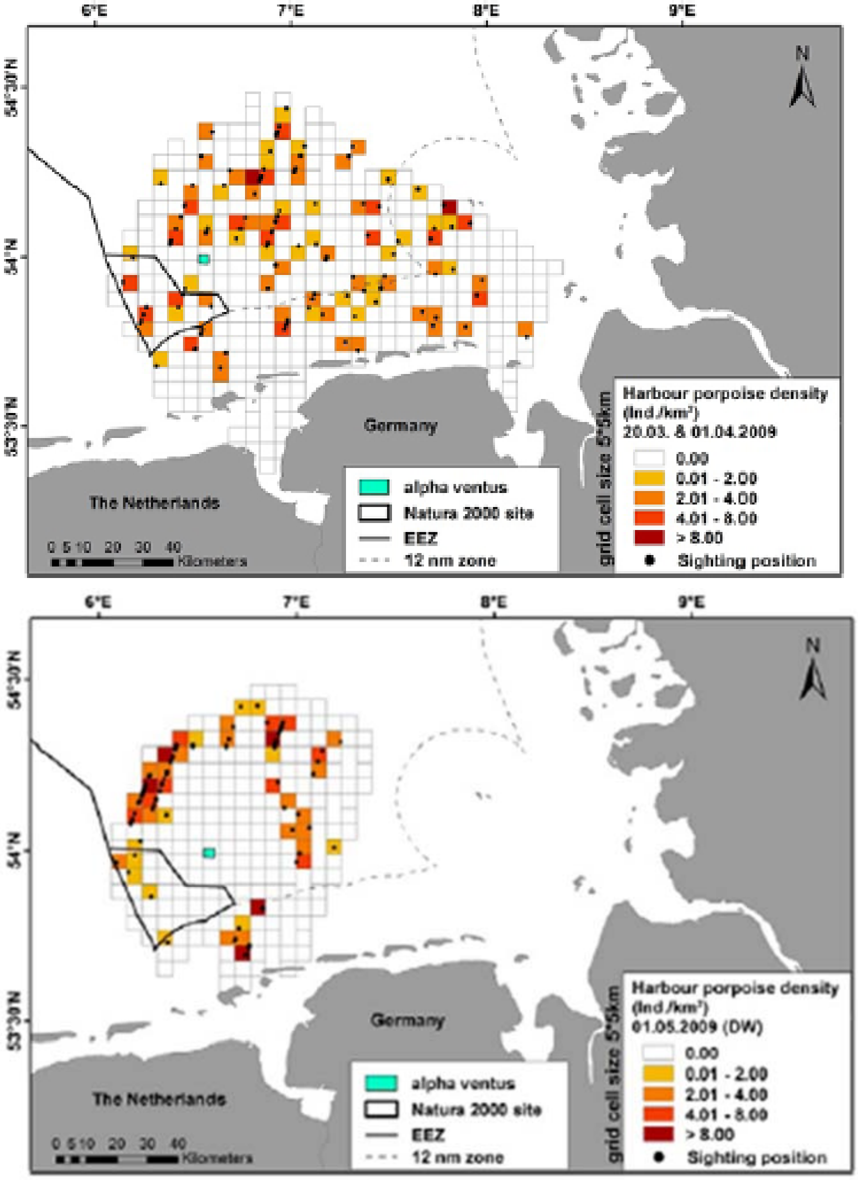


Figure 4.12. Porpoises observed from aerial survey before (top) and during (bottom) pile driving at the German offshore wind farm Alpha Ventus. The blue square indicates the position of pile driving operation. From Dähne *et al.* (2013).

Duration of the deterrence / disturbance appears to be in the range of some hours to at most a day after end of the pile driving (Brandt *et al.* 2011, Dähne *et al.* 2013, Brandt *et al.* 2018). Reaction thresholds for pile driving noise without use of bubble curtains (see 4.6.2 below) appears to be in the range of 140-145 dB re. 1 µPa^{2}s unweighted (Dähne *et al.* 2013).

4.4.2 Behavioural effects of pile driving noise on seals

Comparatively little is known about the reaction of seals to pile driving noise. Blackwell *et al.* (2004) studied the reaction of ringed seals (*Pusa hispida*) to pile driving on an artificial island in the arctic and saw limited reactions to the noise. In contrast to this are results from satellite tracked harbour seals, which showed aversive behaviour up to 25 km from the pile driving sites during pile driving (Russell *et al.* 2016). The latter study thus indicates roughly similar impact zones for seals and porpoises.

4.5 Masking

Masking is the phenomenon where noise can affect the ability of animals to detect and identify other sounds negatively. The masking noise must be audible, roughly coincide with (within tens of milliseconds), and have energy in roughly the same frequency band, as the masked sound. Even if these requirements are fulfilled, the animal has additional possibilities for obtaining what is known as “release from masking”. This covers a range of behavioural modifications and processing capabilities of the auditory system. In case of conspecific communication, the sender can increase the source level of the communication signal (known as the Lombard effect). The receiver can move away from the noise source and thereby reduce masking or simply orient itself so to receive the noise from a different direction than the signal it is trying to receive (spatial release from masking). See Erbe *et al.* (2016) for a current review.

Masking potential of pile driving noise has not been studied specifically; however, some preliminary conclusions can be drawn. Porpoises depend critically on their echolocation, but their echolocation clicks are in the extreme ultrasonic range, above 100 kHz, considerably above the range where pile driving noise is located. This means that it is very unlikely that pile driving noise would mask echolocation of porpoises.

Passive listening by both seals and porpoises could potentially be masked by pie driving noise. The duty cycle of pile driving is relatively low, around 5-10%, which leaves large gaps in between pulses, where signals can be detected (a process known as gap-listening). It is thus difficult to imagine a complete masking of passive listening by pile driving noise.

With respect to the consequences of masking of low-frequency passive hearing in seals and porpoises little can be concluded. Porpoises have poor hearing below a few kHz and it is unknown what they may use this low-frequency hearing for. Seals on the other hand use sound in the low-frequency range for communication and this could potentially be interfered with by the pile driving noise. However, harbour seals and grey seals are not known to vocalize outside the context of mating and this takes place close to the haul-out sites on shore. Pile driving occurring far offshore thus appears unlikely to have any potential to interfere with communication during mating displays.

4.6 Mitigation measures

If noise exposure is assessed to be above levels likely to result in significant impact on populations of marine mammals (see section 5, below) the impact can be reduced by different mitigation measures. In general, there are three different principles available to mitigate impact of noise, irrespective of the type of sound, not listed in any order of priority:

- Reduction of generated noise
- Reduction of radiated noise
- Reduction of noise received by humans / animals.

4.6.1 Reduction of generated noise

The first approach is to reduce the noise generated by the activity. If the impact is from percussive pile driving, such a reduction could potentially be achieved by modifications to the hydraulic hammer or the way the hammer is used, or it could involve a change to an entirely different type of foundation, such as using gravitational or suction bucket foundations, or modified installation methods, such as vibration or percussive pile driving with damping material between hammer and steel monopile. It is, however, beyond the scope of this report to discuss the feasibility (if any) of such measures for the present project and they are thus not considered in the following.

4.6.2 Reduction of radiated noise

Reduction in radiated noise can be achieved in different ways by placing different attenuating barriers around the monopile during pile driving. See for example Rodkin and Pommerenck (2014) for a comprehensive review. A particular type of shielding, air bubble curtains, has received extensive attention in relation to offshore pile driving and extensive experience about effectiveness is thus available. These experiences will be described in some details below, as an example of how radiated noise can be reduced.

Air bubble curtains are well known to provide effective attenuation of underwater noise (Würsig *et al.* 2000, Caltrans 2009, Lucke *et al.* 2011). Considerable effort, in particular in Germany, has gone into developing large-scale operational systems that can be used in deeper waters and on the very large diameter piles used for offshore wind turbines (Nehls & Bellmann 2016). Figure 4.13 shows an early example of such an air bubble system deployed around a pile driving rig.

Figure 4.13. Example of active bubble curtain deployed around the jack-up platform used for pile driving. Air bubbles are visible in the surface as the white ring. The ship in the background is used for deployment and recovery of the hose system and contains the very large compressors needed to feed the bubble curtain with compressed air.

An example of the effect of a bubble curtain (in three different configurations) on the frequency spectrum of the emitted noise pulses is shown in Figure 4.14. The attenuation is seen to be increasingly effective with increasing frequency, due to the smaller wavelength. As the peak frequency of pile driving noise is very low (160 Hz in the example) the effect of the bubble curtain is small on the broadband (unweighted) sound pressure level. However, if signals are weighted with appropriate frequency weighting curves (see 4.3.2), the effect becomes considerably larger (Figure 4.15). This is due to the lesser audibility of the lower frequencies to both seals and porpoises, which means that more weight is put into the higher, more audible parts of the frequency spectrum, which also happens to be the frequencies where the bubble curtain is most effective.

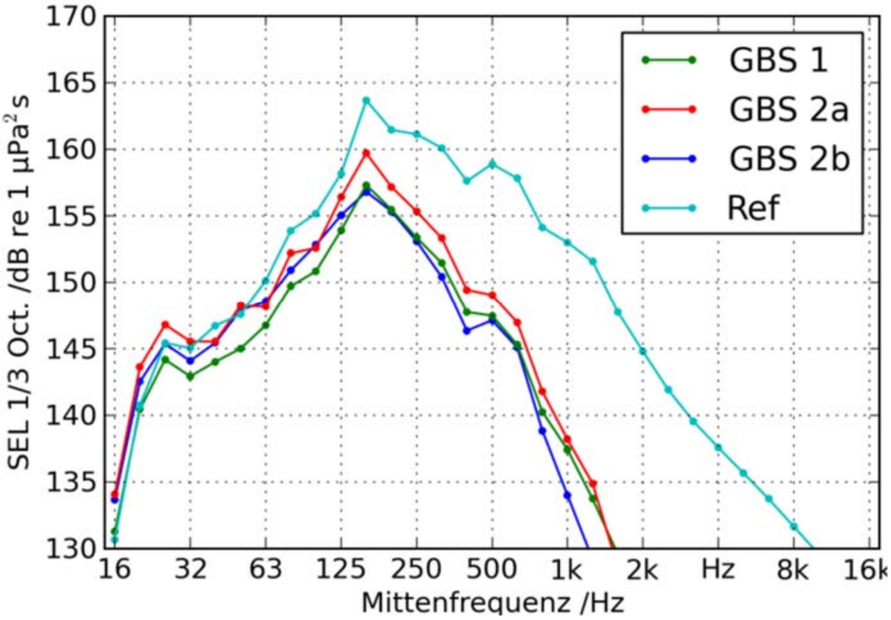


Figure 4.14. Median third-octave band spectra of pile driving noise measured 750 m from pile driving at the GlobalTech 1 offshore wind farm (tripod foundations). Spectra are shown without bubble curtain (Ref) and three different configurations of the bubble curtain. From Nehls and Bellmann (2016).

Figure 4.15 illustrates the difference between evaluation of the effect of bubble curtains on unweighted and weighted levels, respectively. The effect of the bubble curtain is the same in both cases: predominantly attenuating noise above 1 kHz, but in the unweighted spectra the overall level (sum of all third-octave bands) is affected very little, whereas there is a pronounced effect on the weighted spectra (2.3 dB vs. 25.9 dB, respectively; Tougaard & Dähne 2017). Note that due to the inherent logarithmic nature of the dB-scale, the sum of all third-octave bands is almost entirely dominated by the band with the highest level. The result is that the peak in the weighted spectra shifts from 4-5 kHz without bubble curtain to about 200 Hz with bubble curtain, whereas the peak in the unweighted spectra remains unchanged around 200 Hz.

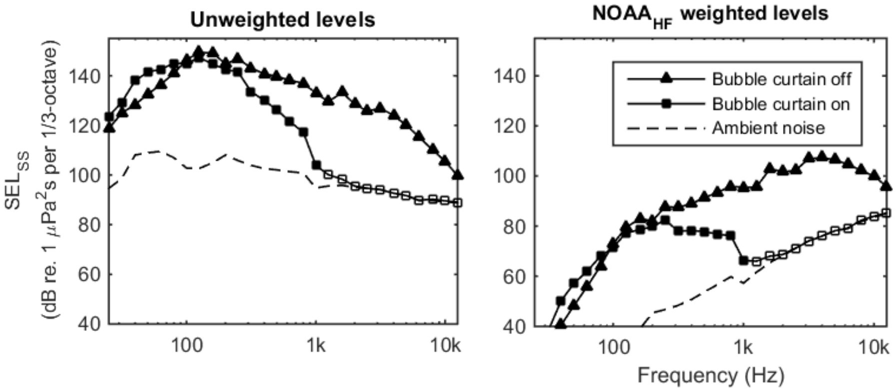


Figure 4.15. Effect of applying the HF-cetacean weighting curve (i.e. appropriate for porpoises) recommended by National Marine Fisheries Service (2016) to spectra of pile driving noise (6 m diameter monopile) with and without a double bubble curtain. Open symbols indicate levels dominated by ambient noise rather than pile driving noise. From DanTysk offshore wind farm (Tougaard & Dähne 2017).

4.6.3 Deterrence and other reduction at the receiver

The third approach, where noise is mitigated at the animals, includes methods and protocols to ensure that no (or very few) animals are present closer than some safety distance during noise exposure. This can be achieved very effectively in locations with a pronounced seasonal pattern in abundance, where noisy activities are placed only in those parts of the year where no (or very few) animals are around. This is likely the case for the critically endangered Baltic Proper population of harbour porpoises. The available data (described in 2.1.1 above) strongly suggests that most of the animals belonging to this population are in the central Baltic (and thus away from Kriegers Flak) in the summer months, whereas they may be encountered also around Kriegers Flak in the winter months. For the seals and the Belt Sea population of harbour porpoises such fortuitous fluctuations in abundance seems not to be present. Alternatively, for large species of whales, it may be possible to visually detect and track animals over large areas around the noise source and either postpone noisy activities, if they are about to start, or abort activities (if technically possible), whenever one or more whales are observed within some critical safety distance (see for example Bröker *et al.* 2015). Harbour porpoises and seals are extremely cryptic at sea and can be very difficult to observe at the surface if there are any kind of waves. Sighting rates of porpoises from a ship thus decreases dramatically when sea surface conditions goes from sea state 1 (only ripples on the surface) to sea state 2 (small wavelets, but still no white caps) (Teilmann 2003) and even under ideal conditions effective detection distances beyond a few hundred meters cannot be achieved from a vessel near the piling site. Passive acoustic monitoring of the echolocation sounds of porpoises is somewhat less affected by sea state, but effective detection distances are equally short, or even shorter than for visual observations (Kyhn *et al.* 2011). Visual and / or acoustic monitoring for porpoises or seals is thus not a reliable mitigation tool to reduce impact from pile driving.

Left is then the approach of actively deterring animals out beyond the safe distance prior to commencing pile driving at full force. This is usually accomplished by two different means: use of a soft-start or ramp-up of the piling sequence or deployment of a dedicated deterrent device.

Pile driving typically includes a shorter or longer soft start period, where a few blows are delivered at low hammer energy after which the pile may be aligned in the exact position and angle. Once the pile is properly in place, the main piling commences and unless problems are encountered, the piling will proceed with constant stroke intervals and gradually increasing hammer energy, as the pile penetrates the seabed and friction increases. The soft start is introduced solely for technical reasons but has the additional beneficial effect of deterring animals away from the piling site before the main piling begins, effectively reducing SEL_{cum} for the individual animal. The soft start sequence is typically very variable; sometimes only a few rapid blows are needed to get the pile in place for penetration but sometimes extensive realigning of the pile is required before the main piling can begin. This means that it can be difficult to model the soft start period. However, modelling the soft-start as a series of low-level strikes with constant strike rate, will lead to an overestimation of SEL_{cum} and is thus precautionary.

Because the soft start procedure can be difficult to plan in details beforehand and may sometimes be very short, it is typically recommended to supplement the soft start with an active deterrent device, most commonly in the form of a seal scarer. Seal scarers are powerful underwater sound emitters originally developed to keep seals away from fishing gear. They are effective in deterring seals out to distances of some hundred meters (see review by Mikkelsen *et al.* 2017b and section 6.4 below) and are even more effective in deterring harbour porpoises. Porpoises are effectively deterred out to at least 1300 m (Hermannsen *et al.* 2015, Mikkelsen *et al.* 2017a) and may affect porpoise behaviour as far away as 10-12 km (Dähne *et al.* 2017). This large zone of disturbance of the seal scarer for porpoises means that the seal scarer may constitute a non-trivial source of disturbance in itself (Dähne *et al.* 2017, Mikkelsen *et al.* 2017a) and should only be used to the extent it can aid in mitigating more serious effects, such as hearing loss (see 6.4.2).

5. Assessment methodology and criteria

This assessment evaluates impact on the four different populations of marine mammals in the area: harbour seals, grey seals, Belt Sea porpoises and Baltic Proper porpoises (see details in section 2) for each of the four acoustic impacts: acoustic trauma, hearing loss, behavioural disturbance and masking. Based on the description of likely designs of the wind farm a worst-case scenario is selected, based on the following criteria:

- Worst sound propagation conditions (bathymetry and hydrography)
- Worst location of foundation, based on sound propagation conditions and proximity to Natura2000 areas
- Most sensitive period of the year for the animals
- Worst case foundation type and installation procedure (hammer energy and number of strikes required to complete piling)
- Worst case regarding mitigation, i.e. no further mitigation measures beyond use of deterrent device (seal scarer, see 4.6.3) and soft-start procedure.

An additional construction scenario is included. This scenario is identical to the worst-case scenario, except that a bubble curtain with attenuating properties similar to the bubble curtain described in general in section 4.6.2. and in details in section 6.2.1 and appendix 1, is used in modelling of sound exposure. This scenario is included as an example of the currently best available technology for reducing impact of pile driving.

The impact of the different scenarios on the different marine mammal populations is assessed based on the criteria listed in Table 5.1.

Table 5.1. Classification of the magnitude of impact, based on impact on individuals and the population.

Impact magnitude	Description
Negligible	Possible short-duration, but insignificant impact on individual animals, without long-term consequences for the population
Minor	Insignificant impact on individuals, unlikely to have any negative consequences for the long time development of the population
Moderate	Significant, but non-lethal impact on individuals, unlikely to have negative consequences for the long time development of the population
Major	Significant impact on the population, likely to have negative consequences for the long time development of the population, or potentially lethal impact on individuals

The population conservation status must be factored into the assessment. Any impact on an animal belonging to a critically endangered population (such as the Baltic Proper porpoises), which is considered to have significant impact on the survival and reproductive success of that individual, must be considered a significant impact on the population. Contrary, a population in favourable status (or in rapid development towards it), such as grey seals, can accommodate considerable impact on individuals without any long-term consequences for the development of the population.

Criteria and assessment methodology for the four different impacts are listed below.

5.1 Acoustic trauma

The exposure thresholds suggested for human divers (Lance *et al.* 2015) are considered applicable and precautionary for marine mammals, based on the fact that the size of the animals and in particular the volume of their lungs, are comparable to humans. Thus, exposure to an impulsive sound with an acoustic impulse above 30 Pa· s, or a corresponding peak pressure of at least 226 dB re 1 μPa is considered unwanted, as this exposure level is associated with a 10% risk of (survivable) tissue damage (Lance *et al.* 2015).

As peak pressures are notoriously difficult to model accurately for complex sound sources, such as a very long and large diameter steel monopile, the peak pressure is estimated by extrapolation from actual measurements from pile driving in other wind farms.

5.2 Hearing loss

As described in section 4.3.6 very little is known about the consequences (both short-term and long term) of hearing loss in the low-frequency range relevant for impact from pile driving noise. Some preliminary conclusions can be derived, however:

- The sonar of porpoises is unlikely to be affected by TTS or even PTS, as the frequency range of the TTS / PTS is well below the frequency range used for echolocation (Kastelein *et al.* 2015).
- The possible energetic consequences for seals and porpoises of small amounts of TTS (less than 40 dB) in the frequency range below 10 kHz are considered insignificant, as the duration of the impact is low (less than an hour, Popov *et al.* 2011).

For these reasons, a criterion for assessment based on PTS is adopted. Thus, noise exposure resulting in less than 40 dB of TTS is considered to have insignificant consequences for the survival, reproduction and energetic budget of both porpoises and seals. Exposure to noise at levels likely to induce 40 dB or more of TTS is considered to carry an increased risk of inducing PTS in the animals. This criterion is likely to be very precautionary, as no consequences of small amounts of low frequency PTS has been demonstrated or plausible mechanisms though which such consequences could arise, have been suggested. In line with recommendations of National Marine Fisheries Service (2016) the exposure limits in Table 5.2 were adopted.

Table 5.2. Adopted exposure limits for hearing loss, defined as the threshold for inducing PTS in seals and porpoises.

Species	PTS Threshold	Comments
Harbour porpoise	155 dB re 1 μPa^{2}s	HF-cetacean-weighted
Harbour seal	185 dB re 1 μPa^{2}s	Phocid seal-weighted
Grey seal	185 dB re 1 μPa^{2}s	Phocid seal-weighted

Both seal and porpoise exposure limits are the lowest (most precautionary) PTS thresholds suggested by National Marine Fisheries Service (2016), i.e. the thresholds applicable to impulsive noise.

These thresholds are derived in slightly different ways than thresholds recommended by Andersson *et al.* (2016) and numerically different due to the absence of frequency weighting on the thresholds of Andersson *et al.* (2016). Recommendations of Andersson *et al.* (2016) with respect to hearing loss are largely based on Skjellerup *et al.* (2015). Frequency weighting were anticipated, but not included in the recommendations of Skjellerup *et al.* (2015), largely because of lack of consensus on how the frequency weighting should be performed. This has changed dramatically with the very thorough review of the National Marine Fisheries Service (2016), which included public hearing and subsequent review and it thus seems inappropriate to continue with thresholds based on unweighted levels.

The method for estimating the cumulated sound exposure level follows the recommendations of Skjellerup *et al.* (2015) with the exception that auditory frequency weighting is adopted (following National Marine Fisheries Service 2016). SELcum is thus modelled over the time a complete pile driving of one monopile is estimated to take, and taking into account that the exposed animals will flee from the noise during piling. The accumulation of acoustic energy over the duration of the pile driving, which typically lasts several hours, is a deviation from the recommendations of the National Marine Fisheries Service (2016), where 24 hours is recommended. Limiting the accumulation period to the pile driving itself (including soft-start) simplifies calculations, as no knowledge about other noise sources is required and as these other sources (most importantly ship noise) are energetically insignificant in relation to the energy radiated in the pile driving noise, the error committed by excluding these sources is negligible.

Should a worst case scenario result in exceedance of the exposure limits described above, the attenuation in radiated noise from the source required to bring exposure below exposure limits is calculated, in accordance with recommendations of Skjellerup *et al.* (2015). Another modelling, exemplifying source radiation reduction by means of currently best practice, is then conducted and animal exposures under this revised scenario is compared to exposure limits and impact assessed.

5.3 Behavioural disturbance

The comprehensive review of Southall *et al.* (2007) suggested a “response severity scale”, which was intended to classify and rank the severity of behavioural reactions to underwater sounds. The scale was based on immediate reactions, however, which means that the long-term consequences (e.g. metabolic cost) of the disturbance was not factored in, which makes the scale less useful in assessing long-term impact (Tougaard *et al.* 2015). The scale has also been criticised for not taking behavioural context into account, reflecting the fact that it is of importance what behaviour is interrupted by the sound (Ellison *et al.* 2011). Instead, the criteria listed in Table 5.3 were developed, in order to classify the magnitude of the impact at the scale of the (local) population of animals.

Table 5.3. Criteria for assessing intensity of behavioural disturbance from pile driving noise.

Impact magnitude	Criteria/conditions
Negligible	Number of animals affected insignificant and/or disturbances very short (such as startle responses), without any significant effect on the time budget of animals
Minor	Disturbance of small parts of the available habitat over short periods of time, unlikely to significantly affect the available habitat and hence energy budget of animals.
Moderate	Significant disturbance of considerable parts of the available habitat and/or over extended time periods, effectively reducing the available habitat and hence energy budget of a significant number of animals,
Major	Extensive disturbance of large areas and long time, effectively reducing the available habitat and hence energy budget of a significant number of animals, sufficient to affect reproductive success and survival.

The key to assessing magnitude of the impact is a judgement of the possible energetic consequences (additional energy expenditure and reduced food intake) of the disturbance and the likelihood that these would be reflected in significant changes to vital parameters (survival and fecundity).

5.4 Masking

Impact from masking is very difficult to assess. Continuous noise can be assessed through the concept of the range reduction factor, which is a dimensionless ratio of the maximum communication range under conditions masked by anthropogenic noise and under natural ambient noise conditions (Møhl 1981). Adaptation of this concept has not been done by anyone for impulsive noise and no other usable frameworks for assessment of masking from impulsive noise are available. Assessment has thus been performed by means of more descriptive, qualitative measures, as listed in Table 5.4. By factoring in the fraction of a population affected and its conservation status, the intensity can be translated into the impact magnitudes in Table 5.1. Thus, a small masking intensity, but affecting a large fraction of a vulnerable population can translate into a moderate or even major impact. Similarly, even a large masking intensity, but affecting only a small fraction of a population in good conservation status can translate into a minor population impact.

Table 5.4. Criteria for assessing intensity of masking by pile driving noise.

Intensity	Criteria/conditions
Insignificant	Lack of overlap in frequency between masking noise and the signals potentially masked and/or noise only rarely above natural ambient at location of animals
Small	Overlap in frequency between masking noise and signals potentially masked, but noise only above natural ambient at location of animals for short periods of time.
Medium	Overlap in frequency between masking noise and signals potentially masked. Noise above natural ambient at location of animals for longer periods of time and considered able to reduce communication/detection range of important signals significantly.
Large	Overlap in frequency between masking noise and signals potentially masked. Noise likely to reduce communication/detection range of important signals over extended periods of time and to a degree where normal behaviour of the animals are significantly affected.

6. Noise exposure model

The core of the assessment framework is an exposure model, aimed at quantifying the exposure to individual marine mammals during pile driving in a way that considers key factors. These factors include properties of the sound source, mitigation measures such as soft start and use of deterrent devices such as seal scarers, sound transmission properties of the environment, evasive behaviour by the animals and the thresholds for developing PTS.

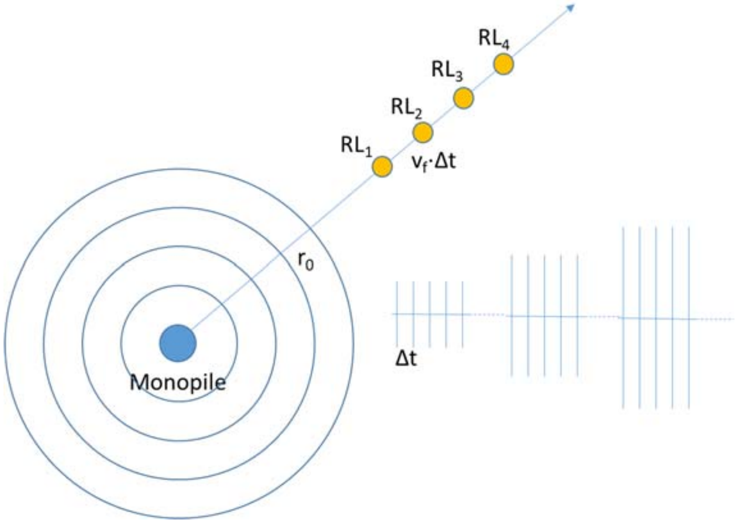


Figure 6.1. Schematic top view of model of noise exposure to a marine mammal. The animal is at distance r0 at the time of the first piling strike and receives a series of pulses with decreasing level (RL), as it moves away with a constant speed v_f. The source level of pulses increases with time, consistent with a soft start scenario.

6.1 Cumulated sound exposure level

The aim of the exposure model is to estimate the total acoustic energy, or cumulated sound exposure level (SEL_{cum}) that an animal has been exposed to at the end of a pile driving. This cumulated sound exposure level is the sum of the energy of the individual pile driving pulses, E_i, at the position where the animal is at corresponding time t_i.

Equation 6.1

$$SEL_{cum} = 10 \log_{10} \frac{\sum E_i}{E_0}$$

Where E_0 is the reference energy level (1 µPa²s).

The received energy E_i for an animal at distance r_i from the pile at the time of the i'th pulse can be found from the source energy level at 1 m of the i'th pulse (SL_i) minus the transmission loss (TL):

Equation 6.2

$$E_i = SL_i - TL(r_i)$$

SL_i is the source energy level at 1 m given in dB re 1 µPa²s.

Combining Equation 6.1 and Equation 6.2 gives the SEL_{cum} after reception of the N'th pile driving pulse:

Equation 6.3

$$SEL_{cum}(N) = 10 \log_{10} \sum_{i=1}^{N} 10^{\frac{SL_i - TL(r_i)}{10}}$$

6.2 Source level

If the source level emitted during piling can be assumed to scale directly with the energy delivered to the monopile by the hammer, then SL_i can be found from the maximum source energy level (SL_{max}) at maximum hammer impact energy and the actual hammer energy of the i'th stroke, S_i.

