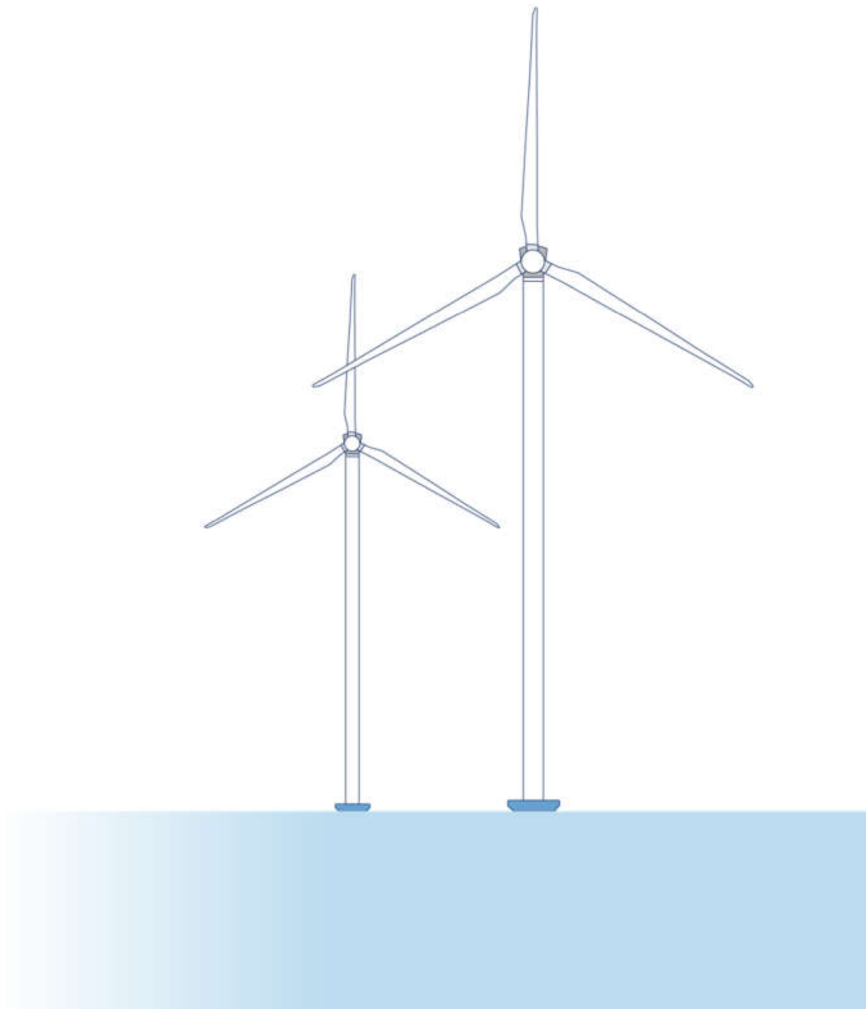
Annex 8

Underwater noise propogation modelling report (45 pages)



Modelling of underwater noise propagation during pile-driving at the area of MWF Curonian Nord

Technical report on numerical modelling of noise propagation during pile driving

Date: 26.05.2025

Glossary & abbreviations

µPa	Micropascal – pressure unit using in underwater acoustics as a reference pressure: 1 µPa = 10^{-6} Pa
$\mu Pa^2 s$	Micropascal squared second
ADD	Acoustic Deterrent Device
AUD INJ	Auditory Injury - damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy (Houser 2021; Finneran 2024). Auditory injury may or may not result in a permanent threshold shift (PTS)
BBC	Big Bubble Curtain
BR	Behavioural reaction
dB	Decibel – logarithmic unit of sound pressure
DBBC	Double Big Bubble Curtain
DHI	Danish Hydraulic Institute
HSD	Hydro Sound Damper
Hz	Hertz – frequency unit 1 Hz = 1 cycle/s
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
Impulsive sound	Transient signals emitted in brief sequences (pulses) with short duration and often high peak sound pressure levels
kHz	Kilohertz
md	Model domain [in our case, R_{max}=200 km]
MWF	Marine Wind Farm
MIKE-UAS	Software MIKE Underwater Acoustic Simulator (UAS) manufactured by DHI
NMFS	National Marine Fisheries Service (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
Octave band	Interval between two discrete frequencies having a frequency ratio of two
1/3-octave band	Interval of 1/3 of an octave (three adjacent 1/3-octave bands span one octave)
Pa	Pascal – unit of pressure equal to one Newton per square metre [1 N/m^2]
PTS	Permanent Threshold Shift - a permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level
PW	Phocid pinnipeds in water
RAM	Range-dependent Acoustic Model

rms	Root-mean-square
SEL	Sound Exposure Level [dB re 1 µPa^2s]
$SEL_{weighted}$	Sound Exposure Level with frequency weighting function according to the audible functional group
SL	Source Level – sound pressure at standard distance R=1m from sound source [dB re 1µPa@1m]
SPL	Sound Pressure Level – acoustic pressure defined by $10*log10(P^2/P_{ref}^2)$, where P – measured pressure and P_{ref} - reference pressure (in underwater acoustics, P_{ref}= 1 µPa), unit [dB re 1µPa]
TL	Transmission Loss – dissipation of sound energy due to geometrical spreading of pressure wave and sound absorption
TTS	Temporary Threshold Shift - a temporary, reversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level
VHF	Very High-Frequency
W(f)	Auditory weighting function

1 Introduction

Numerical modelling of underwater noise propagation during pile driving has been undertaken for the investment project titled “MWF Curonian Nord”. The propagation modelling will form the basis for the environmental impact assessment (EIA) of underwater noise on marine mammals and fishes.

The investment project is located in the Lithuanian EEZ, in the south-eastern part of the Baltic Sea. (Fig. 1).

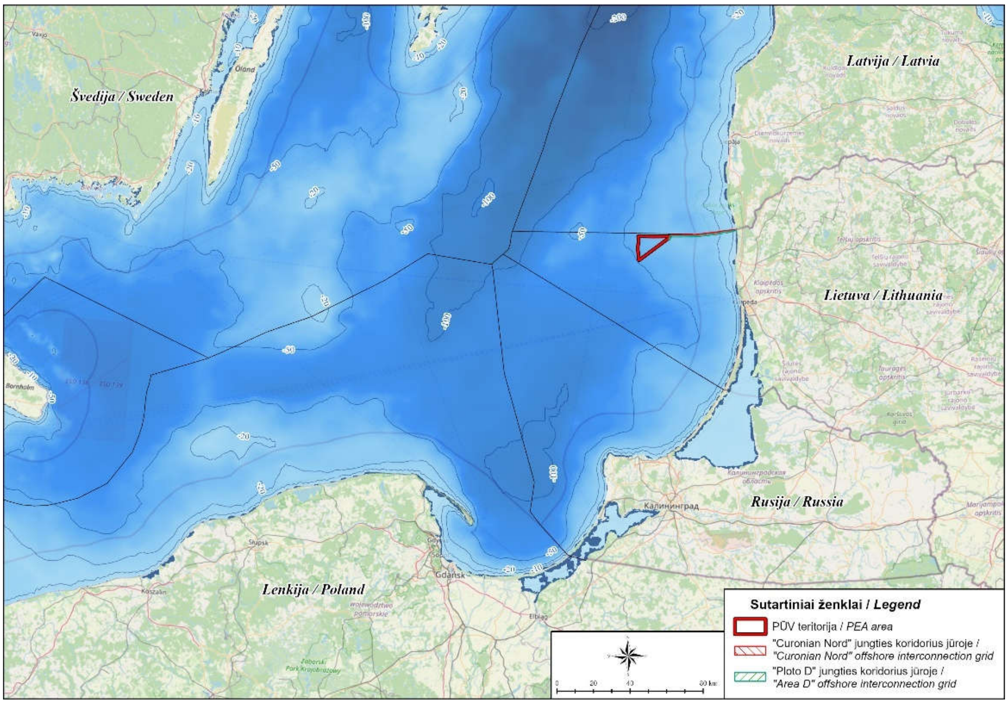


Figure 1. Location of the future marine wind farm MWF Curonian Nord.

The main purpose of this technical report is to determine the range of underwater noise propagation as a result of pile driving in the area of the MWF investment, and to provide information of the impact assessments on the marine environment, primarily on the harbour porpoise (*Phocoena phocoena*), true seals (*Phocid pinnipeds*) and swim-bladdered fishes.

Numerical calculations of anthropogenic noise propagation were preformed, using a sound source located at the most south-western position of the MWF Curonian Nord area with the geographical position depicted in Table 1 and illustrated in Fig. 2. The chosen position (wind turbine #1) is characterized by the deepest point inside of the investigated area, with the sea depth of z=49 m. The particular position was chosen due to the fact that, in general, more favourable conditions of sound propagation in deep sea are observed in comparison to shallow waters (lower amount of sound waves interactions within sea surface and sea bottom, and in consequence – lower transmission loss). By another hand, in geographical point of view, the chosen position is characterized by one of the closest distances to the border of the Natura2000 area Hoburgs bank och Midsjöbankarna (Sweden), where the harbour porpoises are subjected as a protected species.

Table 1. Geographical coordinates of sound source position.

Longitude DD.MM	Latitude DD.MM	UTM-34 Easting [m]	UTM-34 Northing [m]
20°12.8787	55°55.1264	450917	6197318

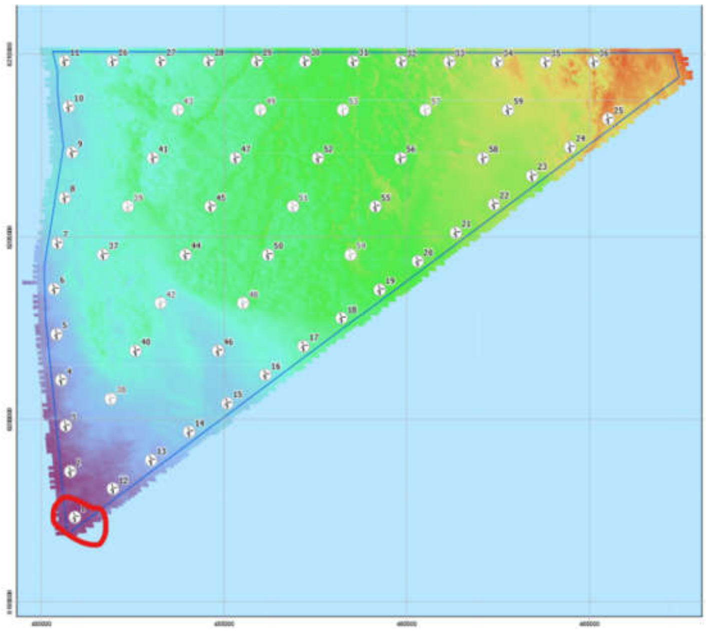


Figure 2. Location of sound source inside the MWF Curonian Nord.

2 Materials and methods

This chapter describes the methodology used in numerical modelling of underwater noise propagation. Description of the applied model and its assumptions, as well as the environmental data used as input parameters are presented, including the sound source spectrum, marine mammal auditory abilities and noise exposure criteria within the appropriate threshold values.

2.1 Description of the MIKE-Underwater Acoustic Simulator (MIKE-UAS) numerical model

The MIKE-Underwater Acoustic Simulator (MIKE-UAS) software developed by the Danish Hydraulic Institute (DHI) was used for numerical calculations of underwater noise propagation. The core of MIKE-UAS is a two-dimensional 2D-acoustic model (in the *r-z* plane) based on the solution of the parabolic equation (Parabolic Equation, PE) for varying propagation conditions with distance (Range-dependent Acoustic Model, RAM). The model calculates the transmission loss *TL* during sound propagation along a given bathymetric cross-section in the entire water column. The assumption of the model is that the sound source is an omnidirectional point source located at the depth *z* (in the water column or in the bottom) at the beginning of the profile *r*=0m (Fig. 3).

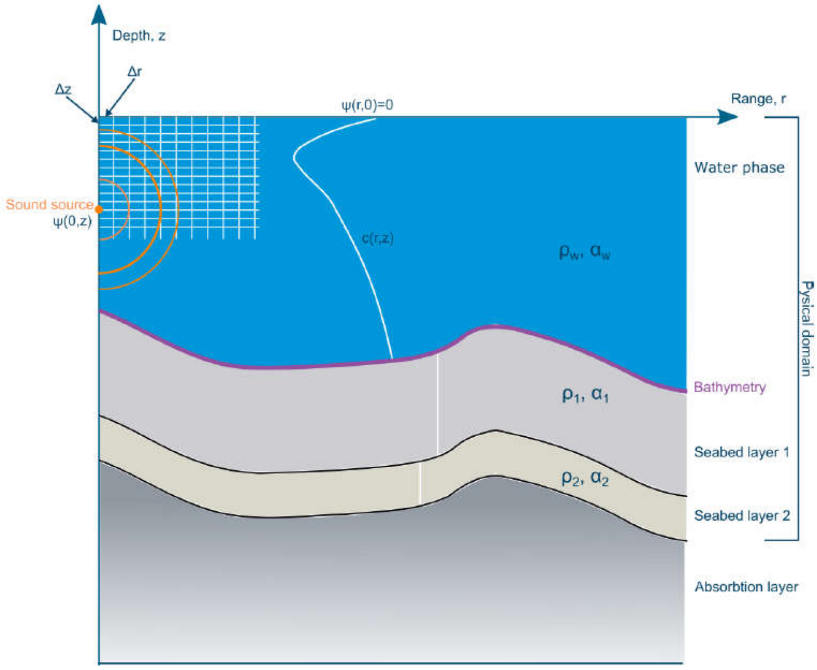


Figure 3. Sketch of the 2D acoustic model [source: Fig.2.1 in „UAS in MIKE. Underwater Acoustic Simulation Module. Scientific Documentation" (DHI, 2017)].

The MIKE-UAS model can be used for numerical calculations of sound wave propagation over a wide frequency range. Generally, the upper limit of the applicability of the model is a 1/3-octave bandwidth with a centre frequency of 40 kHz. However, computation time increases rapidly above 1 kHz. According to the guidelines ("Underwater Acoustic Simulator. Simulation of sound propagation. User Guide" [DHI, 2017]), the basic input parameters to the model are:

1. bottom relief data along the survey profile, i.e. bathymetry data *z(r)* [m];
2. physical parameters of the aquatic environment, including:
    - vertical sound velocity profile *c(z)* [m/s];
    - sound absorption coefficient in seawater α_w [dB/λ], calculated on the basis of data on temperature *T* [ºC], salinity *S* [PSU] and acidity *pH* [according to the empirical formula proposed by Francois and Garrison (1982a, b)];
3. physical parameters of individual bottom layers, including:
    - seabed layer thickness [m];
    - density ρ [kg/m3];
    - sound speed of a compressional wave c_p [m/s];
    - sound absorption coefficient α [dB/λ];
4. position of the sound source in the water column (in our case, 1m above the sea bottom) and its sound exposure level *SEL* [dB re 1µPa^{2}s];
5. frequency range (in 1/3-octave bands);
6. output computational grid is defined by the horizontal step Δr and the vertical step *Δz* and the maximum depth z_{max} (Fig. 3).

2.2 Environmental conditions

2.2.1 Bathymetry

Numerical calculations of transmission loss *TL* were performed along 72 azimuthal transects with an angular spacing of Δθ=5° and a maximum range of R_{max}=200 km (Fig. 4).

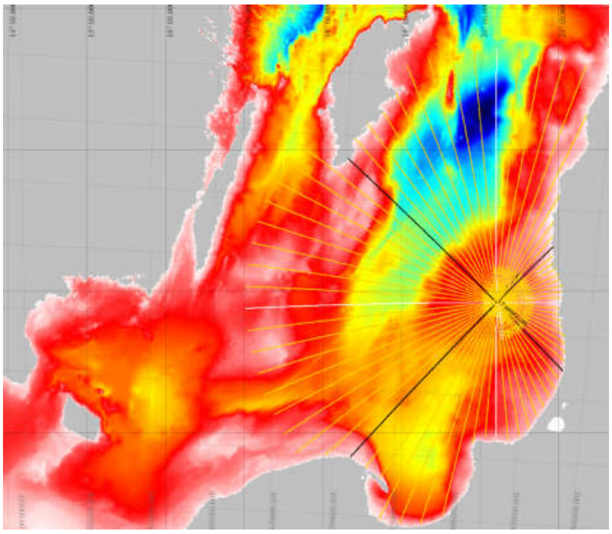


Figure 4. Sketch of the azimuthal profiles along which the numerical modelling of underwater noise propagation was performed.

2.2.2 Seasonality of thermohaline conditions and sound speed

Thermohaline conditions in the Baltic Sea, i.e. vertical profiles of temperature and salinity, as well as sound velocity, show both temporal/seasonal and spatial variability. Examples of representative vertical distributions of temperature, salinity and sound velocity for the southern Baltic area for winter (blue), spring (green), summer (red) and autumn (yellow) stratification are presented in Fig. 5 (according to Klusek (1990)].
The empirical formula proposed by Chen and Millero (1977), also referred to as the UNESCO formula, was used to determine the value of the speed of sound on the basis of data of temperature and salinity. It shows small deviations from the measurement data in a wide range of variability of parameters included in the empirical formula; for temperature from 0 to 40 [°C], for salinity from 0 to 40 [PSU] and hydrostatic pressure from 0 to 100 [MPa] (i.e. approximately to the depth 10 km).

