STAR OF THE SOUTH



Technical attachment

Attachment I - Underwater noise modelling



STAR OF THE SOUTH OFFSHORE WIND FARM

Underwater Noise Technical Report



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Appendices

Appendix A JASCO acoustic modelling report

EXECUTIVE SUMMARY

Overview

Star of the South is Australia's most advanced offshore wind project. Located off the central Gippsland coast, the project comprises an offshore wind farm and supporting transmission infrastructure to transfer energy to the existing electricity network.

A delegate of the Commonwealth Minister for the Environment determined that the project is a controlled action (as set out in notice dated 2 June 2020) and is required to be assessed under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) through preparation of an Environmental Impact Statement (EIS) and the Victorian Minister for Planning determined that an Environment Effects Statement (EES) is required (as set out in notice dated 11 May 2020) under the *Environment Effects Act 1978* (EE Act).

Existing environment

This technical report deals with underwater noise as a key source of potential impact from the Star of the South Offshore Wind Farm Project (the project). The relevant aspects of the existing environment for underwater noise include noise-sensitive receptors and the existing marine soundscape. The key noise-sensitive receptors within the offshore wind farm area (OWFA) include:

- Marine mammals: baleen whales, toothed whales and pinnipeds (Refer Technical Report D)
- Fish: Sharks, rays and bony fish (Refer Technical Report C)
- Diving seabirds and shorebirds (Refer Technical Report E)
- Pelagic and benthic invertebrates (Refer Technical Report B).

An understanding of the existing soundscape of the OWFA was obtained via the passive acoustic monitoring program undertaken between March 2020 and March 2022 (McCauley, 2022). This program determined that the sources of the soundscape included wind and tidal noise, anthropogenic noise, whale signals, fish and snapping shrimp noise, and earthquake or landslip events.

All inshore sites within the OWFA included snapping shrimp noise, resulting in a peak of noise at 10 kHz, however, no snapping shrimp noise was detected at the offshore site. Anthropogenic noise sources detected included shipping traffic and nearby petroleum facility operation activities, with noise appearing at 5 to 100 Hz. Wind was a predominant source of noise within the OWFA throughout the survey period, with noise ranging between 3 Hz and 3 kHz. Higher levels of ambient noise below 6 Hz were observed from August to February (110 dB – 80 dB) compared to March to July (80 dB – 60 dB), thought to be produced by a greater prevalence of strong easterly winds during this time.

This ambient noise analysis can be used as a baseline to compare with the OWFA once the wind farm is installed and operational.

Noise effect ranges for hearing impairment and disturbance of marine fauna

Elevated underwater noise levels can affect marine fauna by causing direct physical effects, such as hearing impairment. Hearing impairment may be temporary (temporary threshold shift – TTS), or permanent (permanent threshold shift – PTS). Noise can also cause disturbance leading to behavioural changes or displacement from important areas. For this report, there is a focus on temporary threshold shift and behavioural disturbance effects. This is because there is published guidance that predicts the noise levels at which these occur, which can be used in acoustic modelling to determine the distances at which marine fauna may be affected by a noise source. Behavioural disturbance is where an animal responds to an instantaneous noise source, while a temporary threshold shift is an auditory impairment that requires continual exposure to a noise source over time, resulting in a time-integrated measure of exposure. Thresholds at which these occur have been predicted for a range of marine fauna in Southall et al. (2019)

and NMFS (2024). The report results generally focus on low-frequency (LF) cetaceans, as effect ranges for the type of noise being modelled are the largest for species of this marine mammal group.

Key findings of the underwater noise modelling

Contemporary input data, as it has become available, have been used over four rounds of underwater acoustic modelling from 2020 to 2025 to predict the underwater noise emissions during construction for the SOTS project. This has included noise generated from monopile and jacket pin pile installation using impact pile driving and vibro-piling methods, and vessel operations associated with the construction of the project. Subsequent rounds of modelling will be undertaken as the project design further develops and as technologies become available.

Throughout the four rounds of modelling, various installation and vessel options were considered, and modelling inputs and methods were updated and refined over the iterations. The modelling results have already been used to influence project decisions about what options can be eliminated as unfeasible, and to determine what would be advanced into further modelling studies and the current environmental impact assessment.

Modelling became progressively more accurate during each of the rounds due to the reduced level of assumption in data inputs. For example, geo-acoustic properties of the project area were initially determined by CMST noise propagation measurements (first round), with site specific geotechnical data for each monopile/jacket location used in the third and fourth round of modelling.

In the fourth modelling round, a combination of three noise abatement systems (NAS) was included, a double big bubble curtain (DBBC), hydro sound dampener (HSD) and modified hammer system (MHS) to reduce ranges to noise effect threshold predictions to as low as possible using current technologies. The MHS system reduces noise emissions at the source by modifying the way that the hammer interacts with the pile. The MHS is placed directly between the hammer and the pile and acts as a fluid cushioning, elongating the impact of the hammer and lowering the peak force.

The outcomes of the modelling undertaken that has been used to inform the EIS is summarised below:

- Concurrent pile driving has been ruled out due to the significant increase in noise generated not only from the pile driving, but also from having multiple vessels operating in proximity.
- While pin piles, due to their smaller diameters, are less noisy to install than monopiles (effect ranges for behavioural disturbance in low frequency whales are two to three km compared with around five to six kilometres), when modelling the installation of multiple pin piles in succession (four pin piles), the effect ranges for TTS are significantly larger (22.4 kilometres) than the effect ranges for monopiles (8.6 kilometres) due to differences in the mitigation systems that can be applied, and because the installation duration is approximately six times as long (14 hours versus 2.5 hours).
- Modelling at deep, intermediate and shallow sites found that maximum effect ranges to temporary threshold shift criteria for LF cetaceans were the largest for all the marine fauna considered. These were in the order of an 8.5 – 9-kilometre radius around the noise source. This predicts that a low-frequency whale may be subject to an auditory impairment if it remained in that radius for a period of 24 hours.
- Animat movement modelling, using realistic behavioural parameters, reduced the ranges to TTS onset by about a half to around 4.5 kilometres for blue, southern right and humpback whales, and less than 1.5 kilometres for minke whales. The results from the animat modelling have been used to inform the marine mammal EIS and associated management for LF cetaceans (Refer Technical Report D), however, it is also considered that ranges to noise exposure thresholds are applicable if whales are displaying movement patterns similar to those parameters entered into the model.
- Behavioural disturbance ranges for LF cetaceans were in the order of 2 – 6 kilometres, depending on the depth/location, around the noise source with a DBBC, HSD and MHS in place.
- Vibro-piling was investigated as an alternative option to impact piling; however, behavioural disturbance and TTS onset ranges were an order of magnitude higher than for impact piling, meaning they would be unmanageable. However, it should be noted that it was not possible to model with mitigations in place, and that where there were no hard layers in the seabed, drive times were extremely short (half an hour).
- Vessel noise modelling that applied assumptions about dynamic positioning thruster power use to represent realistic scenarios found behavioural disturbance effect ranges to be a maximum of 11.6 km for moving animals.

The fourth round of modelling is used to inform the environmental impact assessments for underwater noise for the purposes of approvals. An inherent assumption in the use of modelling is that in field verification of predicted noise will be undertaken once construction commences, and this verification will be used to revise any proposed management measures where required.

Abbreviations

Abbreviation	Definition
AC	Alternating current
AdBm	Adaptive broadband masker
BIA	Biologically important areas (assigned by DCCEEW)
CLV	Cable lay vessel
dB	decibel
DBBC	Double big bubble curtain, a method for mitigating underwater noise
DCCEEW	Department of Climate Change, Energy, the Environment and Water (Commonwealth)
DELWP	Department of Environment, Land, Water and Planning (Victoria; now DTP)
DP	Dynamically position
DTP	Department of Transport and Planning (Victoria)
EE Act	*Victorian Environmental Effects Act 1978*
EES	Environmental effects statement (EE Act – Victoria)
EIA	Environmental impact assessment
EIS	Environmental impact statement (EPBC Act - Commonwealth)
EPBC Act	*Commonwealth Environment Protection and Biodiversity Conservation Act 1999*
FLA	Feasibility Licence Area
GDEM	Generalized Digital Environmental Model
HF	High frequency
HSD	Hydro sound damper
HVAC	High voltage alternating current
JASCO	JASCO Applied Sciences
kJ	Kilojoules
LF	Low frequency
MESP	Marine ecology survey program
MHS	Modified hammer system
NAS	Noise abatement system
NMS	Noise mitigation screens
NMFS	National Marine Fisheries Service
OECA	Offshore export cable area
OIV	Offshore installation vessel
OSS	Offshore substation
OWF	Offshore wind farm
OWFA	Offshore wind farm area
PFLA	Pre-Feasibility Licence Area
PK	Zero-to-peak pressure level
PMI	Potential mortal injury
PTS	Permanent threshold shift
rms	root mean square
SEL	Sound exposure level
SOTS	The Star of the South
SPL	Sound pressure levels
TTS	Temporary threshold shift
WTG	Wind turbine generator

µPa	micro pascal

Glossary

Term	Definition
Accident	An event that would only occur under unexpected circumstances
Activity	Any operations or works carried out in relation to the project that may have an environmental impact e.g. piling of foundations and operating turbines.
Assessment criteria	Defines the environmental performance outcomes that must be achieved
Attenuation	The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium
Baleen whale	Any whale of the suborder Mysticeti, having plates of baleen on the sides of the upper jaw for filtering plankton
Cetacean	A marine mammal of the order Cetacea; a whale, dolphin, or porpoise
Consequence	Outcome of an event affecting a receptor and is based on the assessment of magnitude of impact and sensitivity of the receptor.
Continuous sound	A sound whose sound pressure level remains above ambient sound during the observation period. A sound that gradually varies in intensity with time, for example, sound from a marine vessel
Cumulative impact	The resultant impact of the project, in combination with one or more other existing or proposed projects in the area, on the same environmental asset. The total impact from the contributing projects is the cumulative impact
Decibel (dB)	Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB
Effect	Term used to express the consequence of an impact, that is a change to the environment (including socio-economic changes) resulting from the project that may be positive or negative. The significance for the effect is determined by correlating the magnitude of the impact and the sensitivity of the receptor.
Ensonified	Exposed to sound
Far field	The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears to radiate from a single point
Frequency	The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second
Frequency weighting	The process of applying a frequency weighting function
Geoacoustic	Relating to the acoustic properties of the seabed
Hearing threshold	The sound pressure level for any frequency of the hearing group that is barely audible for a given individual for specified background noise during a specific percentage of experimental trials
Hertz (Hz)	A unit of frequency defined as one cycle per second
Impulsive sound	Qualitative term meaning sounds that are typically transient, brief (less than 1 second), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Examples of impulsive sound sources include explosives, seismic airguns, and impact pile drivers
Magnitude	A combination of geographical extent, duration and severity of an impact. • Geographic extent – spatial extent of the impact e.g. local, regional, widespread • Duration – timescale of the effect e.g. short, medium or long term • Severity – scale or degree of change from the baseline condition as a result of the impact.
Maximum design scenario	Design parameters that represent the greatest potential impact to a defined sensitive receptor group (referred to as the 'maximum design scenario' in this assessment)
Mitigation measures	Actions, commitments or measures that are implemented to avoid, minimise or manage potential impacts. These include boundaries around project design

Term	Definition
	parameters (including construction), as well as the implementation of actions, systems and procedures to avoid, minimise and manage impacts (including monitoring)
Monitoring	Methods used to review the environmental performance and effectiveness of mitigation measures and to determine if project activities are within defined acceptable levels of impact.
Mysticete	An animal that belongs to the suborder Mysticeti or the family of baleen whales, a sub-group of the order Cetacean including blue, fin, minke, southern right whale and humpback whales
Non-impulsive sound	Sound that is not an impulsive sound. A non-impulsive sound is not necessarily a continuous sound
Odontocete	An animal that belongs to the suborder Odontoceti or the family of toothed whales, a sub-group of the order Cetacea including orcas, other dolphins and sperm whales
Offshore export cable area	A 232 square kilometre area extending from the offshore wind farm area to the shore crossing. Includes offshore export cables to connect the wind farm to land. This area traverses Commonwealth waters and Victorian coastal waters.
Offshore project area	The maximum offshore geographical extent that would be used for the development of the project, encompassing both the Offshore Export Cable Area and the Offshore Wind Farm Area
Offshore wind farm area	A 586 square kilometre area extending approximately 10 to 40 kilometres offshore from the shore crossing. Includes offshore wind turbines installed on foundations, offshore substations and offshore transmission cables. This area is in Commonwealth waters.
Otariid	A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus
Permanent threshold shift (PTS)	An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury
Pinniped	Carnivorous aquatic mammals of the suborder Pinnipedia, including seals and sea lions
the Project	Star of the South offshore wind farm
Project design envelope	A description of the range of possible design parameters that make up the proposed project design options under consideration when the exact engineering parameters are not yet known. The range is representative of the smallest and largest project that could be built.
Ramsar site	Wetlands of international importance, designated under the Ramsar Convention near to the project include Corner Inlet and Western Port.
Receptor	The physical or biological resource or user group that could be impacted by the project.
Received level	The level measured (or that would be measured) at a defined location. The type of level should be specified.
Recoverability	Re-establishment of the pre-disturbance population/processes following disturbance (e.g., mortality of the original individuals, through recruitment or colonisation).
Residual impact	The predicted remaining impacts following the implementation of committed mitigation measures, considering the expected effectiveness of these measures
Residual risk	The predicted remaining risk following the implementation of committed mitigation measures, considering the expected effectiveness of these measures.
Risk	The potential impacts because of an accident occurring. Risk is expressed in terms of a combination of the likelihood of an accident occurring and the potential consequences should the accident occur.

Term	Definition
Sensitivity	The sensitivity of a receptor is determined by its vulnerability (potential for harm), resilience to change, recoverability and status (level of protection, uniqueness).
Sensitive receptor	An environmental and socioeconomic feature (receptor) that could be subject to adverse impacts from the project
Significant impact	Under the EPBC Act Significant Impact Guidelines 1.1, a 'significant impact' is an impact which is important, notable, or of consequence, having regard to its context or intensity. Whether or not an action is likely to have a significant impact depends upon the sensitivity, value, and quality of the environment, which is impacted, and upon the intensity, duration, magnitude and geographic extent of the impacts.
Sound	A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.
Sound speed profile	The speed of sound in the water column as a function of depth below the water surface.
Source level	A metric given in decibels (dB) describing the power or intensity produced by a sound source along a particular direction.
Temporary threshold shift (TTS)	Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.
Terms of reference	The terms of reference for the project are defined as the Commonwealth *Guidelines for the Content of an Environmental Impact Statement for the Star of the South Offshore Wind Farm Project*, and the Victorian *Scoping Requirements for Star of the South Offshore Wind Farm Environment Effects Statement*.

1 INTRODUCTION

The Star of the South Offshore Wind Farm (the project) is Australia's most advanced offshore wind farm. The project is located in Commonwealth waters off the coast of Gippsland, and will connect to the electricity network via the proposed VicGrid connection hub in Giffard.

The project represents a significant opportunity to diversify Australia's energy resources. As Australia's ageing coal fleet retires, new sources of power are needed to address the anticipated gap in electricity generation. The project will address this gap, by harnessing Bass Strait's strong, consistent winds and delivering significant amounts of clean, reliable power to the grid starting in 2032. With a capacity of up to 2.2 gigawatts (GW), the project can meet approximately 20 per cent of Victoria's current electricity demand, enough to power around 1.2 million homes annually.

The project is located within both Commonwealth and Victorian jurisdictions and is subject to planning and environmental assessment and approval under Commonwealth and Victorian legislation.

A delegate of the Commonwealth Minister for the Environment and Water has determined the project is a controlled action (as set out in a notice dated 2 June 2020) and must be assessed and approved under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) through an Environmental Impact Statement (EIS). The Victorian Minister for Planning has determined the project requires an Environment Effects Statement (EES) (as set out in a notice dated 11 May 2020) under the *Environment Effects Act 1978* (Vic) (EE Act).

1.1 Purpose of this report

The purpose of this report is to provide a summary of the underwater noise modelling that has been undertaken by JASCO Applied Sciences (JASCO) (Appendix A). The SOTS offshore wind farm (OWF) (the project) has undergone several design changes over the project development period and several noise modelling exercises to understand the predicted noise emissions profile associated with different design options. This report will outline how the potential for noise emission reductions was considered in decision-making by SOTS and contributed to the design of the project at the time of writing. This report will be updated as subsequent rounds of modelling are completed. The report provides the background and the inputs that are used in the environmental impact assessment for underwater noise and to inform any environmental management plans for receptors that may be affected by the project.

The report provides an overview and synthesis of the underwater noise modelling undertaken to assess underwater noise levels associated with the construction of the project. These noise sources include the installation of monopiles and offshore substation (OSS) jacket foundations and associated vessel operations. Where there were various noise effect threshold options and/or modelling was undertaken for multiple scenarios, this report sets out the representative thresholds and scenarios that will be applied to the EIA and a justification for these. The full detail of the predicted noise levels, potential effects on marine fauna and humans that could result from the noise emissions and estimates of the range from the source where each effect can be expected is provided in detailed modelling reports undertaken by JASCO. This technical report will inform the detailed impact assessments on marine mammals, marine turtles, penguins and diving seabirds, fish, invertebrates, and humans in the respective technical reports.

The Project's approach to modelling is to develop realistic modelling scenarios to feed into the EIS/ESS assessment using best available datasets, considering:

- Water Depth
- Distance to receptors (BIA, Corner Inlet)
- Ground conditions (Driveability assessments)
- Monopile diameters
- Feasible Noise Abatement Systems

The modelling has not sought to present overly optimistic modelling based on applying multiple or novel Noise Abatement Systems (NAS) since there is limited 'real world' monitoring of multiple NAS operating together, modellers advise that data on novel or new NAS is sometimes not sufficient to inform robust modelling and modelling is based on realistic construction assumptions that can be delivered in practice. The

project will further refine modelling pre-construction based on the detailed project design and improved knowledge of commercially available NAS.

2 PROJECT DESCRIPTION

Section 2 provides a high-level overview of the project in its entirety. Detailed descriptions of project components and construction processes are provided in Chapter 4 – Project description of the EIS for the whole of project assessment across the Commonwealth jurisdiction, and in Chapter 4 – Victorian works project description of the EES for the Victorian jurisdiction. Specific project parameters that have informed this study are detailed in Sections 6 to 9 of this report.

2.1 Project overview

The offshore wind farm will be installed within a 586-square-kilometre offshore wind farm area, located approximately 10 to 40 kilometres off the coast of Gippsland, as shown in Figure 2-1.

The project comprises an offshore wind farm and supporting transmission infrastructure to generate and transfer power to the grid. The offshore infrastructure extends from the shore crossing at Reeves Beach, to the offshore wind farm area.

The onshore infrastructure primarily comprises of an underground cable system that will connect the project to the proposed VicGrid connection hub in Giffard (also referred to as 'proposed Giffard terminal station area'). The onshore transmission infrastructure is located in Central Gippsland, extending approximately 30 kilometres from Reeves Beach to the proposed VicGrid connection hub.

This technical report focusses on construction, operation and decommissioning of the offshore wind farm and transmission components, within offshore project area shown in Figure 2-3.

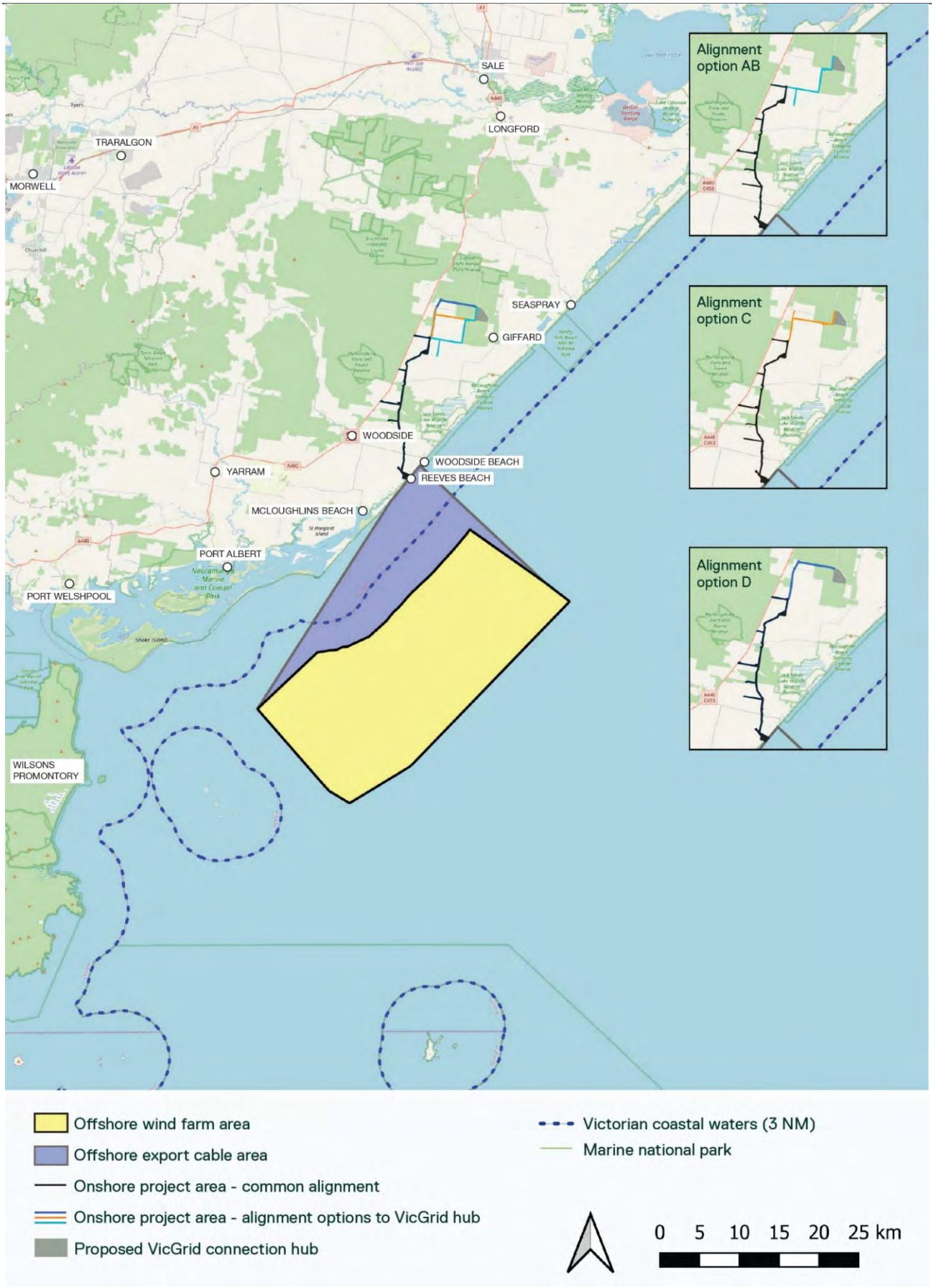


Figure 2-1: Project Location

2.2 Project development

Over several years of project development, opportunities to avoid and minimise environmental impacts have been realised in accordance with the mitigation hierarchy shown in Figure 2-2. The assessment framework has also enabled the identification and adoption of further avoidance and minimisation measures as part of the planning and environmental approvals process.

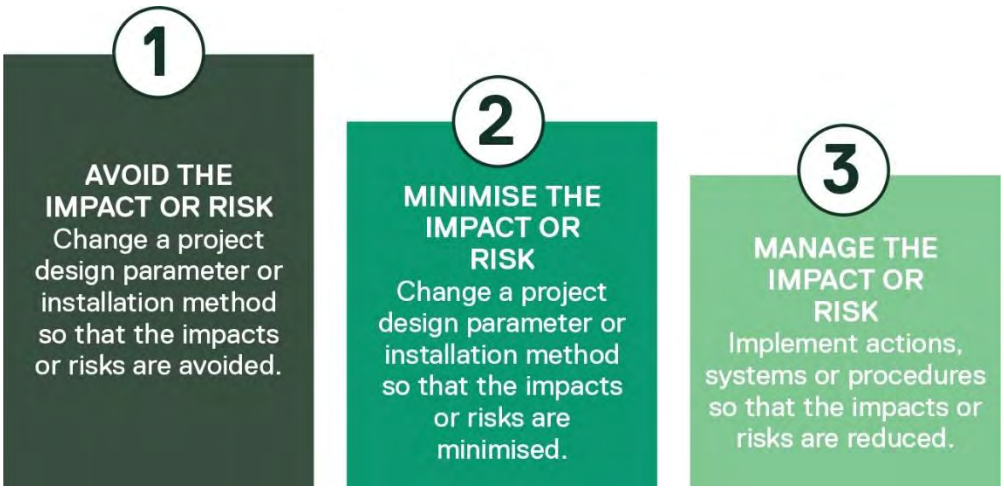


Figure 2-2: Mitigation hierarchy

Avoidance and minimisation of social and environmental impacts are central to the project's decision-making, and the project will continue to be refined in response to technical requirements and potential environmental and social impacts identified during the development phase.

This was considered in the preparation of a project description, which is found in Chapter 4 – Project description of the EIS for the whole of project assessment across the Commonwealth jurisdiction and Chapter 4 – Victorian works project description of the EES for the Victorian jurisdiction.

Examples include the decision to design the shore crossings without directly impacting coastal areas, utilising existing roads for construction site access wherever possible, and adopting construction techniques that avoid impacts on sensitive receptors such as waterways.

After opportunities to avoid impact were exhausted, minimisation and rehabilitation measures were developed. These are described in the construction and operation impact assessment sections below.

2.3 Project area

The project area, shown in Figure 2-3, has been broken down into three main sections - offshore, shore crossing, and onshore areas.

1. **Offshore project area**, comprising:

- **Offshore wind farm area**: A 586 square kilometre area extending approximately 10 to 40 kilometres offshore from the shore crossing. Includes offshore wind turbines installed on foundations, offshore substations and offshore transmission cables. This area is in Commonwealth waters.
- **Offshore export cable area**: A 232 square kilometre area extending from the offshore wind farm area to the shore crossing. Includes offshore export cables to connect the wind farm to land. This area traverses Commonwealth waters and Victorian coastal waters.

2. **Shore crossing**: Located at Reeves Beach, this is where the offshore export cables will transition to land and connect to the underground cable system onshore.
3. **Onshore** project area: An approximately 30 kilometre corridor extending from the shore crossing to the proposed VicGrid connection hub. Includes an underground cable system within a (common) alignment to Giffard West, at which point there are three alignment options (AB, C and D) to reach the proposed VicGrid hub in Giffard.

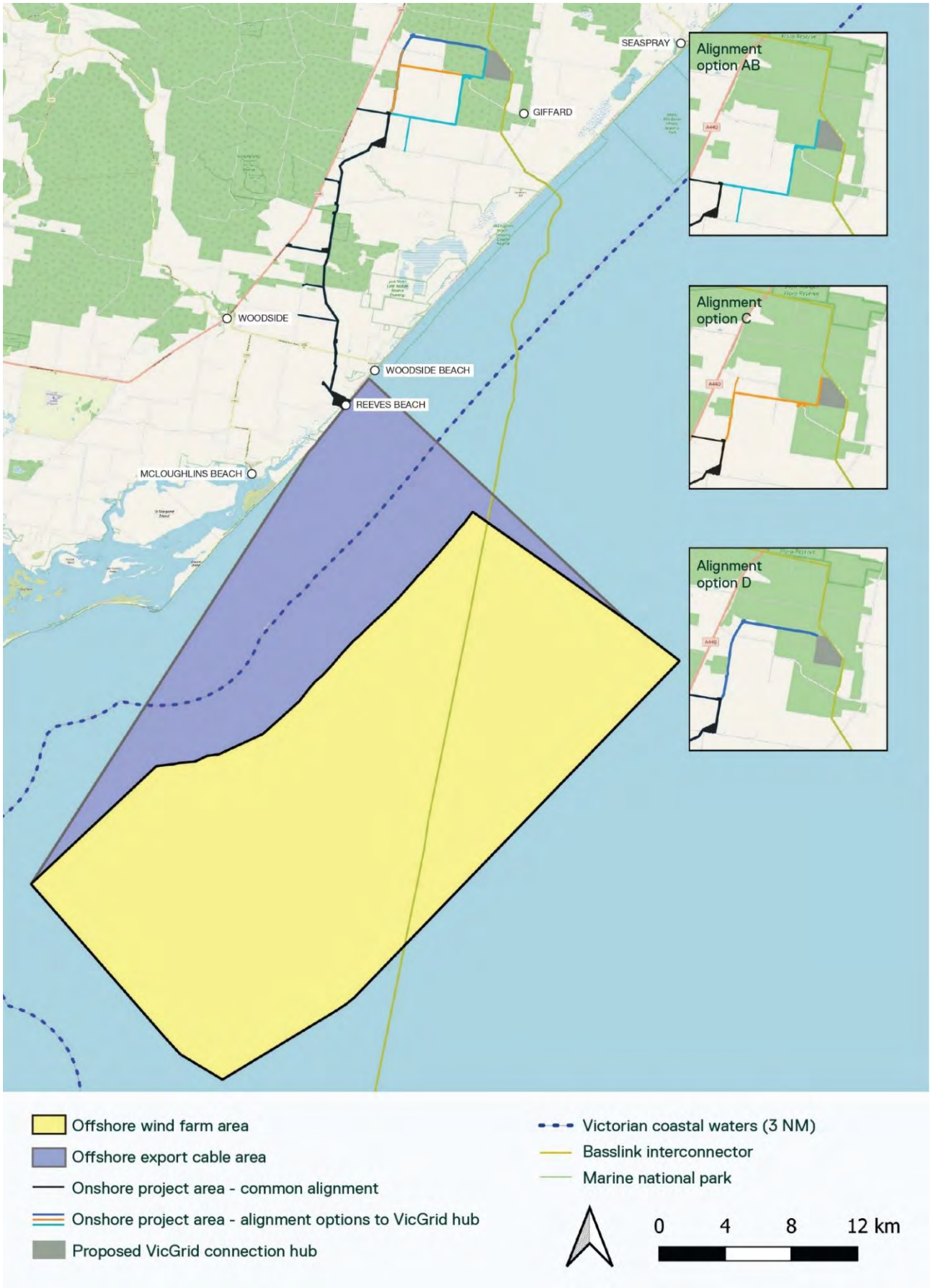

SEASPRAY
GIFFARD
WOODSIDE
WOODSIDE BEACH
REEVES BEACH
MCLOUGHLINS BEACH
Alignment option AB
Alignment option C
Alignment option D
Offshore wind farm area
Offshore export cable area
Onshore project area - common alignment
Onshore project area - alignment options to VicGrid hub
Proposed VicGrid connection hub
Victorian coastal waters (3 NM)
Basslink interconnector
Marine national park
0
4
8
12 km

Figure 2-3: Project overview

2.4 Key project components

The key components that make up the project are the offshore wind farm and transmission infrastructure (inter-array cables, offshore substations and offshore export cables), the shore crossing infrastructure and onshore transmission infrastructure.

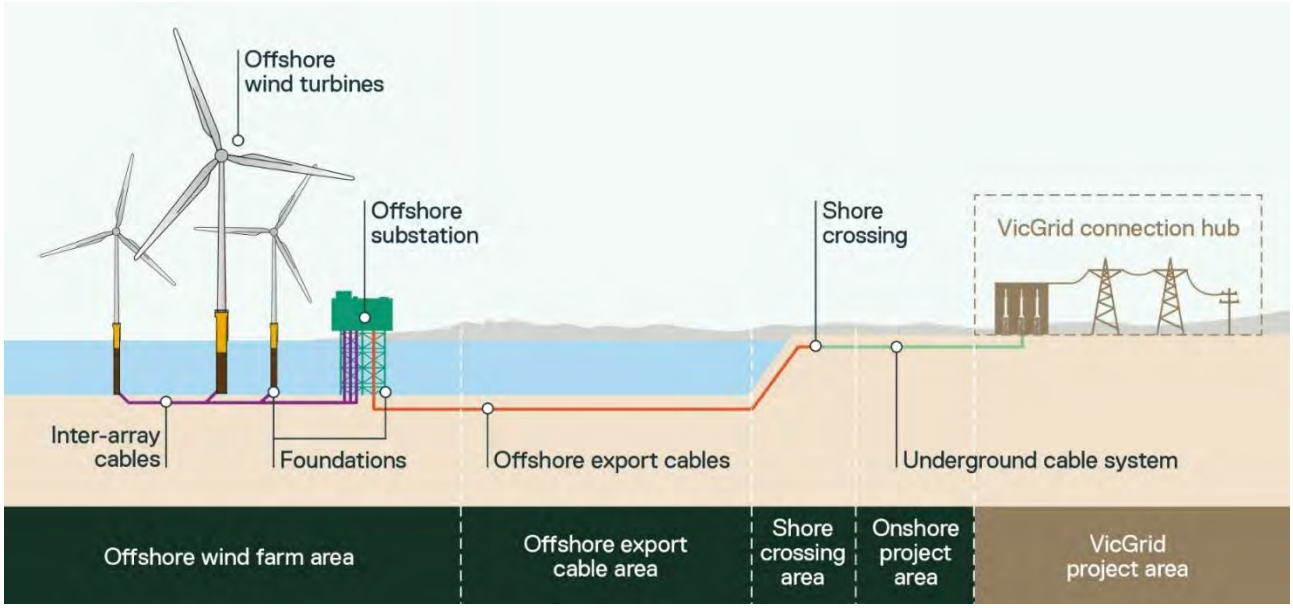


Figure 2-4: Project components

The key components are shown in Figure 24 and include:

- Offshore wind farm and transmission infrastructure:
  - Up to 147 offshore wind turbines installed on foundations with connecting inter-array cables
  - Up to five offshore substations and three interlink cables
  - Up to eight offshore export cables.
- Shore crossing infrastructure:
  - Up to eight trenchless crossings containing the offshore export cables.
- Onshore transmission infrastructure, which consists of:
  - An underground cable system connecting to the proposed VicGrid connection hub

2.5 Construction approach

The offshore components of the project are likely to be constructed according to the general sequence below:

- Site preparation activities
- Offshore export cable installation
- Foundation installation
- Offshore substation topside installation

- Inter-array and interlink cable installation
- Offshore wind turbine installation.

Construction of the shore crossing involves 2 main activities and phases:

- Drilling and duct installation
- Cable pulling

2.6 Project timeline

The project has been under development for approximately seven years. If approvals are obtained in the next few years, construction could start around 2030 and electricity generation from 2032. The operational life of the project is approximately 30 years, with the possibility of repowering to extend its life, if deemed appropriate by Star of the South and regulators closer to the time.



Figure 2-5 Project timeline

2.7 Construction schedule

The project is expected to take up to seven years to construct, if built to its full capacity in a single stage. The project could also be built in two stages, depending on energy market and government requirements and timing. Figure 2-6 shows the order and maximum duration of construction for key components.

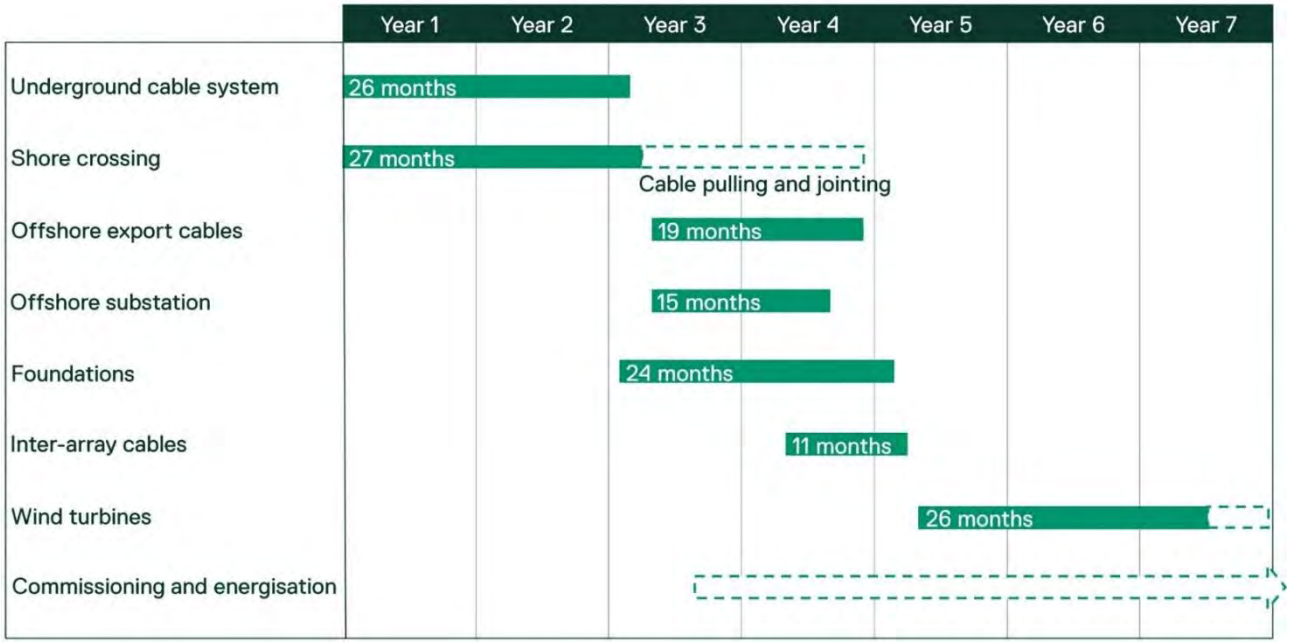


Figure 2-6 Indicative project construction schedule

2.8 Operational requirements

The project is expected to have an operational life of approximately 30 years. The offshore wind turbines will be available to operate continuously during the operations phase. Infrastructure will be monitored and operated remotely from a local O&M facility located at either Barry Beach Marine Terminal or Port Anthony, supported by a service operation vessel (SOV) and/or crew transfer vessel (CTV) logistics strategy.

O&M activities will be both preventative (planned) and corrective (unplanned). Preventative activities are carried out as part of regular scheduled services, such as removing marine growth. Corrective maintenance covers unexpected repairs, component replacement and breakdowns.

2.9 Decommissioning

Key principles that will apply to decommissioning offshore include:

- Planning and budgeting for decommissioning, as required under the Offshore Electricity Infrastructure Act 2021 (Cth)
- Considering environmental conditions and stakeholder interests when developing decommissioning plans
- Returning the seabed to baseline conditions as far as reasonably practicable.

Decommissioning is expected to involve similar types and numbers of vessels and equipment as the construction phase. Requirements at the time will determine the scope of decommissioning activities and impacts. The anticipated duration is up to three years. Indicative activities include:

- Removing offshore substation topsides and foundations to just below the seabed
- Removing offshore wind turbines, transition pieces and monopiles to just below the seabed
- Removing scour protection where reasonably practicable and appropriate to do so
- Retaining offshore cables in situ.

3 TERMS OF REFERENCE

3.1 EIS guidelines

The Guidelines for the Content of an Environmental Impact Statement for Star of the South Offshore Wind Farm Project ('the guidelines') set out the requirements to allow the Commonwealth Minister for the Environment to make an informed decision on the approval of the project under the EPBC Act.

The aspects of the guidelines relevant to the Underwater Noise Technical Report assessment are shown in Table 3-1 as well as where these items have been addressed in this report.

Table 3-1: EIS requirements addressed within this report

Requirement	Sections addressed
Modelling (or other scientifically sound method for predicting impacts) of underwater noise and prediction of impacts during the construction, commissioning, operation and decommissioning stages of the action.	Section 6, Section 7, Section 8, and Section 9
The following will be required to be characterised: Details of the noise to be generated during all stages of the action (construction, commissioning, operation and maintenance, and decommissioning) including the intensity, duration, frequency and extent of underwater noise generated from all relevant activities associated with the proposed action, including cumulative impacts from all noise-generating activities;	Section 4, Section 6, Section 7, Section 8, and Section 9

4 UNDERWATER NOISE BACKGROUND

Anthropogenic noise sources are categorised as ‘impulsive’ or ‘non-impulsive’ (i.e., continuous). Impulsive noise sources are of short duration with a rapid onset (e.g., pile driving), while continuous noise sources are long-lasting and do not have pulse characteristics; however, they can vary in intensity (e.g., vessels).

Impact pile driving is a method used to install piles for marine structure projects, using high-energy impact hammers. A hydraulic hammer repeatedly strikes the top of a pile, driving the pile into the seafloor, which may take several hours, dependent upon the pile diameter, size of the hammer, required penetration depth, and seafloor properties. The impact hammers must accommodate varying diameters of piles, with increasing hammer energy required for increasing pile diameter. The installation of the piles produces high impulsive sound levels, with the underwater noise characterized by intense, low-frequency sounds, which are created by pressure waves that travel through the water, the pile itself, and the seafloor, and can propagate through the surrounding waters.

To assess the potential effects of underwater noise, it is necessary to first establish exposure criteria (thresholds) above which sound levels may be expected to impact on marine fauna. These exposure criteria use different metrics depending on the nature of the sound source, the physiology of the relevant fauna groups, the mechanisms for effects and the metrics that were measured during relevant effect studies.

4.1 Sound metrics

The decibel (dB) scale is used to measure the amplitude, or loudness of a sound wave and is strongly influenced by the density of the medium the sound is travelling through. For underwater sounds, the dB scale is denoted relative to the reference pressure of 1 micropascal (µPa) e.g., dB re 1 µPa.

Several sound level metrics are commonly used to evaluate sound and its effects on marine life. The sound metrics used in this report are:

- Zero-to-peak sound pressure (PK) (dB re 1 µPa): the greatest magnitude of the sound pressure during a specified time interval. PK levels are relevant to the assessment of potential hearing impairment impacts to marine fauna and biota from a single pulse (i.e., one hammer strike on a pile).
- Peak-to-peak sound pressure (PK-PK) (dB re 1 µPa): the sum of the peak compressional pressure and the peak refractional pressure during a specified time interval (approximately double the PK). PK-PK levels are relevant to the assessment of potential physical hearing impairment impacts to marine fauna and biota.
- Root-mean-square (rms) sound pressure level (SPL) (dB re 1 µPa): the time-mean-square sound pressure in a stated frequency band, to the square of the reference sound pressure over the duration of an acoustic event (single strike). The SPL represents the effective sound pressure over the full duration of the acoustic event rather than the maximum instantaneous peak pressure and is therefore regularly used to represent the effective loudness of a sound and to assess the potential for a behavioural response to marine fauna.
- Sound exposure level (SEL) (dB re 1 µPa².s): a measure related to the sound energy (instead of the sound pressure) in one or more pulses, or the ratio of the time-integrated squared sound pressure to the specified value. SEL is specified in terms of either per-pulse SEL or an accumulative SEL (SEL_{cum}) from multiple pulses over a given period. This measure recognises that the effects of sound can be a function of exposure duration as well as maximum instantaneous peak pressure. SEL can therefore be considered a dose-type measurement with SEL_{cum} being used to assess dose-type impacts such as the potential for the gradual onset of hearing impairment impacts to marine fauna hearing because of prolonged exposure to high sound levels. SEL_{cum} assumes that a receptor remains stationary for the defined period. It is standard practice for SEL_{cum} to be assessed over a summation period of 24-hours (SEL_{24h}).
- Particle motion (m/s²): defined as the motion caused by a sound wave within the water, seabed or other medium. Benthic invertebrates and many types of fish are sensitive to particle motion rather than sound pressure, however limited measurements or data are available on the levels that may result in effects.

4.2 Auditory effects

Elevated underwater noise levels can affect marine fauna in three main ways (Richardson et al., 1995; Simmonds et al., 2004):

- By causing direct physical effects, including hearing impairment. Hearing impairment may be temporary (temporary threshold shift – TTS), or permanent (PTS).
- Through disturbance leading to behavioural changes or displacement from important areas.
- By masking or interfering with other biologically important sounds (including vocal communication, echolocation, signals, and sounds produced by predators or prey).

Refer to the Technical Reports for Marine Mammals and Turtles (Technical Report D), Fish (Technical Report C), Seabirds and Shorebirds (Technical Report E) and Infrastructure and Other Users (Technical Report J) for further detail regarding noise effect pathways for specific fauna groups and human divers.

The National Marine Fisheries Service (NMFS) defines auditory injury as damage to the inner ear that can result in destruction of tissue, which may or may not result in PTS. PTS is defined as, a permanent or 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 (NMFS, 2024). TTS is defined as a temporary, reversible increase in the threshold at a specified frequency or portion of an individual's hearing range above a previously established reference level (NMFS, 2024). While the NMFS does not consider TTS as injury, in Australia recent guidance under the Blue Whale Conservation Management Plan (CMP) (DAWE, 2021) defines injury to blue whales as "both permanent and temporary hearing impairment (PTS and TTS)". Given the southern right whale also has a recovery plan, with action areas the same as those in the blue whale CMP, TTS is conservatively considered injury for southern right whales as well. For this report, TTS is referred to as hearing impairment, however, there remains uncertainty about the definition of TTS and its application in Australia with updated policy and guidelines expected to be released by the Department of Climate Change, Energy, Environment and Water (DCCEEW) later this year.

4.3 Noise effect thresholds

The sections below set out the noise effect thresholds that were used to assess the effect ranges for different marine fauna groups in the modelling studies outlined in the sections below.

4.3.1 Marine mammals

The sound exposure thresholds applied to marine mammals for impulsive and continuous noise sources during the first and second round of modelling (see Section 6 and 7) are summarised in Table 4-1 and Table 4-2 respectively. These thresholds represent the contemporary threshold standards applied at the time underwater noise modelling was undertaken. The PTS and TTS onset thresholds are based on Southall et al. (2019) and the marine mammal unweighted behavioural thresholds for behavioural disruption in the tables below are based on the root mean square (rms) sound pressure level (SPL) criterion for marine mammals (NOAA, 2019). Whilst the newly published Southall et al. (2021) provides recommendations and discusses the nuances of assessing behavioural response, the authors did not recommend new numerical thresholds for the onset of behavioural response for marine mammals.

Table 4-1: Sound exposure thresholds for marine mammals to impulsive noise sources (Southall, et al., 2019; NOAA, 2019)

Hearing group	Behavioural	PTS onset		TTS onset	
	SPL (dB re 1 µPa ($_{rms}$))	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)
LF cetaceans	160 (unweighted)	219	183	213	168
Southern right whale cow/calf pairs	140 (weighted – refer Table 4-3)				
HF cetaceans	160 (unweighted)	230	185	224	170
Otariid seals		232	203	226	188

Table 4-2: Sound exposure thresholds for marine mammals to continuous noise sources (Southall et al., 2019; NOAA, 2019)

Hearing group	Behavioural	PTS onset	TTS onset
	Unweighted SPL (dB re 1 µPa ($_{rms}$))	Weighted SEL_{24h} (dB re 1 µPa².s)	Weighted SEL_{24h} (dB re 1 µPa².s)
LF cetaceans	120	199	179
HF cetaceans		198	178
Otariid seals		219	199

Wood et al. (2012) defined behavioural response categories for sensitive species (including harbor porpoise and beaked whales), for migrating mysticetes, and for all other species (Table 4-3). The migrating mysticete category has been used for all species with a behavioural response / disturbance threshold of 160 dB SPL given the highest response (90% response rate). However, for more sensitive life history stages, namely southern right whale cow/calf pairs, a more precautionary threshold of 140 dB SPL has been adopted. For LF cetaceans, the frequency weighting defined in Wood et al. (2012) has been updated to consider the frequency weighting from Southall et al. (2019) for this hearing group. Southern right whales are susceptible to elevated underwater noise (National Recovery Plan for the Southern Right Whale (DCCEEW 2024)), and therefore precaution has been added. In this assessment a more conservative behavioural response threshold of 140 dB re 1 µPa (SPL), based on the Wood et al. (2012) 50 per cent probability of response is applied instead of the usual 160 dB re 1 µPa (SPL) for impulsive noise.

The Darias O'Hara et al. (2025) expert elicitation workshop found that low frequency cetaceans elicited behavioural responses at a threshold of 137 dB re 1 µPa SPL for vessel noise (continuous noise), and 145 dB re 1 µPa SPL for hydroacoustic research equipment and also stated that mother-calf pairs are more likely to elicit more adverse and quicker responses to sound sources than their conspecifics. However, this paper considered animals located in the Antarctic, and notes that it is the most isolated continent. This means that the animals considered in the study may be unaccustomed to noise compared with animals that occur in the Gippsland region, in which there is a long history of shipping and oil and gas activities. While mother-calf pairs in the Antarctic could be predicted to respond at thresholds below those for the average animal, it is unlikely that animals located in Gippsland would be similarly disturbed in the presence of these same noise thresholds, however the threshold of 140 dB for impulsive noise and 120 dB for continuous noise have been applied as conservative measures.

The Wood et al. 2012 study notes that most marine mammals exposed to impulsive noise demonstrate responses of varying magnitude in the 140-180 dB re: 1 µPa (RMS) exposure range, with 10%, 50%, and 90% of individuals exposed assumed to produce a behavioural response at exposures of 140, 160, and 180 dB re: 1 µPa (RMS), respectively (using weighted criteria). They also describe that as a protective approach for marine mammals in specific behavioural modes that are more sensitive to noise exposure, response probabilities were set at 10%, 50%, and 90% for migrating mysticetes and estimated to occur at M-weighted exposure levels of 120, 140, and 160 dB re: 1 µPa (RMS). The example used for a sensitive behavioural mode was migrating bowheads, compared to feeding bowheads.

This is based on the risk-disturbance hypothesis (Frid and Dill, 2002), suggesting that animals perceive human disturbance much like predator risk, and vary their response to optimise trade-offs between the perceived risk and the potential cost of leaving an area or resource. Where animals have a reason for remaining in an area in the face of behavioural disturbance, such as the presence of prey, they are likely to better tolerate higher thresholds, compared with when they can move away with no significant ecological or physiological effect. A context-based approach better explains differences in marine mammal behavioural

responses to anthropogenic sounds (Ellison et al., 2012). The risk-disturbance hypothesis has been suggested to explain the varying responses between individuals and populations of marine mammals, including blue whales, to naval sonar (Harris et al., 2018; Goldbogen et al., 2013 and Friedlaende et al., 2016).

The same principle can be applied to southern right whales in the reproductive BIA or blue whales in the foraging BIA, where these species could be behaviourally disturbed at lower thresholds while migrating, compared with when feeding or undertaking biologically important behaviours in the reproductive BIA (i.e. see Table 3.9 for all other species/behaviours). As such, the thresholds are applied in this report follow the principles as set out in Wood et al 2012 and are consistent with thresholds reported in O'Hara et al. 2025, considering the location of the latter study.

These are extremely conservative thresholds to apply, because even if 50% of individuals have a response, the severity of a response at this level is likely to be at a level of a minor or brief response (see Southall et al. 2021and Section 5.1) and not expected to affect foraging, reproduction or survival. This is because Gippsland has had industrial activity and shipping occurring for decades (see also below), and because this threshold will trigger active mitigation measures to thereafter reduce noise (see Construction Piling Framework).

Table 4-3: Sound pressure levels (SPL) thresholds to evaluate potential behavioural impacts to marine mammals from impulsive sounds (from Wood et al. 2012)

Marine mammal group	Frequency weighted probabilistic response (peak, dB re 1 µPa)			
	>120	>140	>160	>180
Beaked whales and harbor porpoises	50%	90%		
Migrating mysticete whales	10%	50%	90%	
All other species		10%	50%	90%

In October 2024 the NMFS released a new set of guidance, with a new set of sound exposure thresholds for marine mammals. The updated thresholds have higher PK thresholds for low frequency cetaceans from impulsive noise sources and are therefore considered less conservative (Table 4-4). Whereas for continuous noise sources, the updated thresholds have lower PK and SEL_{24h} thresholds for low frequency cetaceans and are therefore considered more conservative (Table 4-5). However, a LF cetacean weighting function that has been included in the new thresholds demonstrates better sensitivity at the lower end of the spectrum, and therefore it is possible that despite less conservative thresholds for impulsive noise than in Southall et al. (2019), impact ranges may be larger. These updated thresholds were applied in the third-round (2024-2025) and fourth round (2025) of modelling to inform the EIA (Section 8 and Section 9). The NMFS updated thresholds did not include any changes to behavioural response thresholds and thus remain the same.

Table 4-4: Sound exposure thresholds for marine mammals to impulsive noise sources (NOAA, 2019; NMFS, 2024)

Hearing group	Behavioural	PTS onset		TTS onset	
	SPL (dB re 1 µPa ($_{rms}$))	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)
LF cetaceans	160 (unweighted)	222	183	216	168
Southern right whale cow/calf pairs	140 (weighted – refer Table 4-3)				
HF cetaceans	160 (unweighted)	230	193	224	178
Otariid seals		230	185	224	170

Table 4-5: Sound exposure thresholds for marine mammals to continuous noise sources (NOAA, 2019; NMFS, 2024)

Hearing group	Behavioural	PTS onset	TTS onset
	Unweighted SPL (dB re 1 µPa (rms))	Weighted SEL_{24h} (dB re 1 µPa².s)	Weighted SEL_{24h} (dB re 1 µPa².s)
LF cetaceans	120	197	177
HF cetaceans		201	181
Otariid seals		199	179

4.3.2 Marine turtles

The sound exposure thresholds applied to marine turtles for impulsive and continuous noise sources are summarised in Table 4-6 and Table 4-7, respectively. The peak pressure levels (PK) and frequency-weighted accumulated sound exposure level (SEL) thresholds are consistent with Finneran et al. (2017) for PTS and TTS onset in turtles. The onset of PTS or TTS is considered to occur when either the PK or SEL metric is exceeded.

The behavioural response threshold is based on the National Marine Fisheries Service (NMFS) and applied in the Arctic Programmatic Environmental Impact Statement (NSF, 2011), and the behavioural disturbance threshold is based on the level reported in McCauley et al. (2000) for impulsive noise.

Table 4-6: Sound exposure thresholds for marine turtles to impulsive noise sources (McCauley et al. 2000; NSF 2011; Finneran et al. 2017,)

Behavioural		PTS onset		TTS onset	
Response	Disturbance	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)
Unweighted SPL (dB re 1 µPa (rms))					
166	175	232	204	226	189

Table 4-7: Sound exposure thresholds for marine turtles to continuous noise sources (Finneran et al., 2017)

PTS onset	TTS onset
Weighted SEL_{24h} (dB re 1 µPa².s)	Weighted SEL_{24h} (dB re 1 µPa².s)
220	200

A recent publication by Accomando et al. (2025) revised the PTS and TTS onset thresholds and auditory weighting functions for marine turtles to impulsive and continuous noise (Table 4-8, Table 4-9). These updated thresholds have slightly lower PK thresholds for both PTS and TTS onset, though the SEL_{24h} thresholds are 20 dB lower than the previous Finneran et al. (2017) thresholds. These updated thresholds have been applied in the fourth round (2025) of modelling (Section 9).

Table 4-8: Sound exposure thresholds for marine turtles to impulsive noise sources (Accomando et al., 2025)

PTS onset		TTS onset	
PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)	PK (dB re 1 µPa)	Weighted SEL_{24h} (dB re 1 µPa².s)
230	184	224	169

Table 4-9: Sound exposure thresholds for marine turtles to continuous noise sources (Accomando et al., 2025)

PTS onset	TTS onset
Weighted SEL_{24h} (dB re 1 µPa².s)	Weighted SEL_{24h} (dB re 1 µPa².s)
198	178

4.3.3 Fish and invertebrates

A fish's susceptibility to injury from noise exposure depends on whether it is among the group of fish with a swim bladder, and if the swim bladder has a role in hearing. Thus, different thresholds have been applied for

fish without a swim bladder (appropriate for shark species), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. In general, whether an impulsive sound adversely effects fish behaviour depends on the characteristics of the sound energy, the fish species, the behavioural state of the individual exposed and the site conditions (e.g., local shelter creating sound barriers).

The sound exposure thresholds applied to fish, fish eggs and larvae for impulsive and continuous noise sources are summarised in Table 4-10 and Table 4-11, respectively. The peak pressure levels (PK) and frequency-weighted accumulated sound exposure level (SEL_{24h}) thresholds for impulsive noise sources are consistent with Popper et al. (2014) and relate to mortality and potential mortal injury (PMI), recoverable injury and TTS onset.

The behavioural response and masking thresholds for impulsive noise sources are expressed as relative risk (high, moderate and low) at three distances from the source (near, intermediate and far), adapted from Popper et al. (2014). Similarly, relative risk is assessed for the response to continuous noise sources.

Table 4-10: Sound exposure thresholds for fish, fish eggs and larvae to impulsive noise sources

Hearing group	Behavioural	Mortality and potential mortal injury		Recoverable injury		TTS onset	Masking
	Relative risk*	PK	SEL_{24h}	PK	SEL_{24h}	SEL_{24h}	Relative risk*
Fish I (no swim bladder)	(N) High (I) Moderate (F) Low	213	219	213	216	186	(N) Moderate (I) Low (F) Low
Fish II (swim bladder not involved in hearing)	(N) High (I) Moderate (F) Low	207	210	207	203	186	(N) Moderate (I) Low (F) Low
Fish III (swim bladder involved in hearing)	(N) High (I) High (F) Moderate	207	207	207	203	186	(N) High (I) High (F) Moderate
Fish eggs and larvae	(N) Moderate (I) Low (F) Low	207	210	(N) Moderate (I) Low (F) Low		(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

PK sound pressure level dB re 1 µPa; SEL_{24h} dB re 1 $\mu Pa^2.s$

* Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N = tens of metres), intermediate (I = hundreds of metres), and far (F = thousands of metres).

Table 4-11: Sound exposure thresholds for fish, fish eggs and larvae to continuous noise sources

Hearing group	Behavioural	Mortality and potential mortal injury	Recoverable injury	TTS onset	Masking
	Relative risk*				
Fish I (no swim bladder)	(N) Moderate (I) Moderate (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate
Fish II (swim bladder not involved in hearing)	(N) Moderate (I) Moderate (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate
Fish III (swim bladder involved in hearing)	(N) High (I) Moderate (F) Low	(N) Low (I) Low (F) Low	170 dB re 1 µPa (SPL_{rms}) for 48 h	158 dB re 1 µPa (SPL_{rms}) for 48 h	(N) High (I) High (F) High
Fish eggs and larvae	(N) Moderate (I) Moderate (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low

The responses of squid were investigated by Fewtrell and McCauley (2012). They found that in one trial, where the received level of the first airgun impulse was 162 dB re 1 $\mu Pa^2 \cdot s$, the squid inked. This response was not observed again within this trial, however the authors stated that it was unknown if this was due to depleted ink reserves or habituation. In two other trials, the initial received levels were lower (132 and 146 dB re 1 $\mu Pa^2 \cdot s$ per–pulse SEL), and although the received levels did ramp up and exceed 162 dB re 1 $\mu Pa^2 s$, no

inking behaviour was observed. The level associated with inking of 162 dB re 1 µPa²·s per–pulse SEL (Fewtrell and McCauley, 2012) has been considered as a startle response level for squid and is used in this assessment.

For crustaceans, a PK–PK threshold sound level of 202 dB re 1 µPa (Payne et al., 2008) is considered to be associated with 'no effect' (i.e. no effects expected at or below this sound level), and therefore applied in the assessment.

Particle motion is considered to be the more relevant metric for predicting impacts to invertebrates. A study into the effects of seismic source discharges on scallops in Australia measured particle acceleration. The maximum particle acceleration assessed for scallops (bivalve) was 37.57 ms^{-2} (Day et al., 2016). This particle acceleration level was associated with a number of sub-lethal effects in scallops.

4.3.4 Penguins and diving seabirds

The sound exposure thresholds applied to marine mammals for impulsive and continuous noise sources during the first and second round of modelling (see Section 6 and 7) are summarised in Table 4-1

There are no regulatory thresholds or criteria established to assess the potential for hearing impairment or behavioural responses by penguins, diving seabirds, or phylogenetically or anatomically related species associated with underwater noise. To allow for assessing the potential for such impacts, an onset criterion for behavioural responses of penguins and diving seabirds of 120 dB re 1 µPa (SPLrms) for impulsive sources was chosen based on information from Sørensen et al. (2020). Sørensen et al. (2020) conducted controlled exposure experiments on captive gentoo penguins in a tank, reporting animals demonstrated strong reactions at 120 dB re 1 µPa. This sound exposure threshold was applied in the second round of modelling (see Section 7).

Further detailed investigation into this approach determined that the study conducted by Sørensen et al. (2020) alone is not enough to underpin behavioural response thresholds for penguins and diving seabirds, with constraints identified in the survey methodology.

To enable assessment of the potential for hearing impairment for penguins and diving seabirds from impact piling and continuous noise sources, hearing thresholds for the least sensitive marine mammal hearing group, otariids, from Southall et al. (2019), has been used as a proxy in the second, third, and fourth rounds of modelling (see Section 7, 8 and 9) (Table 4-1, Table 4-2). This hearing group has been selected due to similar hearing sensitivity in the frequency band of underwater hearing for diving birds and otariid pinnipeds, which are included in the group. This provides a conservative approach, however, as otariids are considered more sensitive to underwater sound at higher frequencies than penguins.

4.3.5 Human diver health assessment

Underwater, the human ear is about 20 dB less sensitive to impulsive low-frequency sound (20 Hz) than it is in air, about 40 dB less sensitive at mid–frequencies (less than 1 kHz), and 70–80 dB less sensitive at higher frequencies (greater than 1 kHz) (Parvin, 1998).

Considering only frequencies between 100 and 500 Hz, Parvin (2005) suggested 145 dB re 1 µPa as a safety criterion for recreational divers and swimmers. Piling impulses are broadband sources, and therefore, to be precautionary, the 145 dB re 1 µPa SPL suggested by Fothergill et al. (2001) and Parvin (2005) has been applied in this study as the impulsive noise threshold for recreational divers and swimmers. This does not imply that this level is associated with the onset of hearing impairment.

4.4 Factors that influence sound source level and propagation

The source levels (dB) of anthropogenic underwater noise are determined by the activity parameters: the source level of pile driving is largely driven by the pile diameter, pile length and hammer energy, with higher noise levels generated by larger pile diameters and lengths, which typically require higher hammer energy (Bellman, 2014; Wagenknecht, 2021). The method used to insert the pile into the ground may also affect source level, with evidence of impact pile driving resulting in higher source levels compared to lower source levels generated from non-impulsive vibration – 'vibro' – piling (Graham et al., 2017).

The greater the source level of a sound, the further it may travel or propagate through the water column. Other factors such as the frequency of the sound, the bathymetry, the geoacoustic parameters of the seafloor, and the sound speed profile (e.g., salinity and water temperature over depth) affect the propagation of sound (Erbe et al., 2021), and thereby the range to effect (e.g., PTS, TTS, behavioural disturbance) on marine fauna. Seasonal changes in water temperature and salinity have the largest effect on the sound speed profile in the water column. As a result, the nature of sound propagation has the potential to change across seasons. The geoacoustic parameters of the seafloor have the potential to be a significant influence on the nature of sound propagation, with soft sediment types (e.g., clay or sand) absorbing and scattering sound waves and hard sediment types (e.g., bedrock) reflecting the sound.

4.5 Noise abatement systems for pile driving

Research and development of noise abatement systems (NAS) for pile driving has primarily been driven by the establishment of noise level limits in Europe from 2008 (Muller et al., 2019). Between 2011 and 2013, the noise level limits could not be readily complied with and this led to a concerted effort to improve existing and develop new NAS to ensure effectiveness in the offshore environment. From 2014, available NAS were proven effective at ensuring compliance with the noise level limits. However, there has been a gradual increase in monopile diameters and water depths as the offshore wind industry matures and the technology improves, and this has required continual innovation to ensure NAS are effective for larger monopiles and deeper water depths.

There are several emerging primary noise reduction methods at various stages of development that are focused on reducing noise emissions at the source by modifying the way that hammers interact with the pile, for example, EQ-Piling, IQIP PULSE and hydrohammer. are primary noise reduction technologies, designed as an add-on feature to a standard hammer, referred to as a modified hammer system (MHS). The MHS system is placed between the hammer and the sleeve and acts as a fluid cushioning, thus elongating the impact of the hammer and lowering the peak force. The amount of fluid between the plungers can be adjusted when the hammer is on the pile to optimise noise reduction without delaying installation. As a relatively new noise abatement technology, limited published literature is available identifying the noise level reduction of MHS in the field. However, IQIP PULSE has been deployed across seven commercial projects in the Northern Hemisphere to install over 200 monopiles and 100 pin piles. From these installations, IQIP PULSE report a 6-10 dB reduction in noise level (SEL) in their testing when using a conventional hammer (IQIP, 2025), and early reports from installation of 9.2 m diameter monopiles for an OWF in Germany demonstrate a noise reduction of 24 dB by PULSE when used in combination with a noise mitigation screen (NMS) and DBBC (Buljan, 2024).

Early available NAS were secondary noise reduction measures that involved putting some form of barrier around the noise source. These measures include hydro sound dampers (HSD), adaptive broadband masker (AdBm), bubble curtains (e.g., double big bubble curtains (DBBC)) and noise mitigation screens (NMS). Systems such as the bubble curtain, NMS and HSD can reduce broadband sound levels by at least 10 dB, and reductions up to 20 dB have been demonstrated (Figure 4-1) (Koschinski and Lüdemann, 2013; Bellmann, 2014; Bellman et al., 2020; Austin et al., 2016; Nehls et al., 2016; Verfus et al., 2019). The AdBm system is a secondary noise reduction method which consists of a series of cups (i.e. resonators) that are moulded within slats and placed on a frame deployed around the sound source. Resonators can be made out of various materials (e.g. plastic, wood and stainless steel). Measured data during pile driving operations in the Belgian North Sea demonstrated a reduction of 8 dB from the AdBm system alone, and up to 20 dB reduction when the AdBm and a single bubble curtain were used in conjunction (Wochner, 2019). The IHC-NMS is another secondary noise reduction measure, which consists of a double-walled steel screen in the form of a tube, which the pile is then inserted into. The space between the two steel screens is filled with air, and air bubbles are fed in between the pile and the NMS, thus reflecting the sound and reducing the noise. The identified noise level reduction of an IHC-NMS is 10-14 dB (Bellmann, 2014). The secondary NAS are well proven within shallower water depths up to 40 m and further testing is required to demonstrate effectiveness in deeper water depths (Wagenknecht, 2021; Verfus et al., 2019).

Primary and secondary NMS can be used in tandem, e.g. HSD, AdBm or MHS and other secondary noise reduction measures such as DBBC. As shown in Figure 4-1, the effectiveness of some NAS used in combination, e.g. IHC NMS and DBBC, may not outperform a single standalone method, such as a DBBC, at certain frequencies.

The NAS investigated during modelling for the SOTS OWF project are the DBBC, HSD and MHS, including in combination (see summary in Section 9.1.4 below). The AdBm system was also included in an early study, however results indicated that the AdBM and DBBC systems performed worse (i.e., lesser noise reduction)

than the HSD and DBBC systems, and ultimately it was decided not to include this in the modelling. The IHC-NMS was considered for the third round of modelling; however, was ruled out due to the varying water depth across the site. The NMS is logistically challenging and needs to be custom fit according to pile size.

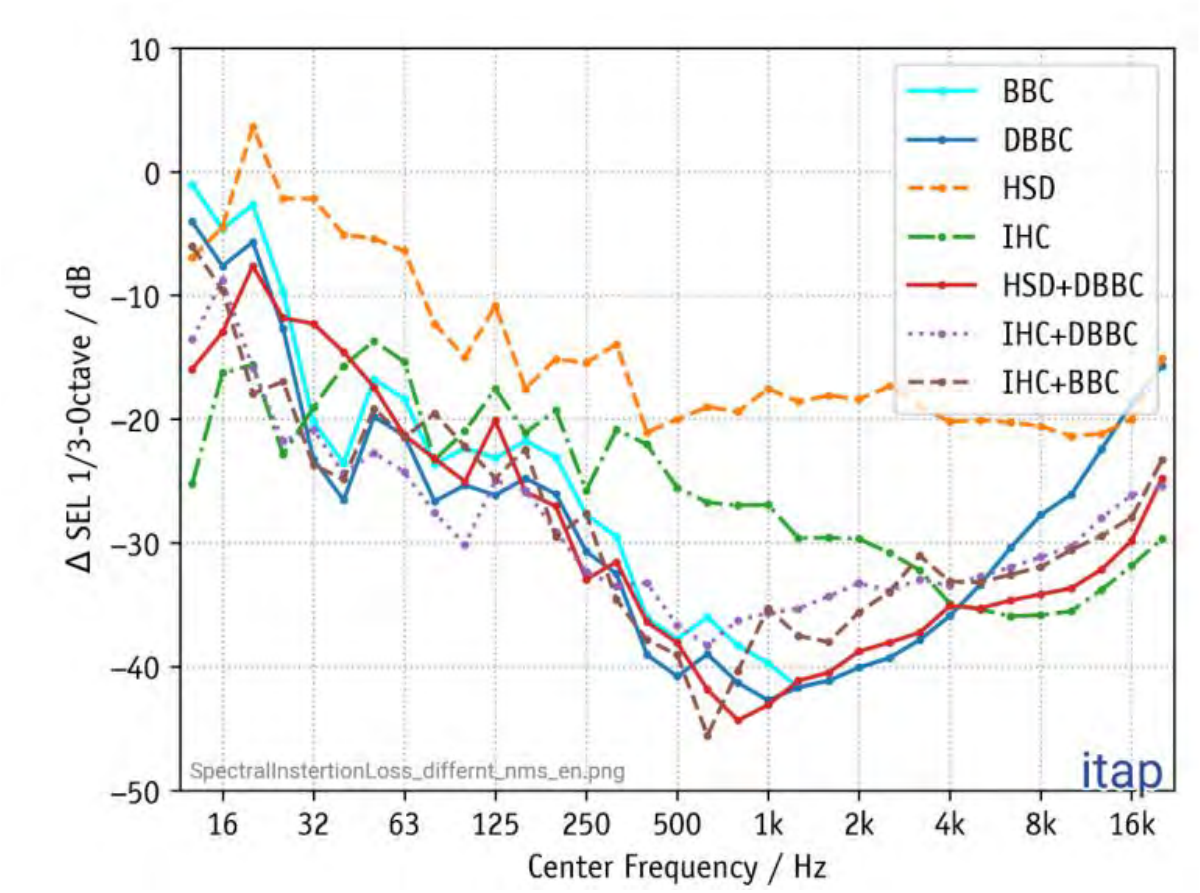


Figure 4-1: Noise abatement system reduction capabilities (Bellman et al., 2020)

4.5.1 Vibratory pile driving

Noise emissions may also be reduced by modifying the method for installing the monopiles: Noise emissions produced from vibro-piling have been documented to be 10-20 dB below mitigated impact pile driving (Gerke and Bellmann, 2012; Koschinski and Lüdemann, 2020). However, as vibro-piling produces continuous, non-impulsive noise (~3.5 hours per monopile) and piling produces impulsive noise, the potential impacts to marine fauna from this continuous source need to be further investigated. Modelling has investigated the effectiveness of vibro-piling in reducing noise in the marine environment at thresholds predicted to cause auditory threshold shifts or disturbance (refer Section 8.1.2.1).

4.6 Dynamically positioned vessel noise

Underwater noise emitted from vessels is produced mainly by propeller and thruster cavitation, with a smaller fraction of noise produced by sound transmitted through the hull, such as by engines, gearing, and other mechanical systems. Sound levels tend to be the highest when thrusters are used to dynamically position (DP) the vessel during foundation installation, and when the vessel is transiting at high speeds. A vessel's sound signature depends on the vessel's size, power output, propulsion system and the design characteristics of the vessels drive system (e.g., blade shape and size). Vessels typically produce broadband acoustic energy with most of the energy emitted below a few kilohertz.

In Australia, regulators are unique in specifically addressing noise emitted from vessels under DP as a distinct environmental concern. However, mitigating DP vessel noise presents a substantial challenge due to the complexity of the noise source as described above, the inherent need for vessels to use their thrusters to maintain position for technical and safety reasons, and no secondary mitigation options currently available.

4.7 Drilling noise

In the event of pile refusal, drilling or jetting may be required as an intervention before pile driving can continue with selected installation method. Based on wind farm developments overseas and geotechnical survey data it is conservatively estimated that seabed conditions may prohibit pile-driving in up to five percent of monopile foundations to their target depth, with the MDS equating to six monopiles. If pile 'refusal' occurs it is likely to be at the final target depth range, meaning that up to 95 per cent of the depth may be drilled. If drilling is required during monopile installation, it is expected that both piling and drilling would be undertaken by the same vessel with each drilling operation lasting up to 24 hours.

Noise emissions from drilling operations (non-impulsive sound) are less than for impact piling activities (impulsive sound) (Huang et al., 2023) and less than for vessels operating on DP, and therefore impact piling and DP are the MDSs. For example, underwater noise modelling for ESSO's drilling activities in the Gippsland in 60 metres water depth predicted TTS ranges for low frequency cetaceans out to a maximum of 190 m (for an eight-hour drilling scenario and with a support vessel holding position using DP alongside the jack-up drilling vessel), (Matthews et al., 2023). Marine mammal behavioural disturbance ranges for the same drilling activity were predicted to be within 2.9 km and 3.7 km, depending on the proximity of the support vessels on DP, i.e. the largest range was when the support vessel was furthest from the drilling vessel (Matthews et al., 2023). Without vessels, behavioural disturbance ranges were in the order of around 30 m with PTS and TTS thresholds not being reached. Underwater noise modelling for drilling activities during Beach's drilling and plug and abandonment (P&A) activities in the Otway in 80 metres water depth predicated TTS onset could occur within 820 metres (for an eight-hour drilling scenario with a support vessel holding position on DP alongside an anchored mobile offshore drilling unit), with behavioural response disturbance ranges out to 6.23 kilometres (Stroot et al., 2022). For an anchored mobile offshore drilling unit, behavioural disturbance thresholds ranges extended only to 2.1 km with TTS onset ranges extending only to 330 m for LF cetaceans and 1.3 km for very high frequency cetaceans. Subsequently, it was determined that modelling for pile drilling would be captured within the impact piling and vessel noise scenarios.