Equation 6.4

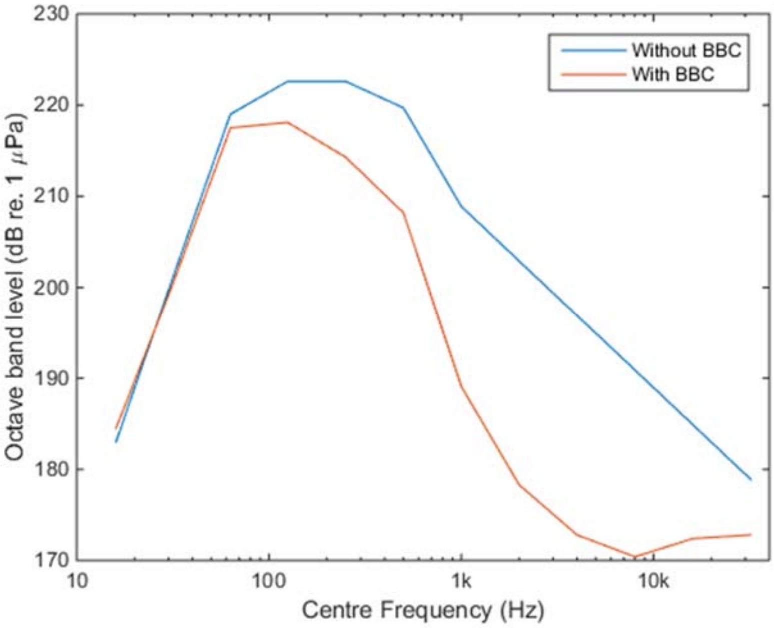
$$SL_i = SL_{max} + 10\log_{10}\frac{S_i}{100\%}$$

A realistic scenario for a pile driving operation is thus needed. This means that an entire sequence of piling strikes with time of occurrence and hammer energy is required. As mentioned in 4.6.3 above, the soft start sequence can be very variable; sometimes only a few rapid blows are needed to get the pile in place for penetration but sometimes extensive realigning of the pile is required before the main sequence can begin. This means that it can be difficult to model the duration of the soft start. However, modelling the soft start as a series of low-level strikes with constant strike rate will likely lead to an overestimation of SEL_{cum} and is thus precautionary.

6.2.1 Source specification at maximum hammer energy

Modelling was performed for two different types of piles: 4 m diameter pin piles for jacket foundations and 15 m diameter piles for monopile foundations. Source levels and spectra were estimated and extrapolated from recordings from a number of pile drivings in the North Sea, as described in Appendix 1. Based on these figures the piling of 15 m diameter monopiles is considered to represent a worst case scenario and this scenario was retained for the impact modelling. Maximum hammer energy is set to 5000 kJ per strike. The estimated source spectrum at maximum hammer energy is shown in Figure 6.2 and broadband (unweighted) source level (SL_{max}) estimated to be 227.4 dB re. 1 μPa^2s. As an illustration of a piling scenario where mitigation in the form of a reduction in radiated noise is employed, a propagation model was also conducted with a source spectrum and level estimated to be representative of piling with an air bubble curtain in place. The source spectrum for maximum hammer energy is also shown in Figure 6.2. SL_{max} unweighted with a bubble curtain in place and used in the propagation modelling was 221.9 dB re. 1 μPa^2s.

Figure 6.2. Source spectra used for modelling of sound transmission from 15 m monopile, both for the scenario without (blue) and with (red) use of a bubble curtain to attenuate the noise.



6.2.2 Pile driving scenario

The following sequence of hammer energy (S_i in Equation 6.4) was used:

Soft start phase (20 minutes)
- 300 pile strikes at 10% hammer energy (750 kJ) and strike rate of 15 / min.

Ramp-up phase (40 minutes)
- 150 pile strikes at 20% Hammer energy (1000 kJ) and strike rate of 15 / min
- 150 pile strikes at 40% Hammer energy (2000 kJ) and strike rate of 15 / min
- 150 pile strikes at 60% Hammer energy (3000 kJ) and strike rate of 15 / min
- 150 pile strikes at 80% Hammer energy (4000 kJ) and strike rate of 15 / min.

Full hammer energy phase (3.5 hours)
- 6300 pile strikes at 100% Hammer energy (5000 kJ) and strike rate of 30 / min.

This pile driving scenario has a total duration of 4.5 hours.

6.3 Transmission loss

Transmission loss can be modelled in different ways, ranging from a proper modelling based on bathymetry, hydrography and sediment properties to heuristic models based on actual measurements under conditions comparable to the project under assessment. Simple, heuristic models have the advantage of being transparent, which is a desirable feature in relation to an impact assessment. A key purpose of impact assessments is to allow not only authorities but also independent experts to judge the methods used in the assessment. This transparency can also be achieved by using well documented and open source modelling tools, but is compromised if modelling is performed by proprietary modelling tools. It is thus a fair demand for modelling within the context of an EIA that sufficient details about modelling methodology and input variables are supplied to allow others to verify the modelling results and compare these to results from alternative modelling methods.

When it comes to pile driving in shallow waters, there is considerable evidence that pile driving noise follows a rather simple transmission loss model. See for example Bailey *et al.* (2010) and Nehls and Bellmann (2016). A generalised model can be realised with two constants specific to the construction site, κ and α:

Equation 6.5

$$\boldsymbol{TL(r) = \kappa \log_{10} r + \alpha r}$$

κ expresses the slope of the geometric spreading loss and α is the volume absorption coefficient.

Sound exposure for the exposure assessment was modelled for two selected positions and followed two steps. First step was a proper modelling of sound propagation of pile driving noise by means of appropriate software packages (dBSea version 2.2.4, developed by Marshall Day Acoustics, see (Pedersen & Keane 2016)). This modelling is described in detail in Appendix 1, and resulted in maps of iso-sound pressure level contours in all directions around the modelled pile driving (Figure 6.3). From these maps worst case scenarios were picked, i.e. directions where sound propagates furthest out from the pile driving and these modelled sound levels are then approximated by Equation 6.5. Sound exposure can thus enter the exposure model in a simple way through the three variables SL, κ and α, which were fitted to the noise modelling results of each modelling scenario.

An example of a modelled noise map is shown in Figure 6.3. All modelled maps for combinations of two pile driving positions (on the shallow part of Kriegers Flak and in the deep part, directly facing the Natura2000 area), two seasons (January and July), and three different frequency weightings (unweighted, HF-cetacean and Phocid seals) are shown in Appendix 2.

Ambient noise (both natural and man-made) has not been included in the modelling of pile driving noise. Ultimately, the extent of the pile driving noise will be limited by the ambient noise, but this noise is expected to be at least 20 dB below the 150 dB re. 1 µPa²s contour, which was the lowest level included in the modelled maps (as exemplified in **Figure 6.3**). Ambient noise levels in the region are considered further below in section 9.1, in connection with noise from operational turbines.

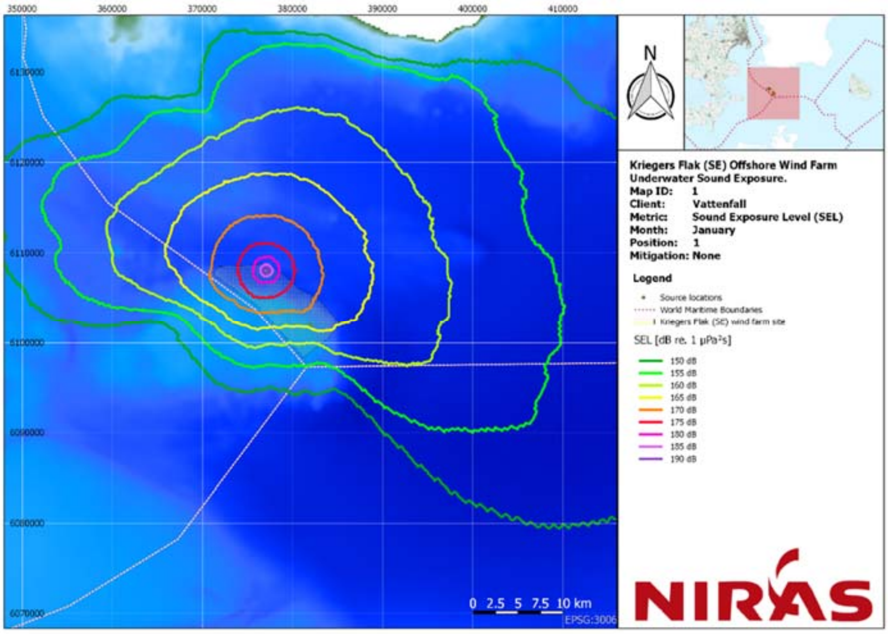
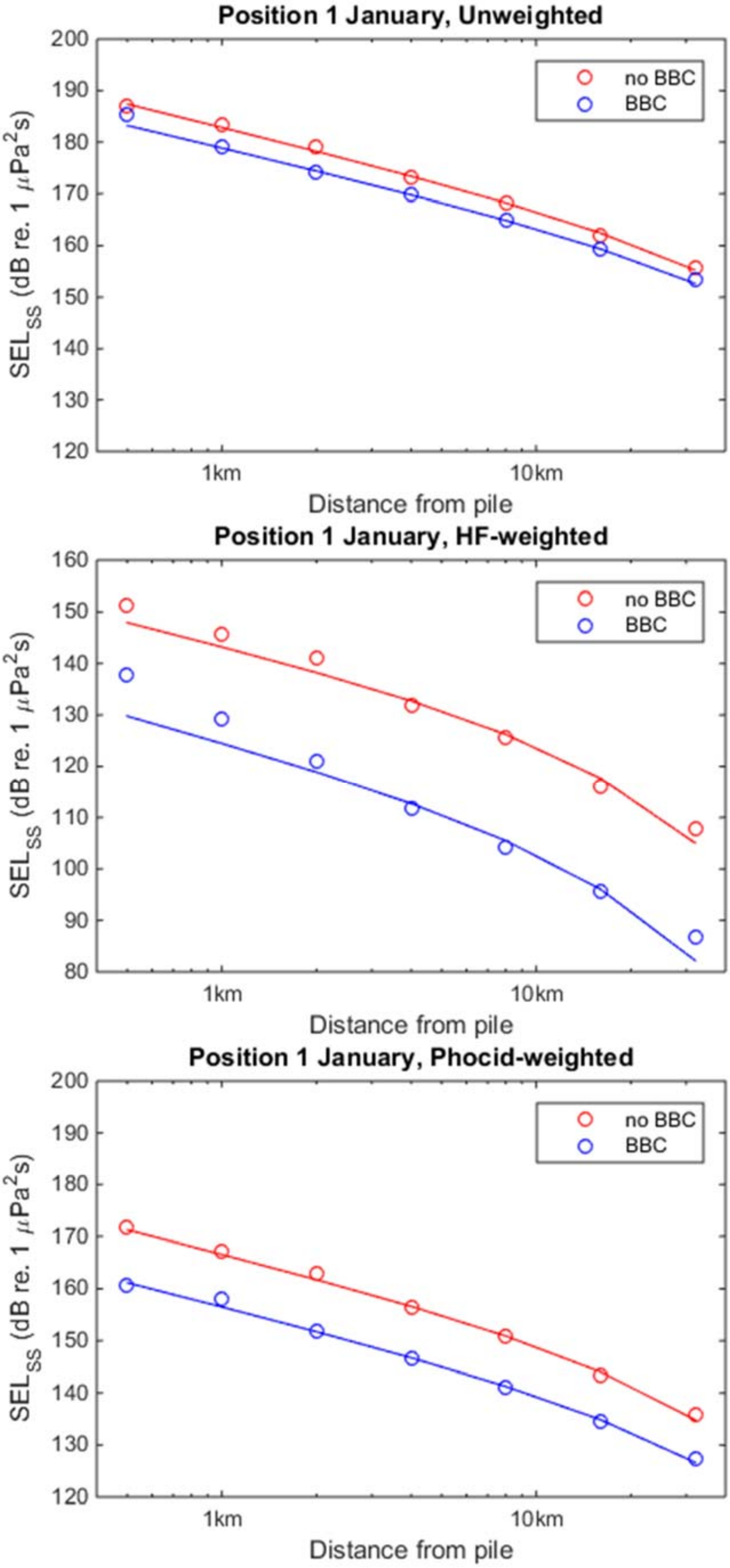


Figure 6.3. Unweighted underwater noise modelling results for position 1 in January, where colour coded contours in 5 dB steps show the Sound Exposure Level.

Transmission loss curves for the worst case scenario (the direction where loss was smallest) were estimated by Equation 6.5. Worst case scenarios (deep pile driving position, January) are shown in Figure 6.4. All fitted curves are shown and all fitted parameters listed in Appendix 3.

Figure 6.4. Modelled (worst case) transmission loss curves for the unweighted, HF-cetacean weighted and phocid weighted levels generated by pile driving of a 15 m diameter monopile. Results of modelling with and without use of a bubble curtain (BBC) is shown.



6.4 Deterrence of animals

An important element of the model is the incorporation of animal responsive movement to the pile driving sound. If the animal moves away from the pile driving site the received noise will (on average) go down and hence reduce the overall sound exposure to the animal. For small cetaceans there is ample evidence that they respond by moving away from loud noise sources (Johnston 2002, Olesiuk *et al.* 2002, Brandt *et al.* 2012, Tougaard *et al.* 2012). The reaction to pile driving noise has been documented in several studies (Tougaard *et al.* 2009a, Brandt *et al.* 2011, Dähne *et al.* 2013) and all are consistent with porpoises moving out to distances of tens of kms from pile driving sites during piling. If a constant speed of fleeing away from the source, v_f is assumed then the distance r_i at time of the i'th pulse is:

Equation 6.6

$$r_i = \begin{cases} \boldsymbol{r_0 + v_f(t_i - t_0)\ for\ t_i \le \frac{r_{max} - r_0}{v_f} + t_0} \\ \boldsymbol{r_{max}\ for\ t_i > \frac{r_{max} - r_0}{v_f} + t_0} \end{cases}$$

Where r_0 is the distance of the animal at t_0, start of the piling, t_i is the time of the i'th pulse and r_{max} is the maximum distance, beyond which animals no longer move away from the noise. Combining Equation 6.6 with the transmission loss model (Equation 6.5) gives the following expression for transmission loss of the i'th pulse:

Equation 6.7

$$\boldsymbol{TL_i = \kappa \log_{10} r_i + \alpha r_i = \kappa \log_{10}\big(r_0 + v_f(t_i - t_0)\big) + \alpha\big(r_0 + v_f(t_i - t_0)\big)}$$

Equation 6.2, Equation 6.4 and Equation 6.7 can be integrated into one equation expressing the cumulated noise exposure level (SEL_{cum}) experienced by an animal after N blows of the piling sequence.

Equation 6.8

$$\boldsymbol{SEL_{cum}(N) = 10 \log_{10} \sum_{i=1}^{N} 10^{\frac{SL_{max} + 10 \log_{10} \frac{S_i}{100\%} - \kappa \log_{10}(r_i) - \alpha r_i}{10}}}$$

where r_i is given by Equation 6.6. For a given piling scenario where SL_{max} and SL_i are specified and a given location where sound transmission is known (constants κ and α) the sound exposure level experienced by an animal at the end of a pile driving operation will be determined by the distance from the pile at start, r_0 and the flee speed v_f. All else being equal, the closer the animal is at start and the slower the animal moves away, the larger the cumulated sound exposure.

Equation 6.8 is the core of the model. As inputs are required a source energy level at maximum hammer energy (SL_{max}), a transmission loss model (given by the parameters α and κ), a sequence of pile driving strikes, each represented by their hammer energy (S_i) and a starting distance, r_0, and flee speed of the animal, v_f. Output of the model is the cumulated SEL experienced by this particular animal at the end of the pile driving sequence, corresponding to the complete piling of one foundation. This SEL_{cum} can then be compared to the thresholds for TTS and PTS, respectively (sections 4.3.4 and 0 above), by which it can be judged whether the animal would be likely to experience TTS / PTS or not.

The key features of the model is transparency and flexibility. The method for computing SEL_{cum} remains constant but the input elements can be replaced to fit a particular piling project and updated as newer and better information becomes available.

The assumptions underlying derivation of source parameters and transmission loss are described in details in Appendix 1, whereas the flee velocity and start distance are discussed in the following.

6.4.1 Flee velocity, v_f

A critical parameter in the modelling is the speed at which animals are assumed to flee from the sound source. This has not been measured directly, but various measures of sustained swimming speed in porpoises and other odontocetes are available.

(Kastelein *et al.* 2018) measured the swimming speed of a porpoise in a small tank during 30 minutes of exposure to pile driving sound. During this period the average swimming speed of the porpoise was 7.1 km/h, equal to 2 m/s. The experimental conditions were very unlike a real pile driving in the sense that the animal could only swim in circles in the 10x12 m pool and thus never managed to distance itself from the sound source. Nevertheless, it shows that porpoises are capable of a sustained swimming speed of 2 m/s for at least 30 minutes. (Otani *et al.* 2000) measured swimming speed on an unrestrained, wild porpoise over a period of 23 hours, during which the animal was undisturbed. The average swimming speed was 0.9 m/s and maximum speed 4.3 m/s. In contrast to the study of (Kastelein *et al.* 2018) the animals were undisturbed and measurements are thus likely to be in the low end of what the animals are capable of if actively fleeing from a disturbing sound.

Other species of odontocetes are capable of considerable sustained speeds. (Lockyer & Morris 1987) measured maximum swimming speeds in bottlenose dolphins over short periods of about 4 m/s, going down to about 1 m/s for a single observation of sustained swimming over 20 minutes. Killer whales are easily capable of sustained average swim speeds of 1.6 m/s (Williams & Noren 2009), despite their much larger size. Overall, it seems a precautionary assumption that porpoises can sustain a swimming speed for an extended period of 1.5 m/s, roughly corresponding to one body length per second. Even if the swimming speed decreases after some tens of minutes the animal will by then be so far away that the decrease in speed will have very little effect on the total modelled sound exposure (as discussed in section 7.1 below).

Few data are available on swimming speed of seals. A single study on grey seals, however, is fully consistent with 1.5 m/s as also being a reasonable, precautionary estimate for seals (Gallon *et al.* 2007).

6.4.2 Distance at first exposure, r_0

Considerable effort has gone into estimating the minimum deterrence distance of seal scarers and other deterrence devices, used to deter animals away from the vicinity of a monopile before pile driving begins. A review of the literature on effects on harbour porpoises (Hermannsen *et al.* 2015) indicated that some seal scarers were more effective than others were. The most effective of the studied seal scarers was the Lofitech device, which appeared to be able to deter porpoises out to at least 1300 m range. Thus, this distance was used in the exposure modelling.

A similar review (Mikkelsen *et al.* 2015) on the effect of seal scarers on seals revealed mixed results. The most important factor was context. Thus, if seal scarers were used in connection with fishing gear, the effect was often limited, and sometimes even attraction (Königson *et al.* 2007). However, if used solely for deterrence (i.e. without a reward in the form of fish in the fishing gear) the Lofitech device was more effective and capable of deterring seals out to at least 200 m from the sound source. Therefore, this distance was used in the exposure modelling.

6.4.3 Maximum flee distance, r_{max}

For porpoises the maximum flee distance is at least 20 km for pile driving without bubble curtains or other reduction of radiated noise levels (Tougaard *et al.* 2009a, Brandt *et al.* 2011, Dähne *et al.* 2013, Haelters *et al.* 2015). Fewer data are available for pile driving with noise reduction in the form of bubble curtains. One study indicated a reduction to about 12 km with the use of a bubble curtain (Dähne *et al.* 2017), whereas another study (compiling data from 7 offshore wind farms) indicated that the maximum distance does not decrease by the use of bubble curtains, but the proportion of affected animals and the duration of the disturbance decreases (Brandt *et al.* 2018). Using a lower value of r_{max} is precautionary (as this will overestimate the exposure in the last part of the pile driving) and thus a value of 12 km was selected.

Little data is available for seals. One study on harbour seals indicated roughly similar reaction distances as for porpoises, i.e. at least 20 km (Russell *et al.* 2016), but no data are available for pile driving with a bubble curtain. In the absence of data the same values were assumed for seals and porpoises.

6.5 Summary of modelling input parameters

All parameters used in the impact modelling are listed in Table 6.1

Table 6.1. Parameters used in the impact modelling (Equation 6.8) for the worst case scenario.

Parameter	Value	Comments
Pile diameter	15 m	
Longitude (easting)	377000 m	EPSG: 3006
Latitude (northing)	6108000 m	EPSG: 3006
Source level (SL), unattenuated	227.4 dB r e. 1 µPa^{2}s.	Source spectrum in Figure 6.2
Source level (SL), with bubble curtains	221.9 dB r e. 1 µPa^{2}s.	Source spectrum in Figure 6.2
Transmission Loss (TL)	$14.9\log_{10}(r) + 5.1x10^{-4}r$	Porpoises, no noise reduction
	$16.7\log_{10}(r) + 5.5x10^{-4}r$	Porpoises, bubble curtain
	$15.1\log_{10}(r) + 2.9x10^{-4}r$	Seals, no noise reduction
	$15.1\log_{10}(r) + 2.3x10^{-4}r$	Seals, bubble curtain
Maximum hammer energy	5000 kJ/strike	
Hammer scenario	4.5 hours, 7200 strikes	See 6.2.2 for soft start and ramp up sequence
Deterrence distance – seals	200 m	Minimum distance, r_0
	20 km	Maximum distance, $r_{max,}$ no noise reduction
	12 km	Maximum distance, r_{max} bubble curtain
Deterrence distance – porpoises	1300 m	Minimum distance, r_0
	20 km	Maximum distance, r_{max} no noise reduction
	12 km	Maximum distance, r_{max} bubble curtain
Flee speed – seals	1.5 m/s	
Flee speed – porpoises	1.5 m/s	
PTS threshold seals	185 dB re. 1 µPa^{2}s	Phocid seal weighted
PTS threshold porpoises	155 dB re. 1 µPa^{2}s	HF-cetacean weighted

7. Results of the exposure model

The transmission loss models developed in section 6.3 can now be combined with the assumptions about initial deterrence distance (r_0) (i.e. distance at first piling exposure) and flee speed into the cumulated exposure model.

7.1 Cumulated sound exposure levels

Figure 7.1 shows examples of results of the exposure modelling. All scenarios modelled are shown in Appendix 2 and final SELcum for all scenarios listed in Table 7.1.

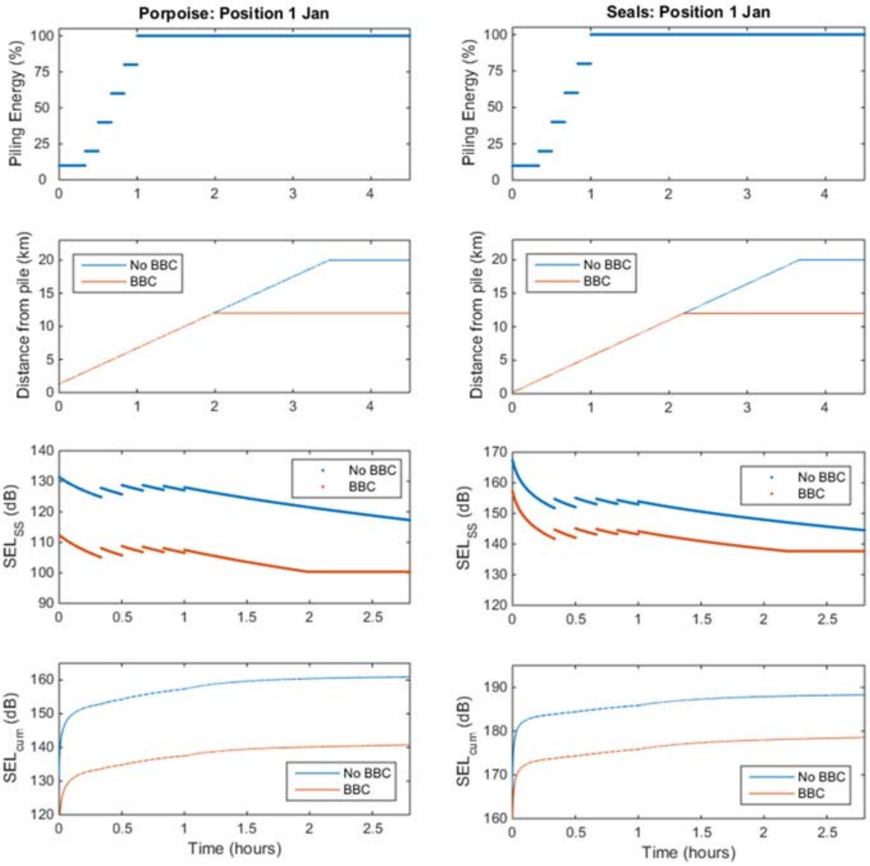


Figure 7.1. Example of results of the exposure model for seals and porpoises. Selected scenario is position 1 in winter (January), which is the worst case scenario, in the sense that it resulted in the highest predicted cumulated sound exposure levels. Sound exposure level for individual hammer strikes (SEL_{SS}) and cumulated sound exposure levels (SEL_{cum}) are shown, both weighted with either HF-cetacean or phocid curves (**Figure 4.5**). Results are included for modelling both with and without bubble curtain (BBC). Note that y-axis scales are different for porpoises and seals (exposure to seals are considerably higher than exposure to porpoises).

The top panel for both porpoises and seals show the pile driving scenario used in the modelling, beginning with a 20 minute soft start at 10 % of maximum hammer energy and then stepwise increase to maximum (see 6.2.2). Total duration of the pile driving scenario was 4 hours 30 minutes.

Second panel from top shows the distance from the pile of an animal located at the minimum deterrence distance (r_0) at the time the soft start procedure begins.

Third panel from the top shows the received level, weighted with either the HF-cetacean or the phocid weighting curve, pulse by pulse. As the animal moves away at constant speed from the pile driving the overall development of the received level is a decrease with time, but with smaller increments corresponding to the stepwise increase in hammer energy. The effect of the bubble curtain is evident: about 20 dB reduction in received levels at all distances for porpoises, about 10 dB for seals.

Bottom panel shows the cumulated sound exposure level over the duration of the pile driving. The increase is very steep in the first 10-15 minutes and then levels off. Part of this development is due to the animal moving away and thus the decreasing received level of the individual pulses, but more important is the logarithmic transformation in the calculation of SELcum (Equation 6.1). This logarithmic relationship means that even for a constant received level of pulses, it requires a doubling of number of pulses received for each 3 dB increase in SELcum. This means that everything else kept constant, SELcum will not increase in proportion to the number of pulses (N), but proportional to $\sqrt{N}$.

Table 7.1. Modelled weighted SEL_{cum} levels for porpoises and seals under the eight different modelling scenarios (combinations of position, time of year and mitigation).

Mitigation	Month	Position	Porpoises	Seals
No	Jan	1	161.2	188.6
		2	159.8	188.2
	Jun	1	158.6	188.1
		2	156.4	187.9
Bubble curtain	Jan	1	141.8	179.5
		2	141.6	179.9
	Jun	1	141.0	178.9
		2	139.8	179.1

Final values of SELcum for all modelled scenarios are shown in Table 7.1. Some immediate conclusions can be seen directly from the table. First of all, there is very little variation between modelling scenarios, with respect to position of the monopile and time of year. This is taken as evidence that the effects of bathymetry and sound speed profile is minimal, as long as we are looking at these worst case scenarios (recall that transmission loss in the direction towards the shallower parts of Krigers Flak was dramatically larger than in the direction towards deeper waters, used here, see Figure 6.3).

Second immediate conclusion from the table is that SELcum values for seals are significantly larger than for porpoises. This is partly due to the difference in weighting curves (Figure 4.5), where the phocid curve includes significantly more energy at the lower frequencies, where most of the energy in the pile driving pulse is located, and partly due to the minimum deterrence distance (r_0) of the seal being much smaller than for the porpoise (200 m vs. 1300 m).

Third immediate conclusion from the table is that the mitigating effect of the bubble curtain is considerable, between 10 and 20 dB, more for porpoises than for seals. The reason it is more effective for porpoises than seals is again due to the differences in weighting functions. Bubble curtains are less effective at lower frequencies than at higher frequencies and as the phocid weighting curve includes more low frequency energy than the HF weighting, the effect of the bubble curtain is less pronounced for the seals.

8. Assessment of impact from construction

The primary impact from construction is considered to be from the underwater noise generated from pile driving. In addition to this are much lower levels of underwater noise from ships and service boats (compared to the pile driving noise), incapable of inducing any injury or hearing loss and thus only considered as a source of masking and behavioural disturbance.