In general, the sound propagation conditions in the southern Baltic Sea, resulting from the geometry of the sound velocity profiles, confirm the presence of a wide near-surface underwater sound channel (waveguide) observed in the winter season and a deep-water sound channel in the summer season.

The presence of a wide sub-surface sound channel in the winter season and the phenomenon of positive refraction, results in lack of interaction of acoustic rays within the sea bottom (in a relatively large range of grazing angles), i.e. there are no significant losses caused by the penetration of acoustic waves into the bottom and subsequent sound attenuation in bottom sediments. This results in part of the acoustic energy emitted by the sound source goes to the waveguide and, due to small propagation

losses in it, that it can spread over very long distances (the so-called favourable propagation conditions). In contrast, during the summer, a seasonal thermocline forms in water column at depths of about 20-40 m and a deep-water acoustic waveguide (layer with a minimum of sound speed) is observed in the middle of the water column. Such a three-layer structure results to the phenomenon of negative refraction, within interaction of acoustic rays with sea bottom (unfavourable sound propagation conditions).
Due to the most contrastingly different sound propagation conditions are observed in the Baltic Sea during the winter and summer time, modelling of pile-driving noise propagation were performed for the characteristic thermohaline conditions occurring in the both of these seasons (Fig. 5; blue and red curves, respectively).

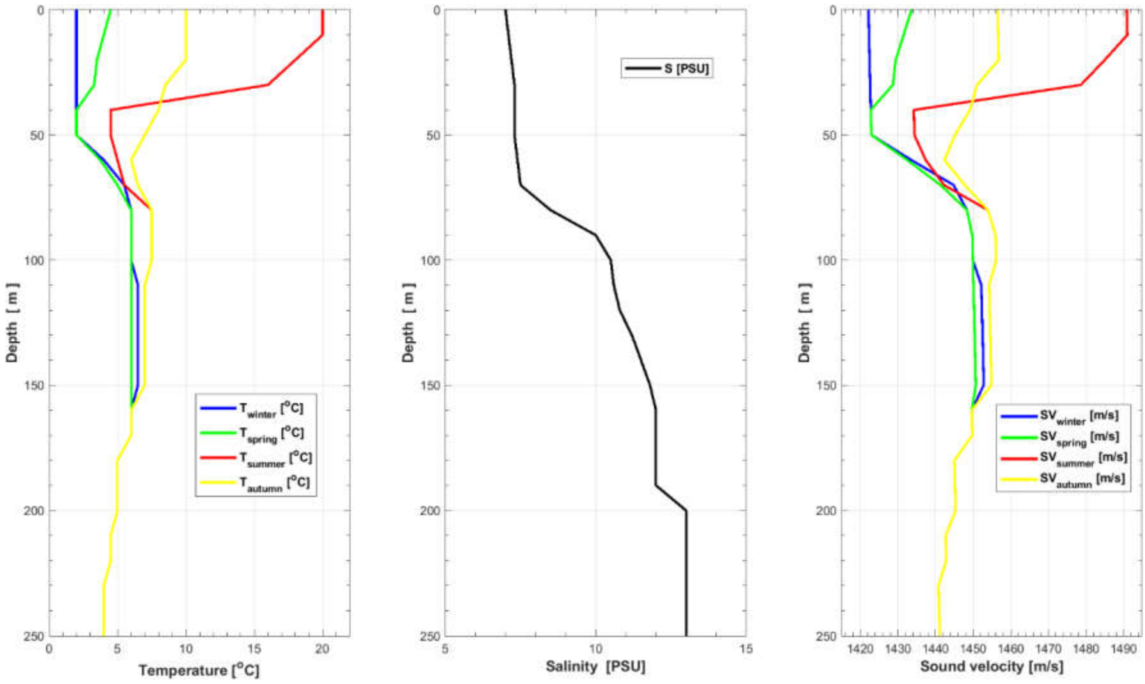


Figure 5. Characteristic thermohaline conditions observed in the southern Baltic Sea – (schematic) vertical profiles of temperature T [°C], salinity S [PSU] and sound velocity SV [m/s] for the appropriate season. Colours: blue, green, red and yellow, winter, spring, summer and autumn, respectively.

2.2.3. Sound absorption

The energy of an acoustic wave, propagating in the water column, is dissipated by sound absorption. The most important feature of the sound absorption coefficient is its dependence on the square of the frequency $\alpha \sim f^2$. In addition, the values of the individual components of the absorption coefficient show dependence on environmental parameters; temperature *T*, salinity *S*, acidity *pH* and depth *z*.
The values of the sound absorption coefficient were calculated on the basis of the empirical formula proposed by Francois and Garrison (1982a,b). This pattern was also implemented in the MIKE-UAS acoustic model used in this work.

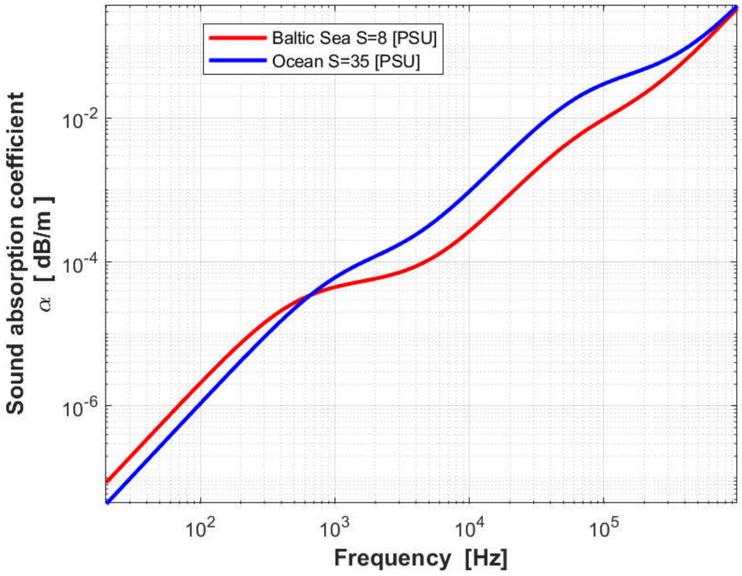


Figure 6. Dependence of sound absorption coefficient α [dB/m] on frequency based on the empirical equation proposed by Francois and Garrison (1982$_{a,b}$). The calculations were performed under the following assumptions; water temperature T=8°C, sea depth z=50 m, pH=8 and salinity S=8 PSU i S=35 PSU for the Baltic Sea water and the Ocean (red and blue curves, respectively).

Due primarily to the significantly lower salinity, the sound absorption in the Baltic Sea waters is fundamentally different from the sound absorption in the Ocean. This difference is clearly observed in the low frequency range up to about of 500 Hz and in the mid-high frequency range from about of 1 kHz to about of 500 kHz (Fig. 6).

2.2.4 Seabed profile

The seabed profile in the investment area was approximated as a 3-layer structure. Geoacoustic parameters (Lurton, 2010) of individual bottom layers are presented in Table 2.

Table 2. Seabed profile within the geoacoustic parameters.

Seabed layer [m]	**Material**	**Geoacoustic properties**
0–2	silty sand	C_p = 1650 m/s α = 1.1 dB/λ ρ = 1800 kg/m^3
2–42	sand-silt-clay	C_p = 1560 m/s α = 0,2 dB/λ ρ = 1600 kg/m^3
42–92	clay	C_p = 1470 m/s α = 0,08 dB/λ ρ =1200 kg/m^3

C_p – sound speed of compressional wave, α – absorption coefficient, ρ – density

2.2.5 Primary physical values

Sound propagation in an aquatic environment is usually described by transmission loss *TL*. This parameter describes the decrease in sound intensity due to the propagation of an acoustic wave (pressure wave) in the direction away from the sound source:

$$TL(R) = 10log_{10}\frac{p^2}{p_0^2}, \tag{1}$$

where *TL* – transmission loss in [dB], *p* – acoustic pressure at distance *R* from sound source, p_0 – acoustic pressure at reference distance *R=1m* from sound source.

The sound exposure level *SEL* is defined as [dB re 1µPa²·s]:

$$\mathrm{SEL} = 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}}\frac{p^2(t)}{p_{ref}^2}\mathrm{d}t\right) , \tag{2}$$

where p_{ref} – reference acoustic pressure = 1µPa, t_{start} i t_{end} – time of start and finish of noise event, e.g. impulsive noise (single strike of vibrohammer).

Since the energy characteristic (spectrum) of the sound source and transmission loss *TL* depend on the frequency, the sound exposure level *SEL* at the position of sound receiver is calculated for 1/3-octave bands $SEL_{1/3oct}$:

$$SEL_{1/3oct} = 10\log\sum_{f_{low}}^{f_{high}} 10^{\frac{\left(SEL_{f1/3oct}^{source}-TL_{f1/3oct}\right)}{10}} , \tag{3}$$

where f_{low}, f_{high} – boundary frequencies for the chosen frequency range in 1/3-octaves $f_{1/3oct}$, $SEL_{f1/3oct}^{source}$ – sound exposure level at the position of sound source in the particular 1/3-octave frequency band.

2.2.6 Sound source and its spectrum

In this work, modelling of noise propagation was carried out for a source of noise emitted during pile driving of 10 m monopile in diameter, with using of a IQ6 hammer of max. power 6600 kJ [Ignitis Renewables, *personal communication*].

The unmitigated source frequency spectrum were provided by the Investor, obtained by the measurements at distance *R*=750 m from the considered sound source (Fig. 7, red curve on the left). In addition to, insertion loss/noise reduction spectra considered using of a mitigation measures in the form of DBBC, HSD and their combination were derived from the comprehensive report published by Bellmann *et al.* (2020), based on the *in-situ* measurements performed by the Authors in open sea conditions during foundation works of large monopile structure at a distance of 750 m from the sound source.

In order to obtain spectrum of sound source expressed in units of Source Level *SL* (defined as a sound pressure at standard distance *R*=1 m from sound source [dB re 1µPa@1m]) or appropriately –in units of "doze of sound energy" normalised to 1 second and expressed by Sound Exposure Level *SEL* [dB re 1µPa²s@1m], the results derived from the numerical calculations of sound propagation/transmission loss (*TL* values) in particular 1/3-octave frequency bands (in the frequency range of interest, i.e. 20Hz-5kHz) were considered. The *SEL* values at distance *R*=1 m were obtained according to the Eq. [4]:

$$SEL_{1/3oct@1m} = SEL_{1/3oct@750m} + TL_{1/3oct@750m} \tag{4}$$

Taking into account the mentioned above, the unmitigated and mitigated spectra illustrated in Fig. 7 were a primary basis for further calculations.

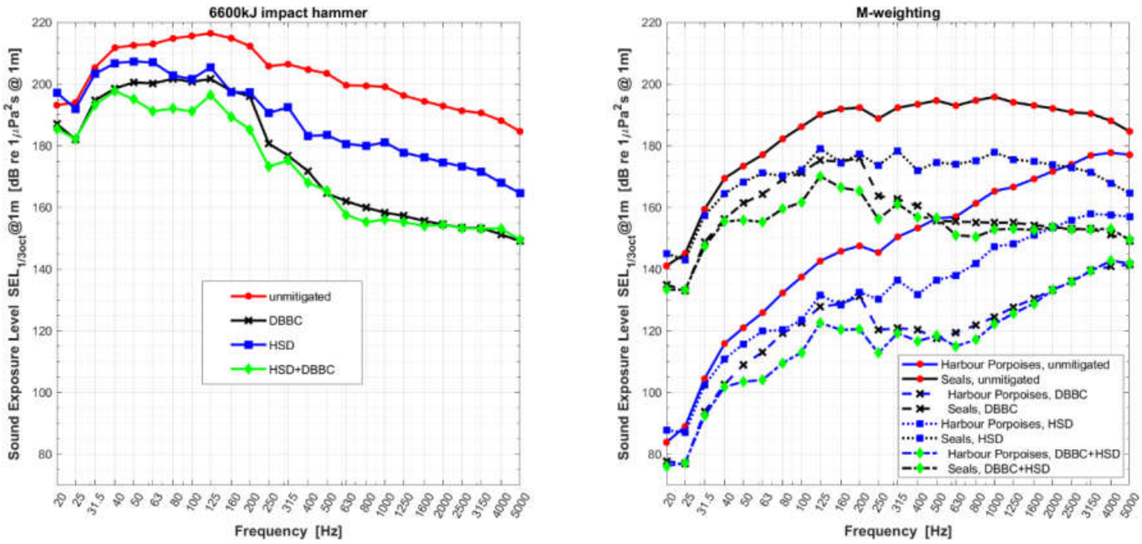


Figure 7. Spectra of the sound source (monopile 10 m in diameter; 6600 kJ impact hammer) expressed in units of sound exposure levels $SEL_{1/3oct}$ at a distance of 1 m [dB re 1μPa²s@1m] for unmitigated (red curve) and within a DBBC, HSD and their combination scenario (black, blue and green curves on the left subplot, respectively).. The appropriate spectra considering the hearing ability of harbour porpoises and true seals (on the right; blue and black curves, respectively).

Moreover, considering the hearing ability of marine mammals of interest (harbour porpoises, seals), the appropriate spectra (Fig. 7, on the right) for all potential scenario were estimated based on the last scientific knowledge (*see* paragraph 2.2.7 below in the text).

2.2.7 Hearing ability of marine mammals

In general, marine mammals are divided into functional groups of hearing based on scientific knowledge regarding the properties of hearing ability and the sound sensitivity of individual groups of animals (Southall *et al.*, 2019). The basic characteristics of hearing, related to a specific frequency range of sounds perceived by representatives of a given group of animals, have been included in the study of the NOAA National Marine Fisheries Service (NMFS, 2024). The frequency weighting functions are described as:

$$W(f) = C + 10\log_{10}\left(\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right), \tag{5}$$

where for marine mammals like harbour porpoises (*Phocoena phocoena*) and true seals (*Phocid pinnipeds PW*), the appropriate parameters in the Eq. [5] are depicted in Table 3 and illustrated in Fig. 8

(solid curves). For comparison, the appropriate curves obtained based on the previous knowledge (NMFS, 2018) are illustrated as well (Fig. 8, dashed curves).

Table 3. Functional hearing marine mammal groups and associated auditory bandwidths together with the appropriate frequency weighting function parameters (NMFS, 2024).

Marine mammals hearing group	***Generalized hearing range***	***a***	***b***	***f_1 [kHz]***	***f_2 [kHz]***	***C [dB]***
Very High-frequency (VHF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)	200 Hz – 165 kHz	2.23	5	5.93	186	0.91
Phocid pinnipeds (PW) (true seals)	40 Hz – 90 kHz	1.63	5	0.81	68.3	0.29

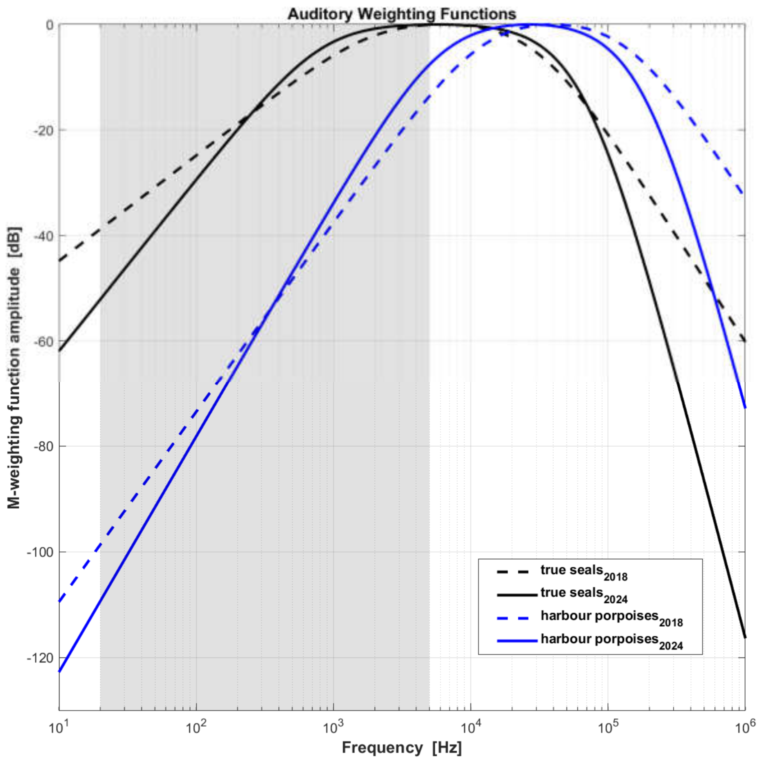


Figure 8. M-weighting frequency functions W(f) for marine mammals using of high-frequency sounds (VHF-cetaceans), including of harbour porpoises (Phocoena phocoena, in blue) and true seals (Phocid Pinnipeds PW, in black), with dashed and solid curves based on the previous (NMFS, 2018) and updated knowledge (NMFS, 2024), respectively. The grey background depicts the frequency range of interest applied in the numerical modelling (20Hz–5kHz).

Taking into account the mentioned above hearing properties of harbour porpoises (*Phocoena phocoena*) and true seals (*Phocid pinnipeds*), the weighted sound exposure level $SEL_{weighted}$ were determined in the final stage of numerical modelling calculations (weighted in the appropriate 1/3-octave frequency bands covering the frequency range of interest), according to the Eq. (6):

$$\text{SELweighted} = 10\log_{10}\left(\sum_f 10^{0.1\,\text{SEL}_f - 0.1\,W(f)}\right) \quad (6)$$

Based on the obtained weighted sound exposure level $SEL_{weighted}$ (Fig. 7, on the right), the ranges of the negative impact of noise on marine mammals from the group of harbour porpoises (*Phocoena phocoena*), true seals (*Phocid pinnipeds*), potentially leading to hearing damage in the form of a temporary (Temporal Threshold Shift, TTS) and/or auditory injury (AUD INJ), which includes, but not limited to, permanent shift of the hearing threshold (Permanent Threshold Shift, PTS), were estimated.