4.8 Operational noise

Underwater noise from operating wind turbines originates from movement of air around turbine blades and mechanical noise of bearings and the generator converting kinetic energy to electricity. Sound generated by blades is produced in the air and is not likely to enter the water directly, while mechanical noise associated with the operating WTG is transmitted into the water as vibration through the foundation and subsea cable. Mechanical noise originates in the moving mechanical parts (gearbox, brake, control electronics) in the nacelle and is almost exclusively at frequencies below 1 kHz, in most cases below 750 Hz (Marmo et al., 2013; Tougaard et al., 2020).

There has not been a specific focus on modelling noise emitted from operating wind turbines in the EIA, and no modelling is included in this report for operational noise. Instead, noise emissions are characterised based on measurements from already operating offshore wind farms in the North and Baltic Seas (e.g., Bellman et al., 2023), and 'simple' models used to determine the distances at which noise from a wind farm was detected above ambient noise level (Thomson et al., 2006; Tougaard et al., 2009; Bellman et al., 2023; Holme et al., 2023; Yoon et al., 2023).

There are no direct measurements to suggest that the source levels of noise emitted from an operating wind farm exceed 145 dB re 1 µPa (rms), and all measurements suggest that the received levels drop to less than 120 dB re 1 µPa at 100 metres and that levels propagating in the water column beyond this point will be low irrespective of propagation conditions (Madsen et al., 2006; Tougaard et al., 2009; Bellman et al., 2023). A shift from using gear boxes to direct drive technology was shown to reduce the sound level emitted by operating wind turbines by 2.5 dB (Bellman et al., 2023).

Simple models of entire OWFs showed that the overall noise level of a wind farm extends out to several kilometres before it is masked by ambient noise. For example, Tougaard et al. (2009) found that sound level from three different WTG types in European waters was only measurable above ambient sound levels at frequencies below 500 Hz, and Thomsen et al. (2006) suggest that at approximately 500 metres from operating WTGs, sound levels are expected to approach ambient levels. Tougaard et al. (2020) used a linear model to fit sound levels as a function of turbine size, wind speed and distance. Their model suggested that sound from multiple WTGs would be detectable out to a few kilometres in areas with very low ambient noise levels but would be below ambient unless "very close" to individual WTGs in areas with high ambient noise from shipping or wind. However, this model is based on only a few smaller turbine types (500 kilowatt to

5 megawatt) with gearboxes, and consequently predictions of the noise conditions were largely overestimated (up to 8 dB) above actually measured operational noise of turbines (Bellman et al., 2023; Holme et al., 2023) and therefore distances may be conservative.

Moreover, underwater noise levels emitted by operating wind turbines are generally below those from large vessels (Tougaard et al., 2020). Consequently, the presence of large ships in an area with wind farms will mask the noise from turbines at considerable ranges (Madsen et al., 2006; Tougaard et al., 2020). Agreeing with this, Bergström et al. (2013) reported that a wind farm is less detectable in intense ship traffic areas, though it is acknowledged that as the size of turbines increase so too may the level of noise emitted (Tougaard et al., 2020; Stöber and Thomsen et al., 2021). In contrast to ships, wind turbines are static, and therefore their contribution to the local soundscape is much more persistent, although not constant (Tougaard et al., 2020).

5 SUMMARY OF NOISE MODELLING

Underwater noise modelling for the SOTS OWF project has been an iterative process, with an evolution of modelling scenarios, site selection, and input parameters across the four rounds of modelling to deliver a comprehensive modelling program. These iterations were based on the availability of contemporary input data, modelling results which informed the elimination of options due to feasibility, testing of different noise abatement systems and changes in noise thresholds. They key variations in the modelling scenarios and input parameters across rounds one to four are summarised in Table 5-1, and the evolution of site selection across modelling rounds is shown in Figure 5-1.

Table 5-1: Evolution of scenarios and input parameters for underwater noise modelling across rounds one to four

Parameters	Round 1	Round 2	Round 3	Round 4
Modelling scenarios	• Monopile WTG foundations (impact piling) • Jacket structure OSS foundations (impact piling)	• Monopile WTG foundations (impact piling) • Jacket structure OSS foundations (impact piling)	• Monopile WTG foundations (vibro-piling) • Jacket structure OSS foundations (vibro-piling) • Vessel activities	• Monopile WTG foundations (impact piling) • Jacket structure OSS foundations (impact piling)
Animal movement exposure modelling	Monopile WTG foundations (impact piling) with a DBBC	Monopile WTG foundations (impact piling) with a DBBC	Vessel noise	Monopile WTG foundations (impact piling) with a DBBC, HSD and MHS
Site selection	• 3 monopile (MP1, MP2 and MP3) • OSS jacket pile • Concurrent piling OSS jacket and monopile (MP1a) Figure 5-1	• 2 monopile (MP1 and MP2) • OSS jacket pile Figure 5-1	• 3 monopile (MP1, MP2, and MP3) • OSS jacket pile Figure 5-1	• 4 monopile (MP1, MP2, MP3, and MP4) • OSS jacket pile Figure 5-1
Geo-acoustic parameters	• Seabed geoacoustic model (McCauley, 2021)	• Seabed geoacoustic model (McCauley, 2021) and Geotechnical sampling program within the SOTS FLA	• Geotechnical sampling program within the SOTS FLA	• Geotechnical sampling program within the SOTS FLA
Driveability	• Engineers created driveability for each of the 4 modelled locations based on assumption of geological layers comprising 'strong sand'	• Engineers advised which driveability using site specific geotechnical data that would be most appropriate for each location – MP1: 23-01 – MP2: 23-13 – shallow site, harder – OSS: 23-04	• The boreholes selected for driveability assessment were chosen as having a median cumulative driving energy in the relevant water depth zone. – MP1: 23-04 – higher cumulative energy than 23-01 – MP3: 23-10 – MP5: 23-22 – relatively harder driving than 23-13 – OSS: 23-04	• The boreholes selected for driveability assessment were chosen as having a median cumulative driving energy in the relevant water depth zone. – MP1: 23-04 – higher cumulative energy than 23-01 – MP3: 23-10 – MP5: 23-22 – relatively harder driving than 23-13 – OSS: 23-04
Hammer energy	• 4,000 kj for monopiles	• 4000 kj hammer for monopiles	• 4000 kj hammer for monopiles	• 4000 kj hammer for monopiles

Parameters	Round 1	Round 2	Round 3	Round 4
	• 2,300 kj for pin piles	• 3500 kj hammer for pin piles	• 3500 kj hammer for pin piles	• 3500 kj hammer for pin piles
Monopile diameter	• OSS – 3.25 m • MPs – 12.5 m • MP deep site – 13.5 m, 12.5 m, 11 m, 9.75 m, 8.75 m	• OSS – 3.25 m • MPs – 11.8 m	• OSS – 3.25 m • MPs – 9.2 m, 11 m, 11.8 m	• OSS – 3.25 m • MPs – 9.2 m, 11 m, 11.8 m
Noise abatement systems	• DBBC • HSD	• DBBC • HSD	Not possible to model	• DBBC • HSD • MHS
Noise effect thresholds	• Marine mammals – Southall, 2019 – NOAA, 2019	• Marine mammals – Southall, 2019 – NOAA, 2019 • Marine turtles – McCauley et al. 2000 – NSF 2011 – Finneran et al. 2017 • Fish and invertebrates – Popper et al., 2014 – Fewtrell and McCauley, 2012 – Day et al. 2016a – Payne et al. 2008 • Penguins and diving seabirds – Southall, 2019	• Marine mammals – NMFS, 2024 – NOAA, 2019 • Marine turtles – Finneran et al. 2017 • Fish and invertebrates – Popper et al., 2014 – Fewtrell and McCauley, 2012 • Penguins and diving seabirds – Southall, 2019	• Marine mammals – NMFS, 2024 – NOAA, 2019 • Marine turtles – Accomando et al., 2025 • Fish and invertebrates – Popper et al., 2014 – Fewtrell and McCauley, 2012 – Day et al. 2016a – Payne et al. 2008 • Penguins and diving seabirds Southall, 2019

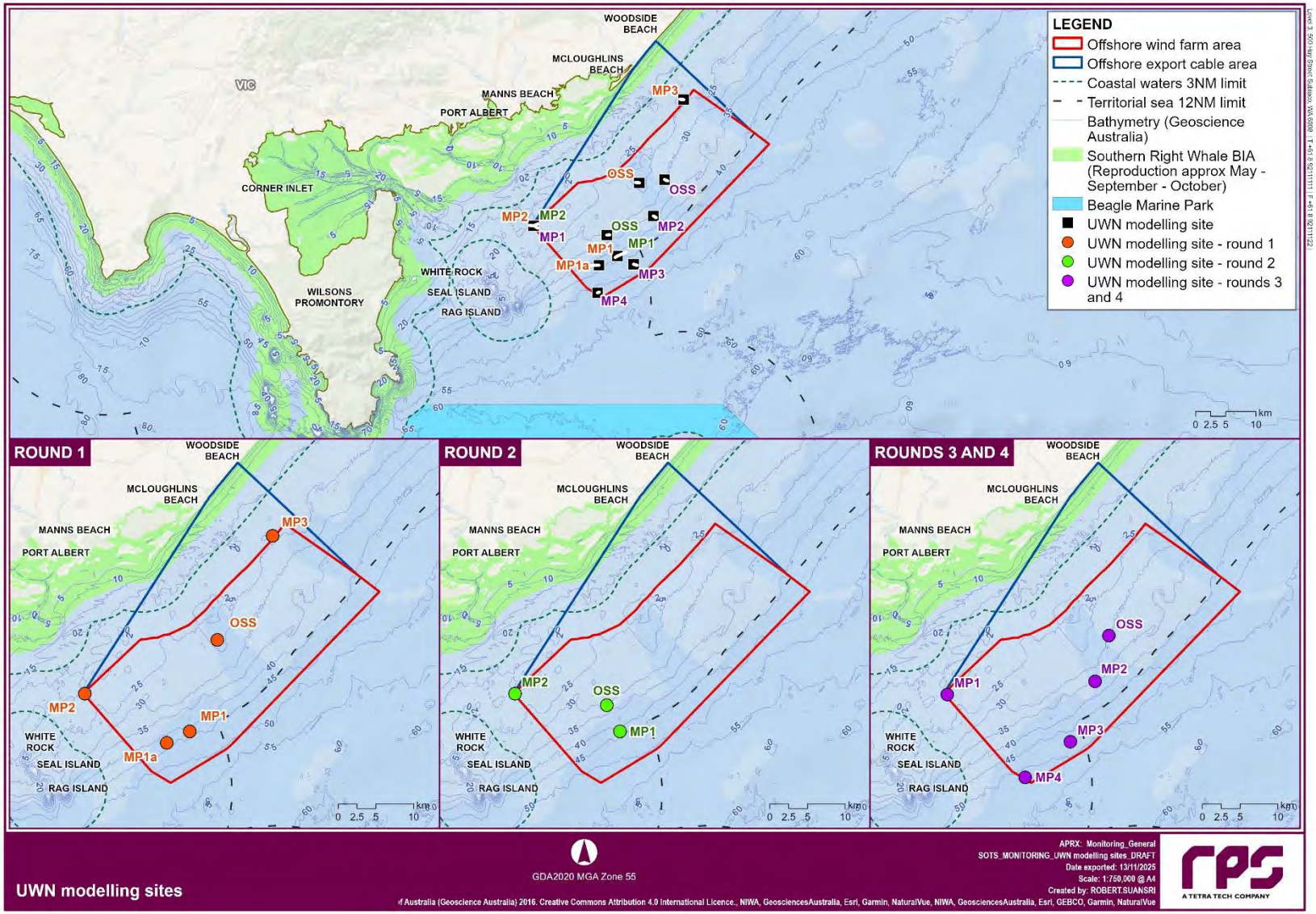


Figure 5-1: Evolution of site selection for underwater noise modelling across rounds one, two, and three and four

5.1 Changing noise thresholds

Updated noise effect thresholds for PTS and TTS onset to impulsive and continuous noise sources were published by the NMFS in 2024 and used in the third and fourth- round modelling for vibro-piling, impact piling and vessels. The new thresholds have lower (more conservative) PK and SEL 24h thresholds for LF cetaceans for continuous noise but higher (less conservative) PK and SEL 24h thresholds for LF cetaceans for impulsive noise. However, a LF cetacean weighting function that has been included in the new thresholds demonstrates better sensitivity at the lower end of the spectrum, and therefore it is possible that despite less conservative thresholds for impulsive noise, impact ranges may be larger. The NMFS updated thresholds did not include any changes to behavioural response thresholds.

The 'protective' lower effect thresholds for PTS and TTS onset to impulsive noise initially proposed by Southall et al. (2007) and updated in Southall et al. (2019) and NMFS (2024) are precautionary, which has led to practical challenges for those trying to enforce regulations, and those seeking to comply with them (Southall, 2021). While research is still ongoing, Southall (2021) emphasise that predicted ranges to PTS and TTS in the range of tens of kilometres is almost certainly an overly precautionary interpretation of the existing threshold.

The behavioural response thresholds currently used in the modelling (160 dB SPL for impulsive and 120 dB SPL for continuous noise) are from NOAA (2019). Southall et al. (2021) proposed a new approach for assessing the behavioural response of free-ranging marine mammals to noise. While the authors do not propose new numerical thresholds, they do provide a scaled severity response for marine mammals to noise, with respect to 1) survival (including resting and social interactions), 2) reproduction (including parenting behaviours) and 3) foraging (Southall et al., 2021). The intent of this severity scale is to provide a means of evaluating behavioural responses in a way that facilitates interpreting consequences in terms of vital rates (Southall et al., 2021). Severity responses ranged from minor to brief (zero to three), higher potential to affect (four to six) and likely to affect (seven to nine). While Southall et al. (2021) does assess behavioural response from pile driving noise, the species considered were harbour porpoises and seals, and consequently no comparisons to LF whales could be made. In response to vessel noise migrating gray whales displayed a severity of response of five, equivalent to avoidance behaviour, while North Atlantic right whales showed no response, though it is likely that they were familiar with this type of noise source (Southall et al., 2021).

The 120 dB SPL continuous noise behavioural response threshold is considered to be conservative as previous studies have identified varying responses for marine mammals to noise between 140 to 180 dB re 1 µPa (SPL), and for LF cetaceans the data indicated no or very limited response at a received level of 90 to 120 dB with an increasing probability of avoidance or behavioural response from 120 to 160 dB (Southall et al., 2007). Dr Brandon Southall provided advice to Beach Energy with regard to an exploration drilling program (continuous noise) as to his opinion of what sound level would be required to disturb/displace blue whales from foraging. Southall's advice was that based on studies on feeding blue whales off California whales were found to respond to sound in the 130 to 140 dB range (Beach Energy, 2020). A recent study by Darias-O'Hara et al. (2025) determined behavioural response thresholds for Antarctic marine mammal species to vessel noise, with cetaceans eliciting a response at 137 dB re 1 µPa (SPL). A response was considered to be of the severity scale of five or above according to Southall et al. (2021). Animals in the Antarctic are considered to be less exposed to anthropogenic noise, and consequently it can be assumed they would display a greater response in comparison to other whales that are more frequently exposed to vessel noise, including in the Gippsland.

6 FIRST ROUND UNDERWATER NOISE MODELLING SCOPE, INPUTS AND METHODS (2020-2022)

The potential impacts of underwater noise on marine fauna, and in particular, endangered whale species that are subject to recovery plans under the EPBC Act and that have “biologically important areas” overlapping the project area, are key environmental considerations for this project. As a result, the potential to reduce underwater noise emissions has been a focus of project design decisions. The below sections provide a summary of the scope, purpose and methods for early underwater noise modelling (before a feasibility licence being granted) and how the results have influenced project design decisions.

SOTS was granted an Exploration Licence in March 2019. Following this, the underwater noise modelling of project activities began in 2020. JASCO performed a first-round modelling study of underwater sound levels associated with construction activities for the SOTS OWF (Koessler et al. 2022).

6.1.1 Acoustic modelling scenarios

Various iterations of this modelling report were produced. Initial modelling (2020-2022) scenarios included:

- Monopile WTG foundations (impact piling)
  - Installation of a single pile at three sites within the OWFA
  - Simultaneous piling of two adjacent foundations in the same day
- Jacket structure OSS foundations (impact piling)
  - Four pin piles installed at a single site within the OWFA
  - Simultaneous piling of a WTG (monopile foundation) and OSS (jacket foundation) in the same day

Modelling scenarios were developed to be representative across different seabed types present in the OWFA and across different times of year (seasons), with a worst-case approach being taken in selection of seabed type and season that allows the greatest propagation of underwater noise.

6.1.2 Site selection

Before the award of the SOTS Feasibility Licence Area (FLA) in April 2024 (refer to Figure 2-1), the proposed OWFA used in the noise modelling aligned with the SOTS Exploration Licence, also referred to as the Pre-Feasibility Licence Area (PFLA), covering an area of 492 km^2. Modelling sites were selected to be representative across the full spatial extent of the PFLA to ensure the modelling outputs would be appropriate to infer the extent and intensity of sound propagation at different locations within this area.

Impact piling of monopiles was modelled at three sites within the OWFA: deep south-east corner (MP1 in 42 m water depth), shallow south-west corner (MP2 in 20 m water depth) and shallow north-west corner (MP3 in 23 m water depth). A further pile driving site labelled with the suffix “a” was considered for the concurrent modelling scenario. This location is consistent with piling operations at an adjacent WTG site, 3,420 m from the original modelled site. A single site in the centre of the OWFA was chosen to model OSS jacket foundation installation (Table 6-1 and Figure 6-1).

Table 6-1: Modelled site locations and site information

Modelling site	Latitude (S)	Longitude (E)	Water depth (m)	Environmental considerations for site selection
MP1 SE Deep	38° 52' 43.9"	146° 53' 54.0"	42	Fish assemblages and whales within and adjacent to the OWF area
MP1a SE Deep	38° 53' 33.2426"	146° 51' 46.8894"	42	Located 3,420 m from MP1
MP2 SW Shallow	38° 50' 0.5"	146° 44' 17.1"	20	Closest proximity to SRW reproduction BIA and Corner Inlet Ramsar site
MP3 NW Shallow	38° 38' 43.9"	147° 1' 29.3"	23	Proximate to reef habitat supporting demersal fish species
OSS Jacket Centre	38° 46' 11.0"	146° 56' 25.7"	24	Fish assemblages and whales within and adjacent to the OWF area

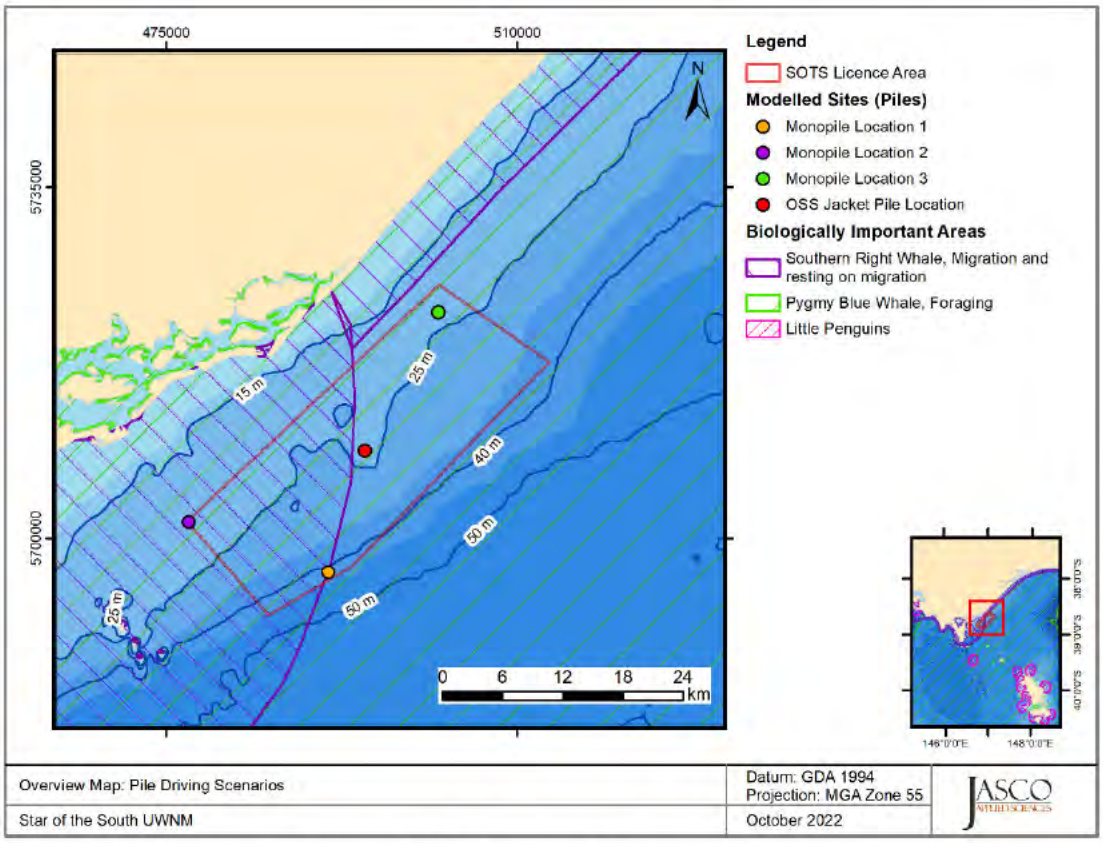


Figure 6-1: Location of sites modelled for impact piling scenarios

6.1.3 Pile driving inputs

The pile-driving parameters used in the model are shown in Table 6-2.

The installation of a single pile requires adjustment of the energy delivered by the hammer as the pile advances into the sediment. Initially the hammer is set to deliver low energy strikes, since this is sufficient to advance the pile when the surficial sediment does not offer too much resistance. As the pile penetrates farther, higher energy settings (up to 4000 kJ for the IHC S-4000) and more strikes are required to advance the pile to its final depth. Maximum sound levels from pile installation usually occur during the last stage of pile driving (Betke, 2008; Koessler et al. 2022).

The hammer penetration/hammering values used in the acoustic modelling study considered the driveability information provided by SOTS project engineers and included the number of strikes and applied hammer energy per metre of the pile drive. The drive was divided into three depth intervals and associated

penetration depths to represent the different portions of the drive. Over each modelled depth interval, the upper 90th percentile of applied energy was selected to represent the hammer energy over the depth range (a suitably conservative approach given the limited understanding of the geology and soil mechanics in the area). The resulting penetration depth, strike count and hammer energy used for acoustic modelling are presented in Table 6-3.

Table 6-2: Pile driving parameters

Modelling site	Maximum pile diameter (m)	Pile length (m)	Final penetration depth (m)
MP1 SE Deep	12.5	81.1	35.1
MP2 SW Shallow	12.5	60.7	28.7
MP3 NW Shallow	12.5		
OSS Jacket Central	3.25	52	49

*Note: 4 pin piles for jacket foundations to be installed per day

Table 6-3: Impact hammer energy, modelled number of strikes and pile penetration for monopile foundations and jacket pin pile foundations

Site description	Hammer model	Hammer energy (kJ)	Strike count	Sediment penetration (m)	Total number of strikes	Strike rate (bpm)	Installation time
MP1	IHC S-4000	2131.2	1150	17.7	6883	36	3.19
		3999.8	1660	26.4			
		3999.8	4073	35.1			
MP2		1197.4	701	14.2	3731		1.73
		3670.8	1200	21.4			
		3999.8	1830	28.7			
MP3		1197.4	701	14.2	3731		1.73
		3670.8	1200	21.4			
		3999.8	1830	28.7			
OSS	IHC S-2300	499.7	2050	21.7	9565	30	5.31
		1371.7	2599	35.3			
		2280.7	4916	49.0			

6.1.4 Sound propagation models

Underwater noise impacts from pile driving were modelled using JASCO's pile driving source model and noise propagation models. Predictions from JASCO's propagation models have been validated from several underwater acoustic measurement programs conducted by JASCO globally (Hannay and Racca, 2005; O'Neill et al., 2010; Racca et al, 2015; McPherson and Martin, 2018). In addition, JASCO have conducted measurement programs associated with a significant number of anthropogenic activities (including pile driving), that have included internal validation of the modelling (McCrodan et al., 2011; Austin, 2014; Austin and Li, 2016; Martin and Popper, 2016).

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss (a measure) in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

Noise modelling was undertaken to determine ranges to noise effect thresholds for static (i.e., unmoving) marine fauna and humans. Results of instantaneous (single strike, PK) and cumulative (multiple strike, SEL_{24h}) noise exposure to impact pile driving were reported (refer to Section 7.2). SEL_{24h} is a cumulative metric that reflects the dosimetric effect of noise levels within 24 hours, based on the assumption that a

receiver (e.g., an animal) is consistently exposed to such noise levels at a fixed position. More realistically, marine animals would not stay in the same location for 24 hours (especially in the absence of location-specific habitat) but rather a shorter period, depending on the animal's behaviour and the source's proximity and movements. Therefore, a reported radius for the SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be impaired, but rather that an animal could be exposed to the sound level associated with impairment (either PTS or TTS) if it remained at that exposure level from the noise source for 24 hours.

6.1.5 Estimating range to exposure thresholds

The acoustic modelling inherently assumes static animals (i.e., animals remaining in a fixed position for the duration of the exposure to anthropogenic noise).

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. The predicted distances to specific levels were computed from these contours. Two distances relative to the source are reported for each sound level:

1. **R_{max}**: the maximum range to the given sound level over all azimuths, and
2. **$R_{95\%}$**: the range to the given sound level after the 5% farthest points were excluded (see examples in Figure 6-2).

In some cases, a sound level contour may have small protrusions with relatively few points excluded in any given direction (Figure 6-2a). In this instance R_{max} can misrepresent the area of the region exposed to such effects, and therefore $R_{95\%}$ is considered more representative. On the other hand, in strongly asymmetric cases $R_{95\%}$ neglects to account for the significant protrusions in the footprint (Figure 6-2b), and therefore R_{max} might be more representative. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

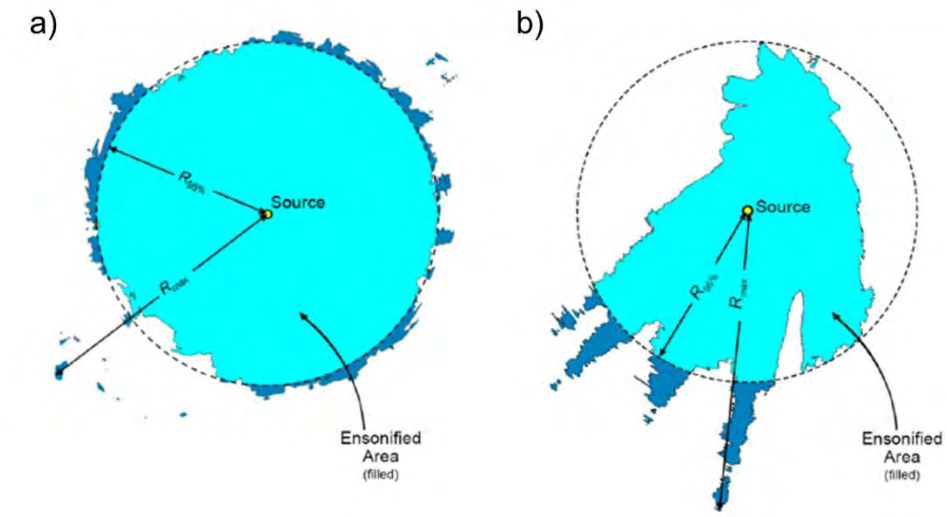


Figure 6-2: Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios, a) largely symmetric sound level contour with small protrusions and b) strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}

6.1.6 Animal movement exposure modelling (Animat)

In addition to the static models, the JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was used to predict the exposure of individual animals (termed 'animats' in the model) to sound arising from driving of monopiles and jacket pin piles during construction of the wind farm. JASMINE integrates the predicted sound field with biologically meaningful movement rules for each whale species modelled (e.g., pygmy blue whale (parameters used due to greater detection in baseline studies), southern right whale, humpback whale and minke whale). This results in an exposure history for each animat in the model. In

JASMINE, the sound received by the animats was determined by the proposed piling operations. Animat modelling may be considered as a more representative estimate of cumulative noise exposure to an animal over a 24-hour period, in comparison to static models, due to the highly mobile nature of marine mammal species.

The parameters used for forecasting realistic behaviours (e.g., diving, and foraging depth, swim speed, surface times) were determined and interpreted from marine mammal studies (e.g., tagging studies) where available, or reasonably extrapolated from related or comparable species (refer to Jasco modelling reports for a full list of references). Within the context of the project specific simulation parameters, including source characteristics, swimming behaviours and bathymetry, a seeding density of four animats per square kilometre was considered to provide sufficient sampling of the model space and to generate statistically reliable exposure range estimates. The seeding density refers to the spatial sample rate, in units of animats per kilometre squared, used in the simulation and is not related to the real-world animal density. With this seeding density, >35,000 animats were considered within the sampled area for each species/scenario, to provide confidence in the model outputs. The number of animats was chosen to maximize sample size while remaining feasible given computational time constraints. Additionally, the simulator programs each animat to sample the model space every five seconds. For example, an animat swimming at one meter per second would sample the sound field every five meters along its track. For cumulative metrics, an individual animat's sound exposure levels were summed over a 24-hour duration to determine its total received energy and then compared to the relevant threshold criteria. For single-exposure metrics, the maximum exposure was evaluated against threshold criteria for each 24-hour period. An example animat movement track is shown in Figure 6-3. The top panel displays the animat track relative to the point source, and the bottom panel displays the accumulation of SEL_{24h} for TTS and PTS onset criteria. At approximately 50 seconds, the animat is exposed so that the TTS threshold is exceeded, and at approximately 700 seconds the animat is exposed so that the PTS threshold is exceeded.

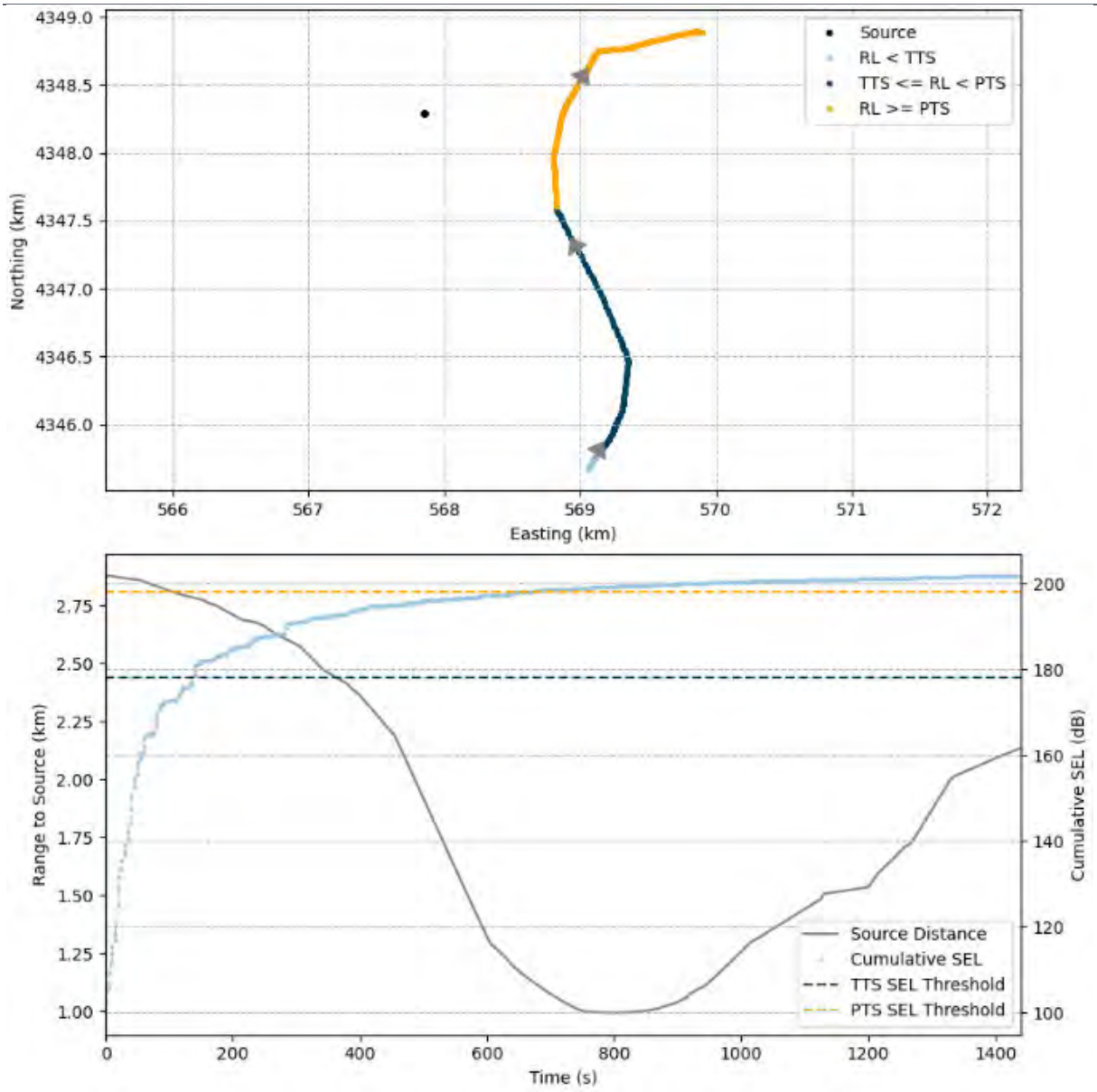


Figure 6-3: Animat track from an example simulation showing northward movement over a duration of 1400 seconds. The upper panel shows a plan view of both a stationary point source and a foraging animat. Animat steps are coloured to indicate whether the accumulated sound energy at that point has exceeded either TTS or PTS threshold criteria. The lower panel shows horizontal distance in kilometres to the source (grey line; left y-axis) and cumulative 24 h SEL ($L_{E,24h}$, dB re 1 µPa²·s; right y-axis) as a function of time. Note: this example does not use data from the current study

The results from the animat model provide a way to estimate the radial distances to noise effect thresholds. The distance to the closest point of approach (CPA) for each of the animats was recorded. The $ER_{95\%}$ (95% Exposure Range) is the horizontal distance that includes 95% of the animat CPAs that exceeded a given effect threshold (Figure 6-4). Within the $ER_{95\%}$, there is generally some proportion of animats that do not exceed threshold criteria. This occurs for several reasons, including the spatial and temporal characteristics of the sound field and the way in which animats sample the sound field over time, both vertically and horizontally. The sound field varies as a function of range, depth, and azimuth based on a variety of factors such as bathymetry, sound speed profile, and geoacoustic parameters. The way the animats sample the sound field depends upon species-typical swimming and diving characteristics (e.g., swim speed, dive depth, surface intervals, and reversals). Furthermore, even within a particular species definition, these characteristics vary with behavioural state (e.g., feeding, migrating). Therefore, the probability that an animat within that distance was exposed above threshold within the $ER_{95\%}$ was also computed (P_{exp}).

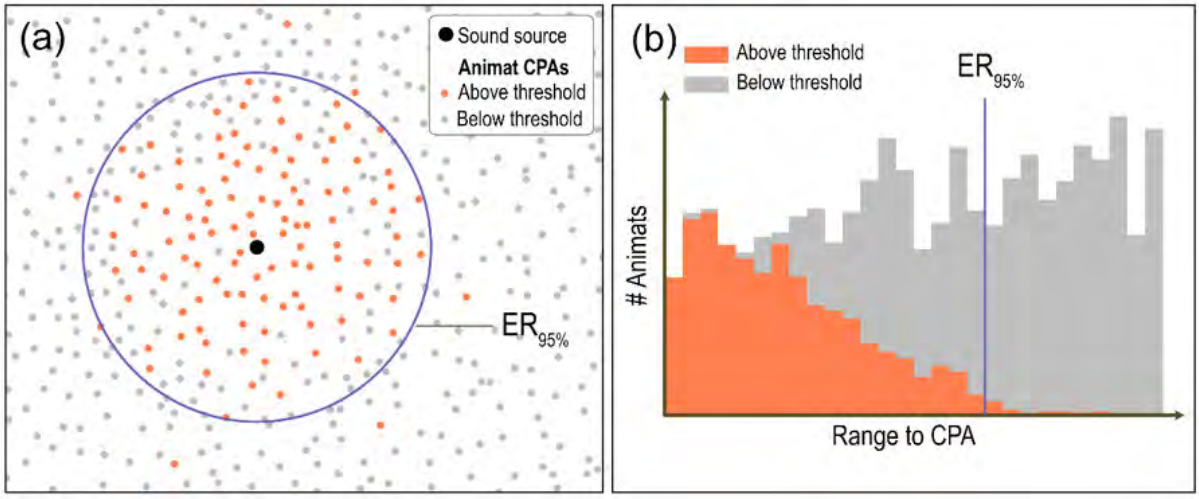


Figure 6-4: Example distribution of animat closest points of approach (CPAs), demonstrating the horizontal distribution of animats near a sound source (a) and the distribution of distances to animat CPAs (b)

6.1.7 Seasonal parameters

The sound speed profiles for the modelled sites were derived from temperature and salinity profiles from the US Naval Oceanographic Office's Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990; Carnes, 2009). Mean monthly sound speed profiles were derived from the GDEM profiles within a 100 km box radius from the centre of the Licence Area. To determine the sound speed profile that was expected to be most favourable to longer-range sound propagation during the proposed survey time frame, each month within the summer and winter periods was assessed to determine which may lead to the farthest propagation within that season. As such, June and January were selected for sound propagation modelling to ensure precautionary estimates of distances to received sound level thresholds.

6.1.8 Noise abatement systems

The first-round underwater noise modelling of piling activities (monopiles and jacket foundations) included two forms of noise mitigation: a DBBC on its own and a DBBC and HSD in combination. The placement of the DBBC rings at two nominal distances of 90 m and 130 m from the centre of the pile was selected by JASCO based on noise attenuation values reported in the literature.

A third NAS was also considered early on but not brought forward into the modelling. This system is known as the AdBM noise mitigation system and like the HSD it is deployed in the immediate proximity of the pile. Results from a preliminary study indicated that the AdBM and DBBC systems performed worse (i.e., lesser noise reduction and therefore greater impact ranges for low frequency cetaceans) than the HSD and DBBC systems, and ultimately it was decided not to include this in the modelling.

6.1.9 Assumptions included in the model

6.1.9.1 Seabed parameters

At the time of this modelling study detailed geotechnical information such as porosity and grain size measurement with depth below the seafloor were not available, and therefore there was some uncertainty with respect to the geoacoustic properties of the seabed and the driveability profile as a pile is driven into the seabed.

The seabed geoacoustic model used in the underwater noise modelling was based on that provided in McCauley (2021), collected during the Marine Ecology Survey Program (MESP) passive acoustic monitoring study. The geophysical and acoustic propagation loss study indicated that the seabed likely consists of a coarse unconsolidated layered sediments underlain by a more cemented horizon (McCauley, 2021).

A pile sensitivity study was conducted to test the sensitivities of different pile diameters and sand combinations and determine their noise propagation potential (see Section 6.1.10.2). Results of the study

showed that the largest ranges would likely be associated with the strong seabed profile, coupled with the increased strike rate required for piling into strong sand. Therefore, the parameters for a seabed with strong mechanical resistance were selected for the acoustic modelling as part of a likely worst-case and conservative modelling approach.

6.1.10 Scenarios scoped out of the project during first round modelling

Results from the first-round modelling determined that concurrent modelling would not be included as part of the project construction activities as ranges to exposure thresholds were too large and that monopile diameter would be refined. Subsequent modelling made further refinements to the modelling scenarios and parameters, which are described in Section 7.

6.1.10.1 Concurrent pile driving operations

Early conversations indicated that it may be more cost-effective and the temporal extent of impacts may be reduced by driving piles concurrently at two locations, and therefore modelling was conducted for concurrent piling for the WTGs, with monopile locations separated by a distance of 3.42 km. Modelling was conducted at the deep water site only (MP1) as this produced the largest ranges to effect for marine fauna and humans in the single pile modelling. The results showed that the temporal extent of impacts was increased with concurrent monopiling, and therefore, it was decided that this would be eliminated from the project design envelope.

It was also deemed possible that simultaneous piling of WTGs and OSSs could occur throughout the project for cost savings and/or schedule purposes, and therefore a further modelling exercise was undertaken to investigate the noise emissions profile associated with concurrent impact piling of a single WTG monopile and OSS jacket pin piles. The results of this modelling showed that concurrent operations resulted in larger distances to noise effect thresholds compared to those for a single monopile. Given the distances to noise effect ranges were large when considering only a single monopile (Section 7.2), a decision was made to eliminate concurrent pile driving operations entirely from the project design envelope.

The results of concurrent pile driving noise modelling for low frequency cetaceans are shown in Table 6-4.

Table 6-4: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from unmitigated (i.e., no noise reduction applied) pile driving of a single monopile, concurrent monopiles and a single monopile and jacket pin piles in winter

Sound exposure threshold	Rmax distance (km)			
	Deep (MP1)			
	Single monopile	Concurrent monopile	Monopile + single jacket pile	Monopile + 4 jacket piles
PTS onset				
183 dB re 1 µPa² (SEL_{24h})	25.2	39.1	N/A	32.60
TTS onset				
168 dB re 1 µPa² (SEL_{24h})	80.6*	>90.00	N/A	>90.00
Behavioural response				
160 dB re 1 µPa (SPL)	23.8	31.3	29.8	N/A

* R95% distance (the range to the given sound level after the 5% farthest points were excluded). R95% was used as it provided a more meaningful estimate of the distance to impact threshold due to the sound propagation path intersecting the Hogan groups islands.

6.1.10.2 Monopile diameter

A modelling study was conducted in 2022 to understand the influence of different monopile diameters, driveability profiles, soil resistance profile types, and water depth. This study considered monopile diameters ranging from 8.75 m to 13.5 m. Eight scenarios were modelled at two sites, MP1 (deep) and MP2 (shallow) (refer to Figure 6-1), with a soft sand and strong sand seabed resistance profile.

One of the key conclusions of the study was that it was difficult to isolate a single parameter as driving the worst-case result. However, the worst-case pile location and driveability profile was deep water with a strong

sand seabed soil resistance profile. This scenario resulted in the largest per-strike hammer energies and the largest number of hammer strikes (Table 6-5). The larger 13.5 m monopile diameter did not result in the worst-case noise levels/effect ranges, however, this was likely due to the fewer number of total hammer strikes required to install the pile. The deep modelled site (scenario 3 to 8) generally produced larger distances to thresholds than the shallow site (scenario 1 and 2) (Table 6-5; Table 6-6), likely a consequence of: 1) the deeper water exposing more pile length to the water column and allowing more energy to couple in the ocean waveguide (a structure that guides waves by restricting the wave movement, resulting in efficient transmission), and 2) deeper water also has a lower acoustic cut off frequency which may allow more energy to propagate within the ocean waveguide. These two influences are interrelated and non-separable consequences of shallow water ocean acoustic physics.

Throughout this process, it was decided that it would be unrealistic to install a 13.5 m diameter pile in a strong sand seabed profile, and therefore the maximum pile diameter considered for the project was 12.5 m, as used in the first round of modelling.

Table 6-5: Monopile drivability profile specifications

Scenario	Modelling site	Soil profile type	Water depth (m)	Maximum pile diameter	Maximum applied energy (kJ)	Total hammer strikes
1	MP2 (shallow)	STRONG Sand	20	12.5	3999.8	3731
2		SOFT Sand		12.5	16.8	4394
3	MP1 (deep)	STRONG Sand	42	12.5	3999.8	6882
4		SOFT Sand		12.5	1177.3	4999
5		SOFT Sand		13.5	1406.5	4791
6		STRONG Sand		8.75	2511.7	2949
7				9.75	2912	3051
8				11.0	3373.4	2946

Table 6-6: Maximum horizontal distance (Rmax) in kilometres from each pile for each penetration depth for marine mammals to a behavioural response during installation of a monopile using impact piling in winter

Sound exposure threshold	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
	Penetration depth (m)											
	14.2	21.4	28.7	26.2	33.4	40.7	17.7	26.4	35.1	34.3	42.7	51.0
	Rmax (km)											
Behavioural response 160 dB re 1 µPa (SPL)	7.38	8.80	9.70	5.27	4.75	5.76	18.10	21.10	20.90	14.10	13.50	12.40

Table 6-7: Maximum horizontal distance (Rmax) in kilometres from each pile for each penetration depth for marine mammals to a behavioural response during installation of a monopile using impact piling in winter (cont.)

Sound exposure threshold	Scenario 5			Scenario 6			Scenario 7			Scenario 8		
	Penetration depth (m)											
	29.9	37.7	45.6	15.5	29.9	37.7	45.6	15.5	29.9	37.7	45.6	15.5
	Rmax (km)											
Behavioural response 160 dB re 1 µPa (SPL)	10.20	12.40	13.20	8.25	13.30	15.60	12.20	15.50	17.00	11.40	14.80	20.00

SOTS project engineers undertook further evaluation of minimum monopile diameters that could be installed across the feasibility licence area and determined that smaller monopile diameters were feasible from a

structural integrity perspective. It was then decided that the largest monopile diameter would be 11.8 m, and this was applied in future modelling.

6.1.10.3 Summer seasonal profile

The first round of modelling indicated only minor differences in noise level estimates between summer and winter environmental conditions, with noise propagating slightly further in the far field in winter (Table 6-8). Therefore, the winter profile was selected for use across all modelling as a conservative approach. Note that the use of the winter profile has also been carried through to the third and fourth round of modelling described in Section 8.

Table 6-8: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of a single monopile with no noise mitigation in summer and in winter

Sound exposure threshold	Rmax distance			
	Summer		Winter	
	Deep (MP1)	Shallow (MP3)	Deep (MP1)	Shallow (MP3)
PTS onset				
183 dB re 1 µPa² (SEL_{24h})	24.7	11.8	25.2	11.9
TTS onset				
168 dB re 1 µPa² (SEL_{24h})	72.2*	15.1	80.6*	15.3
Behavioural response				
160 dB re 1 µPa (SPL)	23.8	15.0	23.8	15.0

* R95% distance (the range to the given sound level after the 5% farthest points were excluded). R95% was used as it provided a more meaningful estimate of the distance to impact threshold due to the sound propagation path intersecting the Hogan groups islands.

6.1.11 Summary of modelling approach (2020-2022)

Although there were some differences in the input parameters used for this first round and each successive round of modelling, results from modelling noise generated by impact piling for monopiles and pin piles with and without mitigations can be compared to show the evolution and refinement of the modelling predictions and results. A summary of parameters that will be used for comparing successive rounds of modelling is provided in Table 6-9.

Table 6-9: Summary of the modelling approach for first round noise modelling in 2020-2022

Parameter	Modelling approach
Installation method	Impact piling only
Sites	• Deep and shallow monopile, central OSS – 3 x MP locations – one shallow NW corner (near fish habitat/reefs 25m), one shallow SW corner (near seal/bird breeding islands 22 m), one deep water SE corner (42 m) – OSS jacket pile in centre of project area (24 m) – Concurrent piling OSS jacket pile and MP deep site
Geo-acoustic properties	CMST noise propagation measurements
Driveability	Engineers created driveability for each of the 4 modelled locations based on assumption of geological layers comprising 'strong sand'
Hammer size and energy	4000 kj hammer for monopiles, 2300 kj hammer for pin piles
Monopile diameter	• 3.25 m at OSS, • MPs (all three sites) – 12.5 m (full modelling) • MP deep site – 13.5 m, 12.5 m, 11 m, 9.75 m, 8.75 m (sensitivity modelling - one radial going offshore)
Mitigations	DBBC and HSD
Noise thresholds for marine mammals	Southall 2019
Animat model	Southern right whale, pygmy blue whale, humpback whale, minke whale

6.2 Modelling results

6.2.1 Impact piling of monopiles

The results for acoustic modelling carried forward into successive rounds is for impact piling of a single monopile at two locations within the OWFA with the inclusion of two noise abatement system scenarios including a DBBC, and HSD with a DBBC (Koessler et al., 2022. The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds for LF cetaceans with these noise abatement systems are shown in Table 6-10.

The modelled noise ranges indicated that the DBBC was more effective at reducing the predicted onset of PTS and TTS distance ranges for LF cetaceans compared to no mitigation (Table 6-10). While the combination of a DBBC with a HSD resulted in smaller predicted onset ranges of PTS, TTS and behavioural response, it was only marginally more effective than DBBC alone at both sites.

Table 6-10: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of a single monopile with no mitigation and with a DBBC, with a HSD, and with a DDBC + HSD in winter

Sound exposure threshold	Rmax distance (km)					
	Deep (MP1)			Shallow (MP3)		
	None	DBBC	DBBC + HSD	None	DBBC	DBBC + HSD
PTS onset						
183 dB re 1 µPa².s (SEL_{24h})	25.2	3.70	2.74	11.9	2.99	2.38
TTS onset						
168 dB re 1 µPa².s (SEL_{24h})	89.9	11.30	10.2	53.5	8.42	7.84
Behavioural response						
160 dB re 1 µPa (SPL) (unweighted)	23.80	7.11	5.96	15.00	6.66	6.42

Acoustic modelling was conducted for impact piling of a single monopile at two locations within the OWFA. The maximum distances (R_{max}) to PTS onset, TTS onset and behavioural response thresholds are shown in Table 7-6.

Unmitigated noise ranges from impact piling of monopiles predicted for PTS were a maximum of 25.2 km for the deep location (MP1), in comparison to only 3.7 km for the same location with a DBBC (Table 6-11). Furthermore, the maximum TTS onset and behavioural response ranges with a DBBC were 11.3 km and 7.11 km, respectively, at the deep site. Drive time for each monopile is estimated to be around 2.5 h.

Table 6-11: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of a single monopile with no mitigation and with a DBBC in winter

Sound exposure threshold	Rmax distance (km)			
	No mitigation		DBBC	
	Deep (MP1)	Shallow (MP3)	Deep (MP1)	Shallow (MP3)
PTS onset				
183 dB re 1 µPa².s (SEL_{24h})	25.2	11.9	3.7	2.99
TTS onset				
168 dB re 1 µPa².s (SEL_{24h})	80.60*	53.5	11.3	8.42
Behavioural response				
160 dB re 1 µPa (SPL) (unweighted)	23.80	15.00	7.11	6.55

*R95% was used as it provided a more meaningful estimate of the distance to impact threshold due to the sound propagation path intersecting with the Hogan Islands group

6.2.2 Impact piling of OSS pin piles

Acoustic modelling was conducted for impact piling of a single jacket pin pile and four pin piles at a single location in the OWFA. The maximum distances (R_{max}) to PTS onset, TTS onset and behavioural response thresholds are shown in Table 6-12.

Modelling of impact piling of OSS pin piles predicted maximum ranges for PTS and TTS of 16km and over 90 km respectively, from pile driving four pin piles with no mitigation; these values substantially decreased for both PTS and TTS to 4.31 and 9.87 with the implementation of a DBBC. The behavioural response range of a single jacket pile with a DBBC was predicted as 2.92 km (Table 6-12). Although the distances for single pin piles were much less, it would be necessary to install four pin piles in a day, and the increased drive time related to this increased the SEL values for this measure. The drive time per pin pile was 3.83 h, and for four pin piles was 15.33 h.

Table 6-12: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of jacket pin piles with no mitigation and with a DBBC in winter

Sound exposure threshold	Rmax distance (km)			
	No mitigation		DBBC	
	Single jacket pile	Four pin piles	Single jacket pile	Four pin piles
PTS onset				
183 dB re 1 µPa².s (SEL24h)	8.06	16	2.72	4.31
TTS onset				
168 dB re 1 µPa².s (SEL24h)	53.30	>90	7.21	9.87
Behavioural response				
160 dB re 1 µPa (SPL) (unweighted)	8.62	N/A	2.92	N/A

6.2.3 Impact piling - Animal movement (Animat) modelling for monopiles

Animat modelling was conducted for pygmy blue whales, southern right whales, humpback whales and minke whales during impact piling of a single monopile at two locations within the OWFA. These species were chosen as they had sufficient demographic and behavioural data to be able to perform the model. The

animat model provided exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) for each of these species (Table 6-13).

Animat modelling predicted pygmy blue whales could experience PTS onset within 0.61 km of impact piling, with a maximum exposure range to TTS and behavioural response of 4.99 km and 6.22 km respectively at the deep (MP1) site. For southern right whales, the animals may experience PTS onset within 1.29 km at the deep site, however, the maximum range to TTS and behavioural response across both sites was 5.18 km and 5.3 km respectively (Table 6-13).

Table 6-13: Exposure ranges ($ER_{95\%}$) in kilometres and the probability of exposure within $ER_{95\%}$ ranges (P_{exp}) to PTS, TTS and behavioural response thresholds for pygmy blue whales, southern right whales and humpback whales to cumulative (multiple strike) noise exposure from pile driving of a single monopile with a DBBC in winter

Species	Sound exposure threshold	Deep (MP1)		Shallow (MP3)	
		$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}
Pygmy blue whale	PTS onset	0.61	58	-	-
	TTS onset	4.99	61	4.29	72
	Behavioural response	6.22	87	6.21	70
Southern right whale	PTS onset	1.29	21	0.60	57
	TTS onset	5.18	56	3.85	66
	Behavioural response	5.10	85	5.30	85
Humpback whale	PTS onset	1.02	29	0.94	41
	TTS onset	5.35	51	3.86	62
	Behavioural response	5.84	89	5.92	76
Minke whale	PTS onset	0.67	67	0.70	77
	TTS onset	5.00	72	3.78	76
	Behavioural response	5.83	87	5.67	83

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

7 SECOND ROUND MODELLING SCOPE, INPUTS AND METHODS (2023-2024)

JASCO performed a second round of underwater noise modelling associated with construction activities for the SOTS OWF (Koessler et al. 2024)

7.1.1 Acoustic modelling scenarios

The underwater noise modelling considered a number of impact piling sources and scenarios, including:

- Monopile WTG foundations (impact piling) - Installation of a single pile at two sites within the OWFA
- Jacket structure OSS foundations (impact piling) - Four pin piles installed at a single site within the OWFA

Modelling scenarios were developed to be representative across different seabed types present in the OWFA and across different times of year (seasons), with a worst-case approach being taken in selection of seabed type and season that allows the greatest propagation of underwater noise.

For each of the impact piling scenarios, the effect of noise abatement system was also modelled. Unmitigated noise levels (i.e. no noise abatement systems) and frequency-dependent attenuation curves for DBBC and HSD systems were modelled.

7.1.1.1 Site selection

As with the first round of modelling (2020-2022), the proposed OWFA used in the noise modelling aligned with the PFLA. Modelling sites were selected to be representative across the full spatial extent of the PFLA to ensure the modelling outputs would be appropriate to infer the extent and intensity of sound propagation at different locations within this area.

Impact piling of monopiles was modelled at two sites within the OWFA: deep south-east corner (MP1 in 42 m water depth) and shallow south-west corner (MP2 in 20 m water depth). A single site was chosen to model OSS jacket foundation installation in 30 m water depth. This water depth was chosen as provided by Wood Thilsted as the maximum depth an OSS could be installed (Table 7-1, Figure 7-1).

The MP1 and MP2 sites were the same locations as the MP1 and MP2 sites in the first round of modelling. However, the OSS site was shifted further west and into deeper water than the first-round modelling OSS site (Figure 6-1, Figure 7-1).

Table 7-1: Modelled site locations and site information

Modelling site	Latitude (S)	Longitude (E)	Water depth (m)	Environmental considerations for site selection
MP1 SE Deep	38° 52' 43.9"	146° 53' 54.0"	42	Fish assemblages and whales within and adjacent to the OWF area
MP2 SW Shallow	38° 50' 0.5"	146° 44' 17.1"	20	Closest proximity to SRW reproduction BIA and Corner Inlet Ramsar site
OSS Jacket	38° 50' 50.9"	146° 52' 40.9"	30	Fish assemblages and whales within and adjacent to the OWF area

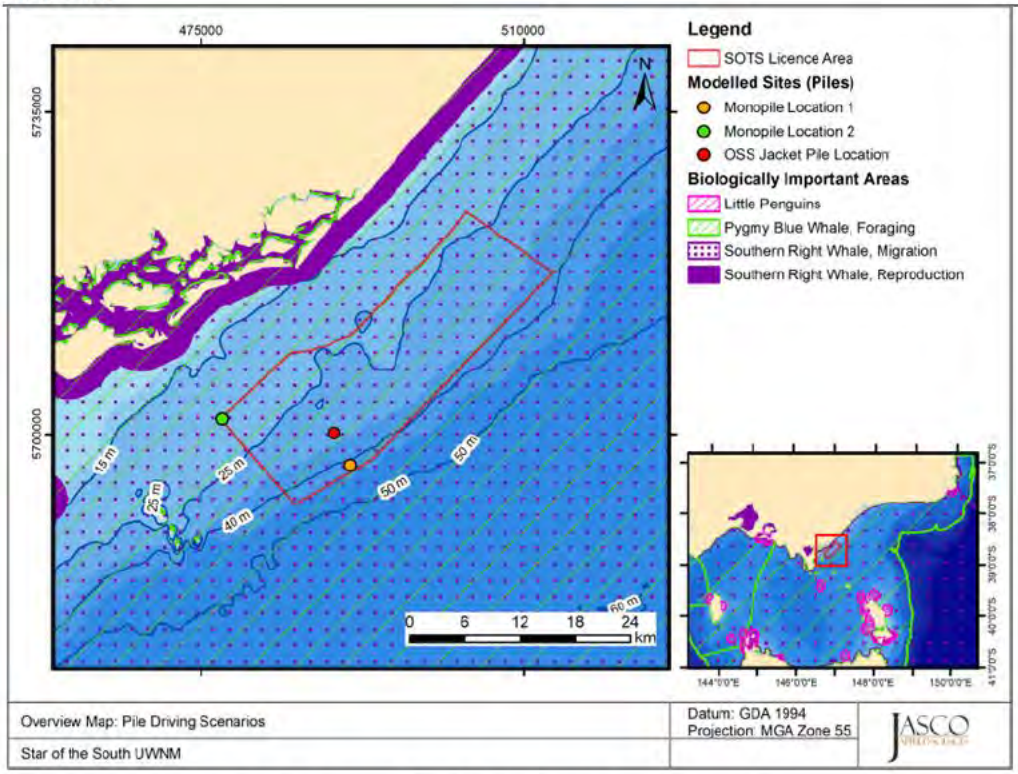


Figure 7-1: Location of sites modelled for impact piling scenarios

7.1.1.2 Pile driving inputs

The pile-driving parameters used in the model are shown in Table 7-2. As for the first-round modelling study the IHC S-4000 impact hammer was selected for monopile installation, however for jacket foundation installation a smaller hammer, the MHU 3500S impact hammer was chosen due to the lower energy required to drive the smaller pin piles.

The hammer penetration/hammering values used in the acoustic modelling study considered the driveability information provided by SOTS project engineers and included the number of strikes and applied hammer energy per metre of the pile drive. The drive was divided into five depth intervals and associated penetration depths to represent the different portions of the drive. Over each modelled depth interval, the upper 90th percentile of applied energy was selected to represent the hammer energy over the depth range (a suitably conservative approach given the limited understanding of the geology and soil mechanics in the area). The resulting penetration depth, strike count and hammer energy used for acoustic modelling are presented in Table 7-3.

Table 7-2: Pile driving parameters

Modelling site	Maximum pile diameter (m)	Pile length (m)	Final penetration depth (m)
MP1 SE Deep	11.8	85.9	36.4
MP2 SW Shallow	11.8	57.8	31.1
OSS Jacket Central	3.25	52	49

*Note: 4 pin piles for jacket foundations to be installed per day

Table 7-3: Impact hammer energy, modelled number of strikes and pile penetration for monopile foundations and jacket pin pile foundations

Site description	Hammer model	Hammer energy (kJ)	Strike count	Sediment penetration (m)	Total number of strikes	Strike rate (bpm)	Installation time
MP1	IHC S-4000	1546.8	952	15.3	5350	36	2.5
		1332.3	1200	20.5			
		1359.1	999	25.8			
		1771.0	1000	31.8			
		2194.4	1200	36.4			
MP2		930.7	550	10.4	4945		2.3
		1168.3	999	15.8			
		1597.2	998	21.3			
		2414.6	1199	26.7			
		2362.1	1200	32.1			
OSS	MHU 3500S	150.5	1449	17.2	8052	35	3.83
		592.1	1598	25.4			
		964.7	1799	33.6			
		1007.6	1607	41.8			
		956.0	1599	50.0			

7.1.2 Sound propagation models

The sound propagation models used were the same for the first round of modelling (refer to 6.1.4). However, to account for the effect of animal movement on noise exposure, animat modelling was also conducted.

7.1.3 Seasonal parameters

The first round of modelling determined that the winter month would be more likely to results in sound travelling further (Section 6.1.10.3), and therefore the physical properties of the water (i.e., temperature, salinity and sound speed) were selected to represent the winter seasonal water column sound speed profile.

7.1.4 Noise abatement systems

The second-round noise modelling replicated the first-round modelling with inclusion of a DBBC and a DBBC in combination with HSD. However, given these systems can be deployed at different distances from the pile (HSD typically located in the immediate proximity of the pile while DBBC are often deployed at a farther range) the modelling study presented results for the DBBC and HSD used in isolation as well as in combination.

7.1.5 Summary of modelling approach (2023-2024)

The modelling approach for the 2023-2024 modelling presented several advancements over the initial noise modelling (2020-2022) (Table 7-4). While both approaches utilised impact piling, the number of sites in the second round (2023-2024) was reduced and concurrent piling was excluded, focusing on two monopile sites. The modelling incorporated site-specific geotechnical data for driveability assessments and refined geo-acoustic properties measurements. Additionally, the hammer size and energy were adjusted for pin piles and he monopile diameter at all monopile sites was set as 11.8m (Table 7-4).

Table 7-4: Summary of modelling approach for modelling in 2023-2024

Parameter	Modelling approach
Installation method	Impact piling only
Sites	• Deep and shallow monopile, deep water OSS – 2 x MP locations – one shallow SW corner (20 m) and deep SE corner (42 m) – OSS 30 m as max depth an OSS could be located – No concurrent piling proposed
Geo-acoustic properties	CMST noise propagation measurements for ground model and site-specific geotech for each location
Driveability	• Engineers advised which driveability using site specific geotechnical data that would be most appropriate for each location • MP1: 23-01 • MP2: 23-13 – shallow site, harder • OSS: 23-04
Hammer size and energy	4000 kj hammer for monopiles, 3500 kj hammer for pin piles
Monopile diameter	3.25 m at OSS, 11.8 m MP at other sites
Mitigations	DBBC and HSD
Noise thresholds for marine mammals	Southall 2019
Animat model	Southern right whale, pygmy blue whale, humpback whale, minke whale

7.2 Modelling results

A summary of the results of the second-round modelling study is included below. Results are shown for low frequency cetaceans only as ranges to exposure thresholds for these species were fundamental in driving most of the decisions to reduce the intensity of noise emissions.

7.2.1 Impact piling of monopiles

7.2.1.1 Marine mammals

Acoustic modelling was conducted for impact piling of a single monopile at two locations within the OWFA with the inclusion of three noise abatement system scenarios including a DBBC, HSD, and HSD with a DBBC. The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds for LF cetaceans with these noise abatement systems are shown in Table 7-5.

The modelled noise ranges indicated that the DBBC was more effective at reducing the predicted onset of PTS and TTS distance ranges for LF cetaceans compared to the HSD (Table 7-5).While the combination of a DBBC with a HSD resulted in smaller predicted onset ranges of PTS, TTS and behavioural response it was only marginally more effective than DBBC alone at both sites (Table 7-5).

Table 7-5: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of a single monopile with no mitigation and with a DBBC, with a HSD, and with a DDBC + HSD in winter

Sound exposure threshold	Rmax distance (km)							
	Deep (MP1)				Shallow (MP2)			
	None	DBBC	HSD	DBBC + HSD	None	DBBC	HSD	DBBC + HSD
PTS onset								
183 dB re 1 µPa².s (SEL_{24h})	16.34	2.22	6.62	1.61	9.50	3.04	4.88	2.36
TTS onset								
168 dB re 1 µPa².s (SEL_{24h})	52.94	8.29	22.05	7.13	50.33	9.87	13.80	9.53
Behavioural response								
160 dB re 1 µPa (SPL) (unweighted)	17.55	5.28	10.51	4.12	10.72	6.52	8.25	6.37
140 dB re 1 µPa (SPL) (weighted)	53.36	7.37	19.03	6.48	56.06	8.09	11.67	7.61

Acoustic modelling was conducted for the impact piling of a single monopile at two locations within the OWFA (refer to Figure 7-1) for marine mammals. The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds are shown in Table 7-6. Contour maps are presented in Figure 7-2 and Figure 7-3.

Modelled noise ranges for LF cetaceans predicted PTS onset at distances of 16.34 km at the deep water site and 9.50 km at the shallow site under no mitigation, while the implementation of a DBBC reduced these distances to 2.22 km and 3.04 km, respectively (Table 7-6, Figure 7-2). TTS onset was observed at a maximum range of 52.94 km in deep waters without mitigation for LF cetaceans, substantially decreasing to 8.29 km with a DBBC. In contrast, the distance ranges for HF cetaceans and otariid seals were notably lower, highlighting the varying sensitivities among these groups. The behavioural response threshold for marine mammals was recorded at a maximum of 6.52 km, with a DBBC (Table 7-6, Figure 7-3). Drive times for monopiles were 2.5 h.

Table 7-6: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine mammals to cumulative (multiple strike) noise exposure from pile driving of a single monopile with no mitigation and with a DBBC in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)			
		No mitigation		DBBC	
		Deep (MP1)	Shallow (MP2)	Deep (MP1)	Shallow (MP2)
PTS onset					
LF cetaceans	183 dB re 1 µPa².s (SEL_{24h})	16.34	9.50	2.22	3.04
HF cetaceans	193 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
Otariid seals	185 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
TTS onset					
LF cetaceans	168 dB re 1 µPa².s (SEL_{24h})	52.94	50.33	8.29	9.87
HF cetaceans	178 dB re 1 µPa².s (SEL_{24h})	0.09	0.06	0.09	0.06
Otariid seals	170 dB re 1 µPa².s (SEL_{24h})	0.20	0.19	0.09	0.09
Behavioural response					
Marine mammals	160 dB re 1 µPa (SPL) (unweighted)	17.55	10.72	5.28	6.52
Southern right whale cow/calf pairs	140 dB re 1 µPa (SPL) (weighted)	53.36	56.06	7.37	8.09

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

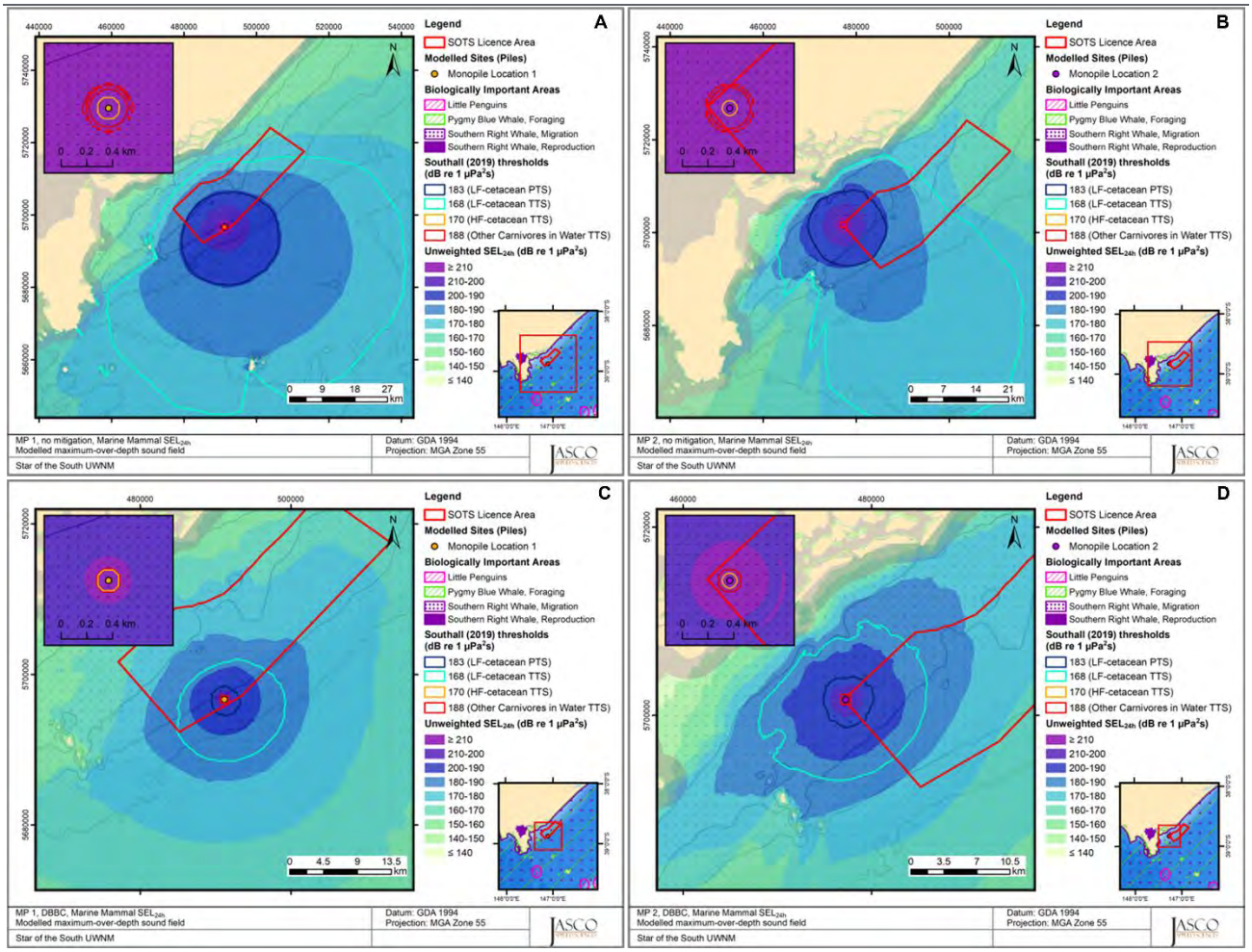


Figure 7-2: Marine mammal SEL_{24h} PTS and TTS threshold contours from cumulative (multiple strike) noise exposure from pile driving of a single monopile with no mitigation at (A) deep (MP1) and (B) shallow (MP2) sites, and with DBBC at (C) deep (MP1) and (D) shallow (MP2) sites

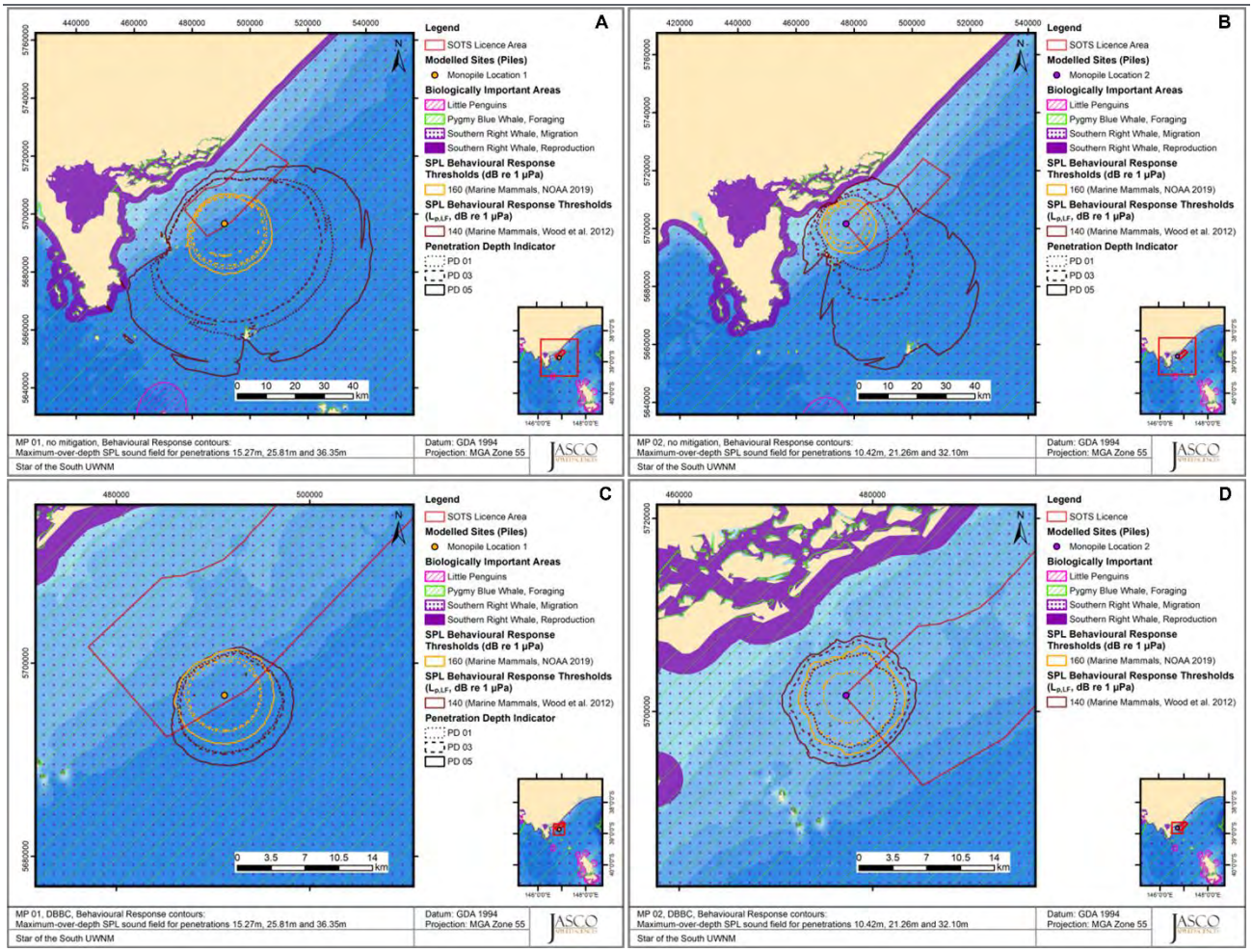


Figure 7-3: Marine mammal SPL behavioural response threshold contours from cumulative (multiple strike) noise exposure from pile driving of a single monopile with no mitigation at (A) deep (MP1) and (B) shallow (MP2) sites, and with DBBC at (C) deep (MP1) and (D) shallow (MP2) sites

7.2.1.2 Marine turtles

Acoustic modelling was conducted for impact piling of a single monopile at two locations within the OWFA (refer to Figure 7-1) for marine turtles. The maximum distances (R_{max}) to PTS onset, TTS onset, behavioural response, and behavioural disturbance thresholds are shown in Table 7-7.