8.1 Acoustic trauma

Peak pressures were not modelled for pile driving at Kriegers Flak, as modelling this quantity is considerably more technically demanding than modelling sound energy (SEL). However, based on a large number of measurements, the peak sound pressure level 750 m (Nehls & Bellmann 2016) from the pile driving site can be estimated for a 15 m diameter pile. Extrapolating the upper curve on Figure 8.1 to 15 m pile diameter gives an estimated peak sound pressure level of 210 dB re. 1 µPa. This should be compared against the threshold for acoustic trauma (section 5.1) of 226 dB re. 1 µPa, 16 dB higher than the level at 750 m. A simple back-calculation, assuming spherical spreading loss (20 log r) shows that the threshold of 226 dB re. 1 µPa is exceeded within 120 m of the monopile. This extrapolation assumes that the monopile can be regarded as a point source, which is not the case (it is a very long cylinder) and will overestimate the sound pressures close to the source. Furthermore as no animals, neither seals, nor porpoises, are expected to be within 200 m for seals and 1300 m for porpoises at onset of piling, due to the use of deterring sounds and soft start procedure, it is unlikely that any animal will be exposed to sound pressures close to the threshold for acoustic trauma. The impact of acoustic trauma from noise exposure during construction is thus assessed as **negligible**.

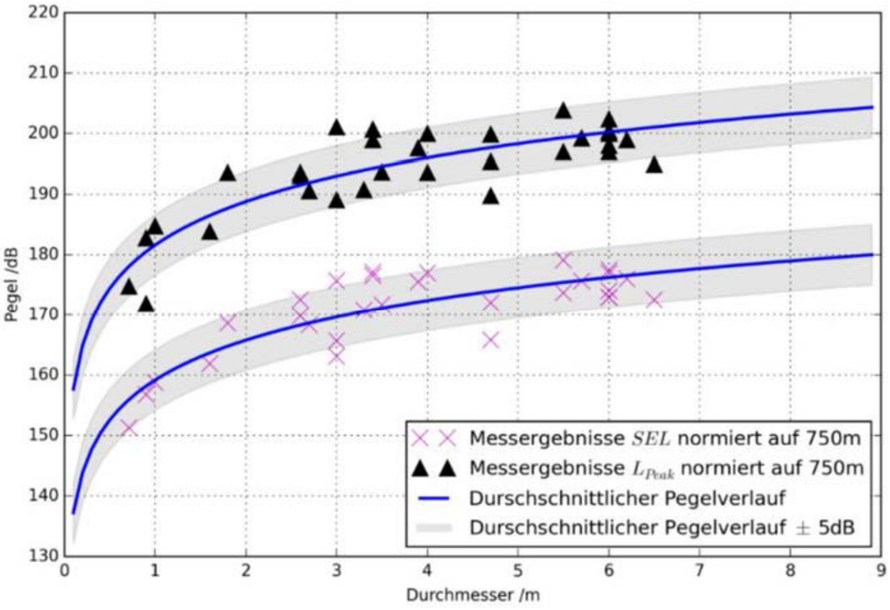


Figure 8.1. Measured sound exposure level (SEL_{SS}, crosses) and peak pressure levels (L_{Peak}, triangles) in a distance of 750 m from the monopile. From (Nehls & Bellmann 2016).

Only one activity is considered capable of generating peak pressures and acoustic impulses sufficiently high to injure marine mammals and this is underwater explosions. Such are not anticipated as part of the wind farm construction, although unexploded ordnance (UXO's) may be encountered everywhere in the Baltic and may require clearance by detonation on site. If such UXO clearance is required, it should be assessed separately and appropriate mitigation measures should be adopted to minimize the risk of injury to marine mammals.

8.2 Hearing loss

Pile driving is the only noise source during construction of the wind farm capable of inducing temporary or permanent hearing loss in marine mammals. Two sound propagation modelling scenarios were used: with and without mitigation in the form of a bubble curtain. In both cases it was assumed that a seal scarer or similar deterrence device was used 15 minutes prior to onset of pile driving (see 4.6.3), to deter seals and porpoises out to safe distances before start of the pile driving.

8.2.1 Piling without reduction in radiated noise

Modelling of cumulated sound exposure levels experienced by seals and porpoises assumed to be located at the minimum deterrence distance of the seal scarer (200 m and 1300 m for seals and porpoises, respectively) when pile driving starts shows that these animals are likely to be exposed to levels capable of inflicting permanent hearing loss in both seals and porpoises. The cumulated sound exposure at the end of a 4.5 hour long pile driving is estimated to be 161 dB re. 1 μPa^2s and 189 dB re. 1 μPa^2s for porpoises and seals, respectively. This amounts to 6 dB and 4 dB above the exposure thresholds for PTS (section 5.2), respectively.

The magnitude of the hearing loss is unknown, but it will likely be restricted to lower frequencies (below 10 kHz) and will manifest itself as slightly elevated hearing thresholds, not deafness (as exposures only exceeds the exposure threshold by small amounts). On individual seals and porpoises such a hearing loss can be considered a moderate impact and may be undesired from an animal welfare perspective. However, the task of this assessment is to assess impact on the level of (sub-)populations.

As described in section 2.1.1 there are two subpopulations of porpoises in the waters around Kriegers Flak. Most of the animals encountered, especially during summer months, are likely to be from the Belt Sea population, which is a population in favourable conservation status. A number of porpoises from this population is likely to suffer permanent, although moderate loss of hearing at low frequencies, due to the high number of animals present in the area. However, it is considered unlikely that this impact will manifest itself in changes in vital parameters of the porpoises (such as fecundity or adult and calf survival rates) large enough to affect the conservation status of the population in the long run. The impact on the **Belt Sea population of porpoises** from pile driving without any measures to reduce radiated noise is thus assessed to be **minor.**

The situation is different for the critically endangered population of porpoises from the Baltic Proper. Even though the likelihood of encountering animals from this population is very low in the waters around Kriegers Flak, the fact that the population status is critically endangered essentially implies that any additional impact on the population is undesired. Although the long-term consequences of a small PTS at low frequencies are unlikely to be significant, the potential impact of pile driving without any measures to reduce radiated noise on the **Baltic Proper population of porpoises** is thus assessed precautionary as **moderate** during winter months and **minor** during summer months. The difference between the two periods relates to the higher likelihood of encountering individuals from this population around Kriegers Flak in winter, although the likelihood is still very low in absolute terms.

Both harbour seals and grey seals in the waters around Kriegers Flak are in good conservation status and it is considered unlikely that inflicting moderate, permanent hearing loss on a limited number of seals will significantly affect the population development. **Impact on populations of harbour and grey seals** by pile driving without bubble curtains is therefore assessed to be **minor**.

8.2.2 Piling with a bubble curtain

Use of a bubble curtain, with the attenuating capabilities assumed in the model (see section 6.2.1) reduces the cumulated noise exposures of seals and porpoises (Table 7.1) to levels well below the exposure limits (Table 5.2), and thus unlikely to induce any permanent hearing loss in neither seals, nor porpoises.

For **porpoises**, the cumulated exposure is reduced to levels exceeding the level required to elicit temporary hearing shift (TTS) by a maximum of 2 dB (**Table 7.1**). As the impacts on individuals are very small (no PTS, minute TTS) and unlikely to have any long-term consequences for the populations, the impact is considered **negligible** for both populations.

For **seals**, the cumulated exposure with application of a bubble curtain exceeds the TTS threshold (Table 4.2) by 10 dB. This exposure is likely capable of inducing appreciable TTS in seals, but still 5 dB below the level required to induce permanent healing loss (Table 4.2). The potential impact of pile driving noise with respect to hearing loss is thus assessed as unlikely to have any long-term consequences for the populations of **harbour seals and grey seals** and is therefore assessed to be **negligible**.

8.3 Behavioural disturbance

Pile driving without use of bubble curtains is known to cause disturbance of seals and porpoises out to at least 20 km from the pile driving site, with the effect lasting up to 24 hours (see section 4.4) after termination of the piling. This means that during this period foraging by the animals in the impacted area, which is of considerable size, will be reduced. As there is nothing indicating that the area immediately on and around Kriegers Flak is of larger importance to seals and porpoises than the surrounding waters, it seems reasonable to assume that the animals displaced from the impacted area are able to forage elsewhere. As there likely will be an increased number of animals in the adjacent areas, due to the displacement, the average foraging efficiency may decrease and in this way impact a larger area. It is not possible to quantify this impact and even less infer the effects on the population level. However, if one considers, in an extremely precautionary assessment, that pile driving affect foraging for a period of 24 hours and for example, 32 turbines are installed with an average interval of 2 days, this translates into a disturbance of the impacted area for 50% of the time over a period of 2 months.

These figures can be combined into a disturbance index, D, which expresses the percentage of the total habitat unavailable to animals due to deterrence by pile driving noise:

Equation 8.1

$$D = \frac{\pi r_{max}^2}{A_{total}} \cdot \frac{dur}{pilinginterval} \cdot \beta \cdot 100\%$$

where r_{max} is the maximum disturbance distance, A_{total} is the area occupied by the local population of the focal species, *dur* is the duration of a single pile driving, *piling interval* is the average turnaround time from start of pile driving at one foundation to start on the following foundation and β is a factor between 0 and 1 representing the fraction of the impact zone that falls into the total area A. The index D thus expresses the percentage of the total area times the total duration where pile driving is conducted unavailable to the animals and has a maximum of 100%, corresponding to the entire region disturbed for the entire period it takes to install all foundations. D = 10% represents a number of different scenarios for example 20% of the area disturbed half of the time; 100% of the area disturbed 10% of the time; 10% of the area disturbed all the time etc.

Maximum deterrence distance (i.e. the range where reaction can be observed in at least some, but not all animals) for both seals and porpoises was assumed to be 20 km without reduction in noise radiation and 12 km with application of a bubble curtain, in line with the assumptions used in the exposure model (6.4.3). Duration of the disturbance was assumed to be 24 hours without noise radiation reduction and reduced to 6 hours with a bubble curtain (Dähne *et al.* 2017, Brandt *et al.* 2018). Turnaround time was assumed to be 48 hours on average.

A critical factor in the calculation of the disturbance index is the total area A_{total}. This area is used as a proxy for the affected population size, as this may often not be known with certainty. The area should thus cover the distribution range of the local population of each of the affected species. The areas were determined by estimating rectangles covering the main distribution ranges in the waters south of Skåne and Blekinge (derived from information presented in section 2) and shown in Figure 8.2. As the wind farm is on the border of the rectangles, except for grey seals, β from Equation 8.1 was set to 0.5, except for grey seals, where it was set to 1.

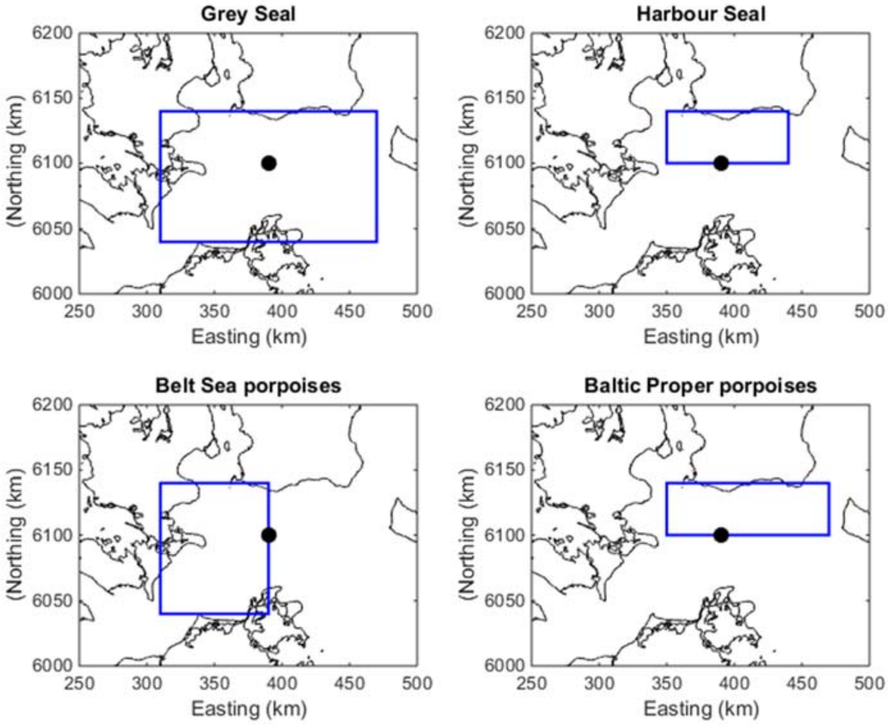


Figure 8.2. Areas used to assess disturbance index for grey seals, harbour seals and porpoises. UTM Zone33. Black circle indicates approximate position of the wind farm.

The areas used, as well as the disturbance indices calculated by Equation 8.1 are shown in Table 8.1 together with the impact magnitude, assessed according to the criteria established in section 5.3.

Table 8.1. Disturbance index for the different populations of marine mammals in the waters around Kriegers Flak and assessment of magnitude of impact under two different scenarios: a worst-case scenario without any reduction in radiated noise and one with use of bubble curtains as attenuation.

Group	A_{total} (km^2)	D-index	Impact magnitude
No reduction in radiated noise			
Harbour seals	3,600	9%	Moderate
Grey seals	16,000	4%	Minor[1]
Belt Sea porpoises	8,000	4%	Minor[2]
Baltic Proper porpoises summer	0[3]	0%	Negligible
Baltic Proper porpoises winter	4,800	7%	Moderate[4]
Use of bubble curtain			
Harbour seals	3,600	0.8%	Minor
Grey seals	16,000	0.4%	Minor
Belt Sea porpoises	8,000	0.4%	Minor
Baltic Proper porpoises summer	0[2]	0%	Negligible
Baltic Proper porpoises winter	4,800	0.6%	Minor

1) Factored into assessment that grey seals around Kriegers Flak are part of one common Baltic population.

2) Factored into assessment that the porpoises belong to a much larger common Belt Sea population.

3) The area is set to zero, as no porpoises from the Baltic Proper are expected to be present in the summer.

4) Although the absolute number of animals likely to be affected is very low, the unfavourable conservation status of the population has been factored into a precautious assessment.

From Table 8.1 it is seen that the greatest impact from disturbance is on harbour seals. This is due to the relatively small area used by the harbour seals at Falsterbo, which is also relatively close to the location of the wind farm. Reduction of radiated noise from the pile driving, exemplified by a bubble curtain, is seen to have a considerable effect on the disturbance index and assessed impact.

8.4 Masking

Masking of other sounds by the pile driving noise is not very likely, as described in section 4.5. Masking of echolocation signals of porpoises is considered to be unlikely, due to the lack of overlap in frequency between noise and echolocation signals. Masking intensity is thus considered insignificant and hence impact of masking on **porpoises** is thus assessed as being **negligible**.

Harbour and grey seals use low frequency sounds in communication and the potential for masking is thus larger. However, mating only occurs close to breeding sites on the coast (Falsterbo), i.e. far from the wind farm area, where received levels of the pile driving noise is low. Furthermore, masking is only possible during pile driving. In a worst-case scenario (in the peak of the breeding season in June-August for harbour seals), with on average 4.5 hours of piling every second day, this would amount to masking in less than 10% of the time. Potential masking intensity is thus assessed in a very precautious manner as medium for the seals at Falsterbo (it is not actually known whether pile driving noise can mask communication of mating calls). Given the favourable conservation status of the population, the overall impact of masking from the pile driving noise without reduction in noise radiation on **seal** populations is thus assessed to be **minor**. Reduction of radiated noise from the pile driving, such as by application of bubble curtains, will reduce noise levels and thus reduce impact, but this reduction cannot be further quantified. In a precautionary manner, the potential impact is thus also assessed to be **minor**.

8.5 Cumulative impact

The impact from construction activities will add in a cumulative way on top of existing pressures from human activities in the area, such as bycatch in gill net fisheries, disturbance from ship traffic and leisure boats, and pollution with heavy metals and organochlorides. As the impact of these pressures on seals and porpoises have not been quantified, it is not possible to quantitatively compare the added impact from construction of the wind farm to the existing anthropogenic impacts. However, some of the existing impacts are generally considered to be of significant magnitude, such as fisheries bycatch of porpoises (ASCOBANS 2002, Koschinski 2002), and pollution with organochlorides in seals and porpoises (Bredhult *et al.* 2008, Jepson *et al.* 2016). As the different impacts from pile driving conducted with appropriate reduction in radiated noise levels (by means of a bubble curtain), all have been assessed to be minor or negligible, it is judged that the cumulative impact from the construction cannot be assessed higher than **minor** as well, and thus without any long-term consequences for the populations of seals and porpoises.

8.5.1 Cumulative impact from construction of other wind farms

Several other offshore wind farms are planned in the waters around Kriegers Flak, listed in **Table 8.2**. One, Arkona, is currently under construction and will therefore be operational once construction at the Swedish Kriegers Flak commences. The second, and most relevant wind farm is the adjacent Danish Kriegers Flak offshore wind farm. Construction of the connecting structures (cables and transformer platforms) has already begun and construction of the wind farm itself is expected to be concluded within the next couple of years, thus well before construction can begin at Swedish Kriegers Flak. Construction times for the two remaining wind farms, Baltic Eagle and Arcadis Ost 1, both in German waters, are not known exactly and could potentially overlap with construction at Kriegers Flak. Both wind farms are located more than 30 km to the south east of Kriegers Flak and they are thus unlikely to add any impact to the waters north and west of Kriegers Flak, which are the areas of greatest importance to the marine mammals in the area. No significant cumulative impact is thus expected, should construction occur simultaneously at Swedish Kriegers Flak and one or the other of the German wind farms.

Table 8.2. Planned offshore wind farms in the waters around Kriegers Flak.

Name	Status	Size	Distance to Kriegers Flak
Arkona	Under construction	60 x 6 MW	62 km
Danish Kriegers Flak	Permitted	49 x 8 MW	1 km
Baltic Eagle	Permitted	83 x 6 MW	44 km
Arcadis Ost 1	Permitted	58 x 6 MW	33 km

8.6 Impact on Natura2000 areas

There is a number of Natura2000 areas in the waters surrounding Kriegers Flak (see section 0). Of these only one area is likely to be directly impacted:

Sydvästskånes Udsjövatten. This Natura2000 area borders and partly overlaps the proposed wind farm area and effectively surrounds it inside the Swedish EEZ. As the pile driving noise will propagate into the Natura2000 area, even if bubble curtains are used, it is to be expected that impacts on seals and porpoises will also occur inside the Natura2000 area.

In the worst case situations, which would be pile driving at the outermost positions of the windfarm bordering the Natura2000 area, the proportion of the Natura2000 area impacted can be estimated using the same method as used to assess behavioural disturbance above (section 8.3 and Equation 8.1). In this case, the total area (A_{total}) is the area of Sydvästskånes Udsjövatten (1151 km^2) and β is set to 0.5, as the wind farm directly borders the Natura2000 area. All other parameters are the same. This results in the following indices of disturbance:

- Without reduction in radiated noise: D = 27 %
- With application of bubble curtain: D = 2.5 %.

These figures are overestimates, as they assume that all pilings occur at the border of the Natura2000 area, which will not be the case.

The impact indices can be interpreted in the way that in the worst-case scenario without application of noise radiation mitigation, 27% of the Natura2000 area will be affected (combined in time and space) over an estimated 2-month construction period. This impact on the Natura2000 area is assessed as **major**. If noise radiation is reduced, such as by application of a bubble curtain, this impact is reduced to 2.5%, assessed as being a **minor** impact.

In both cases the impact on the Natura2000 area is **temporary** and very likely **fully recoverable**.

The remaining Natura2000 areas in the Swedish, Danish and German waters are all located so far away that impact on these areas are considered **negligible**.

9. Noise from operational wind farms

Offshore wind turbines generate noise as the wings, gears and generator rotates. The moving gears in the gearbox is the primary source of the noise transmitted as vibrations down the turbine tower and radiated into the surrounding waters. Thus, the power density spectra of the underwater noise very commonly show that most of the energy is located at single frequencies, corresponding to the engagement frequency (and possibly harmonics) of the moving teeth on the gears (Figure 9.1).

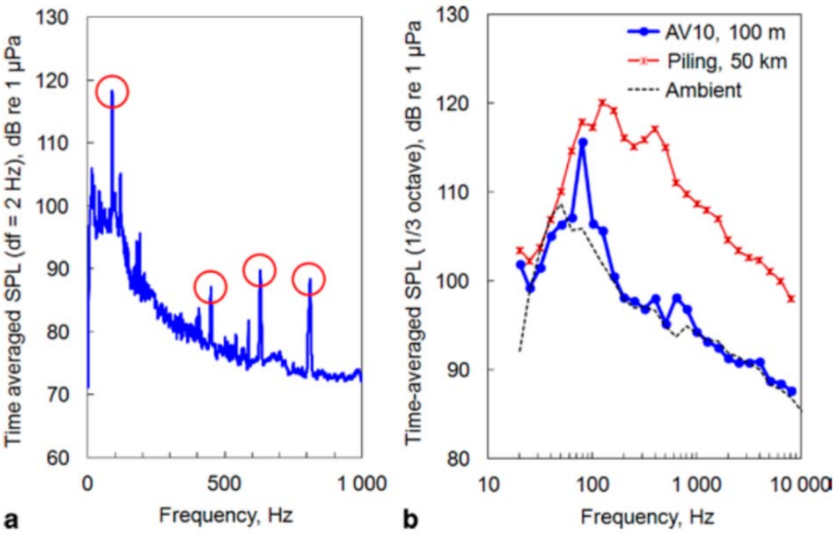


Figure 9.1. Operational noise measured 100 m from a 5 MW turbine at Alpha Ventus offshore wind farm. The turbine was operating at maximal power output. A) shows power density spectrum of the noise. Note the powerful component at 90 Hz and the harmonic overtones at 450 Hz, 630 Hz and 810 Hz. B) Third-octave spectrum of the same noise (blue), together with ambient noise (broken line), recorded at the same location and same wind speed, but before installation of the turbines, and noise from a distant pile driving (red). From Betke (2014)

Numerous recordings of underwater noise from operating turbines exists. A recent example is shown in Figure 9.1 and some of the earlier measurements are shown in Figure 9.2. These recordings span a large range of turbine sizes, from 500 kW nominal power (Vindeby, Figure 9.2), to 5 MW (Alpha Ventus, Figure 9.1), but do not reveal any strong relationship between size and noise level. There is thus nothing in the available data that suggests that larger turbines are more (or less) noisy than smaller turbines, when it comes to underwater noise during operation.

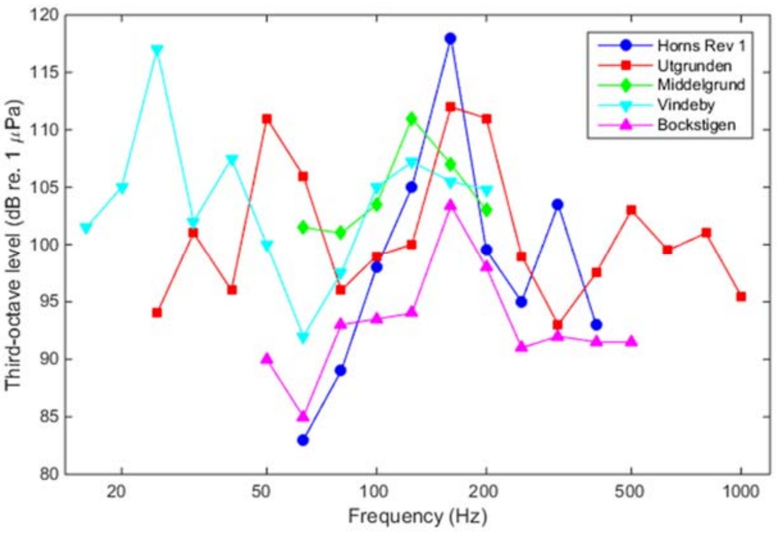


Figure 9.2. Underwater noise recorded from five different turbines, expressed as third-octave levels (and thus directly comparable to figure 1b) and levels normalized to a recording distance of 100 m. Only measurements, where the turbine noise was above ambient noise are included, which explains why curves do not cover the entire frequency range. Sources: Ingemansson Technology AB (2003), Betke (2006), and Tougaard *et al.* (2009b).

The type of foundation could quite possibly affect the noise levels too, but the data in Figure 9.1 and Figure 9.2 are both from turbines with concrete foundations and monopile foundations. The only turbine that really stands out is the small turbine at Utgrunden, Sweden (red, square symbols in Figure 9.2). The noise measured from this turbine was significantly louder than other turbines, especially at the higher frequencies. One possible explanation for this could be its placement on subsea bedrock, whereas all the other turbines are placed on soft bottom (Madsen *et al.* 2006).

9.1 Ambient noise

The possible impact of underwater noise from the turbines is ultimately limited by the hearing abilities of the animals and the ambient noise levels. Figure 9.3 shows the median noise level modelled from AIS and VMS data on ships and natural wave-generated noise for the month of July 2014. Visible in the map are the major shipping lanes from the Kadet Trench and the Sound into the Baltic. Kriegers Flak is located in a relatively quiet part of the area. This is the combined result of most ships passing around Kriegers Flak rather than across it, and the attenuation provided by the shallower parts of Kriegers Flak.

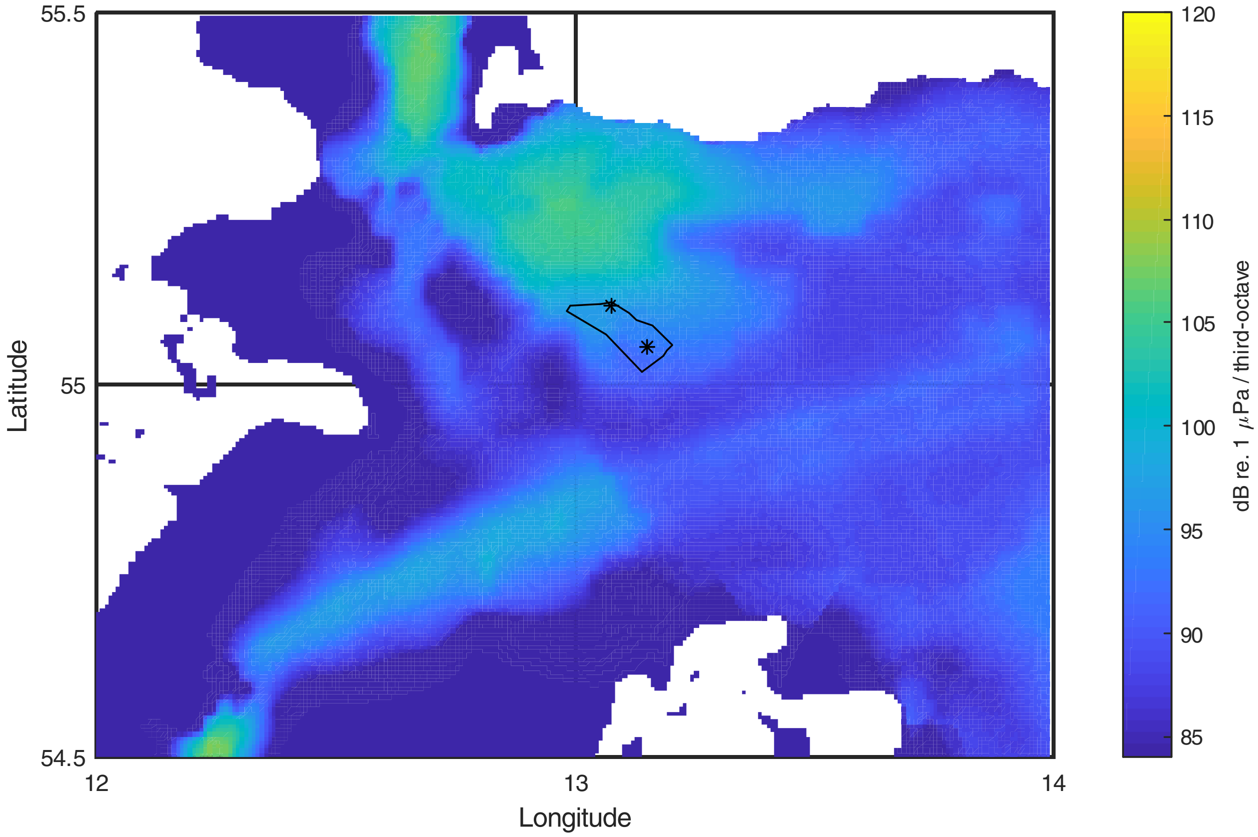


Figure 9.3. Modelled noise levels in the third-octave band centred at 125 Hz. The map shows the median noise level (L50) for July 2014. Polygon shows outline of Swedish Kriegers Flak offshore wind farm and stars indicate the two positions used for modelling of pile driving noise as well as assessment of ambient noise. Source: EU-Life project BIAS (https://biasproject.wordpress.com/).