2.2.8 Cumulative effect

According to the best practice, the cumulative sound exposure level SEL_{cum} of the total sound exposition (considered as a series of particular noise events comprised of single strikes followed one by one) to evaluate the potential biological impact of pile driving in terms of a total noise portion/dose is estimated with using of Eq. (7):

$$\text{SEL}_{\text{cum}} = \text{SELss} + 10\ \log_{10} N \quad (7)$$

where SEL_{ss} is the single strike sound exposure level and *N* is the total number of strikes.

A 5.81-hour cumulative sound exposure level, based on *N*=8713 strikes is considered in accordance to the updated information obtained from Ignitis Renewables (personal communication). This results in an additional $10\log_{10}N=+39.4$ *dB* increasing in sound exposure level (in comparison to single strike event).

In context of estimating the response of behavioural reaction BR to the total portion/dose of underwater noise, the cumulated sound exposure level SEL_{cum} that a "moving receiver" (marine mammal) exposes to as it is swimming away from the "disturbing" sound source area is calculated along "the escaping routes" (i.e. particular azimuthal directions) on the basis of Eq. (8):

$$\text{SEL}_{cum}^{\text{moving}} = 10\log\sum_{i=1}^{N} 10^{\frac{\left(\text{SELweighted}-\text{TL}(r_0+vt_i)\right)}{10}} \quad (8)$$

where *N* – number of hammer strikes (in our case, 8713 ones in total); $SEL_{weighted}$ – the single strike sound exposure level with applying of the weighting function; *TL* – transmission loss derived from the model at a distance of $R = r_0 + vt_i$, with r_0 –a predefined starting distance of the "moving receiver", fleeing speed v and t_i –time from the beginning of pile-driving operation.

Guidelines from the Danish Energy Agency performed by Tougaard (2021), applies a generalized speed of fleeing of v=1.5 [m/s] across all marine mammal species, including of harbour porpoises (*Phocoena phocoena*) and true seals (*Phocid pinnipeds*). This appears as a reasonable precautionary first approximation and was used in further calculations (in regards to BR response estimation).

2.2.9 Impact criteria

In the literature, the type of impact of high-intensity sounds on marine organisms has been classified on the basis of the intensity of the impact and, at the same time, on the basis of the distance from the noise source, according to the scheme proposed by Richardson (1995), which has been further revised by Hawkins and Popper (2016):

- masking;
- behavioural response (BR);
- temporal/permanent shift of the hearing threshold (TTS, PTS) and auditory injury AUD INJ [where the last one is in accordance with the updated definition formulated recently in NMFS (2024)];
- physical and physiological effects;

The revised framework suggests that underwater noise can have a variety of effects on marine organisms (Fig. 9), which can be conceptualised as overlapping zones of influence relative to a sound source. This simplified model assumes that effects are related to the received sound level. The received sound level in turn is dependent on the distance between a sound source and the marine organism potentially affected. Thus, different effects may extend to varying distances from the source (Thomsen *et al.*, 2021).

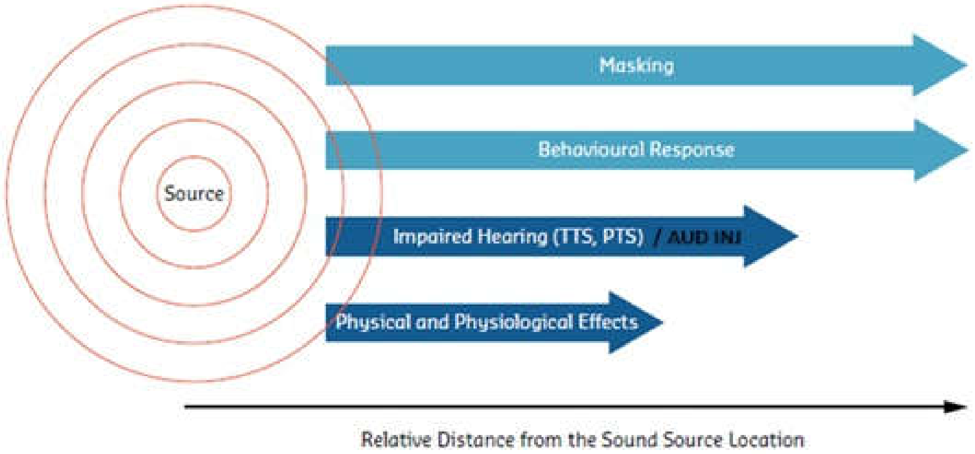


Figure 9. Potential effects of noise at different distances from a sound source (according to the scheme proposed by Richardson (1995) and adapted from Hawkins & Popper (2016)). [The illustration is modified based on Fig. 2 in Thomsen et al. (2021)].

According to the definition, different impact zones could be interpreted as (Thomsen *et al.*, 2021):

- The zone of masking: the area where noise interferes with the detection of biologically relevant signals or cues used for communication and navigation, meaning that these sounds cannot be heard, or are less clear;
- The zone of behavioural response (BR): the area within which a marine animal changes its behaviour in response to noise, e.g. by swimming away or diving deeper;
- The zone of impaired hearing: delineates the areas in which noise can lead to changes in hearing sensitivity. These changes can be temporary (temporary threshold shift, TTS) or permanent (permanent threshold shift, PTS). In most cases, TTS and PTS relate to changed sensitivity to certain frequencies. For an animal to detect a certain frequency, it will need to be louder. Generally, it does not mean that there has been a complete loss of hearing ability.

Recently, in according to the updated report of NMFS (2024), the definition of auditory injury (AUD INJ) was provided as a damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy [Houser, (2021); Finneran, (2024)]. Auditory injury may or may not result in a permanent threshold shift (PTS).

• The zone of physical and/or physiological effects: the zone where tissue damage and physiological effects other than those associated with hearing can occur. In extreme cases, the damage can lead to the death of the marine organism. It should be noted that death can also result, albeit indirectly, from any of the other effects listed above. Physical effects of noise can include damage to internal tissue and/or to the auditory system. Physiological effects of noise can include stress and the release of stress hormones and/or increases in blood pressure.

2.2.10 Threshold values for marine mammals and swim-bladdered fishes

Within this study, the most comprehensive noise exposure criteria (Table 4) presented recently in the updated technical guidance published by the US National Oceanic and Atmospheric Administration (NMFS, 2024), which compiles, interprets and synthesizes the last scientific knowledge, were applied. The one is in accordance with the recommendations proposed earlier by Southall *et al.* (2019), and includes also the updated information within the methodology proposed by J. Finneran in his technical report (Finneran, 2024). In context of behavioural response BR of harbour porpoises (*Phocoena phocoena*), the criteria proposed by J. Tougaard and issued in the guidelines from the Danish Energy Agency (Tougaard, 2021) were used.

Table 4. Noise impact criteria for harbour porpoises (Phocoena phocoena) and true seals (Phocid pinnipeds) applied in the work to estimate impact ranges of pile driving noise.

Reference	Effect	Marine Mammal hearing group	Sound type modelled	Sound Exposure Level (weighted SEL) [dB re 1 µPa^{2}s]
NOAA National Marine Fisheries Service (NMFS 2024)	AUD INJ	VHF cetaceans (harbour porpoise)	Single strike & cumulative	159
	TTS	VHF cetaceans (harbour porpoise)	Single strike & cumulative	144
	AUD INJ	Phocid pinnipeds (PW) (harbour seal and grey seal)	Single strike & cumulative	183
	TTS	Phocid pinnipeds (PW) (harbour seal and grey seal)	Single strike & cumulative	168
Tougaard (2021)	Behavioural Reaction (BR)	VHF cetaceans (harbour porpoise)	Single strike & cumulative	94 (weighted SEL)*
Russel *et al.* 2016	Behavioural Reaction (BR)	Phocid pinnipeds (PW) (harbour seal and grey seal)	Single strike	158 (unweighted SEL)

**recalculated based on $SPL_{rms125ms}$=103 [dB re 1µPa] VHF-weighted value proposed by Tougaard (2021)*

Based on literature data, the noise impact criteria (PTS, TTS) for swim-bladdered fishes have been derived from Popper *et al.* (2014), together with behavioural reaction criteria obtained by study of Hawkins *et al.* (2014). Summary of noise exposure criteria values for swim-bladdered fishes are presented in Table 5.

Table 5. Noise impact criteria for swim-bladdered fishes applied in the work to estimate impact ranges of pile driving noise.

Reference	Effect	Sound type modelled	Sound Exposure Level [dB re 1 $\mu Pa^2 s$]
Popper *et al.* (2014)	PTS	Single strike & cumulative	203
	TTS	Single strike & cumulative	186
Hawkins *et al.* (2014)	Behavioural Reaction (BR)	Single strike	135

3 Results

3.1 2D-distribution of transmission loss TL(r,z) in dependence on distance and depth

Numerical calculations of transmission loss *TL* were performed along a set of azimuthal transects (72 ones in total; *see* Fig. 4). For both seasons (winter and summer) considered in the study, complexity of *TL* in space domain *(r, z)* obtained on the basis of the particular result of modelling performed along the chosen bathymetry profile with the azimuthal direction θ=205 [deg] (relative to the North) is illustrated in Fig. 10. Hereby, seasonal variability of sound propagation conditions in the Baltic Sea is confirmed as well (*see* amongst others, Klusek, 1990; Lisimenka, 2007; Klusek and Lisimenka, 2016).

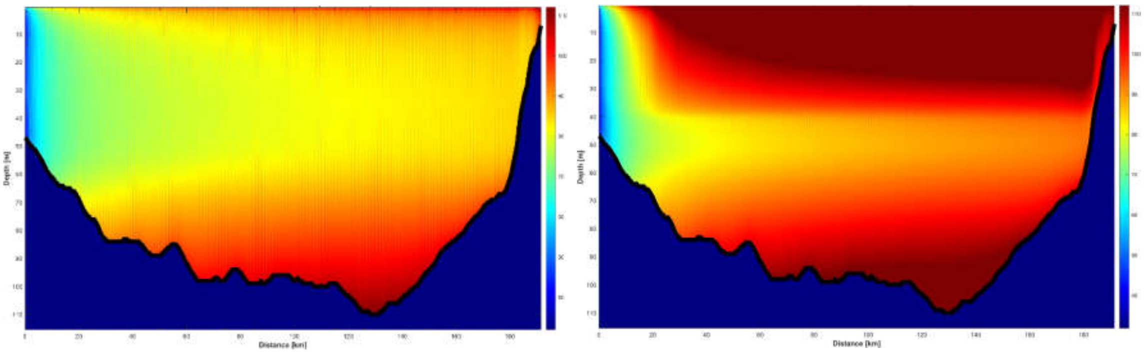


Figure 10. 2D-structure of transmission loss TL(r,z) [dB] obtained as a result of the numerical calculations performed along the chosen transect (205 [deg] relative to North) in broadband frequency range (20 Hz-5 kHz) for the winter (on the left) and summer time (on the right).

In winter time (Fig. 10, on the left), due to positive refraction of acoustic rays, which cause lower losses with almost lossless interaction with the sea surface, sound "fills" a wide subsurface underwater sound channel (waveguide) and indicates significantly lower values of *TL* ("favourable conditions") in comparison to a near bottom layer.

In contrast, sound is subjected to a significant attenuation in summer time (Fig. 10, on the right). Despite an existence of the deep water waveguide, phenomenon of strong negative refraction of sound is observed in summer time. It causes to frequent interaction of sound with the sea bottom what leads to higher *TL* values. In this way, probability of registration of sound emitted by source (in our case, pile-driving noise) is become small, especially starting from a relatively far distances of more about than a few tens of kilometres from the position of the piling. Nevertheless, due to the fact that the modelled sound source is located in water column directly in the axis of the summer waveguide (in our case, z_{source}=48 m), pile-driving noise could propagate on far distances inside of this relatively thin (of about 10-20 m in width) deep water layer. It could be explained by a well-known phenomenon of sound rays bending/refracting towards to regions of lower sound speed (the acoustic ray "is looking for" a coolness). In this way, water layer within the minimum in the sound speed profile acts as an excellent acoustic duct. Thus, a portion of the sound energy emitted from a source is trapped into the waveguide, allowing it to propagate with low loss to far-distance ranges.

3.2 Sound field in space domain

Using of the primary results obtained in the form of the 2D-distrubutions of transmission loss *TL(r, z)*, the most probable trajectory of sound ["the less resistant" propagation path $TL_{min}(r_i, z_i)$] within a subsequent range steps r_i in the whole water column z_i for each particular azimuthal profiles (72 transects in total) were determined. Space interpolation of 2D-scattered data was then performed to obtain the general transmission loss *TL* map. Finally, based on the particular examined spectrum of sound, spatial maps of the sound exposure level SEL were obtained, aiming to determine the potential negative impact ranges on particular species of marine mammals during pile driving (for the specific effects in the form of AUD INJ, TTS, and BR) and swim-bladdered fishes (in context of PTS, TTS, BR) as well.

3.2.1 Unmitigated sound exposure level SEL_{ss} for single strike

Spatial maps of the unmitigated single-strike sound exposure level SEL_{ss} [dB re 1µPa^{2}s], considering the sound spectrum illustrated in Fig. 7 (red curve; on the left) were prepared. These represent the physical propagation conditions of sound energy in the whole model domain for both examined seasons (winter and summer) [Fig. 11, upper and lower panels, respectively]. It forms the primary basis for further examined scenarios like the cumulative effect SEL_{cum} as well as the weighted sound exposure level $SEL_{weighted}$ considered sound perception of the primary representatives of marine mammal fauna in the Baltic Sea (harbour porpoises and seals) in context of the impact ranges estimation.

Due to the specific bathymetry in which the sea depth increases into the Gdansk Deep direction (south-west SW to south-south west SSW azimuths), the sound propagating within the SW-channel shows the highest levels. On the contrary, areas that are characterized by shallow bathymetry create "the acoustic shadow" significantly reducing propagation of the noise in these azimuthal directions (e.g., north N to north-east NE) resulting in a significant reduction of the *SEL*.

During the winter time (Fig. 11, upper panel), a sound exposure level with values of up to *SEL*=144 [dB re 1µPa^{2}s] could be expected in the SW to SSW direction, at far distances of about *R*≈ 164.5 km from the position of the pile driving, what is in very close proximity to the Polish coast (near the Hel Peninsula). In contrast, during the summer season (Fig. 11, lower panel), noise ranges where the mentioned above values of SEL could be observed are significantly smaller and amount to of about *R*≈35 km. Nevertheless, it should be noted that the general picture of the "favourable" SW/SSW-azimuthal directions of noise propagation is kept.

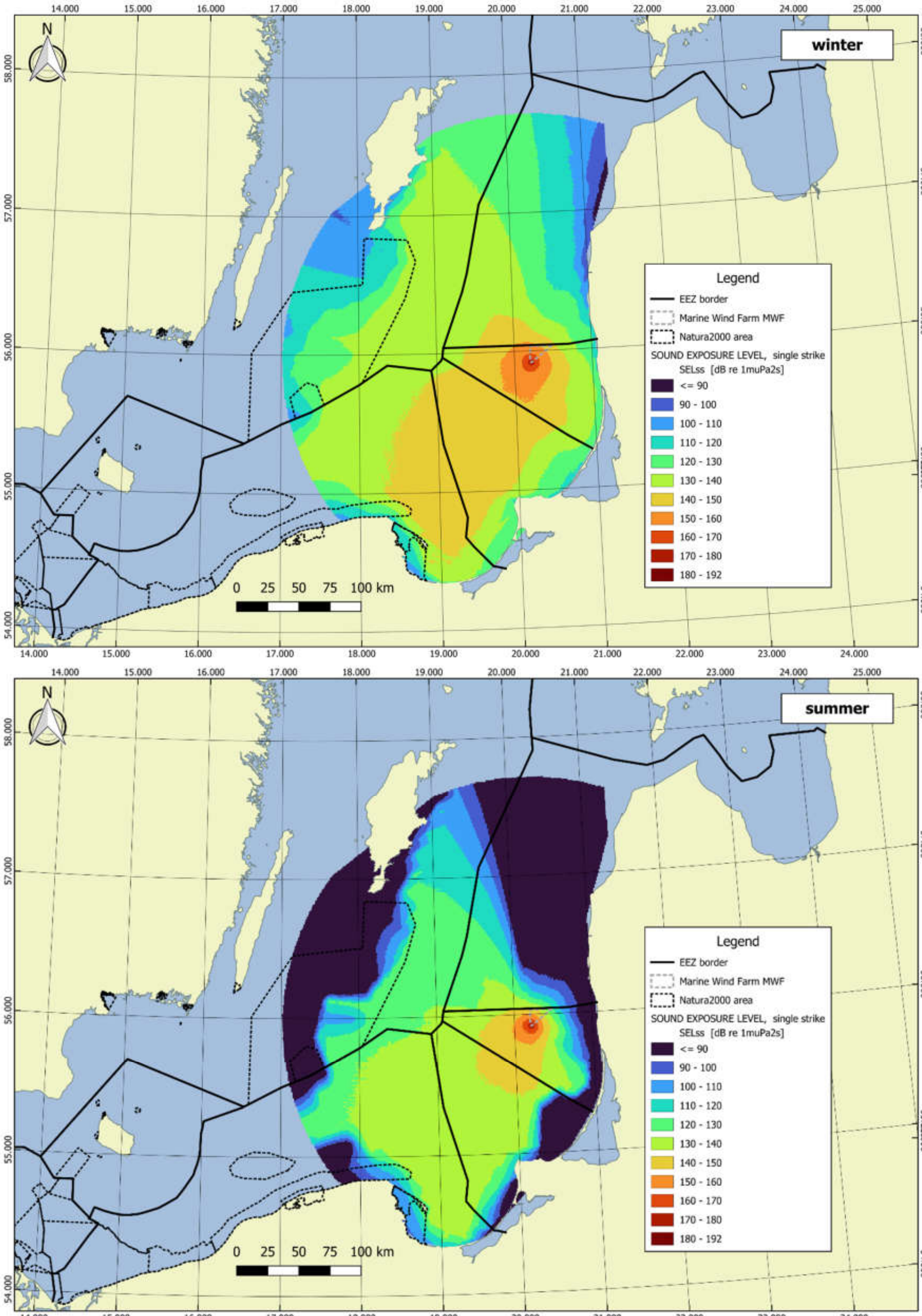


Figure 11. Noise maps of unmitigated Sound Exposure Level SEL_{ss} [dB re 1μPa^{2}s] (unweighted) with single strike emission in broadband frequency range (20 Hz-5 kHz) for winter and summer seasons (upper and lower panels, respectively).