Modelled noise ranges for marine turtles predicted PTS onset at distances of 3.65 km in deep waters and 2.65 km in shallow waters under no mitigation, which were substantially reduced to 0.28 km and 0.51 km, respectively, with the implementation of a DBBC (Table 7-7). TTS onset was observed at a maximum range of 15.60 km without mitigation, decreasing to 2.11 km in deep waters and 3.13 km in shallow waters with DBBC. Additionally, with a DBBC, the behavioural response and behavioural disturbance threshold was recorded at a minimum of 3.00 km and 0.82 km respectively, highlighting the importance of mitigation measures in reducing potential impacts on marine turtles (Table 7-7).

Table 7-7: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine turtles to cumulative (multiple strike) noise exposure from monopile installation using impact piling with no mitigation and with a DBBC in winter

Sound exposure threshold	Rmax distance (km)			
	No mitigation		DBBC	
	Deep (MP1)	Shallow (MP2)	Deep (MP1)	Shallow (MP2)
PTS onset				
204 dB re 1 µPa².s (SEL_{24h})	3.65	2.65	0.28	0.51
TTS onset				
189 dB re 1 µPa².s (SEL_{24h})	15.60	8.88	2.11	3.13
Behavioural response				
166 dB re 1 µPa (SPL) (unweighted)	11.04	7.16	3.00	3.67
Behavioural disturbance				
175 dB re 1 µPa (SPL) (unweighted)	4.76	3.83	0.82	1.32

7.2.1.3 Fish and invertebrates

Acoustic modelling was conducted for impact piling of a single monopile at two locations within the OWFA (refer to Figure 7-1) for fish and invertebrates. The maximum distances (R_{max}) to mortality and PMI, recoverable injury, TTS onset, and startle response thresholds are shown in Table 7-8.

With the inclusion of a DBBC in the modelling, fish and invertebrates could experience mortality and PMI, or a recoverable within a limited distance of under 1 km (Table 7-8). However, fish and invertebrates may experience TTS onset within a minimum of 11.10 km of the impact piling, and squid may experience a startle response within 2.91 km of the impact piling (Table 7-8).

Table 7-8: Maximum predicted horizontal distances (R_{max}) to mortality and PMI, recoverable injury, TTS and startle response thresholds for fish and squid to cumulative (multiple strike) noise exposure from monopile installation using impact piling with no mitigation and with a DBBC in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)			
		No mitigation		DBBC	
		Deep (MP1)	Shallow (MP2)	Deep (MP1)	Shallow (MP2)
Mortality and PMI					
Fish I	219 dB re 1 µPa².s (SEL_{24h})	0.52	0.49	0.09	0.09
Fish II	210 dB re 1 µPa².s (SEL_{24h})	2.36	1.82	0.19	0.44
Fish III	207 dB re 1 µPa².s (SEL_{24h})	3.42	2.53	0.36	0.67
Fish eggs and larvae	210 dB re 1 µPa².s (SEL_{24h})	2.36	1.82	0.19	0.44
Recoverable injury					
Fish I	216 dB re 1 µPa².s (SEL_{24h})	0.92	0.82	0.13	0.13
Fish II, III	203 dB re 1 µPa².s (SEL_{24h})	5.26	3.69	0.78	1.23
TTS onset					
Fish I, II, III	186 dB re 1 µPa².s (SEL_{24h})	23.70	13.11	7.33	11.10
Startle response					
Squid (unweighted)	162 dB re 1 µPa (SPL)	9.18	5.88	1.85	2.91

7.2.1.4 Penguins and diving seabirds

Acoustic modelling was conducted for impact piling of a single monopile at two locations within the OWFA (refer to Figure 7-1) for penguins and diving seabirds. The maximum distances (R_{max}) to PTS onset, TTS onset, behavioural response, and behavioural disturbance thresholds are shown in Table 7-9.

The onset threshold for PTS was not reached, and the predicted TTS onset for penguins and diving seabirds is a minimum of 0.09 km (Table 7-9). With the inclusion of DBBC in the modelling, penguins and diving seabirds could experience onset of a behavioural response reduced to within 3.64 km of piling, outlining a substantial reduction compared to the onset with no mitigation (Table 7-9).

Table 7-9: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for penguins and diving seabirds to cumulative (multiple strike) noise exposure from monopile installation using impact piling with no mitigation and with a DBBC in winter

Sound exposure threshold	R_{max} distance (km)			
	No mitigation		DBBC	
	Deep (MP1)	Shallow (MP2)	Deep (MP1)	Shallow (MP2)
PTS onset				
203 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
TTS onset				
188 dB re 1 µPa².s (SEL_{24h})	0.20	0.19	0.09	0.09
Behavioural response				
120 dB re 1 µPa (SPL) (unweighted)	29.22	49.24	3.64	3.12

7.2.2 Impact piling of OSS pin piles

Acoustic modelling was conducted for impact piling of a single jacket pin pile and four pin piles at a single location in the OWFA (refer to Figure 7-1). The maximum distances (R_{max}) to PTS onset, TTS onset and behavioural response thresholds are shown in Table 7-10. The drive time per pin pile was 3.83 h, and for four pin piles was 15.33 h.

Table 7-10: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of jacket pin piles with no mitigation and with a DBBC in winter

Sound exposure threshold	R_{max} distance (km)			
	No mitigation		DBBC	
	Single jacket pile	Four pin piles	Single jacket pile	Four pin piles
PTS onset				
183 dB re 1 µPa².s (SEL_{24h})	3.61	7.29	0.72	1.77
TTS onset				
168 dB re 1 µPa².s (SEL_{24h})	22.27	43.72	4.72	7.22
Behavioural response				
160 dB re 1 µPa (SPL) (unweighted)	5.01	N/A	1.59	N/A

7.2.3 Impact piling - Animal movement (Animat) modelling for monopiles

The animat model demonstrated a significant reduction in ranges to sound exposure thresholds for LF cetaceans to noise from impact pile driving (Table 7-11).

Table 7-11: Maximum predicted horizontal distances (R_{max}) and exposure ranges ($ER_{95\%}$) in kilometres to PTS, TTS and behavioural response thresholds for low frequency cetaceans to cumulative (multiple strike) noise exposure from pile driving of a single monopile with a DBBC in winter. Results for the animat model use the greatest impact ranges from any species profile

Sound exposure thresholds	Static (R_{max})		Animat ($ER_{95\%}$)	
	Deep (MP1)	Shallow (MP2)	Deep (MP1)	Shallow (MP2)
PTS onset	2.22	3.04	0.56	1.12
TTS onset	8.29	9.87	3.57	5.08
Behavioural response – 160 dB (unweighted)	5.28	6.52	4.67	6.06
Behavioural response southern right whale cow/calf pairs – 140 dB (weighted)	7.37	11.67	6.04	6.09

Animat modelling was conducted for pygmy blue whales, southern right whales, humpback whales and minke whales during impact piling of a single monopile at two locations within the OWFA. These species were chosen as they had sufficient demographic and behavioural data to be able to perform the model. The animat model provided exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) for each of these species (Table 7-12).

Table 7-12: Exposure ranges ($ER_{95\%}$) in kilometres and the probability of exposure within $ER_{95\%}$ ranges (P_{exp}) to PTS, TTS and behavioural response thresholds for pygmy blue whales, southern right whales and humpback whales to cumulative (multiple strike) noise exposure from pile driving of a single monopile with a DBBC in winter

Species	Sound exposure threshold	Deep (MP1)		Shallow (MP2)	
		$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}
Pygmy blue whale	PTS onset	0.26	68	-	-
	TTS onset	3.57	73	5.08	13
	Behavioural response	4.67	88	6.06	72
Southern right whale	PTS onset	0.48	42	0.90	54
	TTS onset	2.83	67	4.01	66
	Behavioural response – 160 dB (unweighted)	3.62	87	5.19	81
	Behavioural response cow/calf pairs – 140 dB (weighted)	6.04	74	6.09	90
Humpback whale	PTS onset	0.56	39	1.12	39
	TTS onset	3.35	60	4.06	71
	Behavioural response	4.20	80	5.52	76
Minke whale	PTS onset	0.11	>99	0.52	73
	TTS onset	2.38	77	3.47	83
	Behavioural response	4.16	92	5.39	83

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

8 THIRD ROUND UNDERWATER NOISE MODELLING (2024-2025)

8.1 Scope, inputs and methods

Prior to the third round of modelling, a feasibility licence was awarded by the Australian Government for the Star of the South OWF in April 2024, and this licence area included a section of deeper water not accounted for in earlier rounds of underwater noise modelling. With the certainty of feasibility licence award, SOTS have further developed the project design, and this is reflected in the scope of the third round of underwater noise modelling study.

The third round of underwater noise modelling study also incorporated learnings from the earlier rounds of modelling summarised above in Sections 6 and 7.

The key focus of this UWN modelling is to examine parameters that are expected to reduce effect ranges. Whilst the main driver for UWN modelling is marine mammals and in particular low frequency cetaceans, the demonstration of reduced noise levels will also form important evidence for the assessment of noise impacts on other fauna groups. The key focus areas for the modelling were:

- Incorporation of the latest SOTS project area specific geotechnical data to improve the accuracy of the noise propagation modelling[1]
- Incorporation of latest monopile diameters across different water depths within the project area
- Application of the latest noise effect criteria for marine mammals, i.e. NMFS 2024

Vibro-piling (continuous noise):

- Quantify reduction in peak noise levels and, therefore, TTS effect ranges for LF cetaceans
- Quantify the behavioural disturbance range for whales, noting the thresholds for continuous noise are lower than for impulsive noise
- Depending on the results of the above, consider application of noise abatement technologies to determine effectiveness at reducing ranges to key thresholds

Installation vessels:

- Determine the effect ranges for marine fauna for realistic vessel source level and thruster power assumptions

The scope and inputs to this round of modelling are set out below.

8.1.1 Site selection

As described above, the FLA for the SOTS OWF had undergone some changes from the original PFLA granted to SOTS in 2019. A 58 km^2 section in the northwest corner of this original Licence Area was removed (as a result of the Commonwealth declaration of the Gippsland Declared Area in December 2022), and a 148 km^2 area was added to the offshore edge (as a result of the SOTS Feasibility Licence granted in April 2024).

8.1.1.1 Monopiles and OSS Jacket

The modelling included three WTG monopile sites, each with a unique monopile specification as set out below in Table 8-1, with the monopile diameters increasing in size with increasing water depth. As a result of this variable monopile size over water depth, and the expected influence of monopile size and water depth

[1] Note that the EIS Guidelines recommend environmental baselines related to substrate and bathymetry to ensure appropriate noise propagation modelling.

on noise intensity, the modelling locations include a cross spectrum of depths from 21 metres at the shallowest to 51.3 metres at the deepest. The monopile diameters assumed in the noise modelling also represent the larger, 19.5 MW wind turbine design and, therefore represent a worst-case scenario in terms of noise emissions. A single site was chosen to model OSS jacket foundation installation in 30 m water depth.

Table 8-1: Modelled site locations and site information

Modelling site	Latitude (S)	Longitude (E)	Water depth (m)	Environmental considerations for site selection
1 NW Shallow	38° 50' 4.50"	146° 44' 28.99"	21.0	Closest proximity to SRW reproduction BIA and Corner Inlet Ramsar site
2 Central Intermediate	38° 49' 8.77"	146° 58' 1.03"	34.7	Fish assemblages and whales within and adjacent to the OWF area
3 SW Deepest	38° 56' 1.14"	146° 51' 36.84"	51.3	Closest location to the Beagle Australian Marine Park
4 OSS Jacket Central	38° 45' 53.06"	146° 59' 17.32"	30	Fish assemblages and whales within and adjacent to the OWF area

When determining the position of the modelling sites within each of the depth ranges, consideration was given to the proximity to noise-sensitive receptors within and adjacent to the OWF area. These positions are shown in Figure 8-1 below. The main drivers of underwater noise are water depth, monopile diameter and the influence of geotechnical conditions on pile driveability/hammer energy. The monopile modelling sites have been selected as representative of shallow, intermediate and deep water depth positions and this will enable extrapolation of results across the relevant water depths of the FLA.

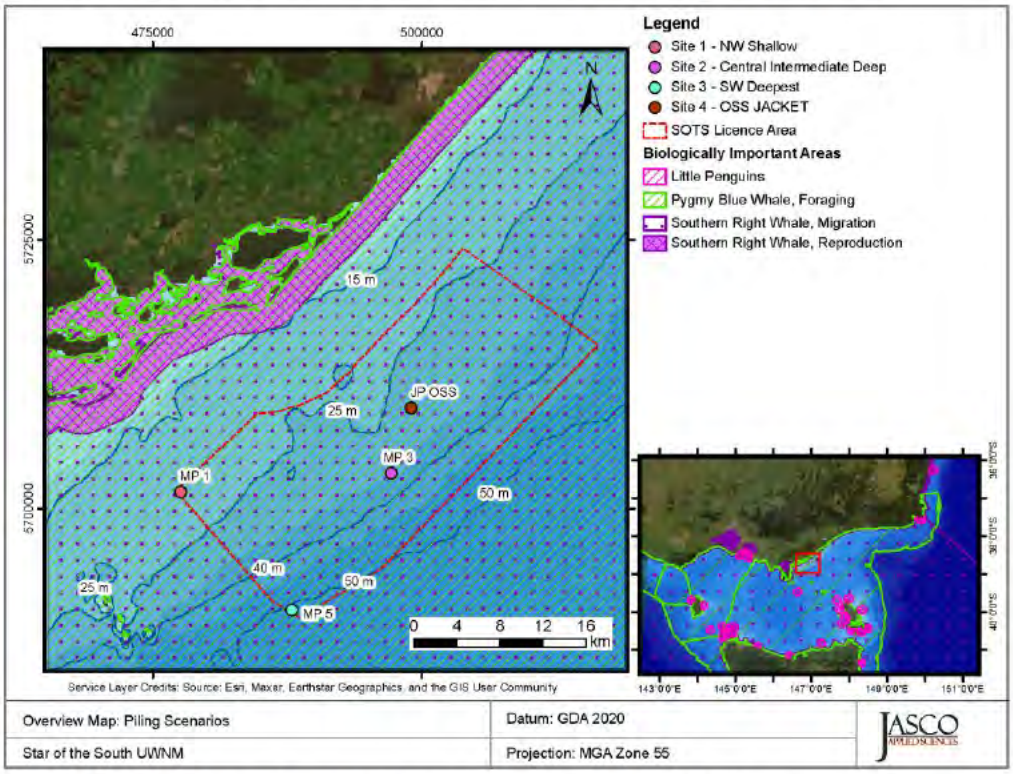


Figure 8-1: Location of sites modelled for vibro-piling scenarios

8.1.1.2 Vessels

Static acoustic modelling of vessels was conducted at twelve sites: ten sites within the OWFA, and two sites in the Offshore Export Cable Area (OECA), (Table 8-2, Figure 8-2). The cable lay vessel (CLV) was modelled along a path laying the export cable within the OECA and laying a section of an array cable within the deepest water depths of the wind farm area.

Table 8-2: Modelled site locations and vessel information

Site	Vessel type	Latitude (S)	Longitude (E)	Water depth (m)
1b	OIV 2	38° 39' 53.21"	147° 3' 37.00"	29.7
2	PSV	38° 39' 58.32"	147° 3' 17.37"	29.4
3b	OIV 2	38° 56' 1.13"	146° 51' 38.48"	51.4
4	PSV	38° 56' 6.20"	146° 51' 18.77"	51.2
5.1	CLV	38° 39' 14.38"	147° 3' 40.57"	27.3
5.2	CLV	38° 37' 48.44"	147° 2' 28.32"	23.8
5.3	CLV	38° 36' 26.59"	147° 1' 19.48"	22.5
6.1	CLV	38° 55' 23.09"	146° 52' 57.51"	50.1
6.2	CLV	38° 53' 41.04"	146° 53' 14.8"	45.9
6.3	CLV	38° 52' 3.8"	146° 53' 31.27"	36.8

Note: OIV: Offshore Installation Vessel, PSV: Platform Support/Supply Vessel, CLV: Cable Lay Vessel

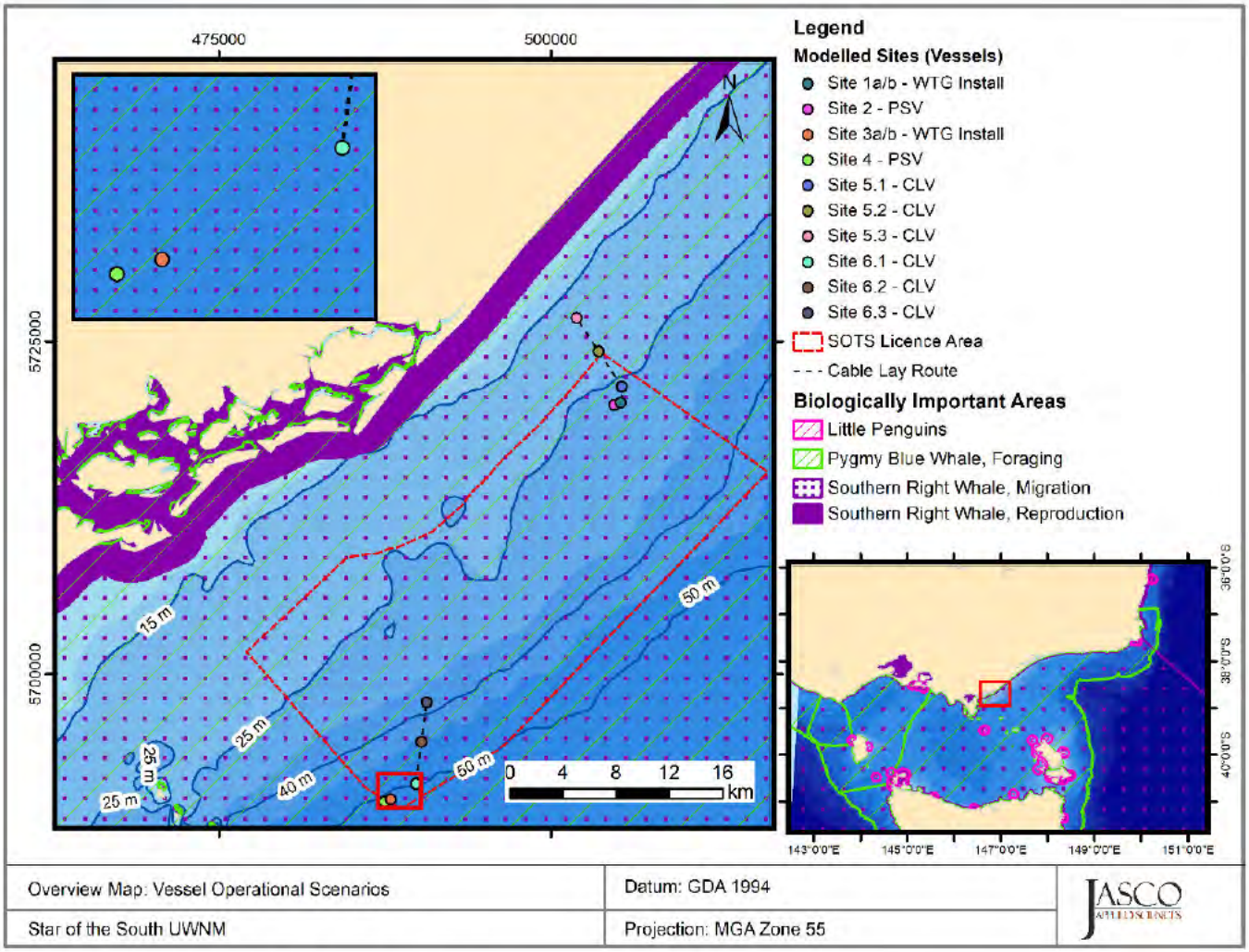


Figure 8-2: Site locations for vessel modelling

8.1.2 Acoustic modelling scenarios

To estimate the extent and magnitude of impacts from underwater noise that may be produced during construction of the Project, SOTS commissioned JASCO to model the sound propagation from vibratory pile

driving and vessel activities. The modelling approach was based on scenarios developed from the project envelope that used realistic parameters. These scenarios have been used to infer the sound propagation across the OWFA at locations that have not been directly modelled. The environmental variables included in the modelling scenarios are water depth, seabed bathymetry, water temperature and proximity to sensitive receptors.

8.1.2.1 Monopile and OSS pin pile scenarios

Foundations for each WTG will be monopiles. The OSS' structures will be installed as either monopile or jacket foundations. A description of the vibro-piling modelling scenarios is outlined in Table 8-3.

Table 8-3: Description of vibro-piling modelling scenarios

Site	Monopile diameter (m)	Monopile length (m)	Hammer vibration frequency (Hz)	Hammer model	Installation duration p/pile (min)
1*	9.2	50.7	23.3	GIANT4000	433.8
2	11	67.1			22
3*	11.8	98			356.9
4	3.25	52			10.7

*Note: installation duration for sites 1 and 3 are significantly overestimated and will be reduced once the model is re-run with mitigations to overcome pile refusal at hard layers.

8.1.2.2 Vessel scenarios

The Jasco modelling report provides further information on the approach and parameters selected for vessel underwater noise modelling. A worst-case scenario has been adopted for the analysis within the Project Design Envelope (PDE). The modelling assumes a conservative configuration involving a large heavy-loft Offshore Installation Vessel (OIV) (i.e., vessel that is used for pile driving and installs topside components) operating on dynamic positioning, supported by a platform support vessel and a cable lay vessel. As the vessel that may perform both of these activities are generally similar, for modelling purposes the vessel in these two activities was the same. Specifications of the candidate vessel/s selected for this modelling are presented in Table 8-4. Surrogate vessels for source level estimates are described in the JASCO acoustic modelling report (Appendix A).

Table 8-4: Vessel specifications for modelled scenarios

Vessel type*	Vessel name	Length (m)	Draft (m)	Width (m)	Power (MCR*) (kW)	Source depth (m)
OIV	Bokalift-1	216.0	9.0	43.0	26,900	6.0
PSV	VOS Shine	60.0	4.6	15.0	5,010	3.0
CLV	Seaway Phoenix	130.0	6.6	28.0	12,000	4.5

*Note: OIV: offshore installation vessel (same vessel used in the modelling for foundation piling and WTG/OSS installation activities); PSV: platform support/supply vessel; CLV: cable lay vessel; MCR: maximum continuous rating.

For the purposes of the modelling, noise emissions from a vessel on DP constitute a worst-case scenario. Therefore, the vessel that installs piles and the topside components were considered to be under DP. However, it should be noted that the actual vessels selected could include jack-up vessels that do not require DP to hold position, and this would eliminate this noise source.

Two scenarios were considered for the vessel noise assessment, as shown in Table 8-5. For each scenario, modelling was conducted for 24 hours continuous operation.

Table 8-5: Description of vessel modelling scenarios

Scenario number	Sites	Vessel (s)	Description
1b	1b, 2, 5.1, 5.2, 5.3	OIV 2 + PSV + CLV	Intermediate Shallow, OIV 2, PSV, and CLV
2b	3b, 4, 6.1, 6.2, 6.3	OIV 2 + PSV + CLV	Deep, OIV 2, PSV, and CLV

Note: OIV: Offshore Installation Vessel, PSV: Platform Support/Supply Vessel, CLV: Cable Lay Vessel

8.1.3 Vessel source level

The latest modelling exercise utilised a newly available vessel source level from a surrogate vessel that was measured during operations in the Gippsland region (Table 8-6).

The Skandi Feistein is an 87.9 m long platform supply vessel with two stern thrusters, a bow tunnel thruster and a bow azimuth thruster (total installed power of 6,620 kW). Noise emissions from this vessel were measured during offshore operations in the Gippsland region, at a location ~90 km north-east of the SOTS FLA, and the vessel operator provided engineering data on the vessel every 30 minutes to provide context for the noise measurements. Thruster power did not exceed 10% of installed power during the measurement program. During the modelling exercise JASCO scaled up the thruster power to 50% of installed power, representing the maximum safe operational limits for this vessel type. The total installed power was also scaled up to represent the installed thruster power of the representative vessels for the OWF construction campaign.

Due to the absence of available source data—since WTG installation vessels are not typically required to monitor underwater noise—no known direct measurements exist for this vessel type globally. As the project-specific vessel has not yet been selected, a surrogate vessel operating in the same region under similar conditions was used to represent the target vessel. Scaling adjustments were applied to account for potential differences in source levels between the surrogate and installation vessels. Vessel noise modelling was conducted using peer-reviewed literature and Jasco's extensive experience in modelling and measuring underwater noise from offshore development activities.

Table 8-6: Vessel source level and vessel specifications for modelled scenarios

Scenario	Vessels	Surrogate vessel	Source level
1b, 2b	OIV 2 + PSV + CLV	Skandi Feistein	186.2 dB re 1 μPa^2 m^2

8.1.4 Noise abatement systems

Vibro-piling poses challenges in accurately modelling and predicting the efficacy of mitigation systems, particularly in saturated soils due to complexities of soil dynamics and the difficulties associated with simulating the installation process. Consequently, the third round modelling of vibro-piling does not include noise abatement systems.

8.1.5 Geo-acoustic properties of project area

This latest modelling exercise was informed by the results of a comprehensive geotechnical sampling program within the SOTS FLA. These results were analysed to provide an accurate geoacoustic model of the seabed based on particle size distributions, porosity and percentage composition of different sediment types across the site and over depth. This information was not available at the time that earlier modelling was undertaken and should improve the accuracy of received noise level estimates for this round of modelling to inform the EIA.

8.1.6 Seasonal parameters

The modelling results for WTG and OSS installation and vessels are presented for winter only in this report as this represents a worst-case sound speed profile. Refer to Section 6.1.10.3 for a summary of previous modelling results which informed this decision, comparing summer and winter seasons to account for changes in sound speed profile associated with seasonal variations changes in water temperature and salinity.

8.1.7 Summary of modelling approach (2024-2025)

The third-round modelling approach reflects several key advancements (Table 8-7). This round of modelling employed vibro-piling for WTG and OSS installation, and used newly available vessel source level information with realistic thruster power.

Table 8-7: Summary of modelling approach for the third round modelling in 2024-2025

Parameter	Modelling approach
Installation method	Vibro-piling
Sites	• Deep, medium and shallow monopile, central OSS – 3 x MP locations to cover shallow, intermediate and deep water, deep site pushed into deeper water to account for FLA extending further offshore, water depths 21-51 m – Central OSS (29.6 m) – No concurrent piling proposed
Geo-acoustic properties	Site specific geotech data for each monopile/jacket location and to build ground model
Driveability	• The boreholes selected for driveability assessment were chosen as having a median cumulative driving energy in the relevant water depth zone. – MP1: 23-04 – higher cumulative energy than 23-01 – MP2: 23-10 – MP3: 23-22 – relatively harder driving than 23-13 – OSS: 23-04
Hammer size and energy	4000 kj hammer for monopiles, 3500 kj hammer for pin piles
Monopile diameter	3.25 m at OSS, MP 9.2 m shallow, 11 m central, 11.8 m deep
Mitigations	Not possible to model
Noise thresholds for marine mammals	NMFS 2024

8.2 Modelling results

8.2.1 Vibro-piling of monopiles

A summary of the results of the vibratory piling modelling is shown below. Results are shown for all marine fauna receptor groups and for static results only, animat modelling was not undertaken.

8.2.1.1 Marine mammals

Acoustic modelling was conducted for vibro-piling of a single monopile at three locations within the OWFA (see Figure 8-1). The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds for marine mammals are shown in Table 8-8. Contour maps are presented in Figure 8-3.

Modelled noise ranges for LF cetaceans predicted PTS onset at distances of 11.10 km at the shallow water site and 21.10 km at the deep site, with the minimum PTS onset observed at the intermediate site (Table 8-8, Figure 8-3). TTS onset was observed at large ranges for both the deep and shallow sites (83.50 km and 68.70), with the minimum range observed at the intermediate site (Table 8-8, Figure 8-3). The behavioural response threshold for marine mammals was recorded at greater than 90 km for all three sites (Table 8-8, Figure 8-3).

Table 8-8: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine mammals to cumulative (multiple strike) noise exposure from monopile installation using vibro-piling with no mitigation in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)		
		Shallow (MP1)*	Intermediate (MP2)	Deep (MP3)*
PTS onset				
LF cetaceans	197 dB re 1 µPa².s (SEL_{24h})	11.10	5.82	21.10
HF cetaceans	201 dB re 1 µPa².s (SEL_{24h})	0.06	-	0.41
Otariid seals	199 dB re 1 µPa².s (SEL_{24h})	0.04	-	0.23
TTS onset				
LF cetaceans	177 dB re 1 µPa².s (SEL_{24h})	83.50	37.00	68.70
HF cetaceans	181 dB re 1 µPa².s (SEL_{24h})	2.90	0.38	6.45
Otariid seals	179 dB re 1 µPa².s (SEL_{24h})	2.20	0.18	5.00
Behavioural response				
Marine mammals	120 dB re 1 µPa (SPL) (unweighted)	>90	>90	>90

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

*Note: installation duration for sites 1 and 3 are significantly overestimated and consequently distances to impact ranges are also overestimated. These will be reduced once the model is re-run with mitigations to overcome pile refusal at hard layers.

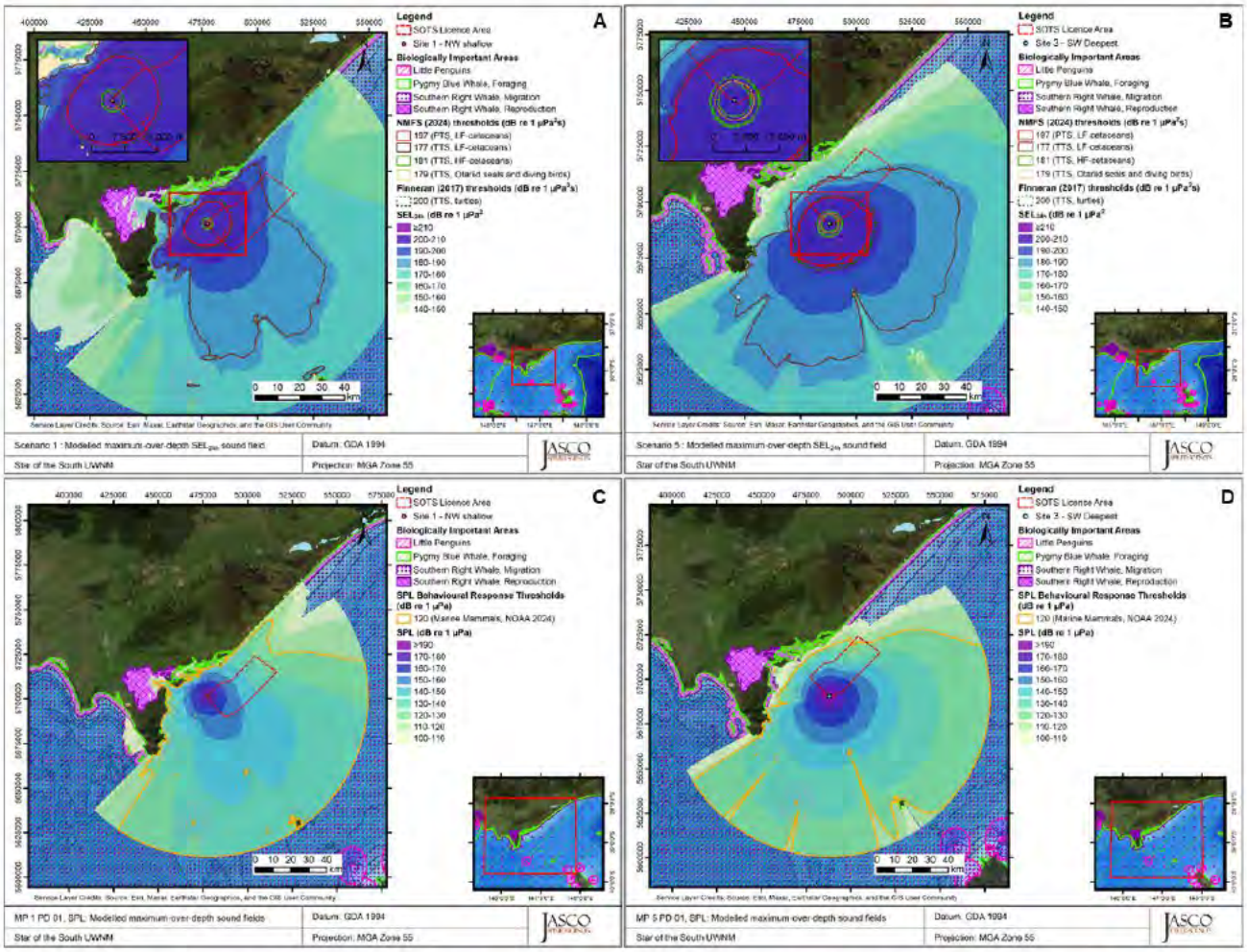


Figure 8-3: Marine mammal SEL_{24h} PTS and TTS threshold contours from cumulative (multiple strike) noise exposure from monopile installation using vibro-piling at (A) shallow (MP1) and (B) deep (MP3) sites, and marine mammal SPL behavioural response threshold contours from cumulative (multiple

strike) noise exposure from monopile installation using vibro-piling at (C) shallow (MP1) and (D) deep (MP3) sites

8.2.1.2 Marine turtles

Acoustic modelling was conducted for vibro-piling of a single monopile at three locations within the OWFA (Table 8-2). The maximum distances (Rmax) to PTS onset and TTS onset thresholds for marine turtles are shown in Table 8-9.

Modelled noise ranges for marine turtles predicted PTS onset at a maximum distance of 17.30 km in deep waters, and a minimum of 3.51 km at the intermediate site (Table 8-9). TTS onset was observed at a distance of 83.20 km at the shallow water site, reducing by approximately 20 km at the deep site, with the minimum TTS onset range of 25.50 km occurring at the intermediate site (Table 8-9).

Table 8-9: Maximum predicted horizontal distances (R_{max}) to PTS and TTS onset thresholds for marine turtles to cumulative (multiple strike) noise exposure from monopile installation using vibro-piling with no mitigation in winter

Sound exposure threshold	R_{max} distance (km)		
	Shallow (MP1)*	Intermediate (MP2)	Deep (MP3)*
PTS onset			
198 dB re 1 µPa².s (SEL_{24h})	7.25	3.51	17.30
TTS onset			
178 dB re 1 µPa².s (SEL_{24h})	83.20	25.50	64.40

*Note: installation duration for sites 1 and 3 are significantly overestimated and consequently distances to impact ranges are also overestimated. These will be reduced once the model is re-run with mitigations to overcome pile refusal at hard layers.

8.2.1.3 Fish and invertebrates

Acoustic modelling was conducted for vibro-piling of a single monopile at three locations within the OWFA (see Table 8-2). The maximum distances (Rmax) to recoverable injury and TTS onset thresholds fish and invertebrates are shown in Table 8-10.

With the implementation of vibro-piling, fish and invertebrates could experience a recoverable injury within a maximum distance of 14.53 km at the intermediate site, and within a minimum distance of 8.75 km at the shallow site (Table 8-10). Further, fish and invertebrates may experience TTS onset within a minimum of 19.60 km of the vibro-piling (Table 8-10).

Table 8-10: Maximum predicted horizontal distances (R_{max}) to mortality and PMI, recoverable injury, TTS and startle response thresholds for fish and squid to cumulative (multiple strike) noise exposure from monopile installation using vibro-piling with no mitigation in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)		
		Shallow (MP1)*	Intermediate (MP2)	Deep (MP3)*
Recoverable injury				
Fish III	170 dB re 1 µPa².s (SEL_{24h})	8.75	14.53	10.10
TTS onset				
Fish III	158 dB re 1 µPa².s (SEL_{24h})	19.60	45.20	22.33

*Note: installation duration for sites 1 and 3 are significantly overestimated and consequently distances to impact ranges are also overestimated. These will be reduced once the model is re-run with mitigations to overcome pile refusal at hard layers.

8.2.1.4 Diving seabirds and penguins

Acoustic modelling was conducted for vibro-piling of a single monopile at three locations within the OWFA (see Table 8-2). The maximum distances (Rmax) to PTS onset, and TTS onset thresholds for diving seabirds and penguins are shown in Table 8-11.

With the implementation of vibro-piling, the predicted PTS and TTS onset for diving seabirds and penguins is 230 metre and 40 metres at the deep and shallow water sites respectively (Table 8-11). However, diving

seabirds and penguins could experience onset of TTS at a maximum distance of 5.00 km at the deep water site (Table 8-11).

Table 8-11: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for penguins and diving seabirds to cumulative (multiple strike) noise exposure from monopile installation using vibro-piling with no mitigation in winter

Sound exposure threshold	R_{max} distance (km)		
	Shallow (MP1)*	Intermediate (MP2)	Deep (MP3)*
PTS onset			
219 dB re 1 µPa².s (SEL_{24h})	0.04	-	0.23
TTS onset			
199 dB re 1 µPa².s (SEL_{24h})	2.20	0.18	5.00

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

*Note: installation duration for sites 1 and 3 are significantly overestimated and consequently distances to impact ranges are also overestimated. These will be reduced once the model is re-run with mitigations to overcome pile refusal at hard layers.

8.2.2 Vibro-piling of OSS pin piles

8.2.2.1 Marine mammals

Acoustic modelling was conducted for vibro-piling of a single jacket pin pile and four pin piles at a single location in the OWFA (see Figure 8-1). The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds for marine mammals are shown in Table 8-16.

Modelled noise ranges for LF cetaceans predicted maximum ranges for PTS and TTS onset of 3.01 km and 24.5 km, respectively from vibratory pile driving of four pin piles with no mitigation. The behavioural response range for a single jacket pile was greater than 90 km (Table 8-16).

Table 8-12: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine mammals to cumulative (multiple strike) noise exposure from vibratory pile driving of jacket pin piles with no mitigation in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)	
		Single jacket pile	Four pin piles
PTS onset			
LF cetaceans	197 dB re 1 µPa².s (SEL_{24h})	1.11	3.01
HF cetaceans	201 dB re 1 µPa².s (SEL_{24h})	-	-
Otariid seals	199 dB re 1 µPa².s (SEL_{24h})	-	-
TTS onset			
LF cetaceans	177 dB re 1 µPa².s (SEL_{24h})	13.20	24.50
HF cetaceans	181 dB re 1 µPa².s (SEL_{24h})	0.05	0.11
Otariid seals	179 dB re 1 µPa².s (SEL_{24h})	-	0.07
Behavioural response			
Marine mammals (unweighted)	120 dB re 1 µPa (SPL)	>90	N/A

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

8.2.2.2 Marine turtles

Acoustic modelling was conducted for vibro-piling of a single jacket pin pile and four pin piles at a single location in the OWFA (see Figure 8-1). The maximum distances (R_{max}) to PTS and TTS onset are shown in Table 8-17.

Modelled noise ranges for marine turtles predicted PTS onset at a maximum distance of 1.21 km and TTS onset at a distance of 13.10 km, from vibratory pile driving of four pin piles with no mitigation (Table 8-13).

Table 8-13: Maximum predicted horizontal distances (R_{max}) to PTS and TTS onset thresholds for marine turtles to cumulative (multiple strike) noise exposure from vibratory pile driving of jacket pin piles with no mitigation in winter

Sound exposure threshold	R_{max} distance (km)	
	Single jacket pile	Four pin piles
PTS onset		
198 dB re 1 µPa².s (SEL_{24h})	0.38	1.21
TTS onset		
178 dB re 1 µPa².s (SEL_{24h})	7.26	13.10

8.2.2.3 Fish and invertebrates

Acoustic modelling was conducted for vibro-piling of a single jacket pin pile at a single location in the OWFA (see Table 8-2). The maximum distances (R_{max}) to recoverable injury and TTS onset thresholds fish and invertebrates are shown in Table 8-18.

During vibro-piling, fish and invertebrates could experience a recoverable injury within a maximum distance of 11.60 km, and TTS onset at a maximum distance of 34.10 km (Table 8-18).

Table 8-14: Maximum predicted horizontal distances (R_{max}) to mortality and PMI, recoverable injury, TTS and startle response thresholds for fish and squid to single strike noise exposure from vibratory pile driving of a single jacket pin pile with no mitigation in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)
Recoverable injury		
Fish III	170 dB re 1 µPa².s (SEL_{24h})	11.60
TTS onset		
Fish III	158 dB re 1 µPa².s (SEL_{24h})	34.10

8.2.2.4 Diving seabirds and penguins

Acoustic modelling was conducted for vibro-piling of a single jacket pin pile and four pin piles at a single location in the OWFA (see Table 8-2). The maximum distances (R_{max}) to PTS onset, and TTS onset thresholds for diving seabirds and penguins are shown in Table 8-19.

Modelled noise ranges predicted that PTS onset would not be reached, and TTS onset could occur at a maximum distance of 70 m during vibratory pile driving of four pin piles with no mitigation (Table 8-15).

Table 8-15: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for penguins and diving seabirds to cumulative (multiple strike) noise exposure from vibratory pile driving of jacket pin piles with no mitigation in winter

Sound exposure threshold	R_{max} distance (km)	
	Single jacket pile	Four pin piles
PTS onset		
219 dB re 1 µPa².s (SEL_{24h})	-	-
TTS onset		
199 dB re 1 µPa².s (SEL_{24h})	-	0.07

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

8.2.3 Vessel operations – static model

A summary of the results of the vessel modelling is shown below. Results are shown for all marine fauna receptor groups for static and animat modelling.

8.2.3.1 Marine mammals

Acoustic modelling was conducted for vessel activities during two realistic scenarios; one shallow and one deep (refer to Section 8.1.2.2). The maximum distances (R_{max}) to PTS onset, TTS onset and behavioural response thresholds are shown in Table 8-16. Sound field maps are presented in Figure 8-4 and Figure 8-5.

Modelled noise ranges for LF cetaceans predicted PTS onset at distances of 70 metres at the deep water site and 80 metres at the intermediate site. TTS onset was observed at a maximum range of 9.16 kilometres in intermediate waters for LF cetaceans, decreasing to 6.35 kilometres at the deep water site (Table 8-16, Figure 8-4). Similarly, the ranges for HF cetaceans and otariid seals to TTS onset were lower in deep water. The behavioural response threshold for marine mammals was recorded at a maximum of 15.6 kilometres in intermediate water and 12 kilometres in deep water (Table 8-16, Figure 8-5).

Table 8-16: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine mammals to vessel noise in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)	
		Scenario 1 WTG MP Intermediate	Scenario 2 WTG MP Deep
PTS onset			
LF cetaceans	197 dB re 1 µPa².s (SEL_{24h})	0.08	0.07
HF cetaceans	201 dB re 1 µPa².s (SEL_{24h})	-	0.02
Otariid seals	199 dB re 1 µPa².s (SEL_{24h})	-	0.02
TTS onset			
LF cetaceans	177 dB re 1 µPa².s (SEL_{24h})	9.16	6.35
HF cetaceans	181 dB re 1 µPa².s (SEL_{24h})	0.16	0.10
Otariid seals	179 dB re 1 µPa².s (SEL_{24h})	0.14	0.09
Behavioural			
Mammals	120 dB re 1 µPa (SPL) (unweighted)	15.6	12.0

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

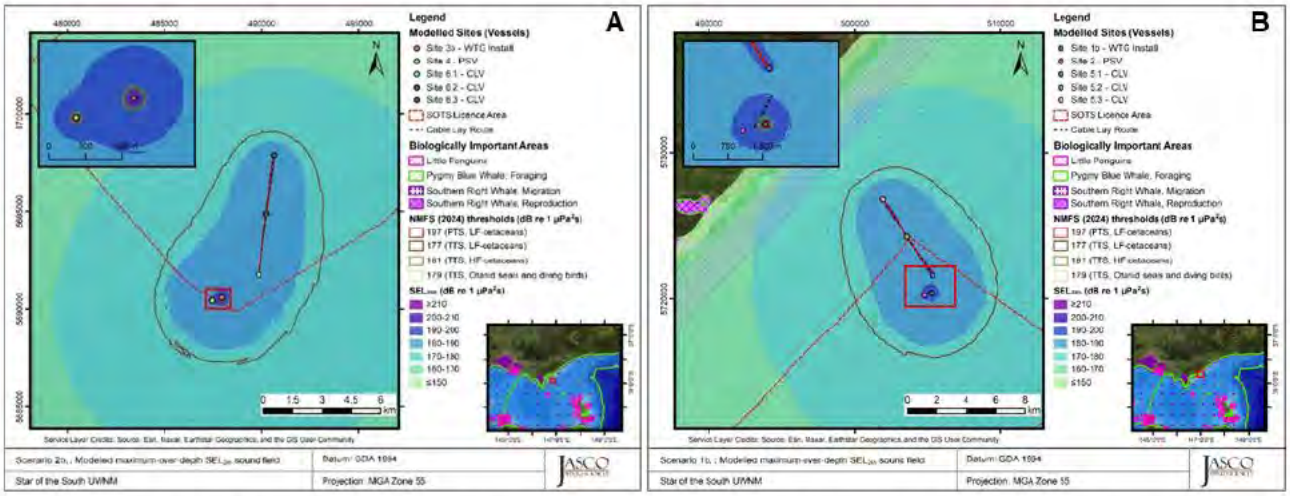


Figure 8-4: Marine mammal SEL_{24h} PTS and TTS threshold contours from noise exposure from vessel operations at (A) deep (scenario 2b) and (B) intermediate (scenario 1b) sites

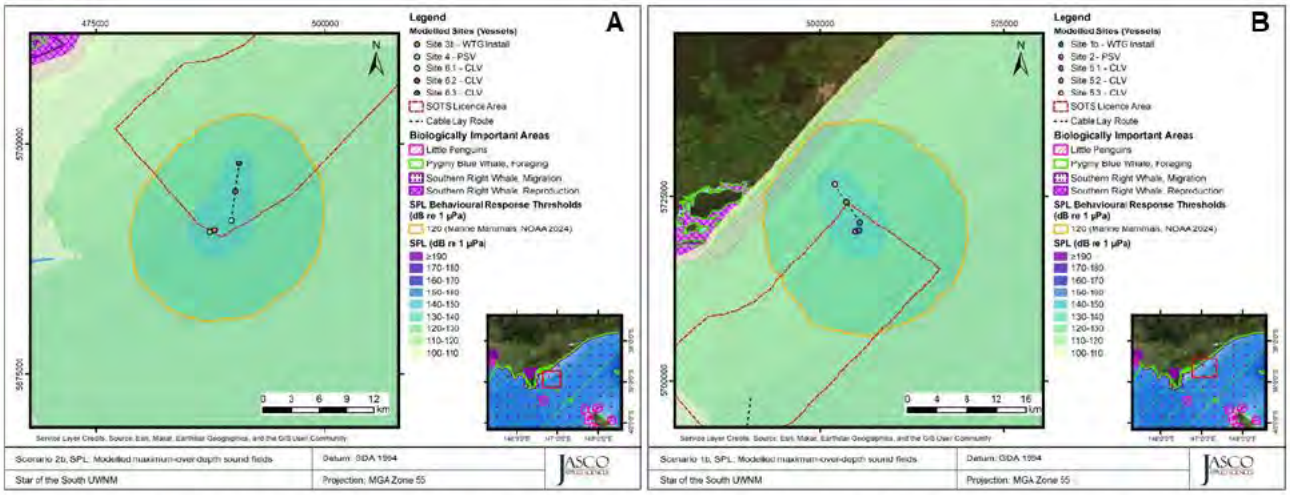


Figure 8-5: Marine mammal SPL behavioural response threshold contours from noise exposure from vessel operations at (A) deep (scenario 2b) and (B) intermediate (scenario 1b) sites

8.2.3.2 Marine turtles

Acoustic modelling was conducted for vessel activities during two realistic scenarios; one shallow and one deep (refer to Section 8.1.2.2). The maximum distances (R_{max}) to PTS onset, TTS onset and behavioural response thresholds for marine turtles are shown in Table 8-17.

Modelled noise ranges predicted PTS and TTS onset for marine turtles at maximum distances of 40 metres in deep and intermediate waters, and 7.05 km in intermediate waters respectively (Table 8-17).

Table 8-17: Maximum predicted horizontal distances (R_{max}) to PTS and TTS onset thresholds for marine turtles to vessel noise in winter

Sound exposure threshold	R_{max} distance (km)	
	Scenario 1 WTG MP Intermediate	Scenario 2 WTG MP Deep
PTS onset		
198 dB re 1 µPa².s (SEL_{24h})	0.04	0.04
TTS onset		
178 dB re 1 µPa².s (SEL_{24h})	7.05	4.80

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

8.2.3.3 Fish and invertebrates

Acoustic modelling was conducted for vessel activities during two realistic scenarios; one shallow and one deep (refer to Section 8.1.2.2). The maximum distances (R_{max}) to recoverable injury and TTS onset thresholds for fish and invertebrates are shown in Table 8-18.

For fish with a swim bladder involved in hearing, modelled noise ranges predicted TTS and recoverable injury within 20 metres (Table 8-18).

Table 8-18: Maximum predicted horizontal distances (R_{max}) to TTS onset and recoverable injury thresholds for fish to vessel noise in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)	
		Scenario 1 WTG MP Intermediate	Scenario 2 WTG MP Deep
Recoverable injury			
Fish III**	170 dB re 1 µPa (SPL 48h)	-	0.02
TTS onset			
Fish III**	158 dB re 1 µPa (SPL 12h)	0.02	0.02

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

8.2.3.4 Diving seabirds and penguins

Acoustic modelling was conducted for vessel activities during two realistic scenarios; one shallow and one deep (refer to Section 8.1.2.2). The maximum distances (R_{max}) to PTS onset, and TTS onset thresholds for diving seabirds and penguins are shown in Table 8-19.

Modelled noise ranges predicted diving seabirds and penguins could experience PTS onset within 20 metres, and TTS onset could occur within 90 metres in deep waters and 140 metres in intermediate waters (Table 8-19).

Table 8-19: Maximum predicted horizontal distances (R_{max}) to PTS and TTS onset thresholds for penguins and diving seabirds to vessel noise in winter

Sound exposure threshold	R_{max} distance (km)	
	Scenario 1 WTG MP Intermediate	Scenario 2 WTG MP Deep
PTS onset		
199 dB re 1 µPa².s (SEL_{24h})	-	0.02
TTS onset		
179 dB re 1 µPa².s (SEL_{24h})	0.14	0.09

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

Acoustic modelling for crustacean, benthic invertebrate, and human diver effect thresholds from vessel noise was not conducted, as there are no regulatory thresholds or criteria established for continuous noise sources for these receptors.

8.2.4 Vessel operations - Animal movement (Animat) modelling

The animat model demonstrated a significant reduction in ranges to sound exposure thresholds for LF cetaceans to noise from vessel operations (Table 8-20). Modelled noise ranges predicted PTS onset threshold was not reached for all modelled species, and TTS onset could occur at a maximum distance of 1.09 km in intermediate water and 1.00 km in deep water for the southern right whale (Table 8-20). The behavioural response threshold was recorded at a maximum of 11.6 kilometres in intermediate water for the pygmy blue whale and 10.8 kilometres in intermediate water for the southern right whale (Table 8-20)

Table 8-20: Exposure ranges ($ER_{95\%}$) in kilometres and the probability of exposure within $ER_{95\%}$ ranges (P_{exp}) to PTS, TTS and behavioural response (120 dB re1 µPa) thresholds for pygmy blue whales, southern right whales and humpback whales to vessel noise in winter

Species	Sound exposure threshold	Scenario 1 WTG MP Intermediate		Scenario 2 WTG MP Deep	
		$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}
Pygmy blue whale	PTS onset	-	-	-	-
	TTS onset	0.21	35	0.15	10
	Behavioural response	11.6	99	7.79	86
Southern right whale	PTS onset	-	-	-	-
	TTS onset	1.09	13	1.00	13
	Behavioural response	10.8	89	7.87	86
Humpback whale	PTS onset	-	-	-	-
	TTS onset	0.77	16	0.83	11
	Behavioural response	10.8	90	7.82	87
Minke whale	PTS onset	-	-	-	-
	TTS onset	0.02	98	0.02	85
	Behavioural response	10.8	97	7.20	94

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

9 FOURTH ROUND UNDERWATER NOISE MODELLING (2025)

9.1 Scope, inputs and methods

As outlined during the third round of modelling, a feasibility licence was awarded to the Star of the South OWF in April 2024, which included a section of deeper water not accounted for in earlier rounds of underwater noise modelling. The refinements of the SOTS project design have been reflected in this fourth round of underwater noise modelling.

The key focus areas for the fourth round of underwater noise modelling were:

- Incorporation of the latest SOTS project area specific geotechnical data to improve the accuracy of the noise propagation modelling[2]
- Incorporation of latest monopile diameters across different water depths within the project area
- Application of the latest noise effect criteria for marine mammals, i.e. NMFS 2024
- Application of additional noise abatement technologies to determine effectiveness at reducing ranges to key thresholds

Impact piling:

- Quantify reduction in peak noise levels and, therefore, TTS effect ranges for LF cetaceans
- Quantify the behavioural disturbance range for whales

The scope and inputs to this final modelling are set out below.

9.1.1 Site selection

Impact piling of monopiles was modelled at four sites within the OWFA (Table 9-1). The modelled site locations at NW shallow (MP1), central intermediate (MP2) and SW deepest (MP3) were the same as those modelling for vibro-piling in the round three modelling, with an additional SW deep site (MP4) added. A single site was chosen to model OSS jacket foundation installation in 30 m water depth, as consistent with the round 2 and round 3 modelling (Table 9-1, Figure 9-1).

As included in the round 3 modelling, monopile diameters increased in size with increasing water depth. The monopile diameters assumed in the noise modelling also represent the larger wind turbine design and, therefore represent a worst-case scenario in terms of noise emissions.

[2] Note that the EIS Guidelines recommend environmental baselines related to substrate and bathymetry to ensure appropriate noise propagation modelling.

Table 9-1: Modelled site locations and site information

Modelling site	Latitude (S)	Longitude (E)	Water depth (m)	Environmental considerations for site selection
1 NW Shallow	38° 50' 4.50"	146° 44' 28.99"	21.0	Closest proximity to SRW reproduction BIA and Corner Inlet Ramsar site
2 Central Intermediate	38° 49' 8.77"	146° 58' 1.03"	34.7	Fish assemblages and whales within and adjacent to the OWF area
3 SW Deepest	38° 56' 1.14"	146° 51' 36.84"	51.3	Closest location to the Beagle Australian Marine Park
4 SW Deep	38° 53' 28.14"	146° 55' 44.92"	47.0	Hardest geotechnical data
5 OSS Jacket Central	38° 45' 53.05"	146° 59' 17.32"	29.6	Fish assemblages and whales within and adjacent to the OWF area

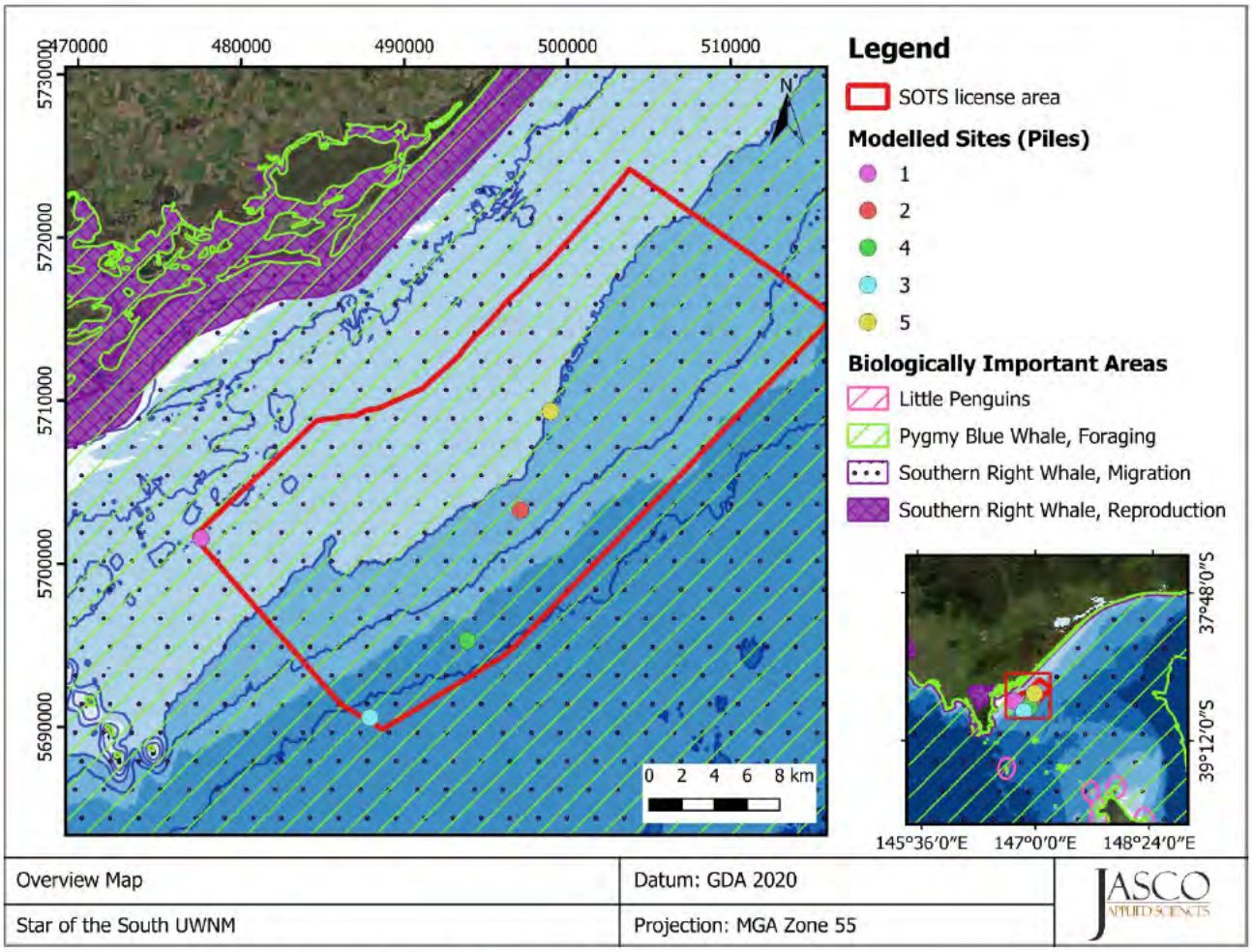


Figure 9-1: Location of sites modelled for impact piling scenarios

9.1.1 Pile driving inputs

The pile-driving parameters used in the fourth-round modelling are shown in Table 9-2. As for the first-round and second round impact pile driving modelling the IHC S-4000 impact hammer was selected for monopile installation. In this instance the same hammer was used to model jacket pin pile installation. This decision was made by the SOTS project engineers as it is not feasible to change hammer during the construction period.

The hammer penetration/hammering values used in the acoustic modelling study considered the driveability information provided by SOTS project engineers and included the number of strikes and applied hammer

energy per metre of the pile drive. The drive was divided into five depth intervals and associated penetration depths to represent the different portions of the drive. Over each modelled depth interval, the upper 90th percentile of applied energy was selected to represent the hammer energy over the depth range (a suitably conservative approach given the limited understanding of the geology and soil mechanics in the area). During this fourth round of modelling, a more refined driveability profile was used that utilised the upper 90th percentile of applied energy at each depth interval. The penetration depth, strike count and hammer energy used for this fourth-round acoustic modelling are presented in Table 9-3.

Table 9-2: Pile driving parameters

Modelling site	Maximum pile diameter (m)	Pile length (m)	Final penetration depth (m)
1 NW Shallow	9.2	50.7	27.8
2 Central Intermediate	11	67.1	29.11
3 SW Deepest	11.8	97.8	36.91
4 SW Deep	11.8	88.5	41.7
5 OSS Jacket Central	3.25	52	50.0

*Note: 4 pin piles for jacket foundations to be installed per day

Table 9-3: Impact hammer energy, modelled number of strikes and pile penetration for monopile foundations and jacket pin pile foundations

Site description	Hammer model	Hammer energy (kJ)	Strike count	Sediment penetration (m)	Total number of strikes	Strike rate (bpm)	Installation time
1	IHC S-4000	500.0	800	12.8	3996	36.0	1.85
		554.3	798	16.5			
		1523.2	800	20.3			
		1969.0	799	24.0			
		2035.7	800	27.8			
2		559.7	799	14.6	3995		1.85
		697.2	799	18.2			
		750.9	600	21.9			
		881.1	800	25.5			
		1178.8	997	29.1			
3		758.8	1397	17.1	5800		2.96
		828.1	1200	23.3			
		1023.6	1200	29.4			
		1332.3	1197	35.6			
		2041.9	1400	41.7			
4		134.2	800	13.0	6393		2.69
		676.2	1199	19.0			
		912.0	1199	24.9			
		1144.0	1205	30.9			
		1304.6	1398	36.9			
OSS		213.0	1400	23.6	6795		3.54
		395.2	1397	30.2			
		501.3	1199	36.8			
		570.7	1399	43.4			
		586.5	1400	50			

9.1.1 Sound propagation models

The sound propagation models used were the same for the previous rounds of modelling (refer to Section 6.1.4). To account for the effect of animal movement on noise exposure, animat modelling was also conducted (refer to Section 6.1.6).

9.1.2 Geo-acoustic properties of project area

As with the third round of modelling, this fourth-round of modelling was informed by the results of a comprehensive geotechnical sampling program within the SOTS FLA. These results were analysed to provide an accurate geoacoustic model of the seabed based on particle size distributions, porosity and percentage composition of different sediment types across the site and over depth. This information was not available and hence not incorporated into previous impact pile driving modelling (round one and two) and should improve the accuracy of received noise level estimates for this final round of modelling to inform the EIA.

9.1.3 Seasonal parameters

The modelling results are presented for winter only in this report as this represents a worst-case sound speed profile. Refer to Section 6.1.10.3 for a summary of previous modelling results which informed this decision.

9.1.4 Noise abatement systems

The second-round noise modelling included two noise abatement systems, a DBBC and HSD. The fourth-round modelling also included MHS, which similar to the HSD, and is deployed at the source, though given the differences in methods it is possible for the HSD and MHS to be used simultaneously. The MHS reduces noise emissions at the source by modifying the way that the hammer interacts with the pile. The MHS is placed directly between the hammer and the pile and acts as a fluid cushioning, elongating the impact of the hammer and lowering the peak force. Other examples of NAS that modify the way that hammers interact with the pile include EQ-Piling and hydrohammer.

Consequently, this round of modelling included a combination of DBBC, HSD and MHS for WTG monopile installation. It is not possible to use a HSD around jacket pin pile structures, and therefore a DBBC and MHS only was modelled for OSS jacket pin pile installation.

9.1.5 Summary of modelling approach (2025)

The fourth round of modelling includes several new advancements not previously included in prior impact pile driving modelling (2020-2024) (Table 9-4). The number of WTG monopile locations was increased from two to four, including a new ‘worst-case’ location with the hardest geotechnical data. As with the round three vibro piling modelling, pile diameter size varied with depth, with the largest pile size used for deeper water. A more refined drivability profile was used for this round that utilised the upper 90th percentile of applied energy at each depth interval. The new NMFS (2024) thresholds and associated frequency weightings for marine mammals were applied, along with the new PTS and TTS onset thresholds for marine turtles to impulsive noise sources in Accomando et al. (2025). Finally, a further NAS, the MHS system, was included in conjunction with a DBBC and HSD.

Table 9-4: Summary of modelling approach for modelling in 2025

Parameter	Modelling approach
Installation method	Impact piling only
Sites	• Deep, intermediate and shallow monopile, central OSS – 4 x MP locations – shallow NW corner, central intermediate and two deep SW corner. Deepest site pushed into deeper water to account for FLA extending further offshore and 'worst-case' hardest geotechnical data site, water depths 21-51 m – OSS 30 m as max depth an OSS could be located – No concurrent piling proposed
Geo-acoustic properties	Site specific geotech data for each monopile/jacket location and to build ground model
Driveability	• The boreholes selected for driveability assessment were chosen as having a median cumulative driving energy in the relevant water depth zone. – MP1: 23-04 – higher cumulative energy than 23-01 – MP2: 23-10 – MP3: T37 – hardest drive – MP4: 23-11 – OSS: 23_08
Hammer size and energy	4000 kj hammer for monopiles and pin piles
Monopile diameter	3.25 m at OSS, MP 9.2 m shallow, 11 m central, 11.8 m x 2 deep
Mitigations	DBBC, HSD and MHS (MP), DBBC and MHS (OSS)
Noise thresholds	NMFS 2024 (marine mammals), Accomando et al. 2025 (marine turtles)
Animat model	Southern right whale, pygmy blue whale, humpback whale, minke whale

9.2 Modelling results

A summary of the results of the fourth-round impact pile driving modelling is shown below. Results are shown for all marine mammal, marine turtle, fish and invertebrate, penguins and diving seabirds, and human divers receptor groups, with animat results shown for LF cetaceans only.

9.2.1 Impact piling of monopiles

9.2.1.1 Marine mammals

Acoustic modelling was conducted for impact pile driving of a single monopile at four locations within the OWFA (see Figure 9-1). The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds for marine mammals are shown in Table 9-5. Contour maps are presented in Figure 9-2.

Modelled noise ranges for LF cetaceans predicted PTS onset at distances of up to 360 m at the deep water sites, 410 m at the intermediate site and 770 m at the shallow site, with the maximum PTS onset observed at the shallowest site (Table 9-5, Figure 9-2). TTS onset was also reached at smaller distances at the deep water sites (3.30 – 3.56 km) and extended to 8.61 km at the shallow water site (Table 9-5, Figure 9-2). The behavioural response threshold for marine mammals was between ~2 km and 6 km with smaller ranges at deeper sites.

Table 9-5: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine mammals to cumulative (multiple strike) noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)			
		Shallow (MP1)	Intermediate (MP2)	Deepest (MP3)	Deep (MP4)
PTS onset					
LF cetaceans	183 dB re 1 µPa².s (SEL_{24h})	0.77	0.41	0.18	0.36
HF cetaceans	193 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
Otariid seals	185 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
TTS onset					
LF cetaceans	168 dB re 1 µPa².s (SEL_{24h})	8.61	5.48	3.30	3.56
HF cetaceans	178 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
Otariid seals	170 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
Behavioural response					
Marine mammals	160 dB re 1 µPa (SPL) (unweighted)	5.64	5.18	2.37	2.72
Southern right whale female and calf pair	140 dB re 1 µPa (SPL) (weighted)	7.17	6.37	3.21	3.17

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

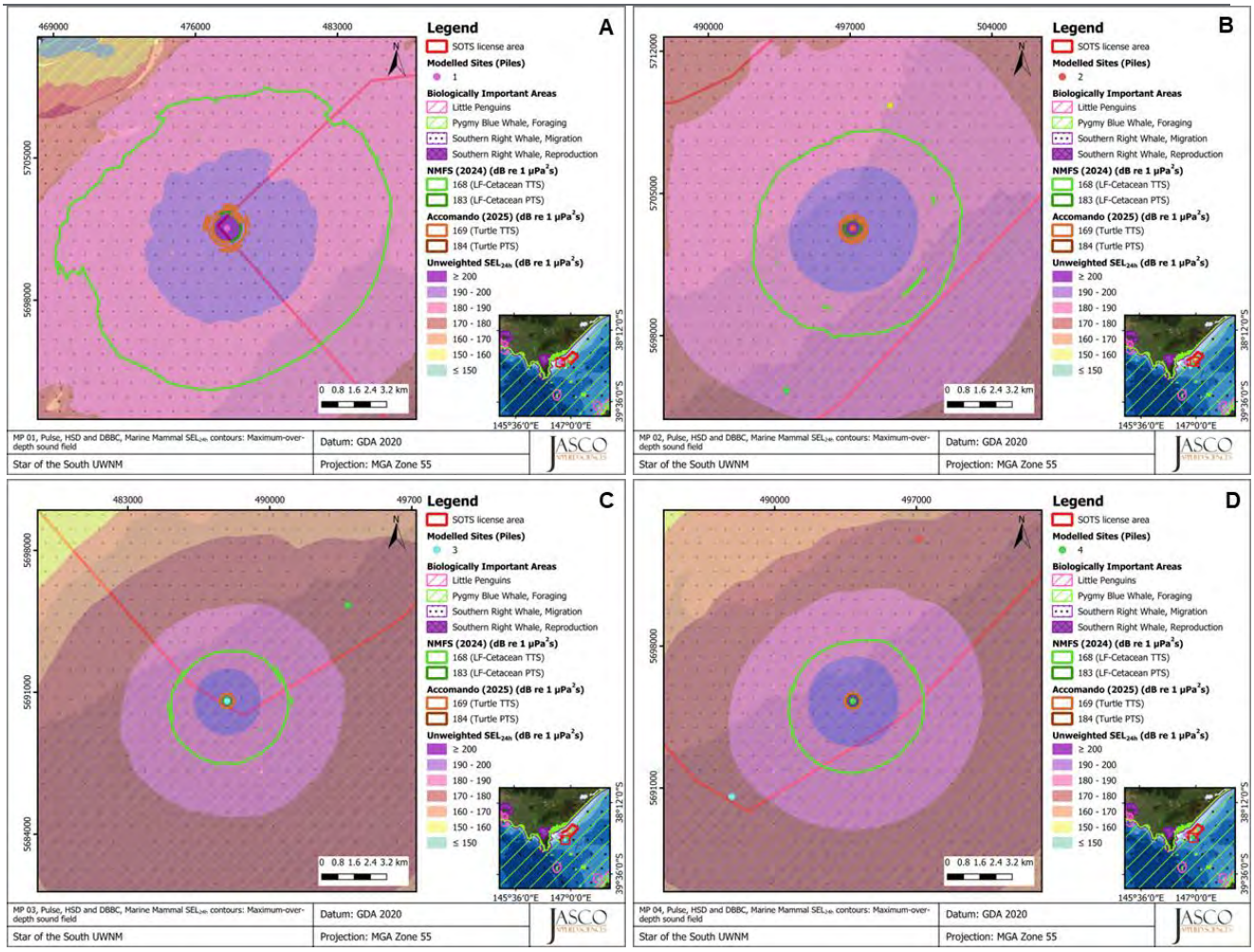


Figure 9-2: LF cetacean SEL_{24h} PTS and TTS threshold contours from cumulative (multiple strike) noise exposure from impact pile driving of a single monopile at (A) shallow (MP1), (B) intermediate (MP2), (C) deepest (MP3) and (D) deep (MP4) sites with DBBC, HSD and MHS

9.2.1.2 Marine turtles

Acoustic modelling was conducted for impact pile driving of a single monopile at four locations within the OWFA (Table 9-1). The maximum distances (R_{max}) to PTS onset, and TTS onset thresholds for marine turtles are shown in Table 9-6.

Modelled noise ranges for marine turtles predicted PTS onset at a maximum distance of 90 m in all water depths (Table 9-6). TTS onset was observed out to a distance of 390 m in deep water, increasing to 750 m at the intermediate site, with the largest range to TTS onset of 1.14 km occurring at the shallow (Table 9-6).

Table 9-6: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine turtles to cumulative (multiple strike) noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS in winter

Sound exposure threshold	R_{max} distance (km)			
	Shallow (MP1)	Intermediate (MP2)	Deepest (MP3)	Deep (MP4)
PTS onset				
184 dB re 1 µPa².s (SEL_{24h})	0.09	0.09	0.09	0.09
TTS onset				
169 dB re 1 µPa².s (SEL_{24h})	1.14	0.75	0.36	0.39
Behavioural response				
166 dB re 1 µPa (SPL) (unweighted)	2.95	2.35	1.12	1.34
Behavioural disturbance				
175 dB re 1 µPa (SPL) (unweighted)	0.62	0.46	0.17	0.28

9.2.1.3 Fish and invertebrates

Acoustic modelling was conducted for impact piling of a single monopile at four locations within the OWFA (Table 9-1). The maximum distances (R_{max}) to mortality and PMI, recoverable injury, TTS onset, and startle response thresholds are shown in Table 9-7.

Fish and invertebrates could experience mortality and PMI, or a recoverable within a limited distance of under a few hundred metres (Table 9-7). However, fish and invertebrates may experience TTS onset within a minimum of 3.05 km of the impact piling in deep water, extending to 7.82 kilometres in shallow water (Table 9-7). Squid may experience a startle response within a maximum distance of 1.83 km at the shallow water site.