9.2 Cumulative noise from several turbines

Little information is available about the cumulative impact from several turbines in the same area. If two or more turbines produce noise at the same frequency and at the same sound pressure level, the two sounds can add and thus result in an increased sound pressure level. Figure 9.4 shows an idealized example of this. The combined sound pressure level from two identical turbines is given as:

Equation 9.1

$$L_{eq-combined} = 10\log_{10}\left(10^{L_{eq1}/10} + 10^{L_{eq2}/10}\right)$$

Where L_{eq1} and L_{eq2} are the received sound pressure levels of the two turbines, respectively.

Only in the region roughly half-way between the turbines does the sum significantly exceed the sound pressure level of the closest turbine. Closer to one or the other turbine the contribution of the distant turbine to the sum is virtually zero. At most, the sum of the sound pressures from the two turbines can be 3 dB more than the noise form the individual turbines (exactly half way between them). Adding more turbines does not change much. If four identical turbines were considered, the combined sound pressure level at the exact centre between them would be 6 dB higher than the noise level of any of the individual turbines and as one moves away from the centre, the noise will be increasingly determined by the closest turbine. To achieve an additional 3 dB increase in sound pressure level, one would have to be at the exact centre between eight identical turbines, at which point the geometry is no longer consistent with the normal layout of wind farms.

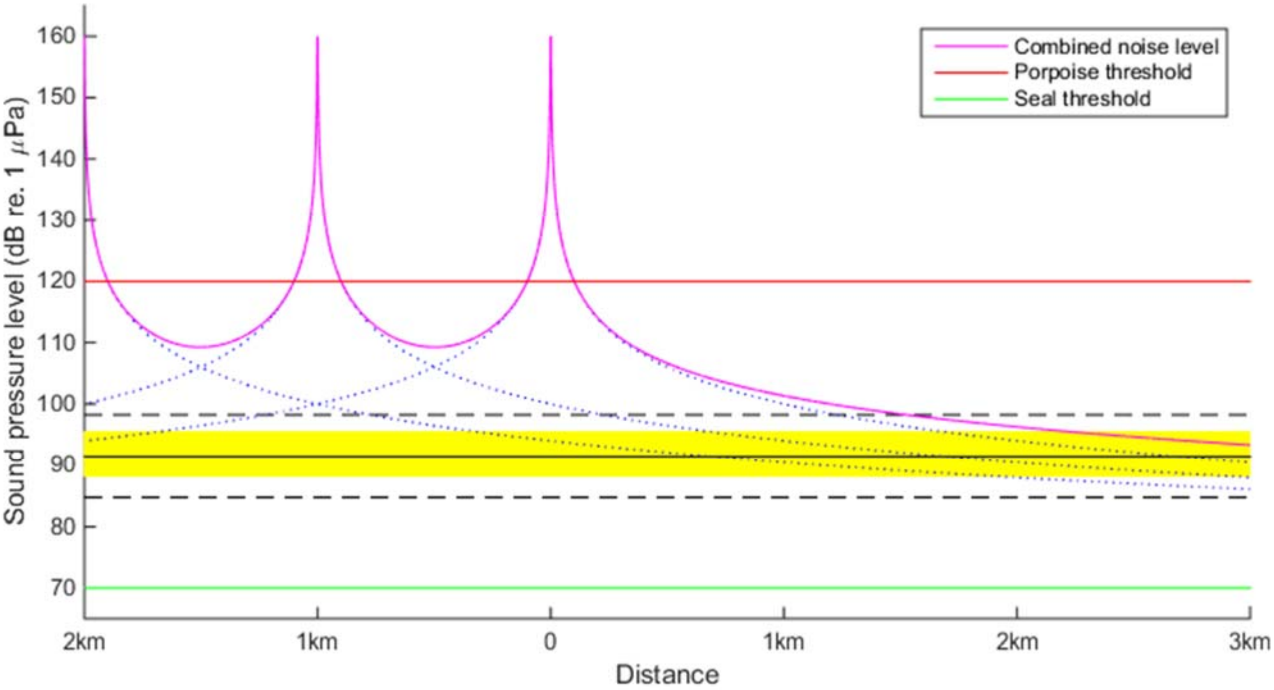


Figure 9.4. Idealized model of summation of noise from two identical turbines placed 1000 m apart. Each turbine is modelled as a point source with a spherical transmission loss (20 log r, dotted lines) and the combined noise level is found from Equation 9.1. (magenta line). The yellow band and associated lines indicate the 25% and 75% exceedance levels of the ambient noise in the 125 Hz third octave band, modelled by the BIAS project at location 2 (**Figure 9.3**); the solid line the median (L_{50}) and the stippled lines the 90% and 10% exceedance levels. Included are also the minimum hearing threshold for a harbour seal (Kastelein *et al.* 2009, green line) and harbour porpoise (Kastelein *et al.* 2010b, red line) estimated at 1-200 Hz.

Harbour porpoises have very poor hearing at the low frequencies of the turbine noise. No measurements are available at 100 Hz, but by extrapolation of the audiogram (Figure 4.1) a threshold of 120 dB re. 1 μPa was estimated. This threshold is so high that the turbine noise is expected to be inaudible to porpoises, unless they are very close to the turbine, approximately with 100 m.

The situation is different for seals. Harbour seals (and presumably also grey seals) have good low-frequency hearing, well below the ambient noise levels at Kriegers Flak (Figure 9.4). Their ability to hear the turbine noise (and in the end be affected by it), is thus limited by the ambient noise rather than the hearing threshold. The simple model in Figure 9.4 suggests that the turbine noise is audible to seals within the wind farm area and extending one or more kilometres out from the edge of the wind farm. Realizing that the simple spherical spreading model (20 log(r)) almost certainly does not apply to the turbine noise but only is used as a first approximation, means that these impact distances are very uncertain. The actual sound propagation loss could be larger (due to shallow-water high-pass filtering and Lloyd’s mirror-effects), or smaller (due to cylindrical, rather than spherical spreading).

10. Assessment of impact from operation

10.1 Effect on abundance of porpoises

A few studies have looked at the effect of operating offshore wind farms on the abundance of porpoises inside the wind farm, compared to baseline measurements before construction began.

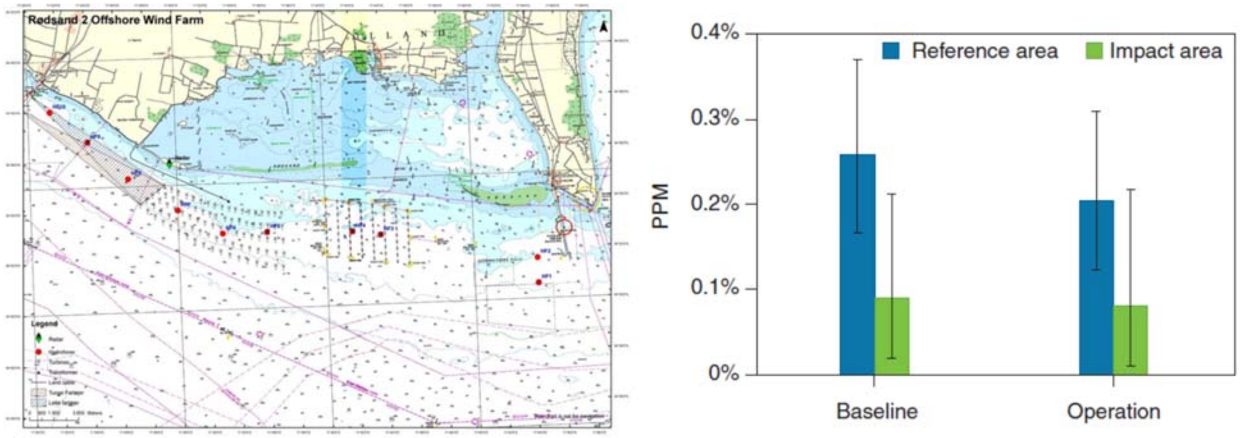


Figure 10.1. Harbour porpoise acoustic detections before and after construction of Rødsand 2 offshore wind farm. Porpoises were monitored acoustically inside the wind farm (five stations indicated with red dots in the western part of the map left and compared to two reference stations located to the east in the map. Two additional stations were located inside an older wind farm (Nysted), in centre of map. Right panel shows porpoise presence, quantified as average percent porpoise positive minutes before and after construction and inside the wind farm and at the reference stations. From Teilmann *et al.* (2012).

One example is shown in Figure 10.1, which is from the Rødsand 2 offshore wind farm located in the Western Baltic Sea. Abundance of harbour porpoises were assessed by passive acoustic monitoring, where dataloggers (C-PODs), recorded the presence of porpoises through detection of their echolocation clicks (Teilmann *et al.* 2012). Porpoise abundance was quantified as percent porpoise positive minutes, which expresses the fraction of a 24 h day where porpoise echolocation clicks could be detected, assessed minute by minute.

The results from Rødsand 2 (Teilmann *et al.* 2012) showed that in general there were more porpoises in the reference area than in the wind farm area, but that the ratio between the two areas was unaffected by the presence of the wind farm, i.e. the relative abundance of porpoises inside the wind farm area was unaffected by the presence of the turbines.

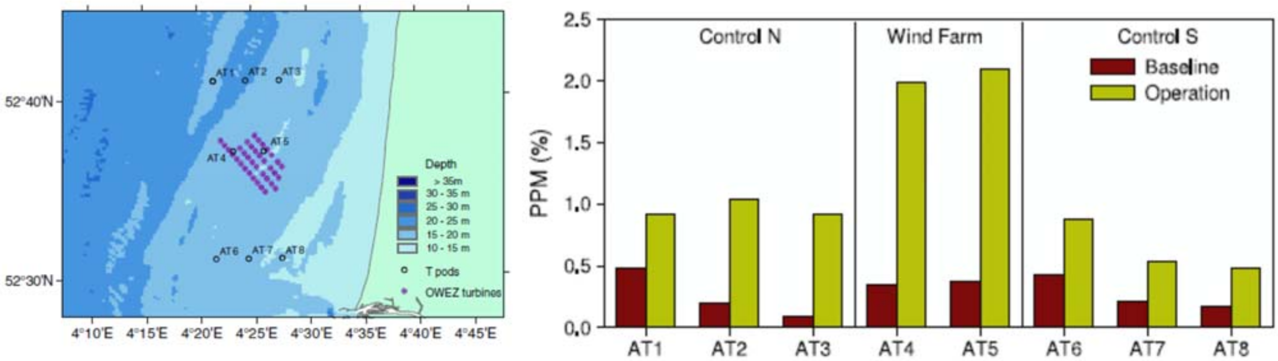


Figure 10.2. Another study of the effect of an offshore wind farm, Egmond aan Zee in the Dutch North Sea. Abundance inside the wind farm area (purple symbols in map, left) was compared to the abundance in two reference areas, north and south of the wind farm, respectively. Porpoise abundance before and after construction and separated out into each recording station (AT1-AT8), is shown to the right. From Scheidat *et al.* (2011) .

A later study in the Egmond aan Zee offshore wind farm off the Dutch North Sea coast (Figure 10.2) showed a general and substantial increase in porpoise abundance from baseline before construction to operational period. This increase is consistent with other observations, supporting a long-term increase in porpoise abundance in the Dutch North Sea (Camphuysen *et al.* 2008) and is as such unrelated to the wind farm. However, the relative increase in porpoise abundance inside the wind farm area was larger than in the reference areas, indicating that there were also more porpoises inside the wind farm relative to the outside, after the wind farm was put into operation.

It could not be determined why porpoises apparently were attracted to the wind farm, but at least two possibilities have been suggested (Scheidat *et al.* 2011). One is that increased food abundance connected to the artificial reefs created around the turbine foundations could have attracted porpoises. The other suggested explanation is that as this part of the North Sea is very heavily trafficked by cargo ships and intense beam trawler fishery, the presence of the wind farm, closed to trawling and shipping, has created a refuge with less disturbance than the outside (Scheidat *et al.* 2011).

An earlier study (Teilmann & Carstensen 2012) looked at abundance of porpoises (measured by passive acoustic monitoring) around the Nysted offshore wind farm, the first large offshore wind farm established in the Baltic. This study showed a significant decrease in porpoise abundance during construction, followed by a recovery during operation. The recovery appeared incomplete, however, as baseline levels were not reached several years after end of construction. This difference between pre-construction baseline and operation is unexplained and difficult to link unequivocally to an impact from the wind farm. This conclusion is based on a number of observations:

- The baseline period was very short, essentially only covering a few months in the year prior to construction. It is thus not evident that the baseline activity was typical for the area over long time.
- A dedicated impact study (Diederichs *et al.* 2008) failed to show any gradient in porpoise abundance away from the wind farm. Such a gradient would be expected if porpoises avoided the wind farm.
- The wind farm Rødsand 2 was later constructed adjacent to the Nysted offshore wind farm and did not affect the abundance of porpoises in the area (results described above and shown in Figure 10.1). Turbine foundations were larger, but of similar type (concrete gravitational) as in the

Nysted wind farm. The lack of an effect of this wind farm supports that the baseline data from Nysted was not representative.

- Noise levels from Nysted offshore wind farm were measured and found to be comparable to what has been seen from other turbines (Betke & Glahn 2008). Noise is thus unlikely to be a disturbing factor and no other source of disturbance potentially capable of producing the deterrence needed could be identified.

The potential negative effects of an operational wind farm at Kriegers Flak on porpoises is thus considered **negligible**. The magnitude of potential positive effects of artificial reefs and protection from fishery and shipping is not possible to assess based on existing evidence.

10.2 Effect on abundance of seals

As mentioned for the Egmond aan Zee offshore wind farm, it is very likely that the hard substrate of turbine foundations and scour protection (large boulders placed around the foundation) will play a role as artificial reefs, with an associated increase in biodiversity and production. The latter through the increased access to the topmost meters of the water column, where there is plenty of light for primary production. This artificial reef effect and the possible beneficial role it may have for larger animals, such as marine mammals, has not been well studied. One example, however, indicates that at least some individuals of harbour seals are able to exploit the resources of the artificial reefs. **Figure 10.3** show that one seal equipped with a satellite transmitter actively sought out the turbine foundations and the Fino 1 platform, presumably to access a profitable food resource on the hard substrate reefs.

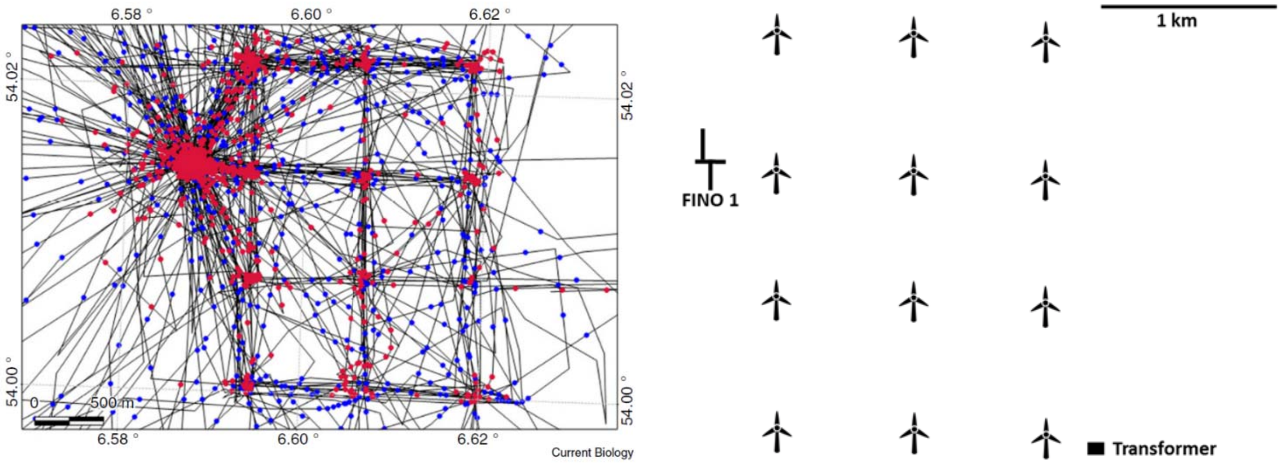


Figure 10.3. Tracks of a single harbour seal, tracked by GPS/satellite transmitter while swimming in and around the German offshore wind farm Alpha Ventus (outline shown on the right). It is evident that the seal actively seeks the turbine foundations, as well as the foundation of the research platform Fino 1 to the west of the wind farm. Partly redrawn from Russell *et al.* (2014).

In contrast to this is a study from Rødsand in the Western Baltic (McConnell *et al.* 2011). In this study, harbour seals were tagged with GPS trackers and their movement in and around the two nearby offshore wind farms Nysted and Rødsand II were studied. A statistical analysis convincingly showed that the seals completely ignored the turbine foundations: they were neither attracted, nor deterred from them, indicating that they did not disturb the seals but at the same time didn't provide any attractive food items either.

Thus, despite the fact that the turbine noise is most likely audible to the seals, both within and beyond the wind farm (Figure 9.4), nothing in the available data suggests that the seals are deterred from the operating wind farms. This likely relates to the very low levels of noise, at maximum 20 dB above the ambient noise. The potential negative effect of an operational wind farm on seals is thus assessed as **negligible**. Whether there are potential positive effects is beyond the scope of this report to assess.

10.3 Impact on Natura2000 areas

The only Natura2000 area potentially affected by the operating wind farm at Swedish Kriegers Flak is Sydvästkånes Udsjövatten. All other Natura2000 areas are too far away for any conceivable impact.

As the turbines are likely to be placed very close to the border of the Natura2000 area and potentially within it in places, the noise from operating turbines will be above ambient noise levels within the Natura2000 area. The impact is considered **negligible**, however, as the noise is inaudible to porpoises and considered to have no effect on seals.

10.4 Cumulative effects from multiple wind farms

Four other offshore wind farms are in operation in the waters around Kriegers Flak, one is under construction and three others are permitted and likely to be constructed in the coming years (Table 8.2). Only two of these offshore wind farms are close enough to be of potential interest with respect to cumulative impact: German Kriegers Flak and Danish Kriegers Flak, both located directly adjacent to Swedish Kriegers Flak. As all three wind farms on Kriegers Flak are considered to have negligible effect on seals and porpoises, once in operation, the cumulative impact of all three are also **negligible**.

Table 10.1. Offshore wind farms, both existing and planned, considered in the cumulative assessment.

Name	Status	Size	Distance to Kriegers Flak
Lillgrund	In operation (2007)	48 x 2.3 MW	44 km
Baltic I	In operation (2011)	21 x 2.3 MW	52 km
German Kriegers Flak (Baltic II)	In operation (2015)	80 x 3.6 MW	1 km
Wikinger	In operation (2017)	70 x 5 MW	57 km
Arkona	Under construction	60 x 6 MW	62 km
Danish Kriegers Flak	Permitted	49 x 8 MW	1 km
Baltic Eagle	Permitted	83 x 6 MW	44 km
Arcadis Ost 1	Permitted	58 x 6 MW	33 km

11. Conclusion

Construction and operation of an offshore wind farm on the Swedish part of Kriegers Flak has been assessed with respect to impacts on marine mammals. The conclusions with respect to abundance of marine mammals, their sensitivity to impact and assessment of impact during construction and operation are summarized below.

11.1 Abundance and sensitivity of marine mammals

- Harbour seals and grey seals are abundant in the area. Both populations are in favourable conservation status.
- Harbour porpoises are also abundant. Most of these are believed to belong to the Danish Belt Sea population, which is in favourable conservation status. Porpoises from the critically endangered Baltic Proper population may be encountered in very low numbers, more likely in winter than in summer.
- Noise from pile driving is likely to constitute the single most disturbing factor for both seals and porpoises.

11.2 Impact from construction

- Pile driving without mitigation in the form of bubble curtains is likely to expose seals and porpoises to levels capable of inflicting permanent hearing loss.
- Although the impact may be significant at the level of individuals and unwanted in itself, the pile driving is unlikely to have long-term consequences for seal and porpoise populations.
- An important exception is the critically endangered population of Baltic Proper porpoises. An impact, which can further worsen the situation for this population or can delay or hamper its recovery, cannot be excluded.
- Use of powerful noise radiation reduction measures, such as bubble curtains to reduce emitted noise levels during pile driving is likely to have a considerable effect on impact ranges and to be able to prevent permanent hearing loss in both seals and porpoises. Furthermore, a bubble curtain or equivalent is likely to reduce negative effects on behaviour of seals and porpoises to levels where they are without long-term consequences for the populations.
- Use of a bubble curtain should be supplemented by the use of an acoustic deterrent device (seal scarer) deployed and turned on during 15 minutes before pile driving begins and then turned off.
- Cumulative effects of simultaneous pile driving at one or more currently planned offshore wind farms in the area are considered negligible.
- Cumulative effects of the impact of construction on top of existing human impact in the form of for example bycatch, competition from fisheries, eutrophication, heavy metals and organochlorides, cannot be assessed quantitatively, but the different impacts from pile driving conducted with appropriate reduction in radiated noise levels (by means of a bubble curtain), all have been assessed to be minor or negligible, it is judged that the cumulative impact from the construction cannot be assessed higher than **minor** as well, and thus without any long-term consequences for the populations of seals and porpoises.

11.3 Impact from operation

- Operation of the wind farm is considered to have negligible negative impact on marine mammals and may have positive effects in the form of creation of artificial reefs on the turbine foundations.
- Cumulative effects of the impact of the operational wind farm on top of existing human impact in the form of for example bycatch, competition from fisheries, eutrophication, heavy metals and organochlorides, cannot be assessed quantitatively, but as the negative impact of the wind farm is considered negligible, the cumulative addition must also be negligible.
- Cumulative effects of adding an offshore wind farm to existing offshore wind farms in the area is likewise considered negligible.

11.4 Impact on Natura2000 sites

- Several Natura2000 areas are designated in Swedish, Danish and German waters, all with seals and/or porpoises as part of the justification for the designation. Only one area, Sydvästskånes Udsjövatten, however, is close enough to the projected wind farm to be impacted directly during the construction. The disturbance of seals and porpoises during the construction period due to pile driving noise is considered to be significant and constitute a major impact. Application of mitigation measures to reduce noise emissions, such as bubble curtains, is considered capable of reducing impact on the Natura2000 area considerable and bring the impact down to minor.
- Impact on Sydvästskånes Udsjövatten due to operation of the wind farm is considered to be negligible.

12. References

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13. Appendix 1 Sound propagation modelling

As described in section 5, the assessment method for the impact of underwater noise on marine mammals, requires extensive modelling of the underwater sound propagation of pile driving noise, in order to derive simple, ad hoc models for transmission loss, which can be used in the modelling of exposure (section 6).

As described in section 5.2, it is proposed to combine the frequency weighted SEL_{cum} metric with the assumption that a marine mammal exposed to unpleasant sound levels will flee in the direction away from the noise. The combined metric is referred to as $SEL_{<Species>cum,fleeing}$ for the remainder of this appendix.

13.1 Source Characteristics

Two possible worst-case scenarios were identified, the first of which uses jacket-foundations with 4 m diameter pin-piles and the second is to use monopile foundations of up to 15 m diameter.

13.1.1 Pile driving source level

In the report, the approach is taken, that the source level is directly proportional to the hammer energy applied, through the relationship

Equation 13.1

$$\boldsymbol{\Delta SL = 10 * log10(\frac{E2}{E1})},$$

E1 and E2 being the energy applied to the two piles and ΔSL being the number of dB difference in source level between the two.

Examining newer literature on measured sound levels compared with pile diameter, such as (Nehls & Bellmann 2016) further indicate a relationship of

Equation 13.2

$$\boldsymbol{\Delta SL = 20 * log10(\frac{D2}{D1})},$$

D1 and D2 being the diameter of the two piles, and ΔSL being the number of dB difference in source level between the two. Based on this relationship, the difference in source level would be approximately 11.4 dB between a 4 m and 15 m pile. A graphic illustration of the proposed relationship is presented in (Nehls & Bellmann 2016), and is shown in Figure 13.1.

From Figure 13.1, it can be seen that measurement data has been acquired for pile diameters up to 6.5 m, and that a curve fit has been made for larger pile diameters. Examining this curve for a 4 m diameter pile, would indicate a sound level, $SEL_{unweighted,ss,750m} = 172.9\ dB\ re\ 1\ \mu Pa^2 s$. It should be noted that variations for a certain pile size do occur, as indicated by the shaded area. This is considered to be a result of varying site conditions and hammer efficiency applied for the individual pile installations. For any project, it should therefore be considered whether the site and project specific conditions call for a more cautious source level estimate.

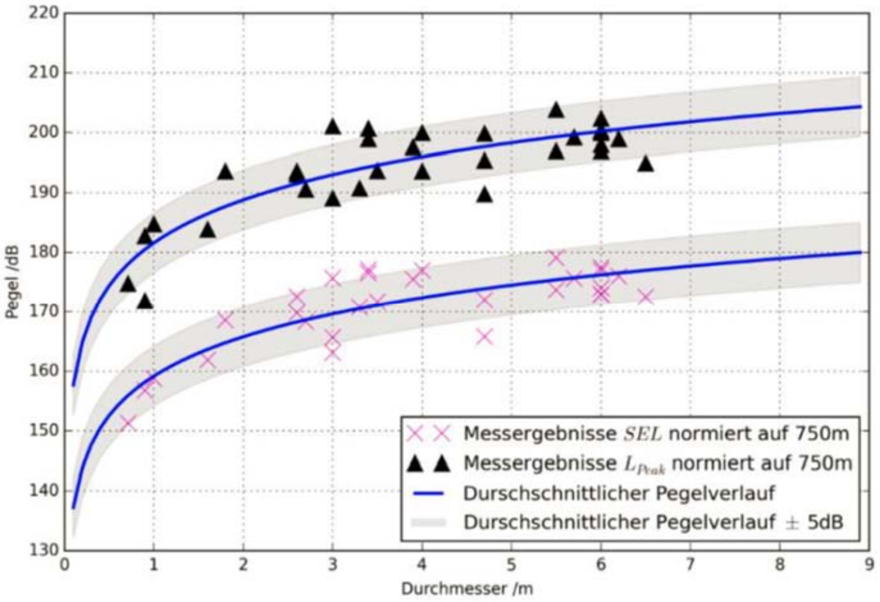


Figure 13.1. Collection of sound level measurements from impact pile driving, where X shows normalized SEL at 750 m distance, Δ shows normalized sound pressure level (Lp) at 750 m. The blue curves show best-fits for the data points, while the shaded area is a ±5 dB tolerance. From (Nehls & Bellmann 2016)

Assuming average conditions, the $SEL_{unweighted,ss,750m} = 172.9\ dB\ re\ 1\ \mu Pa^2 s$ can be used to get the $SEL_{unweighted,ss,1m}$ using Thiele's equation for sound propagation in the Baltic Sea (Thiele 2002) proposing a 4.5 dB increase in sound level pr. halving of distance. The resulting change from 750 m distance to 1 m distance equals 43.1 dB. This would indicate a source level $SEL_{unweighted,ss,1m} = 216\ dB\ re.1\ \mu Pa^2 s$ for the 4 m pile, and $SEL_{unweighted,ss,1m} = 227.4\ dB\ re.1\ \mu Pa^2 s$ for the 15 m monopile.

It is worth noting, that even the newest measurements are limited at 6.5 m monopiles, and that any extrapolation of source level of piles, beyond this size, is associated with considerable uncertainty. In our opinion the data of Nehls and Bellmann (2016) represents the best available knowledge in the field, to date.

13.1.2 Pile driving frequency spectrum

Having determined the unweighted source level $SEL_{unweighted,ss,1m}$ for the 4 m pin pile and the 15 m monopile, the frequency composition of the source must be determined in order to determine the $SEL_{<Species>,ss,1m}$.

Due to the natural variations of measured frequency content between sites, piles, water depths, hammer energy levels and other factors, it was decided to use a generalised spectrum, as it is almost guaranteed that a frequency response measured for one pile will differ for that of any other pile. In Nehls and Bellmann (2016), it is proposed to use the idealized pile spectra, as presented in Figure 13.2 (blue).

It is however deemed necessary to perform a frequency shift of the idealized spectra based on the pile diameter. The general rule is that smaller diameter piles will have their maximum levels at a higher frequency, than those of larger diameter. It was decided for this assessment to use the idealized spectrum as presented in Figure 13.2, for the 4 m pin pile. For the 15 m monopile, it was decided to use the same spectra, but shifted in frequency 2/3 octaves down. That means the upper plateau will no longer be from 125 Hz – 630 Hz, but instead from 80 Hz – 400 Hz.