3.2.2 Mitigated sound exposure level SEL_{ss} for single strike

In offshore wind farm industry, several noise mitigation systems exist to reduce anthropogenic noise emissions during construction phase of wind turbine foundations like impact pile-driving.
In practice, primary and secondary noise mitigation systems are distinguished. The primary ones counteract the generation of noise directly at the sound source (amongst others, innovative BLUE piling technology using of the principle of pulse prolongation as a noise reduction method). Contrary to, the secondary noise mitigation systems reduces the radiation of noise by placing noise shields/barriers at some distance from the pile (e.g., big bubble curtains BBC or double ones DBBC, isolating casings Noise Mitigation Screens, hydro sound dampers HSD, dewatered cofferdams).

During piling, about 1 % of the impact energy on the pile is transformed into unwanted underwater noise by oscillating circumferential expansion along the length of the pile caused by the hammer strike [Elmer *et al.*(2012), cited followed by Koschinski and Lüdemann (2020)]. Some of this noise radiates through the water column whereas another part radiates through the water saturated ground in a specific way and may again couple to the water column at some distance (Dahl and Reinhall, 2013). This effect may limit secondary noise mitigation in their effectiveness if not explicitly addressed by the method (Koschinski and Lüdemann, 2020).

According to the information obtained from the Investor (Ignitis Renewables, *personal communication*), mitigation measures in the form of DBCC, HSD and their combination DBBC+HSD could be considered during the construction phase of the MWF Curonian Nord. After applying of the appropriate frequency insertion loss, the particular mitigated spectra of the sound source, illustrated in Fig. 7 (on the left), were taken into the account in further calculations. Resulting spatial noise maps for the scenario of single strike noise emission are shown in Figs. 12-14, respectively. Moreover, the appropriate values of the unmitigated and mitigated SEL values obtained at the reference distances are presented in Table 9 (*see* paragraph 3.3.4, below in the text).

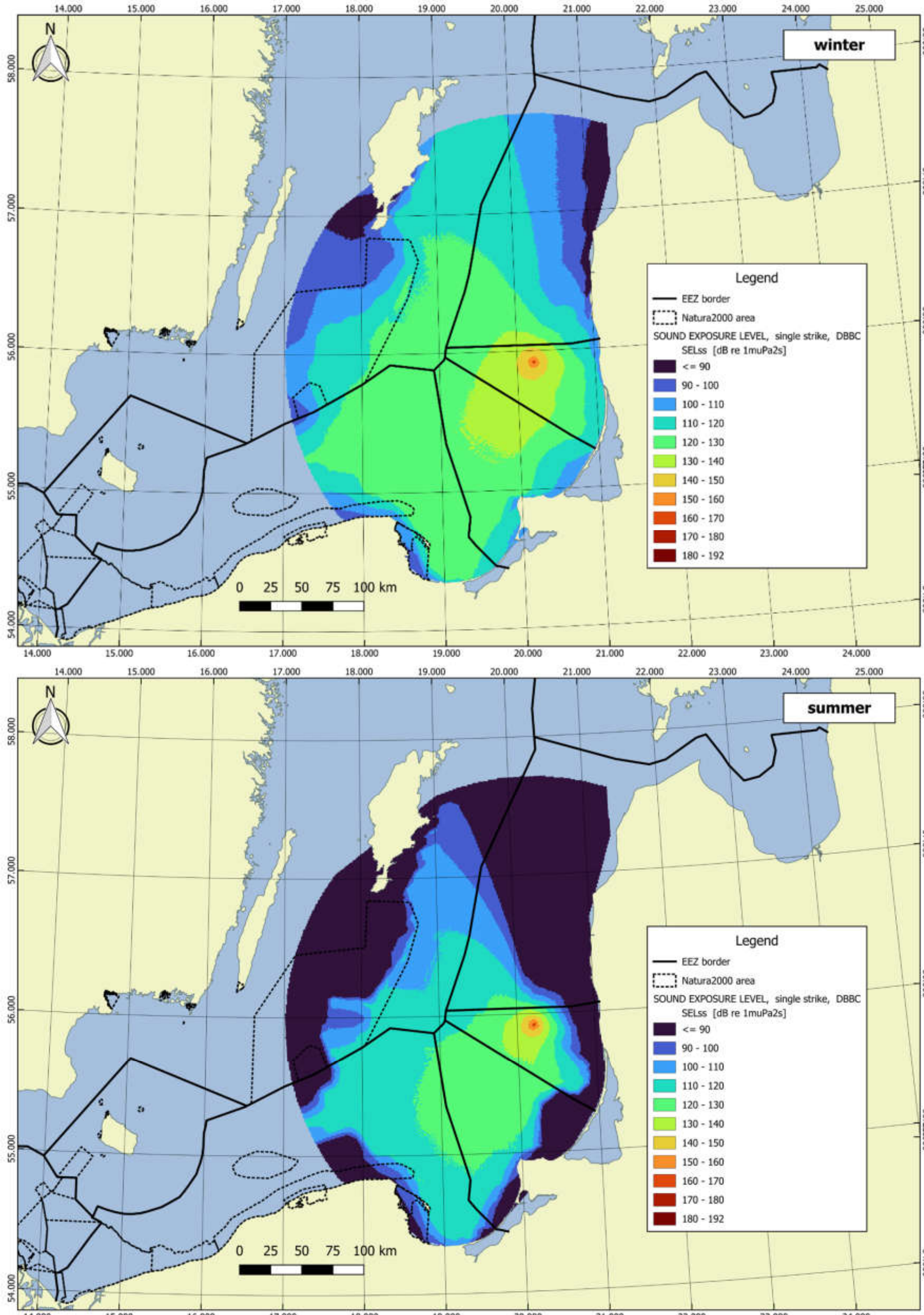


Figure 12. Noise maps of the unweighted broadband Sound Exposure Level $SEL_{ss,\ DBBC}$ [dB re 1μPa²s] with single strike emission and applying of the mitigation measure with using of Double Big Bubble Curtain (DBBC) for winter and summer seasons (upper and lower panels, respectively).

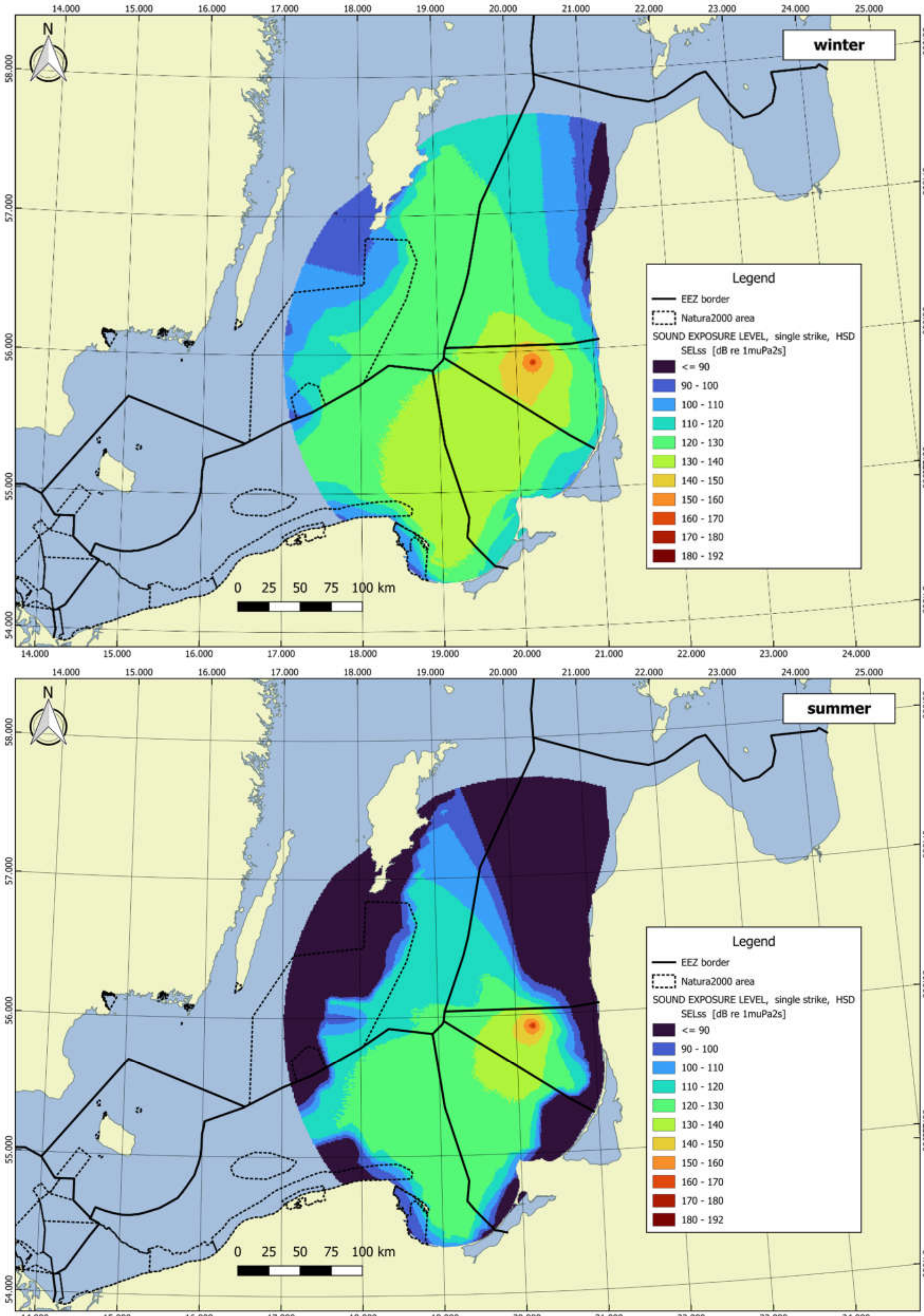


Figure 13. Noise maps of the unweighted broadband Sound Exposure Level $SEL_{ss,\ HSD}$ [dB re 1µPa²s] with single strike emission and applying of the mitigation measure with using of Hydro Sound Damper (HSD) for winter and summer seasons (upper and lower panels, respectively).

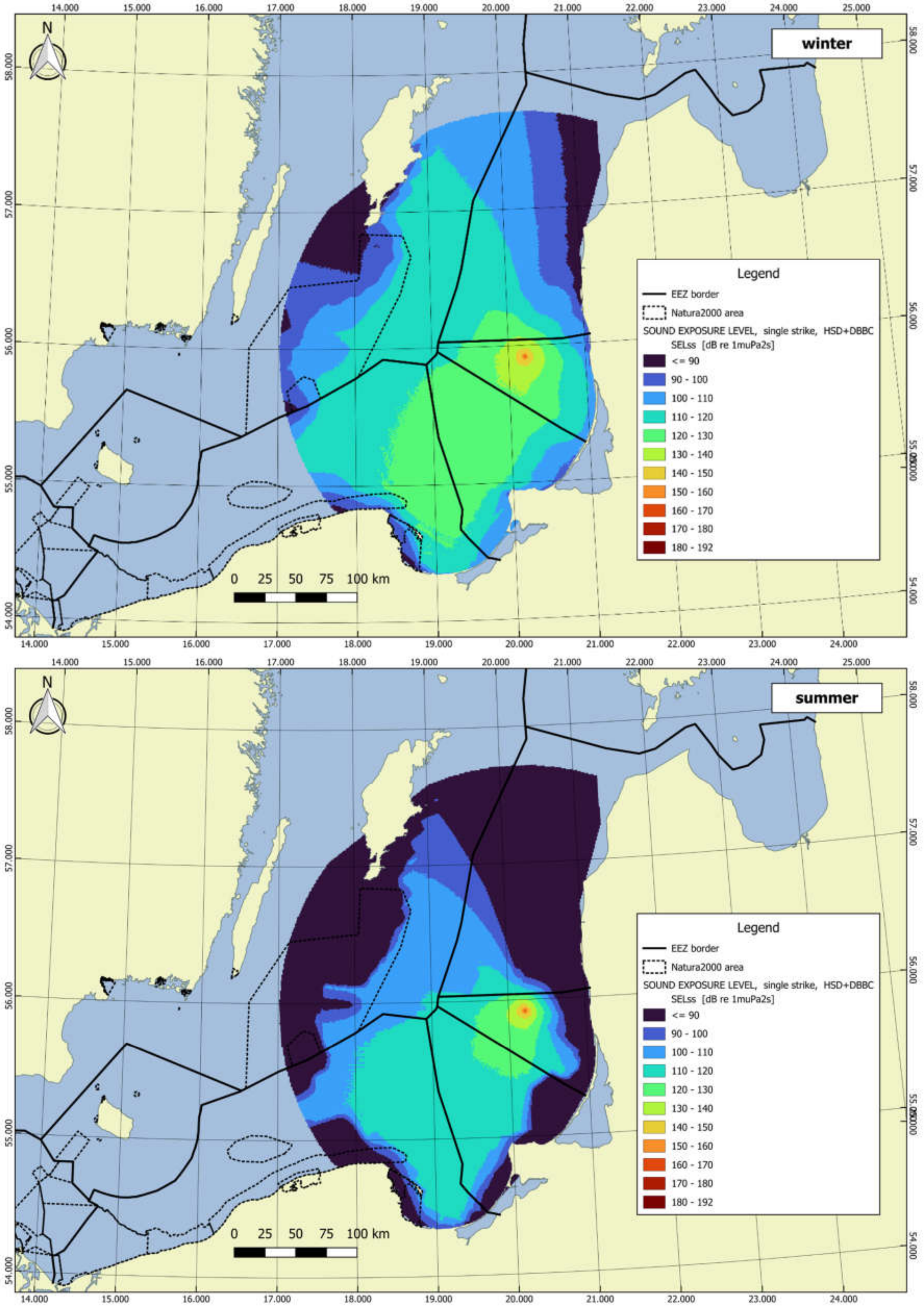


Figure 14. Noise maps of the unweighted broadband Sound Exposure Level $SEL_{ss,\ HSD+DBBC}$ [dB re 1µPa^{2}s] with single strike emission and applying of the mitigation measure with using of combination of Hydro Sound Damper (HSD) and Double Big Bubble Curtain (DBBC) for winter and summer seasons (upper and lower panels, respectively).

3.3 Assessing the effects of pile-driving noise on marine fauna representatives

In accordance with the considered noise exposure criteria (Tables 4-5) for particular representatives of marine fauna (harbour porpoises, seals, swim-bladdered fishes), values of the weighted sound exposure level $SEL_{weighted}$ used to estimate the impact effects in the form of exceeding the TTS and AUD INJ audibility thresholds and behavioural reaction (BR) of harbour porpoises were calculated considering single strike emission as well as the cumulative noise portion/dose. Moreover, values of the unweighted sound exposure level $SEL_{unweighted}$ used to estimate the potential occurrence of the behavioural reaction (considering single strike emission) for seals and swim-bladdered fishes were obtained as well.

For the clarity, graphical presentation of the results and its particular components (AUD INJ, TTS, BR) is based on a significance of the last ones, i.e. in the case of small range of the obtained negative impact of one of them (e.g., limited to couples of pixels), its visualization is omitted and the result is presented in the tabular form only.

3.3.1 Harbour porpoises (*Phocoena phocoena*)

For a single strike scenario, there is no any probability of appearance of auditory injury AUD INJ in each considered cases (unmitigated or mitigated ones). In context of the potential onset of the temporal threshold shift TTS, the results revealed relatively short ranges for both summer and winter season and limited to $R_{max,\ TTS,\ HP}$=0.41 km, for the unmitigated scenario only (Table 6). Moreover, in the case of applying of mitigation measures in the form of DBBC, HSD or their combination DBBC+HSD, probability of the TTS onset is completely vanished.
In context of behavioural reaction (BR), in winter season –the estimated distances revealed exceedance of the model space domain (R_{max}=200 km) in the SSW-SW azimuthal directions, where the “favourable” conditions of sound propagation are observed. In summer, the distance obtained was of about $R_{max,\ BR,\ HP}$=141.2 km (Fig. 15).