Table 9-7: Maximum predicted horizontal distances (R_{max}) to mortality and PMI, recoverable injury, TTS and startle response thresholds for fish and squid to cumulative (multiple strike) noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)			
		Shallow (MP1)	Intermediate (MP2)	Deepest (MP3)	Deep (MP4)
Mortality and PMI					
Fish I	219 dB re 1 µPa².s (SEL_{24h})	0.03	0.02	0.03	0.03
Fish II	210 dB re 1 µPa².s (SEL_{24h})	0.09	0.09	0.09	0.09
Fish III	207 dB re 1 µPa².s (SEL_{24h})	0.13	0.13	0.11	0.13
Fish eggs and larvae	210 dB re 1 µPa².s (SEL_{24h})	0.09	0.09	0.09	0.09
Recoverable injury					
Fish I	216 dB re 1 µPa².s (SEL_{24h})	0.05	0.04	0.05	0.06
Fish II, III	203 dB re 1 µPa².s (SEL_{24h})	0.35	0.30	0.13	0.24
TTS onset					
Fish I, II, III	186 dB re 1 µPa².s (SEL_{24h})	7.82	5.63	3.05	3.74
PK–PK threshold					
Crustaceans*	202 dB re 1 µPa (L_{pkpk})	0.95	0.83	0.89	>1.00
Peak acceleration magnitude					
Benthic invertebrates*	35.75 (m/s^2)	-	-	-	-
Startle response					
Squid (unweighted)	162 dB re 1 µPa (SPL)	1.83	1.11	0.47	0.62

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

The maximum modelling range for crustacean PK-PK threshold is 1 km

* Denotes unmitigated results without NAS, for which it is not possible to model

9.2.1.4 Penguins and diving seabirds

Acoustic modelling was conducted for impact piling of a single monopile at four locations within the OWFA (Table 9-1). The maximum distances (R_{max}) to PTS and TTS onset thresholds are shown in Table 9-8.

With the implementation of DBBC, HSD, and MHS noise abatement systems, the threshold for PTS and TTS onset for diving seabirds and penguins was not reached across all four locations (Table 9-8).

Table 9-8: Maximum predicted horizontal distances (R_{max}) to PTS, TTS, and behavioural response thresholds for penguins and diving seabirds to cumulative (multiple strike) noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS in winter

Sound exposure threshold	R_{max} distance (km)			
	Shallow (MP1)	Intermediate (MP2)	Deepest (MP3)	Deep (MP4)
PTS onset				
185 dB re 1 µPa².s (SEL_{24h})	-	-	-	-
TTS onset				
170 dB re 1 µPa².s (SEL_{24h})	-	-	-	-

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

9.2.1.5 Human diver health assessment

Acoustic modelling was conducted for impact piling of a single monopile at four locations within the OWFA (Table 9-1). The maximum distances (R_{max}) to the human health assessment threshold are shown in Table 9-9.

Human divers could experience onset of the human health assessment threshold within a maximum distance of 20.3 km of the impact piling at the shallow water site, and a minimum of 8.64 km at the deepest site (Table 9-9).

Table 9-9: Maximum predicted distance (R_{max}) to the human health assessment threshold for human divers to cumulative (multiple strike) noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS in winter

Sound exposure threshold	R_{max} distance (km)			
	Shallow (MP1)	Intermediate (MP2)	Deepest (MP3)	Deep (MP4)
145 dB re 1 µPa (SPL)	20.3	17.3	8.64	8.93

9.2.1 Impact piling of OSS pin piles

9.2.1.1 Marine mammals

Acoustic modelling was conducted for impact pile driving of a single jacket pin pile and four pin piles at a single location in the OWFA with DBBC and MHS (see Figure 9-1). The maximum distances (R_{max}) to PTS onset, TTS onset, and behavioural response thresholds for marine mammals are shown in Table 9-10.

Modelling of impact piling of OSS pin piles predicted maximum ranges for PTS and TTS of 4.3 km and 11.4 km respectively, from pile driving four pin piles with a DBBC and MHS system applied. The behavioural response range of a single jacket pile was predicted as 2.60 km (Table 9-10). Although the distances for single pin piles were much less, it would be necessary to install four pin piles in a day, and the increased drive time related to this increased the SEL values for this measure. The drive time per pin pile was 3.54 h, and for four pin piles was 14.16 h.

Table 9-10: Maximum predicted horizontal distances (R_{max}) to PTS, TTS and behavioural response thresholds for marine mammals to cumulative (multiple strike) noise exposure from impact pile driving of jacket pin piles with a DBBC and MHS in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)	
		Single jacket pile	Four pin piles
PTS onset			
LF cetaceans	183 dB re 1 µPa².s (SEL_{24h})	1.93	4.30
HF cetaceans	193 dB re 1 µPa².s (SEL_{24h})	-	-
Otariid seals	185 dB re 1 µPa².s (SEL_{24h})	-	-
TTS onset			
LF cetaceans	168 dB re 1 µPa².s (SEL_{24h})	11.40	22.40
HF cetaceans	178 dB re 1 µPa².s (SEL_{24h})	0.02	0.06
Otariid seals	170 dB re 1 µPa².s (SEL_{24h})	0.05	0.16
Behavioural response			
Marine mammals	160 dB re 1 µPa (SPL) (unweighted)	2.60	N/A
Southern right whale female and calf pair	140 dB re 1 µPa (SPL) (weighted)	9.67	N/A

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

9.2.1.2 Marine turtles

Acoustic modelling was conducted for impact pile driving of a single jacket pin pile and four pin piles at a single location in the OWFA (Table 9-1). The maximum distances (R_{max}) to PTS and TTS onset thresholds for marine turtles are shown in Table 9-11.

Modelled noise ranges for marine turtles predicted PTS onset at a maximum distance of 3.14 km during installation of four pin piles, and TTS onset was predicted to occur within 16.5 km (Table 9-11). Distances to PTS and TTS onset were reduced by around half during installation of a single jacket pin pile (Table 9-11).

Table 9-11: Maximum predicted horizontal distances (R_{max}) to PTS and TTS onset thresholds for marine turtles to cumulative (multiple strike) noise exposure from impact pile driving of jacket pin piles with a DBBC and MHS in winter

Sound exposure threshold	R_{max} distance (km)	
	Single jacket pile	Four pin piles
PTS onset		
184 dB re 1 µPa².s (SEL_{24h})	1.37	3.14
TTS onset		
169 dB re 1 µPa².s (SEL_{24h})	8.71	16.5
Behavioural response		
166 dB re 1 µPa².s (SPL) (unweighted)	1.11	N/A
Behavioural disturbance		
175 dB re 1 µPa (SPL) (unweighted)	0.19	N/A

9.2.1.3 Fish and invertebrates

Acoustic modelling was conducted for impact pile driving of a single jacket pin pile and four pin piles at a single location in the OWFA (Table 9-1). The maximum distances (R_{max}) to mortality and PMI, recoverable injury, TTS onset, and startle response thresholds are shown in Table 9-12.

Fish and invertebrates could experience mortality and PMI, or a recoverable within a limited distance of 620 metres or less (Table 9-12). However, fish and invertebrates may experience TTS onset within 3.90 kilometres during installation of a single jacket pin pile, increasing to 7.74 kilometres for four pin piles (Table 9-12).

Table 9-12: Maximum predicted horizontal distances (R_{max}) to mortality and PMI, recoverable injury, TTS and startle response thresholds for fish and squid to cumulative (multiple strike) noise exposure from impact pile driving of jacket pin piles with a DBBC and MHS in winter

Hearing group	Sound exposure threshold	R_{max} distance (km)	
		Single jacket pile	Four pin piles
Mortality and PMI			
Fish I	219 dB re 1 µPa².s (SEL_{24h})	-	0.02
Fish II	210 dB re 1 µPa².s (SEL_{24h})	0.05	0.17
Fish III	207 dB re 1 µPa².s (SEL_{24h})	0.07	0.23
Fish eggs and larvae	210 dB re 1 µPa².s (SEL_{24h})	0.05	0.17
Recoverable injury			
Fish I	216 dB re 1 µPa².s (SEL_{24h})	-	0.05
Fish II, III	203 dB re 1 µPa².s (SEL_{24h})	0.19	0.62
TTS onset			
Fish I, II, III	186 dB re 1 µPa².s (SEL_{24h})	3.90	7.74
PK–PK threshold			
Crustaceans*	202 dB re 1 µPa (L_{pkpk})	0.06	N/A
Peak acceleration magnitude			
Benthic invertebrates*	35.75 (m/s^2)	-	-
Startle response			
Squid (unweighted)	162 dB re 1 µPa (SPL)	0.45	N/A

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

* Denotes unmitigated results without NAS, for which it is not possible to model

9.2.1.4 Penguins and diving seabirds

Acoustic modelling was conducted for impact piling of a single jacket pin pile and four pin piles at a single location in the OWFA (Table 9-1). The maximum distances (R_{max}) to PTS and TTS onset thresholds are shown in Table 9-13.

With the implementation of DBBC and MHS noise abatement systems, the threshold for PTS was not reached. However, penguins and diving seabirds may experience TTS onset within 50 metres during installation of a single jacket pin pile, increasing to 160 metres for four pin piles. Penguins and diving seabirds may experience a behavioural response from impact piling of jacket pin piles greater than 90 kilometres from the source (Table 9-13).

Table 9-13: Maximum predicted horizontal distances (R_{max}) to PTS and TTS thresholds for penguins and diving seabirds to cumulative (multiple strike) noise exposure from impact pile driving of jacket pin piles with a DBBC and MHS in winter

Sound exposure threshold	R_{max} distance (km)	
	Single jacket pile	Four pin piles
PTS onset		
185 dB re 1 µPa².s (SEL_{24h})	-	-
TTS onset		
170 dB re 1 µPa².s (SEL_{24h})	0.05	0.16

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

9.2.1.5 Human diver health assessment

Acoustic modelling was conducted for impact piling of a single jacket pin pile and four pin piles at a single location in the OWFA (Table 9-1). The maximum distances (R_{max}) to the human health assessment threshold are shown in Table 9-14.

Human divers could experience onset of the human health assessment threshold within a distance of 12.2 km (Table 9-14.).

Table 9-14: Maximum predicted distance (R_{max}) to the human health assessment threshold for human divers to cumulative (multiple strike) noise exposure from impact pile driving of jacket pin piles with a DBBC and MHS in winter

Sound exposure threshold	R_{max} distance (km)	
	Single jacket pile	Four pin piles
145 dB re 1 µPa (SPL)	12.20	N/A

9.2.2 Impact piling - Animal movement (Animat) modelling

9.2.2.1 Monopiles

Animat modelling was conducted for pygmy blue whales, southern right whales, humpback whales and minke whales during impact piling of a single monopile at four locations within the OWFA. These species were chosen as they had sufficient demographic and behavioural data to be able to perform the model. The animat model provided exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) for each of these species (Table 9-15).

Animat modelling predicted pygmy blue whales could experience PTS onset within 60 m of impact piling, with a maximum exposure range to TTS and behavioural response of 4.6 km and 5.2 km respectively at the shallow water site (MP1). For southern right whales, animals may experience PTS onset within 50 m at the deepest site (MP3), while thresholds were not reached within the modelling resolution at the other three sites. The maximum range to TTS onset and a behavioural response (160 dB re 1 µPa) was 1.49 km and 4.49 km respectively at the shallow water site (MP1) (Table 9-15). The maximum ranges to a behavioural response for southern right whale cow/calf pairs (140 dB re 1 µPa) was 5.68 km at the shallow water site. Humpback whales could experience PTS onset within 20 m in deep water and 200 m in shallow water, with TTS onset reached within 1.43 – 4.27 km, although noting that only a small percentage of animals (≤25%) were expected to be impacted (Table 9-15). For humpback whales, a behavioural response could occur within 4.8 km at the shallow water site. The PTS onset threshold was not reached for minke whales; however, TTS onset and a behavioural response was reached at 1.42 km and 4.68 km, respectively at the shallow water site (MP1) (Table 9-15).

Table 9-15: Exposure ranges ($ER_{95\%}$) in kilometres and the probability of exposure within $ER_{95\%}$ ranges (P_{exp}) to PTS, TTS and behavioural response thresholds for pygmy blue whales, southern right whales and humpback whales to cumulative (multiple strike) noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS in winter

Species	Sound exposure threshold	Shallow (MP1)		Intermediate (MP2)		Deepest (MP3)		Deep (MP4)	
		$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}
Pygmy blue whale	PTS onset	-	-	0.03	14	0.04	25	0.06	15
	TTS onset	4.60	53	2.28	82	1.34	74	0.86	61
	Behavioural response	5.20	74	4.65	84	2.38	91	2.08	74
Southern right whale	PTS onset	-	-	-	-	0.05	17	-	-
	TTS onset	1.49	58	0.84	40	0.44	24	0.37	30
	Behavioural response – 160 dB (unweighted)	4.49	73	3.56	91	1.86	83	1.48	65
	Behavioural response cow/calf pairs – 140 dB (weighted)	5.68	82	4.55	91	2.35	85	2.41	70
Humpback whale	PTS onset	0.20	5	-	-	0.02	>99	-	-
	TTS onset	4.27	25	2.45	20	1.48	14	1.43	11
	Behavioural response	4.79	71	4.33	82	2.24	77	1.84	73
Minke whale	PTS onset	-	-	-	-	-	-	-	-
	TTS onset	1.42	58	0.57	61	0.27	22	0.08	74
	Behavioural response	4.68	73	4.40	89	2.29	87	1.83	74

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

9.2.2.2 OSS pin piles

Animat modelling was conducted for pygmy blue whales, southern right whales, humpback whales and minke whales during impact piling of a single pin pile and four pin piles at one location within the OWFA. The animat model provided exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) for each of these species (Table 9-16).

Animat modelling predicted pygmy blue whales could experience PTS and TTS onset within 1.08 km and 10.5 km, respectively, from pile driving four pin piles with a DBBC and MHS system applied. The behavioural response range of installing a single jacket pile was predicted at 2.27 km, reducing slightly to 2.17 km during installation of four pin piles (Table 9-16). For southern right whales, animals may experience PTS and TTS onset within 1.46 km and 7.65 km, respectively, during installation of four pin piles. The behavioural response (160 dB re 1 µPa) range of a single jacket pile was predicted as 2.14 km and for four pin piles was 2.13 km (Table 9-16). The behavioural response range for southern right whale cow/calf pairs (140 dB re 1 µPa) was predicted as 8.21 km for a single jacket pile and 8.23 km for four pin piles.

Table 9-16: Exposure ranges ($ER_{95\%}$) in kilometres and the probability of exposure within $ER_{95\%}$ ranges (P_{exp}) to PTS, TTS and behavioural response thresholds for pygmy blue whales, southern right whales and humpback whales to cumulative (multiple strike) noise exposure from impact pile driving of jacket pin piles with a DBBC and MHS in winter

Species	Sound exposure threshold	Single jacket pile		Four pin piles	
		$ER_{95\%}$	P_{exp}	$ER_{95\%}$	P_{exp}
Pygmy blue whale	PTS onset	0.62	46	1.08	65
	TTS onset	6.61	88	10.50	91
	Behavioural response	2.27	83	2.15	92
Southern right whale	PTS onset	0.51	23	1.46	22
	TTS onset	4.73	75	7.65	70
	Behavioural response – 160 dB (unweighted)	2.14	79	2.13	88
	Behavioural response cow/calf pairs – 140 dB (weighted)	8.21	85	8.23	94
Humpback whale	PTS onset	0.78	21	1.54	19
	TTS onset	6.26	59	8.97	65
	Behavioural response	2.27	81	2.28	86
Minke whale	PTS onset	-	-	0.02	23
	TTS onset	3.40	75	4.66	85
	Behavioural response	2.24	85	2.16	92

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

10 DISCUSSION AND CONCLUSION

Demonstrating that there will be no significant impacts to marine fauna from underwater noise generated primarily during construction of the SOTS OWF is one of the critical approval risks to the project. The proposed method to achieve this is to undertake noise modelling, which comes at a significant cost, in an iterative manner as the project develops to ensure that noise predictions are as robust as possible before construction commences. During the construction period, noise measurements will be required to validate the predictions made to ensure that the monitoring and management measures that will be implemented, based on the noise modelling, are effective at protecting marine fauna according to the actual received noise levels measured in the marine environment.

To achieve this, contemporary input data, as it has become available, have been used over four rounds of underwater acoustic modelling from 2020 to 2025 to predict the underwater noise emissions for the SOTS project. This has included noise generated from impact pile driving of monopile and jacket pin pile foundations, vibro-piling installation of monopile and jacket pin pile foundations, and vessel operations associated with the construction of the project. Subsequent rounds of modelling will likely be undertaken as the project design further develops.

Throughout the four rounds of modelling, various installation and vessel options were considered, and modelling inputs and methods were updated and refined over the iterations. The modelling results have already been used to influence project decisions about what options can be eliminated as unfeasible, and to determine what would be advanced into further modelling studies and the current environmental impact assessment. The updates and variations throughout the modelling process are discussed below.

10.1 Modelling used for Assessment

10.1.1 Impact piling – static model

As previously established in earlier rounds of modelling, the distances to cumulative PTS and TTS onset and a behavioural response were greatest for LF cetaceans. The maximum ranges to PTS and TTS onset during installation of a single monopile with a DBBC, HSD and MHS system applied were 770 m and 8.62 km, respectively. The maximum range to a behavioural response for all marine mammals was 5.64 km.

This modelling round included realistic pile parameters, and site specific geotech data for each location. The pile diameter of monopiles in shallow water was 9.2 m, in intermediate waters was 11 m and 11.8 m in deep water. As with the third-round modelling, given the change in the FLA a deeper water site was included, as well as a new ‘worst-case’ deep water site with the hardest geotechnical data. Jacket structure modelling continued at a representative 3.25 metre diameter pin pile at a single location within the OWFA.

It was determined that it was not feasible to use a HSD during installation of jacket piles, and therefore the model considered only a DBBC and MHS system. Consequently, ranges to PTS and TTS onset during installation of both a single and four consecutive pin piles were greater than those for monopiles.

Distances to PTS and TTS onset and a behavioural response were greatest in shallow waters than in deeper waters, contrary to the results of the first and second round modelling. This is due to the inclusion of the geotechnical data, which found a larger component of coarser sand, which is more reflective, at the shallow water sites. Previous rounds of modelling were less site specific, and therefore differences in impact ranges at depth were due to the hammer energy applied.

The fourth-round modelling identified that a combination of NAS, in this instance DBBC, HSD and MHS systems was effective at reducing ranges to noise effect thresholds for LF cetaceans to a range that can be effectively monitored during construction of the project. This is important for contingency purposes, in case the animat results for LF cetaceans cannot be applied (e.g. the animals are remaining in an area), in which case adaptive management will be applied (refer to Construction Underwater Noise Management Framework).

10.1.2 Impact piling - Animat modelling

Animat modelling was used to predict the exposure of pygmy blue whales, southern right whales, humpback whales, and minke whales to sound arising from installation of monopiles and jacket piles. As previously demonstrated, the inclusion of realistic behavioural parameters for each of these species effectively reduced

ranges to PTS and TTS onset by half. Though the reduction in ranges to a behavioural response were less pronounced. Using the animat model, LF cetaceans were expected to experience PTS and TTS onset within a maximum range of 200 m and 4.6 km, respectively during impact pile driving of monopiles with a DBBC, HSD and MHS. A behavioural response could occur within 5.2 km of the monopile. For jacket pin pile installation, PTS onset could occur within a maximum distance of 1.67 km during installation of four pin piles, while TTS onset could occur within 10.5 km, with a DBBC and MHS applied. A behavioural response could occur within 2.3 km of jacket pin pile installation.

10.1.3 Vessel operations – static model

Assessing vessel noise impacts presents substantial challenges due to the limited availability of source levels for installation vessels and a lack of global examples. To predict vessel noise from the project, the average usage profile of DP thrusters as reported by vessel operators of 50% thruster power was used. This resulted in PTS, TTS and behavioural disturbance ranges of 80 metres, 9.16 kilometres and 15.6 kilometres respectively.

10.1.4 Vessel operations – Animat modelling

Animat modelling was used to predict the exposure of pygmy blue whales, southern right whales, humpback whales, and minke whales in the third-round modelling, incorporating realistic behaviours to sound arising from vessel operations during construction of the wind farm.

The results of the animat model demonstrate that distances to effect ranges are reduced substantially when realistic animal behaviour parameters are accounted for. For example, whilst PTS ranges for static animals was limited (80 metres), the threshold was not reached for any of the species in the animat modelling. Further, TTS ranges dropped markedly, from around 9 kilometres to a maximum of 1 kilometre for southern right whales. The behavioural response ranges also reduced substantially, from 15.6 km for static animals, to a maximum of 11.6 km for pygmy blue whales.

10.1.5 Noise abatement systems

Investigations for the fourth round of modelling included consideration of a primary NAS in the form of the MHS, in combination with a HSD and DBBC as well-proven secondary NAS. The results showed a significant noise reduction compared to the round two modelling results which included a DBBC only. However, it is important to note that pile driving inputs and modelled locations, noise exposure thresholds and LF cetacean frequency weightings also differed during this round of modelling, so therefore are not directly comparable.

10.2 Summary of noise modelling results

Table 10-1: Summary of maximum predicted horizontal distances (static model) and exposure ranges (animat model) in kilometres to noise effect thresholds for receptor groups to noise exposure from impact pile driving of a single monopile with a DBBC, HSD and MHS, and impact pile driving of jacket pin piles with a DBBC and MHS

Receptor / Hearing group and species	Criteria	Threshold	Round four: Monopiles with DBBC, HSD, and MHS		Round four: Jacket pin piles with DBBC and MHS	
			Static	Animat	Static	Animat
Marine mammals						
LF cetaceans	PTS	183 dB re 1 µPa².s (SEL24h)	0.77$^{(MP1)}$	0.06$^{(MP4)}$	4.30$^{(4pp)}$	1.54$^{(4pp)}$
	TTS	168 dB re 1 µPa².s (SEL24h)	8.61$^{(MP1)}$	4.60$^{(MP1)}$	22.40$^{(4pp)}$	10.50$^{(4pp)}$
	Behavioural response	160 dB re 1 µPa (SPL)	5.64$^{(MP1)}$	5.20$^{(MP1)}$	2.60$^{(1pp)}$	2.27$^{(1pp)}$
	Behavioural response cow/calf pairs	140 dB re 1 µPa (SPL)	7.17$^{(MP1)}$	5.68$^{(MP1)}$	9.67$^{(1pp)}$	8.23$^{(4pp)}$
HF cetaceans	PTS	193 dB re 1 µPa².s (SEL24h)	-		-	
	TTS	178 dB re 1 µPa².s (SEL24h)	-		0.06$^{(4pp)}$	
	Behavioural response	160 dB re 1 µPa (SPL)	5.64$^{(MP1)}$			
Otariid seals	PTS	185 dB re 1 µPa².s (SEL24h)	-		-	
	TTS	170 dB re 1 µPa².s (SEL24h)	-		0.16$^{(4pp)}$	
	Behavioural response	160 dB re 1 µPa (SPL)	5.64$^{(MP1)}$			
Marine turtles	PTS	184 dB re 1 µPa².s (SEL24h)	0.09$^{(MP1)}$		3.14$^{(4pp)}$	
	TTS	169 dB re 1 µPa².s (SEL24h)	1.14$^{(MP1)}$		16.5$^{(4pp)}$	
	Behavioural response	166 dB re 1 µPa (SPL)	2.95$^{(MP1)}$		1.11$^{(1pp)}$	
	Behavioural disturbance	175 dB re 1 µPa (SPL)	0.62$^{(MP1)}$		0.19$^{(1pp)}$	
Fish and invertebrates						
Fish	TTS onset	186 dB re 1 µPa².s (SEL24h)	7.82$^{(MP1)}$		7.74$^{(4pp)}$	
Fish I	Mortality & PMI	219 dB re 1 µPa².s (SEL24h)	0.03$^{(MP1)}$		0.02$^{(4pp)}$	
	Recoverable injury	216 dB re 1 µPa².s (SEL24h)	0.06$^{(MP4)}$		0.05$^{(4pp)}$	
Fish II	Mortality & PMI	210 dB re 1 µPa².s (SEL24h)	0.09$^{(MP1)}$		0.17$^{(4pp)}$	
	Recoverable injury	203 dB re 1 µPa².s (SEL24h)	0.35$^{(MP1)}$		0.62$^{(4pp)}$	

Receptor / Hearing group and species	Criteria	Threshold	Round four: Monopiles with DBBC, HSD, and MHS		Round four: Jacket pin piles with DBBC and MHS	
			Static	Animat	Static	Animat
Fish III	Mortality & PMI	207 dB re 1 µPa².s (SEL24h)	0.13(MP1)		0.23(4pp)	
	Recoverable injury	203 dB re 1 µPa².s (SEL24h)	0.35(MP1)		0.62(4pp)	
Fish eggs and larvae	Mortality & PMI	210 dB re 1 µPa².s (SEL24h)	0.09(MP1)		0.17(4pp)	
Crustaceans*	PK–PK threshold	202 dB re 1 µPa (L_{pkpk})	>1.00(MP4)		0.06(1pp)	
Benthic invertebrates*	Peak acceleration magnitude	35.75 (m/s²)	-		-	
Squid	Startle response	162 dB re 1 µPa (SPL)	1.83(MP1)		N/A	
Penguins and diving seabirds						
Penguins and diving seabirds	PTS	185 dB re 1 µPa².s (SEL_{24h})	-			
	TTS	170 dB re 1 µPa².s (SEL_{24h})	-		0.16(4pp)	
Human health assessment						
Human diver	Human health assessment threshold	145 dB re 1 µPa (SPL)	20.3(MP1)		12.20(1pp)	

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

The maximum modelling range for crustacean PK-PK threshold is 1 km

MP1-MP4 denotes the monopile location at which the maximum modelling distance occurred

1pp and 4pp denotes the number of pin piles at which the maximum modelling distance occurred

* Denotes unmitigated results without NAS, for which it is not possible to model

Table 10-2: Summary of maximum predicted horizontal distances (static model) and exposure ranges (animat model) in kilometres to noise effect thresholds for receptor groups to noise exposure from vessel noise

Receptor group / hearing group and species	Criteria	Threshold	Round three: Vessel noise	
			Static	Animat
Marine mammals				
LF cetaceans	PTS	197 dB re 1 µPa².s (SEL_{24h})	0.08(S1)	-
	TTS	177 dB re 1 µPa².s (SEL_{24h})	9.16(S1)	1.09(S1)
	Behavioural response	120 dB re 1 µPa (SPL)	15.6(S1)	11.6(S1)
HF cetaceans	PTS	201 dB re 1 µPa².s (SEL_{24h})	-	
	TTS	181 dB re 1 µPa².s (SEL_{24h})	0.16(S1)	
	Behavioural response	120 dB re 1 µPa (SPL)	15.6(S1)	
Otariid seals	PTS	199 dB re 1 µPa².s (SEL_{24h})	-	
	TTS	179 dB re 1 µPa².s (SEL_{24h})	0.14(S1)	
	Behavioural response	120 dB re 1 µPa (SPL)	15.6(S1)	
Marine turtles				
Marine turtles	PTS	220 dB re 1 µPa².s (SEL_{24h})	-	
	TTS	200 dB re 1 µPa².s (SEL_{24h})	0.04(S1)	
Fish and invertebrates				
Fish III	Recoverable injury	170 dB re 1 µPa (SPL 48h)	-	
	TTS	158 dB re 1 µPa (SPL 12h)	0.02(S1)	
Penguins and diving seabirds				
Penguins and diving seabirds	PTS	199 dB re 1 µPa².s (SEL_{24h})	-	
	TTS	179 dB re 1 µPa².s (SEL_{24h})	0.14(S1)	

A dash denotes that the threshold was not reached within the minimum limit of the modelling resolution (20 m), indicating predicted horizontal distances of <20 m

S1 and S2 denotes the scenario in which the maximum distance occurred

Crustacean, benthic invertebrate and human diver noise effect thresholds not modelled as there are no regulatory continuous noise thresholds for these receptors

Contemporary input data, as it has become available, have been used over the four rounds of modelling. However, despite the inclusion of the best available input data, the modelling still includes a large degree of conservatism, such as noise effect thresholds (Section 5), seasonal parameters (Section 6.1.10.3), largest pile diameter (Section 6.1.10.2), pile driving input parameters (e.g., 95% percentile energy in each layer, maximum hammer energy, total pile duration, strike rate), geotechnical information, and the use of static modelling results.

The purpose of including this level of conservatism is to ensure that validated noise emissions during construction are equal to or less than the predicted noise impact ranges from the modelling study, and to ensure no impacts to marine fauna. However, it is possible that modelled predicted ranges, for example TTS onset to LF cetaceans at a range of nine kilometres, may be overly cautious and in practice ranges may be much smaller, such as in deeper waters with a smaller pile diameter in the summer months.

10.3 Comparison to other studies

As there have been no wind farms installed in Australian waters, no direct comparisons can be made. However, examples of modelled and measured data from wind farms in the United States and United Kingdom are included below.

Rand (2024) measured the noise from impact pile driving with a DBBC and HSD in place during construction of the Vineyard OWF. For LF cetaceans, the PTS onset threshold was exceeded during pile driving at noise exposures of 13 minutes at 500 metres, 45 minutes at one kilometre and two hours at 1.8 kilometres. The TTS onset threshold was exceeded at noise exposures of two minutes at 1.2 kilometres, five minutes at 2.2 kilometres and 10 minutes at 3.2 kilometres (Rand, 2024). The distance to behavioural response (160 dB SPL unweighted) during pile driving was 3.3 kilometres (Rand, 2024).

A similar study compared the predicted noise effect ranges to measured noise effect ranges during installation of the Vineyard OWF (Küsel et al., 2024). In this study, NAS again included DBBC and HSD. Static underwater noise modelling only was conducted and therefore ranges to noise exposure thresholds do not account for animal behaviour or movement. For LF cetaceans, the underwater noise modelling study predicted PTS onset would occur at a range of ~ 3.2 kilometres, though measured data reported a maximum range of 3.6 kilometres. For installation of jacket pin piles (four pin piles) the predicted range to PTS onset was 7.2 kilometres, though measured data reported a range of just 2.8 kilometres (Küsel et al., 2024). For the behavioural response threshold (160 dB SPL unweighted), predicted ranges during pile driving of monopiles to marine mammals was ~ 4.1 kilometres, and actual measured data extended out to ~ 6.9 kilometres (Küsel et al., 2024). For jacket pin piles (four pin piles) a behavioural response was predicted to occur out to ~ 3.3 kilometres, with measured data again demonstrating that ranges were much less, out to ~1.2 kilometres (Küsel et al., 2024). Following maintenance and optimisation of the DBBC, measured data showed that ranges to PTS onset for LF cetaceans during monopile installation were within the predicted range, and ranges to behavioural response were between 3 to 5 kilometres (Küsel et al., 2024).

Modelled predictions of distances to noise exposure thresholds for LF cetaceans (static modelling only) during impact pile driving of monopiles at the Coastal Virginia OWF in the United States reported PTS onset within 12.4 kilometres, and behavioural response (160 dB SPL) within 15 kilometres, with no NAS (Tetra Tech Inc., 2023). For installation of pin piles, PTS onset was predicted within 6.8 kilometres, and behavioural response within 5.5 kilometres with no mitigation (Tetra Tech Inc., 2023). With the inclusion of -6 dB and -10 dB mitigation (expected performance of NAS, such as BBC), ranges to PTS onset and behavioural response during monopile installation were reduced to 4.3 to 6 kilometres, and 6.2 to 8.7 kilometres, respectively (Tetra Tech Inc., 2023).

In the United Kingdom, unmitigated underwater noise modelling (static modelling only) for the Norfolk Vanguard OWF in water depths of 35 – 40 metres predicted PTS onset and TTS onset for LF cetaceans at ranges of up to 22 kilometres and 154 kilometres, respectively during pile driving of monopiles (> seven metre pile diameter) at maximum hammer blow energy (5000 kJ), in this instance 5000 kilojoules, with no NAS in place (Barham, 2018). During installation of jacket pin piles (four metre pile diameter, 2700 kJ hammer energy), distances were 16 kilometres and 91 kilometres for PTS and TTS onset, respectively (Barham, 2018). The range at which behavioural avoidance was likely (152 dB SPL) for LF cetaceans during pile driving of monopiles was up 42 kilometres at maximum hammer energy, and up to 20 kilometres during soft starts (Barham, 2018). The predicted ranges to noise exposure thresholds during pile driving of monopiles for the Vanguard OWF were greater than the unmitigated ranges in the first-round modelling (25 kilometres to PTS onset, 80 kilometres to TTS onset, 23 kilometres to behavioural response (160 dB SPL)),

though it is acknowledged that the hammer energy applied is greater than that modelled for the SOTS project.

Measurements of vessel noise from the Orion installation vessel used in the Vineyard OWF by Rand (2024) found that marine mammals could experience a behavioural response, defined as level B harassment (120 dB SPL), at a distance of over six kilometres from the vessel. However, this was later disputed as not credible due to the likely interference of vessels in closer proximity to the underwater noise recorder than the installation vessel (SMRU Consulting, 2024). Project vessels manoeuvring on DP were modelled for the Block Island wind farm, with predicted ranges to behavioural disturbance of ~ nine kilometres (Deepwater Wind, 2012). Modelled static ranges to behavioural response thresholds for marine mammals to project vessels on DP for the SOTS project were slightly larger at 12 kilometres in deep water and 15.6 km in intermediate water, though accounted for modelling of OIV on DP and associated support vessels. In comparison to the static model, the animal movement exposure modelling of behavioural response were substantially reduced, with a maximum of 7.87 kilometres in deep water and 11.6km in intermediate waters.

While it is acknowledged that differences in bathymetry, sediment type and pile driving parameters will affect distances to noise exposure thresholds, the above studies demonstrate that the modelled predictions in this study are within similar ranges to other wind farms. Moreover, the implementation of soft starts and NAS systems has been shown to effectively reduce noise exposure ranges during impact pile driving.

10.4 Conclusion

A comprehensive modelling program over several years has been undertaken by the SOTS project team to make robust predictions of the potential noise that may be generated during the construction of the SOTS OWF from construction piling and vessels. For the Gippsland region in which this project is proposed, this is particularly important for listed endangered species of LF cetaceans such as the blue whale and southern right whale, for which there are designated “biologically important areas” overlapping with the project area and that have Recovery Plans in force. There are also other species of noise-sensitive fauna including whales, dolphins, turtles, pinnipeds, fish, invertebrates and seabirds that inhabit the area, that need to be considered for environmental impact assessment. The final data from modelling provide a robust basis for assessment of underwater noise impacts to sensitive receptors, and the results presented from the fourth round will be used to develop the environmental impact assessment for the project, including the development of management plans that will ensure marine fauna are protected from noise generated by the wind farm project. The results presented outlines the history and progression of the noise modelling that has been undertaken as the project has developed and will continue to be applied to the design development, impact assessment and management measures. Ultimately, the modelling results reported here will be updated when further information becomes available about the project parameters, verified in the field to reduce any residual uncertainty in the environmental impact assessment.

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Appendix A
JASCO acoustic modelling report

Star of the South Underwater Noise Modelling Report

Consolidated Acoustic Modelling Report

JASCO Applied Sciences (Australia) Pty Ltd

3 December 2025

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Disclaimer:
This report is based on the scope, conditions and limitations, as described in the report. The report has been prepared for RPS for the sole purpose of satisfying the scoping requirements for the environment effects statement and the EIS guidelines for the environmental impact statement for the Star of the South project. JASCO Applied Sciences accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

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Executive Summary

JASCO Applied Sciences (JASCO) performed a series of modelling studies (modelling rounds) to understand underwater sound levels and predicted marine fauna effect ranges associated with construction activities for the proposed Star of the South (SOTS) offshore wind farm (OWF). Modelling was undertaken as an iterative process over several years with scenarios being continually refined to be reflective of the most up to date project development concept. Within each modelling round, the most relevant site locations, scenarios and impact threshold criteria were modelled and applied. The most recent underwater noise modelling (third and fourth modelling rounds) considered multiple development scenarios, specifically:

- Wind turbine generator (WTG) foundations consisting of monopiles were modelled as being installed using impact piling.
- Wind turbine generator (WTG) foundations, consisting of monopiles were modelled as being installed using vibro piling.
- Jacket structures were considered for Offshore Sub-Station (OSS) foundations, installed using impact piling and vibro piling.
- Mitigation was considered for impact piling activities. The mitigation scenario considered for WTG monopiles in the most recent modelling round is:
    - The modified hammer forcing function with the PULSE and specific frequency dependent attenuation curves to represent the application of both a hydro sound damper (HSD) and a double big bubble curtain (DBBC) system.
- The mitigation scenario considered for jacket piles in the most recent modelling round is:
    - The modified hammer forcing function with the PULSE and specific frequency dependent attenuation curves to represent the application of a double big bubble curtain (DBBC) system.
- Vessel operations associated with the OWF at two representative locations within the License Area (Intermediate Shallow, and Deep). The considered types of operations include:
    - A Wind Turbine Generator Installation Vessel (WTGIV) stationary under dynamic positioning (DP).
    - A Platform Support Vessel (PSV) holding position under DP deploying some type of pile driving noise mitigation, e.g., a bubble curtain.
    - A single cable lay vessel moving along a cable lay path using DP during cable laying operations.

The objective of the modelling studies was to predict the ranges to acoustic impact criteria including those for injury and behavioural disturbance of marine fauna. The thresholds used in the modelling studies represented the best available science at the time of modelling. It is worth noting that new criteria were published in 2024 and so the most recent modelling studies (third and fourth rounds) apply these most up-to-date criteria. The fauna considered in modelling studies included low- and high-frequency cetaceans, sea turtles, fish including fish larvae and eggs, penguins, and invertebrates. A human health assessment threshold for divers was also considered.

The modelling methodology considered the dynamics of pile driving, source levels of vessels and range-dependent environmental properties. A winter sound speed profile was utilised for modelling as it was likely to result in the worst case (farthest) prediction of impact ranges. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p); zero-to-peak pressure levels (PK, L_{pk}); peak-to-peak pressure levels (PK-PK; $L_{pk\text{-}pk}$); particle acceleration (ms^{-2}); and either single-strike (i.e., per-strike) or accumulated sound exposure levels (SEL, L_E) as appropriate for different noise effect criteria and noise sources. The range at which these levels exceeded relevant thresholds was

then used to predict the range to potential impacts. In this report, the duration period for SEL accumulation is defined as a 24-hour period over which sound energy is integrated; the level is specified with the abbreviation SEL_{24h}.

SEL_{24h} is a cumulative metric that reflects the dosimetric effect of noise levels within 24 hours, based on the assumption that a receiver (e.g., an animal) is consistently exposed to such noise levels at a fixed position. More realistically, marine animals would not stay in the same location for 24 hours (especially in the absence of site-attached habitat) but rather a shorter period, depending on the animal's behaviour and the source's proximity and movements. Therefore, a reported radius for the SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be impaired, but rather that an animal could be exposed to the sound level associated with impairment (either PTS/AUD INJ or TTS) if it remained within the ensonified area for 24 hours.

While acoustic modelling inherently assumes static animals, the JASCO Animal Simulation Model Including Noise Exposure (JASMINE) combines modelled sound fields with the realistic movements of simulated animals ('animats') to predict how animals might be impacted through sound exposure. JASMINE provides a framework for understanding and predicting realistic sound exposure for species of interest, resulting in a more refined prediction of impact ranges.

The following tables present a summary of the results of the latest modelling rounds (third and fourth) using the most up-to-date noise effect criteria. Animal movement modelling results are also summarised for each activity; in this study, the moving receivers ('animats') were set to simulate the real-world movements of pygmy blue whales, humpback whales, southern right whales, and minke whales.

For both monopiles and jacket piles, the implementation of mitigation significantly reduced the predicted impact ranges for all fauna groups, with the biggest reduction in predicted impact ranges being achieved for low frequency cetaceans. While noise mitigation measures did not completely remove the potential for noise induced effects to marine fauna, its implementation did reduce the predicted ranges to these effects to more manageable distances that may be able to be addressed with other operational and mitigation approaches.

Impact Piling Operations:

Table 1. *Monopile foundation summary (Monopiles 1 and 2), no mitigation, and PULSE+DBBC+HSD*: ranges (R_{max} in km) to acoustic thresholds for marine fauna and humans for each monopile at the penetration depth that results in the farthest ranges. Since $L_{E,24h}$ accounts for the accumulation of all hammer strikes required to drive a single pile, the distances to the corresponding thresholds encompass all the hammer energy settings. A dash (-) indicates that the acoustic threshold was not reached.

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 1		Monopile 2	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Low-frequency (LF) cetaceans	PTS [a]	$L_{E,24h}$	183	12.1	0.77	17.4	0.41
	TTS [a]	$L_{E,24h}$	168	83.6	8.61	78.6	5.48
	Weighted behavioural response [h]	L_p	160	8.22	0.51	12.1	0.31
	Weighted behavioural response (migrating mysticetes) [h]	L_p	140	84.7	7.17	78.9	6.37
High-frequency (HF) cetaceans	PTS [a]	$L_{E,24h}$	193	0.06	–	0.03	–
	TTS [a]	$L_{E,24h}$	178	0.89	–	0.66	–
Otariid seals	PTS [a]	$L_{E,24h}$	185	0.08	–	0.09	–
	TTS [a]	$L_{E,24h}$	170	1.43	–	1.21	–
All marine mammal groups	Behavioural Response [b]	L_p	160	14.0	5.64	20.8	5.18
Fish without swim bladder	Mortality and Potential mortal injury [c]	$L_{E,24h}$	219	0.29	0.03	0.26	0.02
	Recoverable injury [c]	$L_{E,24h}$	216	0.54	0.05	0.48	0.04
	TTS [c]	$L_{E,24h}$	186	15.1	7.82	22.6	5.63
	Recoverable injury [c]	L_{pk}	213	0.09	–	0.12	–
Fish with swim bladder not involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	210	1.47	0.09	1.38	0.09
	Recoverable injury [c]	$L_{E,24h}$	203	3.46	0.35	3.78	0.3
	TTS [c]	$L_{E,24h}$	186	15.1	7.82	22.6	5.63
	Recoverable injury [c]	L_{pk}	207	0.26	–	0.28	–

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 1		Monopile 2	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Fish with swim bladder involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	207	2.19	0.13	2.22	0.13
	Recoverable injury [c]	$L_{E,24h}$	203	3.46	0.35	3.78	0.3
	TTS [c]	$L_{E,24h}$	186	15.1	7.82	22.6	5.63
	Recoverable injury [c]	L_{pk}	207	0.26	–	0.28	–
Sea turtles	PTS [d]	$L_{E,24h}$	184	9.56	0.09	13.2	0.09
	TTS [d]	$L_{E,24h}$	169	83.4	1.14	78.2	0.75
	Behavioural disturbance [e]	L_p	175	4.23	0.62	4.63	0.46
	Behavioural response [e]	L_p	166	8.67	2.95	11.7	2.35
Penguins	PTS [a]	$L_{E,24h}$	185	0.08	–	0.09	–
	TTS [a]	$L_{E,24h}$	170	1.43	–	1.21	–
Humans	Human health assessment threshold [f]	L_p	145	83.8	20.3	79.1	17.3
Squid	Startle response [g]	L_E	162	6.52	1.83	9.15	1.11
Benthic invertebrates	Peak acceleration magnitude [i]	m/s^2	35.75	–	–	–	–

L_{pk}= unweighted peak sound pressure level (dB re 1 µPa).
L_p= unweighted sound pressure level (dB re 1 µPa).
L_E= sound exposure level for single strike (dB re 1 μPa^2 s).
$L_{E,24h}$= sound exposure level over 24 hours (dB re 1 μPa^2 s), unweighted for fish and frequency weighted for all other groups.
[a] NMFS (2024) criteria for marine fauna.
[b] NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
[c] Popper et al. (2014).
[d] Accomando et al. (2025a).
[e] McCauley et al. (2000).
[f] Human health assessment threshold derived from Parvin (2005).
[g] Fewtrell and McCauley (2012).
[h] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[i] Day et al (2016a).

Table 2. *Monopile foundation summary (Monopiles 3 and 4), no mitigation, and PULSE+DBBC+HSD*: ranges (R_{max} in km) to acoustic thresholds for marine fauna and humans for each monopile at the penetration depth that results in the farthest ranges. Since $L_{E,24h}$ accounts for the accumulation of all hammer strikes required to drive a single pile, the distances to the corresponding thresholds encompass all the hammer energy settings. A dash (-) indicates that the acoustic threshold was not reached.

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 3		Monopile 4	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Low-frequency (LF) cetaceans	PTS [a]	$L_{E,24h}$	183	14.9	0.18	11.8	0.36
	TTS [a]	$L_{E,24h}$	168	42.9	3.30	36.0	3.56
	Weighted behavioural response [h]	L_p	160	9.65	0.13	8.27	0.13
	Weighted behavioural response (migrating mysticetes) [h]	L_p	140	42.8	3.21	38.7	3.17
High-frequency (HF) cetaceans	PTS [a]	$L_{E,24h}$	193	0.13	–	0.03	–
	TTS [a]	$L_{E,24h}$	178	1.35	–	0.76	–
Otariid seals	PTS [a]	$L_{E,24h}$	185	0.16	–	0.12	–
	TTS [a]	$L_{E,24h}$	170	2.20	–	1.25	–
All marine mammal groups	Behavioural Response [b]	L_p	160	13.2	2.37	12.3	2.72
Fish without swim bladder	Mortality and Potential mortal injury [c]	$L_{E,24h}$	219	0.59	0.03	0.32	0.03
	Recoverable injury [c]	$L_{E,24h}$	216	1.01	0.05	0.53	0.06
	TTS [c]	$L_{E,24h}$	186	18.1	3.05	14.4	3.74
	Recoverable injury [c]	L_{pk}	213	0.16	–	0.14	–
Fish with swim bladder not involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	210	2.50	0.09	1.52	0.09
	Recoverable injury [c]	$L_{E,24h}$	203	5.14	0.13	3.50	0.24
	TTS [c]	$L_{E,24h}$	186	18.1	3.05	14.4	3.74
	Recoverable injury [c]	L_{pk}	207	0.43	–	0.30	–
Fish with swim bladder involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	207	3.45	0.11	2.25	0.13

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 3		Monopile 4	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
	Recoverable injury [c]	$L_{E,24h}$	203	5.14	0.13	3.50	0.24
	TTS [c]	$L_{E,24h}$	186	18.1	3.05	14.4	3.74
	Recoverable injury [c]	L_{pk}	207				
Sea turtles	PTS [d]	$L_{E,24h}$	184	12.5	0.09	9.85	0.09
	TTS [d]	$L_{E,24h}$	169	42.7	0.36	28.3	0.39
	Behavioural disturbance [e]	L_p	175	4.55	0.17	3.62	0.28
	Behavioural response [e]	L_p	166	9.41	1.12	7.93	1.34
Penguins	PTS [a]	$L_{E,24h}$	185	0.16	–	0.12	–
	TTS [a]	$L_{E,24h}$	170	2.20	–	1.25	–
Humans	Human health assessment threshold [f]	L_p	145	42.8	8.64	39.7	8.93
Squid	Startle response [g]	L_E	162	6.19	0.47	7.50	0.62
Benthic invertebrates	Peak acceleration magnitude [i]	m/s^2	35.75	–	–	–	–

L_{pk}= unweighted peak sound pressure level (dB re 1 µPa).
L_p= unweighted sound pressure level (dB re 1 µPa).
L_E= sound exposure level for single strike (dB re 1 μPa^2 s).
$L_{E,24h}$= sound exposure level over 24 hours (dB re 1 μPa^2 s), unweighted for fish and frequency weighted for all other groups.
[a] NMFS (2024) criteria for marine fauna.
[b] NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
[c] Popper et al. (2014).
[d] Accomando et al. (2025a).
[e] McCauley et al. (2000).
[f] Human health assessment threshold derived from Parvin (2005).
[g] Fewtrell and McCauley (2012).
[h] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[i] Day et al (2016a).

Table 3. *Monopiles*: Summary of animat simulation results indicating the maximum of the 95th percentile exposure ranges ($ER_{95\%}$) (in km) for each species at each modelled site for the monopiles. A dash (-) indicates that no animat was exposed above the threshold.

Species	PULSE+DBBC+HSD			
	Monopile 1	Monopile 2	Monopile 3	Monopile 4
PTS SEL_{24h} (183 dB re 1 µPa² s) [a]				
Pygmy blue whale	–	0.03	0.04	0.06
Humpback whale	0.20	–	0.02	–
Southern right whale	–	–	0.05	–
Minke whale	–	–	–	–
TTS SEL_{24h} (168 dB re 1 µPa² s) [a]				
Pygmy blue whale	4.60	2.28	1.34	0.86
Humpback whale	4.27	2.45	1.48	1.43
Southern right whale	1.49	0.84	0.44	0.37
Minke whale	1.42	0.57	0.27	0.08
Behavioural response SPL (160 dB re 1 µPa) [b]				
Pygmy blue whale	5.20	4.65	2.38	2.08
Humpback whale	4.79	4.33	2.24	1.84
Southern right whale	4.49	3.56	1.86	1.48
Minke whale	4.68	4.40	2.29	1.83
Behavioural response SPL ('Other' mysticetes, low-frequency weighted 160 dB re 1 µPa) [c]				
Pygmy blue whale	–	0.27	0.12	0.12
Humpback whale	0.42	0.15	0.11	0.10
Southern right whale	0.40	0.11	0.07	0.09
Minke whale	0.44	0.21	0.10	0.09
Behavioural response SPL (Migrating mysticetes, low-frequency weighted 140 dB re 1 µPa) [c]				
Pygmy blue whale	6.57	5.58	2.77	2.75
Humpback whale	6.33	5.13	2.36	2.58
Southern right whale	5.95	4.69	2.35	2.41
Minke whale	6.27	5.20	2.49	2.41

a NMFS (2024) criteria for marine fauna.
b NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
c Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)

Table 4. Sub-station Jacket Piles (x4), no mitigation and PULSE+DBBC: ranges (R_{max} in km) to acoustic thresholds for marine fauna and humans for each jacket pile at the penetration depth that results in the farthest ranges. Since $L_{E,24h}$ accounts for the accumulation of all hammer strikes required to drive four piles, the distances to the corresponding thresholds encompass all the hammer energy settings. A dash (-) indicates that the acoustic threshold was not reached.

Fauna group / Receiver	Threshold	Metric	Threshold	Jacket Pile (x4)	
				Unmitigated	PULSE+DBBC
Low-frequency (LF) cetaceans	PTS [a]	$L_{E,24h}$	183	10.1	4.30
	TTS [a]	$L_{E,24h}$	168	59.9	22.4
	Weighted behavioural response [h]	L_p	160	2.87	1.10
	Weighted behavioural response (migrating mysticetes) [h]	L_p	140	49.1	9.67
High-frequency (HF) cetaceans	PTS [a]	$L_{E,24h}$	193	0.02	–
	TTS [a]	$L_{E,24h}$	178	0.33	0.06
Otariid seals	PTS [a]	$L_{E,24h}$	185	0.05	–
	TTS [a]	$L_{E,24h}$	170	0.60	0.16
All marine mammal groups	Behavioural Response [b]	L_p	160	6.57	2.60
Fish without swim bladder	Mortality and Potential mortal injury [c]	$L_{E,24h}$	219	0.09	0.02
	Recoverable injury [c]	$L_{E,24h}$	216	0.19	0.05
	TTS [c]	$L_{E,24h}$	186	15.3	7.74
	Recoverable injury [c]	L_{pk}	213	–	–
Fish with swim bladder not involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	210	0.58	0.17
	Recoverable injury [c]	$L_{E,24h}$	203	2.04	0.62
	TTS [c]	$L_{E,24h}$	186	15.3	7.74
	Recoverable injury [c]	L_{pk}	207	0.02	–
Fish with swim bladder involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	207	1.06	0.23
	Recoverable injury [c]	$L_{E,24h}$	203	2.04	0.62
	TTS [c]	$L_{E,24h}$	186	15.3	7.74
	Recoverable injury [c]	L_{pk}	207	0.02	–
Sea turtles	PTS [d]	$L_{E,24h}$	184	7.29	3.14
	TTS [d]	$L_{E,24h}$	169	49.4	16.5
Penguins	PTS [a]	$L_{E,24h}$	185	0.05	–
	TTS [a]	$L_{E,24h}$	170	0.60	0.16
Humans	Human health assessment threshold [f]	L_p	145	49.1	12.2
Squid	Startle response [g]	L_E	162	1.71	0.45
Benthic invertebrates	Peak acceleration magnitude [i]	m/s^2	35.75	–	–

L_p= unweighted sound pressure level (dB re 1 µPa).
L_E= sound exposure level for single strike (dB re 1 µPa^2 s).
$L_{E,24h}$= sound exposure level over 24 hours (dB re 1 µPa^2 s), unweighted for fish and frequency weighted for all other groups.
[a] NMFS (2024) criteria for marine fauna.
[b] NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
[c] Popper et al. (2014).
[d] Accomando et al. (2025a).
[e] McCauley et al. (2000).
[f] Human health assessment threshold derived from Parvin (2005).
[g] Fewtrell and McCauley (2012).
[h] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[i] Day et al (2016a).

Table 5. *Sub-station Jacket Piles*: Summary of animat simulation results indicating the maximum of the 95th percentile exposure ranges ($ER_{95\%}$) (in km) for each species for the OSS Jacket Pile.

Species	Sub-station Jacket Piles x4
	PULSE+DBBC
PTS SEL_{24h} (183 dB re 1 µPa² s) [a]	
Pygmy blue whale	1.08
Humpback whale	1.67
Southern right whale	1.46
Minke whale	0.02
TTS SEL_{24h} (168 dB re 1 µPa² s) [a]	
Pygmy blue whale	10.5
Humpback whale	8.97
Southern right whale	7.65
Minke whale	4.66
Behavioural response SPL (160 dB re 1 µPa) [b]	
Pygmy blue whale	2.15
Humpback whale	2.28
Southern right whale	2.13
Minke whale	2.16
Behavioural response SPL ('Other' mysticetes, low-frequency weighted 160 dB re 1 µPa) [c]	
Pygmy blue whale	0.87
Humpback whale	0.81
Southern right whale	0.82
Minke whale	0.83
Behavioural response SPL (Migrating mysticetes, low-frequency weighted 140 dB re 1 µPa) [c]	
Pygmy blue whale	8.58
Humpback whale	8.37
Southern right whale	8.23
Minke whale	8.10

a NMFS (2024) criteria for marine fauna.
b NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
c Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)

Vibro Piling Operations:

Table 6. Monopile foundation (GIANT 4000 hammer): distance (R_{max} in km) to SPL acoustic behavioural response thresholds for vibro piling. Maximum distances over penetration depth are presented.

Fauna group	SPL (L_p; dB re 1 µPa)	Monopile 1	Monopile 2	Monopile 3	OSS Jacket Pile
Fish recoverable injury [a]	170	8.75	14.5	10.1	11.6
Fish TTS [b]	158	19.6	45.2	22.3	34.1
Marine mammal behavioural response [c]	120	>90.0	>90.0	>90.0	>90.0

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).

Table 7. Monopile foundation (GIANT 4000 hammer): distance (R_{max} in km) to SEL_{24h} acoustic thresholds for marine mammals, sea turtles, and penguins for vibro piling.

Hearing group	$L_{E,24h}$ threshold	Monopile 1	Monopile 2	Monopile 3	Single Jacket Pile	Four Jacket Piles
PTS						
LF cetaceans	197	11.1	5.82	21.1	1.11	3.01
HF cetaceans	201	0.06	–	0.41	–	–
Otariid seals	199	0.04	–	0.23	–	–
Sea turtles	198	7.25	3.51	17.3	0.38	1.21
Penguins	199	0.04	–	0.23	–	–
TTS						
LF cetaceans	177	83.5	37.0	68.7	13.2	24.5
HF cetaceans	181	2.90	0.38	6.45	0.05	0.11
Otariid seals	179	2.20	0.18	5.00	–	0.07
Sea turtles	178	83.2	25.5	64.4	7.26	13.1
Penguins	179	2.20	0.18	5.00	–	0.07

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Vessel Operations:

Table 8. Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to the marine mammal behavioural response NOAA (2024) criterion of 120 dB re 1 µPa (SPL) from the most appropriate location for considered sources per scenario.

Scenario Description	R_{max} (km)	$R_{95\%}$ (km)
Intermediate Shallow; WTGIV, PSV and CLV	15.6	14.1
Deep; WTGIV, PSV and CLV	12.0	10.9

WTGIV = Wind Turbine Generator Installation Vessel, PSV = Platform Support Vessel, CLV = Cable Lay Vessel

Table 9. Summary: Maximum (R_{max}) horizontal distances (in km) and ensonified area (km²) for the NMFS (2024) frequency-weighted LF-cetacean SEL_{24h} TTS thresholds from the most appropriate location for the considered scenario.

Scenario Description	R_{max} (km)	Area (km²)
Intermediate Shallow; WTGIV, PSV and CLV	9.16	104
Deep; WTGIV, PSV and CLV	6.35	72.5

WTGIV = Wind Turbine Generator Installation Vessel, PSV = Platform Support Vessel, CLV = Cable Lay Vessel

Table 10. *Vessel operations:* Summary of animat simulation results indicating the maximum of the 95th percentile exposure ranges ($ER_{95\%}$) (in km) for each species for each modelled vessel scenario. A dash (-) indicates that no animat was exposed above the threshold.

Species	Intermediate Shallow; WTGIV, PSV and CLV	Deep; WTGIV, PSV and CLV
PTS SEL_{24h} (199 dB re 1 µPa² s) [a]		
Pygmy blue whale	–	–
Humpback whale	–	–
Minke whale	–	–
Southern right whale	–	–
TTS SEL_{24h} (179 dB re 1 µPa² s) [a]		
Pygmy blue whale	0.21	0.15
Humpback whale	0.77	0.83
Minke whale	0.02	0.02
Southern right whale	1.09	1.00
Behavioural response SPL (120 dB re 1 µPa) [b]		
Pygmy blue whale	11.6	7.79
Humpback whale	10.8	7.82
Minke whale	10.8	7.20
Southern right whale	10.8	7.87

a NMFS (2024) criteria for marine fauna.
b NOAA (2024) recommended unweighted behavioural threshold for marine mammals.

1. Introduction

JASCO Applied Sciences (JASCO) performed a series of modelling studies in the span of four years of underwater acoustic noise levels associated with construction activities for the Star of the South (SOTS) offshore wind farm (OWF). The modelling studies specifically predicted the distances from piling and vessel operations at which underwater sound levels exceeded noise effect criteria applicable to marine fauna including marine mammals, sea turtles, penguins, fish and invertebrates, as well as human divers. The key criteria which were utilised for the prediction of noise effects include behavioural response, impairment (temporary threshold shift (TTS) and permanent threshold shift (PTS)), and injury. PTS is a form of auditory injury as it is referred to in NMFS (2024) (using the acronym AUD INJ). However, it is noted that the definition of injury will vary by jurisdiction and TTS may also be considered to constitute a recoverable form of injury. In this report, for consistency with previous work, the term PTS is used.

For the impulsive sound source of impact pile driving, estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p); zero-to-peak pressure levels (PK, L_{pk}), and either single-strike (i.e., per-strike) or accumulated sound exposure levels (SEL, L_E) as appropriate for different noise effect criteria. For non-impulsive (continuous) noise sources, such as vibro pile driving and vessels, estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), and accumulated sound exposure levels (SEL, L_E). In this report, the duration period for SEL accumulation is defined as a 24-hour period over which sound energy is integrated; the level is specified with the abbreviation SEL_{24h}.

SEL_{24h} is a cumulative metric that reflects the dosimetric effect of noise levels within 24 hours, based on the assumption that a receiver (e.g., an animal) is consistently exposed to such noise levels at a fixed position. More realistically, marine mammals, fish, and sea turtles would not stay in the same location for 24 hours (especially in the absence of location-specific habitat) but rather a shorter period, depending on the animal's behaviour and the source's proximity and movements. Therefore, a reported radius for the SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be impaired, but rather that an animal could be exposed to the sound level associated with impairment (either temporary threshold shift (TTS) or permanent threshold shift (PTS)) if it remained within the ensonified area for 24 hours.

A more realistic representation of the potential exposures for pygmy blue whales (*Balaenoptera musculus brevicauda*), humpback whales (*Megaptera novaeangliae*), southern right whales (*Eubalaena australis*), and minke whales (dwarf minke whales, *B. acutorostrata* unnamed subspecies and Antarctic minke whales, *B. bonaerensis*) was undertaken using animal movement modelling ('animat modelling') using the JASCO Animal Simulation Model Including Noise Exposure (JASMINE). The acoustic modelling results were used in conjunction with realistically modelled animal movements to predict the distances at which whales are expected to be exposed above threshold criteria for TTS, PTS, and behavioural response. Sound exposure distribution estimates are determined by moving large numbers of simulated animals (animats) through a modelled time-evolving sound field, computed using specialised sound source and sound propagation models. This approach provides the most realistic prediction of the maximum expected SPL and SEL for comparison against the relevant thresholds.

This report is further structured as follows: the remainder of Section 1 provides details on the scenarios considered for modelling; Section 2 explains the metrics used to represent underwater acoustic fields and the effect criteria considered; Section 3 details the methodology for modelling the sound propagation, including the specifications of the considered sound sources and the environmental parameters. Section 3 also explains animal movement and exposure modelling methods. Sections 4 to 6 present the acoustic results as tabulated ranges to thresholds and contour maps, and the animal movement modelling results. All the most up to date modelling results are then summarised in Section 7.

1.1. Modelling Scenarios

Over the past four years, starting in 2022, JASCO has performed a total of four rounds of underwater noise modelling studies. Within each round, the most relevant criteria, scenarios and site locations at the time were used, along with the best available piling methodology information (i.e. drivability, pile dimensions, hammer model, etc). Table 11 presents a summary of the scenarios and relevant criteria considered in each modelling round corresponding to the results presented in this report (mitigation system abbreviations are expanded in the text below the table).

Table 11: Summary of the four modelling rounds

Modelling Round	Operations	Sites	Season	Results Presented (Mitigations)	Associated report	Noise effect threshold
First	Impact Piling: Monopile	MP1, MP3	Summer, Winter	Acoustic (Unmitigated)	Koessler 2025a	Southall et al. 2019
	Impact Piling: Concurrent Monopiles	MP1, MP1a	Winter	Acoustic (Unmitigated)		
	Impact Piling: Monopile	MP1, MP3	Winter	Acoustic (DBBC, DBBC + HSD); ANIMAT (DBBC)	(Koessler 2025b)	Southall et al. 2019
	Impact Piling: Jacket Pile	OSS		Acoustic (Unmitigated, DBBC)		
	Impact Piling: Concurrent Monopile and Jacket Pile	MP1, OSS		Acoustic (Unmitigated)		
Second	Impact Piling: Monopile	MP1, MP2	Winter	Acoustic (Unmitigated, DBBC, HSD, DBBC + HSD); ANIMAT(DBBC)	(Koessler 2025c)	Southall et al. 2019
	Impact Piling: Jacket Pile	OSS		Acoustic (Unmitigated, DBBC)		
Third	Vibro Piling: Monopile	MP1, MP2, MP3	Winter	Acoustic (Unmitigated); ANIMAT (Unmitigated)	(Koessler 2025d)	NMFS (2024)
	Vessels	1,2,3,4,5,6		Acoustic ANIMAT		
Fourth	Impact Piling: Monopile	MP1, MP2, MP3, MP4	Winter	Acoustic (Unmitigated, DBBC + HSD + PULSE); ANIMAT (DBBC + HSD + PULSE)	(Koessler 2025d)	NMFS (2024)
	Impact Piling: Jacket Pile	OSS		Acoustic (Unmitigated, DBBC + PULSE); ANIMAT (DBBC + PULSE)		

Those underwater noise modelling studies consider the following activities for assessing underwater noise:

- Installation of Wind Turbine Generator (WTG) foundation monopiles through impact pile driving.
- Installation of Offshore Sub-Station (OSS) foundation jacket piles through impact pile driving.
- Mitigation was considered for the impact piling activities. The mitigation systems that have been considered in the latest (fourth) round of modelling comprise:

  - No mitigation.
  - Specific frequency dependent attenuation curves to represent the application of a double big bubble curtain (DBBC) system.
  - Specific frequency dependent attenuation curves to represent the application of a hydro sound damper (HSD).
  - Adjusted impact hammer forcing functions for the application of a hydraulic damping mechanism to represent the application of the PULSE noise mitigation system.
- Simultaneous construction operations concepts (concurrent piling activities) to understand the potential underwater noise impacts.
- Installation of Wind Turbine Generator (WTG) foundation monopiles through vibro pile driving.
- Installation of Offshore Sub-Station (OSS) foundation jacket piles through vibro pile driving.
- Vessel operations associated with the OWF at two representative locations within the License Area (Intermediate Shallow, and Deep). The considered types of operations include:
  - A Wind Turbine Generator Installation Vessel (WTGIV) stationary under dynamic positioning (DP).
  - A Platform Support Vessel (PSV) holding position under DP deploying some type of pile driving noise mitigation, e.g., a bubble curtain.
  - A single cable lay vessel moving along a cable lay path using DP during cable laying operations.

1.1.1. Pile Driving Operations

The specified project design has indicated that foundations for WTGs will consist of a single monopile. Monopiles will have a tapered geometry that will vary in overall length depending on the water depth at the installation site. The geographical locations, and corresponding water depth, of modelled monopile and jacket pile installation sites (referred to as modelled sites) for the different modelling rounds are provided in Table 12. Full waveform acoustic modelling (Appendix C.2.2) was used in this report to estimate the noise effects on marine fauna.

To enable an assessment of the cumulative effect of multiple piles being driven at one time a scenario considering concurrent piling at two sites was modelled. The piling site labelled with the suffix “a” in Table 12 was considered for a concurrent modelling scenario. This location is consistent with piling operations at an adjacent WTG site, at a distance of 3420 m from the original modelled site. At this location, the modelled pile driving sound field footprints were translated from the original site to the new “a” site. The sound fields were then combined to estimate the combined footprint from concurrent pile driving activities. Additional technical detail on this procedure is provided in Section 3. The method captures large-scale sound propagation features, which dominate the sound field and is thus considered to provide a meaningful representation of noise emissions whilst saving computational effort.

The acoustic modelling effort considered both impact pile driving (at all sites) and vibratory (vibro) pile driving at a sub-set of sites as outlined in Table 11. Impact pile driving considers an impact hammer, which produces an impulsive sound source, while vibratory (vibro) pile driving utilises a vibrational hammer forcing the pile into the sediment and is considered a non-impulsive sound source. In both instances (impact and vibro pile driving), modelling was undertaken for full pile installation.

The modelling studies summarised here also considered the performance of several mitigation systems for impact pile driving, including a double big bubble curtain (DBBC), a hydro-sound-damper (HSD), and the IQIP-PULSE system. Combinations of the three mitigation systems outlined above were also modelled to assess whether more substantial levels of attenuation could be achieved. JASCO understands that it is not possible to apply a HSD around a sub-sea pile, which is why this mitigation option has not been considered for jacket piles in this study. Further details about the mitigation systems are included in Section 3.4. During the first modelling round, simple broadband attenuation levels (6 dB and 12 dB) were also considered to represent the application of mitigation systems; some of the results from this modelling are included in the Results sections for first-round modelling, but this method was superseded by the application of specific mitigation solutions in later modelling rounds.

Mitigation options have not been modelled for vibro pile driving due to a deficit of measurement studies examining the effectiveness of mitigation for vibro pile driving, and therefore a lack of certainty to be able to apply such a system within the modelling.

Table 12. Location details for the modelled sites between different modelling rounds.

Modelling Rounds	Site	Description	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 55		Water depth (m)
					X (m)	Y (m)	
First	1	MP 1	38° 52' 43.9"	146° 53' 54.0"	491181	5696661	42
	1a	MP 1a	38° 53' 33.2"	146° 51' 46.9"	488121	5695136	42
	2	MP 2	38° 50' 0.5"	146° 44' 17.1"	477268	5701671	20
	3	MP 3	38° 38' 43.9"	147° 1' 29.3"	502158	5722560	23
	4	OSS JP	38° 46' 11.0"	146° 56' 25.7"	494829	5708776	24
Second	1	MP 1	38° 52' 43.9"	146° 53' 54.0"	491181	5696661	42
	2	MP 2	38° 50' 0.5"	146° 44' 17.1"	477268	5701671	20
	4	OSS JP	38° 50' 50.9"	146° 52' 40.9"	489415	5700143	30
Third/Fourth	1	MP 1	38° 50' 4.50"	146° 44' 28.99"	477554	5701548	21.0
	2	MP 2	38° 49' 8.77"	146° 58' 1.03"	497131	5703297	34.7
	3	MP 3	38° 56' 1.14"	146° 51' 36.84"	487886	5690577	51.3
	4	MP 4	38° 53' 28.14"	146° 55' 44.92"	493855	5695300	47.0
	5	JP OSS	38° 45' 53.06"	146° 59' 17.32"	498970	5709330	29.6

MGA: Map Grid of Australia
MP: Monopile
JP OSS: Offshore sub-station jacket pile

Figures 1 to 3 show the modelling sites for pile driving operations. It should be noted that between the first and second modelling rounds, the Biologically Important Areas (BIAs) for southern right whales were updated. Therefore, the BIAs included on the maps in this section, and throughout Sections 4.1.2 and 4.2.2, are appropriate to the time when the modelling was undertaken.

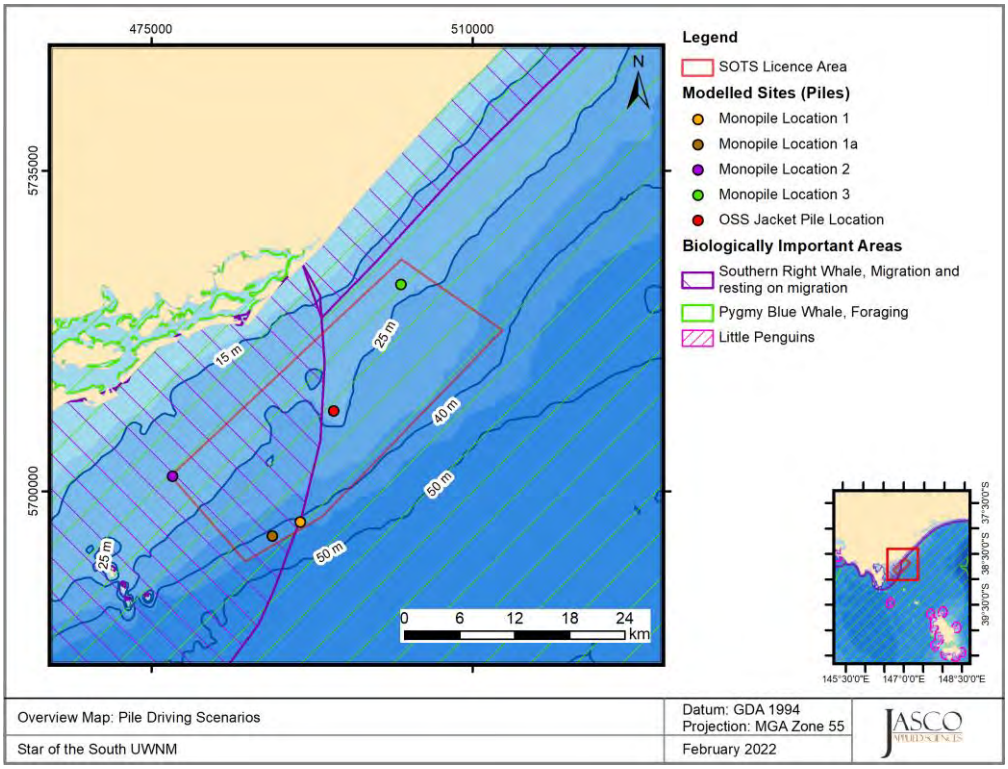


Figure 1. Overview map of the modelled sites for the first modelling round for impact pile driving scenarios.

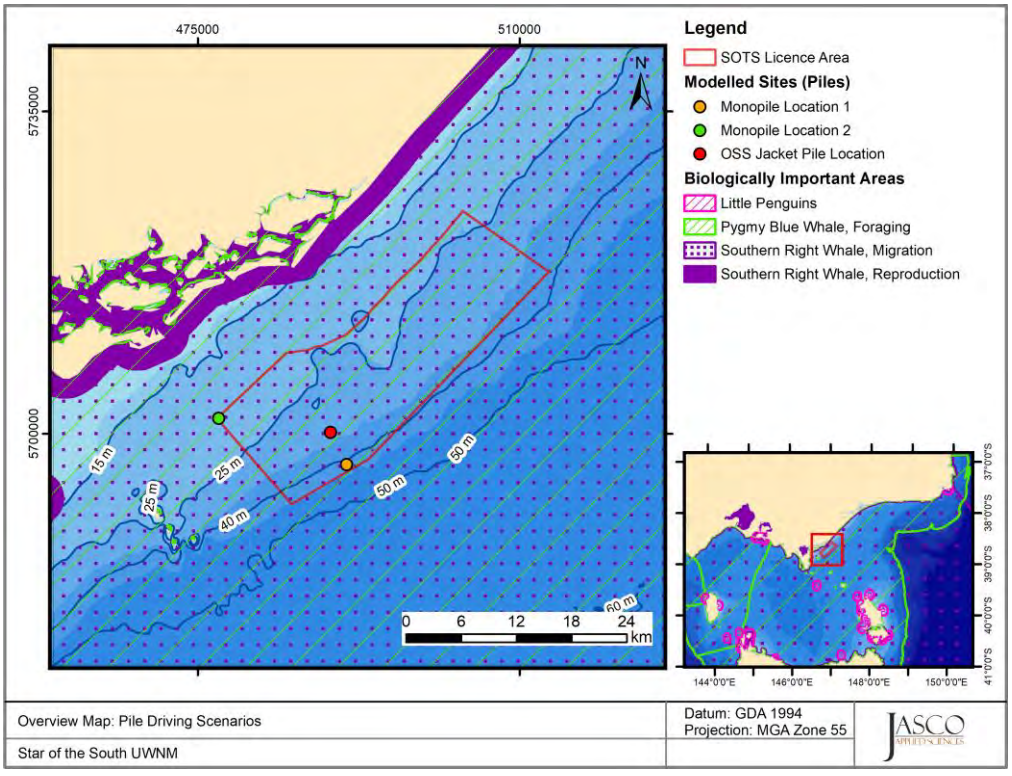


Figure 2. Overview map of the modelling sites for the second modelling round for impact pile driving scenarios.