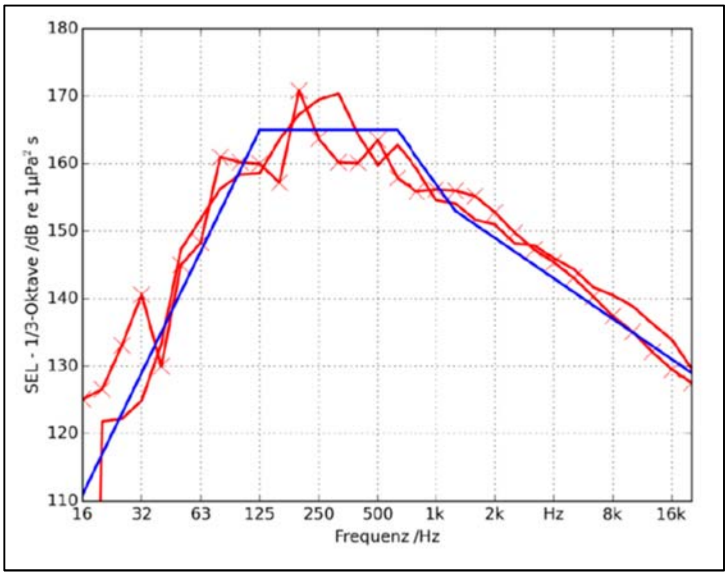


Figure 13.2. Idealized pile driving frequency spectrum (blue). Source: (Nehls & Bellmann 2016).

13.1.3 Marine mammal weighted source levels

Combining the $SEL_{unweighted,ss,1m}$ with the idealized frequency spectrum presented in Figure 13.2 (blue), and the weighting curves for the marine mammal groups identified in 4.3.2, it is now possible to determine the weighted source level $SEL_{<Species>,ss,1m}$. This weighted source levels are only used for comparing the pin pile to the monopile scenario, as actual sound propagation modelling was done individually for each individual octave band. The 15 m monopile source levels are listed in Table 13.1.

For porpoises, the HF-cetacean weighted source level becomes $SEL_{HF,ss,1m} = 181\ dB$ re. 1 µPa²s for the 4 m pin pile and $SEL_{HF,ss,1m} = 188.3\ dB$ re. 1 µPa²s for the 15 m monopile. This strongly indicates that the 15 m monopile presents the worst case scenario. For the seals, the phocid-weighted source level becomes $SEL_{PW,ss,1m} = 204\ dB$ re. 1 µPa²s for the 4 m pin pile and $SEL_{PW,ss,1m} = 212.2\ dB$ re. 1 µPa²s for the 15 m monopile, again indicating the 15 m monopile as the worst case scenario.

13.1.4 Frequency spectrum range tests

To assess the frequency spectrum range of interest, and to confirm whether or not the monopile would still result in the highest levels over long distances, test calculations were run in three directions from a random location within the Swedish Kriegers Flak wind farm site. At both 750 m, 4 km and 10 km distance, all tests indicated that the monopile resulted in the highest unweighted and weighted levels by more than 7 dB compared to the pin pile.

The tests furthermore revealed that the frequency range of interest, can be limited to 32 kHz as the highest octave band, without affecting neither unweighted nor weighted results. The noise level in the frequency band above 32 kHz were, at all distances, more than 10 dB below the highest level observed within the frequency range of 16 Hz – 25 kHz. Thus the upper frequency range of the modelling was limited to the 32 kHz octave band.

13.1.5 Detailed source levels

Based on the weighted source levels (0) and test modelling of sound propagation (13.1.4), it was decided to proceed with the 15 m monopile as the source for this project. The source parameters for the 15 m monopile, to be used for this project, are summarized in Table 13.1.

Table 13.1. Source level estimates in 1/1 octave frequency bands and overall weighted source level (SL) for a 15 m monopile. Top row indicate octave band centre frequency (Hz). Levels are given in dB weighted according to the weighting given in the leftmost column, either no weighting (broad band), HF-cetacean (porpoises) or phocid seals (harbour seal and grey seal). Unit for all values are dB re. 1 µPa²s.

Weighting	16	31.5	63	125	250	500	1k	2k	4k	8k	16k	32k	SL
Unweighted	183	201	219	222.6	222.6	219.7	208.9	202.9	196.9	190.9	184.9	178.9	227.4
HF	81.7	110.5	139.3	153.7	164.3	172.3	172.2	176.8	180.9	183.3	182.6	178.7	188.3
Phocid	142.5	166.4	190.5	200.1	205.9	208.8	203.1	200.8	196.5	190.8	183.4	173.3	212.2

13.1.6 Source mitigation measures

Due to the high source level of the pile installation procedure, it is expected that source mitigation measures will be required to avoid negative impact caused by excessive noise levels. Vattenfall therefore requested, that source levels both with and without mitigation in the form of a bubble curtain should be considered in this project.

In this section, the technical aspect of the application of noise mitigation is described, whereas the reader is referred to section 4.6.2 for general information.

In Nehls and Bellmann (2016), the noise mitigation effect of different versions of the so-called Big Bubble Curtain (BBC) for a previous offshore wind farm installation are examined, and the achieved sound mitigation in dB is presented in 1/3 octave bands (see Figure 13.3). This was implemented in the software dBSea in 1/1 octave bands, and the resulting mitigated source levels are presented in Table 13.2. Overall broad band attenuation of the bubble curtain is thus 5.5 dB (found by comparing unweighted source levels from Table 13.1 and Table 13.2), whereas attenuation is higher for both HF-weighted and phocid-weighted levels, 13.1 dB and 10 dB, respectively.

Table 13.2. Source level estimates in 1/1 octave frequency bands and overall weighted source level (SL) for a 15 m monopile, with BBC source mitigation system. Top row indicate octave band centre frequency (Hz). Levels are given in dB weighted according to the weighting given in the leftmost column. Unit for all values are dB re. 1 µPa²s. Compare to **Table 13.1** for source characteristics without noise reduction implemented.

Weighting	16	31.5	63	125	250	500	1k	2k	4k	8k	16	32	SL
Unweighted	184.5	200.3	217.5	218.1	214.3	208.2	189.1	178.3	172.8	170.4	172.4	172.8	221.9
HF	83.2	109.8	137.8	149.2	156	160.8	152.4	152.2	156.8	162.8	170.1	172.6	175.2
Phocid	144	165.7	189	195.6	197.6	197.3	183.3	176.2	172.4	170.3	170.9	167.2	202.2

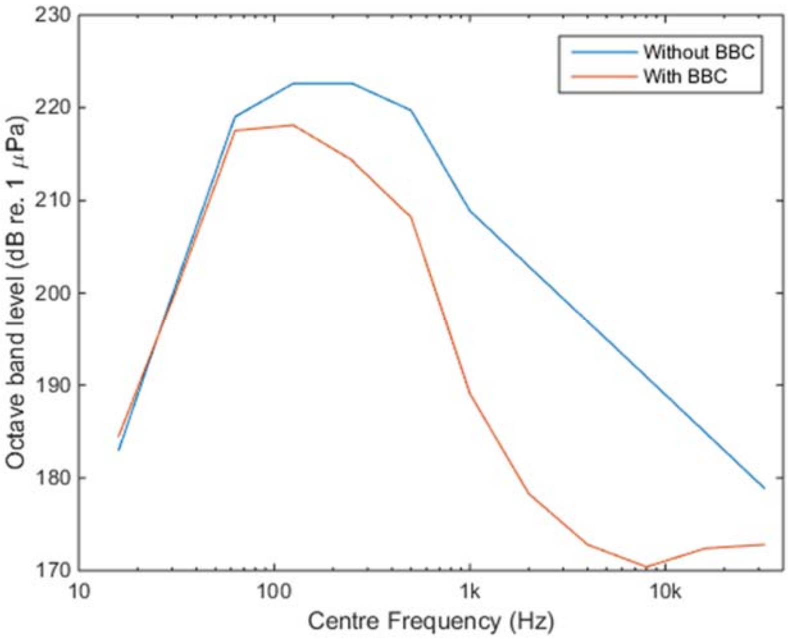


Figure 13.3. Unweighted source spectra used for modelling of sound transmission from 15 m monopile, both for the scenario without (blue) and with (red) use of a bubble curtain to attenuate the noise.

13.2 Pile Installation Procedure

This section describes the expected pile installation procedure for the project, and identifies the parameter values S_i, N and Δt_i, which describes the pile driving hammer scenario used for this assessment (described in section 6.2.2). Foundations are expected to be installed at a maximum rate of one foundation per day. Each pile installation will consist of three phases. The first phase is a pre-piling deterrent phase, where pingers and / or seal scarers are used to clear marine mammals from the immediate area around the pile location. See section 4.6.3 and 6.4.2 for additional details. The second phase is a soft-start piling phase, where a low hammer energy is used to settle the pile followed by a gradual ramp-up of hammer energy based on the sediment conditions, to account for the increased friction and resistance of harder sediment layers. Ultimately the third and final phase is reached, where piling continues with maximal hammer energy until the monopile has reached the desired penetration.

For this assessment, a final pile design and driveability analysis has not been performed, and it is therefore not yet known what the frequency of pile strikes, nor the hammer energy applied, will be. It was therefore decided to take a precautious approach, for the sake of this assessment representing the worst-case scenario. This scenario was described above in section 6.2.2.

13.3 Underwater Sound Propagation

This section will give a brief overview of underwater sound propagation theory and the software program used to model it, followed by a description of the environmental inputs required by the sound propagation model.

13.3.1 Underwater sound propagation theory

The theory in this section is drawn from the book, Computational Ocean Acoustics, 2nd edition (Jensen *et al.* 2011), chapter 1 and 3.

The section seeks to provide a brief introduction to sound propagation in saltwater. The interested reader is referred to Computational Ocean Acoustics, 2nd edition, for a more exhaustive explanation of underwater sound propagation theory.

In saltwater, the sound pressure level generally decreases with increasing distance from the source. However, many parameters influence the propagation and makes it a complex process.

The speed of sound in the sea, and thus the sound propagation, is a function of pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean, and as such are very location specific.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile.

Snell's law states that:

Equation 13.3

$$\frac{\cos(\theta)}{c} = constant$$

Where θ is the ray angle, and c is the speed of sound [m / s], thus implying that sound bends toward regions of low sound speed(Jensen *et al.* 2011). The implications for sound in water are, that sound that enters a low velocity layer in the water column, can get trapped there. This results in the sound being able to travel far with a very low transmission loss.

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to as an upward refraction. This causes the sound waves to be reflected by sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes reduced transmission loss. This scenario will always be the worst case situation in terms of sound transmission loss.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled steeper towards the seabed rather than the sea surface, and it will thus be the absorption and reflection of the seabed, that determines the transmission loss.

In any general scenario, the upward refraction scenario will cause the lowest transmission loss, and thus be considered worst case.

In waters with strong currents, the relationship between temperature and salinity is relatively constant as the water is well-mixed throughout the year. In the Baltic Sea however, the waters are generally not well-mixed and great differences in the relation between temperature and salinity over depth, can be observed. Furthermore, this relationship depends heavily on the time of year, where the winter months are usually characterized by upward refracting or iso-velocity sound speed profiles. In the opposite end of the scale, the summer months usually have downward refracting sound speed profiles. In between the two seasons, the sound speed profile gradually change between upward and downward refraction.

The physical properties of the sea surface and the seabed, further affect the sound propagation by reflecting, absorbing and scattering the sound waves.

Roughness, density and media sound speed, are among the properties that define how the sound propagation is affected by the upper and lower boundaries.

The sea surface state is affected mainly by the climate above the water. The bigger the waves, the more rough the sea surface, and in turn, the bigger the transmission loss from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective medium with very low sound absorption. In rough seas, the sound waves will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss in the outward direction. In the context of implementing these changes into the model, the different surface conditions are simply too unpredictable, to serve as a reliable variable. It is therefore always the most conservative scenario, being a completely smooth sea surface, that is used in the calculations.

Another parameter that has influence on especially the high frequency transmission loss over distance, is the volume attenuation, defined as an absorption coefficient reliant on chemical conditions of the water column. This parameter has been approximated by:

Equation 13.4

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4} f^2 \qquad (dB/km)$$

Where f is the frequency of the wave in kHz (Jensen *et al.* 2011). This infers that increasing frequency also leads to increased absorption.

13.3.2 Underwater noise modelling software

Software for underwater noise modelling software was dBSea version 2.2.4, developed by Marshall Day Acoustics (Pedersen & Keane 2016).

The software uses bathymetry, sediment and sound speed input data to build a 3D acoustic model of the environment. This model, paired with accurate sound propagation models, such as dBSeaPE, a Parabolic Equation algorithm and dBSeaRay, a Ray Theory algorithm, make for accurate prediction of the sound propagation.

Parabolic equation algorithms are known to be the most accurate for modelling low frequencies in shallow water scenarios, while ray theory algorithms deliver the best performance at higher frequencies.

As described in section 13.3.1, the sound propagation depends primarily on the site bathymetry, sediment and sound speed conditions. These are examined in the following.

13.3.3 Bathymetry

dBSea incorporates range-dependent bathymetry modelling, and supports raster and vector bathymetry import. Several open databases, such as the EMODnet Bathymetry portal - http://www.emodnet-bathymetry.eu provide bathymetric maps for all of EU, however with limited resolution of 0.125 arc-minutes between data points.

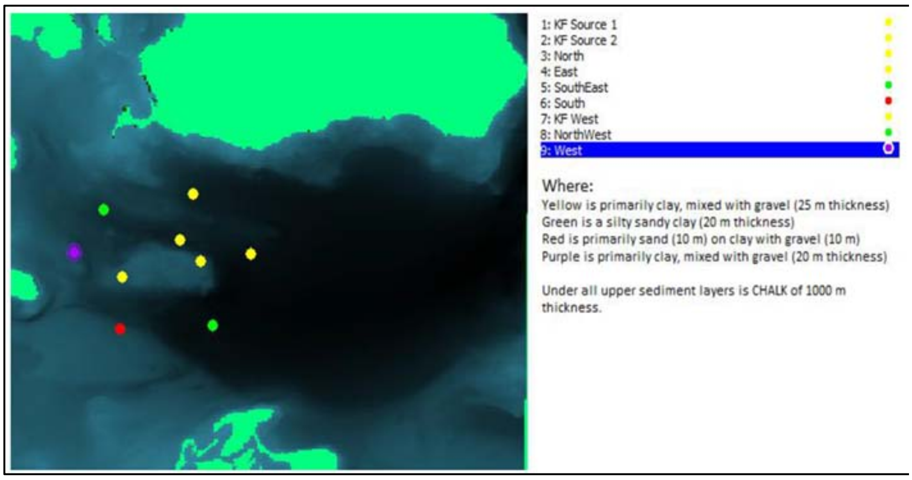
For long range sound propagation modelling as is the case in this project, the resolution is generally considered sufficient. A bathymetry map from the EMODnet portal was therefore acquired, and implemented in dBSea.

dBSea provides the option of using either a single or a multi-point sediment model. The multi-point model allows for different sediment profiles within the project area, while the single point sediment model uses the same sediment composition for the entire project area.

For small project areas, the sediment variations in the project area will usually be acoustically insignificant, and single point models will therefore be preferred. For projects where long distance sound propagation is required, a multipoint model could deliver more accurate results.

Niras has, with the help of Jakob Tougaard, attempted to identify the different sediment layers in the surrounding area both on and off Kriegers Flak. Sources studied include the geological maps supplied by Vattenfall A/S, the geological reports, and publicly available databases GEUS.dk, SGU.se, BGR.de. Also, the book "Danmarks Geologi" chapter 4, was used to identify the thickness of the chalk layer.

Due to the highly varying nature of sediment composition on and near Kriegers Flak, it was chosen to use a multi-point sediment model representing the broad average of the area. This resulted in a 9 point model as illustrated in Figure 13.4. Between points, dBSea interpolates the layer information.



1: KF Source 1 🟡
2: KF Source 2 🟡
3: North 🟡
4: East 🟡
5: SouthEast 🟢
6: South 🔴
7: KF West 🟡
8: NorthWest 🟢
9: West 🟣

Where:
Yellow is primarily clay, mixed with gravel (25 m thickness)
Green is a silty sandy clay (20 m thickness)
Red is primarily sand (10 m) on clay with gravel (10 m)
Purple is primarily clay, mixed with gravel (20 m thickness)

Under all upper sediment layers is CHALK of 1000 m thickness.

Figure 13.4. Multi-point sediment model as implemented in dBSea.

13.3.4 Sound speed profiles

As described, the sound propagation depends not only on bathymetry but also the season dependent sound speed profile. Temperature, depth and salinity information from NOAAs World Ocean Atlas database (WOA13v2), available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa13/ was thus inspected. Through the Coppens Equation, this was used to calculate the sound speed profile (Coppens 1981) for all 12 months of the year at the location nearest the Kriegers Flak site. It was decided to proceed with the months of January and June. January represents a worst-case scenario with a surface sound speed minimum, which will lead to upward-refraction of the sound and thus increased sound exposure in the water column. July represents a typical summer scenario, taken to be representative for the time of year where installation is likely to take place.

The WOA13v2 database was then accessed again, to extract additional information from the 4 positions nearest Kriegers Flak, for which information was available for the month of January and June. The positions are shown on Figure 13.5 and information from these locations have been assigned to the closest positions used in the sediment map.

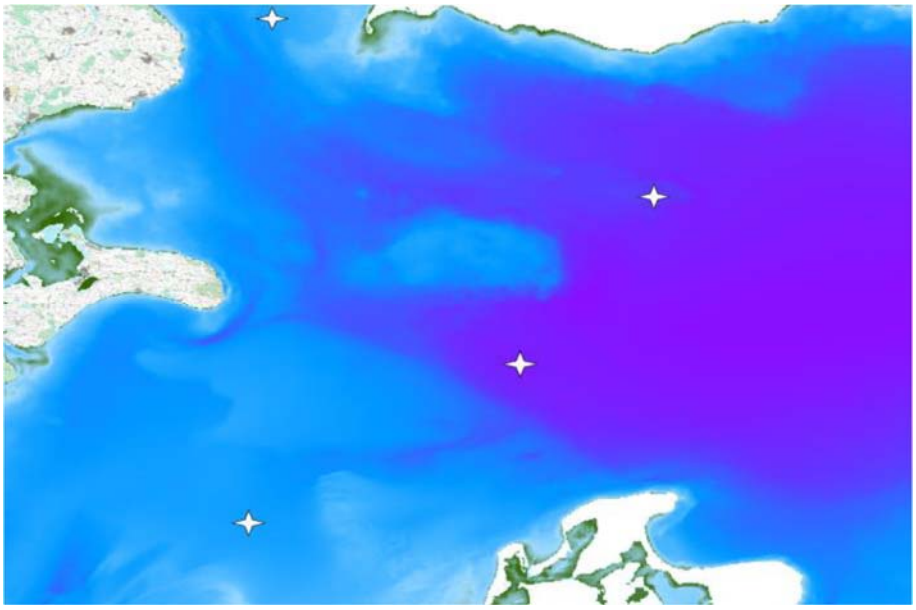


Figure 13.5. Illustration of Kriegers Flak, and the nearest data points from WOA13 with temperature and salinity information for the months of January and June. The four stars indicate the 4 positions used for calculations of the sound speed profiles.

The sound speed profiles calculated for the four positions, are shown in Figure 13.6 for January (blue) and June (red).

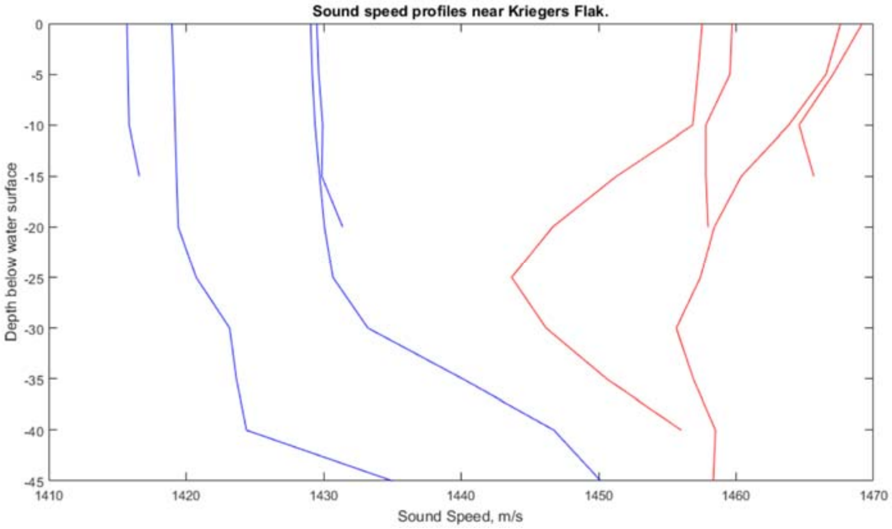


Figure 13.6. Sound speed profile for the four positions in January (blue) and June (red).

The profiles are taken from the four shown positions, where:

- The 15 m depth profiles are from the northernmost position
- The 20 m depth profiles are from the southernmost position
- The 45 m depth profiles with the lowest overall sound speed for each month are taken from the position east of Kriegers Flak
- The 45 m depth profiles with the highest overall sound speed for each month are taken from the position south of Kriegers Flak.

As shown in Figure 13.6 winter conditions tend to lead to upward refracting (lower calculated transmission loss), and summer to downward refraction (higher calculated transmission loss).

13.3.5 Summary of environmental inputs

- Bathymetry from EMODNET is used. Resolution is 0.125 arc-minutes.
- Sediment profiles are implemented in 9 positions on and around Kriegers Flak
- Sound speed profiles for January and June have been calculated from WOA13v2 from 4 nearest positions, and mapped to the 9 sediment positions.

13.3.6 Choice of pile installation locations

Based on the layout of the Swedish Kriegers Flak offshore wind farm site, two positions were chosen for further modelling. The positions are shown in Figure 13.7, where position 1, was chosen due to its location off the Flak, in the deepest part of the site and directly facing the Natura2000 area “Skånes Utsjövätten”. Position 2 was chosen due to its location on the edge of the Flak, thereby offering insight into the sound propagation over the shallower parts, as well as downhill towards the east and south.

The longitude, latitude coordinates (EPSG: 3006) are 377000, 6108000 for position 1 and 382000, 6102000 for position 2.

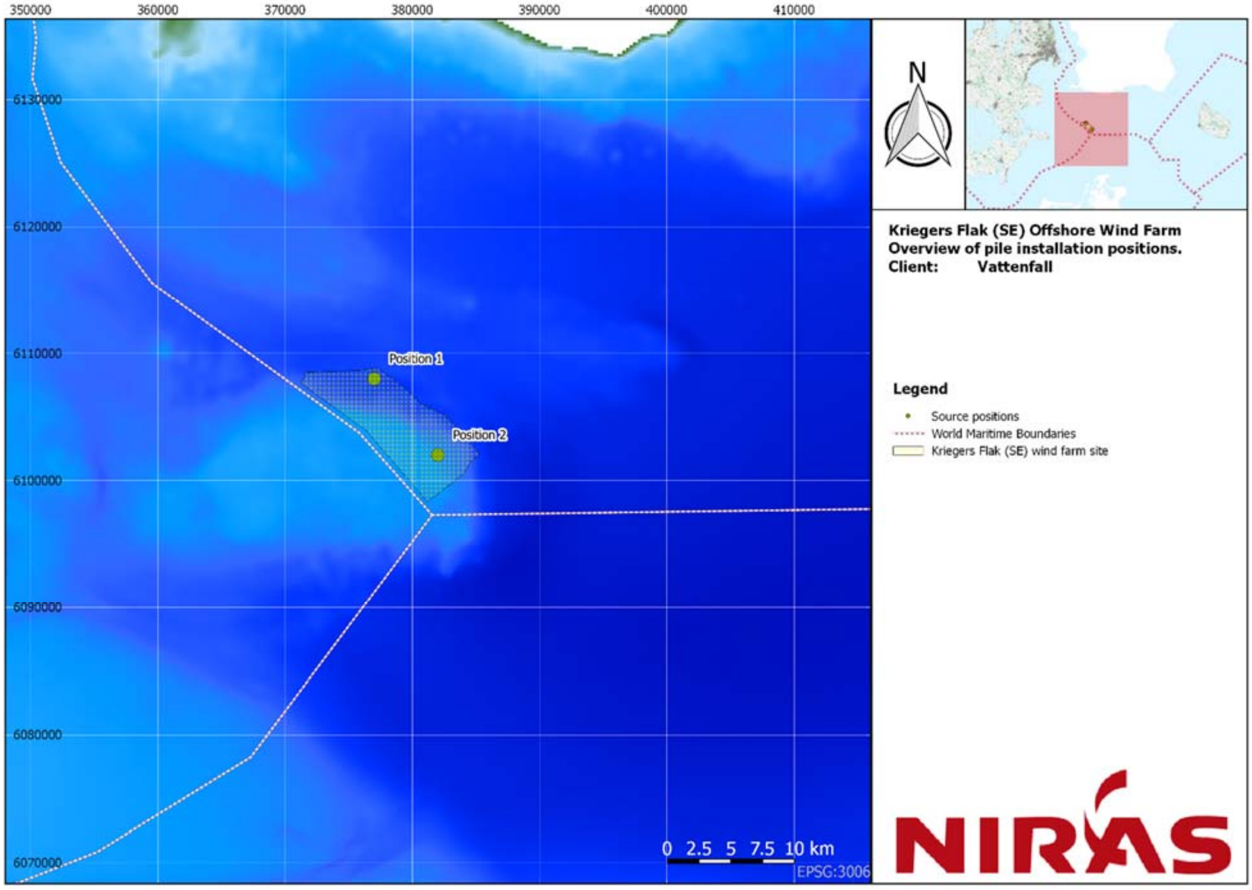


Figure 13.7. Overview of chosen pile installation positions for the Swedish Kriegers Flak offshore wind farm, where Position 1: [377000 ; 6108000] and Position 2: [382000 ; 6102000].

13.4 Sound propagation modelling results

To determine the parameters κ and α required by the simple, geometric transmission loss model (Equation 6.5), a sound propagation model was built in dBSea 2.2.4, based on all source and environment information presented so far.

Based on the water depth for the area, it was decided to use a split-solver approach, where the dBSeaPE algorithm was used for the low frequencies from 16 Hz – 500 Hz, and where the dBSeaRay algorithm was used for the high frequencies from 1 kHz – 32 kHz.

It was decided to model the sound exposure level at $\cong 115\ m$ interval, matching the bathymetry detail level, and with a spatial resolution of 1° (360 directions). The depth interval between each sampling was 1 m. Individual models were designed in dBSea for each combination of source position (1, 2), months (January, June) and active mitigation measures (none, BBC), to a total of 8 dBSea models.

From each of these models, three sound exposure level maps where created. One for each metric (unweighted, HF Cetacean, Pinniped in Water), totalling 24 sound exposure level maps. For graphic presentation of the sound propagation modelling results, 5 dB contour plots were made from the dBSea output for each modelled scenario. All results are given as the maximum sound exposure level at any depth. One example of a sound exposure map is shown in Figure 13.8. All modelled maps are shown in Appendix 2.