Considering the cumulative effect (*N=8713* strikes, during the total time duration of τ=5.81 [h]), an appearance of the auditory injury AUD INJ could be expected (Fig. 14). In the case of the unmitigated scenario –the one is within the ranges up to $R_{max,\ AUD\ INJ,\ HP}$=8.72 km and $R_{max,\ AUD\ INJ,\ HP}$=7.5 km in winter and summer, respectively. Within the mitigated scenario, exceedance of the AUD INJ threshold value could be observed at relatively small ranges up to $R_{max,\ AUD\ INJ,\ HP}$=0.62 km (winter) and $R_{max,\ AUD\ INJ,\ HP}$=0.84 km (summer), but if using the HSD as a mitigation measure only.
For the unmitigated scenario, the negative effect of pile-driving noise in the form of the temporal threshold shift TTS onset could be expected within the distances up to $R_{max,\ TTS,\ HP}$=87.4 km and $R_{max,\ TTS,\ HP}$=31.5 km in winter and summer, correspondingly. In the case of the mitigated measures, the potential TTS onset ranges are significantly smaller, and revealed distances of about $R_{max,\ TTS,\ HP}$≈5 km and $R_{max,\ TTS,\ HP}$≈0.5 km for HSD and DBBC or the combination of both DBBC+HSD, respectively (Table 6).

With regard to the estimation of BR, considering a harbour porpoise individual as a “moving receiver” with the fleeing speed of v=1.5 m/s (*see* section 2.2.8) and with the start point position located directly close to the position of pile-driving (in our case, r_0=*100 m*), marine mammal could flee away on distance *R*=31374 m during the whole process of piling. This distance is schematically illustrated as a semi-transparent circle in Figs. 16-19.

Considering the mentioned above and taking also into account "the escape model" (Eq. 8), the cumulative portion/doze of sound energy received by a harbour porpoise individual was obtained along the particular straight-line fleeing routes (in our case, 72 azimuthal profiles) and could be estimated as a (median) values of SEL_{cum}=167.4 [dB re 1µPa^{2}s] (unmitigated) and the mitigated ones: $SEL_{cum,\ DBBC}$= 130.7 [dB re 1µPa^{2}s], $SEL_{cum,\ HSD}$=148.1 [dB re 1µPa^{2}s] and $SEL_{cum,\ DBBC+HSD}$=131.1 [dB re 1µPa^{2}s], appropriately.

Table 6. Estimated impact distances for harbour porpoises (Phocoena phocoena).

Negative effect	**Threshold** $SEL_{VHF\text{-}weighted}$ **[dB re 1 µPa²s]**	**Maximum distance R_{max} [km]**							
		unmitigated		***DBBC***		***HSD***		***DBBC+HSD***	
		winter	**summer**	**winter**	**summer**	**winter**	**summer**	**winter**	**summer**
AUD INJ (single-strike)	159	-	-	-	-	-	-	-	-
AUD INJ (5.81h cum.)		8.72	7.5	-	-	0.62	0.84	-	-
TTS (single-strike)	144	0.41	0.41	-	-	-	-	-	-
TTS (5.81h cum.)		87.4	31.5	0.43	0.5	5.2	4.84	0.46	0.52
BR (single-strike)	94	≥md	141.2	2.33	2.30	19.5	12.4	2.44	2.64

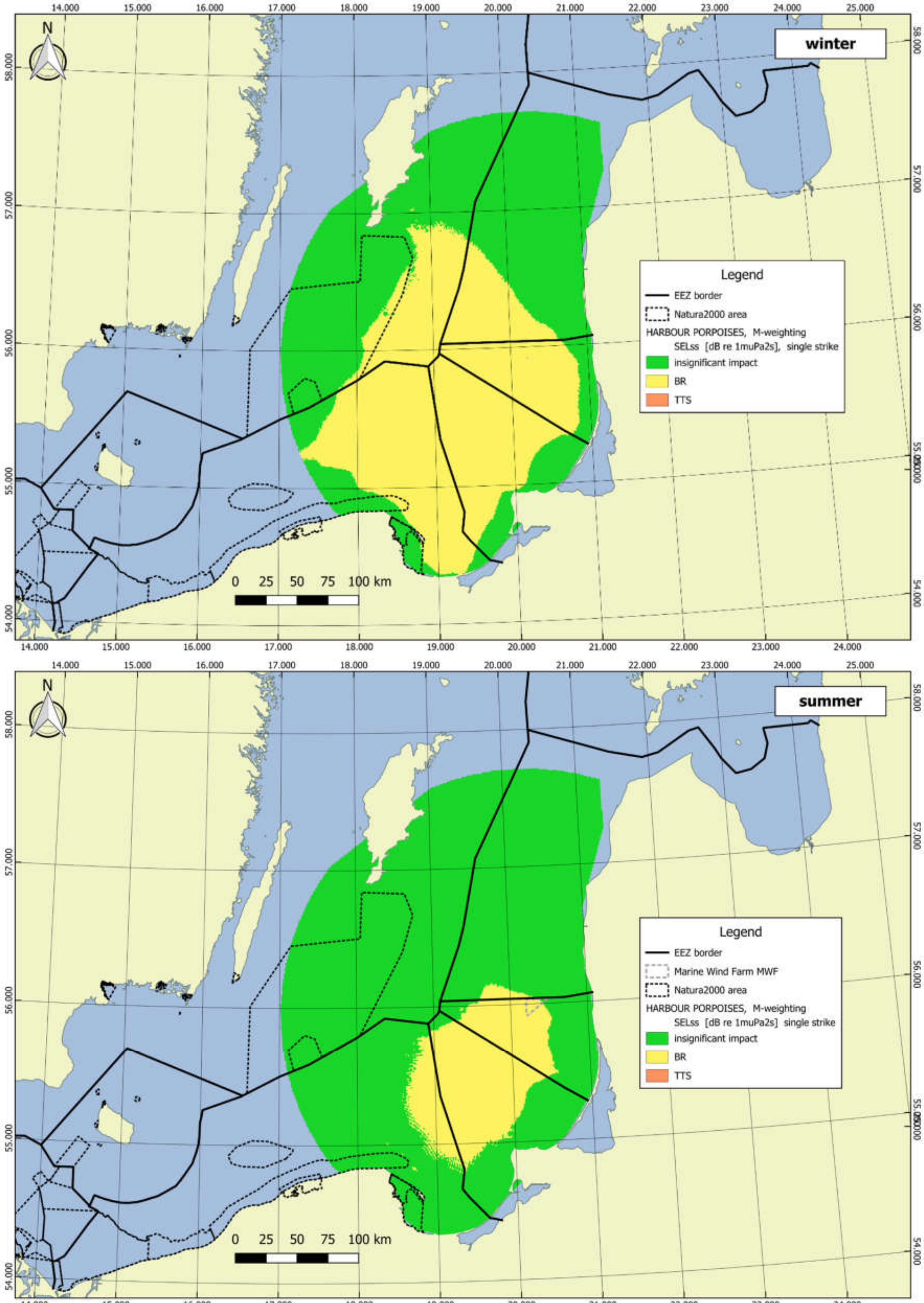
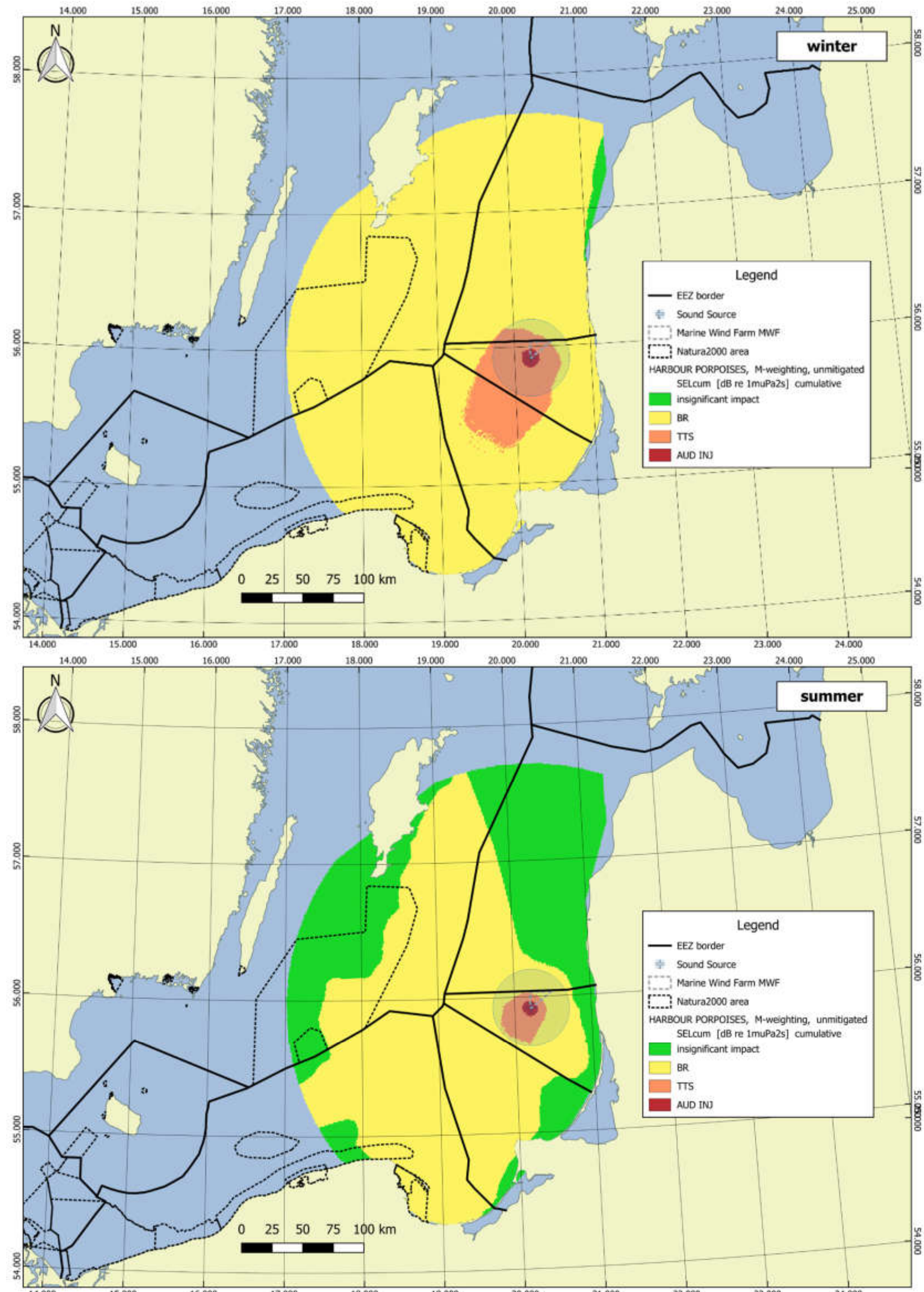
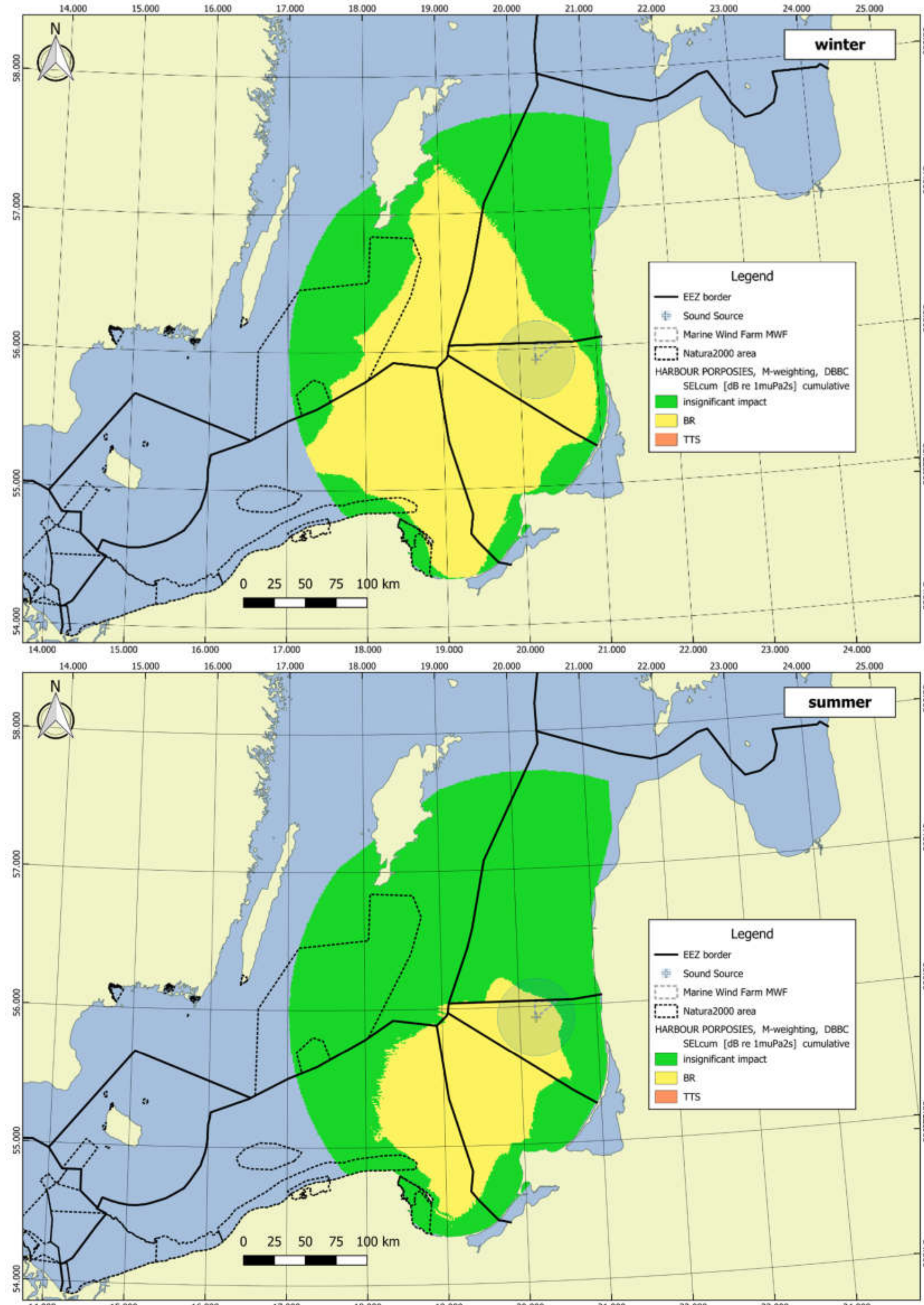


Figure 15. Noise maps of potential impact on harbour porpoises (Phocoena phocoena) obtained based on the scenario of the unmitigated single-strike SEL_{ss} [dB re 1µPa^{2}s] (VHF-weighted) for winter and summer (on the upper and lower panels, respectively).



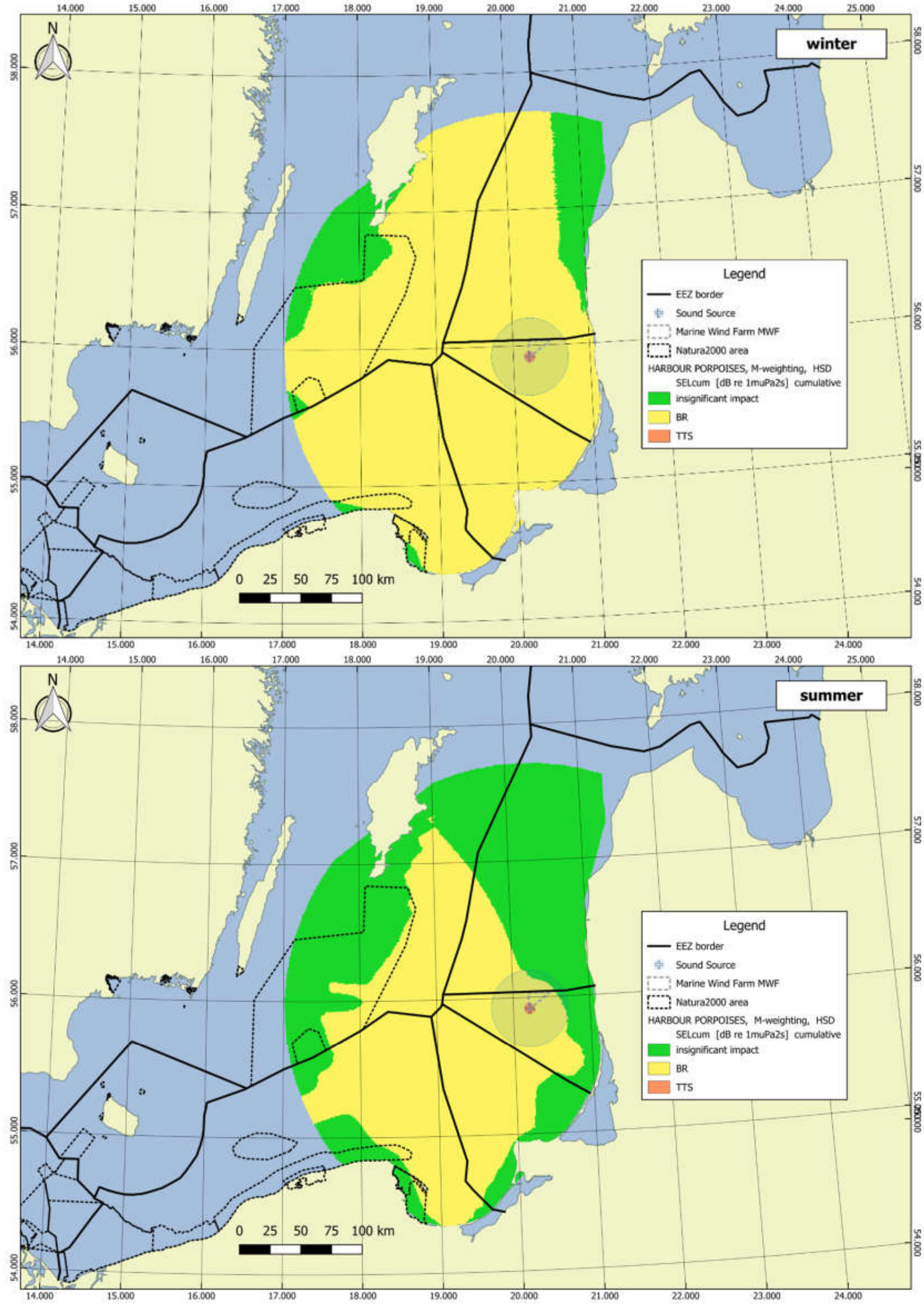
**- the yellow iso-level contour (BR) corresponding to a VHF-weighted sound exposure level SEL=94 [dB re 1μPa^{2}s] (see Table 4) is presented informatively only, assuming the case of the stationary position of the individual*

Figure 16. Noise maps of potential impact on harbour porpoises (Phocoena phocoena) obtained based on the scenario of the unmitigated cumulative SEL_{cum} [dB re 1μPa^{2}s] (VHF-weighted) for winter and summer (on the upper and lower panels, respectively). Semi-transparent blue circle radius r=31374 m.