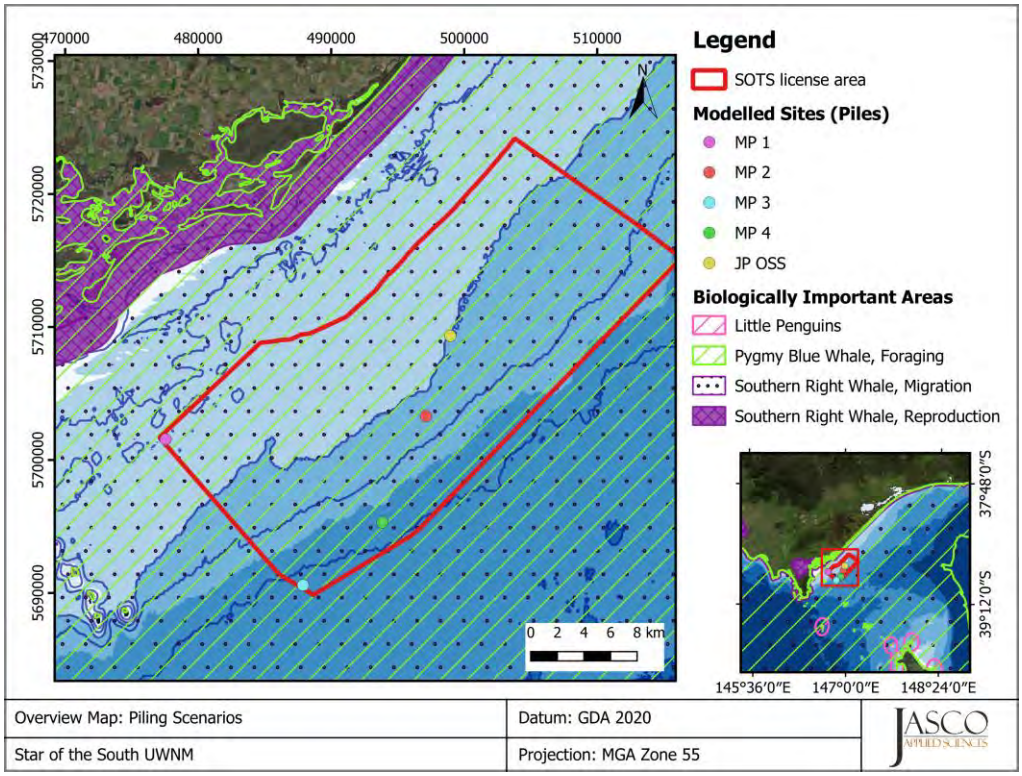


Figure 3. Overview map of the modelling sites for the third and fourth modelling round scenarios. Some locations are the same for vibratory and impact pile scenarios.

1.1.2. Vessel Operations

At the current stage for the project, the exact vessel selection is not known as vessel operators have not been contracted, thus specifications are also unknown. The following scenarios were defined based on the project envelope as defined by Star of the South, as well as a vessel candidate, and activity duration list also provided by the Star of the South.

The acronyms used for vessel types below and throughout the body of this report are as follows.

- WTGIV: Wind Turbine Generator Installation Vessel
- PSV: Platform Support/Supply Vessel
- CLV: Cable Lay Vessel

The Bokalift-1 has been proposed as a candidate vessel for the WTGIV. As there are no publicly available measurements of the sound produced by the Bokalift-1, JASCO considered the *Skandi Feinstein* as a proxy sound source for the Bokalift-1.

The vessel scenarios represent the installation of WTG foundation monopiles in shallow ('Intermediate Shallow') and deeper ('Deep') water regions within the Licence Area, and cable laying operations comprising the construction of the export cable to the mainland or between WTGs (i.e. the inter-array cable). The modelled operations consist of the following:

- A Wind Turbine Generator Install Vessel (WTGIV) holding position under dynamic positioning (DP) whilst installing a WTG.
- A Platform Support Vessel (PSV) holding position under DP deploying some type of pile driving noise mitigation, e.g., a bubble curtain.

- A Cable Lay Vessel (CLV) under DP transiting along a 6 km track whilst laying cable and advancing at a rate of 250 m/hr.

Ten unique geographic sites were considered to model the noise footprints from the vessels. Details of the modelled sites are presented in Table 13, the sites relevant to each scenario are outlined in Table 14, and Figure 4 displays an overview of the modelling area showing modelling sites, Biologically Important Areas (BIAs) for pygmy blue whales (*Balaenoptera musculus brevicauda*), southern right whales (*Eubalaena australis*) and little penguins (*Eudyptula minor*), and the regional bathymetry.

At this stage, it is not understood whether piles and/or the topside component will be installed using a vessel that can "jack-up" or with a vessel that maintains position using dynamic positioning (DP). For the purposes of this study, and from a noise emission perspective, a vessel on DP would constitute a worst-case scenario. Therefore, the vessel that installs piles and the topside components was considered to be under DP while undertaking operations. As the vessels that perform pile installation and topside installation are generally similar, for modelling purposes the vessel in these two activities was the same (WTGIV). Additional details on the vessel types, nominated vessels, specifications and vessel source levels can be found in Section 6. In the defined scenarios, all static and transiting noise sources have been modelled as being active for the entire assessment period of 24 hours. This period is also consistent with vessel activities and durations indicated by SOTS.

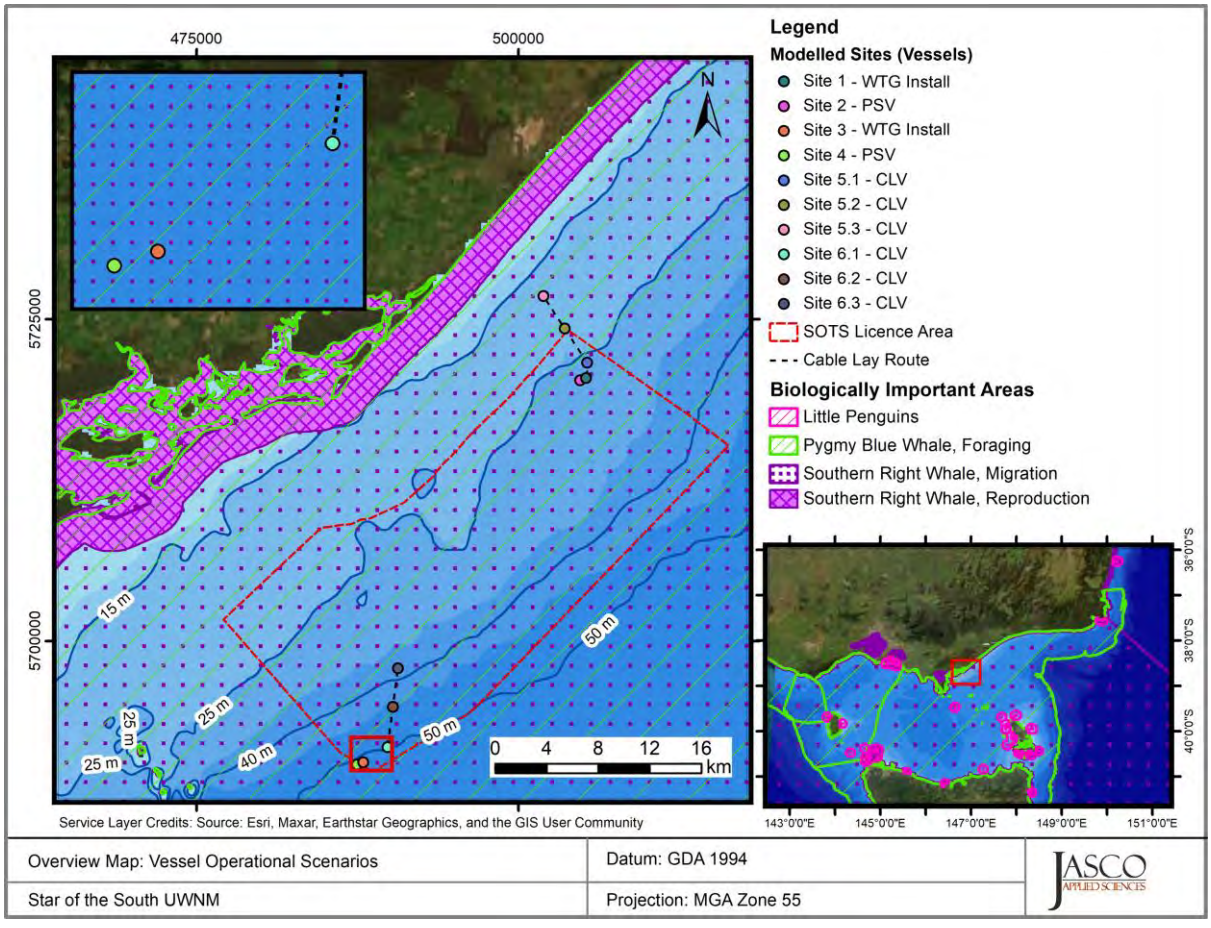


Figure 4. Overview map of the modelled sites for vessel operation scenarios.

Table 13. Modelled site locations and source information.

Site	Vessel Type	Latitude (S)	Longitude (E)	MGA Zone 55 (GDA94)		Water Depth (m)
				X (m)	Y (m)	
1	WTGIV	38° 39' 53.22"	147° 3' 37.00"	505244	5720420	29.7
2	PSV	38° 39' 58.33"	147° 3' 17.37"	504770	5720263	29.4
3	WTGIV	38° 56' 1.13"	146° 51' 38.49"	487926	5690577	51.4
4	PSV	38° 56' 6.20"	146° 51' 18.77"	487451	5690420	51.2
5.1	CLV	38° 39' 14.38"	147° 3' 40.58"	505331	5721617	27.3
5.2	CLV	38° 37' 48.44"	147° 2' 28.32"	503586	5724267	23.8
5.3	CLV	38° 36' 26.59"	147° 1' 19.48"	501922	5726790	22.5
6.1	CLV	38° 55' 23.09"	146° 52' 57.52"	489827	5691753	50.1
6.2	CLV	38° 53' 41.05"	146° 53' 14.85"	490240	5694899	45.9
6.3	CLV	38° 52' 3.84"	146° 53' 31.28"	490633	5697896	36.8

MGA: Map Grid of Australia
WTGIV: Wind Turbine Generator Install Vessel
PSV: Platform Support/Supply Vessel
CLV: Cable Lay Vessel

Table 14. Description of modelled vessel scenarios.

Scenario Description	Site(s)	Vessels	Operation Duration
Intermediate Shallow: WTGIV, PSV and CLV	1, 2, 5.1, 5.2, 5.3	WTGIV + PSV + CLV	24 h
Deep: WTGIV, PSV and CLV	3, 4, 6.1, 6.2, 6.3	WTGIV + PSV + CLV	24 h

1.2. Animal Movement Modelling Scenarios

Animal movement modelling simulations were run for pygmy blue whales (*Balaenoptera musculus brevicauda*), humpback whales (*Megaptera novaeangliae*), southern right whales (*Eubalaena australis*) and minke whales (*Balaenoptera bonaerensis* and *Balaenoptera acutorostrata unnamed subsp.*). Across the species, animats were considered in feeding or migrating behaviour states, and humpback and southern right whales were considered both with calves and without calves, to represent the different behaviours that these species may undertake in the project area.

Animats were randomly placed, or seeded, within the simulation area at a specified density (animats/km^2) within the species preferred depth range. During simulations, if an animats' movement takes it outside of its preferred depth range, it will begin to make movements (while still following the parameters within its species behaviour file) back towards its preferred depth range. For all simulations, animats were seeded at a nominal horizontal sampling density of 4 animats/km^2. Each of the animat simulations were run for a representative 24-hour duration.

2. Noise Effect Criteria

To assess the potential effects of a sound–producing activity, it is necessary to first establish exposure criteria (thresholds) for which sound levels may be expected to have a negative effect on animals. Whether acoustic exposure levels might injure or disturb marine fauna is an active research topic. Since 2007, several expert groups have developed SEL–based assessment approaches for evaluating auditory injury, with key works including Southall et al. (2007), Finneran and Jenkins (2012), Popper et al. (2014), United States National Marine Fisheries Service (NMFS 2018), Southall et al. (2019), NMFS (2024) and Accomando et al. (2025a). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially. Table 15 summarizes the noise effect criteria applied to each modelling round.

The perceived loudness of sound, especially impulsive noise such as from pile driving, is not generally proportional to the instantaneous acoustic pressure. Rather, perceived loudness depends on the pulse rise-time and duration, and the frequency content. Several sound level metrics, such as PK, SPL, and SEL, are commonly used to evaluate noise and its effects on marine life (Appendix A). The period of accumulation associated with SEL is defined, with this report referencing either a "per-strike" assessment or over 24 hours. The acoustic metrics in this report reflect the ISO standard for acoustic terminology, ISO/DIS 18405:2017 (2017a).

Table 15. Summary of noise effect criteria on all modelling rounds

Modelling Round and Associated Report	Animal Type	Measurement	Unit of Measurement	Criteria Reference
Impulsive				
First, Second (Koessler , Koessler 2025d), (Koessler 2025b), (Koessler 2025c)	Marine Mammals	Peak pressure levels	PK; L_{pk}	Southall et al. (2019)
		Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	
		Marine mammal behavioural thresholds	SPL; L_p	Wood et al. (2012a) Southall et al. (2019)
	Fish	Fish (with or without swim bladders), fish eggs, and larvae	SPL; L_p	Popper et al. 2014
	Sea Turtle	Sea Turtle behavioural response threshold	SPL; L_p	NSF (2011)
		Sea Turtle behavioural disturbance	SPL; L_p	McCauley et al. 2000b, 2000a)
		Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	Finneran et al. (2017)
	Penguin	Peak pressure levels	PK; L_{pk}	Southall et al. (2019)
		Frequency–weighted accumulated sound exposure	SEL; $L_{E,24h}$	
		Behavioural response	SPL; L_p	Sørensen et al. (2020)
	Invertebrates	Peak-peak pressure levels	PK-PK; $L_{pk\text{-}pk}$	Day et al. (2016a), Day et al. (2019), Day et al. (2016b),

		Particle acceleration at the seafloor	(ms^{-2})	Day et al. (2017) and Payne et al. (2008)
		Squid startle (inking) response sound level(Fewtrell and McCauley 2012)	SEL (L_E)	Fewtrell and McCauley 2012)
	Human	Health assessment threshold for swimming and diving	SPL; L_p	Parvin (2005), Ainslie (2008)
Fourth (Koessler 2025d)	Marine Mammals	Peak pressure levels	PK; L_{pk}	NMFS (2024)
		Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	NMFS (2024)
		Marine mammal behavioural thresholds non-migratory species	SPL; L_p	Wood et al. (2012a) NMFS (2024)
	Fish	Fish (with or without swim bladders), fish eggs, and larvae	SPL; L_p	Popper et al. (2014)
	Sea Turtle	Sea Turtle behavioural response threshold	SPL; L_p	NSF (2011)
		Sea Turtle behavioural disturbance	SPL; L_p	McCauley et al. 2000b, 2000a)
		Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	Accomando et al. (2025a)
	Penguin	Peak pressure levels	PK; L_{pk}	NMFS (2024)
		Frequency–weighted accumulated sound exposure	SEL; $L_{E,24h}$	NMFS (2024)
Non-Impulsive				
Third (Koessler 2025d)	Marine Mammals	Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	NMFS (2024)
		Marine mammal behavioural thresholds	SPL; L_p	NOAA (2024)
	Fish	Fish (with or without swim bladders), fish eggs, and larvae	SPL; L_p	Popper et al. (2014)
	Sea Turtle	Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	Accomando et al. (2025a)
	Penguins	Frequency–weighted accumulated sound exposure levels	SEL; $L_{E,24h}$	NMFS (2024)

2.1. Impulsive Noise

Impact pile driving activities have been assessed as an impulsive noise source consistent with the considered thresholds and guidelines.

The following thresholds and guidelines applied within each modelling round were chosen because they represented the best available science at the time. All noise effect criteria are discussed in detail in Appendix A, and the points below summarise the thresholds and guidelines (and sound levels presented in literature for fauna with no defined thresholds) for the most recent third and fourth rounds of modelling, and therefore the current best available guidance, with superseded criteria (applied in the first and second modelling rounds) also included as sub-points:

- Marine mammals:
  - Peak pressure levels (PK; L_{pk}) and frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from NMFS (2024) for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) in marine mammals for impulsive sources. As discussed within NMFS (2024), intense noise exposures can cause auditory injury (represented by either AUD INJ or AINJ) without PTS occurring. In this report, the terms PTS and auditory injury can be considered to be used interchangeably, however it is acknowledged that auditory injury may occur without PTS.
    - SUPERSEDED: Peak pressure levels (PK; L_{pk}) and frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Southall et al. (2019) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals for impulsive sources.
  - Marine mammal behavioural thresholds based on the U.S. National Oceanic and Atmospheric Administration (NOAA) (2024) unweighted criterion for marine mammals of 160 dB re 1 µPa (SPL; L_p) for impulsive sound sources.
    - SUPERSEDED: Marine mammal behavioural thresholds based on the U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) unweighted criterion for marine mammals of 160 dB re 1 µPa (SPL; L_p) for impulsive sound sources.
  - Marine mammal behavioural thresholds based on the Wood et al. (2012a) frequency-weighted criteria for impulsive sound sources of 160 dB re 1 µPa (SPL; L_p) for non-migratory species and 140 dB re 1 µPa (SPL; L_p) for migrating mysticetes, using the weighting functions from NMFS (2024).
    - SUPERSEDED: Marine mammal behavioural thresholds based on the Wood et al. (2012a) frequency-weighted criteria for impulsive sound sources of 160 dB re 1 µPa (SPL; L_p) for non-migratory species and 140 dB re 1 µPa (SPL; L_p) for migrating mysticetes, using the weighting functions from Southall et al. (2019).
- Fish, fish eggs, and larvae:
  - Sound exposure guidelines for fish (with or without swim bladders), fish eggs, and larvae (Popper et al. 2014).
- Sea turtles:
  - Sea Turtle behavioural response threshold of 166 dB re 1 µPa (SPL; L_p) as applied by the US NMFS for impulsive noise, along with a sound level associated with behavioural disturbance 175 dB re 1 µPa (SPL; L_p) (McCauley et al. 2000b, 2000a).
  - Peak pressure levels (PK; L_{pk}) and frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Accomando et al. (2025a) for the onset of TTS and PTS in turtles for impulsive sound sources.

        - SUPERSEDED: Frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) for the onset of PTS and TTS in turtles for impulsive sound sources.
- Diving birds (penguins):
    - Thresholds for otariid pinnipeds are used as a proxy (Section A.3.1.4): Peak pressure levels (PK; L_{pk}) and frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from NMFS (2024) for the onset of PTS and TTS in otariids.
        - SUPERSEDED: Thresholds for otariid pinnipeds are used as a proxy (Section A.3.1.4): Peak pressure levels (PK; L_{pk}) and frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Southall et al. (2019) for the onset of PTS and TTS in otariids.
    - Due to the limited availability of data relating to noise effects on marine avifauna, a precautionary approach to the management of underwater noise is recommended, but despite this, no behavioural response thresholds, or auditory frequency weighting function for behavioural response is currently recommended or applied.
        - SUPERSEDED: Behavioural response to impulsive sound of 120 dB re 1 µPa (SPL; L_p) for diving birds based on information from Sørensen et al. (2020). This metric was used in earlier modelling rounds, however in the most recent modelling rounds this was not included owing to concerns regarding the veracity of the Sørensen et al. (2020) study and its applicability in this context.
- Invertebrates:
    - Peak-peak pressure levels (PK-PK; $L_{pk\text{-}pk}$) and particle acceleration (ms^{-2}) at the seafloor to help assess effects of noise on crustaceans through comparing to results in Day et al. (2016a), Day et al. (2019), Day et al. (2016b), Day et al. (2017) and Payne et al. (2008).
    - Squid: An squid startle (inking) response sound level of 162 dB re 1 μPa^2s per–pulse SEL (L_E) (Fewtrell and McCauley 2012).
- Human divers:
    - An SPL human health assessment threshold of 145 dB re 1 µPa (SPL; L_p) for sound exposure from impulsive noise to people swimming and diving derived from Parvin (2005), and considering Ainslie (2008).

Appendix A expands on the thresholds, guidelines and sound levels for all marine fauna and the human health assessment threshold.

2.2. Non-Impulsive Noise

The following thresholds and guidelines applied within each modelling round were chosen because they represented the best available science at the time. All noise effect criteria are discussed in detail in Appendix A, and the points below summarise the thresholds and guidelines (and sound levels presented in literature for fauna with no defined thresholds) for the most recent third and fourth rounds of modelling, and therefore the current best available guidance, with superseded criteria also included as sub-points:

- Marine mammals:
    - Frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from NMFS (2024) for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) in marine mammals for non-impulsive sources. As discussed within NMFS (2024), intense noise

exposures can cause auditory injury (represented by either AUD INJ or AINJ) without PTS occurring. In this report, the terms PTS and auditory injury are used interchangeably, however it is acknowledged that auditory injury may occur without PTS.

- SUPERSEDED: Frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Southall et al. (2019) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals for non-impulsive sources.

- Marine mammal behavioural thresholds based on the U.S. National Oceanic and Atmospheric Administration (NOAA) (2024) unweighted criterion for marine mammals of 120 dB re 1 µPa (SPL; L_p) for non–impulsive sound sources.
  - SUPERSEDED: Marine mammal behavioural thresholds based on the U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) unweighted criterion for marine mammals of 120 dB re 1 µPa (SPL; L_p) for non–impulsive sound sources.

- Fish, fish eggs, and larvae:
  - Sound exposure guidelines for fish (with or without swim bladders), fish eggs, and larvae (Popper et al. 2014).
- Sea turtles:
  - Frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Accomando et al. (2025a) for the onset of PTS (a form of auditory injury referred to as AINJ in Accomando et al. (2025b)) and TTS in turtles for non–impulsive sound sources.
    - SUPERSEDED: Frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) for the onset of PTS and TTS in turtles for non–impulsive sound sources.
- Diving birds (penguins):
  - Thresholds for otariid pinnipeds are used as a proxy (Section A.3.1.4): frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from NMFS (2024) for the onset of PTS and TTS in otariids.
    - SUPERSEDED: Thresholds for otariid pinnipeds are used as a proxy (Section A.3.1.4): frequency–weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Southall et al. (2019) for the onset of PTS and TTS in otariids.

Appendix A expands on the thresholds, guidelines and sound levels for all marine fauna and the human health assessment threshold.

3. Methods

The OWF construction will occur along the continental shelf of South-eastern Australia, with water depths ranging from about 20–50 m (see Appendix C.1.1) within the Licence Area. The physical properties of the water (i.e., temperature, salinity and sound speed) were initially selected to represent summer and winter seasonal water column sound speed profiles (first modelling round). The modelling work determined that the winter month would be more likely to result in sound travelling further and June was selected for sound propagation modelling within all later modelling rounds to ensure precautionary estimates of distances to received sound level thresholds. Refer to Appendix C.1.2 for further details on the sound speed profiles.

Within the Licence Area of the OWF, the geophysical and acoustic propagation loss studies indicate that the seabed consists of coarse unconsolidated layered sediments underlain by a more cemented horizon (Fitzallen 2020, McCauley 2021). During the first and second modelling rounds, detailed geotechnical information such as porosity and grain size measurement with depth below the seafloor were not available at the time of this study. During the third and fourth modelling rounds, geotechnical site investigations and borehole data had been gathered for Star of the South. These data sources were considered together to define four geoacoustic profiles, each of which corresponded to a different water depth regime. Geoacoustic profile details are provided in Appendices C.1.3 and C.1.4.

The following sections provide a description of the inputs and methods used for this underwater noise modelling study.

3.1. Impulsive Noise

The impulsive noises are sourced from pile driving activities, including monopile and jacket pile installation operations. The sections below provide additional detail on the input parameters used to generate the sound field predictions from impact pile driving activities.

To estimate sound generated during piling, the following modelling steps were performed:

1. Forcing functions were computed for the hammer and strike energy settings, by using GRLWEAP software (Pile Dynamics 2010) as described in Appendix B.1.
2. Equivalent acoustic source levels were determined using the GRLWEAP-generated forcing functions as input to JASCO's Pile Driving Source Model (PDSM) (MacGillivray 2014, Lippert et al. 2016, Lippert 2018).
3. Propagation of sound from the pile was modelled using JASCO's Full Wave Range-dependent Acoustic Model (FWRAM). FWRAM uses the equivalent acoustic source from Step 2 to compute synthetic pressure waveforms, at multiple ranges and depths. Synthetic pressure waveforms were modelled over the frequency range 10 – 1024 Hz, inside a 1 s window.
4. The propagated sound field was used to compute maximum-over-depth received levels over a large regular grid, from which distances to effect criteria thresholds are calculated.

3.1.1. Per-strike Modelling

Two sound propagation models were used to predict the acoustic field around driven pile sources:

- Full Waveform Range-dependent Acoustic Model (FWRAM, Appendix C.2.2), Monopiles and Jacket piles).
- Wavenumber integration model (VSTACK, Appendix C.3.3), unmitigated pile driving only.

JASCO's Time-domain Full Waveform Range-dependent model (FWRAM; Appendix C.2.2) was used in conjunction with the vertical array of discrete point sources from PDSM (Appendix B.1.) to model sound propagating away from the driven pile along 72 radial planes (every 5 degrees), out to a maximum range of 90 km from the pile, with a 10 m receiver range step which increase with distance from the source. In addition, an empirical extrapolation was applied to extend the received level frequency range up to 25 kHz using a 20 dB/decade decay rate based on acoustic measurements of impact pile driving (Illingworth & Rodkin 2007, Matuschek and Betke 2009).

The propagated sound field was used to compute maximum-over-depth received levels over a Cartesian regular grid. Received levels grids were computed for all per-strike metrics including unweighted and weighted SEL, unweighted PK, per-strike SPL and accumulated SEL across the entire driving sequence for a given pile. The synthetic waveforms from FWRAM were also used to compute SEL-to-SPL conversions (Appendix C.2.2), which was then used to compute regular grids of weighted per-strike SPL. From these grids, distances to and contours of SPL effect criteria thresholds could be calculated.

VSTACK was used to calculate PK-PK levels and particle motion for a receiver at 5cm above the seafloor, along a single transect at close range from driven monopiles to a maximum distance of 1 km. PK-PK levels are provided for unmitigated scenarios only as VSTACK does not currently have the ability to incorporate sound attenuating mitigation systems.

3.1.2. Accumulated SEL Modelling for Pile Driving

For impact piling, 24-hour SEL results were determined through the accumulation of energy across the entire pile driving operation, accounting for the per-strike sound fields modelled for five phases representing different seafloor penetration depths. Accumulated SEL over the monopile and jacket pile installation operation was calculated from the number of strikes based on the penetration rate data detailed in Sections 4.1.1 and 4.2.1. The SEL for each section of the piling operation was estimated using the following equation:

$$L_{E,\text{cumulative}} = L_E + 10\log_{10}(N) \quad (1)$$

where L_E is the per-strike energy source level and N is the number of strikes. These were appropriately summed to give SEL across the entire driving sequence for the pile.

3.1.3. Concurrent Pile Driving

For the concurrent modelling scenario (first modelling round), the additional locations considered are consistent with construction operations at an adjacent WTG site, 3420 m from the original modelled site.

At these locations the modelled radial grids of sound field footprints were translated from the original site to the new "1a" site. The grids of maximum-over-depth sound levels for each strike at Site 1 and Site 1a were then resampled (by linear triangulation) to produce a such that they had the same regular Cartesian grid; the sound field grid cell was 20 m. The sound field resulting from concurrent pile driving strikes at different locations was predicted by summing these grids and the contours and threshold ranges were calculated from these flat regular grids of the modelled acoustic fields.

This method captures large-scale sound propagation features, which dominate the sound field, and is thus considered to provide a meaningful representation of noise emissions whilst saving computational effort.

3.2. Non-Impulsive Noise

3.2.1. Vibratory Pile Driving

During vibratory (vibro) pile driving, a vibratory hammer creates a rapid set of deformations that propagate down the pile and cause the surrounding soil to liquefy, thereby reducing skin friction that supports the pile and placing more pressure on the bottom end of the pile (referred to as the toe). The vibrations also lead to small penetrations of the toe so that the entire pile sinks into the seabed.

3.2.1.1. SPL Modelling for Pile Driving

Vibratory forcing functions were computed for monopile and jacket pile foundations, using GRLWEAP (GRLWEAP, Pile Dynamics 2010). Further details are provided in Sections 5.1.1 and 5.2.1.

The resulting forcing functions served as inputs to JASCO's pile driving source model (PDSM, Appendix B.1), which is used to estimate an equivalent acoustic source represented by a linear array of monopoles evenly distributed along the pile. As with impact pile driving, sound propagation of the vibratory pile driving source signature is performed using FWRAM.

3.2.1.2. Accumulated SEL Modelling for Pile Driving

For vibro piling, SPL modelling results were converted to SEL by the duration of the modelled activity, which is appropriate for a non-impulsive noise source. As SEL was assessed over 24 h period, and any single would be installed with that period. The conversion from SPL was obtained by increasing the levels by $10*\log_{10}(T_i)$. Accumulated SEL over the monopile and jacket pile installation operation were calculated from the duration data detailed in Section 4.1.1 and Sections 5.1.1, respectively. The SEL for each modelled section of the piling operation was estimated using the following equation:

$$L_{E,\text{cumulative}} = L_E + 10\log_{10}(T_i) \quad (2)$$

where L_E is a 1 second SPL for a given modelled penetration depth and T_i is duration of the drive at a given phase of driving. These were appropriately summed to give SEL across the entire vibratory driving sequence for a given pile.

3.2.2. Vessel Modelling

The sections below provide additional detail on the input parameters used to generate the sound field predictions from activities that produce non-impulsive noise.

The following modelling steps were performed:

- Determine a representative decidecade source level spectrum for the considered noise source. This can be accomplished by specifications, publicly available noise measurement, broadband scaling of levels from surrogate sources where there is limit available noise information.
- Sound propagation of sound from the source was modelled using JASCO's Marine Operations Noise Model and the BELLHOP ray tracing model for all frequencies of interest (MONM-BELLHOP; Appendix C.3.2).
- The propagated sound field was used to compute maximum-over-depth received levels over a large regular grid, from which distances to effect criteria thresholds are calculated.

JASCO's MONM model was used to predict the acoustic field at frequencies of 10 Hz to 1 kHz for all vessels and stationary noise sources. To supplement the MONM results, high-frequency results for propagation loss were modelled using Bellhop for frequencies from 1.26 to 25 kHz. The sound field modelling calculated propagation losses up to 100 km from a given source, with a horizontal separation of 20 m between receiver points along the modelled radials. A horizontal angular resolution of $\Delta\theta$ = 2.5° for a total of N = 144 radial planes were used. Receiver depths were chosen to span the entire water column over the modelled areas, from 2 m to a maximum of 1000 m, with step sizes that increased with depth.

For stationary vessels, the SPL modelling results were converted to SEL by the duration of the measurement, which is appropriate for a non-impulsive noise source. As SEL was assessed over 24 h and for a stationary vessel over a day, the conversion from SPL was obtained by increasing the levels by $10*\log_{10}(T)$, where T is 86,400 (the number of seconds in 24 h). For scenarios where a vessel was transiting along a track a similar adjustment to the SPL was applied, however the time factor was determined based on the step size along the track and the vessel's speed. See Appendix C.3.4 for detail.

3.2.2.1. Vessel Sound Sources (Third Modelling Round)

Figure 5 presents a summary plot of all considered vessel source spectra in the most recent (third) vessel modelling round for comparison purposes. The source spectra plot shows the distribution of sound across the decidecade frequency bands that the modelling considers.

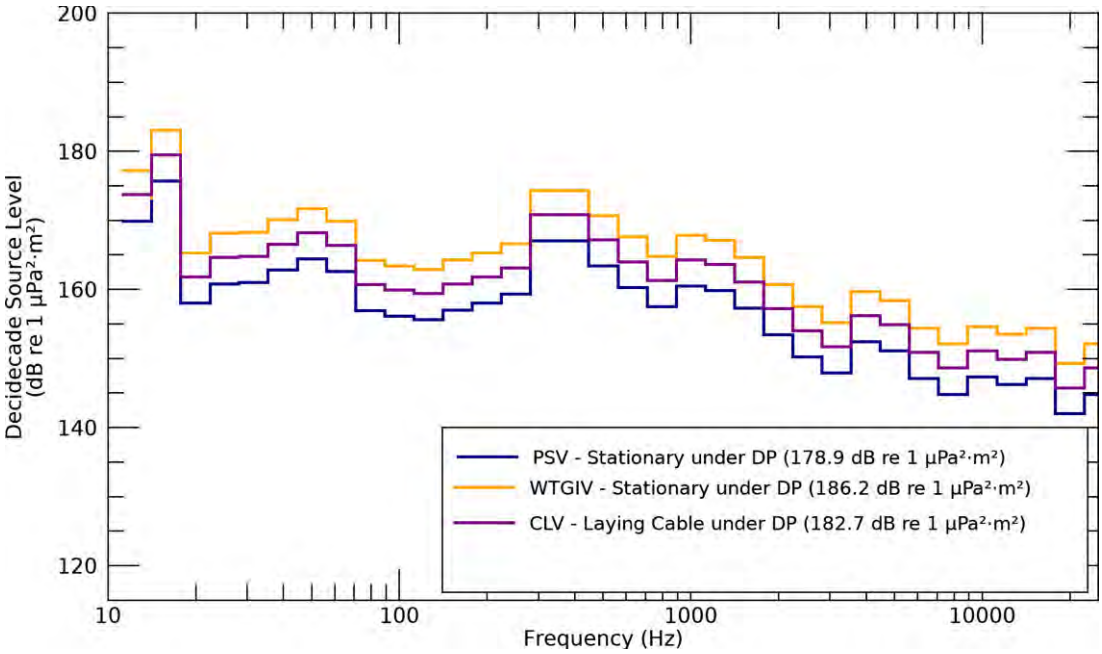


Figure 5. Source level spectra (in decidecade frequency-band) for all sound sources.

3.2.2.1.1. Wind Turbine Generator Install Vessel (WTGIV)

The Bokalift–1 (Figure 6) was selected considering several potential candidates for an offshore installation vessel. Whilst all considered vessels had similar specifications, Bokalift–1 had the most installed power and the greatest number of thrusters, which lead to its selection as part of a conservative approach given the unknowns.

At the time of this study, JASCO was not aware of any sound source characterisation studies and measurements for WTGIVs. As such there is ambiguity around the source level characteristics and noise generation potential whilst maintaining position to install pile foundations. The approach taken

was to investigate potential upper and lower bounds of the source level based on other vessels which do have source level measurements while on DP.

The selected source level used within the modelling presented in this report was based on a noise monitoring study that JASCO undertook to measure DP levels of the *Skandi Feistein* at a location approximately 90 km north-east of the SOTS area. The *Skandi Feistein* conducted multiple movement trials enabling noise measurements for different activities including four dynamic positioning (DP) exercises. From these data a regression curve was obtained between source level and thruster power utilisation.

JASCO were advised by SOTS that a total power usage of 50% represents the maximum safe operational thrust combination during normal DP field operations.

Using regression correlation with a total power usage of 50%, the broadband source level of the *Skandi Feistein* while under DP was used to obtain a second source level estimate for the WTGIV.

To account for the difference in thruster power, and differences in vessel size between the WTGIV and the *Skandi Feistein*, the surrogate levels were scaled by the difference in maximum installed thruster power following Equation (3)

$$\mathrm{SL} = \mathrm{SL}_{\mathrm{ref}} + 10\log_{10}\left(\frac{P}{P_{surrogate}}\right) \quad (3)$$



Figure 6. Photo of the vessel BOKALIFT 1 – Transportation & installation vessel (refer to: Heavy lift vessels (boskalis.com))

3.2.2.1.2. Platform Support Vessel (PSV) and Cable Lay Vessel (CLV)

To model operations that include DP and standby operations a surrogate vessel was also used to model thruster noises for the PSV and CLV.

As there are no publicly available measurements of the source level of the VOS Shine PSV or the Seaway Phoenix CLV, the source levels of these vessels under DP were estimated using the source levels associated with the *Skandi Feistein*. The *Skandi Feistein* was considered a potential surrogate, primarily because of its similar size and vessel class.

In a similar approach applied to the WTGIV, using regression correlation with a total power usage of 50%, the broadband source level of the *Skandi Feistein* while under DP was applied.

To account for the difference in thruster power, the source levels of the PSV and CLV were scaled by the difference in maximum installed thruster power following Equation (4).

$$\mathrm{SL} = \mathrm{SL}_{\mathrm{ref}} + 10\log_{10}\left(\frac{P}{P_{surrogate}}\right) \quad (4)$$



Figure 7. (Left panel) Photo of the vessel VOS Shine offshore-support vessel (refer to: https://www.vroon.nl/Fleet.aspx). (Right panel) Photo of the vessel Seaway Phoenix cable lay vessel (refer to: Datasheets (subsea7.com)).

3.2.3. Geometry and Modelled Regions

JASCO's Marine Operations Noise Model (MONM; see Appendix C.3.2) was used to predict the acoustic field at frequencies of 10 Hz to 25 kHz for all vessels. To supplement the MONM results (10 Hz to 1 kHz), high-frequency results for propagation loss were modelled using BELLHOP (Porter and Liu 1994) for frequencies from 1.26 to 25 kHz. The MONM and BELLHOP results were combined to produce results for the full frequency range of interest.

The sound field modelling calculated propagation losses up to 100 km from the source, with a horizontal separation of 20 m between receiver points along the modelled radials. The sound fields were modelled with a horizontal angular resolution of $\Delta\theta$ = 2.5° for a total of N = 144 radial planes. Receiver depths were chosen to span the entire water column over the modelled areas, from 2 m to a maximum of 1000 m.

To produce the maps of received sound level isopleths, and to calculate distances to specified sound level thresholds, the maximum-over-depth level was calculated at each sampling point within the modelled region. The radial grids of maximum-over-depth levels were then resampled (by linear triangulation) to produce a regular Cartesian grid. The contours and threshold ranges were calculated from these grids of the modelled acoustic fields.

3.2.4. Accumulated SEL

In this study, the sound sources were considered to be continuously operating with new sound energy constantly being introduced to the environment. The reported source levels are usually in terms of sound pressure levels (SPL), representing the root-mean-square (rms) pressure level of a considered source. The evaluation of the cumulative sound field (i.e., in terms of SEL_{24h}) depends on the number of seconds of operation during the accumulation period.

The SPL modelling results were converted to SEL by the duration of the measurement, which is appropriate for a non-impulsive noise source. Here, SEL was assessed over 24 hours. For a stationary vessel, the conversion from SPL was obtained by increasing the levels by $10*\log_{10}(T)$, where T is 86,400 (the number of seconds in 24 hours), or a shorter duration as required. For scenarios where a vessel was transiting along a track, a similar adjustment to the SPL was applied, however the time

factor was determined based on the step size along the track and the vessel's speed. See Appendix C.3.4 for details.

3.3. Animal Movement and Exposure Modelling

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was used to predict the exposure of animats to sound arising from the modelled scenarios. JASMINE integrates the predicted sound field with biologically meaningful movement rules for marine mammal species (pygmy blue whales, humpback whales, southern right whales and minke whales for the current analysis) that results in an exposure history for each animat in the model. An overview of the exposure modelling process using JASMINE is shown in Figure 8.

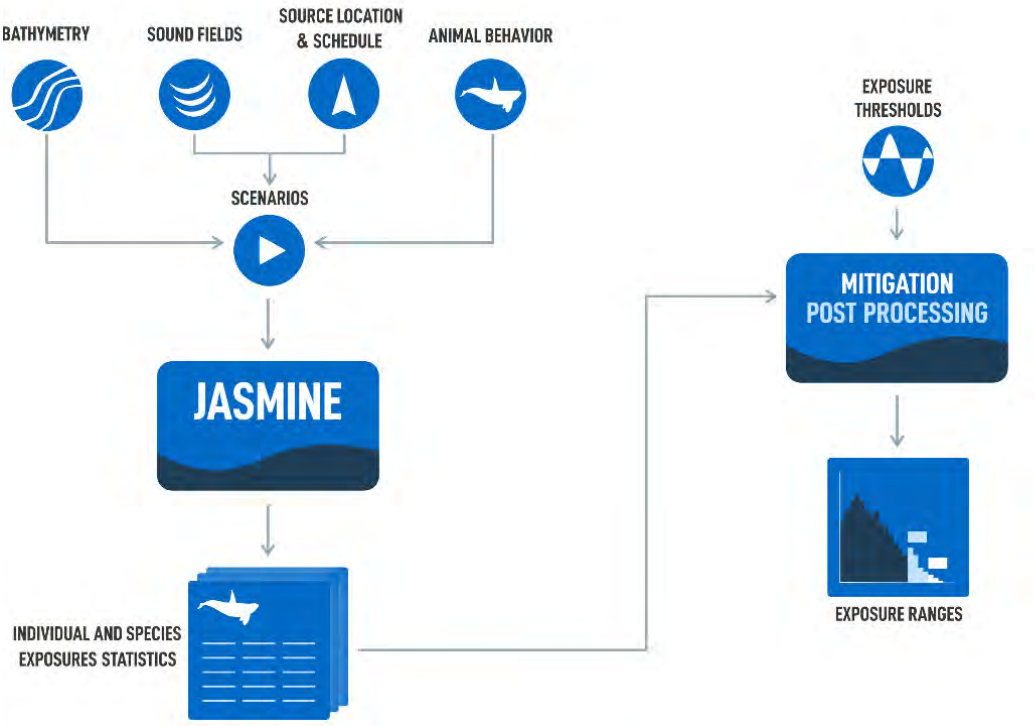


Figure 8. Exposure modelling process overview.

In JASMINE, the sound received by the animats is determined by the proposed piling operations. As illustrated in Figures 9 and 10, animats are programmed to behave like the marine animals that may be present in an area. The parameters used for forecasting realistic behaviours (e.g., diving and foraging depth, swim speed, surface times) are determined and interpreted from marine mammal studies (e.g., tagging studies) where available, or reasonably extrapolated from related or comparable species. For cumulative metrics, an individual animat's sound exposure levels are summed over a 24-hour duration to determine its total received energy, and then compared to the relevant threshold criteria. For single-exposure metrics, the maximum exposure is evaluated against threshold criteria for each 24-hour period. For additional information on JASMINE, see Appendix D.

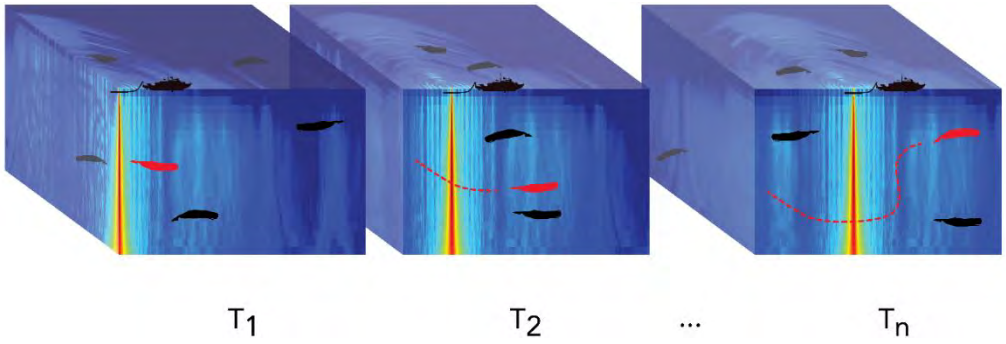


Figure 9. Depiction of animats in a moving sound field. Example animat (red) shown moving with each time step (T_n). The acoustic exposure of each animat is determined by where it is in the sound field, and its exposure history is accumulated as the simulation steps through time.

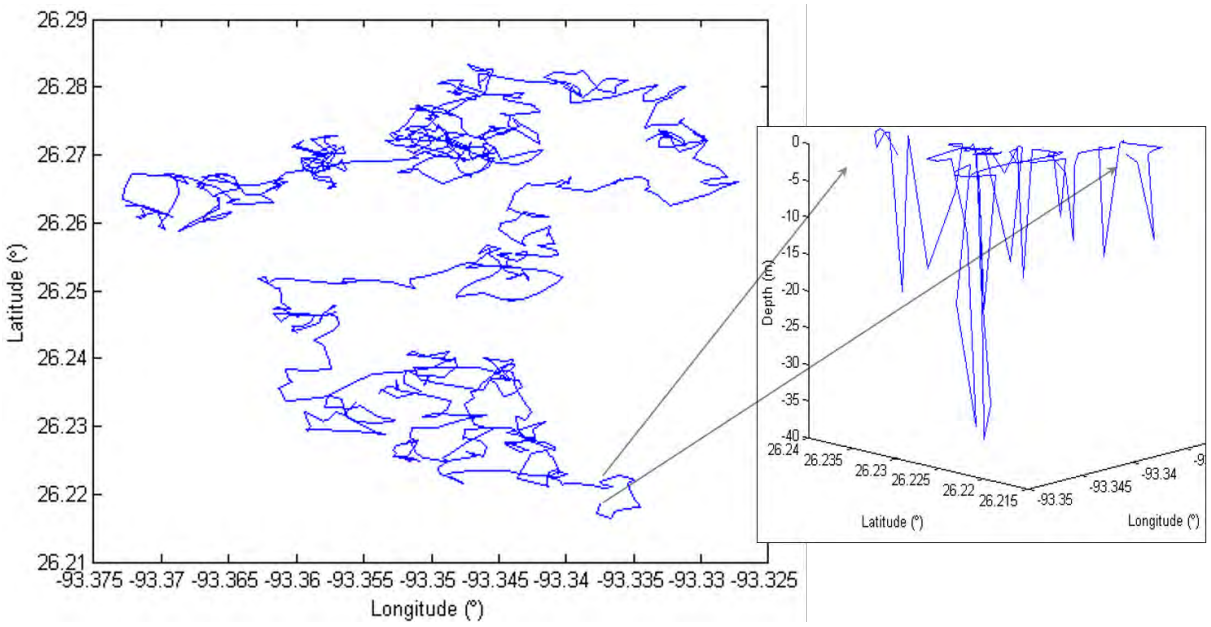


Figure 10. Overview of an example animat track (left panel) and an excerpt of the dive profile for a portion of the track (right panel) , demonstrating both the vertical and horizontal movement of an animat.

The same monopiles, sub-station jacket pile and vessel scenarios from a subset of the static acoustic modelling scenarios were considered for the animal exposure modelling. Each simulation was run for a representative period of 24 hours to coincide with the scheduled piling activity. Animats were populated in the model ('seeded') depending on species-specific depth preferences, which resulted in biologically realistic restrictions to animat distribution within the modelling extents (Figure 11). Additionally, all animats were seeded within the entire modelling area (i.e., not restricted to a BIA), to ensure that exposures from animats migrating into a BIA through the larger extents of the project area

were assessed. To evaluate PTS, TTS, and behavioural response, exposure results were obtained using detailed behavioural information for modelled species (described in Section 3.3.2).

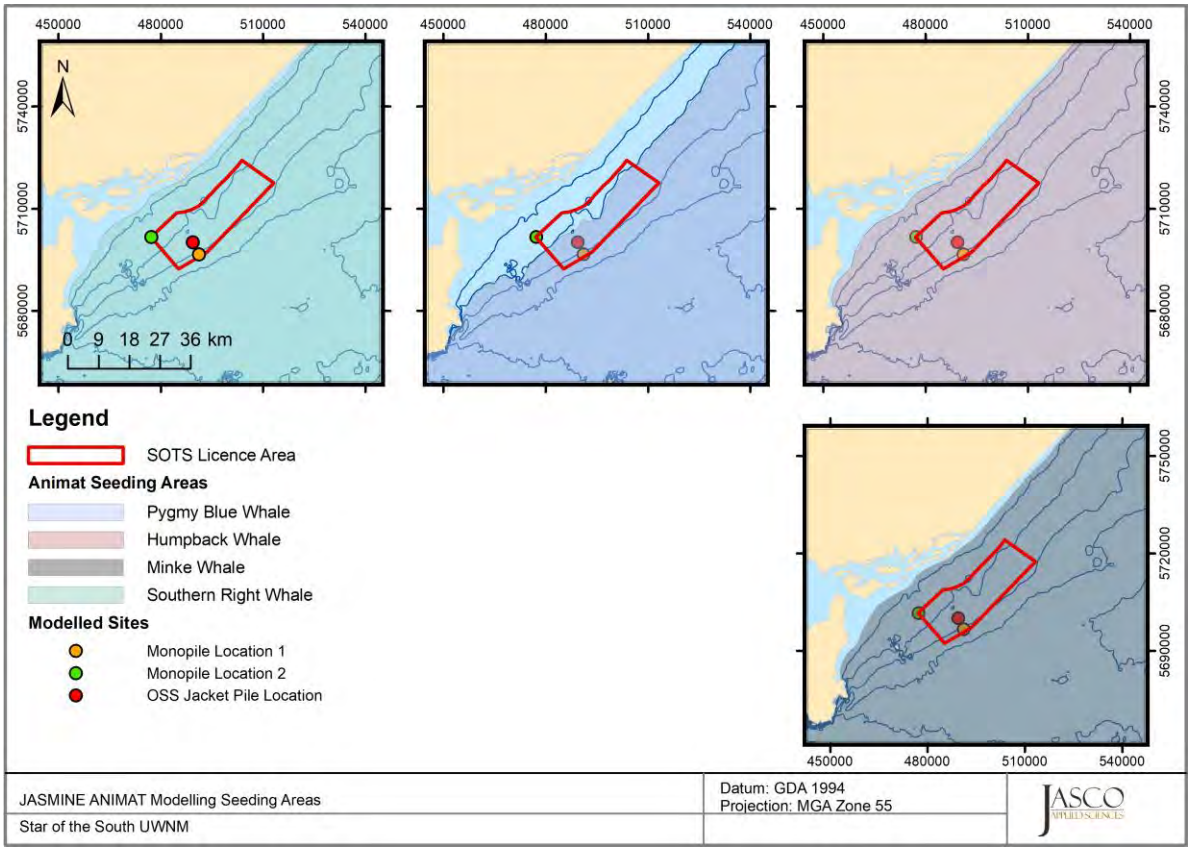


Figure 11. Animat modelling seeding areas for each of the four modelled species.

Model parameters related to spatial and temporal sampling were selected to appropriately capture both the swimming behaviours and the predicted sound fields. Within the context of the project-specific simulation parameters, including source characteristics, swimming behaviours, and bathymetry, a seeding density of 4 animats per km^2 was determined to provide sufficient sampling of the model space and to generate statistically reliable exposure range estimates (see Appendix D.3) for additional details). Additionally, each animat was programmed to sample the model space every 5 seconds. For example, an animat swimming at 1 m/s would sample the sound field every 5 meters along its track.

Figure 12 shows an example animat track (generated for information purposes only and not related to the results presented in this report) with associated received levels from a stationary point source. The top panel displays the animat track relative to the point source, and the bottom panel displays the accumulation of SEL_{24h} for TTS and PTS criteria. At approximately 100 seconds, the animat is exposed so that the TTS threshold is exceeded, and at approximately 700 seconds the animat is exposed so that the PTS threshold is exceeded.

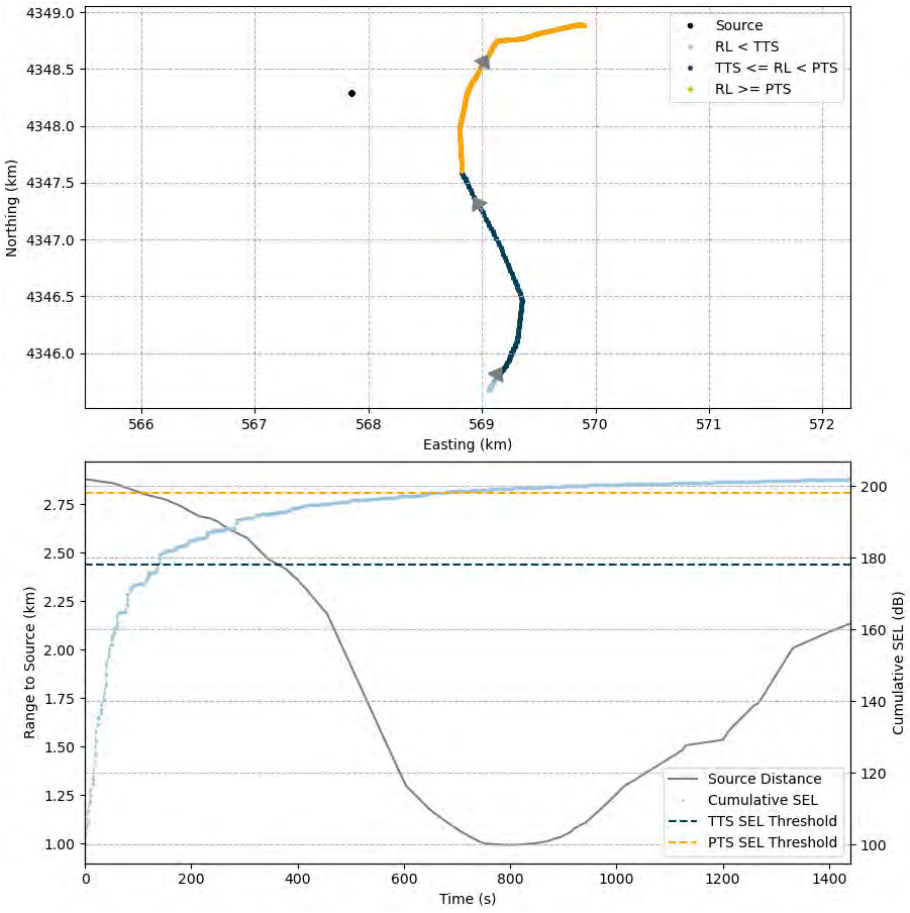


Figure 12. Animat track from an example simulation showing northward movement over a 1400 s duration. The upper panel shows a plan view of both a stationary point source and a foraging animat. Animat steps are coloured to indicate whether the accumulated sound energy at that point has exceeded either TTS or PTS threshold criteria. The lower panel shows horizontal distance in kilometres to the source (grey line; left y-axis) and cumulative 24-h SEL ($L_{E,24h}$, dB re 1 µPa²·s; right y-axis) as a function of time. Note that this example does not use data from the current study.

3.3.1. Exposure-based Radial Distance Estimation

The results from the animal movement and exposure modelling provided a way to estimate radial distances to effect thresholds. The distance to the closest point of approach (CPA) for each of the animats was recorded. The $ER_{95\%}$ (95% Exposure Range) is the horizontal distance that includes 95% of the animat CPAs that exceeded a given effect threshold (Figure 13). Within the $ER_{95\%}$, there is generally some proportion of animats that do not exceed threshold criteria. This occurs for several reasons, including the spatial and temporal characteristics of the sound field and the way in which animats sample the sound field over time, both vertically and horizontally. The sound field varies as a function of range, depth, and azimuth based on a variety of factors such as bathymetry, sound speed profile, and geoacoustic parameters. The way the animats sample the sound field depends upon species-typical swimming and diving characteristics (e.g., swim speed, dive depth, surface intervals, and reversals). Furthermore, even within a particular species definition, these characteristics vary with behavioral state (e.g., feeding, migrating). As this results in some animats not exceeding threshold criteria even within the $ER_{95\%}$, the probability that an animat within that distance was exposed above threshold within the $ER_{95\%}$ was also computed (P_{exp}) to provide additional context.

Acoustic ranges are reported for both $R_{95\%}$ and R_{max}, however, exposure ranges are reported for $ER_{95\%}$ only since, statistically, ER_{max} is not defined. JASMINE is a Monte Carlo simulation, and the results are

probabilistic in nature. This is in contrast with acoustic modelling, where there is a specific maximum isopleth range for a given source/environment setup.

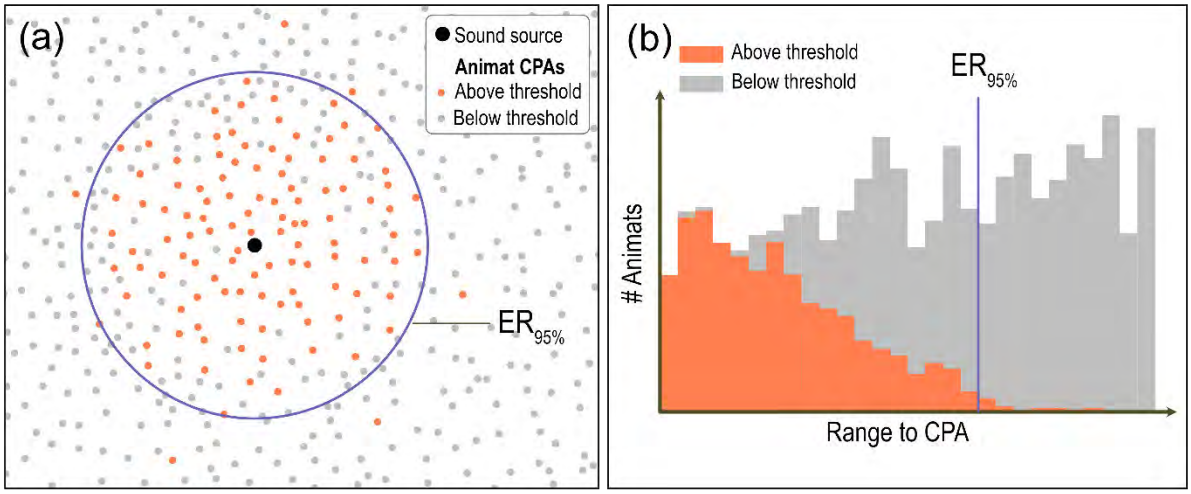


Figure 13. Example distribution of animat closest points of approach (CPAs). Panel (a) shows the horizontal distribution of animats near a sound source. Panel (b) shows the distribution of distances to animat CPAs. The 95% exposure range ($ER_{95\%}$) is indicated in both panels.

3.3.2. Species-Specific Behaviour Profile Parametrisation

3.3.2.1. Pygmy Blue Whale Behaviour Profile

The project area is located in a possible foraging Biologically Important Area (BIA) for pygmy blue whales. The primary profile considered was based around feeding behaviours, as shown in the species profile (Appendix D.1.1.1).

Data on fine-scale foraging behaviour for pygmy blue whales was primarily obtained from Thums et al. (2025) who used multi-sensor tags to record fine-scale dive and movement behaviour of pygmy blue whales in Western Australia. Multi-sensor tags typically record the depth of an animal along with various movement parameters such as swim speed and their body's orientation.

A second set of profiles considered were based around migration (Appendix D.1.1.1). Although the project area is not known to overlap with a previously known or likely migratory route (DoE (AU) 2015-2025), baseline monitoring during ecological investigations (McCauley 2021) has demonstrated the possibility of migration. The migratory profile included both migratory and exploratory dives (i.e., no lunges recorded which would indicate feeding) based on detailed information from Owen et al. (2016), who equipped a sub-adult pygmy blue whale with a multi-sensor tag off Western Australia. Exploratory dives were considered to be part of migratory behaviour, and so the two dive types were modelled together here such that the animats were migrating 95% of the time and engaged in exploratory dives 5% of the time. Most fine-scale movement data for the migratory dive profile for pygmy blue whales was obtained from Thums et al. (2025). Both north-bound and south-bound migrations were modelled using different directional travel biases.

Additional parameter values to complete the pygmy blue whale profiles were obtained from other sources. The remaining parameters were primarily sourced from Goldbogen et al. (2011), who deployed 25 multi-sensor suction cup tags (DTAGs) on blue whales off the coast of California. The exceptions were the values for travel rate and some transition probabilities, which were derived from satellite tags deployed on pygmy blue whales off southern and western Australia (Möller et al. 2020b).

3.3.2.1. Humpback Whale Behaviour Profile

Although the project area is not located in or directly adjacent to a BIA, it is considered part of the core range for humpback whales, which utilise this area as part of their seasonal migratory movements. Evidence suggests that whales undergoing the southern migration off the eastern Australian coast travel along the coastline and then move either across the Bass Strait, across the Tasman Sea, or down the eastern coast of Tasmania before continuing on to their summer feeding grounds in the Antarctic (Andrews-Goff et al. 2018). However, humpback whales are also known to or are likely to opportunistically feed in several locations along this migratory corridor, including areas in or around the project area (Andrews-Goff et al. 2018). Therefore, the species profile included both migratory and feeding behaviours (Appendix D.1.1.2).

The acoustic modelling indicated the winter season to be the worst-case scenario, which falls closer to the timing of the southern migration than the northern migration (McCauley 2021). Therefore, the behavioural profile for humpback whales assumed they were passing through the project area on their southward migration. At this time, many females will be accompanied by young calves. As with right whales, the behaviour of mother/calf pairs can be dramatically different from the behaviour of other demographics, for example the amount of time spent resting and the speed of travel (Noad and Cato 2007, Bejder et al. 2019). Therefore, these two demographics were modelled separately.

Data on humpback whale movement were obtained from studies that used multi-sensor tags (DTAGs or Acousondes) to capture fine-scale dive and movement behaviour from South Pacific (Noad and Cato 2007, Friedlaender et al. 2013, Owen et al. 2015, Kavanagh et al. 2017, Bejder et al. 2019) as well as North Pacific humpback whales (Goldbogen et al. 2008, Ware et al. 2011, Szesciorka 2015).

3.3.2.2. Minke Whale Behaviour Profile

Baseline monitoring in the project area determined the presence of minke whales, specifically Antarctic minke whale (*Balaenoptera bonaerensis*) and the dwarf minke whale (*B. acutorostrata* unnamed subspecies) (McCauley 2021). This aligns with information within the preliminary report by (Birtles et al. 2015)

There are no fine scale behavioural data available for minke whales off Australia, and their behaviour during migration is unknown. Therefore, only one behavioural state (migrating) was included for this species (Appendix D.1.1.3. Data for migrating minke whales were predominately taken from common minke whales in the North Atlantic (Blix and Folkow 1995a, Christiansen et al. 2011b, Risch et al. 2014b) and Antarctic minke whales (Gough et al. 2021).

3.3.2.3. Southern Right Whale Behaviour Profile

The project area partially overlaps with a southern right whale migration and resting on migration BIA and is located in their known core range BIA.

Winter (the worst-case scenario indicated by the acoustic modelling) corresponds closest to the end of their calving/breeding season and the start of their migration (McCauley 2021). At this time, most pregnant females will likely have given birth, and sightings of mother/calf pairs have been documented in this area (Stamation et al. 2020). The behaviour of right whale mother/calf pairs can be dramatically different from other demographics, particularly in regards to the amount of time spent resting at the surface (Cusano et al. 2019, Nielsen et al. 2019). Therefore, separate behavioural profiles were modelled for mother/calf pairs and for all other demographics, with only migrating and resting behaviours included (Appendix D.1.1.4).

Fine-scale behavioural data on southern right whales are limited, however travel speed was derived from satellite-tagged southern right whales (Mackay et al. 2020). The remaining parameters used for

the species profiles were primarily sourced from multi-sensor tags (DTAGs) deployed on North Atlantic right whales (Baumgartner and Mate 2003, Nousek McGregor 2010, Dombroski et al. 2021).

3.4. Mitigation

The modelling studies summarised here considered the performance of several mitigation systems including a double big bubble curtain (DBBC), a hydro-sound-damper (HSD), and the IQIP-PULSE system. Measurement studies have observed reductions of up to 24 dB through mitigation (Robinson and Merchant 2020), and companies such as IHC-IQUIP are promoting and testing the use of multiple mitigation systems simultaneously to achieve higher levels of attenuation. Accordingly, combinations of the three mitigation systems outlined above were also modelled to assess whether more substantial levels of attenuation could be achieved. The following sections outline these three types of noise attenuation system (NAS).

The IQIP-PULSE is typically deployed between the piling hammer and the pile anvil to aid in attenuating noise at the sound source, a HSD surrounds the pile itself, and a DBBC is typically deployed at a farther range from the pile. For the placement of the DBBC rings within the modelling, two nominal distances of 90 m and 130 m from the centre of the pile were selected for modelling based on the values reported in Bellmann (2014).

JASCO understands that it is not possible to apply a HSD around a sub-sea pile, which is why this mitigation option has not been considered for jacket piles in this study. Mitigation options also have not been modelled for vibro pile driving due to a deficit of measurement studies examining the effectiveness of mitigation for vibro pile driving, and therefore a lack of certainty to be able to apply such a system within the modelling.

During the first modelling round, simple broadband attenuation levels (6 dB and 12 dB) were considered to represent the application of mitigation systems; some of the results from this modelling are included in the Results sections for first-round modelling, but this method was superseded by the application of specific mitigation solutions in later modelling rounds.

3.4.1. Double Big Bubble Curtain (DBBC)

A Big bubble curtain (BBC) is a NAS that can be deployed at a distance of several tens to over one hundred meters around the piling location. These systems may be specially manufactured by a piling contractor, but two companies, Hydrotechnik Lübeck and Weyres, produce BBCs on a commercial scale. The Hydrotechnik Lübeck BBC is the most commonly used and most tested on large-scale wind farm projects (Koschinski and Lüdermann 2019, Bellmann et al. 2020). BBCs can be deployed as single or multiple rings at increasing distances from the pile. Most available data describing their effectiveness are for double big bubble curtains (DBBC, Figure 14).

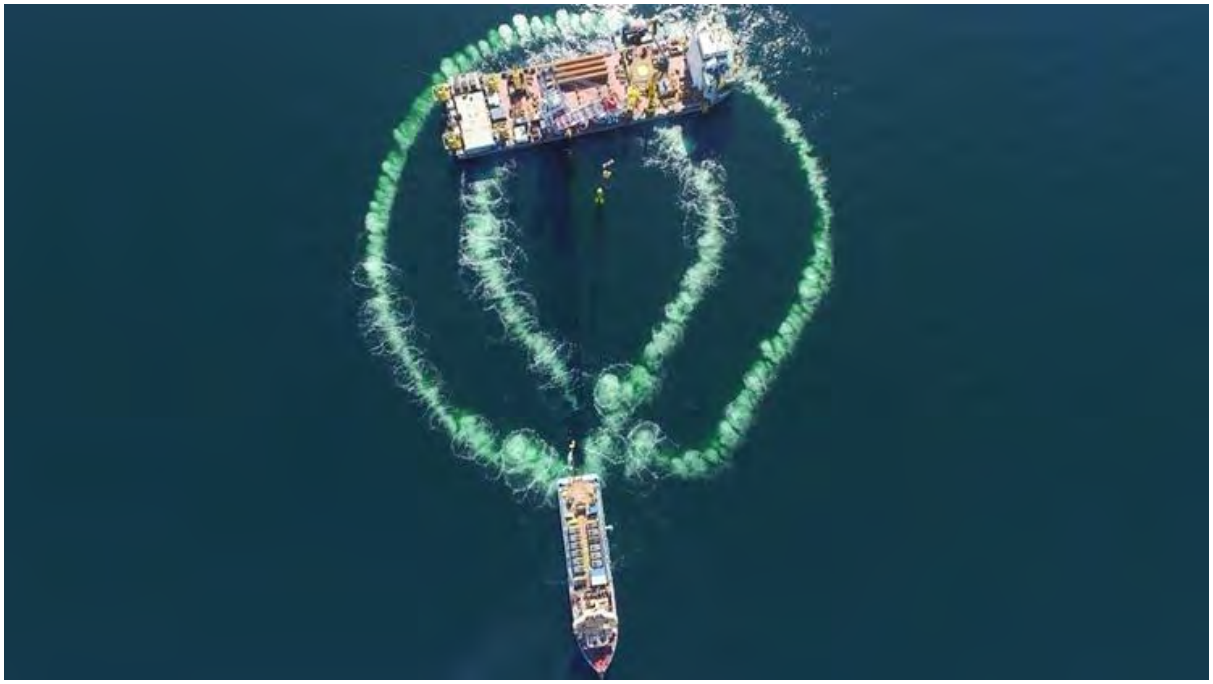


Figure 14. The Hydrotechnik Lübeck Double Big Bubble Curtain deployed at Wikinger Offshore Wind Farm in the Baltic Sea, Germany (© Iberdrola).

Structurally, BBCs consist of large diameter hoses that are deployed on the seafloor around the piling platform by a support vessel, following a pre-determined layout. These hoses are connected to a supply vessel carrying air compressors. Air is forced through the hoses and escapes through small holes along their length, generating a curtain of bubbles rising through the water column. The bubbles create a discontinuity in the water that absorbs and reflects sound in a frequency-dependent manner. The sound reduction efficiency of BBCs, as indicated by measurements at several offshore wind farm construction sites, depends largely on the flow rate at which the air is supplied and the density of bubbles within the water column and around the pile. Therefore, the efficacy can be affected by local environment conditions such as water depth, current speed, and current direction (Verfuss et al. 2019). At water depths of ~30 m, a single BBC system (flow rate > 0.4 m^3/(min m)) in combination with an HSD (see Section 3.4.2) has showed a reduction in per-strike broadband SEL of 15–20 dB (Bellmann et al. 2020). At water depths of ~40 m, a double BBC system (flow rate >0.5 m^3/(min m)) in combination with an HSD has showed a reduction in per-strike broadband SEL of 18–19 dB (Bellmann et al. 2020).

Small bubble curtains have been measured to reduce sound levels from ~10 dB to more than 20 dB but are highly dependent on depth of water and current, and configuration and operation of the curtain (Koschinski and Lüdemann 2013, Bellmann 2014, Austin et al. 2016, Koschinski and Lüdemann 2020). Larger bubble curtains tend to perform better and more reliably, particularly when deployed with two rings as a double big bubble curtain (DBBC) (Koschinski and Lüdemann 2013, Bellmann 2014, Nehls et al. 2016, Koschinski and Lüdemann 2020). A California Department of Transportation (CalTrans) study, however, tested several systems and found that the best attenuation systems resulted in 10-15 dB of attenuation, summarising that attenuation greater than 10 dB is not reliably predicted (Buehler et al. 2015).

3.4.2. Hydro-Sound-Damper (HSD)

The HSD NAS (Figure 15) is a cylindrical net containing foam elements held in position by a frame (ballast box) surrounding the pile and deployed on the seafloor from the installation vessel using a lifting device. The size of the HSD is fitted to the dimensions of the pile. The size and number of foam

elements can be adjusted according to project requirements. At water depths of up to 40 m, HSD systems have showed a reduction in per-strike broadband SEL of 10–12 dB when used on their own (Bellmann et al. 2020). HSDs are particularly effective at frequencies below 200 Hz and are often used in combination with other mitigation tools.

Encapsulated resonator systems (e.g. HSDs) are in principle unlimited by water depth. However, adverse weather conditions (high current speeds and wave heights) may present challenges when attempting to keep the device in position around the pile. Furthermore, it is not possible to apply the HSD mesh around a sub-sea pile, which is why this mitigation option has not been considered for jacket piles in this study.

Further details on the HSD are presented in Section 3.4.4.1.



Figure 15. Hydro-Sound-Damper (HSD) (left) full length onshore and (right) Deployed during pile driving. Images from OffNoise Solutions GmbH, as presented in (Bellmann et al. 2020).

3.4.3. Hydraulic Damping Mechanism (IQIP-PULSE)

Hammer damping mechanisms or noise reduction units are used to modify the duration of the hammer pulse. This results in a shift of the frequency of the peak energy primarily reducing the amount of energy at mid to high frequencies. For impact driving target is to reduce the energy within the 100 Hz – 1 kHz range. Currently, only two such systems are commercially available:

1.) The IHC-IQIP PULSE system, which is an add-on piece of equipment placed between the hammer and the sleeve/anvil/helmet that can be filled with an adjustable amount of water to alter the force-generation characteristics of the hammer strike.

2.) The Menck Noise Reduction Unit (MNRU) is composed of a series of steel block components that alter the force-generation characteristics of the hammer strike.

The IHC-IQIP PULSE system was considered in this study. The forcing functions for the IQ4 hammer with the PULSE system in this report were provided by Star of the South (obtained from data provided by IQIP); the hammer forcing function was then integrated into the processing work flow, at the beginning of the process. Refer to the start of Section 3.1 for a review of the steps within the modelling methodology.

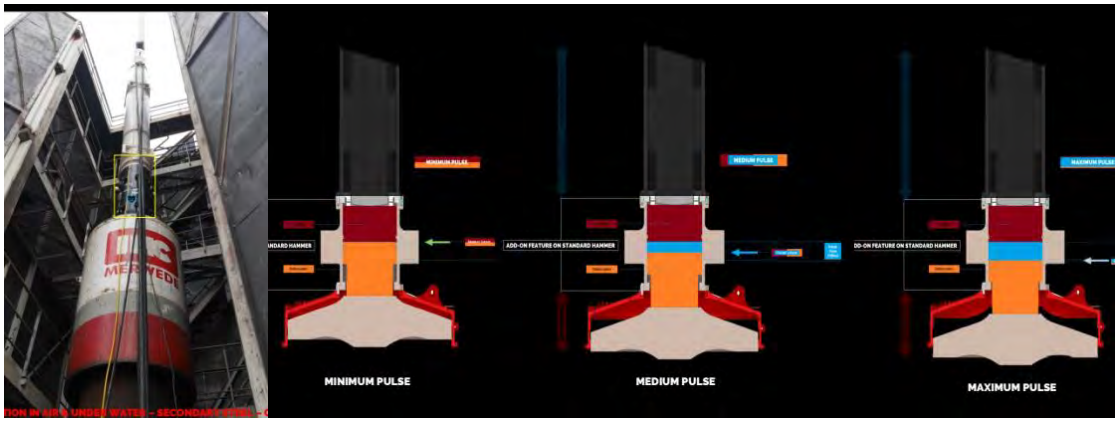


Figure 16. Diagram showing (left) the PULSE section inserted on a standard hammer and (right) the PULSE system concept (Van Vessem 2018).