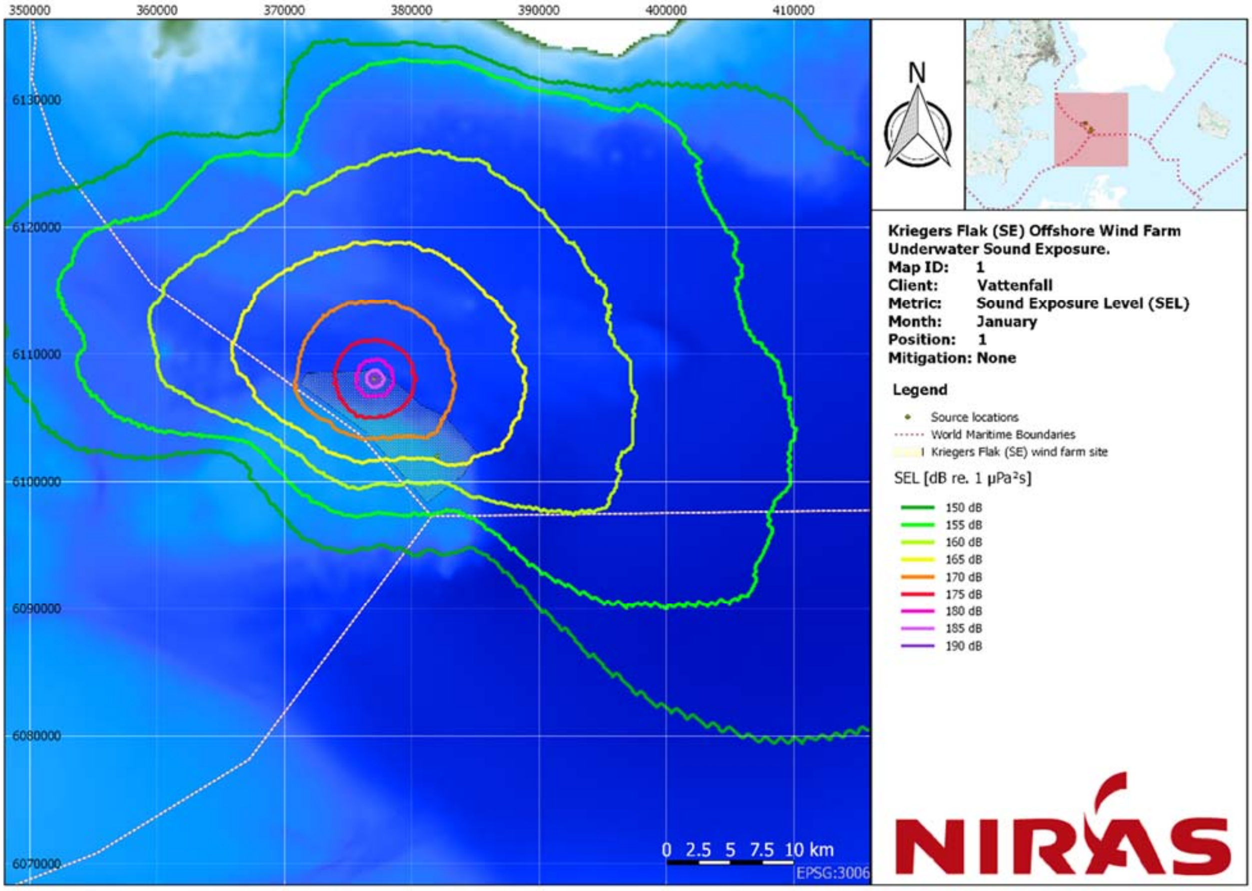


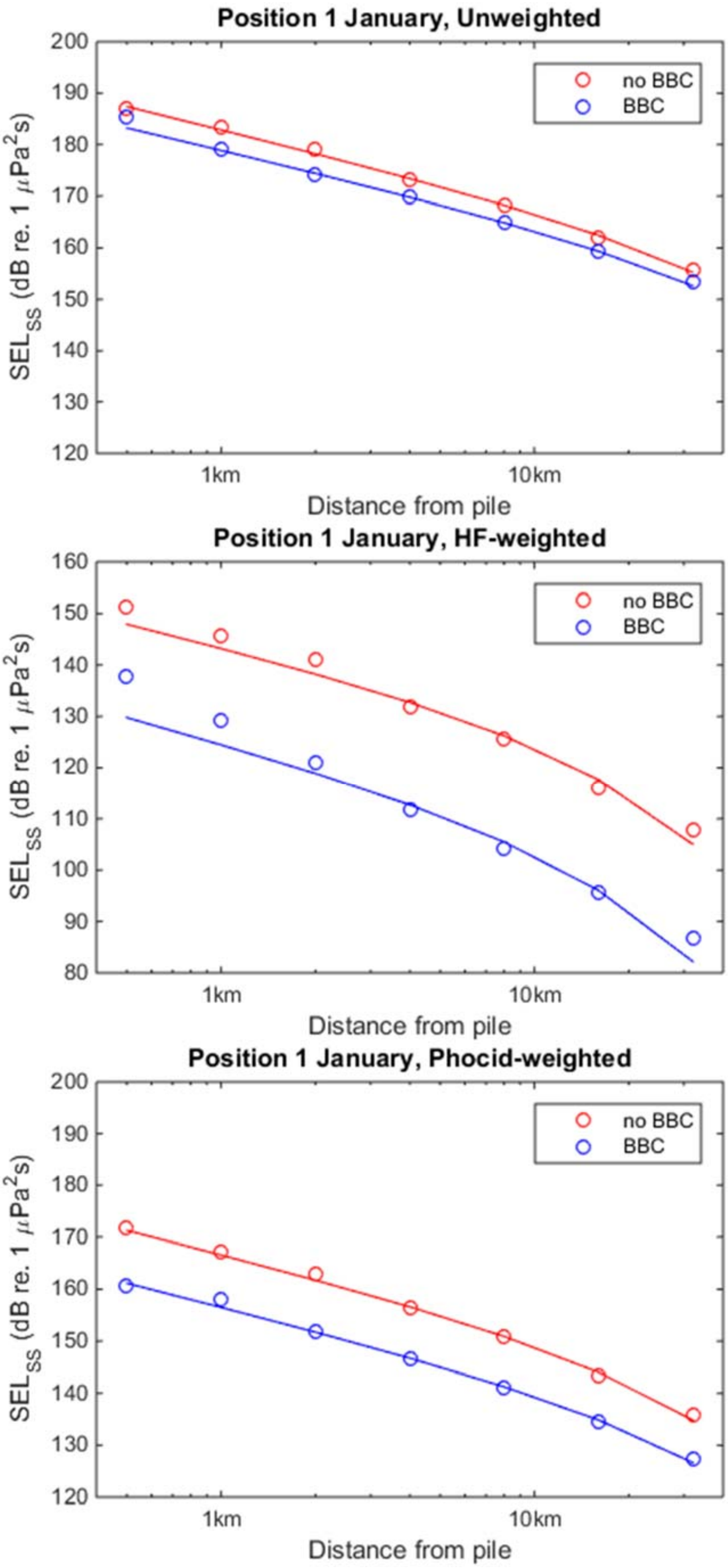
Figure 13.8. Unweighted underwater noise modelling results for position 1 January, where colour coded contours in 5 dB steps show the Sound Exposure Level.

Each map was exported to QGIS, where the sound exposure level was examined manually at distances of 500 m, 1 km, 2 km, 4 km, 8 km, 16 km and 32 km radius, and the maximum occurring sound exposure levels along these radii were read. From these distances, SEL results, a curve fit was applied to each of the 24 maps, in the form: $TL = SEL_{<Species>,ss,1m} - \kappa * log10(r) - \alpha * r$, where TL is the sound transmission loss in dB and "r" is the distance from the pile installation in meters. Solving this equation for the sound propagation parameters κ and α resulted in 24 equations for the worst-case sound propagation, one for each map. These results are presented in Table 13.3. Examples of sound transmission models derived as described above and subsequently used in the exposure modelling, as described in section 7, are shown in Figure 13.9.

Table 13.3. Sound propagation modelling results, by month, position, mitigation measures and species-specific frequency weighting. Where κ and α are the sound propagation parameters in the transmission loss formula: $\mathrm{TL} = \mathrm{SEL}_{<\mathrm{Species}>,\mathrm{ss},1\mathrm{m}} - \kappa * \log 10(\mathrm{r}) - \alpha * \mathrm{r}$.

Month	Position	Mitigation	Weighting	κ	α
January	1	None	Unweighted	14.80	0.00017
			HF Cetaceans	14.86	0.00051
			Phocid	15.11	0.00029
		BBC	Unweighted	14.30	0.00015
			HF Cetaceans	16.73	0.00055
			Phocid	15.09	0.00023
	2	None	Unweighted	14.65	0.00015
			HF Cetaceans	15.22	0.00052
			Phocid	15.24	0.00028
		BBC	Unweighted	14.11	0.00014
			HF Cetaceans	16.79	0.00055
			Phocid	15.04	0.00020
June	1	None	Unweighted	15.01	0.00021
			HF Cetaceans	14.97	0.00082
			Phocid	15.23	0.00030
		BBC	Unweighted	14.57	0.00020
			HF Cetaceans	16.99	0.00053
			Phocid	15.29	0.00022
	2	None	Unweighted	14.91	0.00021
			HF Cetaceans	15.89	0.00064
			Phocid	15.38	0.00025
		BBC	Unweighted	14.42	0.00022
			HF Cetaceans	17.58	0.00039
			Phocid	15.28	0.00019

Figure 13.9. Modelled (worst case) transmission loss curves for the unweighted, HF-cetacean weighted and phocid weighted levels generated by pile driving of a 15 m diameter monopile. Results of modelling with and without use of a bubble curtain (BBC) is shown.



14. Appendix 2 – Sound propagation results

14.1 Unweighted single strike SEL

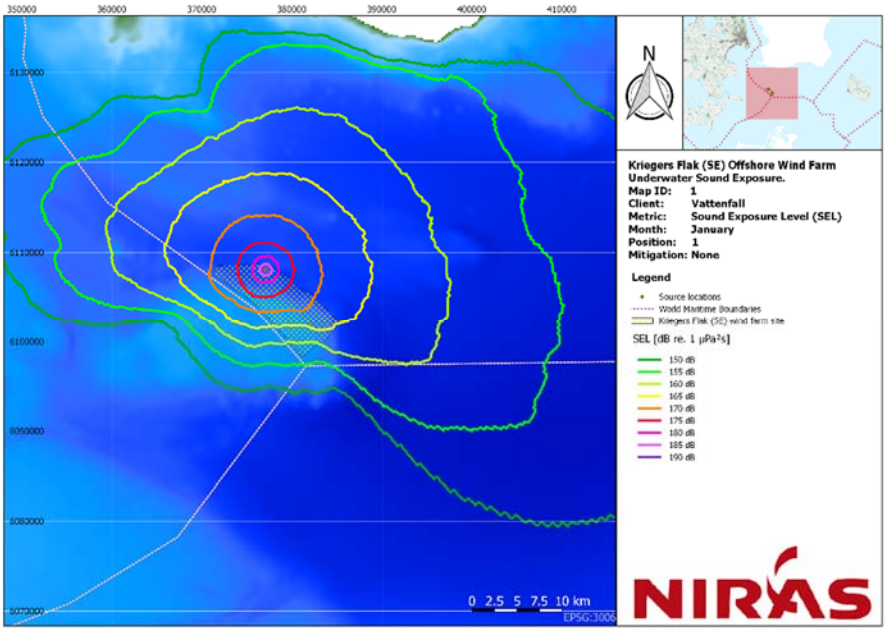


Figure 14.1. Unweighted (broadband) SEL of single pile driving pulses. Position 1, January, no bubble curtain.

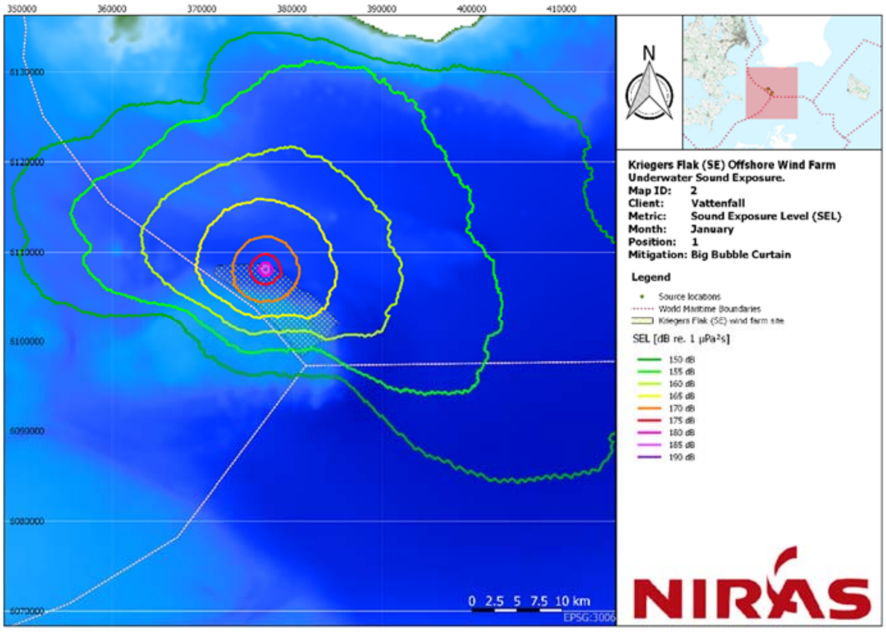


Figure 14.2. Unweighted (broadband) SEL of single pile driving pulses. Position 1, January, bubble curtain.in operation.

Figure 14.3. Unweighted (broadband) SEL of single pile driving pulses. Position 2, January, no bubble curtain.

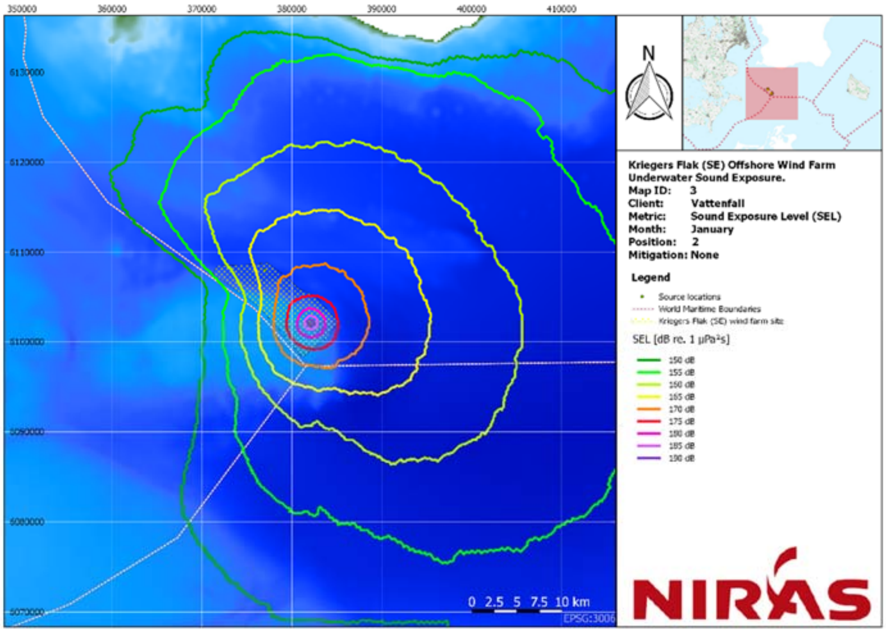


Figure 144.4. Unweighted (broadband) SEL of single pile driving pulses. Position 2, January, bubble curtain.in operation.

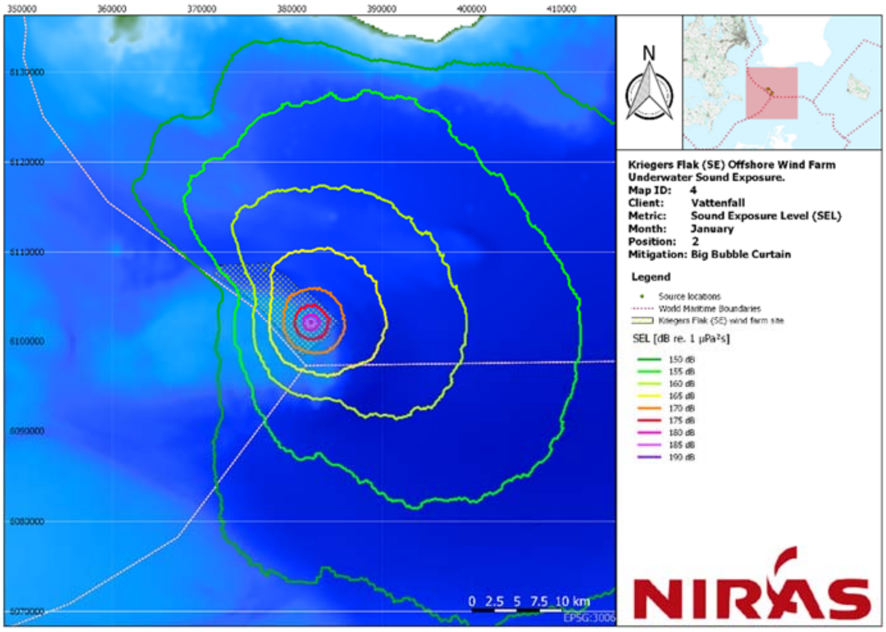


Figure 14.5. Unweighted (broadband) SEL of single pile driving pulses. Position 1, June, no bubble curtain.

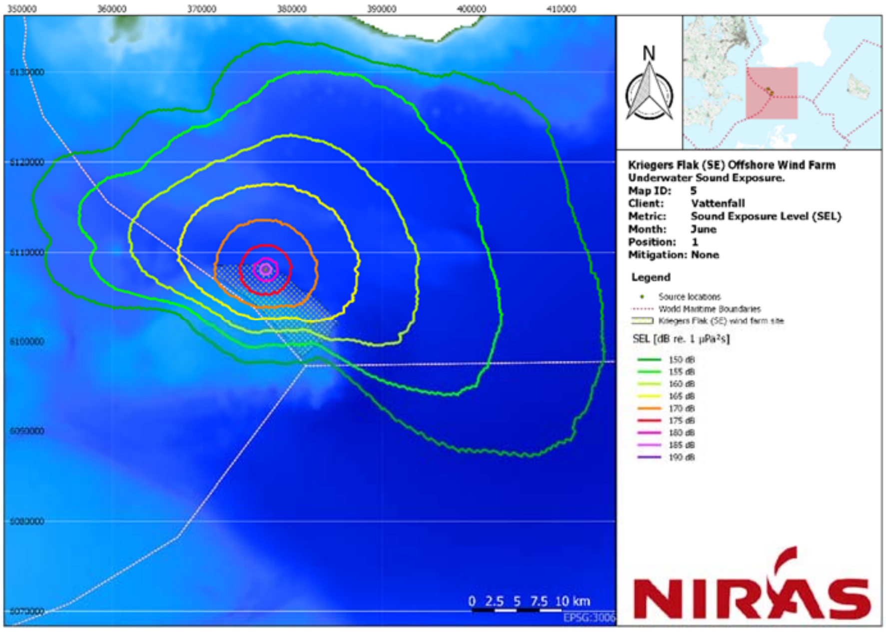
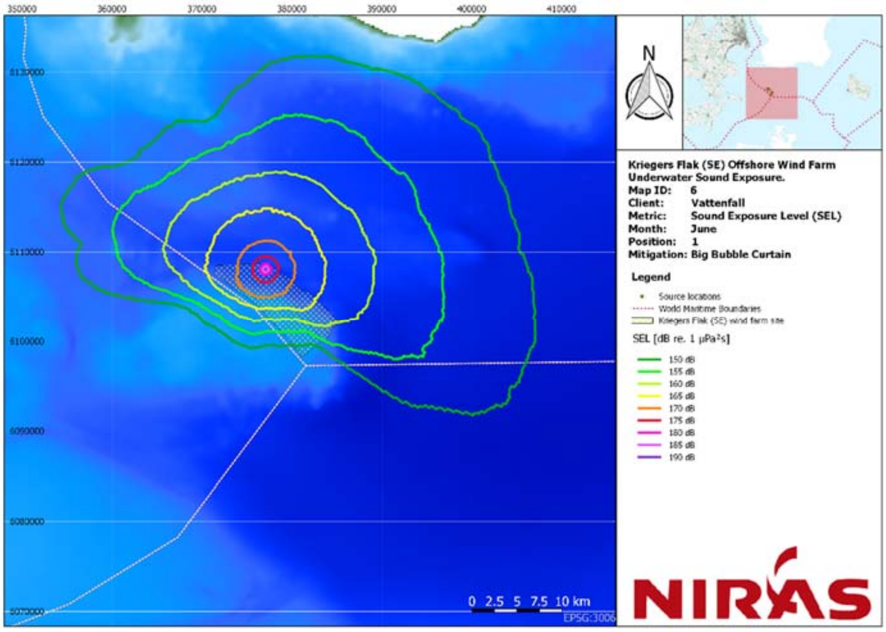


Figure 14.6. Unweighted (broadband) SEL of single pile driving pulses. Position 1, June, bubble curtain.in operation.



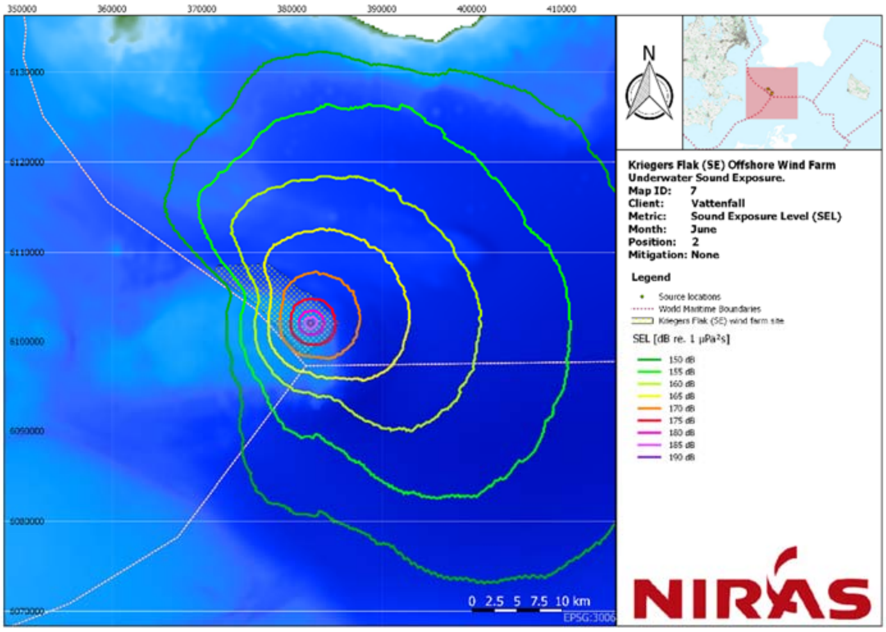


Figure 14.7. Unweighted (broadband) SEL of single pile driving pulses. Position 2, June, no bubble curtain.

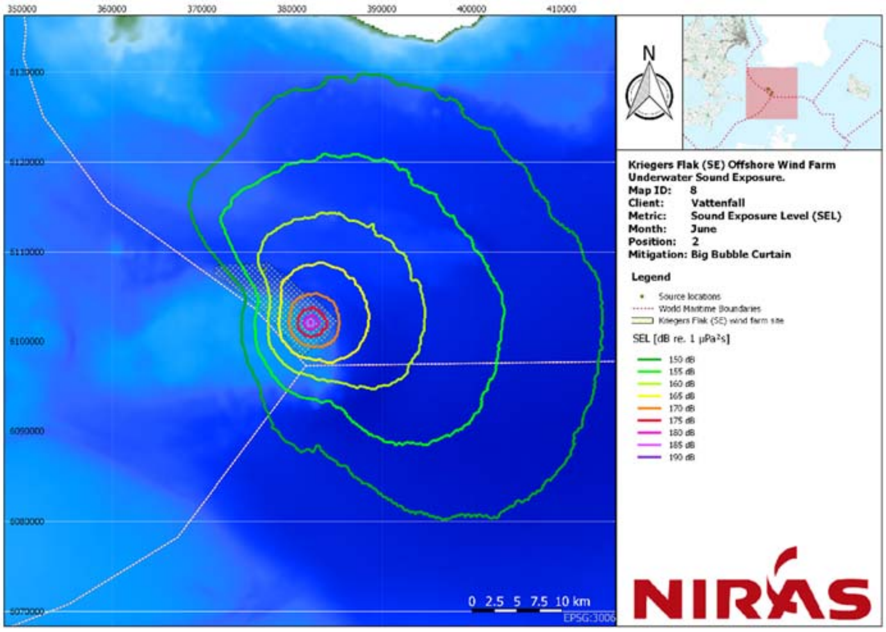


Figure 14.8. Unweighted (broadband) SEL of single pile driving pulses. Position 2, June, bubble curtain.in operation.

14.2 HF-cetacean weighted single strike SEL

Figure 14.9. HF-cetacean weighted SEL of single pile driving pulses. Position 1, January, no bubble curtain.

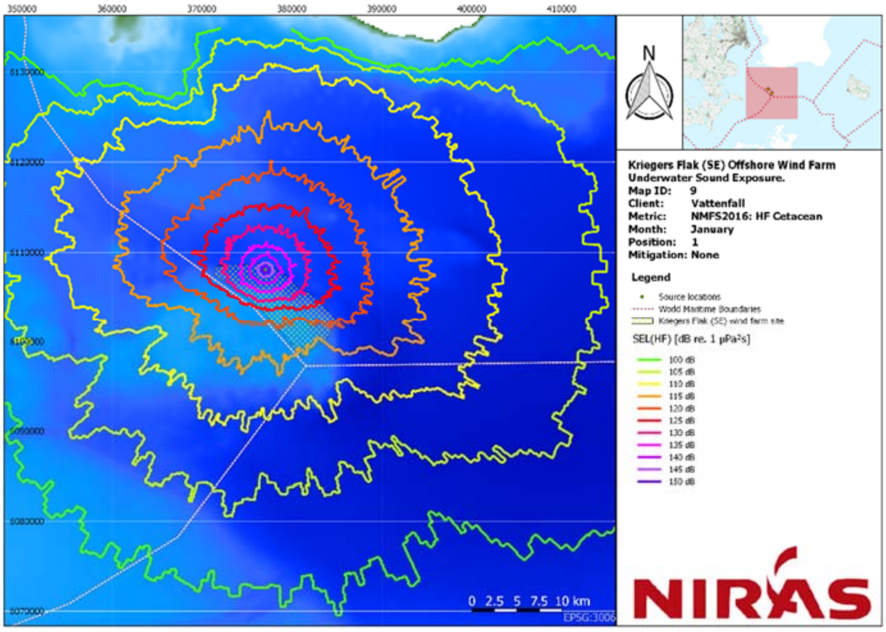
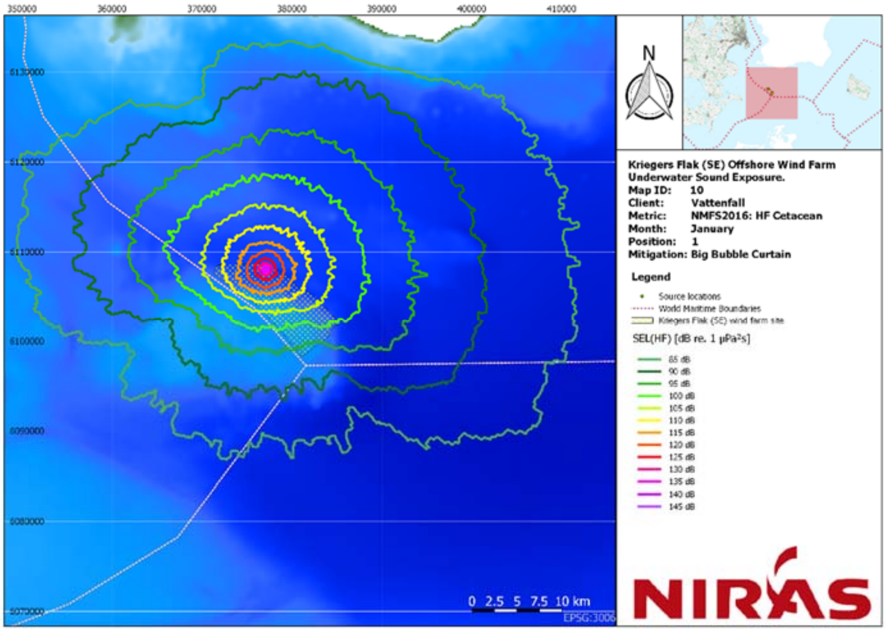


Figure 14.10. HF-cetacean weighted SEL of single pile driving pulses. Position 1, January, bubble curtain in operation.



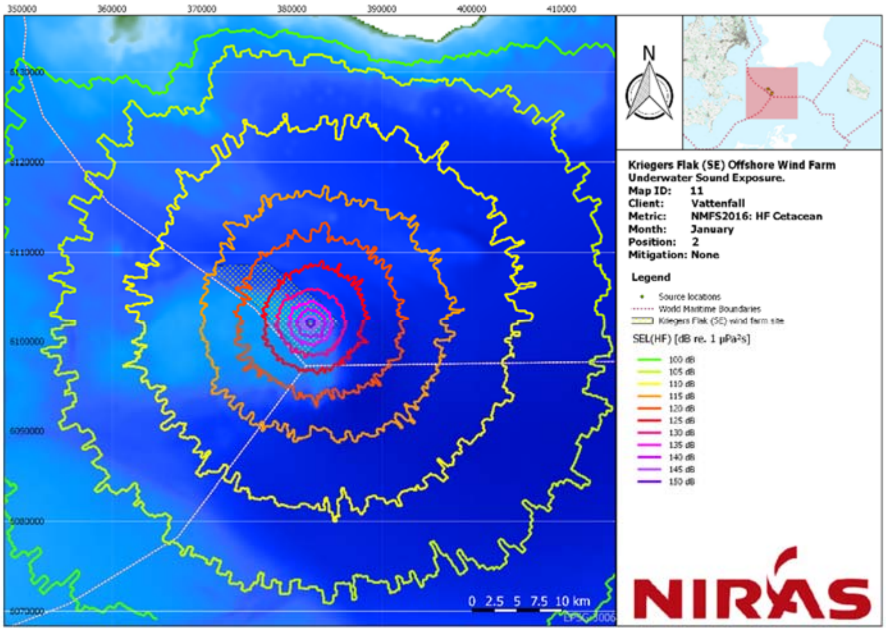


Figure 144.11. HF-cetacean weighted SEL of single pile driving pulses. Position 2, January, no bubble curtain.