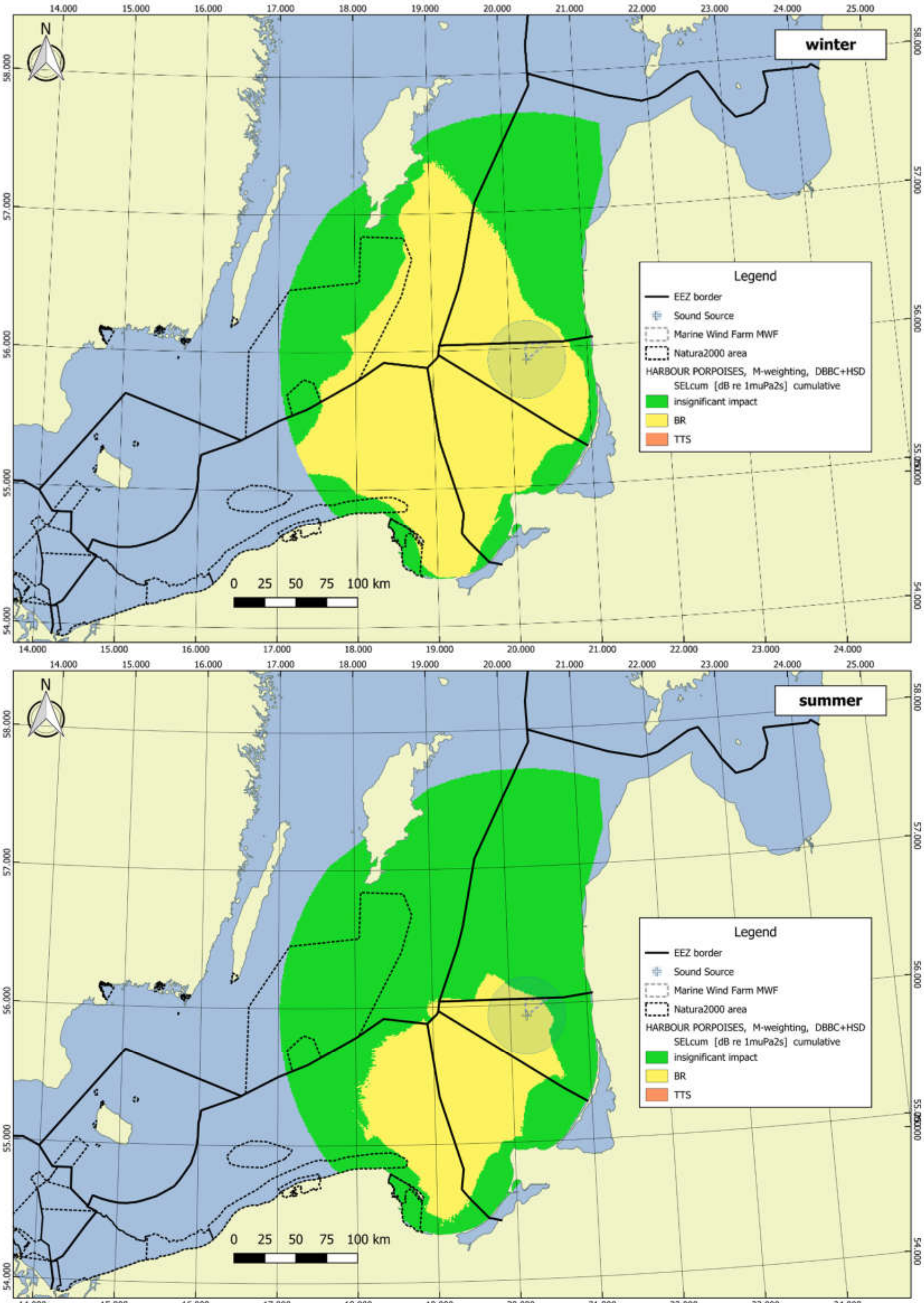
**- the yellow iso-level contour (BR) corresponding to a VHF-weighted sound exposure level SEL=94 [dB re 1µPa²s] (see Table 4) is presented informatively only, assuming the case of the stationary position of the individual*

Figure 17. Noise maps of potential impact on harbour porpoises (Phocoena phocoena) obtained based on the scenario of the DBBC-mitigated cumulative $SEL_{cum,\ DBBC}$ [dB re 1µPa^{2}s] (VHF-weighted) for winter and summer (on the upper and lower panels, respectively). Semi-transparent blue circle radius r=31374 m.



**- the yellow iso-level contour (BR) corresponding to a VHF-weighted sound exposure level SEL=94 [dB re 1μPa²s] (see Table 4) is presented informatively only, assuming the case of the stationary position of the individual*

Figure 18. Noise maps of potential impact on harbour porpoises (Phocoena phocoena) obtained based on the scenario of the HSD-mitigated cumulative $SEL_{cum,\ HSD}$ [dB re 1μPa²s] (VHF-weighted) for winter and summer (on the upper and lower panels, respectively). Semi-transparent blue circle radius r=31374 m.



- the yellow iso-level contour (BR) corresponding to a VHF-weighted sound exposure level SEL=94 [dB re 1μPa^{2}s] (see Table 4) is presented informatively only, assuming the case of the stationary position of the individual

Figure 19. Noise maps of potential impact on harbour porpoises (Phocoena phocoena) obtained based on the scenario of the combination DBBC+HSD-mitigated cumulative $SEL_{cum,\ DBBC+HSD}$ [dB re 1μPa^{2}s] (VHF-weighted) for winter and summer (on the upper and lower panels, respectively). Semi-transparent blue circle radius r=31374 m.

3.3.2 Harbour seals and grey seals (*Phocid pinnipeds*)

For harbour and grey seals as the Baltic Sea representatives of *Phocid pinnipeds* hearing group, there are no probability of appearance of the AUD INJ onset in any considered cases for a single strike noise event (Table 7). Nevertheless, the distances of about $R_{max,\ TTS,\ PW}$≈0.2 km for the potential onset of the TTS were observed in the case of the unmitigated scenario for both of the considered seasons.
In relation to the behavioural reaction BR (unweighted), the potential impact ranges are limited to $R_{max,\ BR,\ PW}$=10.7 km and $R_{max,\ BR,\ PW}$=8.6 km for winter and summer, respectively (Fig. 20).

Considering the unmitigated cumulative effect, appearance of the auditory injury AUD INJ at distances up to $R_{max,\ AUD\ INJ,\ PW}$≈6.2-6.3 km could be expected. In the case of the potential TTS-onset, distances of about $R_{max,\ TTS,\ PW}$=54.5 km and $R_{max,\ TTS,\ PW}$=22.1 km were observed for winter and summer seasons, respectively (Fig. 21).

Consecutively, taking into account an implementation of the DBBC mitigation measure within the cumulative scenario, the results revealed a relatively small distances of about $R_{max,\ AUD\ INJ,\ PW}$=0.22-0.25 km for the probable onset of the AUD INJ effect. In the case of HSD mitigation measure, ranges up to $R_{max,\ AUD\ INJ,\ PW}$=0.59 km and $R_{max,\ AUD\ INJ,\ PW}$=0.82 km are obtained for winter and summer, respectively. It should be noted that the probability of appearance of the AUD INJ for the case of using a combination DBBC+HSD is absent at all. In the case of the mitigated measures, the potential TTS onset ranges are significantly smaller than in the case of the unmitigated one and revealed distances of about $R_{max,\ TTS,\ PW}$=4.8 km – *in the case of HSD,* $R_{max,\ TTS,\ PW}$≈2.4-2.6 km – in the case of DBBC and $R_{max,\ TTS,\ PW}$≈0.7-0.9 km for the combination of both DBBC+HSD, respectively.

Potential appearance of the BR caused by unmitigated single strike, considering unweighted threshold value for seals, the maximum distances up to $R_{max,\ BR}$=10.7 km and $R_{max,\ BR}$=8.6 km were obtained for winter and summer, respectively (Fig. 20). In the case of using of the mitigation measures, the BR onset is reduced up to distances of $R_{max,\ BR,\ HSD}$=3.6-4.0 km (HSD), $R_{max,\ BR,\ DBBC}$=2.0-2.2 km (DBBC) and $R_{max,\ BR,\ DBBC+HSD}$=0.7-0.9 km (DBBC+HSD), respectively.

Table 7. Estimated impact distances for seals (Phocid pinnipeds).

Negative effect	**Threshold** $SEL_{PW\text{-}weighted}$ **[dB re 1 µPa²s]**	**Maximum distance R_{max} [km]**							
		unmitigated		***DBBC***		***HSD***		***DBBC+HSD***	
		winter	**summer**	**winter**	**summer**	**winter**	**summer**	**winter**	**summer**
AUD INJ (single-strike)	183	-	-	-	-	-	-	-	-
AUD INJ (5.81h cum.)		6.3	6.2	0.25	0.22	0.59	0.82	-	-
TTS (single-strike)	168	0.21	0.19	-	-	-	-	-	-
TTS (5.81h cum.)		54.5	22.1	2.36	2.6	4.8	4.8	0.72	0.91

BR (single-strike)	158unweighted	10.7	8.6	2.05	2.2	4.0	3.6	0.7	0.91

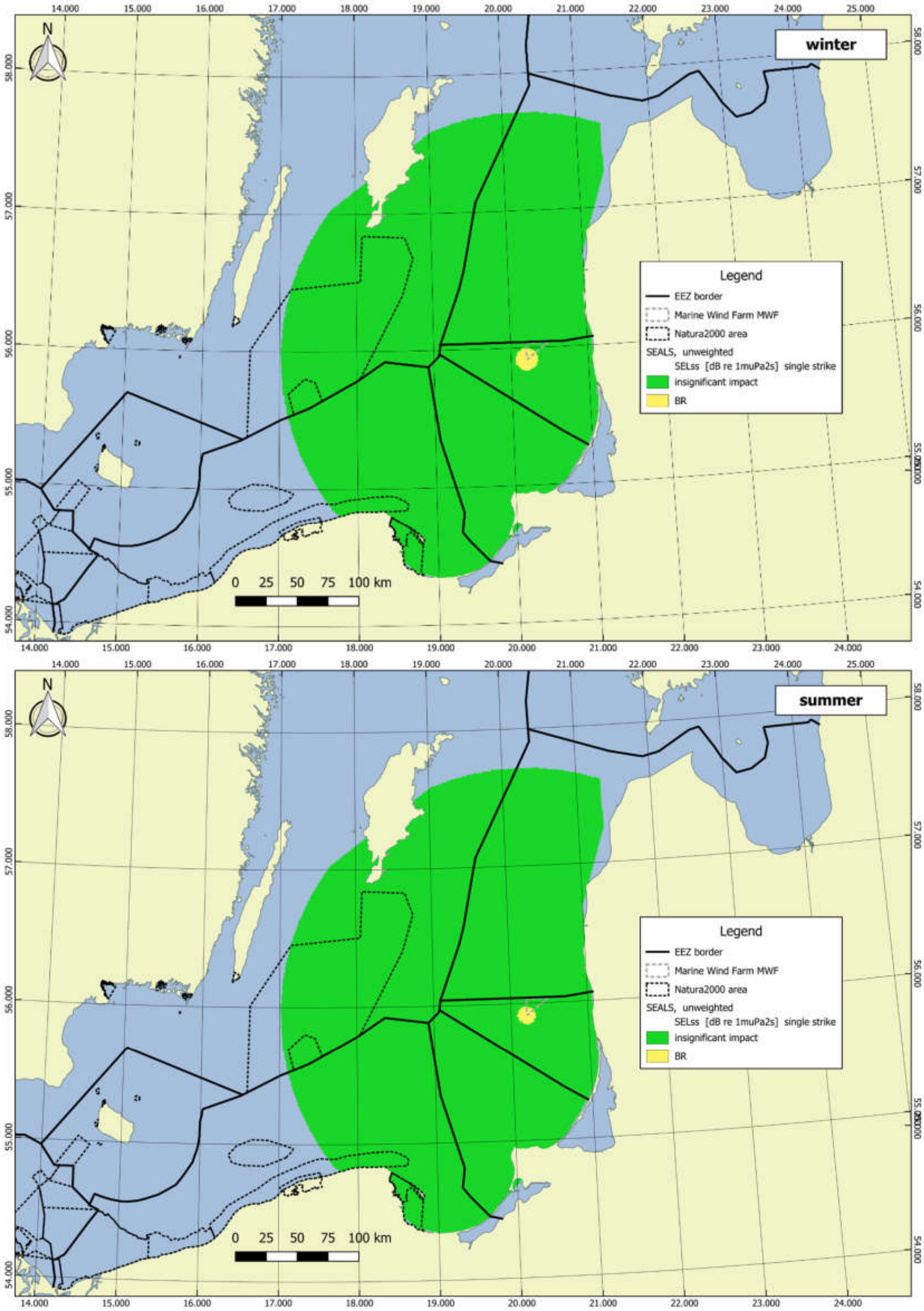


Figure 20. Noise maps of potential impact on seals (Phocid pinnipeds) in the form of onset of the behavioural reaction BR obtained based on the scenario of the unmitigated single-strike SEL_{ss} [dB re 1µPa^{2}s] (unweighted) for winter and summer (on the upper and lower panels, respectively).

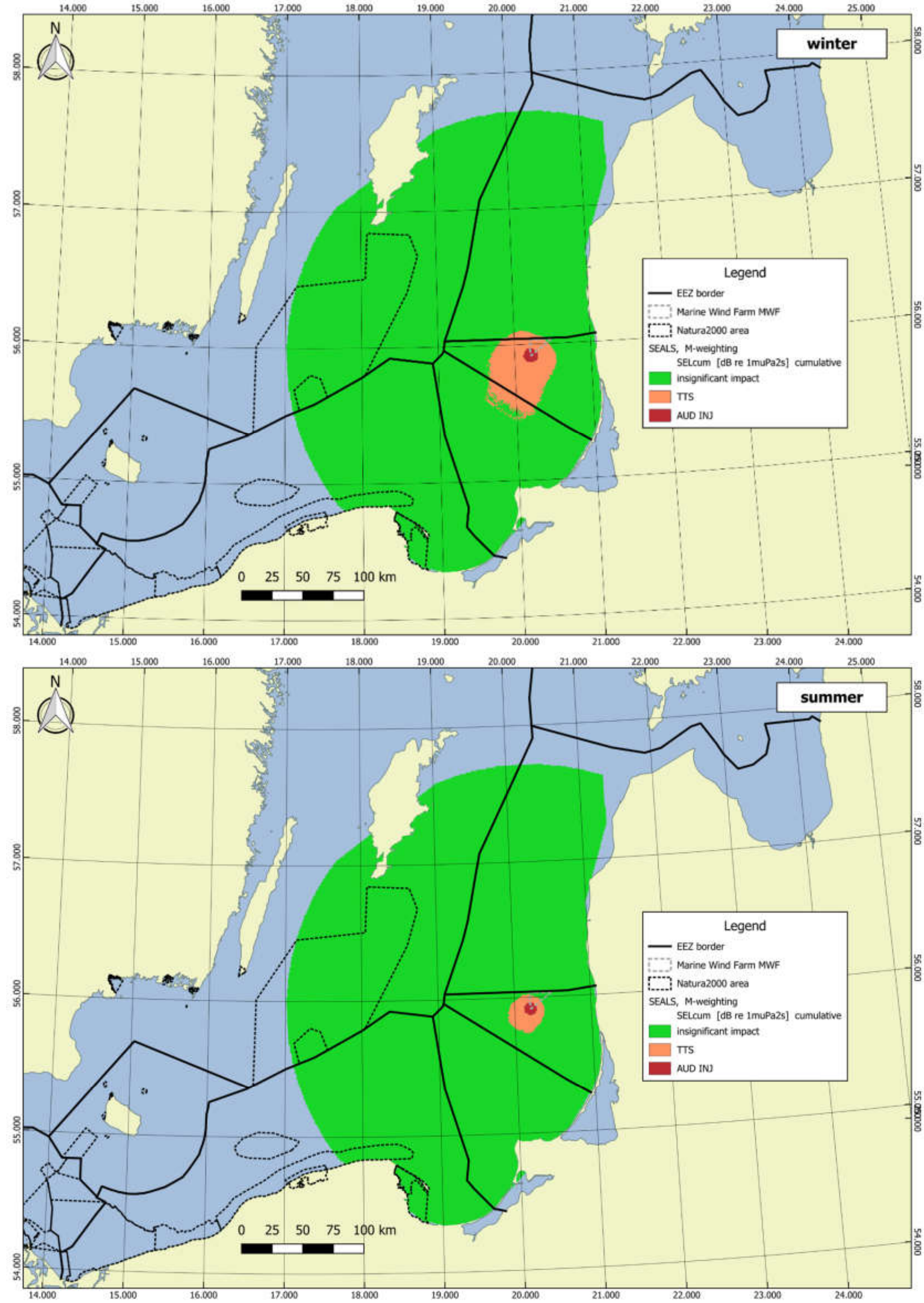


Figure 21. Noise maps of potential impact on seals (Phocid pinnipeds) obtained based on the scenario of the unmitigated cumulative SEL_{cum} [dB re $1\mu Pa^2 s$] (PW-weighted) for winter and summer (on the upper and lower panels, respectively).