3.4.4. Frequency Dependent Reduction

This modelling study considered the performance of a double big bubble curtain (DBBC), a hydro sound damper (HSD), along with the performance of the two mitigation systems applied simultaneously, and a hydraulic damping mechanism NAS, or 'PULSE', to achieve better levels of attenuation. The HSD NAS is typically located within the immediate proximity of the pile, while a BBC or DBBC can be deployed at a farther range. For the placement of the DBBC rings, two nominal distances of 90 m and 130 m from the centre of the pile were selected based on the values reported in Bellmann (2014).

3.4.4.1. NASs Insertion Loss

The DBBC system was modelled here by incorporating into the FWRAM configuration two BBCs at distances of 90 m and 130 m from the pile. Figure 17 shows the BBC insertion loss curve used for modelling in this study. The BBC insertion loss is based on Bellmann et al. (2020) for an air flow rate of 0.55 m^3/(min m). Although Bellmann et al. (2020) also provide insertion losses for lower air flow rates (0.25–0.42 m^3/(min m)), the higher flow rate was selected because it is typically used in waters ~40 m deep, consistent with the 46 m water depth at the deepest modelled location. Further details on the DBBC are presented in Section 3.4.1.

The HSD insertion loss in this study is also patterned on Bellmann et al. (2020). At 20 Hz, Bellmann reported a greater than zero ΔSEL at 20 Hz (implying an amplification of acoustic energy at that frequency), which could be an anomaly of the insertion loss curve limited to specific conditions. For this reason, our model uses 0 dB (i.e., no insertion loss) in the 20 Hz band. Further details on the HSD are presented in Section 3.4.2.

The IQIP-PULSE system was incorporated into the model via the hammer forcing function within GRLWEAP; Sections 4.1.1 and 4.2.1 provide further information.

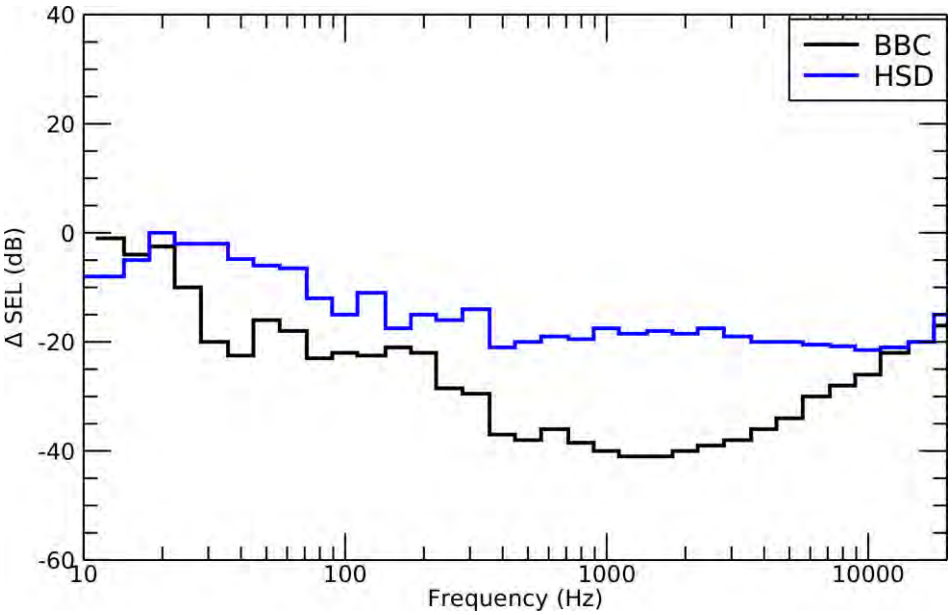


Figure 17. Frequency-dependent attenuation characteristics of various NASs, used for modelling in the present study, based on HSD and BBC curves from Bellmann et al. (2020).

4. Impact Pile Driving

Table 16 presents an overview of the modelling round, the type(s) of results presented, a reference to find the sound source parameters, and the key noise effect criteria thresholds considered. Details can be found in the corresponding result sections.

Table 16. Overview of impact pile driving results presentation.

Scenario	Mitigation	Modelling round	Results presented	Sound source parameters	Noise effect criteria reference
Monopile					
1	None	First	Acoustic	Appendix C.2.3.1	Southall et al. 2019
2	DBBC	First	Acoustic, Animat	Appendix C.2.3.1	Southall et al. 2019
3	DBBC + HSD	First	Acoustic	Appendix C.2.3.1	Southall et al. 2019
4	None	Second	Acoustic	Appendix C.2.3.1	Southall et al. 2019
5	DBBC	Second	Acoustic, Animat	Appendix C.2.3.1	Southall et al. 2019
6	HSD	Second	Acoustic	Appendix C.2.3.1	Southall et al. 2019
7	DBBC + HSD	Second	Acoustic	Appendix C.2.3.1	Southall et al. 2019
8	None	Fourth	Acoustic	Appendix C.2.3.1	NMFS 2024
9	DBBC + HSD + PULSE	Fourth	Acoustic, Animat	Appendix C.2.3.1	NMFS 2024
Jacket Pile					
1	None	First	Acoustic	Appendix C.2.3.1	Southall et al. 2019
2	DBBC	First	Acoustic	Appendix C.2.3.1	Southall et al. 2019
3	None	Second	Acoustic	Appendix C.2.3.2	Southall et al. 2019
4	DBBC	Second	Acoustic	Appendix C.2.3.2	Southall et al. 2019
5	None	Fourth	Acoustic	Appendix C.2.3.1	NMFS 2024
6	DBBC + PULSE	Fourth	Acoustic, Animat	Appendix C.2.3.1 Appendix C.2.3.3	NMFS 2024
Concurrent					
1	None	First	Acoustic	Appendix C.2.3.1	Southall et al. 2019
2	None	First	Acoustic	Appendix C.2.3.1 Appendix C.2.3.1	Southall et al. 2019

4.1. Monopile Installation Operations

Pile driveability assessments and corresponding pile designs have been commissioned by Star of the South and incorporated into noise modelling methodology. The IHC S-4000 impact hammer considered for this study was selected based on the project requirements/assumptions considered in the driveability study and defined by Star of the South. This hammer was used for the WTG foundation monopile modelling scenarios. The tables of parameters used for each modelling round, including general specifications of the considered piles extracted from the driveability study as pertaining to the modelled monopile foundation locations are in Appendix C.2.3.

The table below provides a summary of the different scenarios included in Sections 4.1.2 and 4.1.3.

Table 17. Summary of the modelled scenarios presented in the sections below. MP: monopile

Scenario	Operation	Mitigation	Modelling round	Site	Site description (water depth)	Max. pile diameter	Hammer model	Season	Results presented	Sound source parameters	Noise effect criteria reference
1	Impact, monopile	None	First	MP1	Deep SE (42 m)	12.5 m	IHC S-4000	Summer	Acoustic	Appendix C.2.3.1	Southall et al. 2019
								Winter			
			First	MP3	Shallow NW (23 m)			Summer			
								Winter			
2		DBBC	First	MP1	Deep SE (42 m)	12.5 m		Winter	Acoustic, Animat	Appendix C.2.3.1	Southall et al. 2019
				MP3	Shallow NW (23 m)						
3		DBBC + HSD	First	MP1	Deep SE (42 m)	12.5 m		Winter	Acoustic	Appendix C.2.3.1	Southall et al. 2019
				MP3	Shallow NW (23 m)						
4		None	Second	MP1	Deep SE (42 m)	11.8 m		Winter	Acoustic	Appendix C.2.3.2	Southall et al. 2019
				MP2	Shallow SW (20 m)						
5		DBBC	Second	MP1	Deep SE (42 m)	11.8 m		Winter	Acoustic, Animat	Appendix C.2.3.2	Southall et al. 2019
				MP2	Shallow SW (20 m)						
6		HSD	Second	MP1	Deep SE (42 m)	11.8 m		Winter	Acoustic	Appendix C.2.3.2	Southall et al. 2019
				MP2	Shallow SW (20 m)						
7		DBBC + HSD	Second	MP1	Deep SE (42 m)	11.8 m		Winter	Acoustic	Appendix C.2.3.2	Southall et al. 2019
				MP2	Shallow SW (20 m)						
8		None	Fourth	MP1	Shallow NW (21 m)	9.2 m	IQ4	Winter	Acoustic	Appendix C.2.3.3	NMFS 2024
				MP2	Intermediate (34.7 m)	11.0 m					
				MP3	Deepest SW (51.3 m)	11.8 m					
				MP4	Deep (47 m)	11.8 m					
9		PULSE + DBBC + HSD	Fourth	MP1	Shallow NW (21 m)	9.2 m	IQ4 + PULSE	Winter	Acoustic, Animat	Appendix C.2.3.3	NMFS 2024
				MP2	Intermediate (34.7 m)	11.0 m					
				MP3	Deepest SW (51.3 m)	11.8 m					
				MP4	Deep (47 m)	11.8 m					

4.1.1. Parameterisation and Methodology: Monopiles

JASCO's pile driving source model (PDSM, MacGillivray 2014) was used in conjunction with the GRLWEAP 2010 wave equation model (Pile Dynamics 2010) to predict source levels associated with impact pile driving activities.

GRLWEAP, which includes a database of commercial impact hammers, was used to model a forcing function at the top of the pile. PDSM computes the underwater vibration and sound radiation of a pile using a finite difference scheme which utilises the forcing function of the hammer at the top of the pile and the mechanical resistance of the seabed at the base of the pile. See Appendix B.1 for more detail. Given that piles are distributed sources (Appendix B.1), they cannot be accurately approximated by a point source. As such, the sound radiating from the pile itself is simulated using a vertical array of discrete point sources, as described in Appendix B.1.

The installation of a single pile requires adjustment of the energy delivered by the hammer as the pile advances into the sediment. Initially the hammer is set to deliver low energy strikes, since this is sufficient to advance the pile when the surficial sediment does not offer too much resistance. As the pile penetrates farther, higher energy settings (up to 4000 kJ for the IHC S-4000) and more strikes are required to advance the pile to its final depth, where maximum sound levels from pile installation usually occur during the last stage of pile driving (Betke 2008).

The hammer penetration/hammering values used in this acoustic modelling study was developed in considering the driveability information provided by the Star of the South, which included number of strikes and applied hammer energy per metre of the pile drive. The drive was divided into up to five depth intervals and associated penetration depths to represent the different portions of the drive. Over each modelled depth interval, the upper 90th percentile of applied energy was selected to represent the hammer energy over the depth range (a conservative approach, but reasonable given the limited understanding of the geology and soil mechanics). Parameter tables and figures presenting resulting the penetration depth, strike count and hammer energy used for acoustic modelling, the pile geometry used by GRLWEAP and PDSM, the hammer forcing functions from GRLWEAP are presented in Appendix C.2.3.

4.1.2. Results: Acoustic Modelling

Received levels at 10 m – Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. The figures below show the decidecade–band levels for the receiver with the highest SEL at a horizontal range of 10 m, for the considered piles and for each of the modelled penetrations per modelling round. The levels above 1000 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports and literature, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

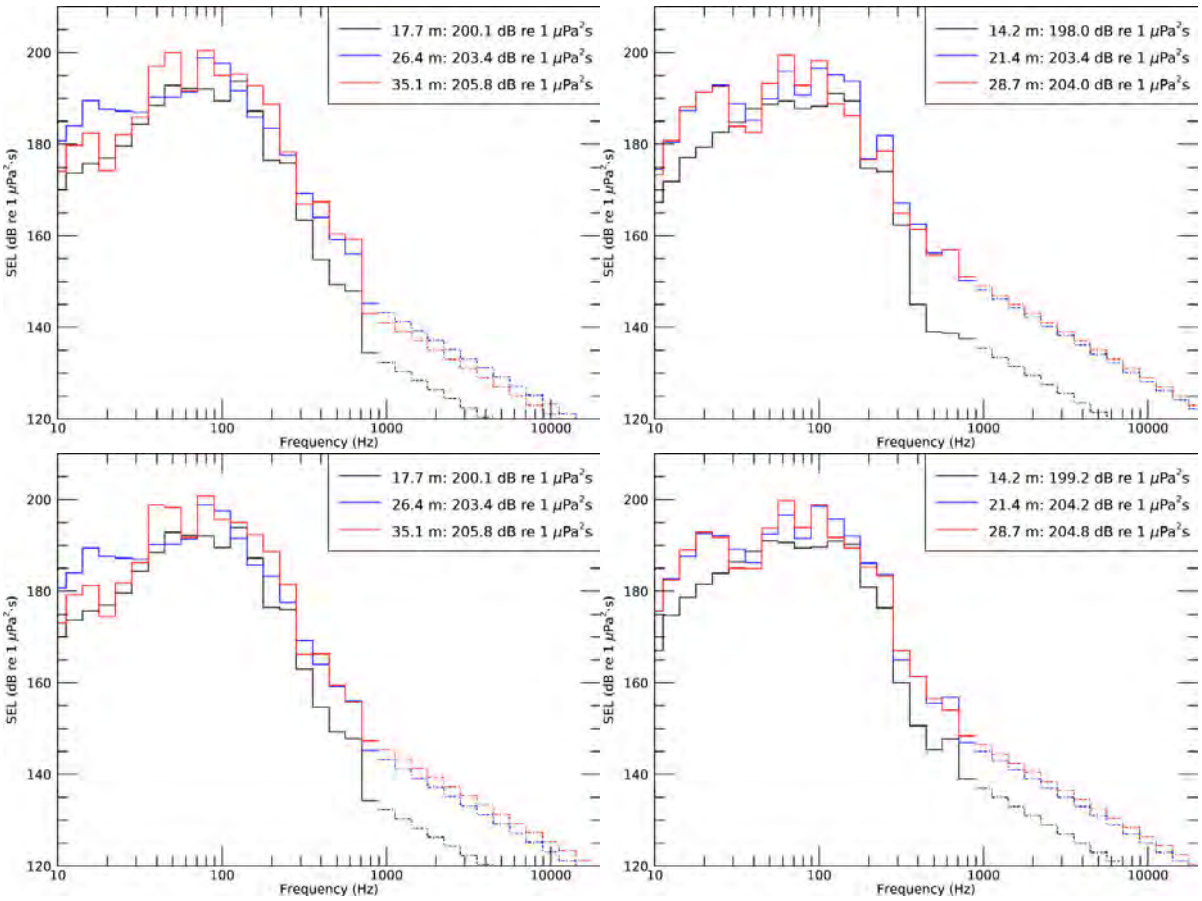


Figure 18. *Monopile 1 (left) and 3 (right), summer (top row) and winter (bottom row), first modelling round*: Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IHC S4000 hammer, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 μPa²·s.

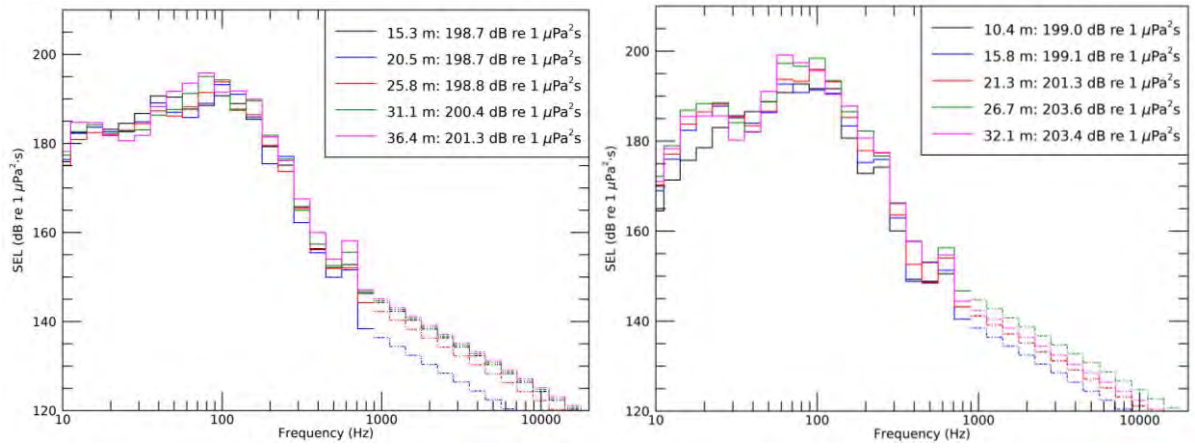


Figure 19. *Monopile 1 (left) and 2 (right), winter, second modelling round:* Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IHC S4000 hammer, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 μPa²·s.

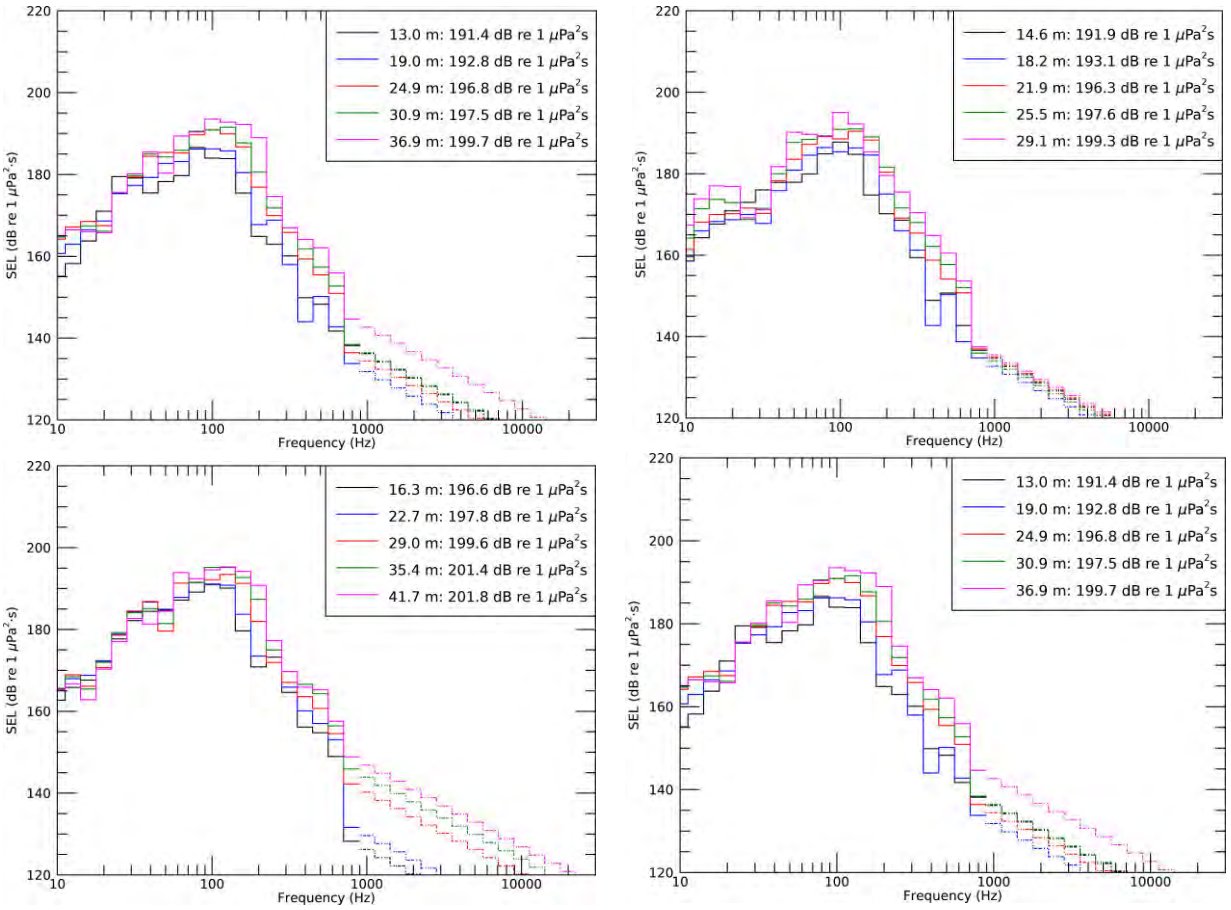


Figure 20: *Monopile 1 (top left), Monopile 2 (top right), Monopile 3 (bottom left), Monopile 4 (bottom right), winter, fourth modelling round*: Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IQ4 hammer, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 μPa²·s.

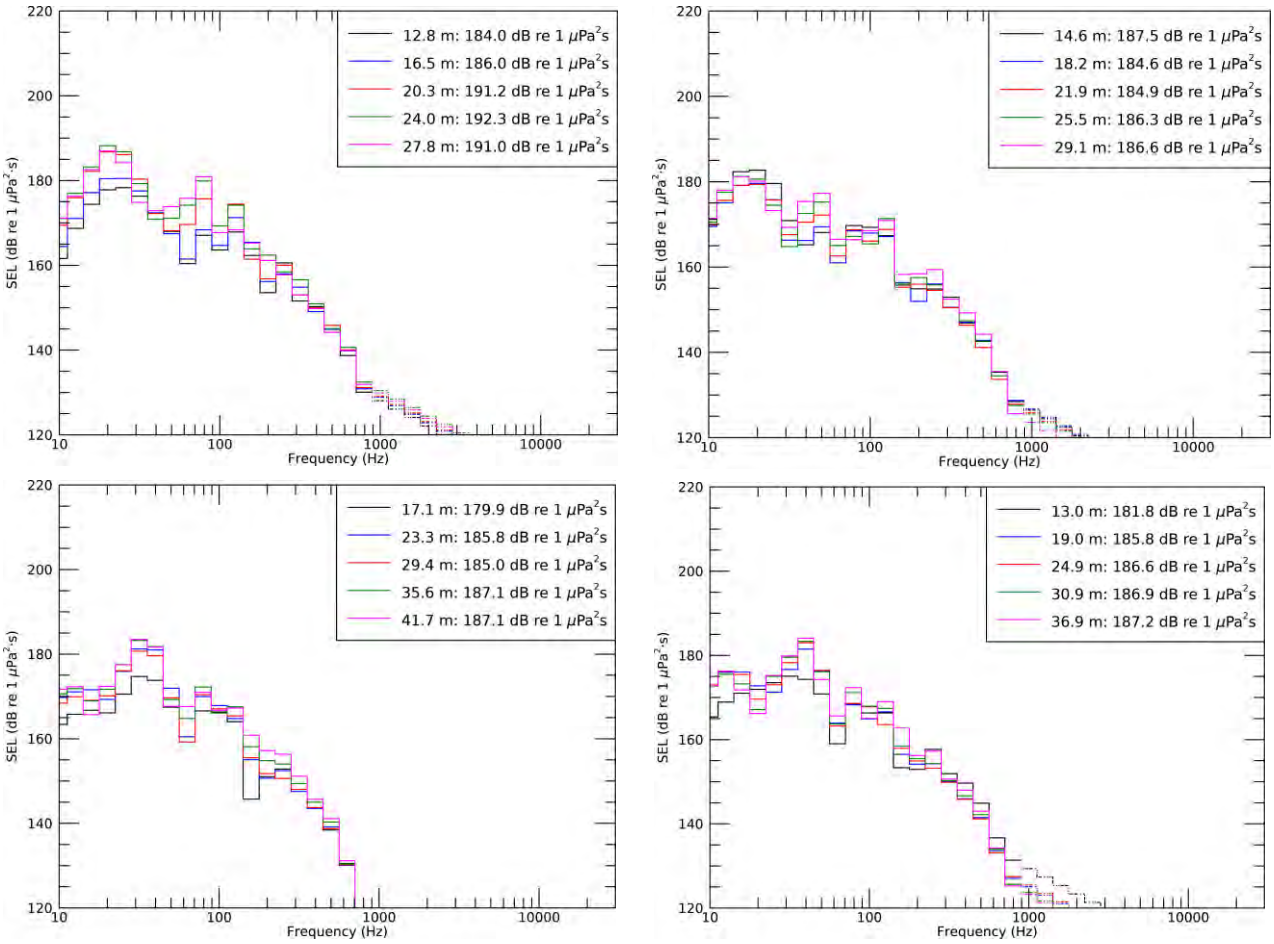


Figure 21. *Monopile 1 (top left), Monopile 2 (top right), Monopile 3 (bottom left), Monopile 4 (bottom right), winter, fourth modelling round:* Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IQ4 hammer with the PULSE, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 μPa²·s.

4.1.2.1. Scenario 1 – Unmitigated (First Modelling Round)

4.1.2.1.1. Per–strike sound fields in summer

The per–strike sound fields for the three modelling sites are presented below. The results are presented in terms of per–strike SPL, SEL, PK sound fields and particle motion fields.

Vertical slice plots of the SPL sound field are presented in Appendix F.1.1.1 for each monopile considering the third penetration depth. The orientation of the slice transects are such that the first bearing listed in the caption corresponds with the positive distance and the second bearing corresponds with the negative distances.

Table 18. *Monopiles, summer, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Pile 1						Pile 3					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.10	0.10	0.20	0.19	0.32	0.31	0.04	0.04	0.17	0.17	0.20	0.19
180	0.62	0.59	1.47	1.38	2.05	1.93	0.36	0.35	0.99	0.96	1.28	1.22
170	3.03	2.89	5.1	4.84	6.37	6.03	1.72	1.63	3.44	3.29	3.97	3.79
162[a]	7.12	6.71	11.1	10.3	13.2	12.2	3.81	3.64	6.78	6.43	7.66	7.18
160	8.68	8.08	13.1	12.2	15.4	14.25	4.48	4.25	7.95	7.44	8.88	8.3
150	21.4	19.9	28.8	26.9	31.4	29.2	9.44	8.50	16.0	14.4	18.4	16.6
140	45.8	42.0	57.1	53.4	62.3	58.0	18.7	16.9	34.8	30.6	47.0	41.8
130	>90.0	/	>90.0	/	>90.0	/	44.6	40.1	74.2	68.4	>90.0	/

[a] Startle response level for squid and octopus (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 19. *Monopiles, summer, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Pile 1						Pile 3					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.09	0.09	0.18	0.17	0.24	0.22	0.03	0.03	0.12	0.12	0.18	0.17
190	0.49	0.45	1.08	1.05	1.53	1.43	0.26	0.26	0.82	0.79	1.04	1.01
180	2.09	2.00	3.58	3.37	4.46	4.17	1.47	1.4	2.51	2.4	2.91	2.81
170	6.42	6.03	9.74	9.01	11.6	10.6	3.47	3.31	5.79	5.3	6.93	6.19
160	18.0	16.6	23.2	21.5	22.8	21.1	7.33	6.56	12.6	11.3	14.9	13.3
150	37.6	34.6	46.0	42.2	51.5	47.6	14.9	13.5	27.5	24.8	38.5	34.6
145[a]	49.6	46.0	69.3	62.7	73.3	67.5	21.8	19.7	40.5	36.2	61.8	55.9
140	70.7	64.0	>90.0	/	90.0	86.1	33.7	30.6	57.6	52.4	90.0	84.4
130	>90.0	/	>90.0	/	>90.0	/	76.3	69.3	>90.0	/	>90.0	/

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 20. *Monopiles, summer, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Pile 1						Pile 3					
		Penetration depth (m)						Penetration depth (m)					
		17.7		26.4		35.1		14.2		21.4		28.7	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Turtle behavioural response [a]	175	3.73	3.56	5.96	5.59	7.13	6.65	2.36	2.26	3.69	3.54	4.57	4.31
Turtle behavioural disturbance [b]	166	9.99	9.23	14.1	13.0	15.4	14.2	4.60	4.31	8.02	7.14	9.16	8.12
Marine mammal behavioural response [c]	160	18.4	16.9	23.8	22.0	23.8	21.9	7.3	6.5	12.6	11.3	15.0	13.4
LF-cetacean weighted behavioural response [d]	160	7.98	7.43	11.89	11.02	12.82	11.88	3.73	3.53	6.43	5.80	7.93	7.04
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	45.3	41.5	66.3	60.1	73.0	67.4	19.3	17.5	39.0	35.2	68.1	61.7
Penguin behavioural response [e]	120	20.8	19.4	27.8	25.9	33.2	30.4	9.25	8.33	17.6	16.0	30.6	28.2

[a] Threshold for turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 21. *Monopiles, summer, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each pile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Pile 1			Pile 3		
		Penetration depth (m)			Penetration depth (m)		
		17.7	26.4	35.1	14.2	21.4	28.7
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS							
LF cetaceans	219	–	0.09	0.09	–	0.03	0.04
HF cetaceans	230	–	–	–	–	–	–
Otariid seals	232	–	–	–	–	–	–
Sea turtles	232	–	–	–	–	–	–
Penguins	232	–	–	–	–	–	–
TTS							
LF cetaceans	213	0.11	0.15	0.16	0.03	0.16	0.17
HF cetaceans	224	–	–	–	–	–	–
Otariid seals	226	–	–	–	–	–	–
Sea turtles	226	–	–	–	–	–	–
Penguins	226	–	–	–	–	–	–
Mortality and potential mortal recoverable injury thresholds							
Fish I	213	0.11	0.15	0.16	0.03	0.16	0.17
Fish II, III Fish eggs and larvae	207	0.23	0.38	0.46	0.17	0.27	0.28

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 22. *Monopiles, summer, PK–PK thresholds*: Maximum (R_{max}) horizontal distances (m) from each pile to modelled seafloor peak–peak pressure level (PK–PK) thresholds for invertebrates for each third depth.

Marine Fauna	PK–PK threshold (L_{pkpk}; dB re 1 µPa)	MP 1	MP 3
		Penetration depth	
		35.1 m	28.7
		R_{max} (m)	R_{max} (m)
Crustaceans [a]	202	>1000 *	958

[a] Payne et al. (2008), lobster

* Maximum modelling range is 1 km, see Section 3.1.1

Table 23. *Monopiles, summer, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from each pile to modelled seafloor and *Peak acceleration magnitude* level (m/s^2) thresholds for benthic invertebrates for the third penetration depth.

Marine Fauna	Peak Acceleration Magnitude (m/s^2)	MP 1	MP 3
		R_{max} (m)	R_{max} (m)
Benthic invertebrates [a]	35.75	123	44

[a] Day et al. (2016a) – Crustaceans and bivalves

4.1.2.1.2. Multiple–strike sound fields in summer

The multiple–strike sound fields for two modelling sites are presented below.

Table 24. *Monopiles, summer, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Pile 1		Pile 3	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	24.7	22.9	11.8	10.6
HF cetaceans	185	–	–	–	–
Otariid seals	203	–	–	–	–
Sea turtles	204	6.70	6.26	3.03	2.83
Penguins	203	–	–	–	–
TTS					
LF cetaceans	168	78.7	72.2	49.6	44.9
HF cetaceans	170	0.14	0.14	0.06	0.06
Otariid seals	188	0.43	0.41	0.22	0.21
Sea turtles	189	24.2	22.4	11.2	9.98
Penguins	188	0.43	0.41	0.22	0.21

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 25. *Monopiles, summer, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Pile 1		Pile 3	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	1.61	1.47	0.60	0.59
II, Fish eggs and fish larvae	210	4.84	4.61	2.28	2.14
III	207	6.55	6.16	3.16	2.97
Fish recoverable injury					
I	216	2.51	2.29	1.03	0.98
II, III	203	9.63	8.88	4.56	4.27
Fish temporary threshold shift (TTS)					
I, II, III	186	40.0	32.7	15.7	14.4

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.1.3. Per–strike sound fields in winter

The per–strike sound fields for two modelling sites are presented below. The results are presented in terms of per–strike SPL, SEL, PK sound fields and particle motion fields.

Table 26. *Monopiles, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 1						Monopile 3					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.10	0.10	0.20	0.19	0.32	0.30	0.04	0.04	0.17	0.17	0.20	0.19
180	0.62	0.59	1.46	1.37	2.03	1.92	0.36	0.35	0.99	0.96	1.28	1.22
170	3.01	2.88	5.07	4.81	6.35	6.01	1.71	1.63	3.44	3.27	3.95	3.75
162[a]	7.08	6.68	11.1	10.3	13.2	12.3	3.77	3.6	6.69	6.36	7.59	7.11
160	8.66	8.07	13.2	12.3	15.4	14.3	4.44	4.21	7.90	7.36	8.84	8.22
150	21.9	20.4	29.7	27.6	32.3	30.0	9.35	8.42	15.7	14.2	18.5	16.6
140	47.8	43.9	61.9	57.0	68.9	62.7	18.7	16.9	35.0	31.3	49.8	44.8
130	>90.0	/	>90.0	/	>90.0	/	46.9	42.1	81.5	74.6	>90.0	/

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 27. *Monopiles, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1						Monopile 3					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.09	0.09	0.18	0.17	0.24	0.22	0.03	0.03	0.13	0.13	0.17	0.17
190	0.48	0.45	1.08	1.04	1.53	1.43	0.26	0.26	0.81	0.79	1.04	1.01
180	2.08	2.00	3.56	3.36	4.48	4.17	1.46	1.39	2.49	2.38	2.90	2.79
170	6.46	6.06	9.81	9.06	11.6	10.6	3.43	3.28	5.72	5.26	6.93	6.17
160	18.4	16.9	23.8	22.0	23.8	21.9	7.32	6.52	12.6	11.3	15.0	13.4
150	38.7	35.7	49.0	45.2	54.9	51.1	14.9	13.5	27.9	25.3	40.6	36.5
145[a]	52.3	48.5	76.3	68.8	82.2	72.8	22.1	19.9	41.7	37.3	68.0	61.1
140	77.0	69.7	>90.0	/	>90.0	/	35.2	31.7	59.9	55.0	>90.0	/
130	>90.0	/	>90.0	/	>90.0	/	84.2	75.7	>90.0	/	>90.0	/

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 28. *Monopiles, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1						Monopile 3					
		Penetration depth (m)						Penetration depth (m)					
		17.7		26.4		35.1		14.2		21.4		28.7	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	3.73	3.56	5.96	5.59	7.13	6.65	2.36	2.26	3.69	3.54	4.57	4.31
Sea turtle behavioural response [a]	166	9.99	9.23	14.1	13.0	15.4	14.2	4.60	4.31	8.02	7.14	9.16	8.12
Marine mammal behavioural response [c]	160	18.4	16.9	23.8	22.0	23.8	21.9	7.3	6.5	12.6	11.3	15.0	13.4
LF-cetacean weighted behavioural response [d]	160	7.98	7.43	11.89	11.02	12.82	11.88	3.73	3.53	6.43	5.80	7.93	7.04
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	45.3	41.5	66.3	60.1	73.0	67.4	19.3	17.5	39.0	35.2	68.1	61.7
Penguin behavioural response [e]	120	20.8	19.4	27.8	25.9	33.2	30.4	9.25	8.33	17.6	16.0	30.6	28.2

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 29. *Monopiles, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1			Monopile 3		
		Penetration depth (m)			Penetration depth (m)		
		17.7	26.4	35.1	14.2	21.4	28.7
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS							
LF cetaceans	219	–	0.09	0.09	–	0.03	0.04
HF cetaceans	230	–	–	–	–	–	–
Otariid seals	232	–	–	–	–	–	–
Sea turtles	232	–	–	–	–	–	–
Penguins	232	–	–	–	–	–	–
TTS							
LF cetaceans	213	0.11	0.15	0.17	0.04	0.16	0.17
HF cetaceans	224	–	–	–	–	–	–
Otariid seals	226	–	–	–	–	–	–
Sea turtles	226	–	–	–	–	–	–
Penguins	226	–	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury							
Fish I	213	0.11	0.15	0.17	0.04	0.16	0.17
Fish II, III Fish eggs and larvae	207	0.23	0.38	0.46	0.17	0.26	0.28

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 30. *Monopiles, winter, PK–PK thresholds*: Maximum (R_{max}) horizontal distances (m) from each monopile to modelled seafloor peak–peak pressure level (PK–PK) thresholds for invertebrates for each penetration depth.

Marine Fauna	PK–PK threshold (L_{pkpk}; dB re 1 µPa)	Monopile 1	Monopile 3
		Penetration depth	
		35.1 m	28.7
		R_{max} (m)	R_{max} (m)
Crustaceans [a]	202	>1000	956

[a] Payne et al. (2008), lobster

Table 31. *Monopiles, winter, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from two monopiles to modelled seafloor peak acceleration magnitude level (m/s^2) thresholds for benthic invertebrates for the third penetration depth, 35.1 m for Monopile 1 and 28.7 m for Monopile 3.

Marine fauna	Peak acceleration magnitude (m/s^2)	Monopile 1	Monopile 3
Benthic invertebrates [a]	35.75	123	90

[a] Day et al. (2016a) – Crustaceans and bivalves

4.1.2.1.4. Multiple–strike sound fields in winter

The multiple–strike sound fields for two modelling sites are presented below.

Table 32. *Monopiles, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 $\mu Pa^2 \cdot s$)	Monopile 1		Monopile 3	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	25.2	23.4	11.9	10.6
HF cetaceans	185	–	–	–	–
Otariid seals	203	–	–	–	–
Sea turtles	204	6.69	6.24	3.02	2.83
Penguins	203	–	–	–	–
TTS					
LF cetaceans	168	89.9	80.6	53.5	48.7
HF cetaceans	170	0.14	0.14	0.06	0.06
Otariid seals	188	0.43	0.41	0.22	0.21
Sea turtles	189	24.7	22.9	11.2	9.99
Penguins	188	0.43	0.41	0.22	0.21

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 33. *Monopiles, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 3	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	1.60	1.46	0.60	0.59
II, Fish eggs and fish larvae	210	4.83	4.59	2.28	2.13
III	207	6.53	6.13	3.15	2.94
Fish recoverable injury					
I	216	2.50	2.29	1.02	0.96
II, III	203	9.61	8.87	4.51	4.22
Fish temporary threshold shift (TTS)					
I, II, III	186	40.1	34.0	15.8	14.3

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.1.5. Sound field maps

The per-strike sound field maps are presented below. Unmitigated results are compared with 6 dB and 12 dB mitigated results.

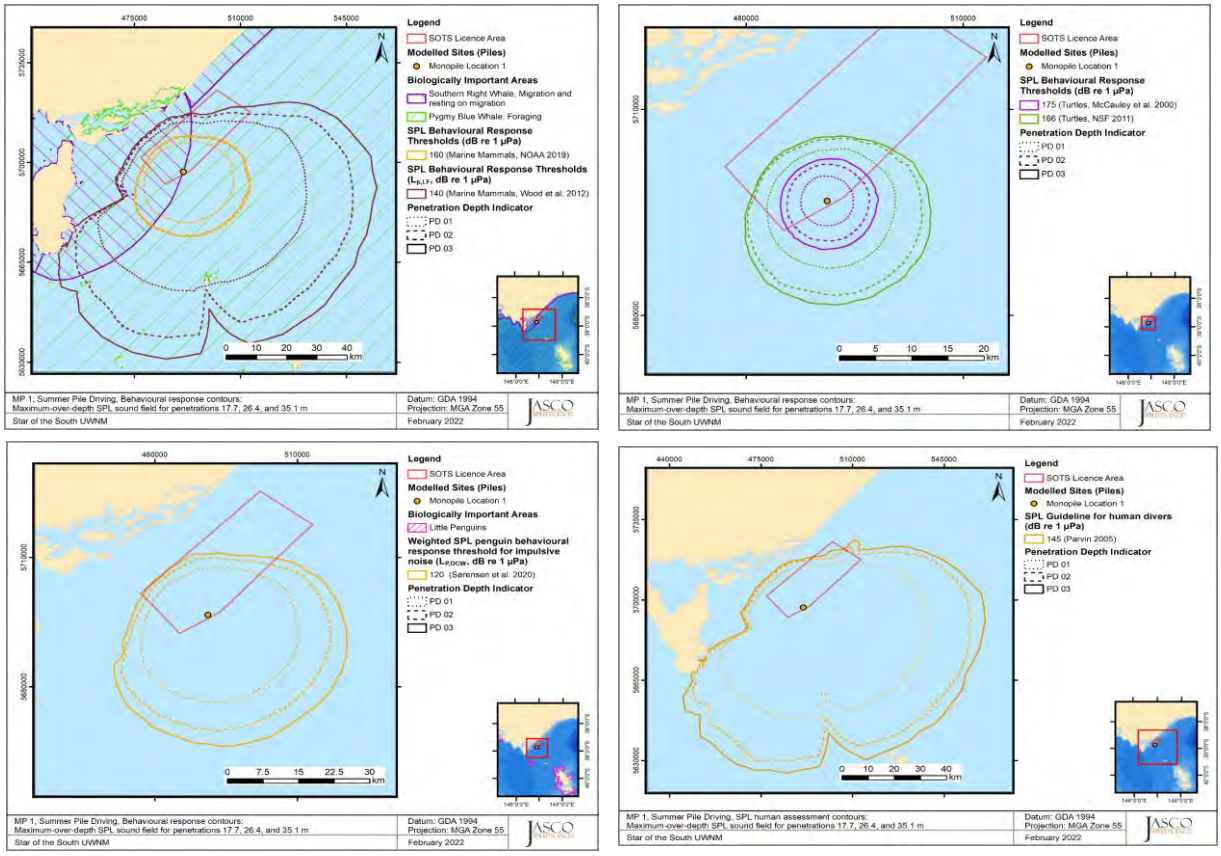


Figure 22. *Monopile 1, summer, first modelling round, marine mammal behavioural criteria, (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL: Sound level contour map showing maximum–over–depth SPL results for the third penetration depth.*

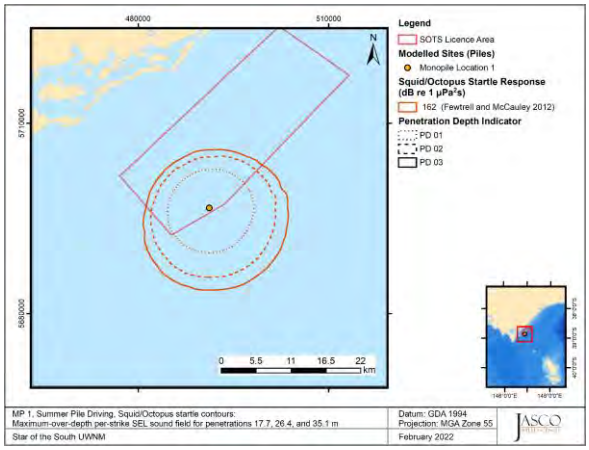


Figure 23. *Monopile 1, summer, first modelling round, squid/octopus* startle response criteria*, per–strike SEL: Sound level contour map showing maximum–over–depth SPL results for the third penetration depth*.

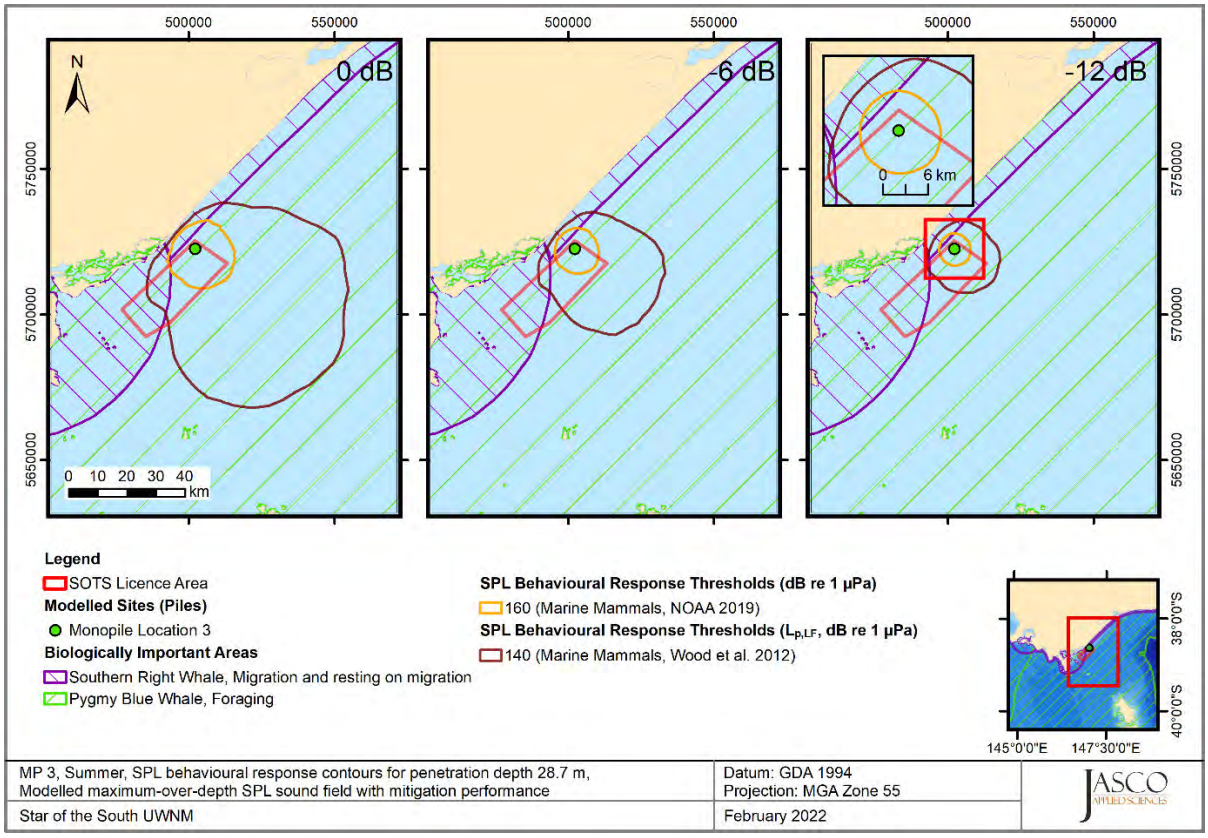


Figure 24. *Monopile 3, summer, first modelling round, marine mammal behavioural criteria, SPL*: Sound level contour map showing maximum–over–depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (Left), 6 dB of mitigation (Centre), 12 dB of mitigation sound level contours.

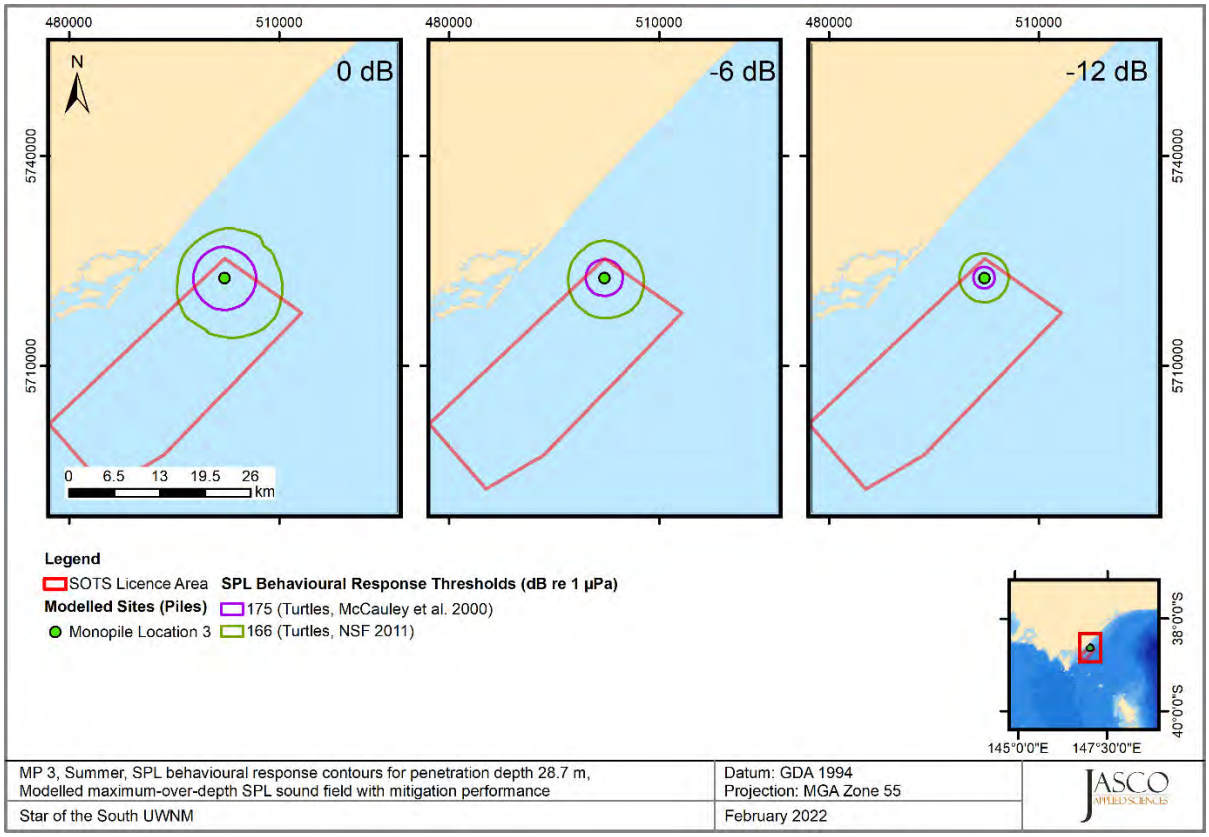


Figure 25. *Monopile 3, summer, first modelling round, sea turtle behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

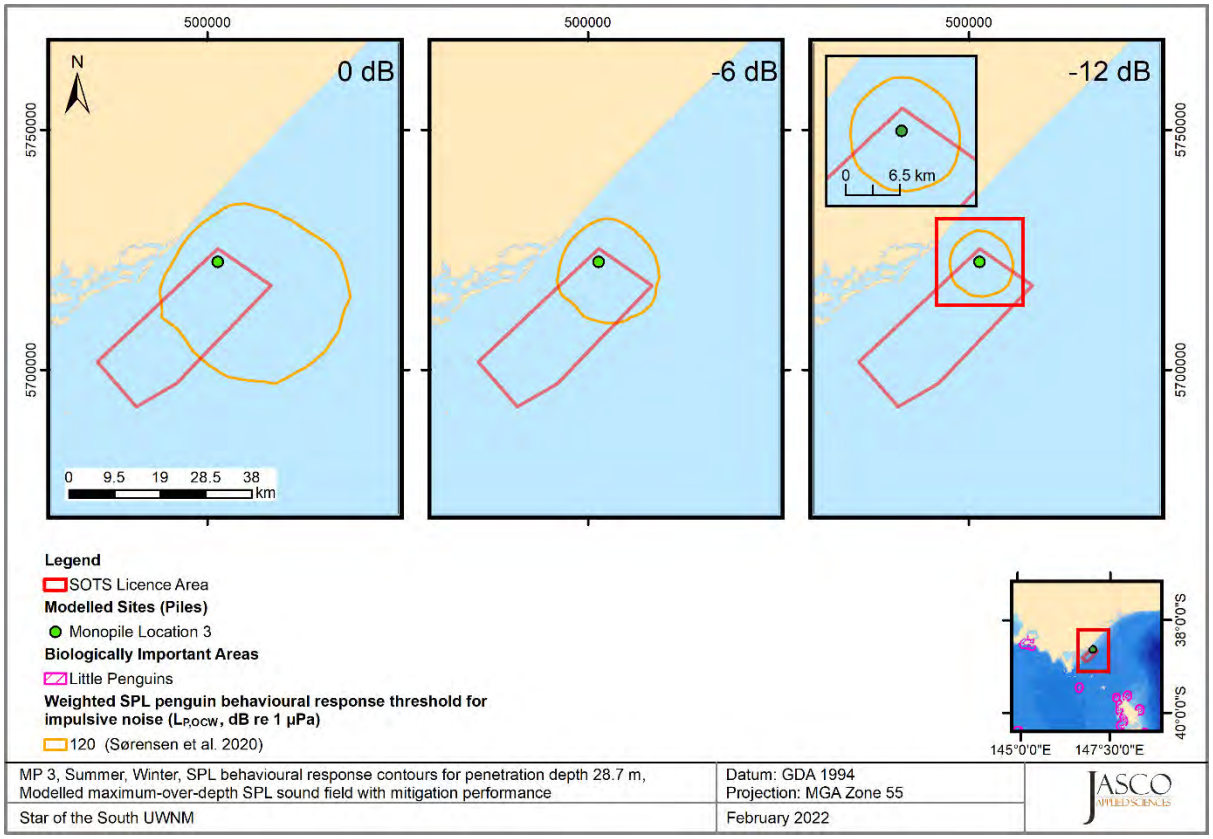


Figure 26. *Monopile 3, summer, first modelling round, penguin behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

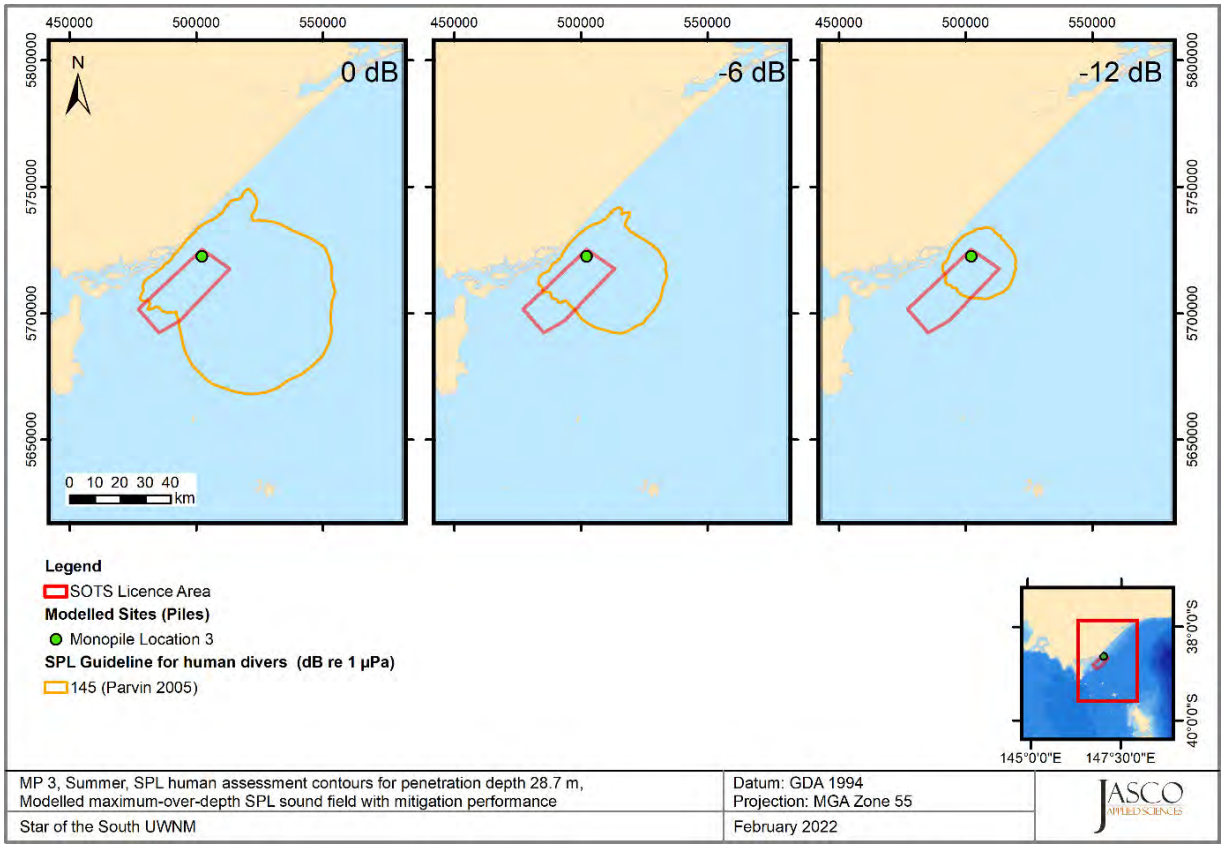


Figure 27. *Monopile 3, summer, first modelling round, human health assessment criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

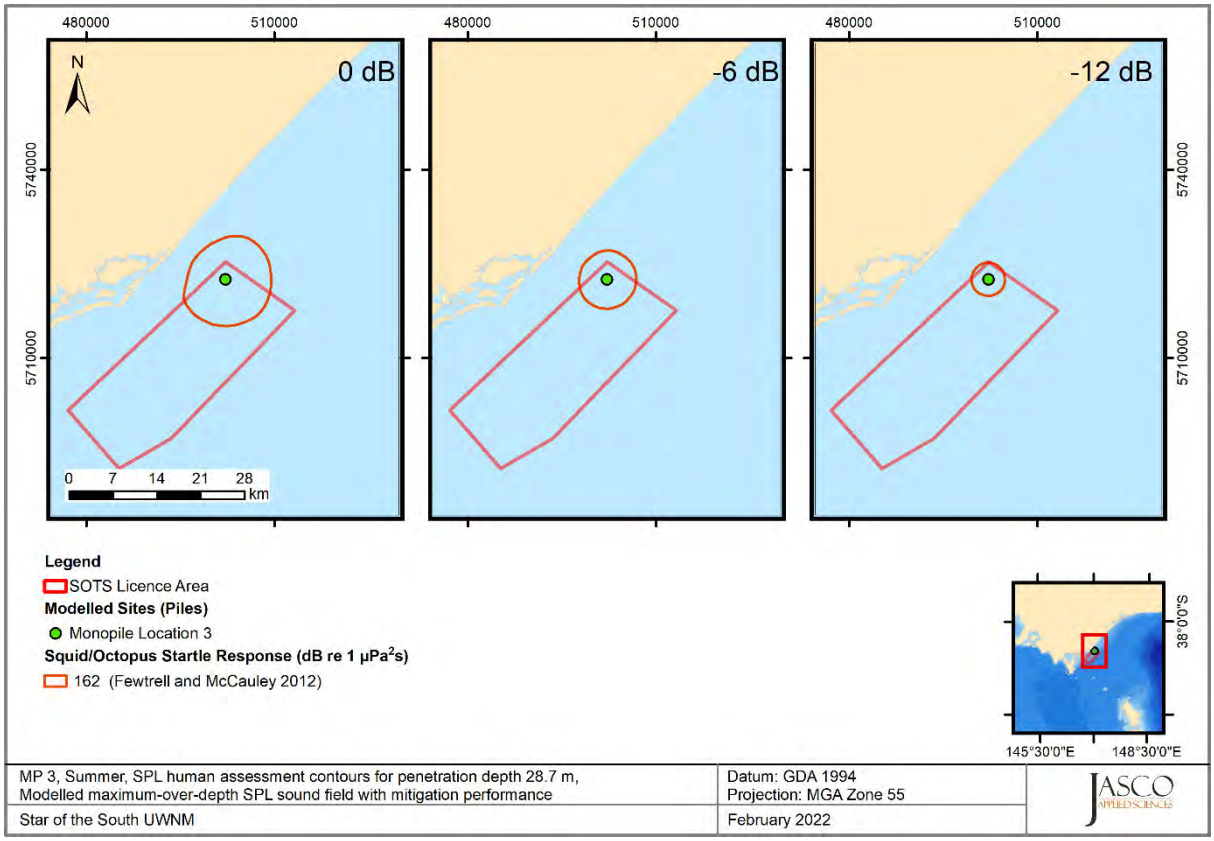


Figure 28. *Monopile 3, summer, first modelling round, squid/octopus* startle response criteria*, per–strike SEL*: Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

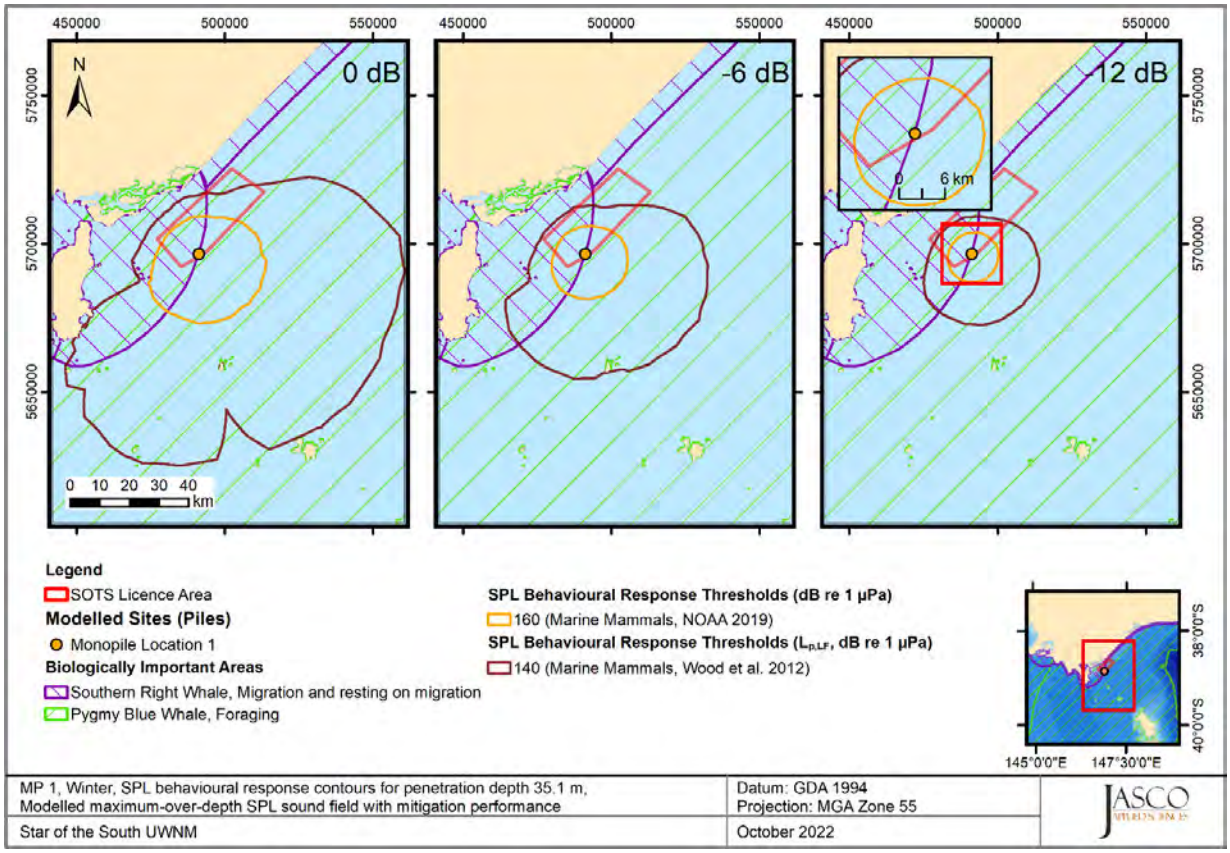


Figure 29. *Monopile 1, winter, first modelling round, marine mammal behavioural criteria, SPL*: Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

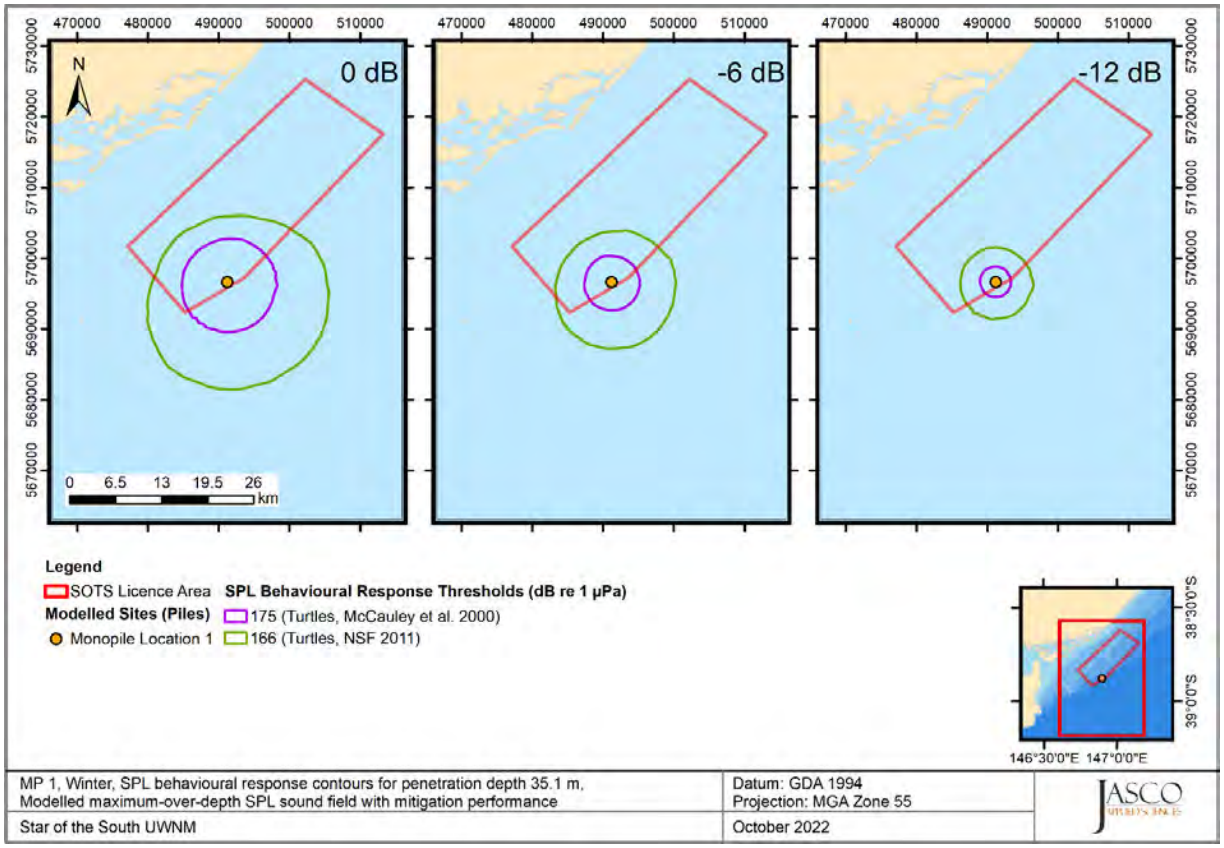


Figure 30. *Monopile 1, winter, first modelling round, sea turtle behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

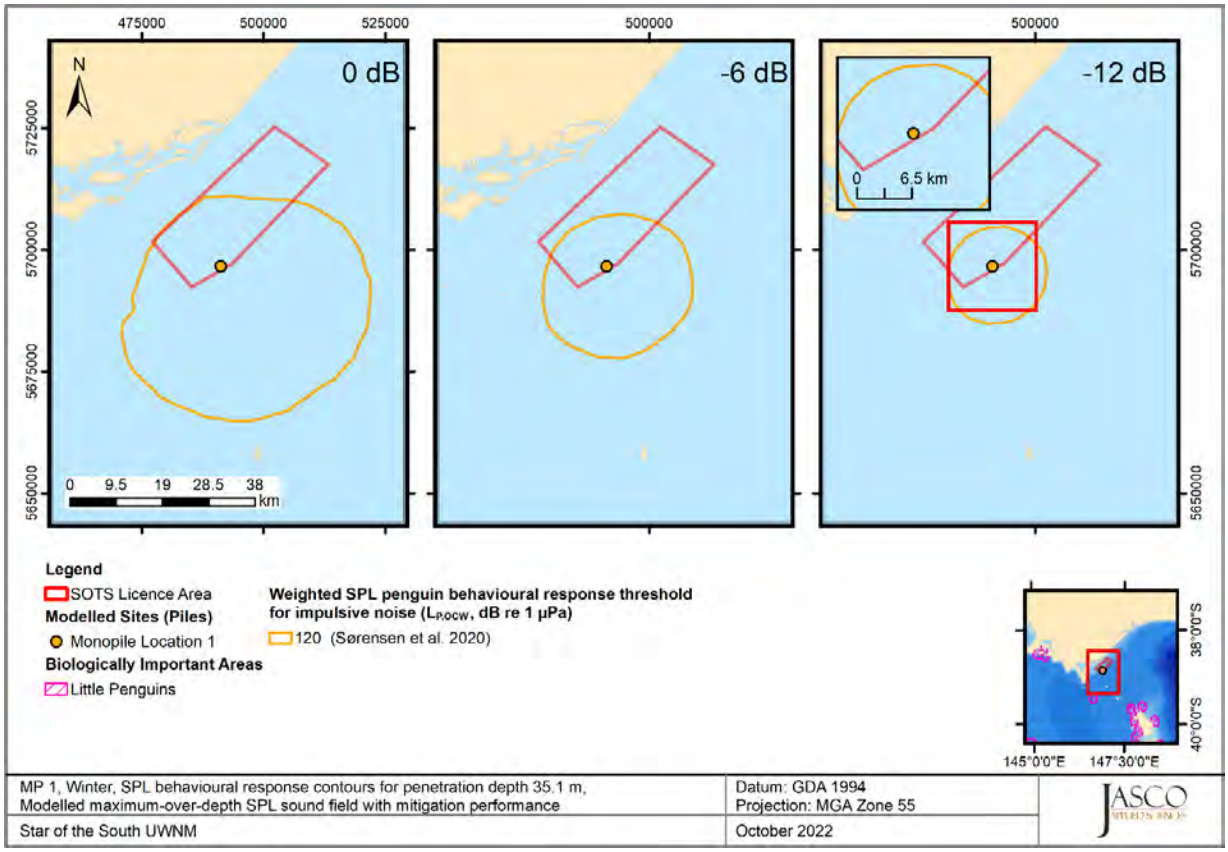


Figure 31. *Monopile 1, winter, first modelling round, penguin behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

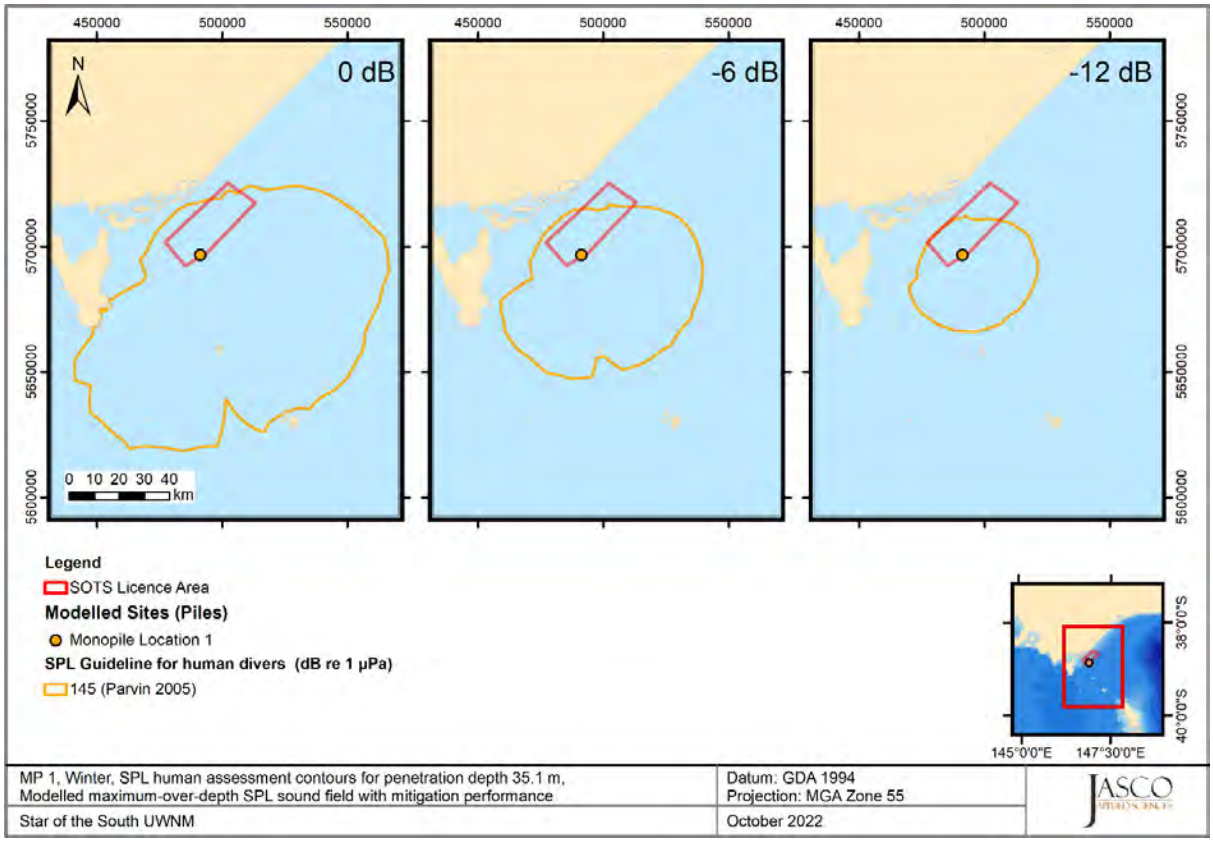


Figure 32. *Monopile 1, winter, first modelling round, human health assessment criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

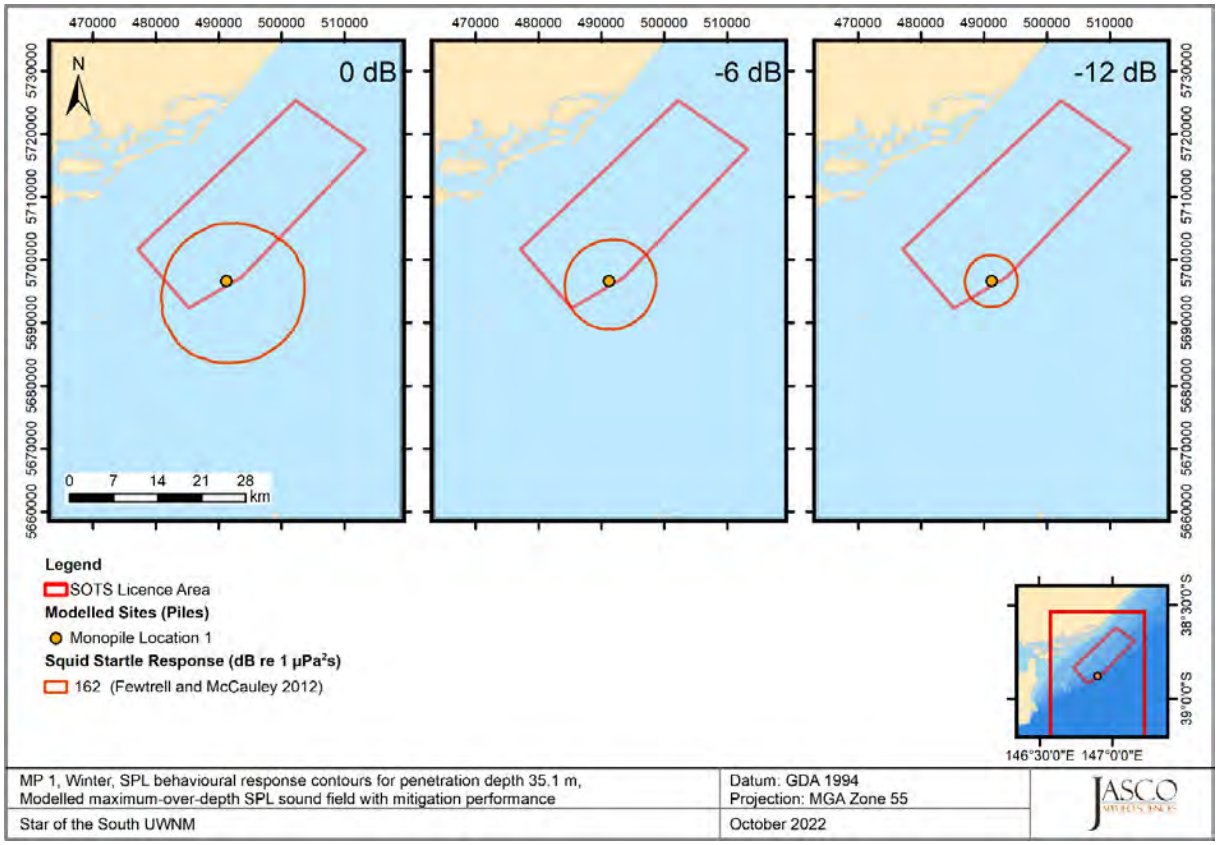


Figure 33. *Monopile 1, winter, first modelling round, squid startle response criteria, per–strike SEL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

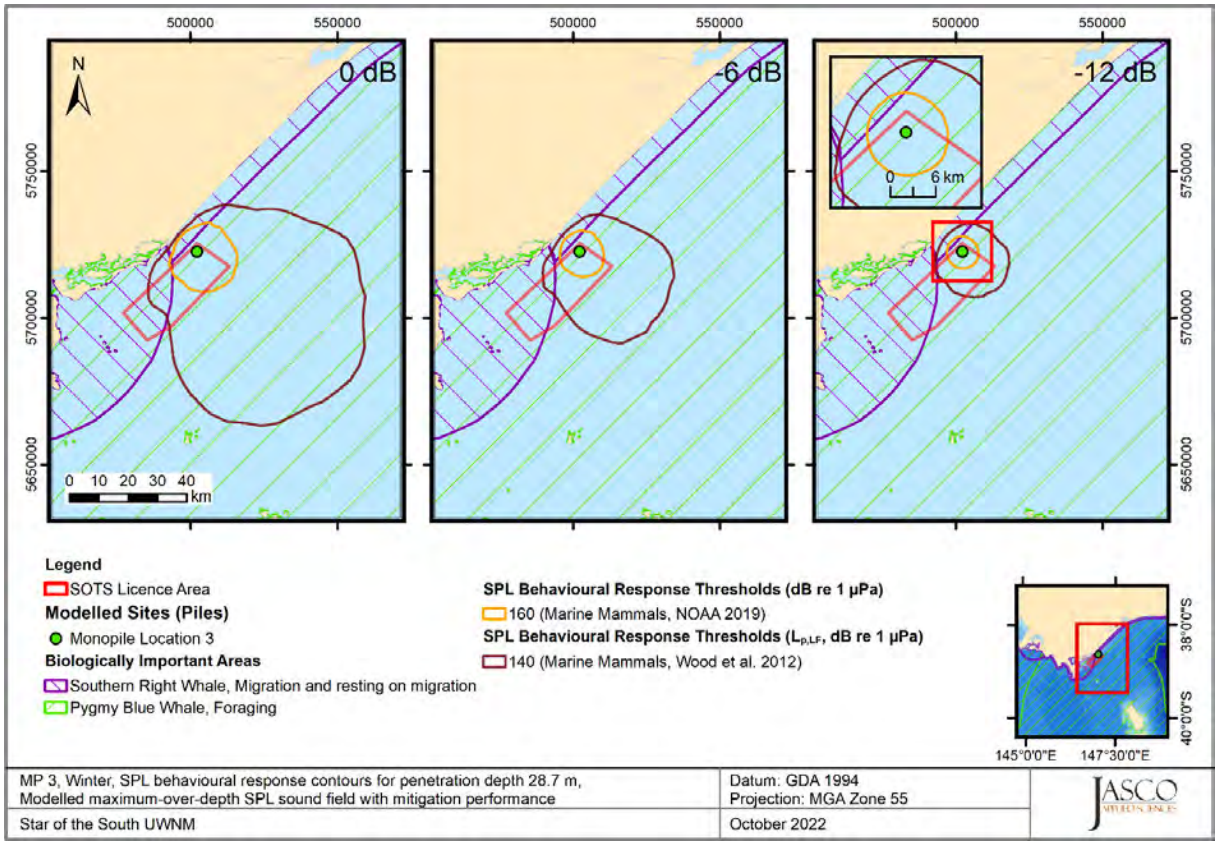


Figure 34. *Monopile 3, winter, first modelling round, marine mammal behavioural criteria, SPL*: Sound level contour map showing maximum–over–depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (Left), 6 dB of mitigation (Centre), 12 dB of mitigation sound level contours.