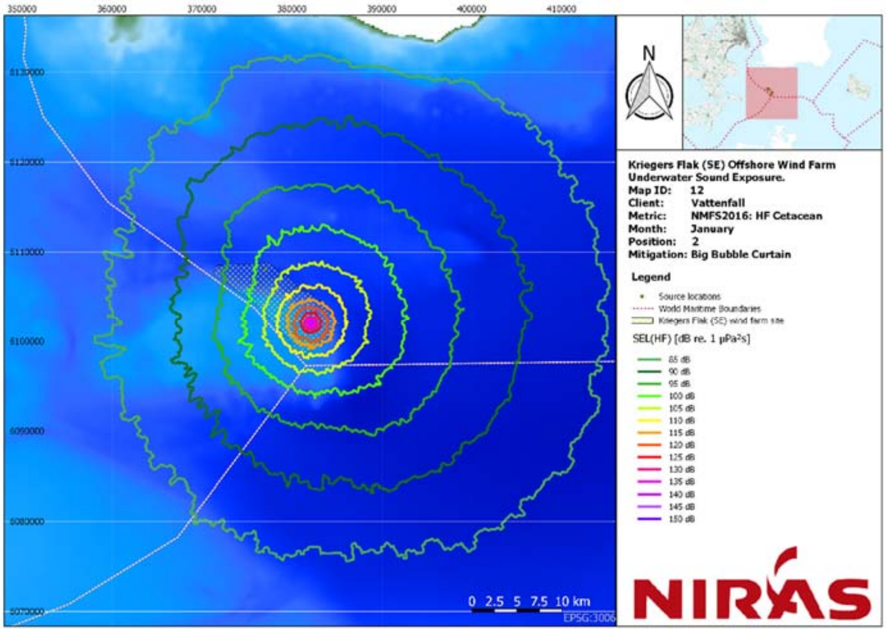


Figure 14.12. HF-cetacean weighted SEL of single pile driving pulses. Position 2, January, bubble curtain in operation.

Figure 14.13. HF-cetacean weighted SEL of single pile driving pulses. Position 1, June, no bubble curtain.

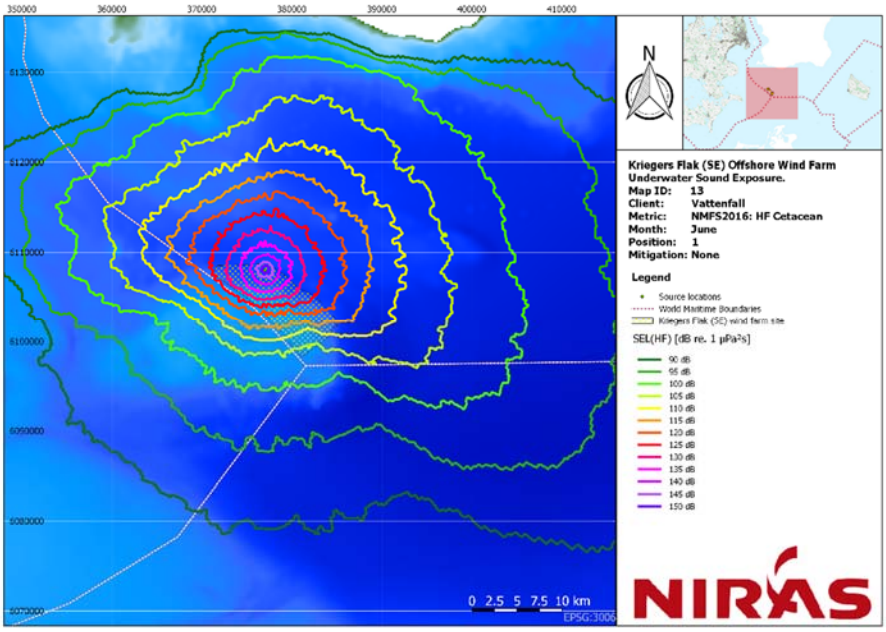
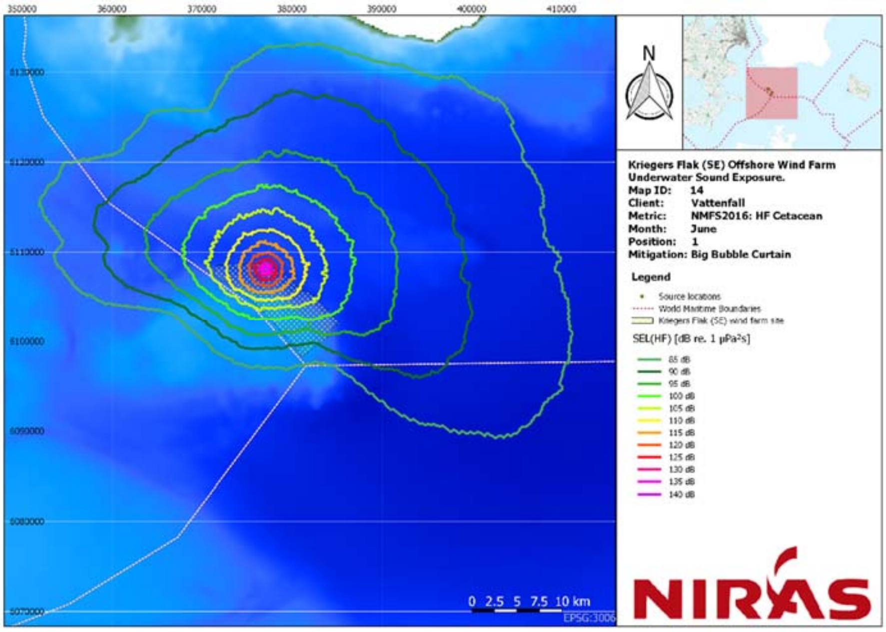


Figure 14.14. HF-cetacean weighted SEL of single pile driving pulses. Position 1, June, bubble curtain in operation.



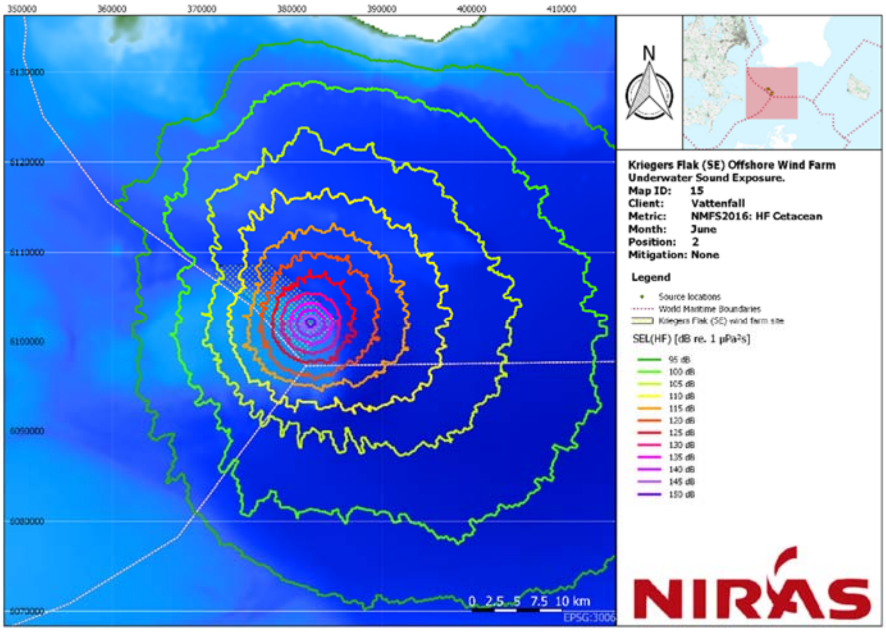


Figure 14.15. HF-cetacean weighted SEL of single pile driving pulses. Position 2, June, no bubble curtain.

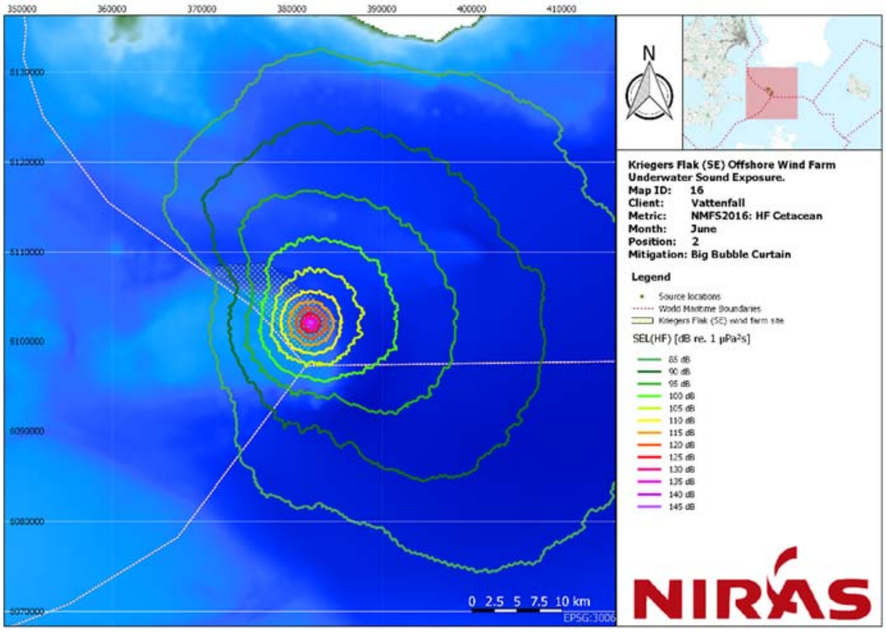


Figure 14.16. HF-cetacean weighted SEL of single pile driving pulses. Position 2, June, bubble curtain in operation.

14.3 Phocid-weighted single strike SEL

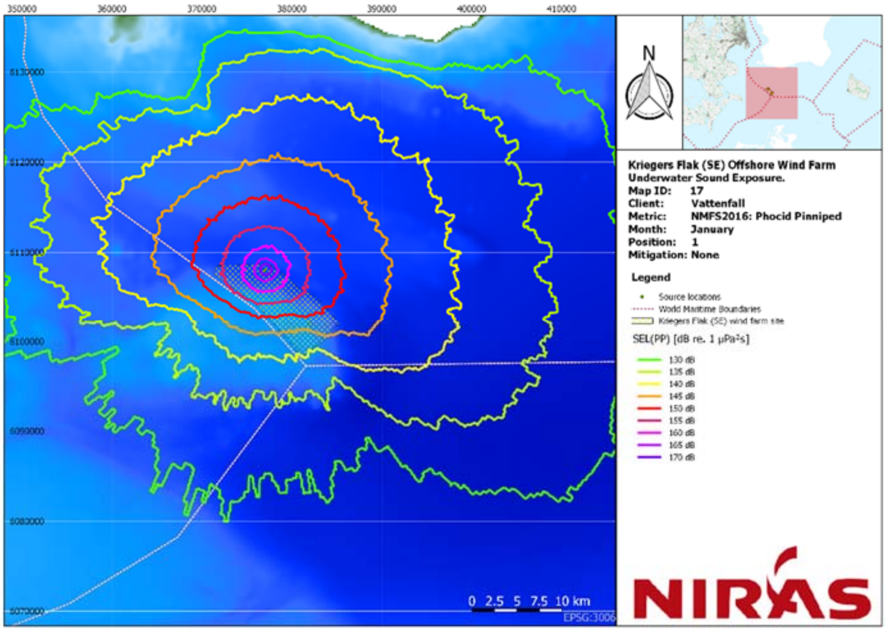


Figure 14.17. Phocid weighted SEL of single pile driving pulses. Position 1, January, no bubble curtain.

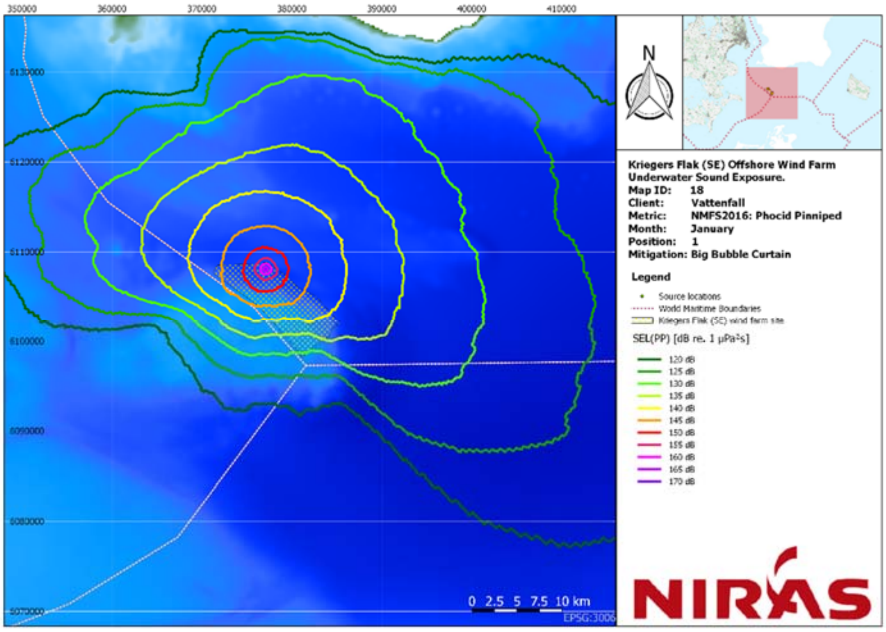


Figure 14.18. Phocid weighted SEL of single pile driving pulses. Position 1, January, bubble curtain in operation.

Figure 14.19. Phocid weighted SEL of single pile driving pulses. Position 2, January, no bubble curtain.

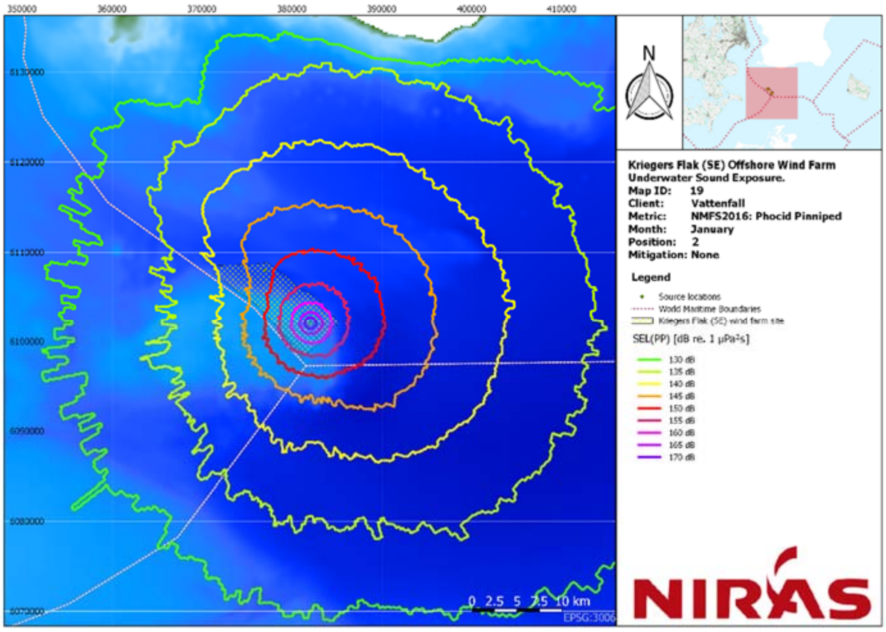


Figure 14.20. Phocid weighted SEL of single pile driving pulses. Position 2, January, bubble curtain in operation.

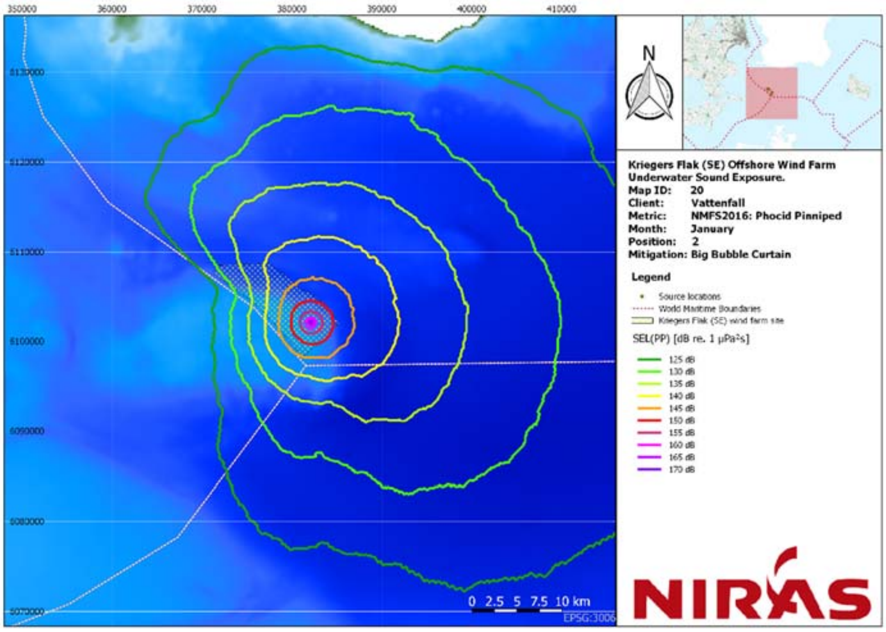


Figure 14.21. Phocid weighted SEL of single pile driving pulses. Position 1, June, no bubble curtain.

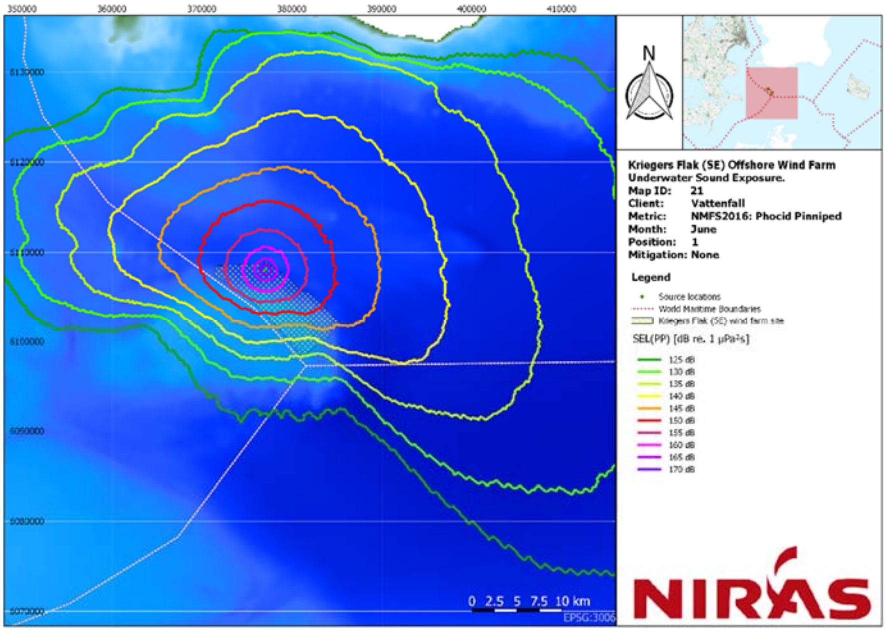
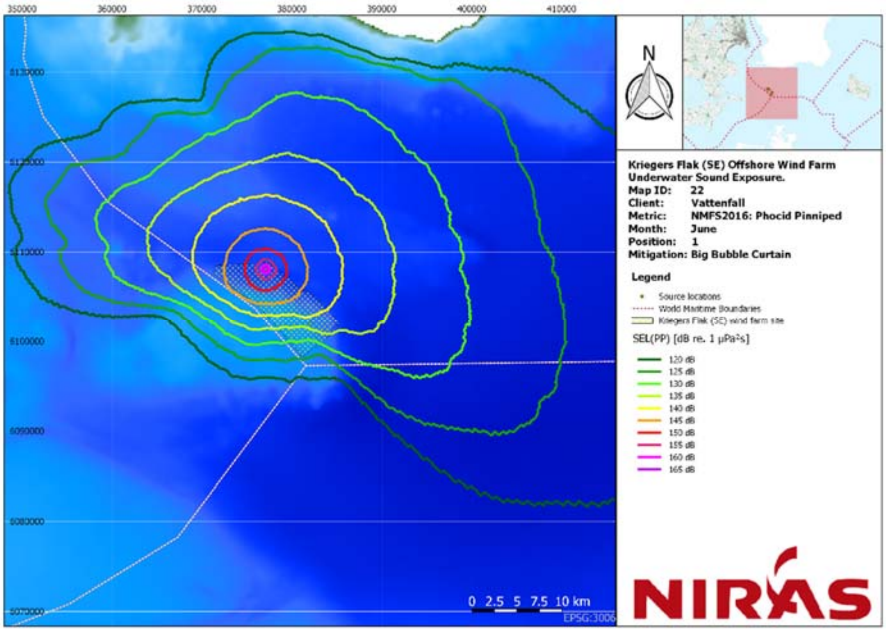


Figure 14.22. Phocid weighted SEL of single pile driving pulses. Position 1, June, bubble curtain in operation.



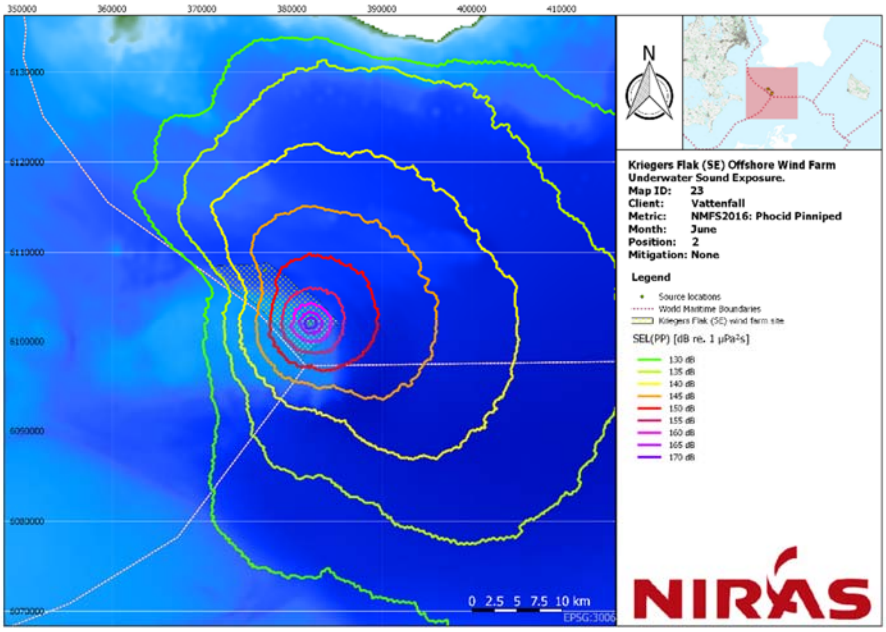


Figure 14.23. Phocid weighted SEL of single pile driving pulses. Position 2, June, no bubble curtain.