3.3.3 Swim-bladdered fishes

Results obtained for swim-bladdered fishes within the unmitigated single-strike SEL_{ss} scenario showed that the BR range was close to the model space domain limit of R_{max}=200 km in winter season and about of $R_{max, BR}$=125 km in summer. Potential appearance of TTS-onset could be observed at very close distances of about $R_{max, TTS}$≈0.2 km to the sound source.

Considering the 5.81 h-cumulative effect, appearance of PTS could be expected. Significant reducing of the appropriate onset-distances (roughly 10 times as much) in the case of using combination of DBBC+HSD ($R_{max, PTS}$≈0.3-0.4 km) in comparison to the unmitigated scenario ($R_{max, PTS}$≈5.1-5.5 km) is observed. In context of the efficiency of the particular mitigation measures, the same tendency (like in the PTS case) is kept for the potential TTS-onset as well. All appropriate distances are summarized in Table 8.

Table 8. Estimated impact distances for swim-bladdered fishes.

Negative effect	**Threshold** $SEL_{unweighted}$ **[dB re 1 µPa²s]**	**Maximum distance R_{max} [km]**							
		unmitigated		***DBBC***		***HSD***		***DBBC+HSD***	
		winter	**summer**	**winter**	**summer**	**winter**	**summer**	**winter**	**summer**
PTS (single-strike)	203	-	-	-	-	-	-	-	-
PTS (5.81h cum.)		5.5	5.1	0.74	0.92	2.01	1.82	0.33	0.42
TTS (single-strike)	186	0.24	0.21	-	-	-	-	-	-
TTS (5.81h cum.)		64.1	24.3	7.9	6.73	14.2	9.93	4.1	3.64
BR (single-strike)	135	≥md	125.3	42.3	18.0	92.0	33.4	15.2	10.8

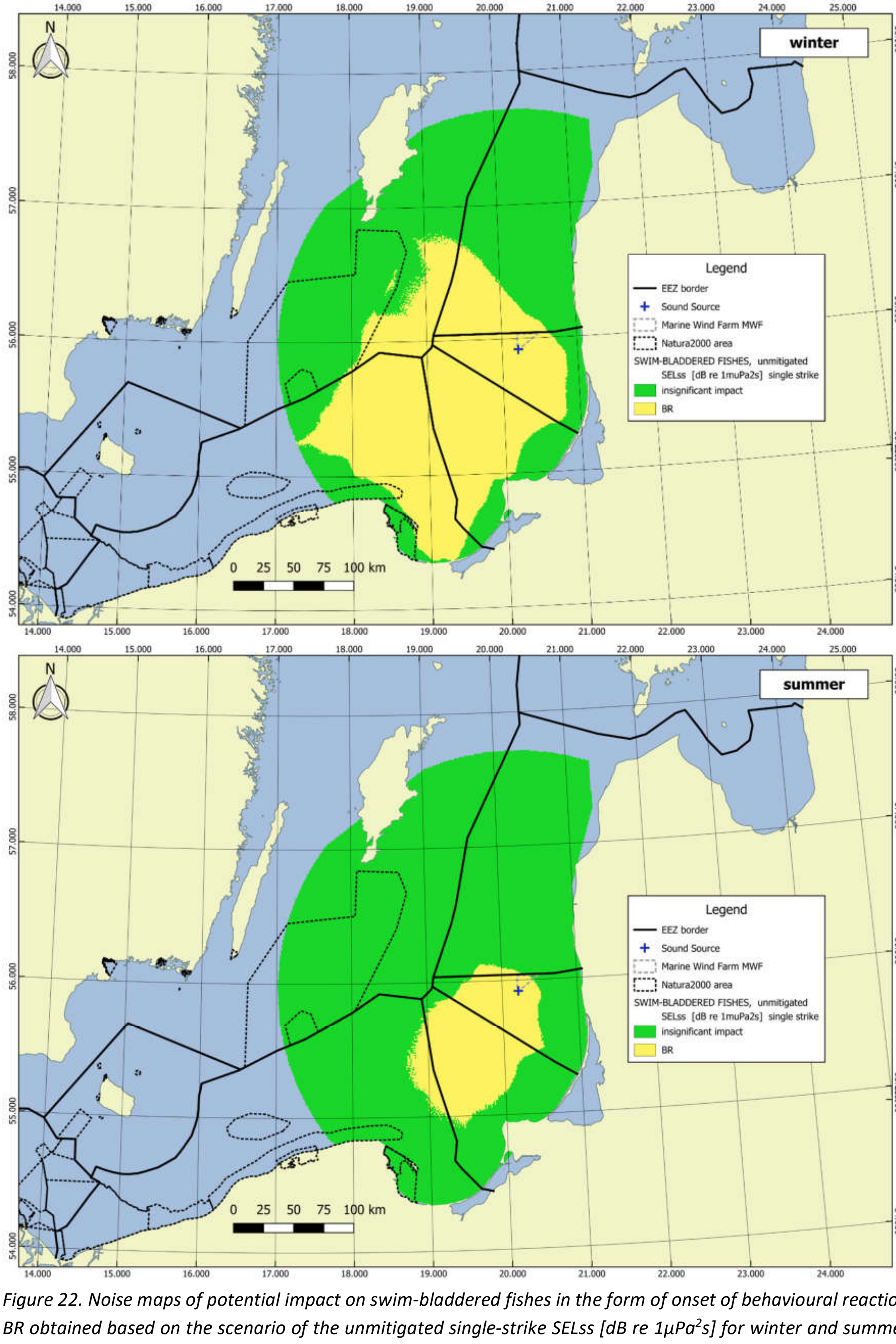
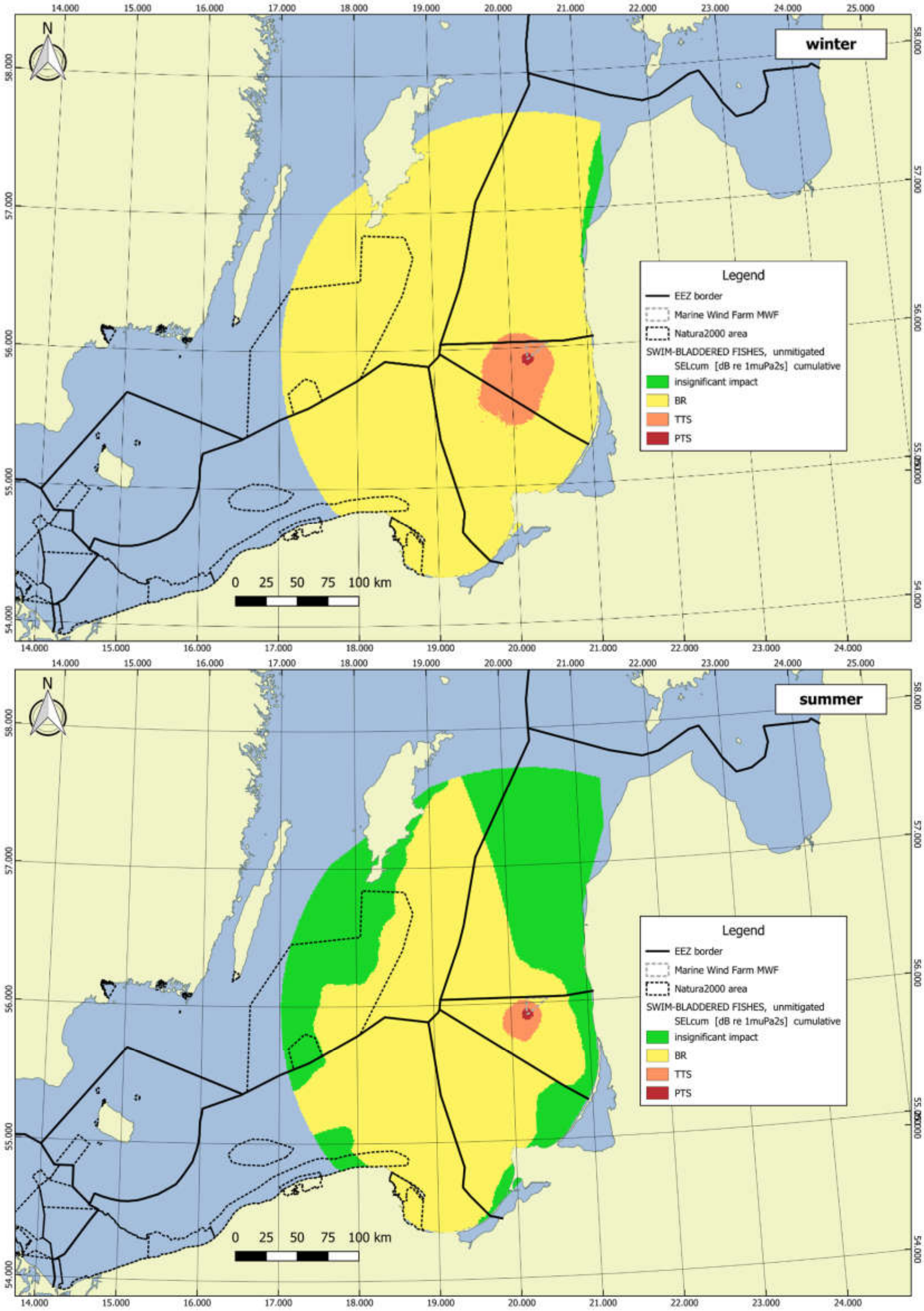


Figure 22. Noise maps of potential impact on swim-bladdered fishes in the form of onset of behavioural reaction BR obtained based on the scenario of the unmitigated single-strike SELss [dB re 1µPa²s] for winter and summer (on the upper and lower panels, respectively).



**- impact ranges considering onset of the behavioural reaction BR were estimated assuming stationary position of the individual fish and presented informatively only*

Figure 23. Noise maps of potential impact on swim-bladdered fishes obtained based on the scenario of the unmitigated cumulative SEL_{cum} [dB re 1μPa^{2}s] for winter and summer (on the upper and lower panels, respectively).

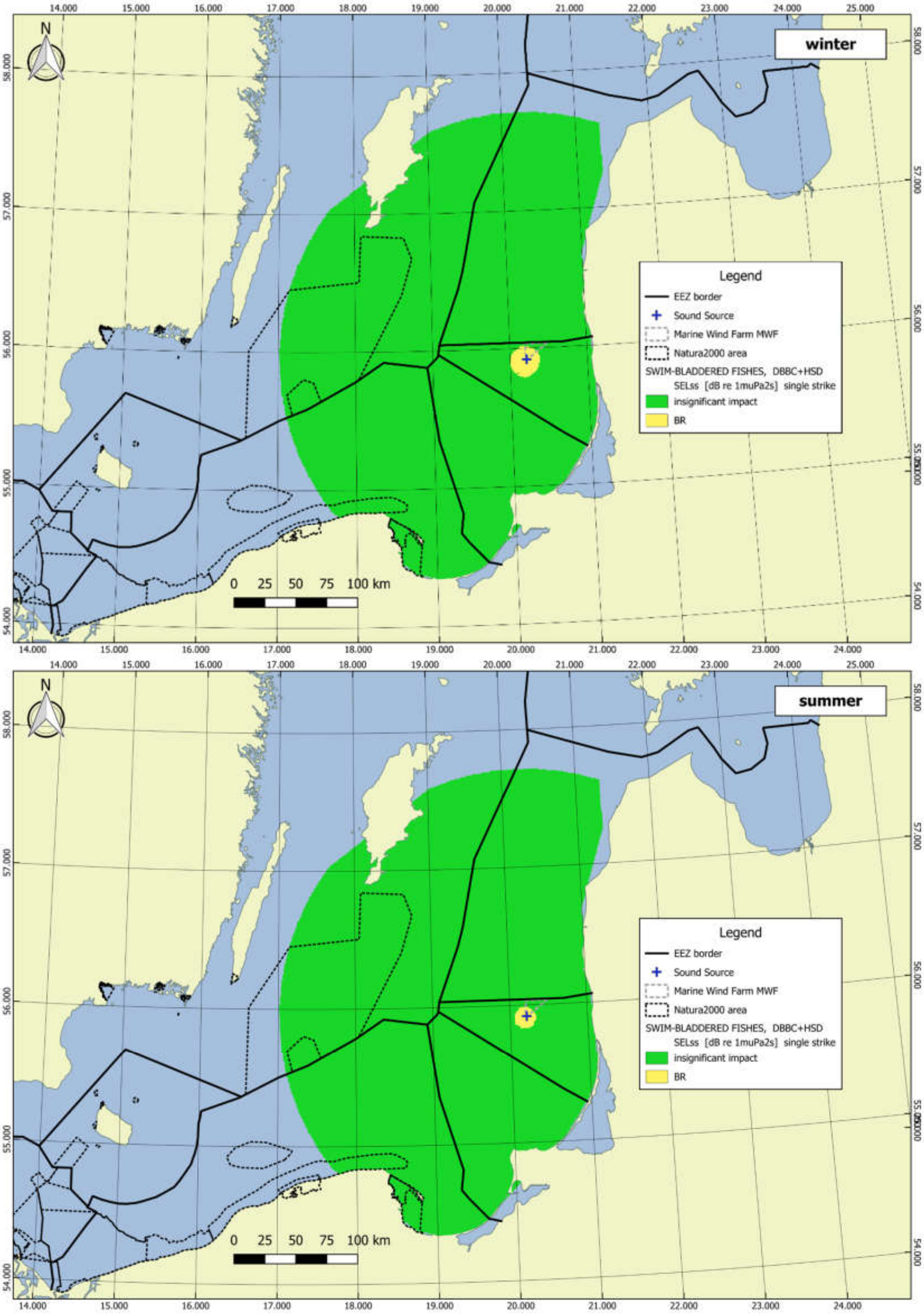
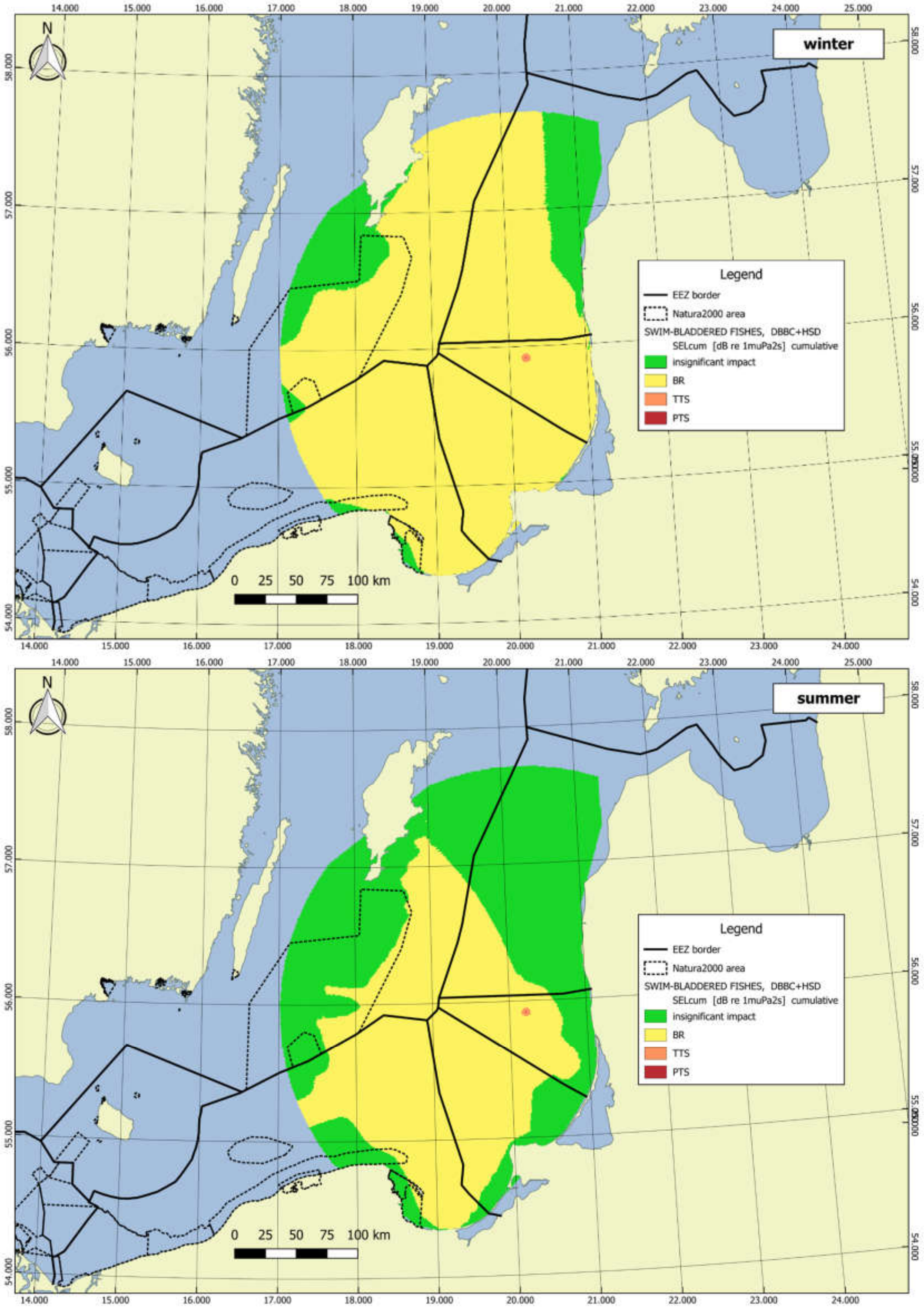


Figure 24. Noise maps of potential impact on swim-bladdered fishes in the form of onset of behavioural reaction BR obtained based on the mitigated DBBC+HSD single-strike $SEL_{ss,\ DBBC+HSD}$ [dB re 1μPa²s] scenario for winter and summer (on the upper and lower panels, respectively).