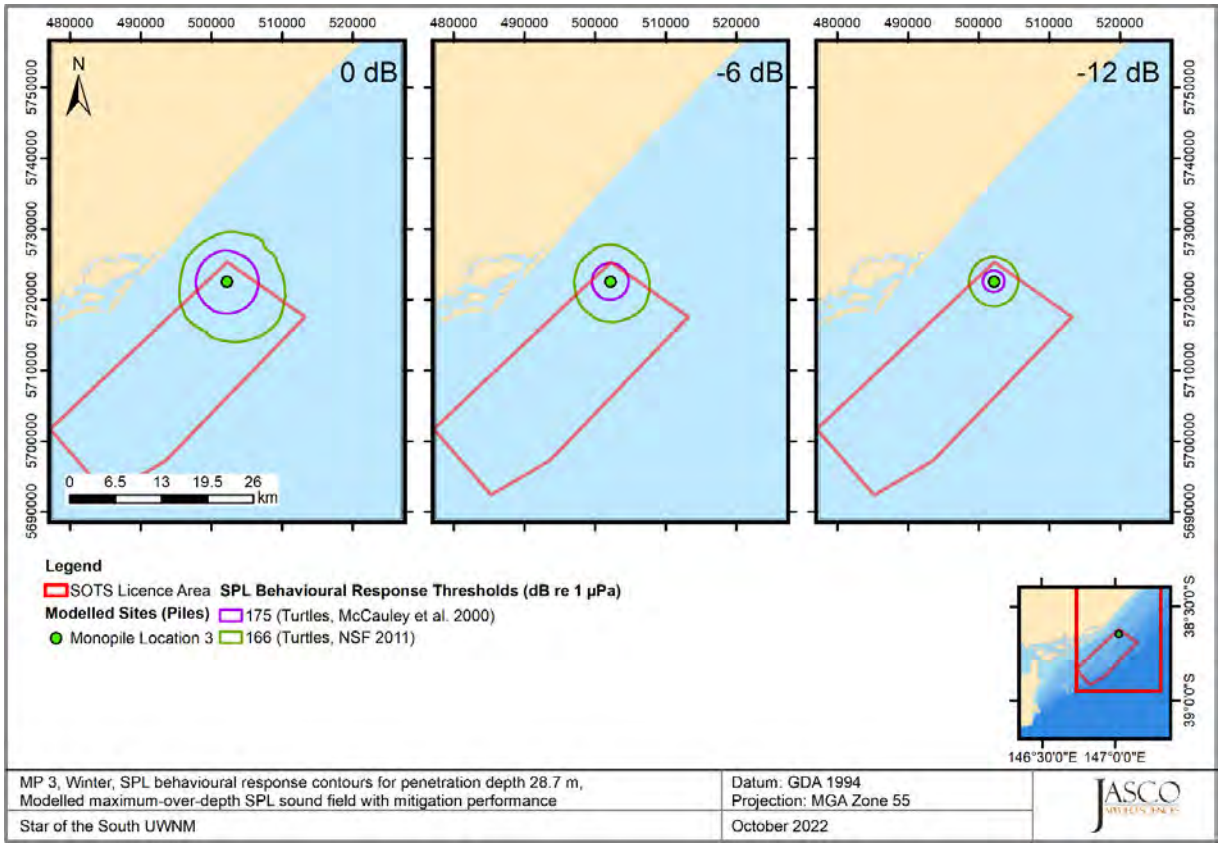


Figure 35. *Monopile 3, winter, first modelling round, sea turtle behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

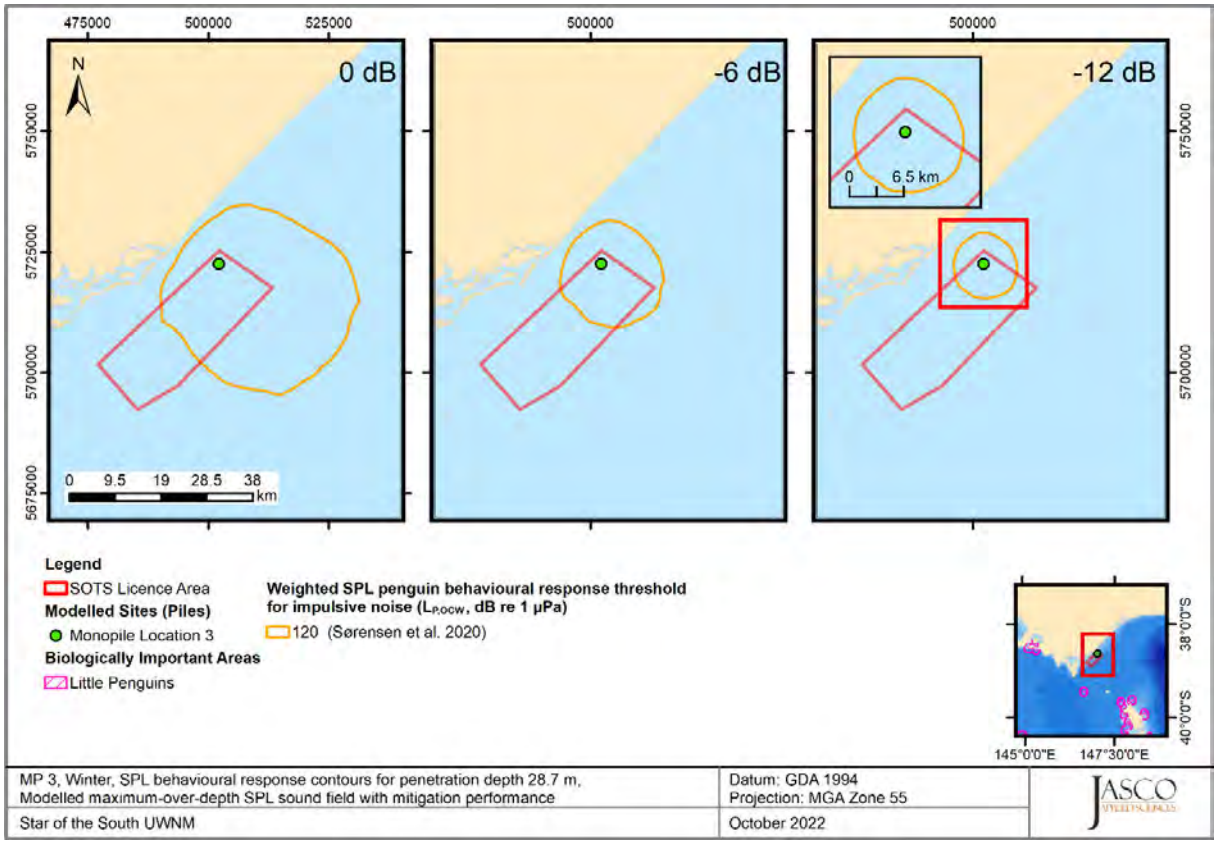


Figure 36. *Monopile 3, winter, first modelling round, penguin behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

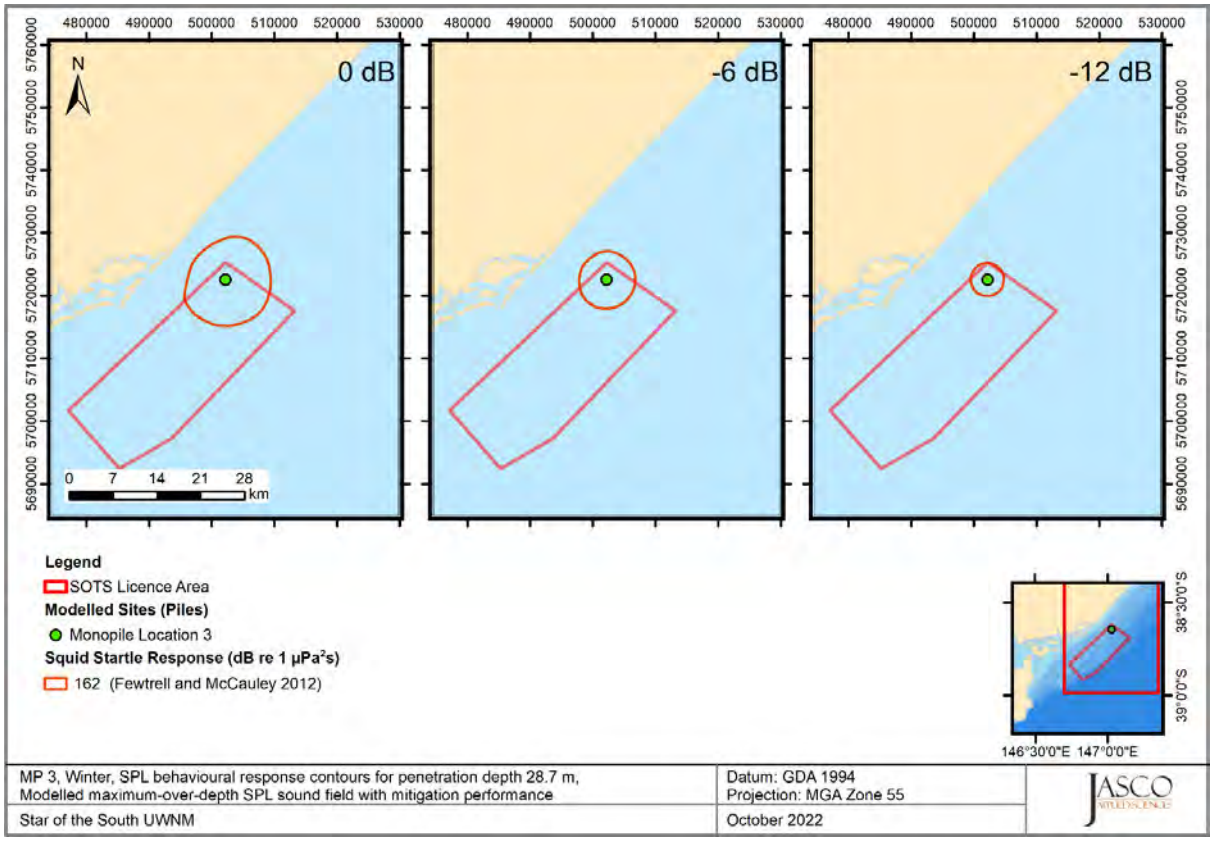


Figure 37. *Monopile 3, winter, first modelling round, squid startle response criteria, per–strike SEL*: Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

The following presents the multiple strike sound field maps.

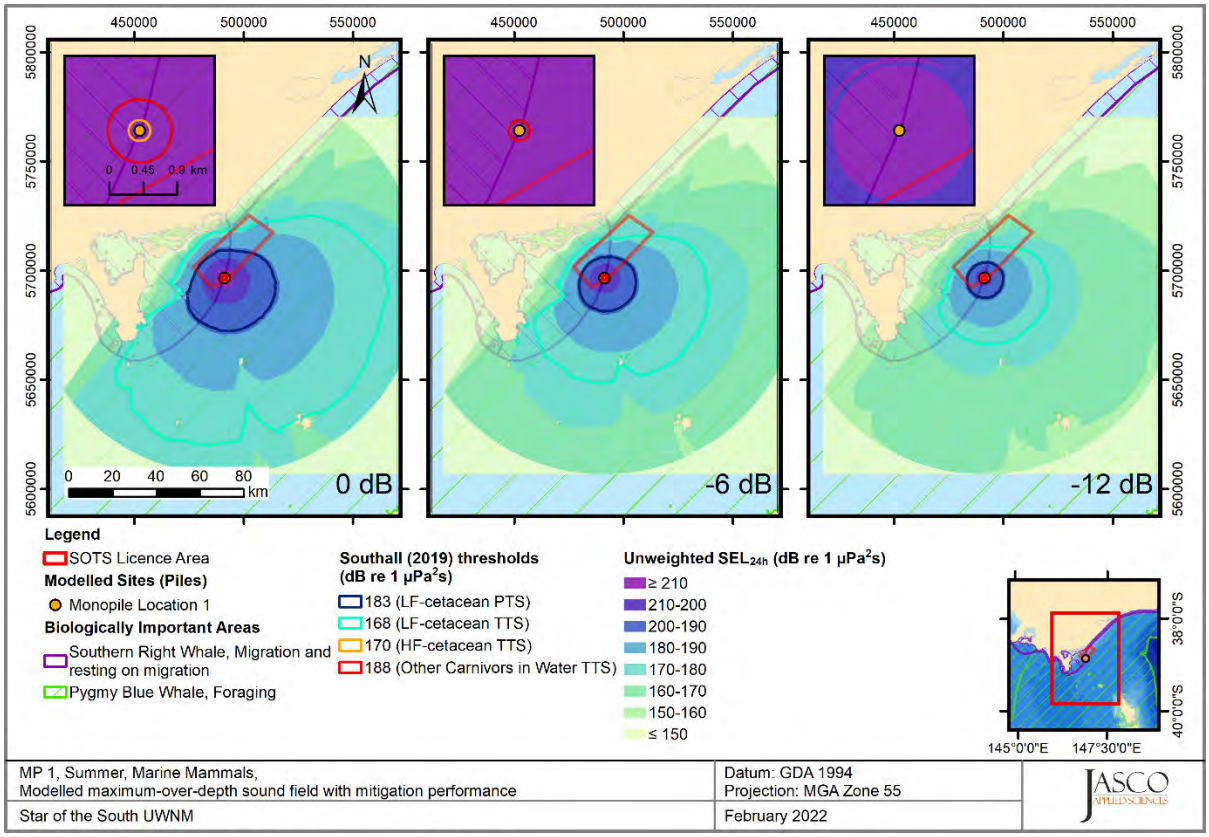


Figure 38. *Monopile 1, summer, first modelling round, marine mammals, SEL_{24h}*: Contour map showing maximum–over–depth unweighted SEL_{24h} isopleths. Panels from left to right showing unmitigated (Left), 6 dB of mitigation (Centre), 12 dB of mitigation (Right) sound level contours. Thresholds omitted here were not reached or not large enough to display graphically.

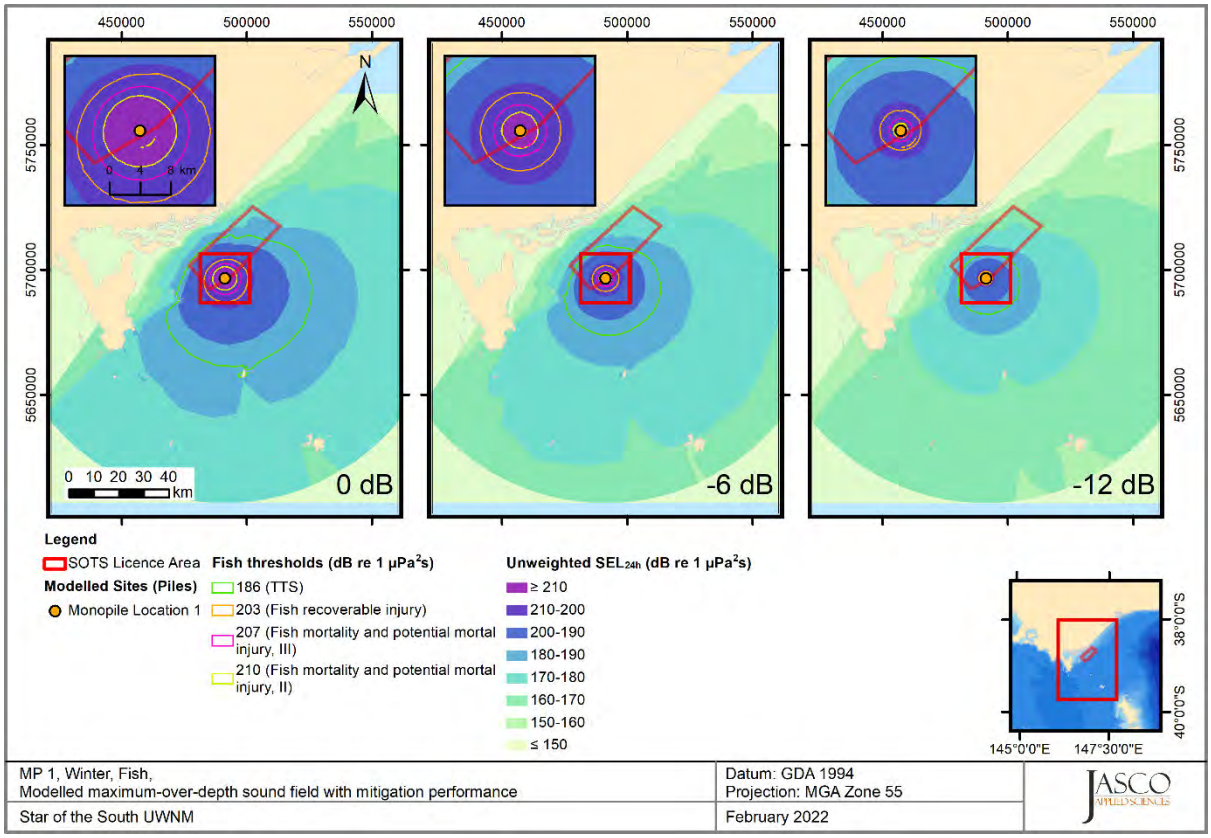


Figure 39. *Monopile 1, summer, first modelling round, fish, SEL$_{24h}$*: Contour map showing maximum–over–depth unweighted SEL24h isopleths. Panels from left to right showing unmitigated (Left), 6 dB of mitigation (Centre), 12 dB of mitigation (Right) sound level contours. Thresholds omitted here were not reached or not large enough to display graphically.

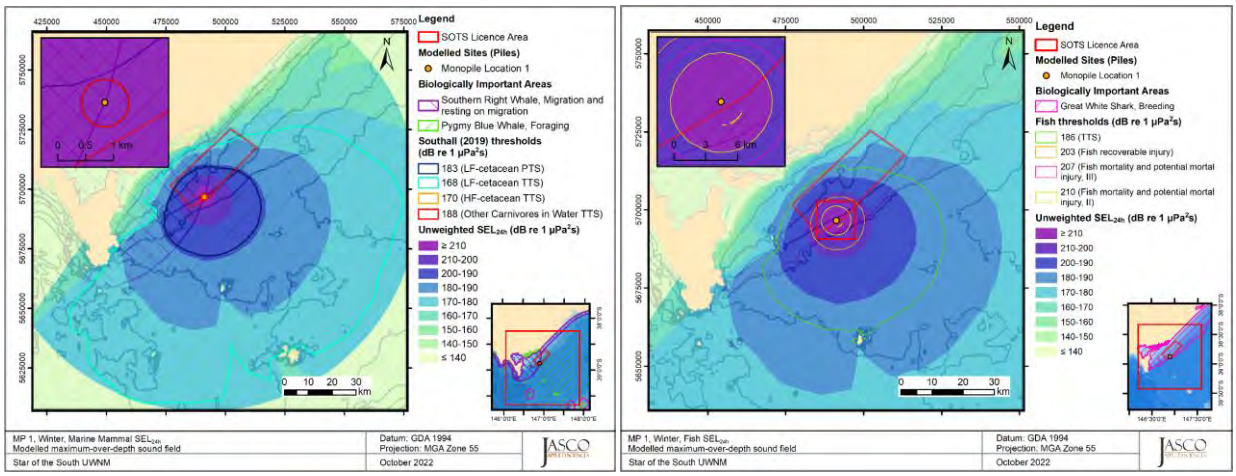


Figure 40. *Monopile 1, winter, first modelling round, marine mammals (left), fish (right), SEL$_{24h}$*: Contour map showing maximum–over–depth unweighted SEL$_{24h}$ isopleths. Thresholds omitted here were not reached or not large enough to display graphically.

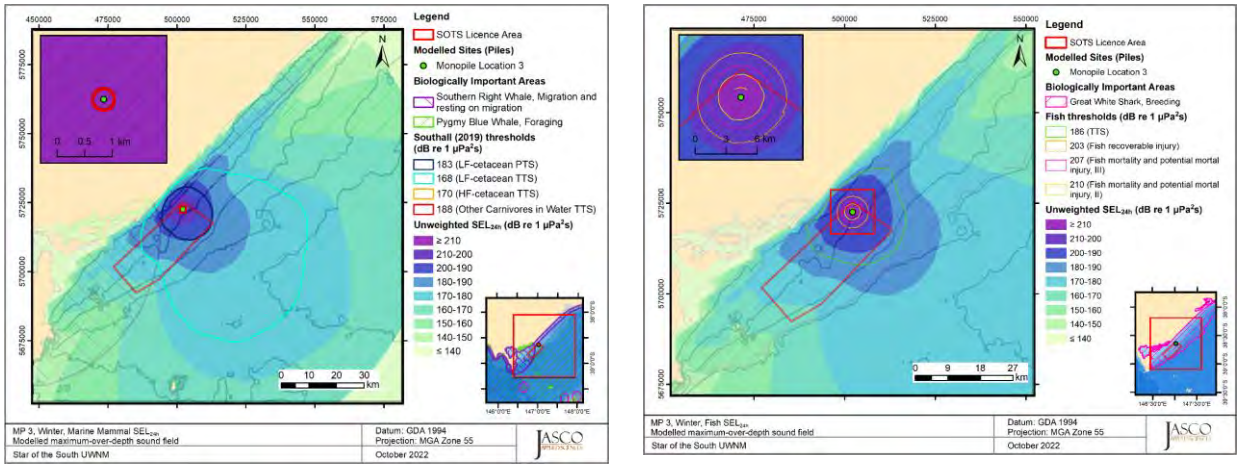


Figure 41. Monopile 3, winter, first modelling round, marine mammals (left), fish (right), SEL_{24h}: Contour map showing maximum–over–depth unweighted SEL24h isopleths. Thresholds omitted here were not reached or not large enough to display graphically.

4.1.2.2. Scenario 2 – DBBC (First Modelling Round)

4.1.2.2.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented below.

Vertical slice plots of the SPL sound field (winter only) are presented in Appendix F.1.1.2 for NAS scenario DBBC considering the third penetration depth. The orientation of the slice transects are such that the first bearing listed in the caption corresponds with the positive distance and the second bearing corresponds with the negative distances.

Table 34. *Monopiles with frequency dependent reduction (DBBC), winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each NAS scenario and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 1 (DBBC)						Monopile 3 (DBBC)					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	$R_{95\%}$ (km)	R_{max} (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)
190	0.10	0.10	0.15	0.14	0.16	0.16	0.04	0.04	0.12	0.11	0.13	0.13
180	0.18	0.18	0.20	0.19	0.21	0.20	0.15	0.14	0.21	0.20	0.21	0.20
170	0.24	0.23	0.69	0.67	1.04	1.00	0.29	0.28	1.07	1.00	1.09	1.03
162[a]	1.00	0.95	2.47	2.35	3.23	3.09	0.96	0.91	3.12	2.86	3.15	2.93
160	1.42	1.33	3.12	2.96	3.97	3.78	1.28	1.16	3.76	3.45	3.79	3.51
150	4.79	4.54	7.82	7.41	8.90	8.40	3.84	3.52	7.79	7.23	7.80	7.30
140	11.0	9.90	15.3	14.3	16.3	15.4	7.72	7.16	13.4	12.4	13.4	12.5
130	21.0	17.9	24.4	21.3	24.3	22.3	13.2	12.2	18.9	17.5	19.0	17.7

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 35. *Monopiles with frequency dependent reduction (DBBC), winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each NAS scenario and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1 (DBBC)						Monopile 3 (DBBC)					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.09	0.09	0.14	0.13	0.15	0.14	0.04	0.04	0.11	0.11	0.12	0.12
190	0.18	0.17	0.19	0.19	0.2	0.19	0.14	0.14	0.19	0.19	0.19	0.19
180	0.22	0.21	0.50	0.48	0.80	0.77	0.22	0.21	0.84	0.79	0.87	0.83
170	1.02	0.98	2.43	2.33	3.16	3.01	0.98	0.92	2.87	2.64	3.02	2.81
160	3.30	3.12	5.73	5.15	7.11	6.61	3.05	2.78	6.55	5.98	6.66	6.21
150	7.40	6.61	10.08	9.09	12.3	11.0	6.56	5.97	11.1	10.0	11.1	10.2
145[a]	11.1	9.29	14.2	12.5	15.7	14.4	8.57	7.81	14.4	13.3	14.4	13.5
140	15.9	13.6	18.2	16.1	19.0	17.1	10.8	9.70	16.9	15.6	16.8	15.8
130	25.8	20.8	28.9	24.1	28.2	24.7	16.6	15.3	22.6	20.8	22.5	20.9

[a] Human health assessment threshold derived from Parvin (2005).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 36. *Monopile 1 with frequency dependent reduction (DBBC), winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL (L_p; dB re 1 µPa)	Monopile 1 (DBBC)					
		Penetration depth (m)					
		17.7		26.4		35.1	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.44	0.42	1.19	1.14	1.77	1.70
Sea turtle behavioural response [a]	166	1.88	1.79	3.55	3.35	4.47	4.23
Marine mammal behavioural response [c]	160	3.30	3.12	5.73	5.15	7.11	6.61
LF-cetacean weighted behavioural response [d]	160	0.76	0.71	1.34	1.21	1.89	1.73
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	5.97	5.54	8.31	7.70	9.47	8.71
Penguin behavioural response [e]	120	2.84	2.57	3.78	3.43	4.54	4.13

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 37. *Monopile 3 with frequency dependent reduction (DBBC), winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL (Lp; dB re 1 µPa)	Monopile 3 (DBBC)					
		Penetration depth (m)					
		14.2		21.4		28.7	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.46	0.44	1.70	1.57	1.79	1.67
Sea turtle behavioural response [a]	166	1.68	1.55	4.10	3.75	4.26	3.95
Marine mammal behavioural response [c]	160	3.05	2.78	6.55	5.98	6.66	6.21
LF-cetacean weighted behavioural response [d]	160	1.04	0.98	2.10	1.92	1.87	1.72
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	5.84	5.36	9.16	8.45	8.62	7.87
Penguin behavioural response [e]	120	2.83	2.55	3.77	3.41	3.45	3.13

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 38. *Monopiles with frequency dependent reduction (DBBC), winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1 (DBBC)			Monopile 3 (DBBC)		
		Penetration depth (m)			Penetration depth (m)		
		17.7	26.4	35.1	14.2	21.4	28.7
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS							
LF cetaceans	219	–	0.09	0.09	–	0.03	0.04
HF cetaceans	230	–	–	–	–	–	–
Otariid seals	232	–	–	–	–	–	–
Sea turtles	232	–	–	–	–	–	–
Penguins	232	–	–	–	–	–	–
TTS							
LF cetaceans	213	0.10	0.14	0.14	0.04	0.10	0.12
HF cetaceans	224	–	–	–	–	–	–
Otariid seals	226	–	–	–	–	–	–
Sea turtles	226	–	–	–	–	–	–
Penguins	226	–	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury							
Fish I	213	0.10	0.14	0.14	0.04	0.10	0.12
Fish II, III Fish eggs and larvae	207	0.16	0.18	0.19	0.11	0.15	0.16

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 39. *Monopiles with frequency dependent reduction (DBBC),* maximum–over–depth per–strike SEL for each penetration at 1000 m from the centre of the pile with and without the NAS systems applied. The dB reduction in maximum–over–depth per–strike SEL (ΔSEL) is also provided.

Scenario	Monopile Location	NAS System	Penetration depth (m)	Per–strike SEL (L_E;dB re 1 µPa²·s)		ΔSEL (dB)
				Unmitigated	Mitigated	
M1	Monopile 1	DBBC	17.7	177.7	162.2	15.5
			26.4	182.8	168.2	14.6
			35.1	185.4	170.8	14.6
M3	Monopile 3	DBBC	14.2	174.3	161.5	12.8
			21.4	180.5	170.8	9.7
			28.7	181.9	170.9	11.0

4.1.2.2.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 40. *Monopiles with frequency dependent reduction (DBBC), winter, single pile SEL: marine mammals, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to SEL_{24h} based fish criteria.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
		R_{max}(km)	$R_{95\%}$(km)	R_{max}(km)	$R_{95\%}$(km)
PTS					
LF cetaceans	183	3.70	3.26	2.99	2.67
HF cetaceans	185	–	–	–	–
Otariid seals	203	–	–	–	–
Sea turtles	204	0.47	0.45	0.42	0.40
Penguins	203	–	–	–	–
TTS					
LF cetaceans	168	11.3	10.3	8.42	7.71
HF cetaceans	170	0.10	0.09	0.06	0.06
Otariid seals	188	0.10	0.10	0.09	0.09
Sea turtles	189	3.45	3.14	3.01	2.70
Penguins	188	0.10	0.10	0.09	0.09

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 41. *Monopiles with frequency dependent reduction (DBBC), winter, single pile SEL*: fish, *single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to SEL_{24h} based fish criteria.

Fauna group	SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
		R_{max}(km)	$R_{95\%}$(km)	R_{max}(km)	$R_{95\%}$(km)
Mortality and potential mortal injury					
I	219	0.14	0.13	0.10	0.10
II, Fish eggs and fish larvae	210	0.64	0.61	0.47	0.45
III	207	1.09	1.04	0.80	0.73
Fish recoverable injury					
I	216	0.20	0.19	0.14	0.14
II, III	203	1.96	1.87	1.46	1.37
Fish temporary threshold shift (TTS)					
I, II, III	186	9.46	8.96	7.05	6.53

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.2.3. Sound Field Maps

The sound level contours for Monopile 1 with the different NAS scenarios applied are presented in Figure 42 and Figure 43.

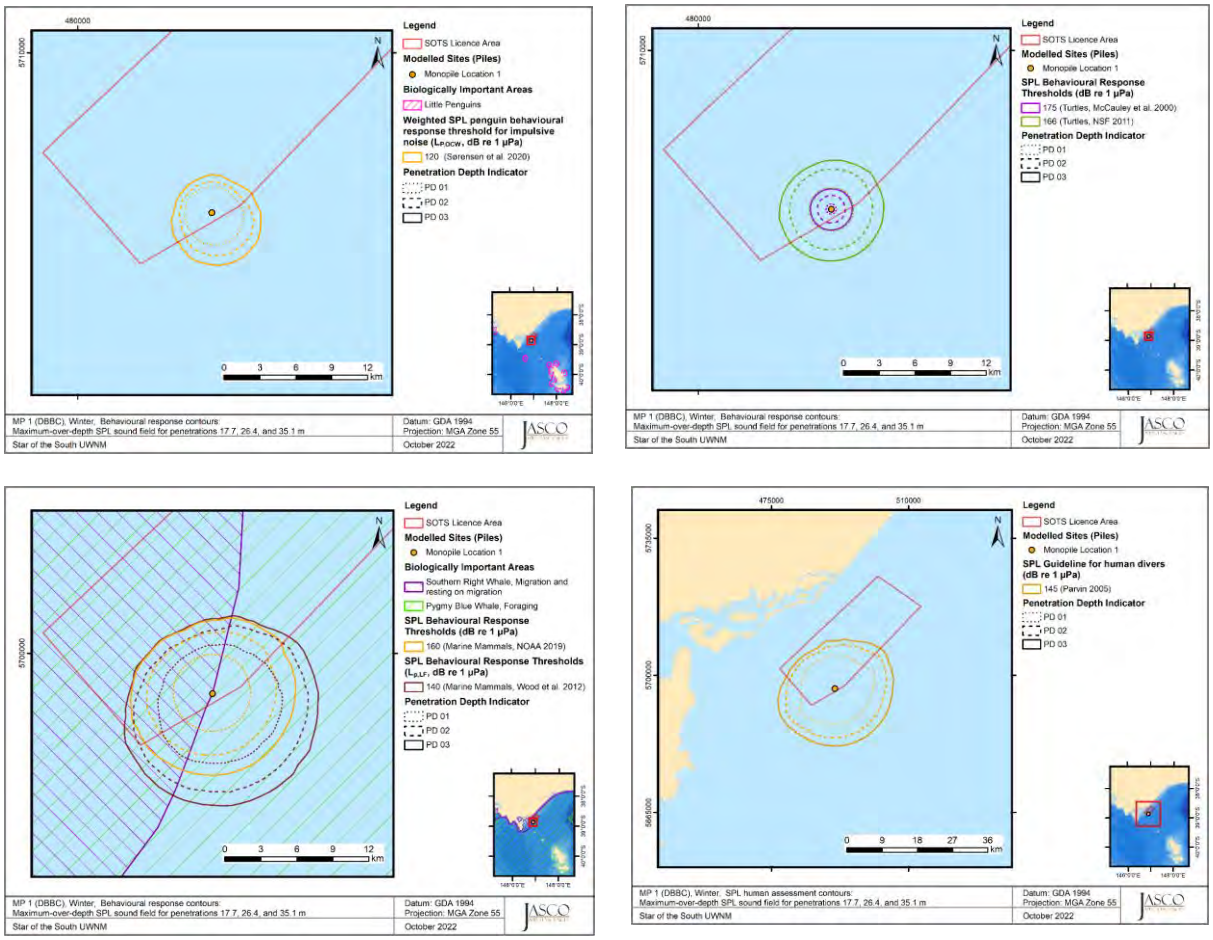


Figure 42. *Monopile 1, DBBC, winter, marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL: Sound level contour map showing maximum–over–depth results for all penetration depth.*

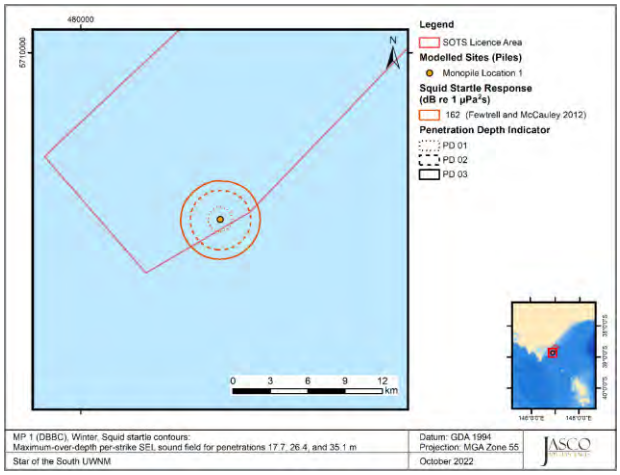


Figure 43. *Monopile 1, DBBC, winter, squid* startle response criteria*, per–strike SEL*: Sound level contour map showing maximum–over–depth results for all penetration depths.

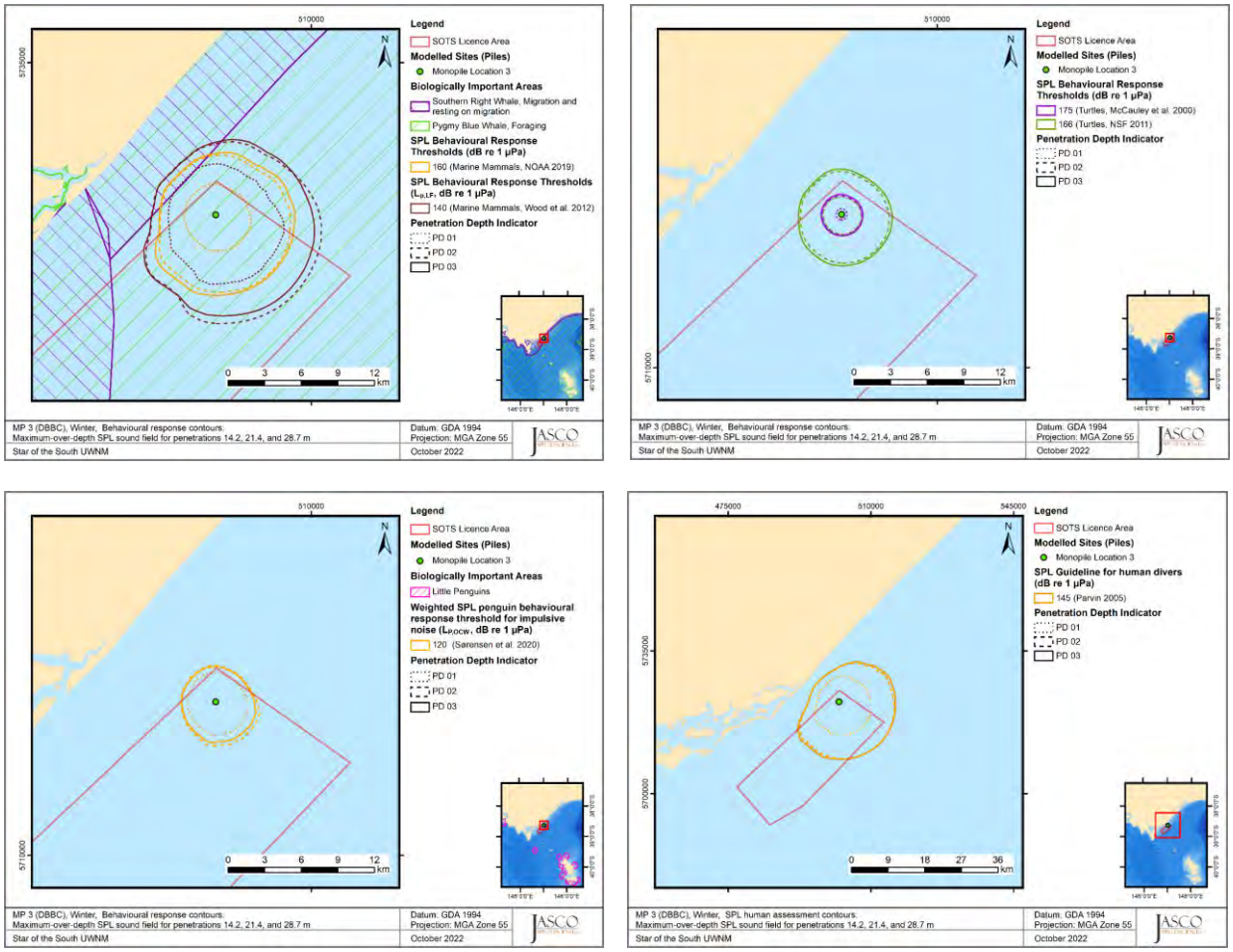


Figure 44. *Monopile 3, DBBC, winter, marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL:* Sound level contour map showing maximum–over–depth results for all penetration depths.

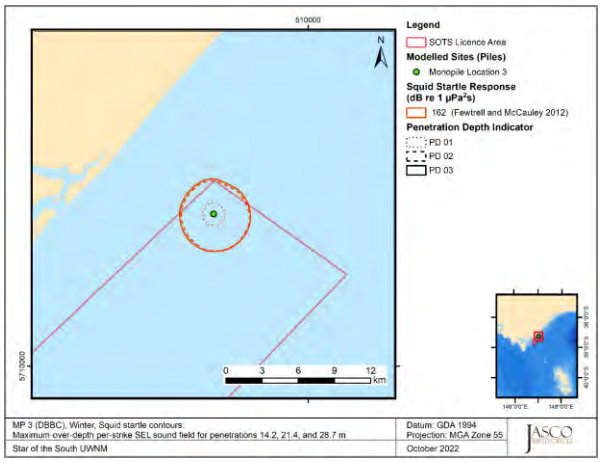


Figure 45. *Monopile 3, DBBC, winter, squid startle response criteria, per–strike SEL*: Sound level contour map showing maximum–over–depth results for all penetration depths.

Following presents the multi-strikes contour maps:

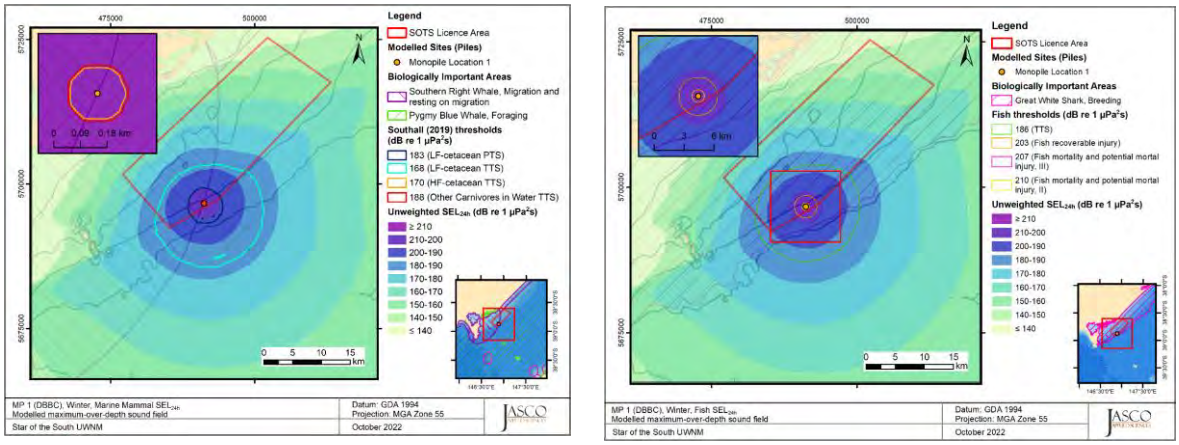


Figure 46. *Monopile 1, DBBC, winter, Marine Mammals (left), fish (right), SEL_{24h}*: Contour map showing maximum–over–depth unweighted SEL_{24h} isopleths and weighted thresholds.

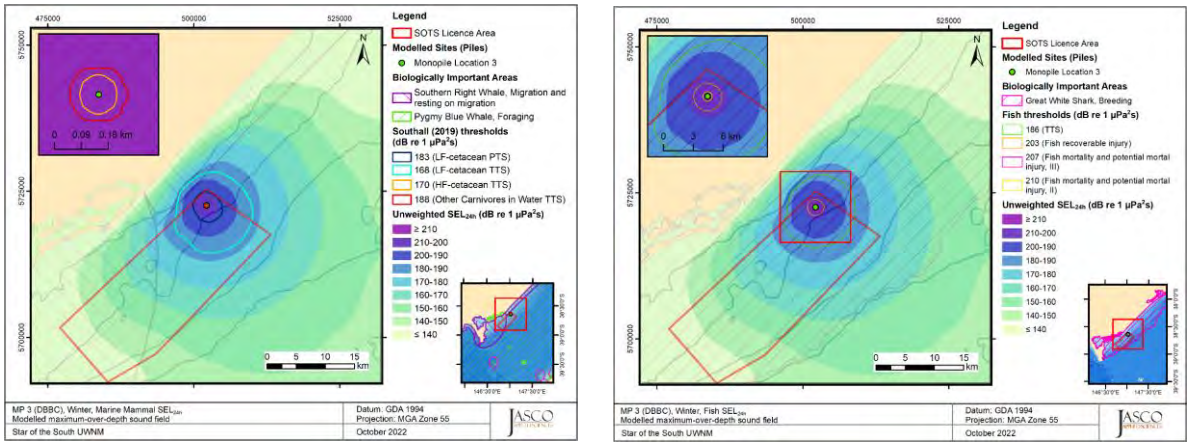


Figure 47. *Monopile 3, DBBC, winter, Marine Mammals (left), fish (right), SEL_{24h}*: Contour map showing maximum–over–depth unweighted SEL_{24h} isopleths and weighted thresholds.

4.1.2.3. Scenario 3 – DBBC + HSD (First Modelling Round)

4.1.2.3.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented below.

Vertical slice plots of the SPL sound field (winter only) are presented in Appendix F.1.1.3 for NAS scenario HSD+DBBC considering the third penetration depth. The orientation of the slice transects are such that the first bearing listed in the caption corresponds with the positive distance and the second bearing corresponds with the negative distances.

Table 42. *Monopiles with frequency dependent reduction (HSD+DBBC), winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each NAS scenario and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 1 (HSD+DBBC)						Monopile 3 (HSD+DBBC)					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.03	0.03	0.10	0.10	0.11	0.10	–	–	0.10	0.10	0.10	0.10
180	0.14	0.14	0.18	0.17	0.19	0.19	0.12	0.11	0.19	0.18	0.19	0.19
170	0.20	0.19	0.44	0.42	0.73	0.69	0.19	0.19	0.94	0.88	1.01	0.95
162[a]	0.70	0.67	1.85	1.77	2.47	2.39	0.65	0.62	2.85	2.62	2.98	2.77
160	0.98	0.93	2.42	2.30	3.13	3.00	0.91	0.86	3.47	3.19	3.60	3.35
150	3.98	3.75	6.70	6.37	7.79	7.35	3.26	2.98	7.46	6.92	7.56	7.10
140	9.30	8.80	13.5	12.8	15.0	14.1	7.17	6.61	12.9	11.9	13.1	12.2
130	18.9	16.5	22.4	19.9	22.4	21.0	12.5	11.4	18.5	17.2	18.7	17.4

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 43. *Monopiles with frequency dependent reduction (HSD+DBBC), winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each NAS scenario and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1 (HSD+DBBC)						Monopile 3 (HSD+DBBC)					
	Penetration depth (m)						Penetration depth (m)					
	17.7		26.4		35.1		14.2		21.4		28.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.02	0.02	0.07	0.07	0.1	0.1	–	–	0.04	0.04	0.10	0.07
190	0.13	0.13	0.17	0.17	0.18	0.18	0.11	0.11	0.18	0.17	0.18	0.18
180	0.19	0.19	0.35	0.34	0.49	0.47	0.19	0.18	0.72	0.68	0.79	0.75
170	0.76	0.73	1.89	1.81	2.45	2.36	0.72	0.68	2.65	2.46	2.86	2.66
160	2.71	2.59	4.74	4.41	5.96	5.50	2.52	2.31	6.13	5.64	6.42	5.99
150	5.87	5.57	9.05	8.19	10.3	9.39	5.72	5.20	10.4	9.49	10.6	9.88
145[a]	9.33	8.20	12.1	10.8	14.2	12.8	7.88	7.20	13.9	12.8	14.0	13.2
140	14.2	12.2	16.8	15.1	17.2	15.9	9.80	8.99	16.4	15.3	16.5	15.6
130	23.8	19.4	27.0	22.3	26.1	23.3	16.0	14.7	22.1	20.4	22.1	20.6

[a] Human health assessment threshold derived from Parvin (2005).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 44. *Monopile 1 with frequency dependent reduction (HSD+DBBC), winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL (L_p; dB re 1 µPa)	Monopile 1 (HSD+DBBC)					
		Penetration depth (m)					
		17.7		26.4		35.1	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.32	0.31	0.86	0.83	1.19	1.14
Sea turtle behavioural response [a]	166	1.36	1.29	2.91	2.77	3.65	3.48
Marine mammal behavioural response [c]	160	2.71	2.59	4.74	4.41	5.96	5.50
LF-cetacean weighted behavioural response [d]	160	0.44	0.42	0.83	0.77	1.23	1.12
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	4.95	4.63	7.22	6.71	8.50	7.77
Penguin behavioural response [e]	120	1.74	1.58	2.49	2.28	3.50	3.15

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 45. *Monopile 3 with frequency dependent reduction (HSD+DBBC), winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL (Lp; dB re 1 µPa)	Monopile 3 (HSD+DBBC)					
		Penetration depth (m)					
		14.2		21.4		28.7	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.33	0.31	1.49	1.39	1.64	1.53
Sea turtle behavioural response [a]	166	1.23	1.12	3.83	3.54	4.08	3.8
Marine mammal behavioural response [c]	160	2.52	2.31	6.13	5.64	6.42	5.99
LF-cetacean weighted behavioural response [d]	160	0.61	0.58	1.6	1.46	1.54	1.42
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	4.69	4.27	8.57	7.86	8.13	7.4
Penguin behavioural response [e]	120	1.87	1.68	3.03	2.74	2.95	2.68

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 46. *Monopiles with frequency dependent reduction (HSD+DBBC), winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1 (HSD+DBBC)			Monopile 3 (HSD+DBBC)		
		Penetration depth (m)			Penetration depth (m)		
		17.7	26.4	35.1	14.2	21.4	28.7
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS							
LF cetaceans	219	–	–	–	–	–	–
HF cetaceans	230	–	–	–	–	–	–
Otariid seals	232	–	–	–	–	–	–
Sea turtles	232	–	–	–	–	–	–
Penguins	232	–	–	–	–	–	–
TTS							
LF cetaceans	213	–	0.06	0.03	–	0.03	0.03
HF cetaceans	224	–	–	–	–	–	–
Otariid seals	226	–	–	–	–	–	–
Sea turtles	226	–	–	–	–	–	–
Penguins	226	–	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury							
Fish I	213	–	0.06	0.03	–	0.03	0.03
Fish II, III Fish eggs and larvae	207	0.11	0.12	0.12	0.04	0.12	0.12

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 47. *Monopiles with frequency dependent reduction (HSD+DBBC),* maximum–over–depth per–strike SEL for each penetration at 1000 m from the centre of the pile with and without the NAS systems applied. The dB reduction in maximum–over–depth per–strike SEL (ΔSEL) is also provided.

Monopile Location	NAS System	Penetration depth (m)	Per–strike SEL (L_E;dB re 1 µPa²·s)		ΔSEL (dB)
			Unmitigated	Mitigated	
Monopile 1	HSD+DBBC	17.7	177.7	160.0	17.7
		26.4	182.8	166.0	16.7
		35.1	185.4	168.5	16.8
Monopile 3	HSD+DBBC	14.2	174.3	159.4	14.9
		21.4	180.5	169.7	10.7
		28.7	181.9	170.2	11.7

4.1.2.3.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 48. *Monopiles with frequency dependent reduction (HSD+DBBC), winter, single pile SEL: marine mammals, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to SEL_{24h} based fish criteria.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1 (HSD+DBBC)		Monopile 3 (HSD+DBBC)	
		R_{max}(km)	$R_{95\%}$(km)	R_{max}(km)	$R_{95\%}$(km)
PTS					
LF cetaceans	183	2.74	2.44	2.38	2.15
HF cetaceans	185	–	–	–	–
Otariid seals	203	–	–	–	–
Sea turtles	204	0.30	0.29	0.30	0.29
Penguins	203	–	–	–	–
TTS					
LF cetaceans	168	10.2	8.99	7.84	7.14
HF cetaceans	170	–	–	–	–
Otariid seals	188	0.06	0.06	0.03	0.03
Sea turtles	189	2.70	2.35	2.39	2.16
Penguins	188	0.06	0.06	0.03	0.03

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 49. *Monopiles with frequency dependent reduction (HSD+DBBC), winter, single pile SEL*: fish, *single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to SEL_{24h} based fish criteria.

Fauna group	SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1 (HSD+DBBC)		Monopile 3 (HSD+DBBC)	
		R_{max}(km)	$R_{95\%}$(km)	R_{max}(km)	$R_{95\%}$(km)
Mortality and potential mortal injury					
I	219	0.12	0.12	0.10	0.09
II, Fish eggs and fish larvae	210	0.43	0.40	0.39	0.37
III	207	0.76	0.71	0.68	0.66
Fish recoverable injury					
I	216	0.14	0.13	0.14	0.13
II, III	203	1.41	1.35	1.34	1.24
Fish temporary threshold shift (TTS)					
I, II, III	186	8.44	7.79	6.79	6.29

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.3.3. Sound Field Maps

The following presents the maps:

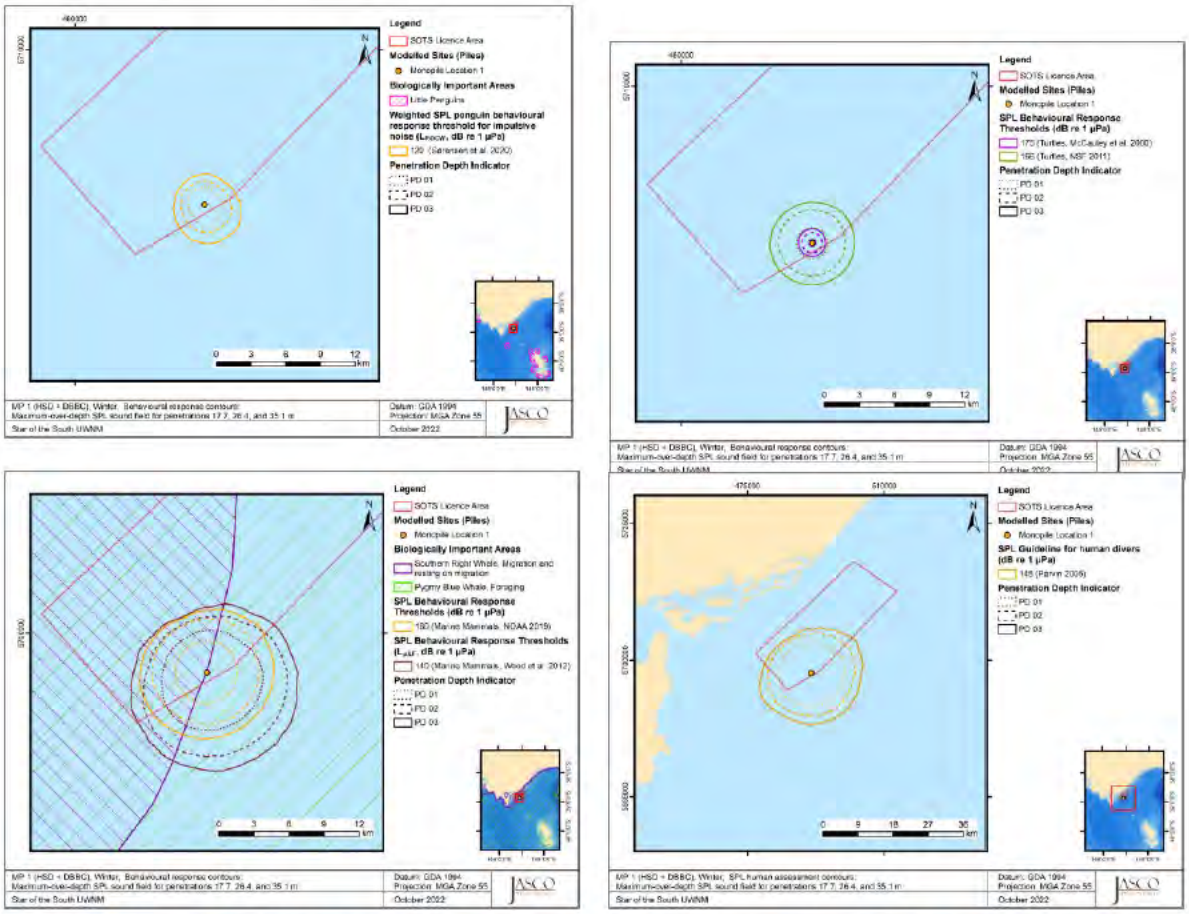


Figure 48. *Monopile 1, HSD + DBBC, winter, marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right),, SPL: Sound level contour map showing maximum–over–depth results for all penetration depth.*

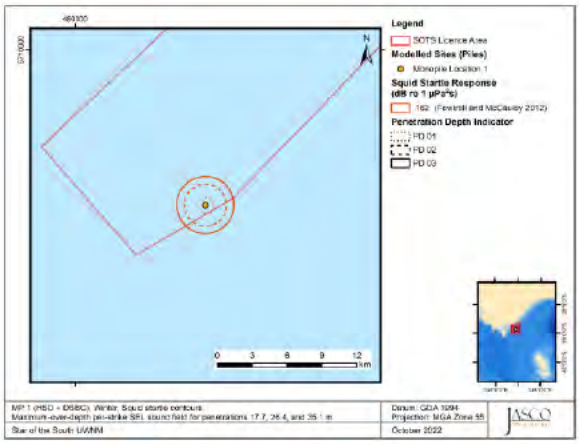


Figure 49. *Monopile 1, HSD + DBBC, winter, squid startle response criteria, per–strike SEL: Sound level contour map showing maximum–over–depth results for all penetration depth.*

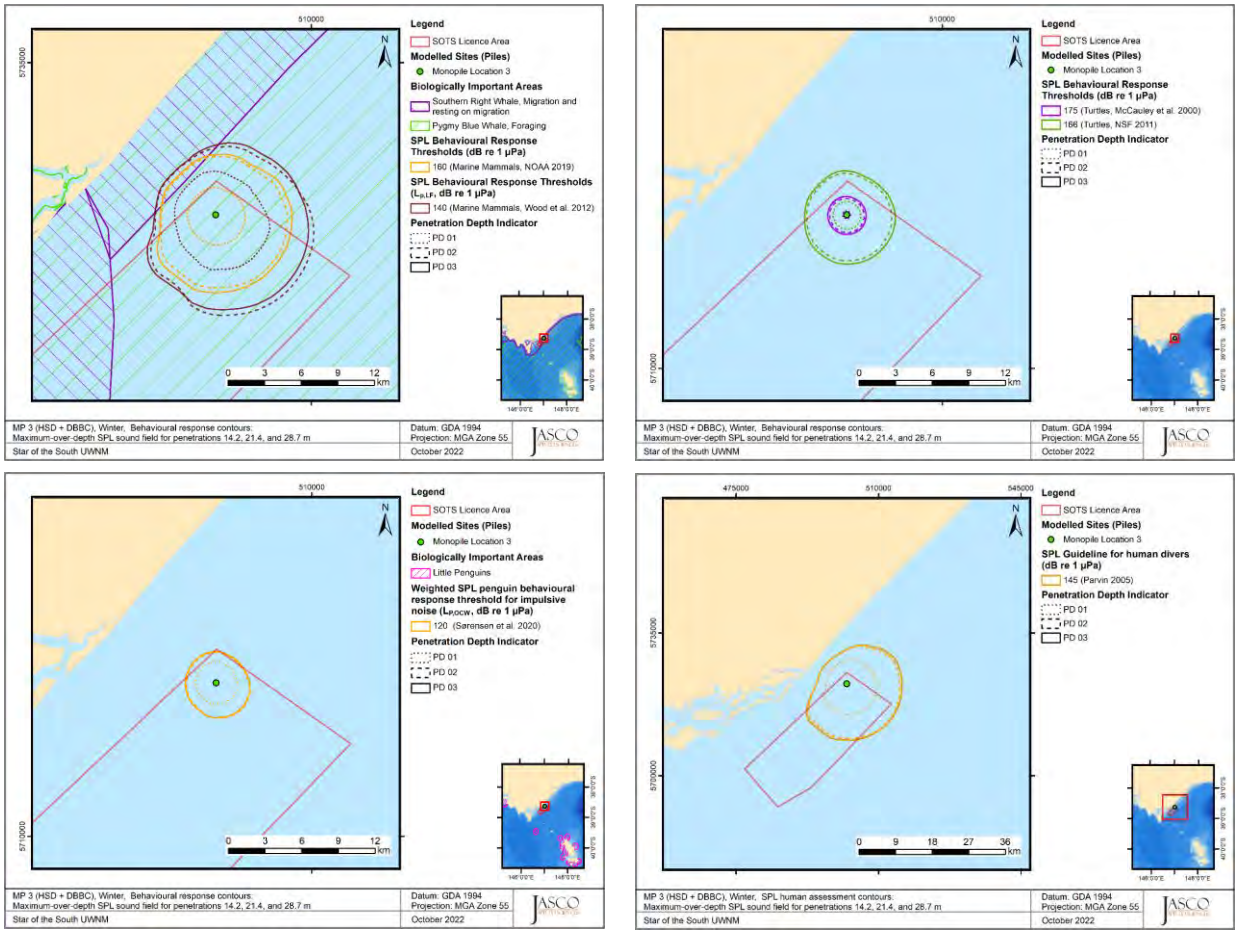


Figure 50. *Monopile 3, HSD + DBBC, winter, marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL: Sound level contour map showing maximum–over–depth results for all penetration depths.*

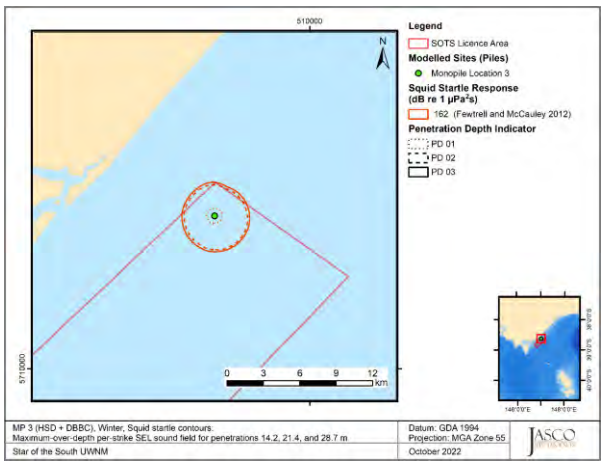


Figure 51. *Monopile 3, HSD + DBBC, winter, squid* startle response criteria*, per–strike SEL*.

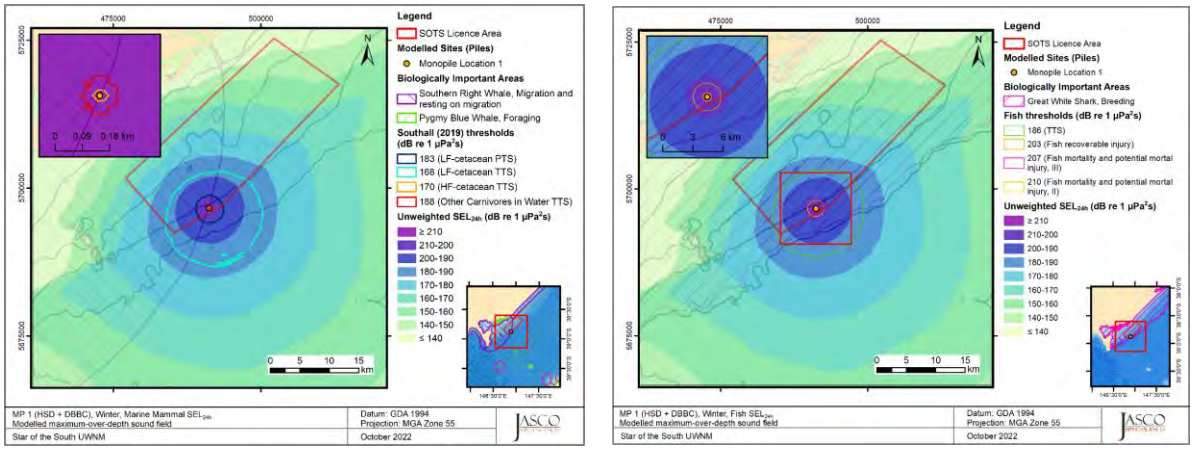


Figure 52. *Monopile 1, HSD+DBBC, winter, Marine Mammals (left), fish (right), SEL$_{24h}$*: Contour map showing maximum–over–depth unweighted SEL$_{24h}$ isopleths and weighted thresholds.

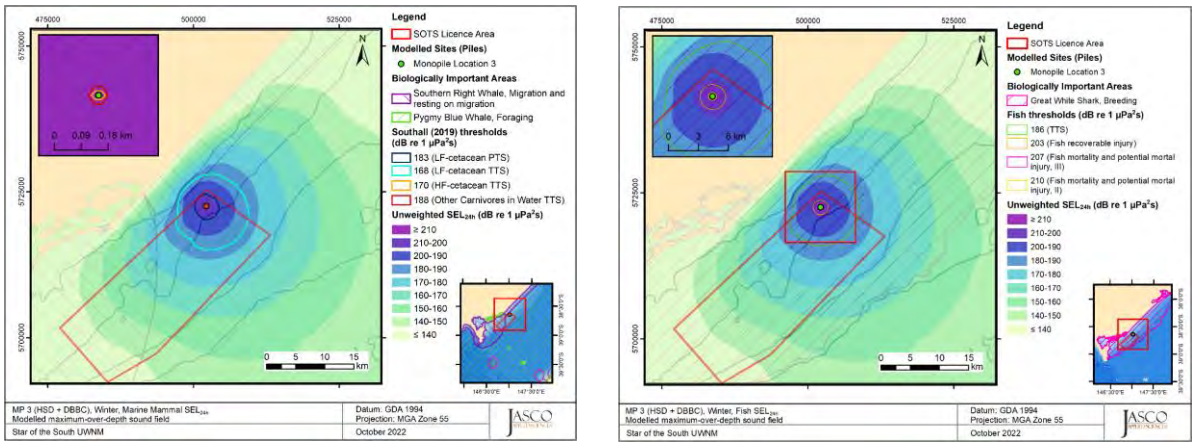


Figure 53. *Monopile 3, HSD+DBBC, winter, Marine Mammals (left), fish (right), SEL$_{24h}$*: Contour map showing maximum–over–depth unweighted SEL$_{24h}$ isopleths and weighted thresholds.

4.1.2.4. Scenario 4 – Unmitigated (Second Modelling Round)

4.1.2.4.1. Per–strike sound fields in winter

The per–strike sound fields for the three modelling sites are presented below. The results are presented in terms of per–strike SPL, SEL, PK sound fields and particle motion fields.

Table 50. *Monopiles, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.09	0.09	0.09	0.09	0.09	0.09	0.11	0.11	0.13	0.13	0.04	0.04	0.05	0.05	0.05	0.05	0.15	0.14	0.15	0.14
180	0.56	0.53	0.67	0.63	0.52	0.51	0.87	0.81	1.12	0.95	0.4	0.34	0.37	0.36	0.55	0.53	0.9	0.85	0.9	0.85
170	2.92	2.77	2.92	2.78	2.83	2.68	3.48	3.31	4.11	3.88	1.68	1.58	1.81	1.69	2.24	2.11	2.99	2.81	2.98	2.81
162[a]	6.69	6.35	6.81	6.44	6.65	6.29	7.9	7.37	9.18	8.44	3.62	3.4	4.05	3.84	4.72	4.42	5.8	5.44	5.88	5.49
160	8.18	7.6	8.26	7.72	8.12	7.56	9.57	8.85	11.01	10.14	4.23	3.97	4.82	4.55	5.44	5.14	6.71	6.28	6.76	6.34
150	19.4	17.74	19.58	17.86	19.15	17.56	22.26	20.44	24.46	22.58	8.26	7.57	10.71	9.46	11.39	10.28	13.96	12.38	14.71	12.81
140	42.44	38.82	42.02	38.17	41.49	37.79	47.73	43.5	52.16	47.9	18.56	15.81	23.56	20.33	27.5	23.27	49.28	32.92	49.4	39.18
130	83.91	74.57	80.74	72.03	82.44	73.72	>90.0	/	>90.0	/	49.45	42.81	59.51	52.81	65.9	57.93	>90.0	/	>90.0	/

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 51. *Monopiles, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.09	0.08	0.08	0.08	0.08	0.08	0.1	0.1	0.12	0.11	0.03	0.03	0.03	0.03	0.05	0.05	0.14	0.14	0.14	0.14
190	0.49	0.47	0.49	0.47	0.47	0.45	0.67	0.65	0.87	0.82	0.27	0.26	0.34	0.33	0.46	0.44	0.75	0.72	0.74	0.71
180	1.92	1.84	2.04	1.91	2.05	1.93	2.49	2.34	2.92	2.74	1.43	1.35	1.51	1.41	1.87	1.76	2.3	2.18	2.43	2.3
170	5.7	5.33	5.85	5.42	5.68	5.3	6.76	6.28	7.85	7.22	3.39	3.21	3.62	3.42	4.31	3.99	5.36	4.95	5.56	5.15
160	15.81	14.49	16.05	14.57	15.01	13.69	16.93	15.38	17.55	16.2	6.77	6.19	7.88	7.08	8.88	7.89	10.24	9.16	10.72	9.78
150	39.81	32.33	39.62	31.64	32.02	29.31	40.13	34.12	43	39.16	14.41	12.36	19.83	16.83	21.83	18.68	28.83	25.13	49.17	30.84
145[a]	46.4	43.44	45.65	42.34	43.02	39	54.79	50.85	59.32	55.65	22.04	19.53	49.05	29.28	49.02	30.62	49.48	43.04	54.49	48.7
140	63.37	58.27	60.03	54.93	62.2	56.16	79	70.62	86.37	75.76	49.15	31.4	50.78	45.33	50.79	45.26	83	67.97	88.87	75.66
130	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/	82.9	69.19	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 52. *Monopiles, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1										Monopile 2									
		Penetration depth (m)										Penetration depth (m)									
		15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	3.35	3.18	3.55	3.34	3.48	3.28	4.17	3.81	4.76	4.42	2.28	2.15	2.43	2.32	2.83	2.68	3.6	3.37	3.83	3.59
Sea turtle behavioural response [a]	166	8.53	7.82	8.55	7.82	8.44	7.72	10.08	9.27	11.04	9.76	4.54	4.24	5.04	4.68	5.86	5.35	6.87	6.3	7.16	6.52
Marine mammal behavioural response [c]	160	15.81	14.49	16.05	14.57	15.01	13.69	16.93	15.38	17.55	16.2	6.77	6.19	7.88	7.08	8.88	7.89	10.24	9.16	10.72	9.78
LF-cetacean weighted behavioural response [d]	160	7.12	6.64	7.43	6.87	7.28	6.77	8.69	8.08	9.82	9.03	3.83	3.59	4.01	3.76	4.78	4.41	5.7	5.29	6.16	5.73
LF-cetacean weighted behavioural response (migrating mysticetes)[d]	140	40.27	36.72	40.15	35.36	40.05	32.53	49.54	43.03	53.36	49.59	18.34	15.76	29.45	25.89	30.93	27.11	49.48	43.74	56.06	50.11
Penguin OCW-weighted behavioural response [e]	120	19.05	17.39	19.16	17.66	19.57	18.1	22.85	21.44	29.22	27.03	7.41	6.76	9.18	8.12	10.34	9.28	21.92	18.9	49.24	28.95

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020), OCW weighted.