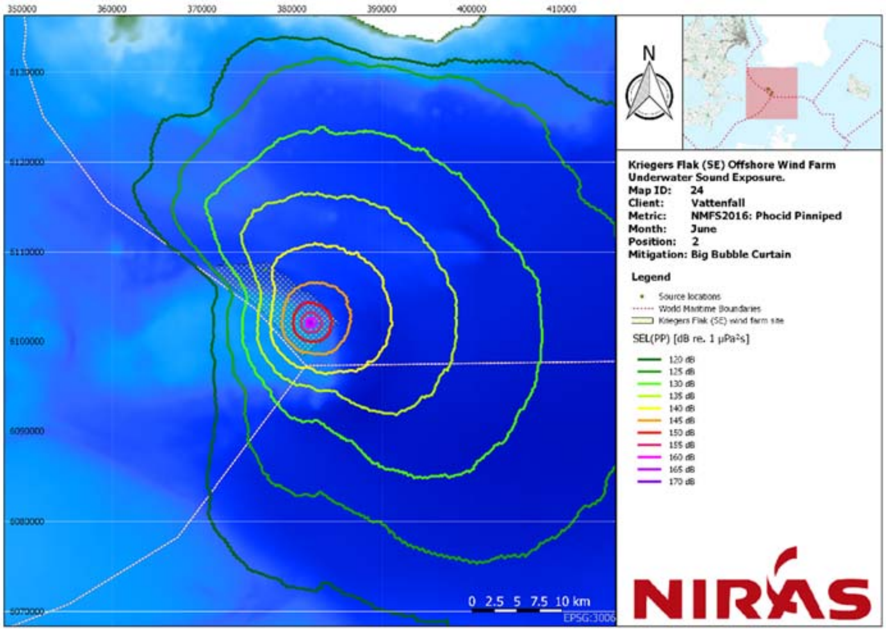
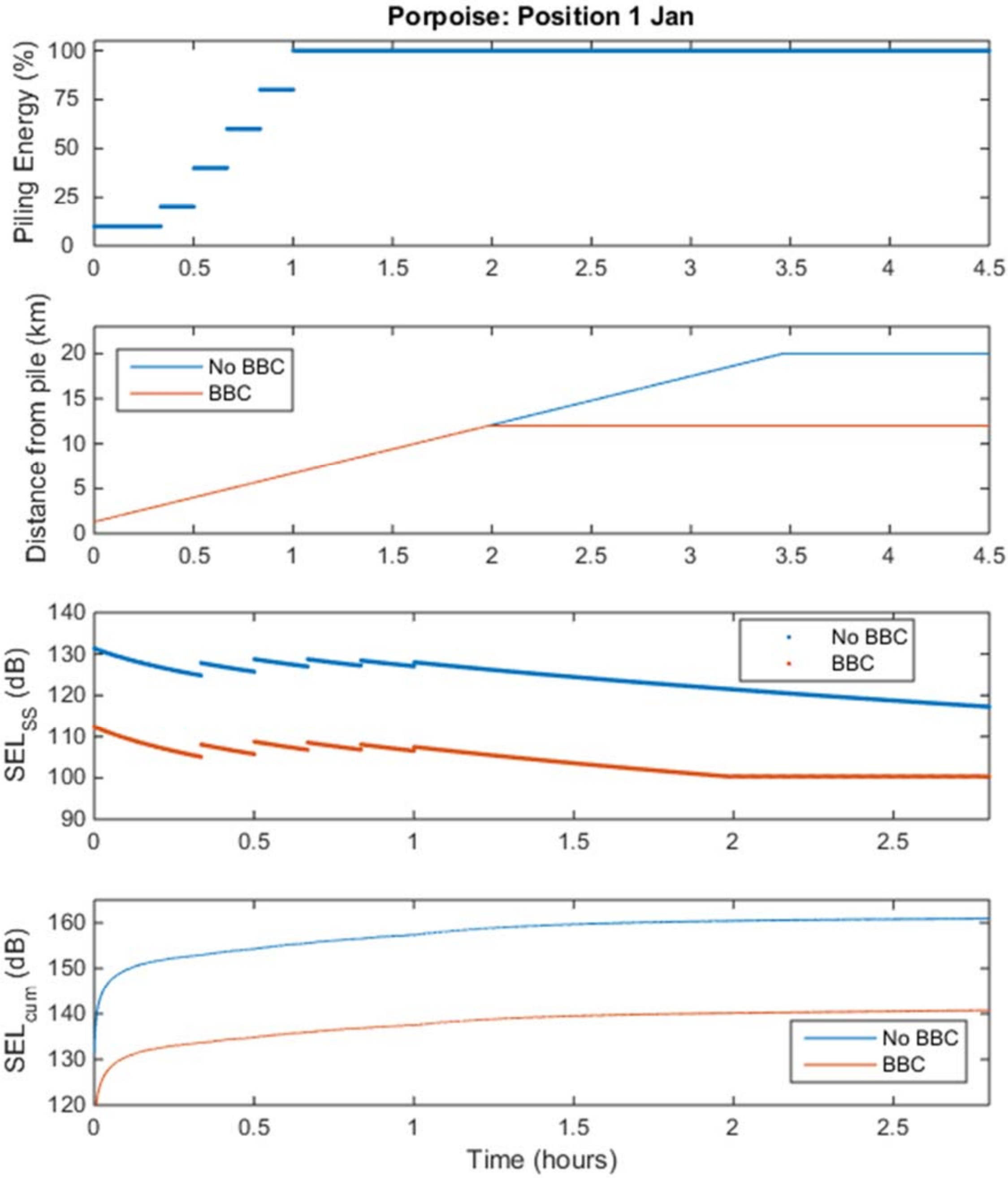
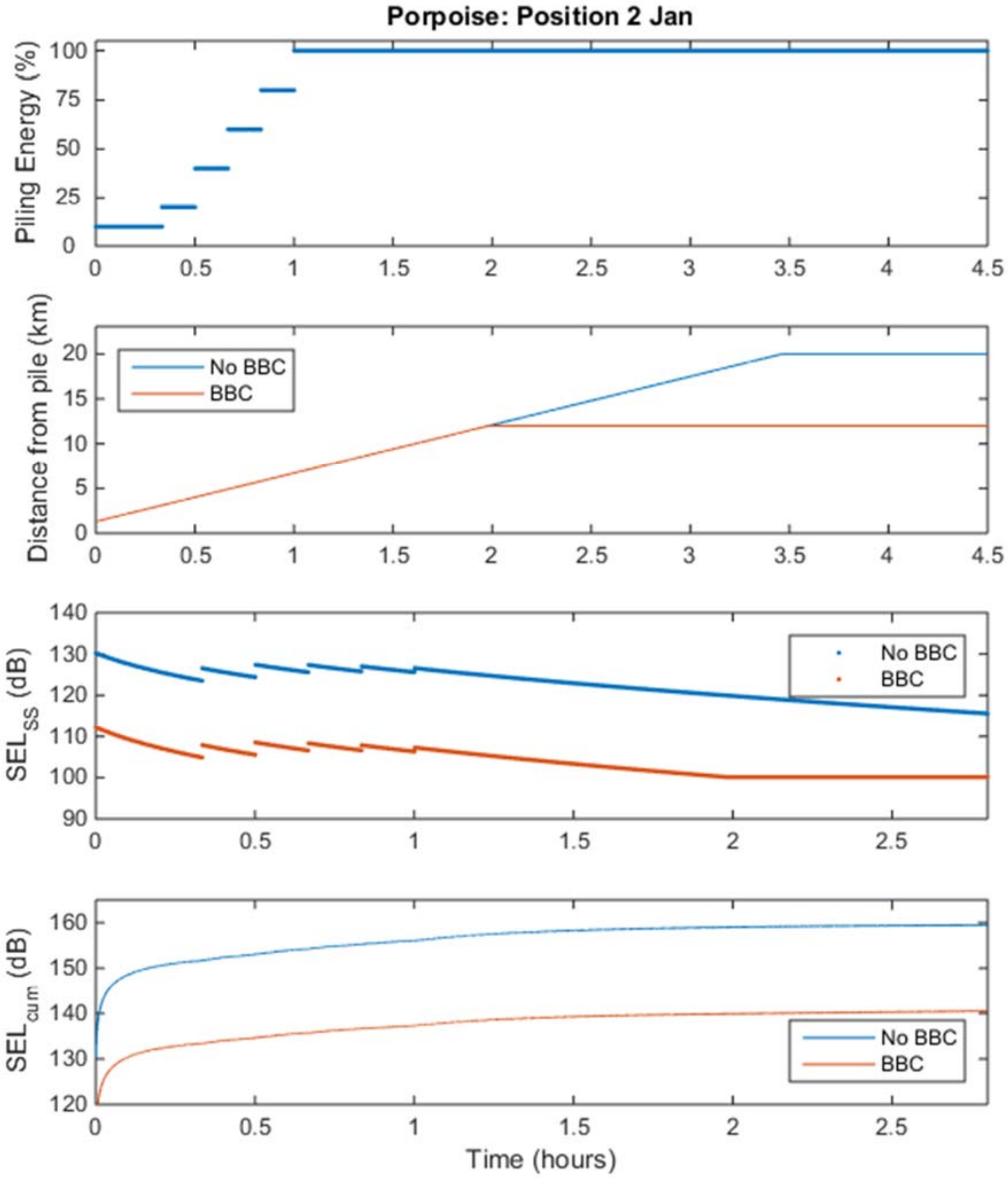
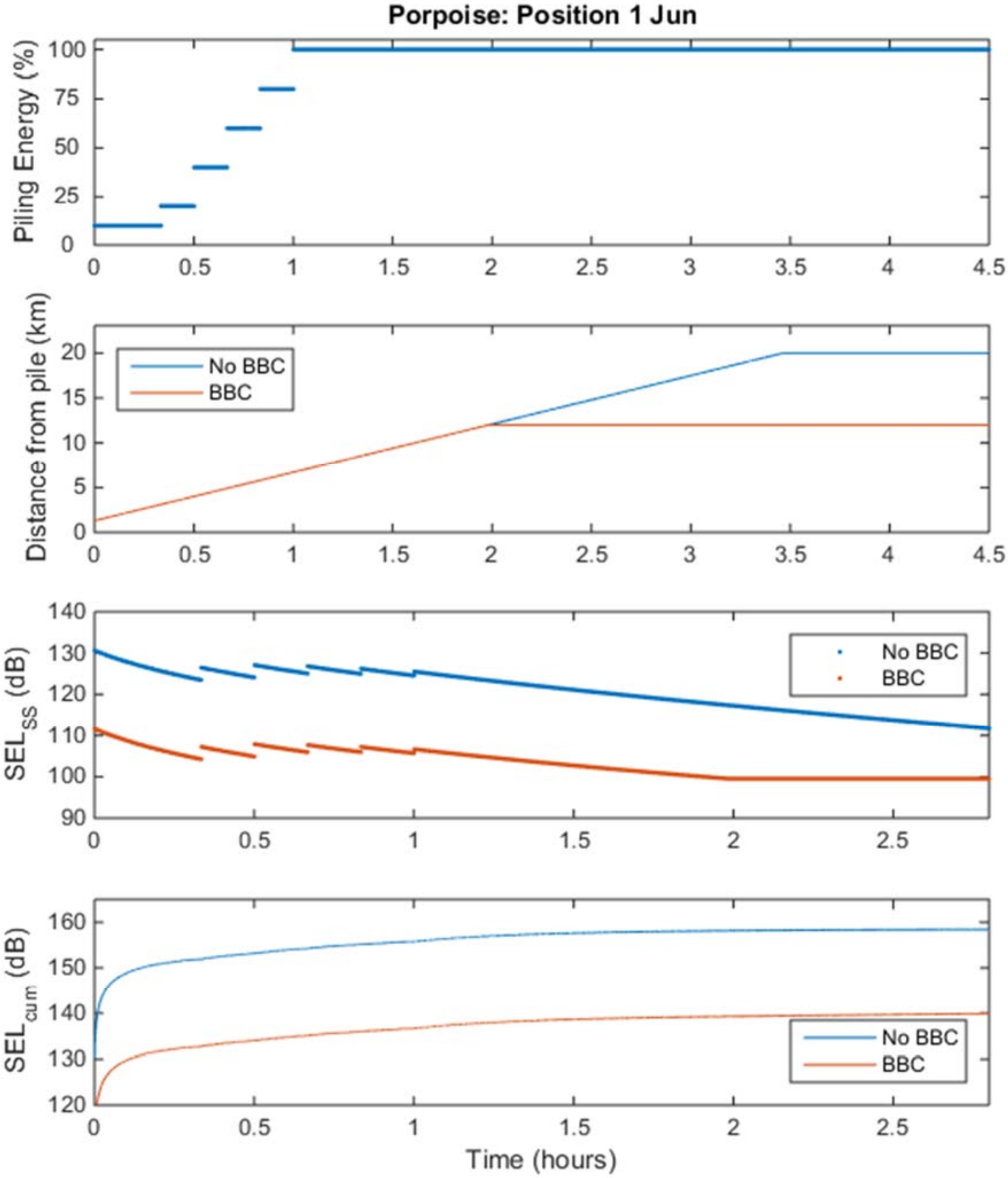


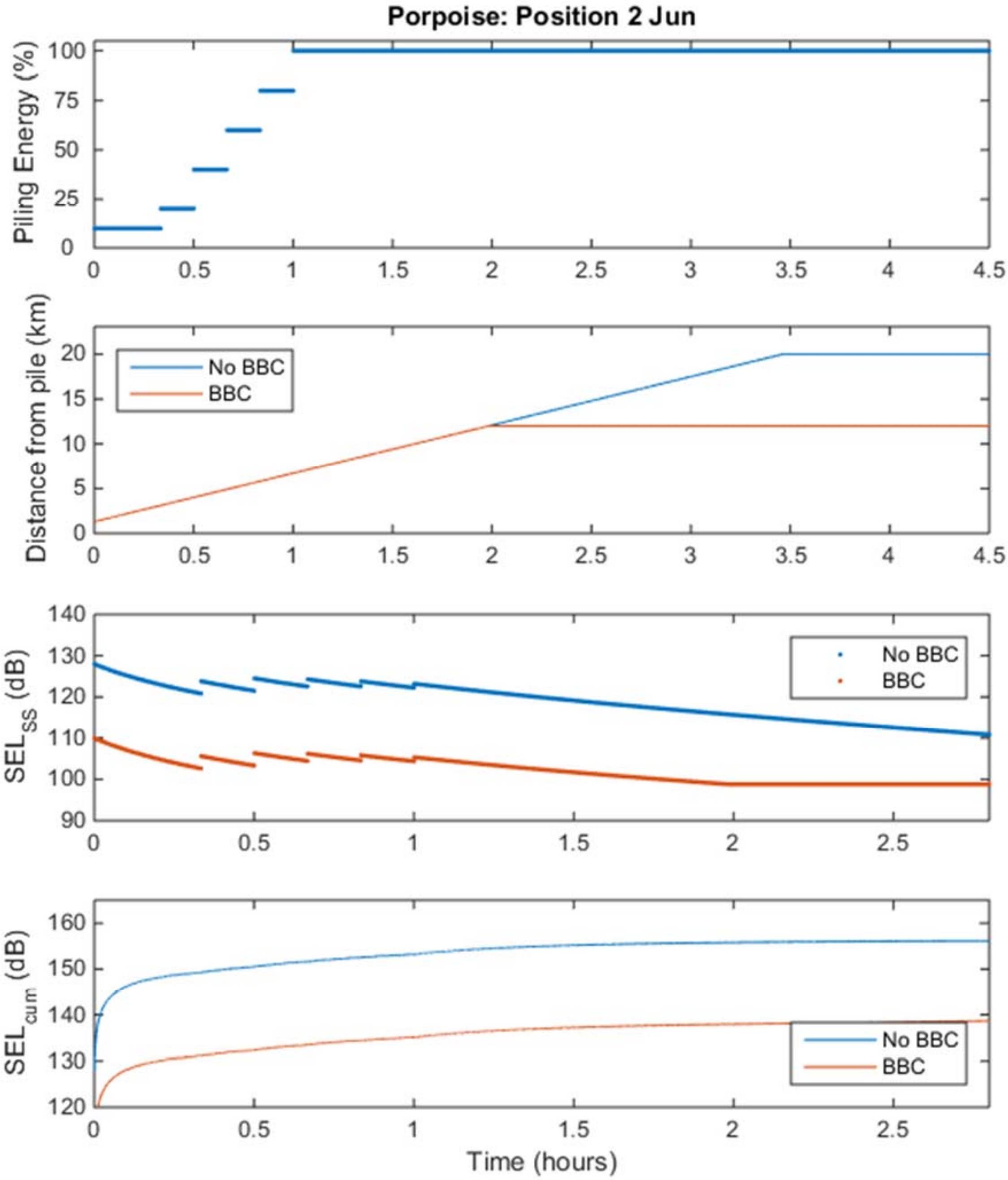
Figure 14.24. Phocid weighted SEL of single pile driving pulses. Position 2, June, bubble curtain in operation.

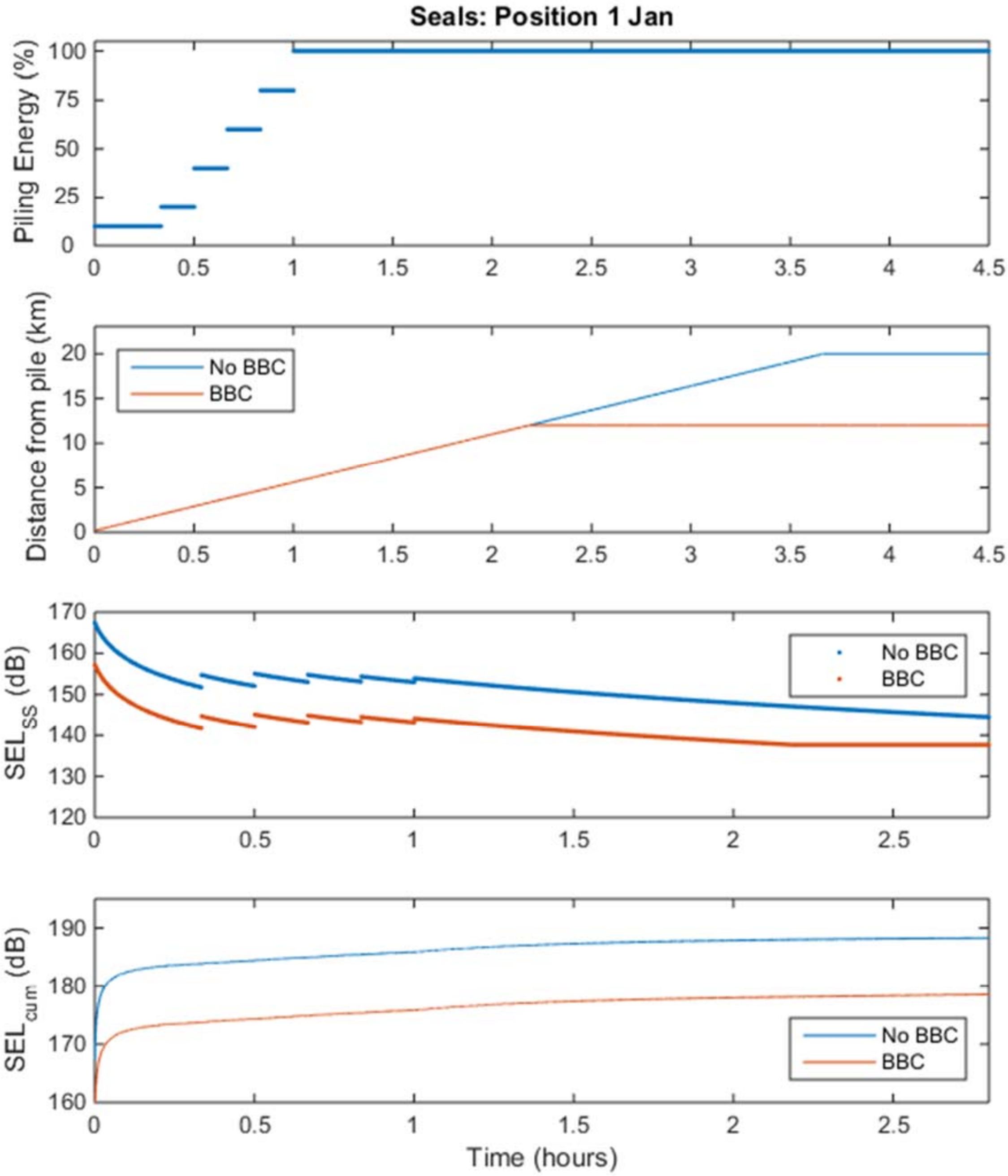
15. Appendix 3 Exposure modelling results

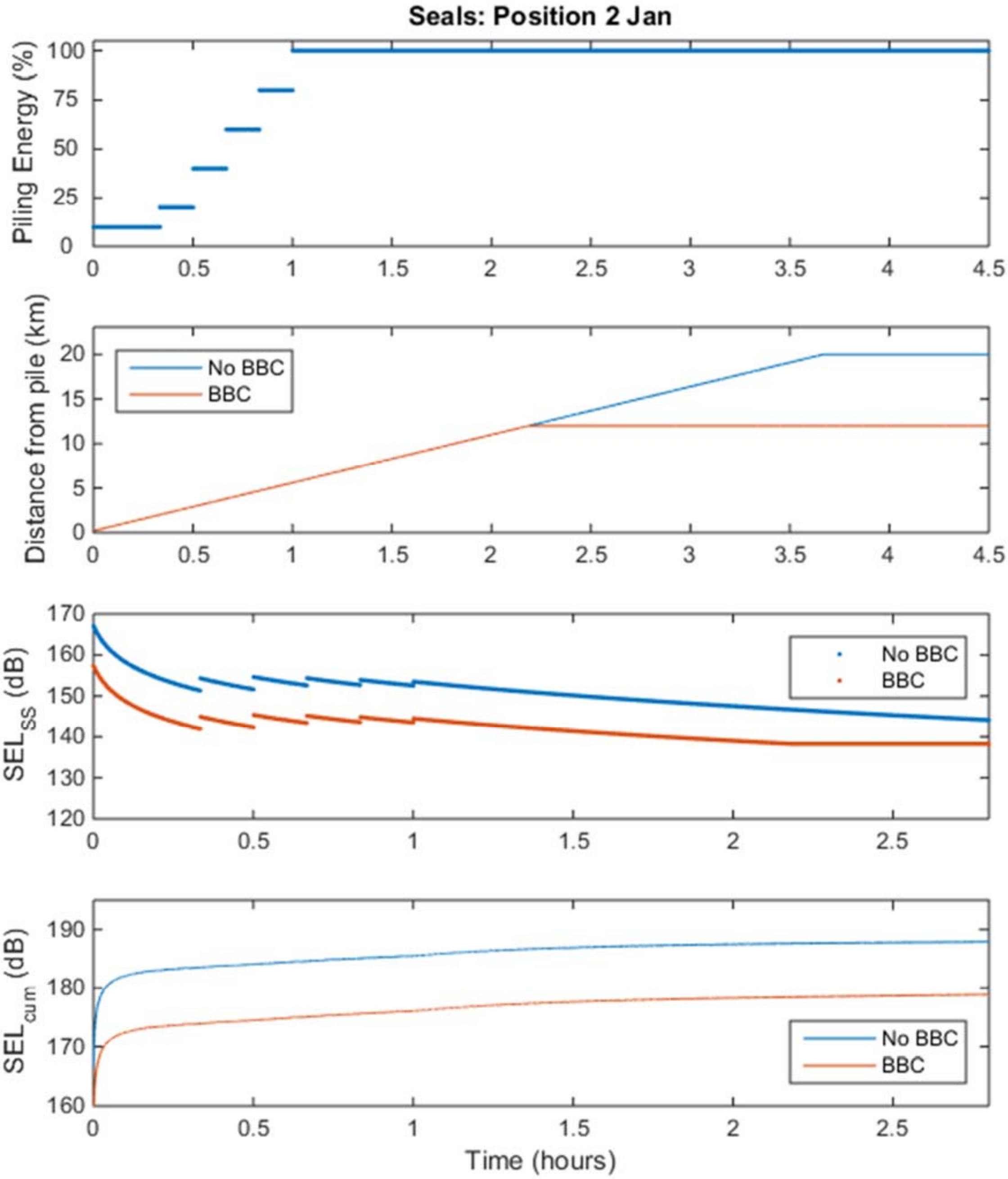


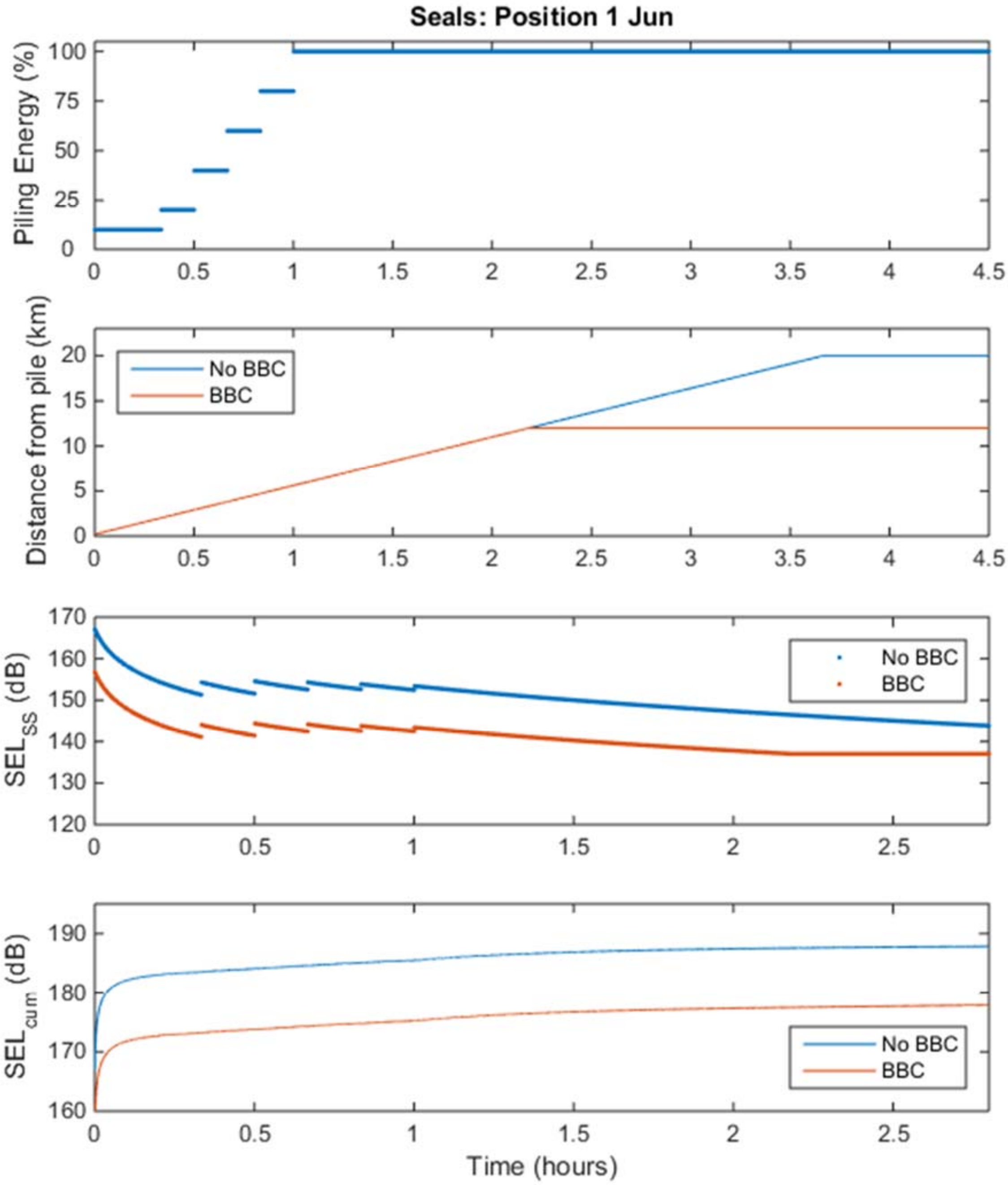

Porpoise: Position 2 Jan
Piling Energy (%)
100
75
50
25
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance from pile (km)
20
15
10
5
0
No BBC
BBC
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
SEL_{SS} (dB)
140
130
120
110
100
90
No BBC
BBC
0
0.5
1
1.5
2
2.5
SEL_{cum} (dB)
160
150
140
130
120
No BBC
BBC
0
0.5
1
1.5
2
2.5
Time (hours)

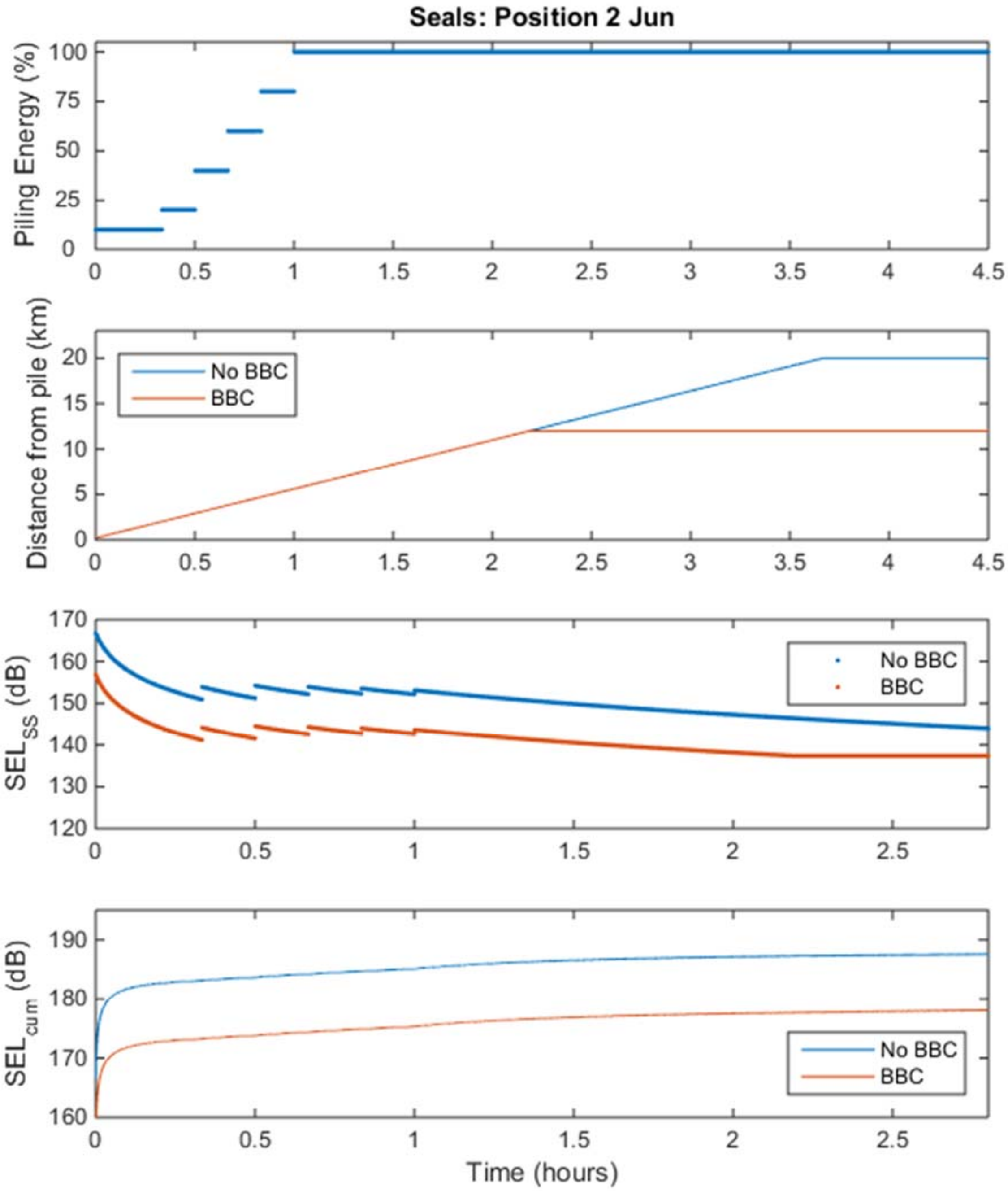

Porpoise: Position 1 Jun
Piling Energy (%)
Distance from pile (km)
No BBC
BBC
SEL$_{SS}$ (dB)
SEL$_{cum}$ (dB)
Time (hours)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
25
50
75
100
5
10
15
20
90
100
110
120
130
140
150
160


Porpoise: Position 2 Jun
Piling Energy (%)
100
75
50
25
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance from pile (km)
No BBC
BBC
20
15
10
5
0
SEL$_{SS}$ (dB)
140
130
120
110
100
90
No BBC
BBC
SEL$_{cum}$ (dB)
160
150
140
130
120
No BBC
BBC
Time (hours)


Seals: Position 1 Jan
Piling Energy (%)
100
75
50
25
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance from pile (km)
20
15
10
5
0
No BBC
BBC
SEL_{SS} (dB)
170
160
150
140
130
120
No BBC
BBC
SEL_{cum} (dB)
190
180
170
160
No BBC
BBC
Time (hours)


Seals: Position 2 Jan
Piling Energy (%)
100
75
50
25
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance from pile (km)
20
15
10
5
0
No BBC
BBC
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
SEL_{SS} (dB)
170
160
150
140
130
120
No BBC
BBC
0
0.5
1
1.5
2
2.5
SEL_{cum} (dB)
190
180
170
160
No BBC
BBC
0
0.5
1
1.5
2
2.5
Time (hours)


Seals: Position 1 Jun
Piling Energy (%)
100
75
50
25
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance from pile (km)
20
15
10
5
0
No BBC
BBC
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
SEL_{SS} (dB)
170
160
150
140
130
120
No BBC
BBC
0
0.5
1
1.5
2
2.5
SEL_{cum} (dB)
190
180
170
160
No BBC
BBC
0
0.5
1
1.5
2
2.5
Time (hours)


Seals: Position 2 Jun
Piling Energy (%)
100
75
50
25
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance from pile (km)
20
15
10
5
0
No BBC
BBC
SEL_{SS} (dB)
170
160
150
140
130
120
No BBC
BBC
SEL_{cum} (dB)
190
180
170
160
No BBC
BBC
Time (hours)

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EFFECTS OF LARGER TURBINES FOR THE OFFSHORE WIND FARM AT KRIEGER'S FLAK, SWEDEN

Assessment of impact on marine mammals

Construction and operation of an offshore wind farm on the Swedish part of Kriegers Flak has been assessed with respect to potential impacts on marine mammals. Underwater noise is assumed the main source of potential impact from construction, in particular percussive piling of turbine foundations. Impact was modelled by estimating the cumulated sound exposure for marine mammals near the construction site and by assessing disturbance to animals in time and space. Provided that adequate mitigation measures are adopted, such as use of deterring sounds prior to pile driving and reduction of radiated noise the construction is not considered to have long-term impact on the abundance or population development of marine mammals in the area. Likewise is the operation of the wind farm considered to be without significant long-term impact on marine mammals.

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