**- impact ranges considering onset of the behavioural reaction BR were estimated assuming stationary position of the individual fish and presented informatively only*

Figure 25. Noise maps of potential impact on swim-bladdered fishes obtained based on the mitigated DBBC+HSD cumulative $SEL_{cum,\ DBBC+HSD}$ [dB re 1μPa^{2}s] scenario for winter and summer (on the upper and lower panels, respectively).

3.3.4 SEL values obtained at the reference distances

In order to verify of propagation model by *in-situ* measurements and demonstrate of compliance with acoustic criteria, a set of control distances was proposed in the guideline published by Danish Energy Agency (Tougaard *et al.*, 2023). If measurements performed during piling, a minimum set of receiver ranges should be considered like the reference one *R*=750 m and a set of other ones, including of 1000, 1500, 2000, 3000 m from the position of pile-driving. Moreover, according to the mentioned above document, it is recommended to include a hydrophone position in between 5000 and 10000 meters as well.

The appropriate values of unmitigated and mitigated *SEL* were estimated at all of the recommended distances (Table 9). The particular source level spectra (insertion loss) of the modelled pile-driving noise for different types of scenarios considered in the study were the basis for a such calculations. The ones were derived from the comprehensive experimental study performed by Bellmann *et al.* (2020) and illustrated below in Fig. 26.

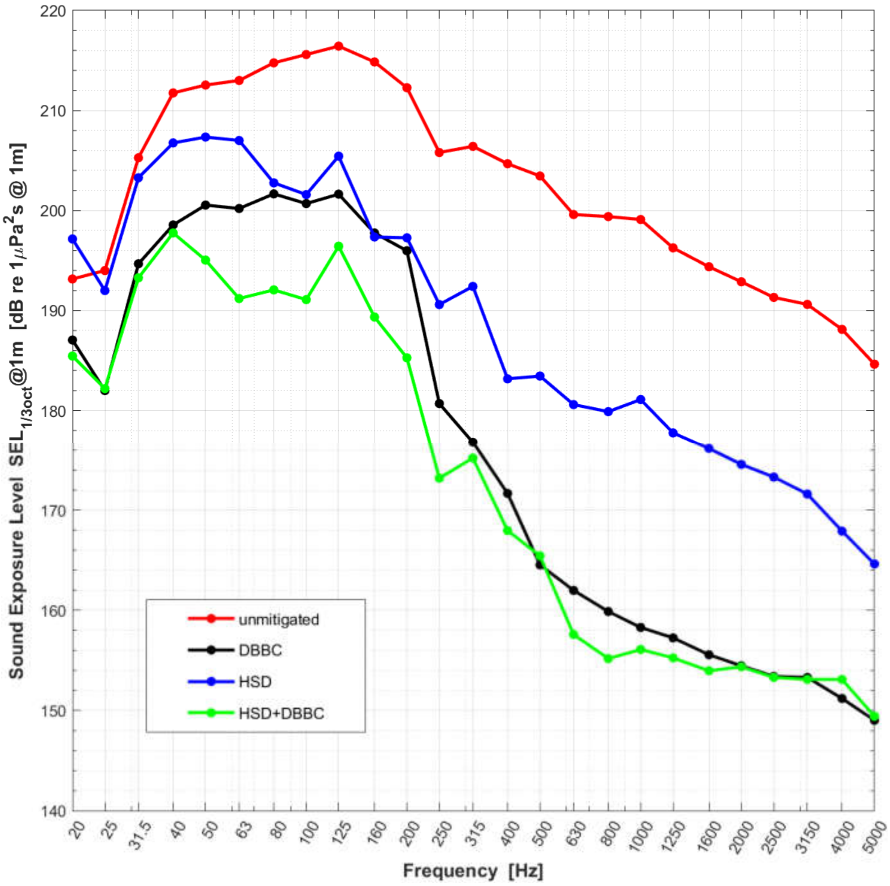


Figure 26. Source level spectra of the modelled pile-driving noise defined as sound exposure level SEL in 1/3-octave bands [dB re 1μPa^{2}s@1m], in frequency range applied in modelling (20Hz−5kHz). The unmitigated $SEL_{unmitigated}$ (red curve) and with mitigation measures in the form of: double big bubble curtain SEL_{DBBC}, hydro sound damper SEL_{HSD} and with a combination of both $SEL_{DDBC+HSD}$ (black, blue and green curves, respectively) [on the basis of the results published in Bellmann et al. (2020)]

Table 9. Broadband sound exposure level SEL at different distances from the pile-driving.

Season	**Distance [m]**	**Broadband Sound Exposure Level $SEL_{20Hz\text{-}5kHz}$ [dB re 1µPa^{2}s]**			
		unmitigated	**DBBC**	**HSD**	**DBBC+HSD**
Winter / Summer	750	178.0 178.9	163.6 164.5	168.6 169.5	157.8 158.7
	1000	176.8 176.3	162.4 161.9	167.4 166.9	156.6 156.1
	1500	174.2 173.4	159.8 159.0	164.8 164.0	154.0 153.2
	2000	173.3 171.5	158.9 157.1	163.9 162.1	153.1 151.3
	3000	169.4 169.7	155.0 155.3	160.0 160.3	149.2 149.5
	5000	164.2 163.8	149.8 149.4	154.8 154.4	144.0 143.6
	10000	158.1 155.4	143.7 141.0	148.7 146.0	137.9 135.2

4 Summary

In this technical report, modelling of the anthropogenic underwater noise emission during pile-driving for the planned marine wind farm MWF “Curonian Nord” located in the Lithuanian EEZ of the Baltic Sea was investigated. The analysis was performed under an assumption of using the monopile structure of 10 m in diameter driving into seabed by 6600 kJ impact hammer and considering also contrastingly different sound propagation conditions which are observed in the Baltic Sea during the winter and summer time.

In context of the characteristics of the underwater sound source, two case scenarios were undertaken in the modelling. The first scenario (as a reference one) – in which no mitigation measures where applied and the other one –with the using of secondary mitigation measures like double big bubble curtain DBBC, hydro sound damper HSD and simultaneous combination of both DBBC+HSD mitigation techniques.

Based on the acoustic modelling of sound fields using the MIKE-Underwater Acoustic Simulator (MIKE-UAS) software, the impact zones of potential hearing injury in the form of the auditory injury (AUD INJ), temporal threshold shift (TTS) and behavioural reaction (BR) were estimated for the primary representatives of the Baltic marine fauna: harbour porpoises (*Phocoena phocoena*), seals (*Phocid Pinnipeds*) and swim-bladdered fishes.

This report should be treated as a technical background report for further steps of the environmental impact assessment (EIA) on marine mammals and fishes.

The obtained results of modelling revealed that the sound transmission depends strongly on bathymetry along the particular azimuthal directions resulting in a significant space anisotropy (directional differences) of the noise field. In the sound maps, the "favourable" SW/SSW-azimuthal directions of noise propagation are clearly emphasized. The noise levels were larger in the directions to the southwest to south-southwest in comparison to another azimuths.

<u>In the case of single-strike scenario</u>, the estimated impact ranges of negative effect in the form of AUD INJ is not be expected for the any marine fauna representatives considered in the study. In context of temporary changes of sensitivity of hearing (i.e. temporal threshold shift, TTS), impact ranges with distances up to $R_{max,\ TTS,\ HP}$≈0.4 km for harbour porpoises, $R_{max,\ TTS,\ PW}$≈0.2 km for seals and up to $R_{max,\ TTS,\ F}$≈0.24 km for swim-bladdered fishes could be expected in the case of unmitigated scenario. Moreover, behavioural responses BR could be expected to happen at distances close to of the model space domain (R_{max}=200 km) and $R_{max,\ BR,\ HP}$≈141 km ($R_{max,\ BR,\ F}$≈125 km) –for harbour porpoises and for swim-bladdered fishes in winter and summer, respectively. The appropriate BR distances for seals are significantly smaller and revealed values of $R_{max,\ BR,\ PW}$=10.7 km and $R_{max,\ BR,\ PW}$=8.6 km, correspondingly. Applying a DBBC, HSD or combination of both DBBC+HSD will reduce the emitted sound levels and thus cut the potential negative impact ranges significantly resulting in a lack of AUD INJ/TTS effects at all. Naturally, all of the mitigated scenario reduce the behavioural response BR distances as well. The most effective is using of combination of both DBBC+HSD mitigation techniques. It lets to reduce BR distances up to $R_{max,\ BR,\ HP,\ DBBC+HSD}$≈2.44-2.64 km for harbour porpoises, $R_{max,\ BR,\ PW,\ DBBC+HSD}$≈0.7-0.9 km for seals and $R_{max,\ BR,\ F,\ DBBC+HSD}$≈10.8-15.2 km and $R_{max,\ BR,\ F,\ DBBC}$=16.5 km for swim-bladdered fishes. Nevertheless, it should be noted that considering harbour porpoises BR with applying a single DBBC mitigation measure, the results revealed a comparable with the DBBC+HSD values (in fact, a little bit smaller ones) –up to $R_{max,\ BR,\ HP,\ DBBC}$≈2.30-2.33 km. The last one could be explained by the fact that, in general, the HSD mitigation system is significantly less effective in comparison with the DBBC one, especially in the mid-frequency range (>≈1 kHz), where harbour porpoises reveal better hearing ability in contrast to low frequencies.

<u>For cumulative effect</u> (in our case, multiple strikes N=8713 in total), the appropriate estimates showed considerably larger impact zones compared to the single-strike scenario. Considering no response movement (stationary position of individual during the whole 5.81 h exposition), in the case of unmitigated scenario, AUD INJ effect could be observed at distances up to $R_{max,\ AUD\ INJ,\ HP}$=7.5-8.7 km for harbour porpoises and $R_{max,\ AUD\ INJ,\ PW}$=6.2-6.3 km for seals. In context of potential PTS-onset, the results revealed distances up to $R_{max,\ PTS,\ F}$=5.1-5.5 km for swim-bladdered fishes. TTS ranges up to $R_{max,\ TTS,\ HP}$=87.4 km and $R_{max,\ TTS,\ HP}$=31.5 km for harbour porpoises, $R_{max,\ TTS,\ PW}$=54.5 km and $R_{max,\ TTS,\ PW}$=22.1 km for seals, and $R_{max,\ TTS,\ F}$=55 km and $R_{max,\ TTS,\ F}$=22.7 km for swim-bladdered fishes, could be observed in winter and summer, respectively.

Using of DBBC, HSD and both DBBC+HSD mitigation systems revealed that the potential negative impact ranges are reduced significantly. In general, lack of AUD INJ effect for harbour porpoises could be expected in the case of using DBBC or combination of both DBBC+HSD mitigation techniques. Although, in the case of applying a single HSD-system only, the auditory injury AUD INJ could be observed at relatively short distances up to $R_{max,\ AUD\ INJ,\ HP}$=0.62 km and $R_{max,\ AUD\ INJ,\ HP}$=0.84 km in winter and summer, respectively. For seals, AUD INJ could be observed in the case of applying DBBC and HSD mitigation systems (as a single ones), within an expected ranges up to $R_{max,\ AUD\ INJ,\ PW,\ DBBC}$≈0.25 km and $R_{max,\ AUD\ INJ,\ PW,\ HSD}$≈0.82 km, respectively. In context of TTS, for harbour porpoises, the onset ranges reduced up to $R_{max,\ TTS,\ HP,\ DBBC}$=0.43-0.5 km in the case of DBBC and within a comparable values of $R_{max,\ TTS,\ HP,\ DBBC+HSD}$=0.46-0.52 km in the case of combination both DBBC+HSD. Contrary to, in the case of using a single HSD system, the estimated TTS-onset ranges of about 10-fold larger ($R_{max,\ TTS,\ HP,\ HSD}$=4.84-5.2 km). For seals, TTS-onset distances up to $R_{max,\ TTS,\ PW,\ HSD}$=4.8 km, $R_{max,\ TTS,\ PW,\ DBBC}$≈2.36-2.6 km and $R_{max,\ TTS,\ PW,\ DBBC+HSD}$≈0.72-0.91 km for the mitigated scenario considered using of HSD, DBBC and combination of both DBBC+HSD.

Appearance of potential negative effect in the form of AUD INJ (e.g., in the case of single DBBC) as well as more higher appropriate TTS-onset ranges for seals could at least partially explained by the fact that *Phocid Pinnipeds* (PW) possess better hearing perception in low frequency range (where the primary part of sound energy from pile-driving is concentrated) in comparison to harbour porpoises which, in turn, are characterized by better hearing ability in very high frequency (VHF) range (*see* Fig. 8 and Tables 6-7, for details). In context of swim-bladdered fishes, the estimates for multiply strikes showed that PTS could be observed at distances up to $R_{max,\ PTS,\ F}$≈5.5 km (unmitigated scenario), within a significant more shorter distances in the case of applying mitigation measures, leading to reduce the negative range up to $R_{max,\ PTS,\ F,\ DBBC+HSD}$≈0.33-0.42 km like in the case of combination of both DBBC+HSD mitigation systems (*see* Table 8).

Considering a harbour porpoise individual as a "moving receiver", with regard to the estimation of behavioural reaction (BR) [*see* section 2.2.8], it was found that marine mammal could flee away of a distance r=31374 m during the complete process of piling, assuming the total number of strikes N=8713 and time duration of τ=5.81 h. In that way, the cumulative portion/doze of sound energy received by a harbour porpoise individual along the particular straight-line fleeing routes (in our case, 72 azimuthal profiles) could be estimated as a (median) values of SEL_{cum}=167.4 [dB re 1μPa^{2}s] (unmitigated) and the mitigated ones: $SEL_{cum,\ DBBC}$=130.7 [dB re 1μPa^{2}s], $SEL_{cum,\ HSD}$=148.1 [dB re 1μPa^{2}s] and $SEL_{cum,\ DBBC+HSD}$=131.1 [dB re 1μPa^{2}s] for DBBC, HSD and combination of both DBBC+HSD systems, appropriately. The mentioned above results revealed that the M-weighted behavioural reaction threshold proposed by Tougaard (2021) were exceeded in all the considered cases in the study.

It should be emphasized that due to limited knowledge on how sound energy is accumulated at the marine mammal organism and well-established validity of the proposed impact criteria for the case of multiply impulsive noise events (hammer strikes), the results of modelling in context of cumulative effect could, naturally, comprise many uncertainties and should be considered, in some extent, with a circumspection.

Additionally, in order to have a possibility to verify of propagation model in future (for example, on the basis of results obtained by *in-situ* measurements performed during pile-driving procedure), values of unmitigated and mitigated *SEL* with using of different kind of mitigation techniques (DBBC, HSD) and their combinations (DBBC+HSD), were estimated for the set of control distances (Table 9), in according to the recommendation proposed in the guideline published by Danish Energy Agency (Tougaard *et* *al.*, 2023). The last one could be used as a specific/reliable indicator for the proper choice of the particular mitigation system planned to use during the construction works. Moreover, reference to the use of an acoustic deterrent device (ADD), aiming to produce non-injuring discomfort to the marine mammals and cause them to move away from the noise source, the ADD activation could be potentially considered, but only in the case of applying HSD mitigation system as a single one. Followed by the recommendations published in the Danish guideline, the usage of ADD is become justified due to the fact that the observed onset of AUD INJ (which could be leading to a permanent threshold shift PTS) are characterized by ranges of $R_{max,\ AUD\ INJ}$≈0.6-0.8 km for both of marine mammals considered in the study (harbour porpoises and seals). The observed distances are three-four times higher than the proposed threshold, taking into account that when R_{PTS}<200 m the use of an ADD is generally prohibited. In the case of DBBC, the appropriate potential impact ranges $R_{max,\ AUD\ INJ}$≈0.22-0.25 km (for summer and winter, respectively) are insignificantly higher than the mentioned above condition, but only considering *Phocid Pinnipeds* representatives (seals) as an object of protection. Considering a proper operation of chosen mitigation system during construction phase, the usage of ADD is not justified and redundant in all other scenarios.

5 Literature

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