Table 53. *Monopiles, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1					Monopile 2				
		Penetration depth (m)					Penetration depth (m)				
		15.27	20.54	25.81	31.8	36.35	10.42	15.84	21.26	26.68	32.10
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS											
LF cetaceans	219	-	-	-	0.04	0.07	0.02	0.02	0.03	0.03	0.04
HF cetaceans	230	-	-	-	-	-	-	-	-	-	-
Otariid seals	232	-	-	-	-	-	-	-	-	-	-
Sea turtles	232	-	-	-	-	-	-	-	-	-	-
Penguins	232	-	-	-	-	-	-	-	-	-	-
TTS											
LF cetaceans	213	0.09	0.09	0.09	0.12	0.13	0.03	0.04	0.05	0.15	0.15
HF cetaceans	224	-	-	-	-	-	-	-	-	-	-
Otariid seals	226	-	-	-	-	-	-	-	-	-	-
Sea turtles	226	-	-	-	-	-	-	-	-	-	-
Penguins	226	-	-	-	-	-	-	-	-	-	-
Mortality and potential mortal injury / recoverable injury											
Fish I	213	0.09	0.09	0.09	0.12	0.13	0.03	0.04	0.05	0.15	0.15
Fish II, III Fish eggs and larvae	207	0.22	0.22	0.21	0.27	0.32	0.15	0.16	0.19	0.22	0.34

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 54. *Monopiles, winter, PK–PK thresholds*: Maximum (R_{max}) horizontal distances (m) from each monopile to modelled seafloor peak–peak pressure level (PK–PK) thresholds for invertebrates for each penetration depth.

Marine Fauna	PK–PK threshold (L_{pkpk}; dB re 1 µPa)	Monopile 1					Monopile 2				
		Penetration depth (m)					Penetration depth (m)				
		15.27	20.54	25.81	31.8	36.35	10.42	15.84	21.26	26.68	32.10
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Crustaceans [a]	202	566	536	565	784	942	358	440	559	805	773

[a] Payne et al. (2008), lobster

Table 55. *Monopiles, winter, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from two monopiles to modelled seafloor peak acceleration magnitude level (m/s^2) thresholds for benthic invertebrates for each penetration depth.

Marine fauna Benthic	Peak acceleration magnitude (m/s^2)	Monopile 1					Monopile 2				
		Penetration depth (m)					Penetration depth (m)				
		15.27	20.54	25.81	31.8	36.35	10.42	15.84	21.26	26.68	32.10
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Benthic invertebrates [a]	35.75	24	30	26	34	29	26	24	28	38	36

[a] Day et al. (2016a) – Crustaceans and bivalves

4.1.2.4.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 56. *Monopiles, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 $\mu Pa^2 \cdot s$)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	16.34	15.03	9.5	8.54
HF cetaceans	185	-	-	-	-
Otariid seals	203	-	-	-	-
Sea turtles	204	3.65	3.47	2.65	2.49
Penguins	203	-	-	-	-
TTS					
LF cetaceans	168	52.94	48.97	50.33	45.42
HF cetaceans	170	0.09	0.09	0.06	0.06
Otariid seals	188	0.2	0.18	0.19	0.19
Sea turtles	189	15.6	14.41	8.88	7.96
Penguins	188	0.2	0.18	0.19	0.19

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 57. *Monopiles, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.52	0.5	0.49	0.45
II, Fish eggs and fish larvae	210	2.36	2.24	1.82	1.73
III	207	3.42	3.26	2.53	2.37
Fish recoverable injury					
I	216	0.92	0.87	0.82	0.75
II, III	203	5.26	4.99	3.69	3.47
Fish temporary threshold shift (TTS)					
I, II, III	186	23.7	21.74	13.11	11.9

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.4.3. Sound field maps

The following presents the contour maps:

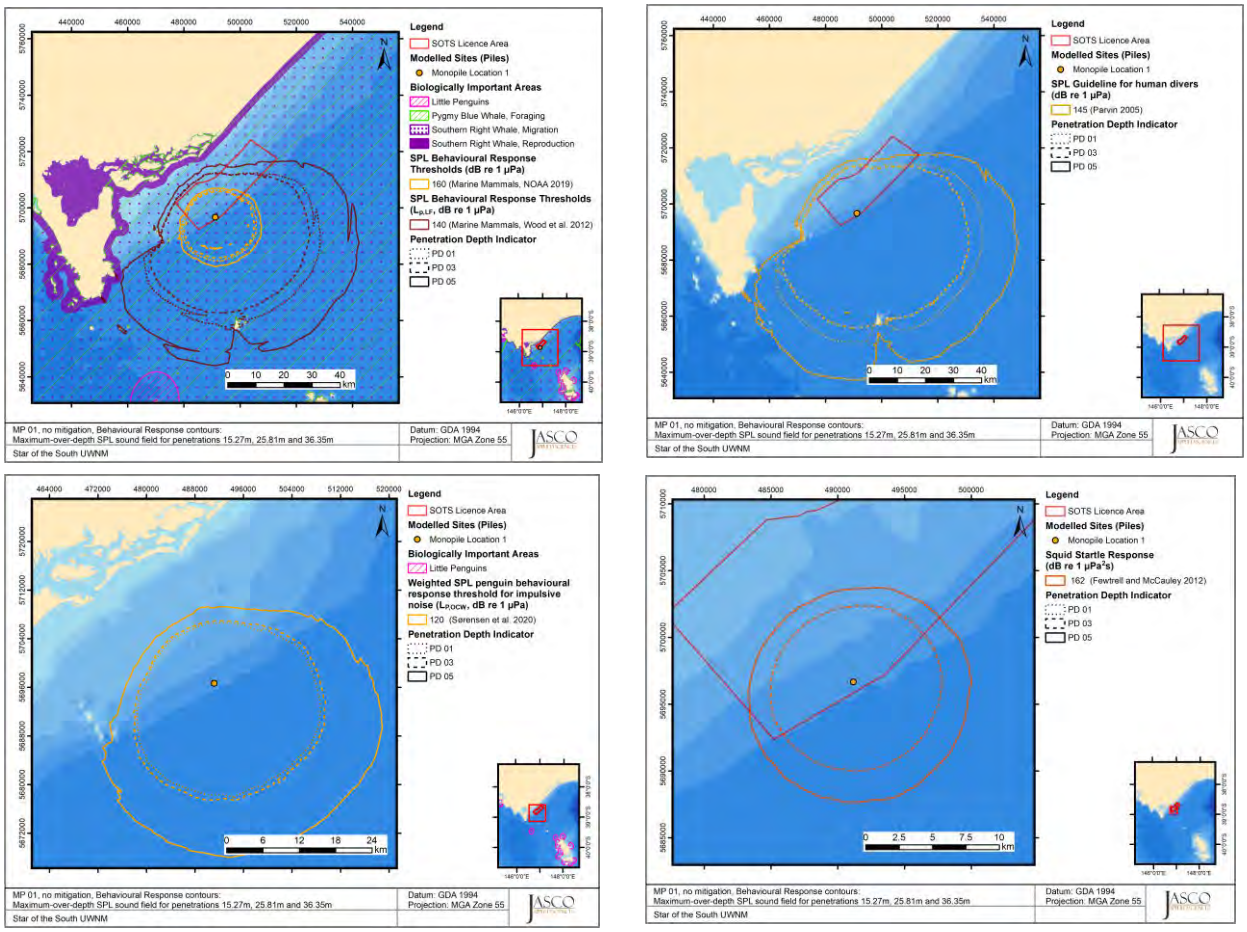


Figure 54. *Unmitigated per-strike sound fields for MP 1,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

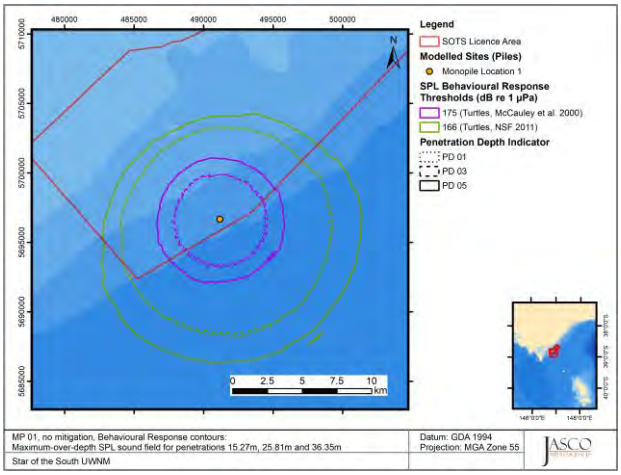


Figure 55. *Unmitigated per-strike sound fields for MP 1,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

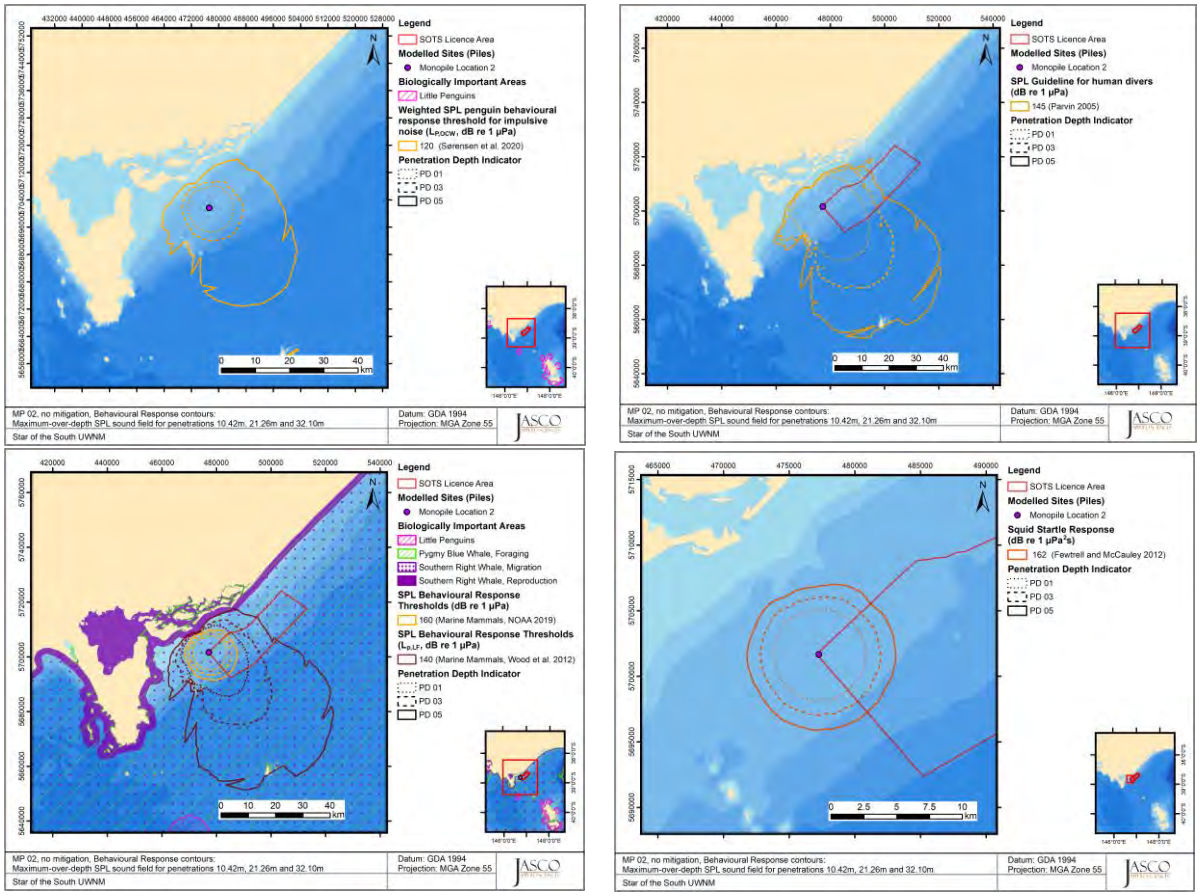


Figure 56. *Unmitigated per-strike sound fields for MP 2,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

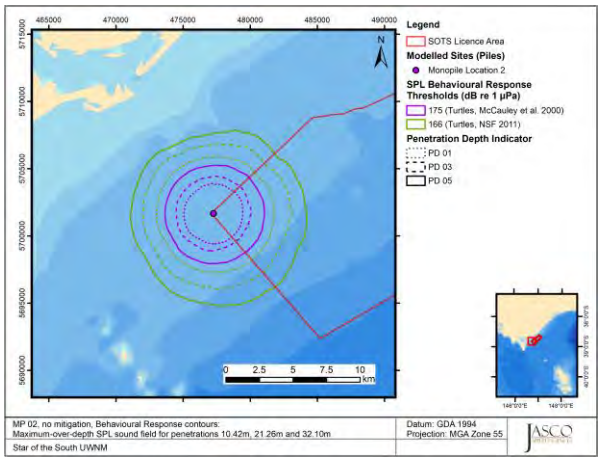


Figure 57. *Unmitigated per-strike sound fields for MP 2,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

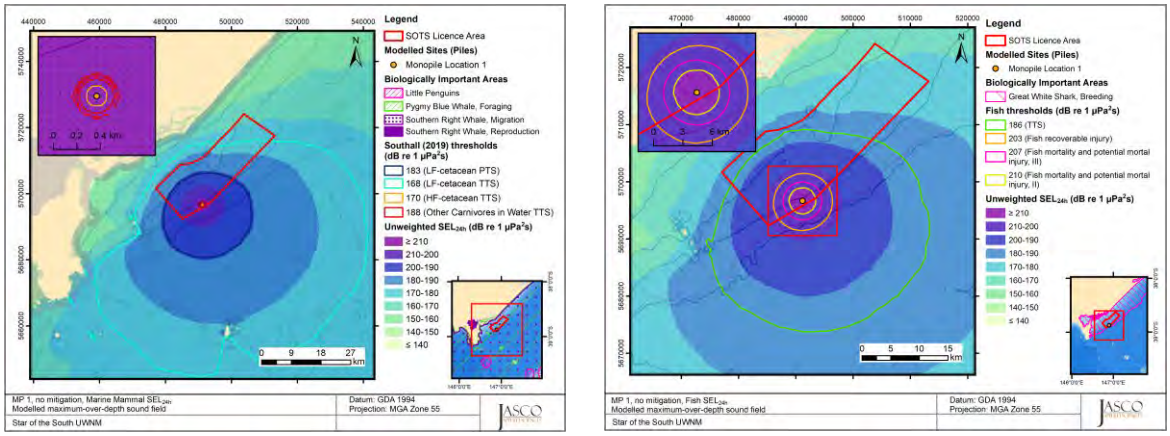


Figure 58. *Unmitigated, MP 1.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

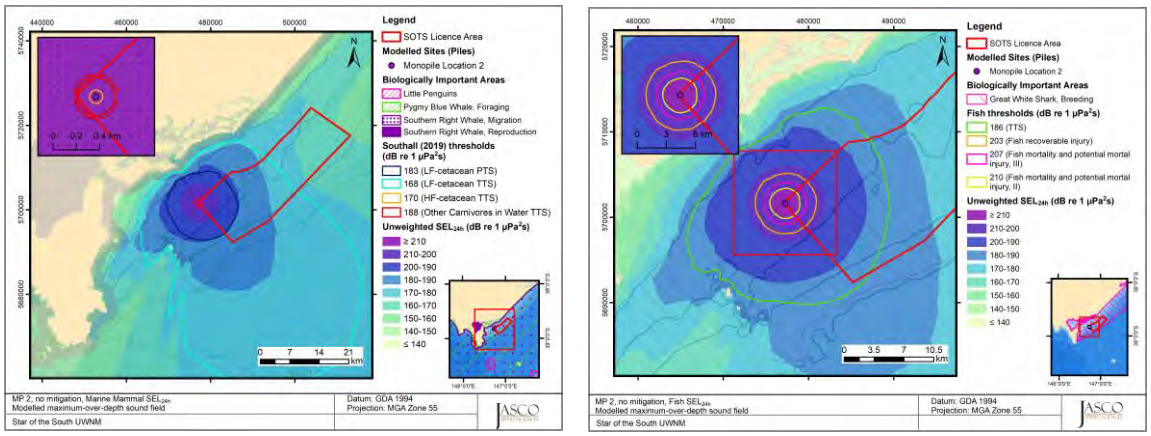


Figure 59. *Unmitigated, MP 2.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

4.1.2.5. Scenario 5 – DBBC (Second Modelling Round)

4.1.2.5.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented below.

Table 58. *Monopiles, NAS – DBBC, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa^2·s)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.80		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.04	0.04	0.05	0.05	0.05	0.05	0.09	0.09	0.09	0.09
180	0.09	0.09	0.09	0.09	0.09	0.09	0.11	0.1	0.13	0.13	0.09	0.09	0.09	0.09	0.13	0.13	0.13	0.13	0.13	0.13
170	0.3	0.29	0.31	0.29	0.29	0.28	0.32	0.31	0.45	0.43	0.27	0.27	0.5	0.45	0.63	0.51	0.87	0.74	0.86	0.72
162[a]	1.29	1.2	1.35	1.28	1.13	1.07	1.47	1.39	1.85	1.72	1.13	0.94	1.76	1.59	2.03	1.82	2.91	2.62	2.67	2.44
160	1.74	1.64	1.83	1.73	1.61	1.48	2.03	1.89	2.45	2.31	1.4	1.28	2.35	2.13	2.63	2.42	3.69	3.41	3.51	3.19
150	5.93	5.49	6.17	5.7	5.59	5.22	6.69	6.22	7.68	7.09	4.12	3.72	7.78	6.76	9.32	7.66	11.93	10.49	11.4	9.85
140	13.83	11.83	14.55	12.25	13.67	11.73	16.16	13.52	18.04	15.05	10.66	9.09	17.71	14.72	18.72	15.63	24.44	18.4	21.83	17.85
130	30.38	23.93	32.03	25.58	28.83	23.08	34.67	27.58	37.24	30.26	20.71	16.57	34.78	24.58	37.02	26.43	44.12	32.55	43.22	31.69

[a] Startle response level for squid (Fewtrell and McCauley 2012).

A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 59. *Monopiles, NAS – DBBC, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.09	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.03	0.03	0.03	0.03	0.05	0.05	0.09	0.09	0.09	0.09
190	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.11	0.11	0.09	0.09	0.09	0.09	0.09	0.09	0.13	0.13	0.13	0.13
180	0.27	0.26	0.28	0.27	0.26	0.18	0.29	0.28	0.31	0.3	0.26	0.26	0.44	0.43	0.46	0.44	0.65	0.62	0.65	0.62
170	1.33	1.26	1.38	1.31	1.16	1.1	1.48	1.39	1.81	1.7	1.15	1.08	1.65	1.52	1.83	1.68	2.39	2.23	2.31	2.12
160	4.2	3.82	4.35	3.95	3.76	3.55	4.61	4.27	5.28	4.88	2.98	2.72	4.71	4.31	5.12	4.71	6.52	5.95	6.16	5.56
150	9.47	8.15	10.07	8.44	9.22	7.8	10.82	9.06	12.59	10.04	6.43	5.86	11.59	9.76	12.84	10.65	15.72	12.92	15.34	12.51
145[a]	13.53	10.88	14.27	11.42	13.37	10.46	16.11	12.31	17.39	13.92	9.68	8.17	15.98	13.14	18.27	14.14	25	17.43	20.89	17.05
140	19.48	15.17	20.01	15.8	18.18	14.75	22.73	17.52	23.62	19.55	14.6	11.51	25.12	17.64	25.99	19.25	34.48	22.92	34.12	22.34
130	37.19	29.47	38.13	30.21	37.08	28.88	41.07	31.98	44.15	34.32	26.35	20.31	40.94	31.47	42.94	33.07	58.58	38.57	57.62	36.72

[a] Human health assessment threshold derived from Parvin (2005).

A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 60. *Monopiles, NAS – DBBC, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1										Monopile 2									
		Penetration depth (m)										Penetration depth (m)									
		15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.6	0.52	0.66	0.59	0.48	0.47	0.66	0.62	0.82	0.78	0.66	0.5	0.94	0.82	0.96	0.91	1.31	1.19	1.32	1.16
Sea turtle behavioural response [a]	166	2.26	2.13	2.32	2.2	2.04	1.93	2.55	2.38	3	2.81	1.8	1.58	2.54	2.37	2.84	2.61	3.67	3.43	3.41	3.14
Marine mammal behavioural response [c]	160	4.2	3.82	4.35	3.95	3.76	3.55	4.61	4.27	5.28	4.88	2.98	2.72	4.71	4.31	5.12	4.71	6.52	5.95	6.16	5.56
LF-cetacean weighted behavioural response [d]	160	0.83	0.74	0.91	0.81	0.92	0.81	1.07	0.92	1.2	1.09	1.18	1.11	1.36	1.23	1.48	1.36	1.7	1.56	1.84	1.65
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	6.07	5.59	6.3	5.83	6.24	5.76	7	6.32	7.37	6.89	5.43	4.93	6.34	5.84	6.53	6.05	8.09	7.15	7.45	6.69
Penguin OCW-weighted behavioural response [e]	120	2.7	2.4	2.99	2.64	3.13	2.74	3.31	2.92	3.64	3.25	2.32	2.09	2.47	2.25	2.9	2.58	3.12	2.78	3.1	2.81

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020), OCW weighted.

Table 61. *Monopiles, NAS – DBBC, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1					Monopile 2				
		Penetration depth (m)					Penetration depth (m)				
		15.27	20.54	25.81	31.8	36.35	10.42	15.84	21.26	26.68	32.10
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS											
LF cetaceans	219	-	-	-	0.04	0.07	0.02	0.02	0.03	0.03	0.04
HF cetaceans	230	-	-	-	-	-	-	-	-	-	-
VHF cetaceans	202	-	-	-	-	-	-	-	-	-	-
Sea turtles	232	-	-	-	-	-	-	-	-	-	-
Penguins	232	-	-	-	-	-	-	-	-	-	-
TTS											
LF cetaceans	213	0.09	0.09	0.09	0.09	0.09	0.03	0.04	0.05	0.09	0.09
HF cetaceans	224	-	-	-	-	-	-	-	-	-	-
VHF cetaceans	196	-	-	-	-	-	-	-	-	-	-
Sea turtles	226	-	-	-	-	-	-	-	-	-	-
Penguins	226	-	-	-	-	-	-	-	-	-	-
Mortality and potential mortal injury / recoverable injury											
Fish I	213	0.09	0.09	0.09	0.09	0.09	0.03	0.04	0.05	0.09	0.09
Fish II, III Fish eggs and larvae	207	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.5.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 62. *Monopiles, NAS – DBBC, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	2.22	2	3.04	2.74
HF cetaceans	185	-	-	-	-
Otariid seals	203	-	-	-	-
Sea turtles	204	0.28	0.27	0.51	0.48
Penguins	203	-	-	-	-
TTS					
LF cetaceans	168	8.29	7.78	9.87	8.51
HF cetaceans	170	0.09	0.09	0.06	0.06
Otariid seals	188	0.09	0.09	0.09	0.09
Sea turtles	189	2.11	1.86	3.13	2.8
Penguins	188	0.09	0.09	0.09	0.09

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 63. *Monopiles, NAS – DBBC, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.09	0.09	0.09	0.09
II, Fish eggs and fish larvae	210	0.19	0.18	0.44	0.42
III	207	0.36	0.31	0.67	0.63
Fish recoverable injury					
I	216	0.13	0.12	0.13	0.13
II, III	203	0.78	0.72	1.23	1.13
Fish temporary threshold shift (TTS)					
I, II, III	186	7.33	6.78	11.1	9.57

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.5.3. Sound field maps

The following presents the contour maps:

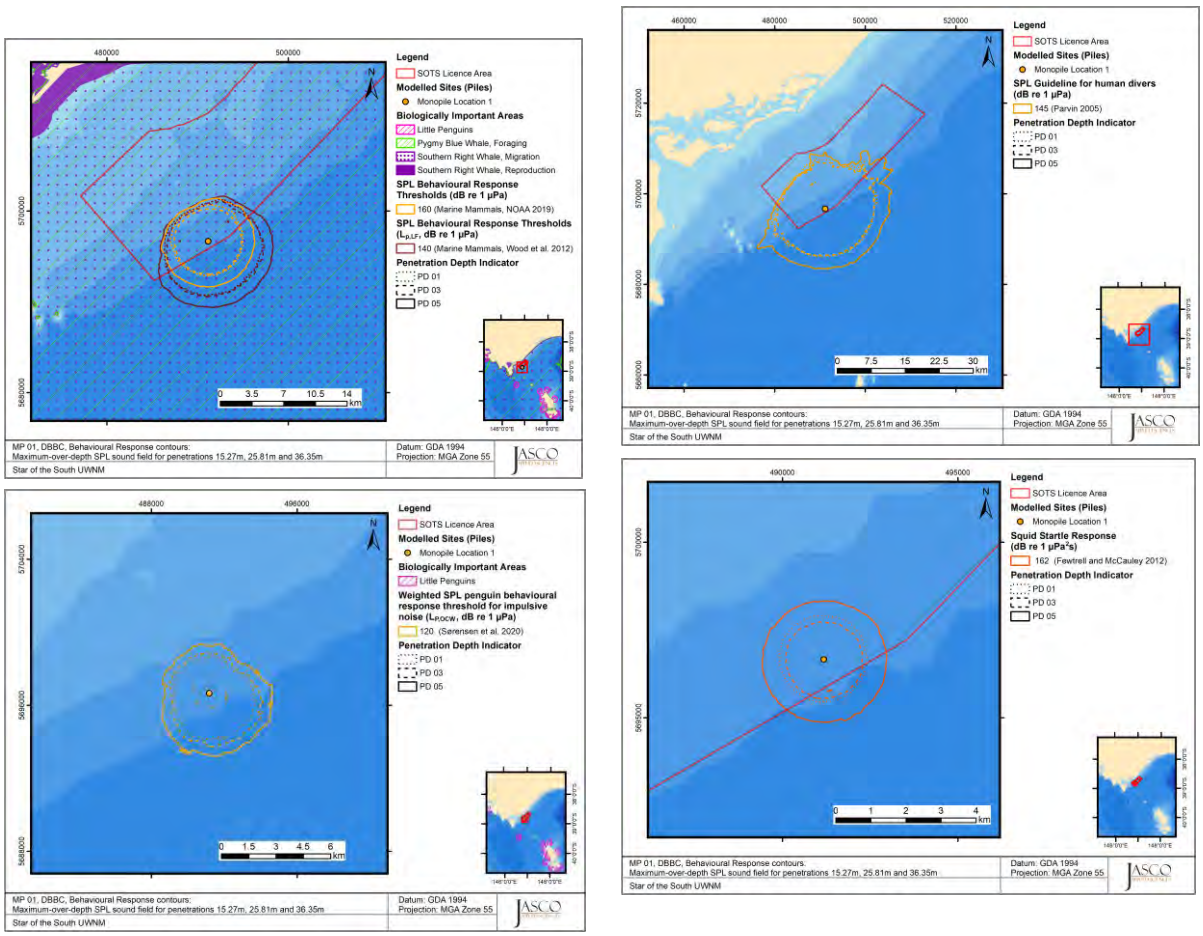


Figure 60. *DBBC per-strike sound fields for MP 1,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

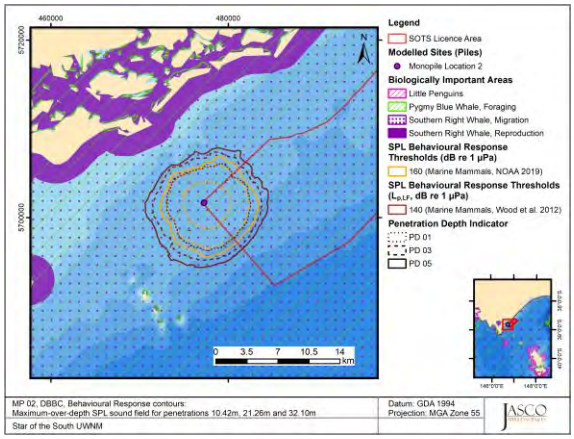


Figure 61. DBBC per-strike sound fields for MP 1, SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

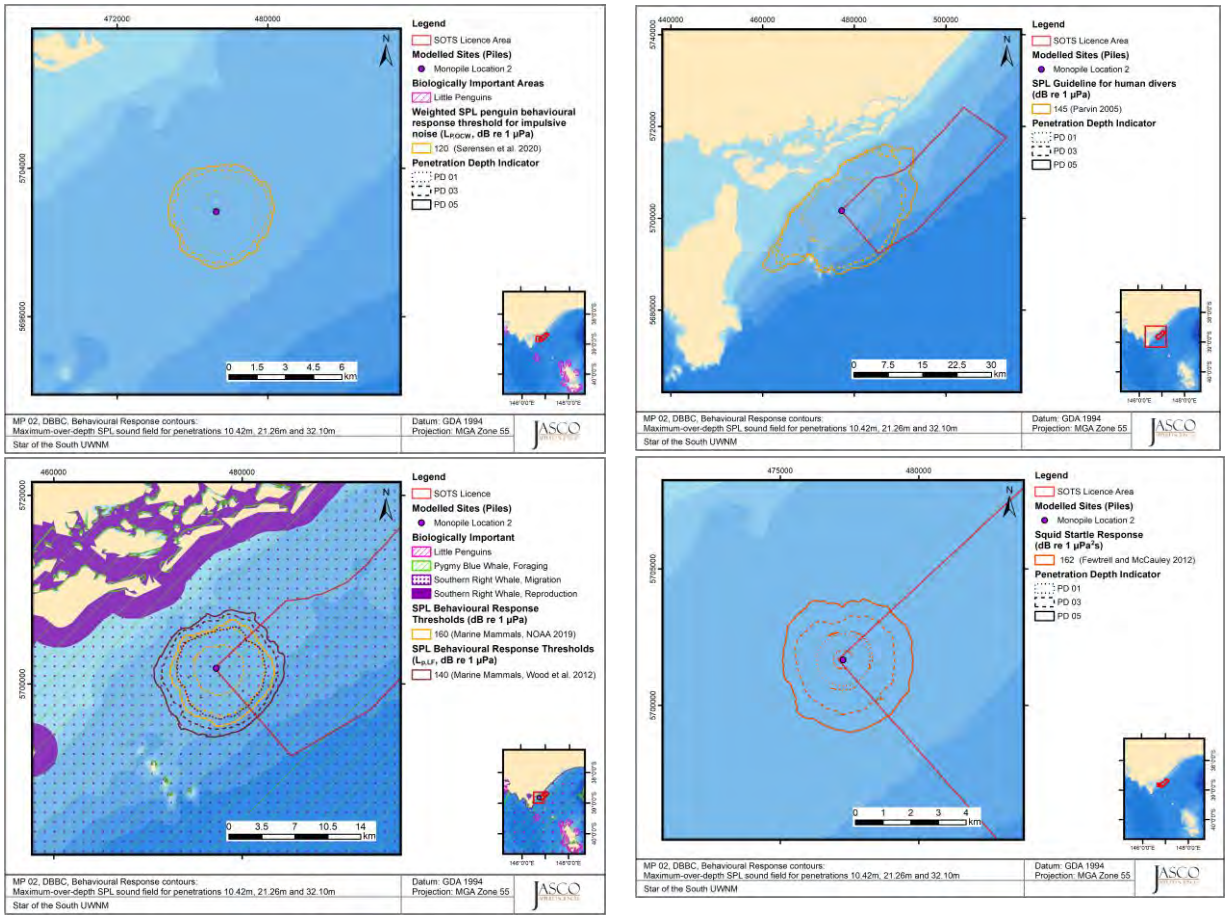


Figure 62. *DBBC per-strike sound fields for MP 2,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

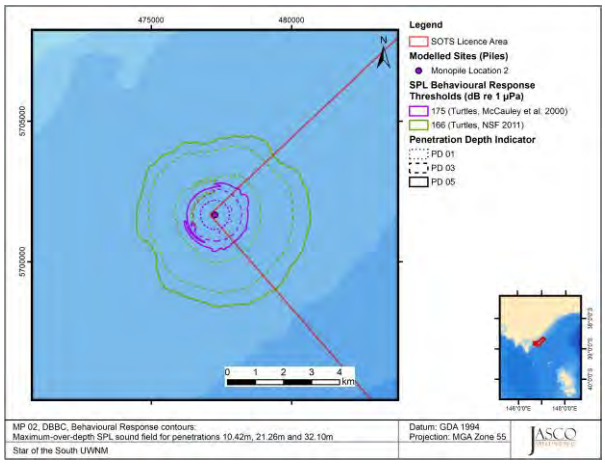


Figure 63. *DBBC per-strike sound fields for MP 2,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

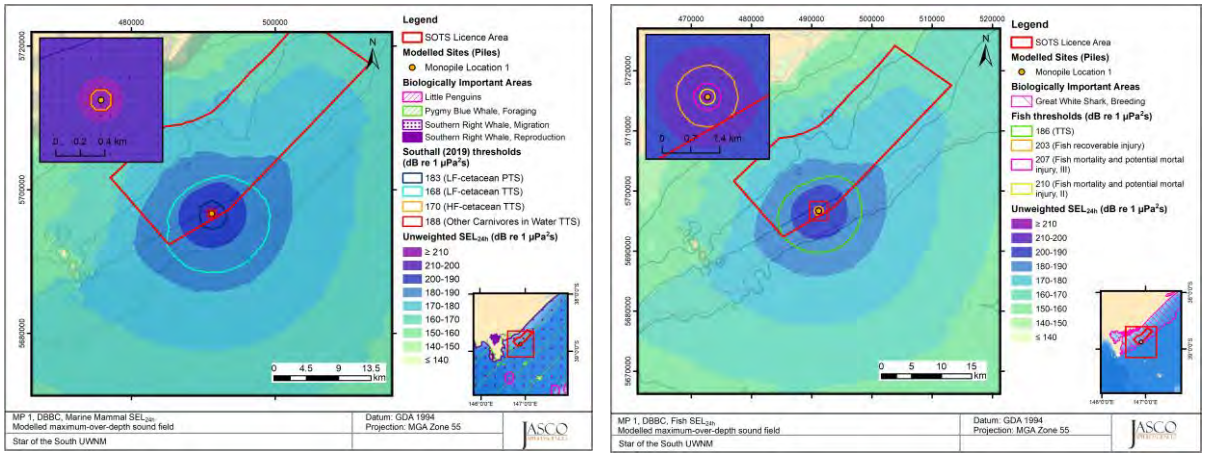


Figure 64. *DBBC, MP 1.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

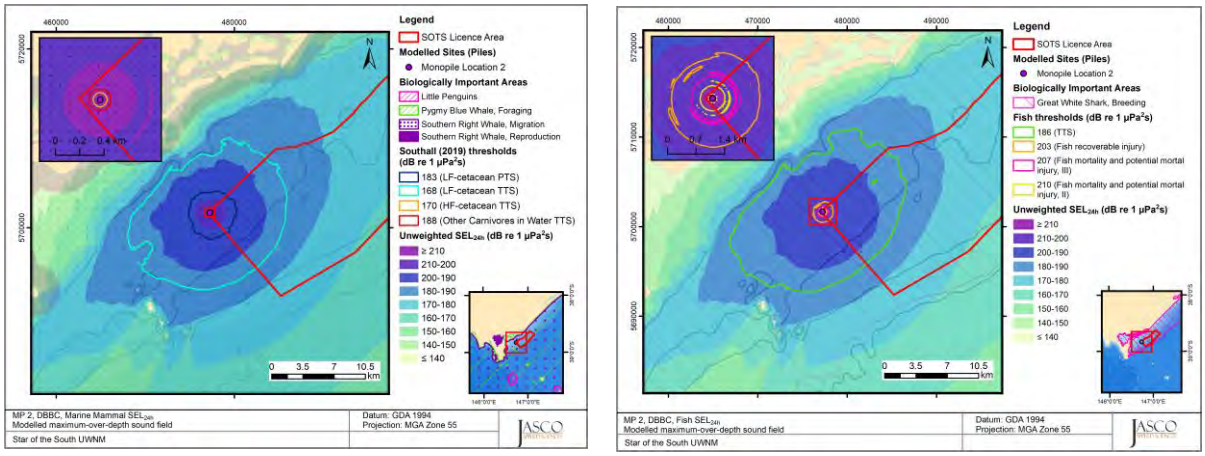


Figure 65. *DBBC, MP 2.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

4.1.2.6. Scenario 6 – HSD (Second Modelling Round)

4.1.2.6.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented below.

Table 64. *Monopiles, NAS – HSD, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa^2·s)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.02	0.02	0.02	0.02	-	-	0.02	0.02	0.03	0.03	-	-	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
180	0.19	0.19	0.17	0.16	0.17	0.16	0.2	0.19	0.3	0.29	0.14	0.14	0.15	0.15	0.2	0.2	0.37	0.33	0.33	0.32
170	1.27	1.21	1.22	1.15	1.13	1.04	1.45	1.34	1.71	1.61	0.82	0.77	1.06	0.97	1.23	1.16	1.75	1.63	1.68	1.58
162[a]	3.79	3.56	3.65	3.45	3.49	3.26	4.13	3.85	4.67	4.39	2.31	2.16	2.93	2.76	3.33	3.12	4.32	4.07	4.1	3.85
160	4.63	4.39	4.51	4.26	4.32	4.08	5.06	4.74	5.67	5.35	2.79	2.64	3.61	3.41	4.04	3.82	5.3	4.94	4.97	4.67
150	10.71	10	10.6	9.92	10.56	9.85	12.1	11.17	13.26	12.24	6.14	5.82	10.27	8.75	11.06	9.47	13.67	11.56	13.01	11.1
140	20.73	19.09	21.68	19.82	21.75	19.85	24.25	22.26	25.8	23.71	12.48	10.72	19.56	15.57	20.81	16.56	25.37	19.63	25.06	18.92
130	40.22	36.81	42.47	38.45	41.72	37.82	44.89	40.43	45.87	41.6	21.68	19.05	36.06	24.99	40.5	26.51	44.97	32.37	49.17	34.03

[a] Startle response level for squid (Fewtrell and McCauley 2012).

A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 65. *Monopiles, NAS – HSD, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.02	0.02	-	-	-	-	-	-	0.02	0.02	-	-	-	-	0.02	0.02	0.03	0.03	0.03	0.03
190	0.17	0.16	0.15	0.15	0.15	0.14	0.17	0.17	0.17	0.16	0.13	0.13	0.15	0.14	0.15	0.15	0.32	0.31	0.31	0.26
180	0.98	0.94	0.94	0.89	0.88	0.82	1.12	0.99	0.98	0.94	0.67	0.64	0.85	0.79	1.02	0.92	1.38	1.3	1.35	1.27
170	2.97	2.78	2.91	2.76	2.59	2.46	3.18	2.92	2.97	2.78	2.33	2.21	2.75	2.64	3	2.86	3.67	3.49	3.48	3.32
160	6.77	6.31	6.93	6.38	7.24	6.64	9	8.27	6.77	6.31	4.86	4.56	6.32	5.89	6.8	6.27	8.25	7.44	7.72	6.92
150	16.07	14.72	18.03	16.3	18.02	16.12	19.64	17.72	16.07	14.72	8.67	7.98	13.57	11.15	14.86	11.83	17.58	13.66	16.4	13.29
145[a]	24.36	22.2	26.53	24.16	25.52	23.3	27.06	24.56	24.36	22.2	11.29	10.25	18.31	14.1	19.25	15.31	25.43	18.5	25.17	17.75
140	33.92	31.07	39.95	33.93	35.23	31.95	39.65	33.05	33.92	31.07	15.81	13.53	25.63	18.81	26.33	20.29	35.98	23.75	34.97	23.72
130	57.41	53.71	62.25	57.88	58.17	54.25	59.41	55.26	57.41	53.71	49.17	31.83	49.43	39.84	49.71	43.41	61.05	48.64	64.9	57.9

[a] Human health assessment threshold derived from Parvin (2005).

A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 66. *Monopiles, NAS – HSD, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1										Monopile 2									
		Penetration depth (m)										Penetration depth (m)									
		15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	1.77	1.68	1.69	1.59	1.55	1.46	1.86	1.71	2.26	2.08	1.39	1.32	1.64	1.56	1.89	1.78	2.36	2.23	2.3	2.17
Sea turtle behavioural response [a]	166	4.26	3.93	4.25	3.93	4	3.64	4.8	4.36	5.82	5.25	3.24	3.07	3.89	3.76	4.23	4.04	5.19	4.83	4.74	4.44
Marine mammal behavioural response [c]	160	6.77	6.31	6.93	6.38	7.24	6.64	9	8.27	10.51	9.46	4.86	4.56	6.32	5.89	6.8	6.27	8.25	7.44	7.72	6.92
LF-cetacean weighted behavioural response [d]	160	2.8	2.62	2.77	2.61	2.69	2.52	3.22	3.04	3.9	3.58	2.31	2.14	2.24	2.08	2.64	2.41	3.22	2.95	3.22	2.97
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	15.47	14.26	16.89	15.56	16.56	15.26	18.37	16.95	19.03	17.59	8.0	7.32	8.66	8.08	9.53	8.81	11.25	10.24	11.67	10.41
Penguin OCW-weighted behavioural response [e]	120	5.86	5.49	6.21	5.77	6.07	5.66	7.6	7.06	9.05	8.34	4.06	3.78	4.02	3.73	4.67	4.3	5.36	4.96	5.57	5.16

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020), OCW weighted.

Table 67. *Monopiles, NAS – HSD, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1					Monopile 2				
		Penetration depth (m)					Penetration depth (m)				
		15.27	20.54	25.81	31.8	36.35	10.42	15.84	21.26	26.68	32.10
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS											
LF cetaceans	219	-	-	-	-	-	-	-	-	-	-
HF cetaceans	230	-	-	-	-	-	-	-	-	-	-
Otariid seals	232	-	-	-	-	-	-	-	-	-	-
Sea turtles	232	-	-	-	-	-	-	-	-	-	-
Penguins	232	-	-	-	-	-	-	-	-	-	-
TTS											
LF cetaceans	213	-	-	-	0.02	0.03	-	-	0.02	0.03	0.03
HF cetaceans	224	-	-	-	-	-	-	-	-	-	-
Otariid seals	226	-	-	-	-	-	-	-	-	-	-
Sea turtles	226	-	-	-	-	-	-	-	-	-	-
Penguins	226	-	-	-	-	-	-	-	-	-	-
Mortality and potential mortal injury / recoverable injury											
Fish I	213	-	-	-	0.02	0.03	-	-	0.02	0.03	0.03
Fish II, III Fish eggs and larvae	207	0.08	0.08	0.08	0.09	0.12	0.03	0.03	0.13	0.14	0.14

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.6.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 68. *Monopiles, NAS – HSD, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	6.62	6.2	4.88	4.48
HF cetaceans	185	-	-	-	-
Otariid seals	203	-	-	-	-
Sea turtles	204	1.15	1.07	1.2	1.1
Penguins	203	-	-	-	-
TTS					
LF cetaceans	168	22.05	20.18	13.8	11.91
HF cetaceans	170	-	-	-	-
Otariid seals	188	0.02	0.02	0.02	0.02
Sea turtles	189	6.73	6.32	4.91	4.49
Penguins	188	0.02	0.02	0.02	0.02

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 69. *Monopiles, NAS – HSD, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.16	0.15	0.16	0.15
II, Fish eggs and fish larvae	210	0.87	0.83	0.91	0.87
III	207	1.45	1.35	1.39	1.31
Fish recoverable injury					
I	216	0.29	0.28	0.33	0.32
II, III	203	2.55	2.41	2.34	2.2
Fish temporary threshold shift (TTS)					
I, II, III	186	12.71	11.82	12.75	10.84

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.6.3. Sound field maps

The following presents the contour maps:

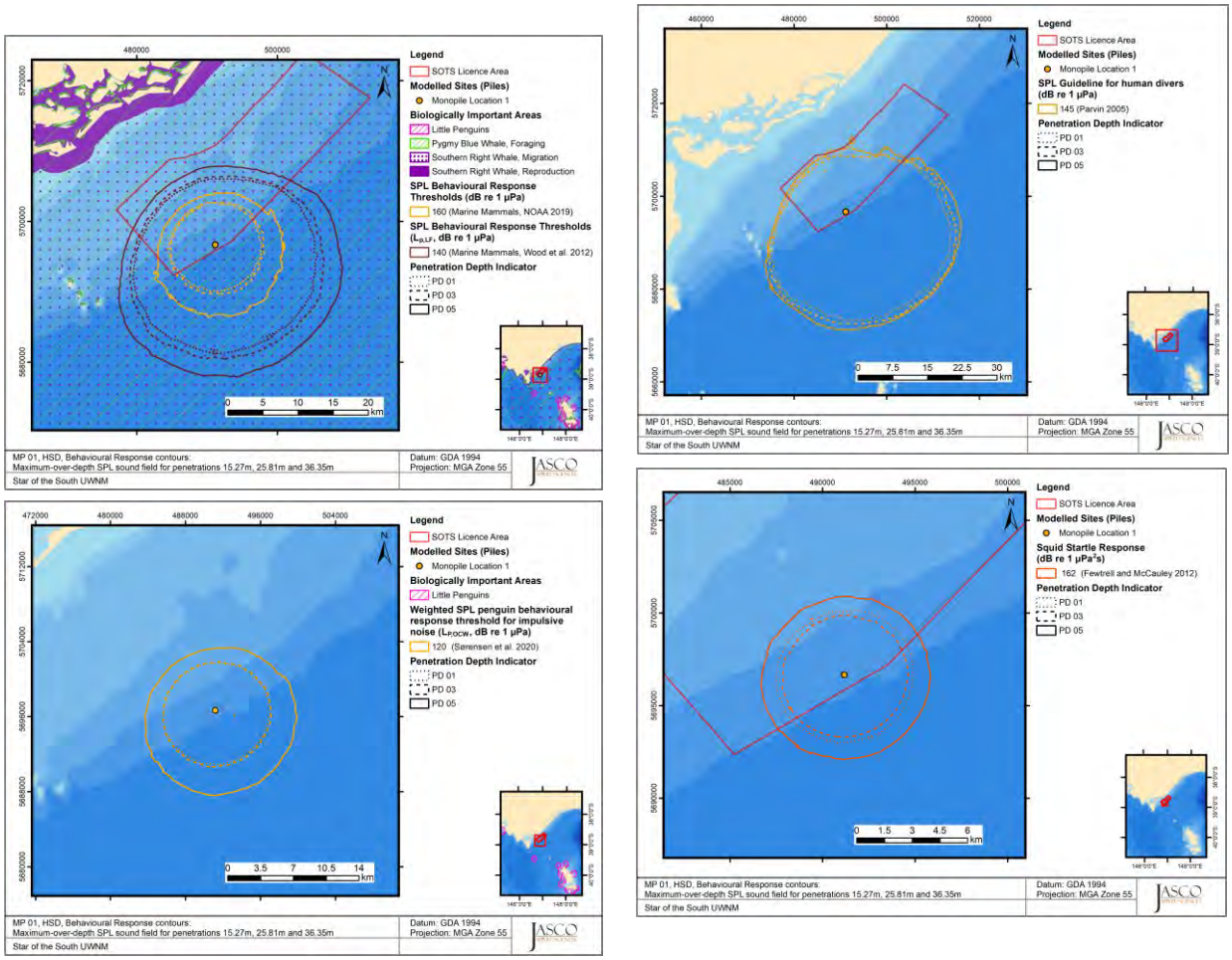


Figure 66. *HSD per-strike sound fields for MP 1,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

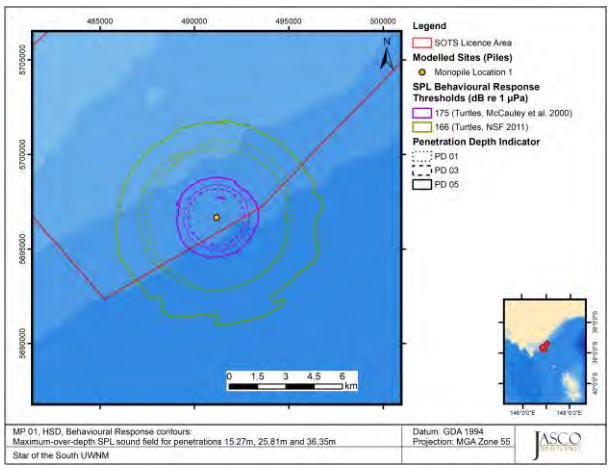


Figure 67. *HSD per-strike sound fields for MP 1,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

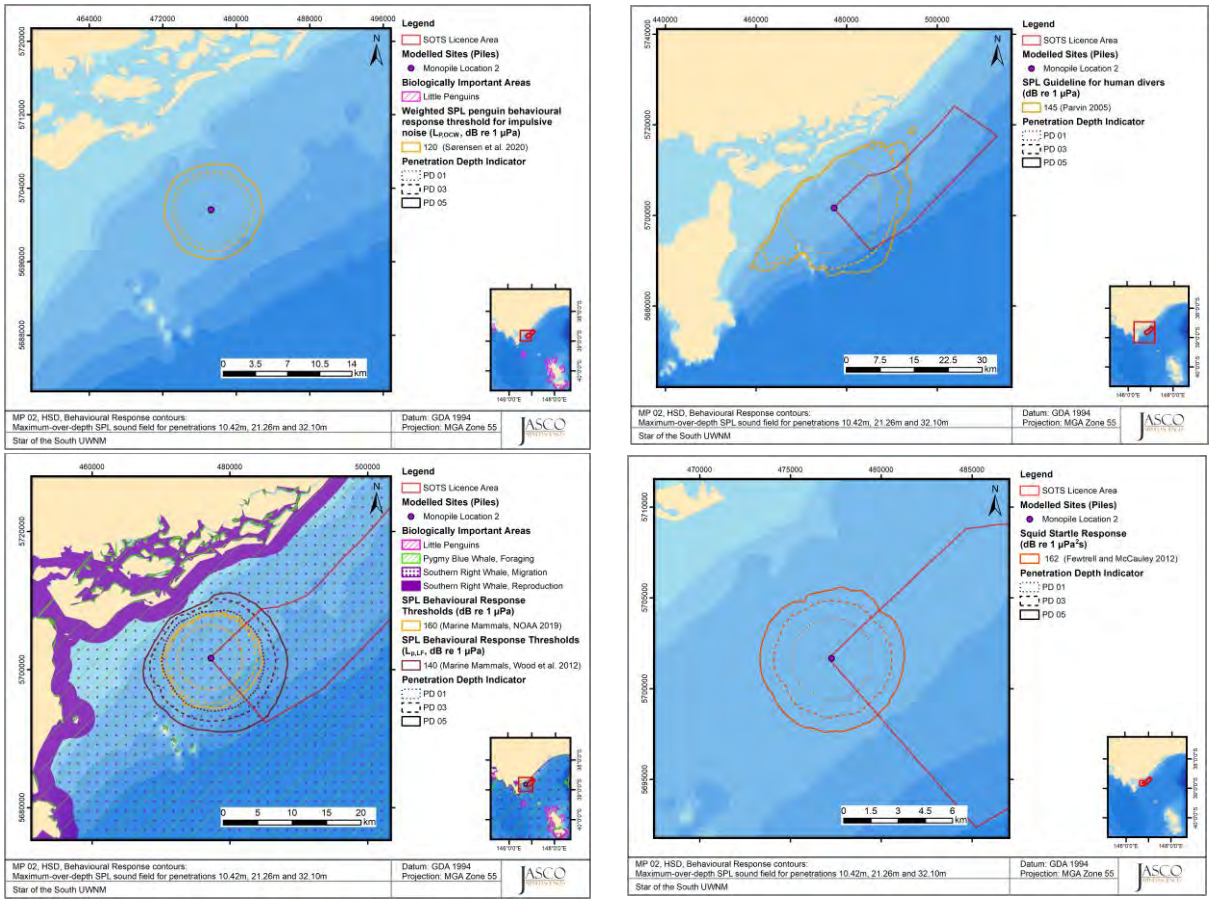


Figure 68. *HSD per-strike sound fields for MP 2,* SPL: Sound level contour map of weighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

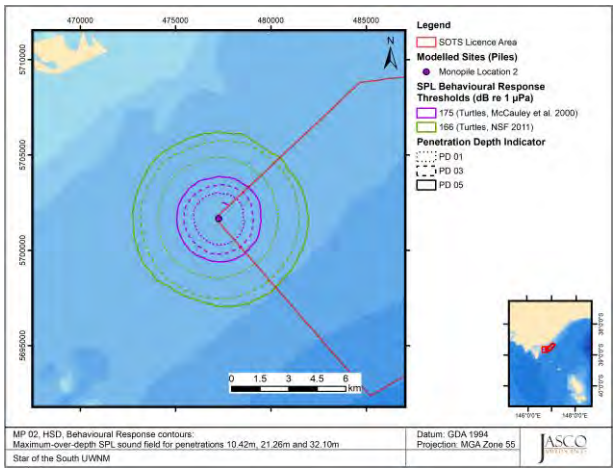


Figure 69. *HSD per-strike sound fields for MP 2,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

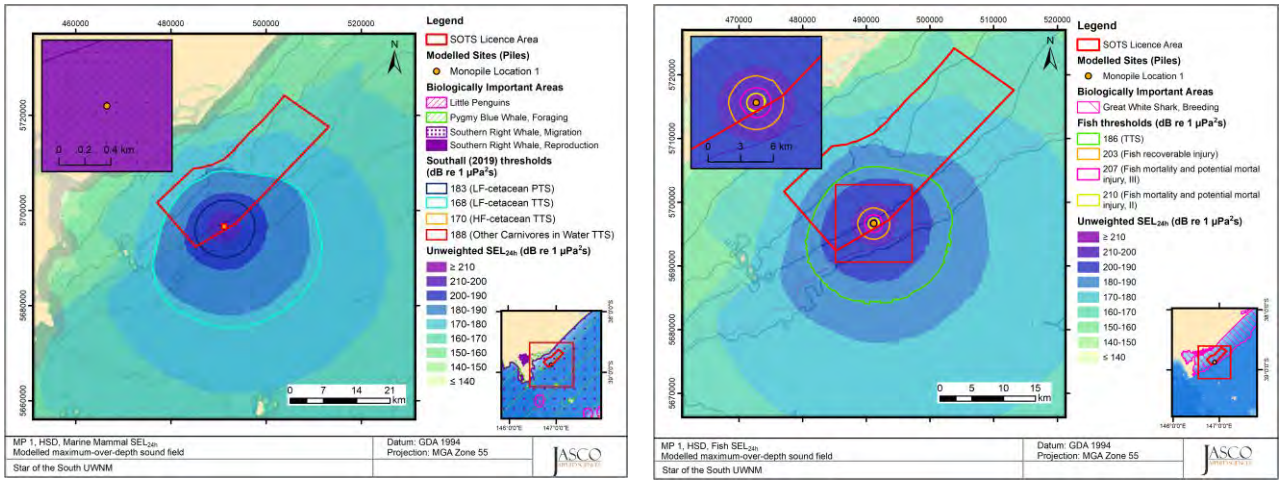


Figure 70. *HSD, MP 1.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

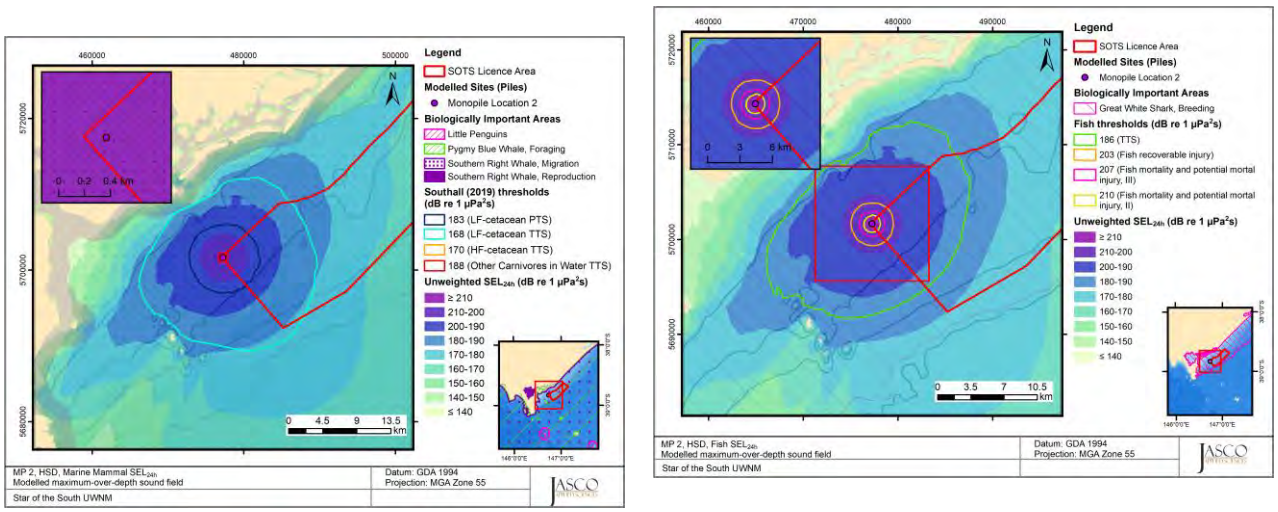


Figure 71. *HSD, MP 2.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

4.1.2.7. Scenario 7 – DBBC + HSD (Second Modelling Round)

4.1.2.7.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented below.

Table 70. *Monopiles, NAS – HSD+DBBC, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa^2·s)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.02	0.02	0.02	0.02	-	-	0.02	0.02	0.03	0.03	-	-	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
180	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
170	0.13	0.13	0.17	0.17	0.13	0.13	0.26	0.26	0.29	0.28	0.21	0.21	0.33	0.27	0.44	0.41	0.69	0.63	0.65	0.53
162[a]	0.79	0.75	0.83	0.78	0.75	0.69	0.98	0.92	1.26	1.19	0.71	0.67	1.4	1.28	1.64	1.5	2.65	2.38	2.38	2.15
160	1.11	1.06	1.16	1.11	1.03	0.99	1.4	1.29	1.74	1.63	0.94	0.89	1.99	1.75	2.33	2.1	3.45	3.18	3.15	2.87
150	4.36	4.14	4.55	4.3	4.36	4.05	5.25	4.93	6.14	5.77	3.42	3.1	7.49	6.41	8.86	7.36	11.74	10.31	11.25	9.69
140	11.01	9.81	11.4	10.17	11.07	10.03	13.21	11.63	14.77	13.02	10.37	8.78	17.53	14.42	18.48	15.42	24.04	18.09	21.66	17.67
130	22.68	18.31	23.67	19.61	23.65	19.1	27.64	22.52	32.55	26.06	20.56	16.27	34.65	23.95	36.18	25.92	44	31.85	42.96	31.16

[a] Startle response level for squid (Fewtrell and McCauley 2012).

A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 71. *Monopiles, NAS – HSD+DBBC, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1										Monopile 2									
	Penetration depth (m)										Penetration depth (m)									
	15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.02	0.02	-	-	-	-	-	-	0.02	0.02	-	-	-	-	0.02	0.02	0.03	0.03	0.03	0.03
190	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
180	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.26	0.24	0.13	0.13	0.24	0.24	0.26	0.26	0.49	0.45	0.46	0.44
170	0.85	0.81	0.88	0.84	0.78	0.75	1	0.95	1.24	1.16	0.72	0.69	1.35	1.24	1.53	1.41	2.21	2.03	2.03	1.86
160	3.14	2.92	3.2	3.01	2.94	2.78	3.55	3.32	4.12	3.89	2.39	2.21	4.33	4.02	4.93	4.48	6.37	5.79	5.94	5.37
150	7.34	6.68	7.72	6.78	7.23	6.28	8.74	7.39	10.04	8.46	5.95	5.44	11.36	9.48	12.17	10.42	15.62	12.74	15.18	12.33
145[a]	10.56	9.1	11.23	9.24	10.65	8.84	12.68	10.23	14.53	11.67	8.91	7.82	15.9	12.92	16.92	13.66	24.35	17.14	21.01	16.82
140	14.88	12.19	16.4	12.64	14.71	12.69	17.36	14.77	20.67	16.4	13.84	11.25	24.89	17.32	25.68	18.86	34.65	22.59	34.05	22.02
130	31.64	23.51	32.21	25.23	30.81	24.27	36.03	28.44	40.01	31.07	26.25	20.02	40.81	30.97	42.77	32.46	58.24	37.8	57.28	36.19

[a] Human health assessment threshold derived from Parvin (2005).

A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 72. *Monopiles, NAS – HSD+DBBC, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1										Monopile 2									
		Penetration depth (m)										Penetration depth (m)									
		15.27		20.54		25.81		31.8		36.35		10.42		15.84		21.26		26.68		32.10	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.32	0.31	0.35	0.32	0.31	0.3	0.45	0.42	0.56	0.48	0.26	0.26	0.67	0.62	0.76	0.69	1.12	1.02	1.03	0.92
Sea turtle behavioural response [a]	166	1.57	1.48	1.62	1.54	1.44	1.36	1.85	1.72	2.25	2.11	1.19	1.12	2.26	2.1	2.57	2.38	3.46	3.24	3.15	2.93
Marine mammal behavioural response [c]	160	3.14	2.92	3.2	3.01	2.94	2.78	3.55	3.32	4.12	3.89	2.39	2.21	4.33	4.02	4.93	4.48	6.37	5.79	5.94	5.37
LF-cetacean weighted behavioural response [d]	160	0.62	0.46	0.66	0.62	0.66	0.62	0.74	0.67	0.86	0.77	0.71	0.69	0.95	0.87	1.08	0.93	1.29	1.16	1.34	1.18
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	5.15	4.77	5.41	5	5.45	5.04	6.06	5.61	6.48	5.98	4.4	3.92	5.69	5.12	6.04	5.48	7.61	6.73	6.84	6.3
Penguin OCW-weighted behavioural response [e]	120	1.84	1.67	2.23	1.99	2.15	1.88	2.65	2.32	2.73	2.47	1.63	1.44	1.83	1.64	2.18	1.99	2.6	2.32	2.48	2.27

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020), OCW weighted.

Table 73. *Monopiles, NAS – HSD+DBBC, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1					Monopile 2				
		Penetration depth (m)					Penetration depth (m)				
		15.27	20.54	25.81	31.8	36.35	10.42	15.84	21.26	26.68	32.10
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS											
LF cetaceans	219	-	-	-	-	-	-	-	-	-	-
HF cetaceans	230	-	-	-	-	-	-	-	-	-	-
Otariid seals	232	-	-	-	-	-	-	-	-	-	-
Sea turtles	232	-	-	-	-	-	-	-	-	-	-
Penguins	232	-	-	-	-	-	-	-	-	-	-
TTS											
LF cetaceans	213	-	-	-	0.02	0.03	-	-	0.02	0.03	0.03
HF cetaceans	224	-	-	-	-	-	-	-	-	-	-
Otariid seals	226	-	-	-	-	-	-	-	-	-	-
Sea turtles	226	-	-	-	-	-	-	-	-	-	-
Penguins	226	-	-	-	-	-	-	-	-	-	-
Mortality and potential mortal injury / recoverable injury											
Fish I	213	-	-	-	0.02	0.03	-	-	0.02	0.03	0.03
Fish II, III Fish eggs and larvae	207	0.08	0.08	0.08	0.09	0.09	0.03	0.03	0.08	0.09	0.09

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.7.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 74. *Monopiles, NAS – HSD+DBBC, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	1.61	1.45	2.36	2.16
HF cetaceans	185	-	-	-	-
Otariid seals	203	-	-	-	-
Sea turtles	204	0.22	0.21	0.29	0.28
Penguins	203	-	-	-	-
TTS					
LF cetaceans	168	7.13	6.66	9.53	8.05
HF cetaceans	170	-	-	-	-
Otariid seals	188	0.02	0.02	0.02	0.02
Sea turtles	189	1.51	1.36	2.37	2.18
Penguins	188	0.02	0.02	0.02	0.02

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 75. *Monopiles, NAS – HSD+DBBC, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.09	0.09	0.09	0.09
II, Fish eggs and fish larvae	210	0.13	0.13	0.25	0.24
III	207	0.27	0.26	0.47	0.44
Fish recoverable injury					
I	216	0.09	0.09	0.09	0.09
II, III	203	0.47	0.46	0.98	0.91
Fish temporary threshold shift (TTS)					
I, II, III	186	5.72	5.38	10.93	9.4

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.7.3. Sound field maps

The following presents the contour maps:

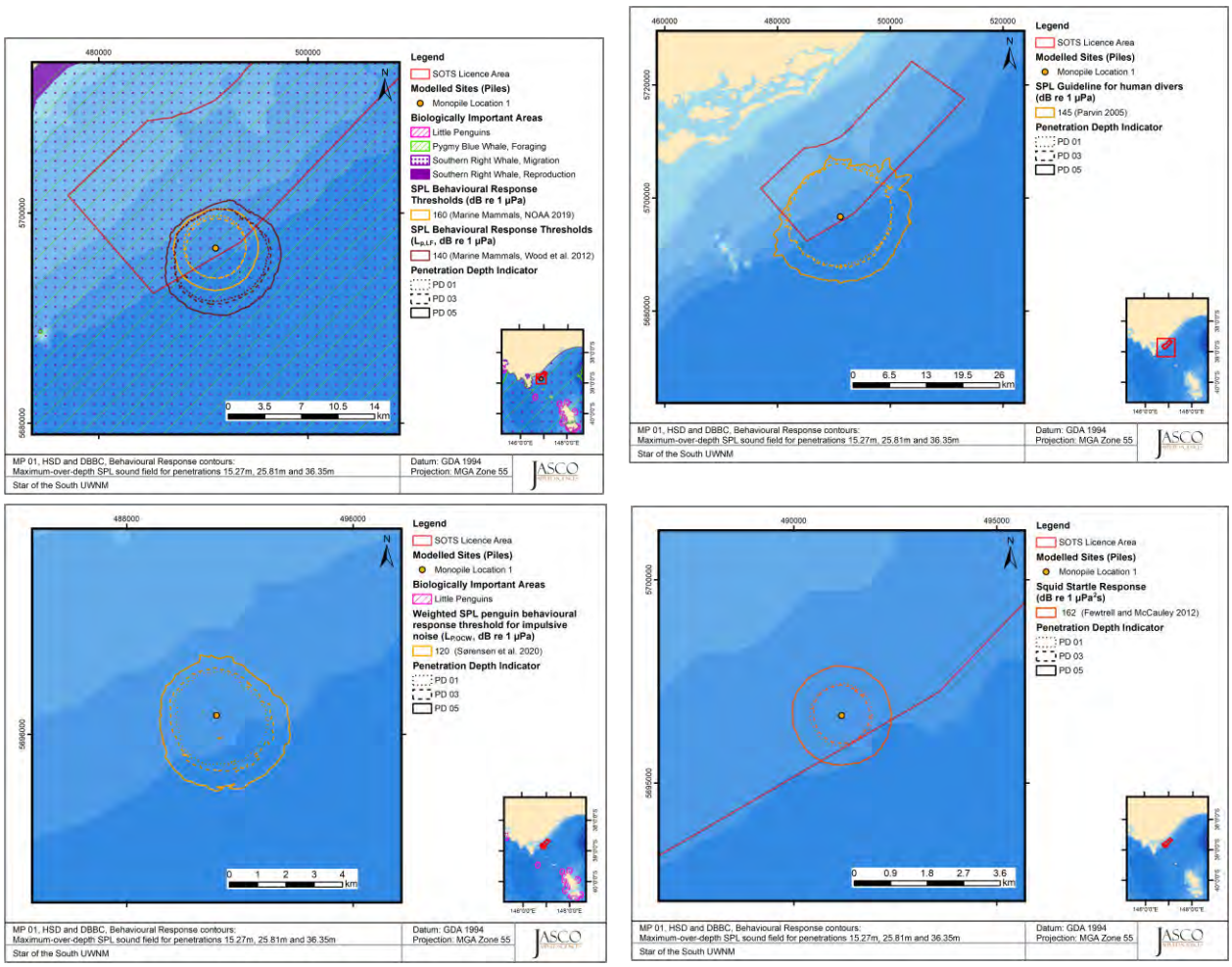


Figure 72. *HSD and DBBC per-strike sound fields for MP 1,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

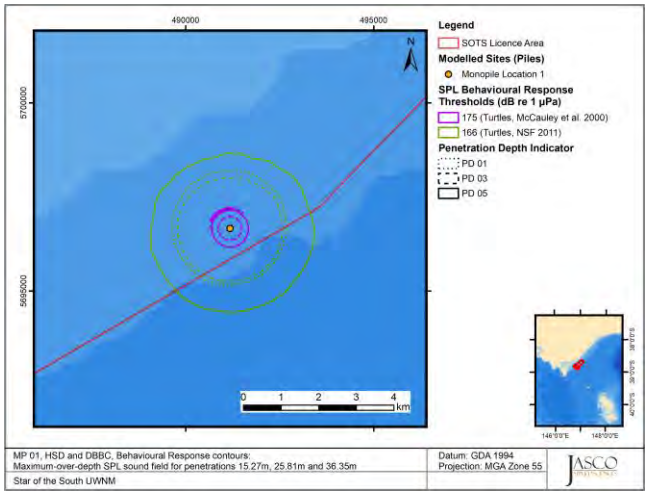


Figure 73. *HSD and DBBC per-strike sound fields for MP 1,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

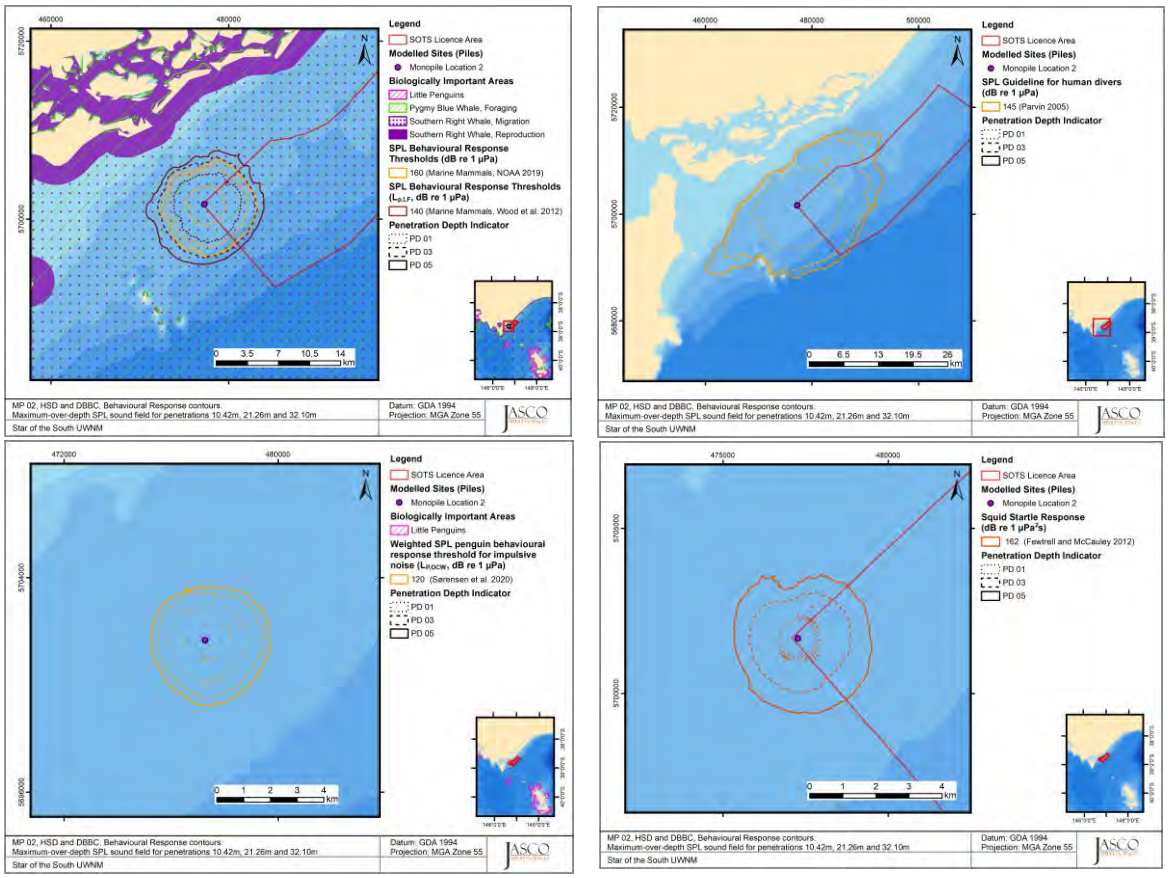


Figure 74. *HSD and DBBC per-strike sound fields for MP 2,* SPL: Sound level contour map of weighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), humans (top right), penguins (bottom left), squids (bottom right).

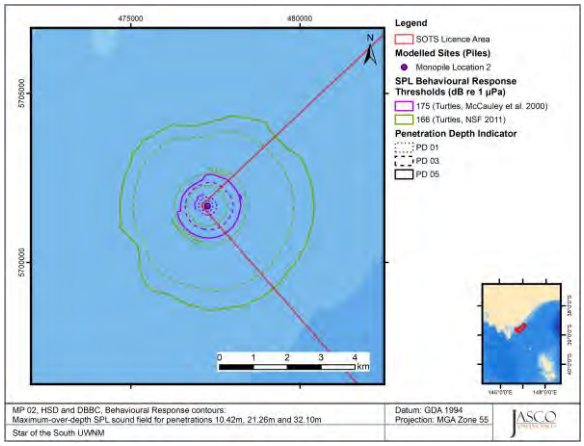


Figure 75. *HSD and DBBC per-strike sound fields for MP 2,* SPL: Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

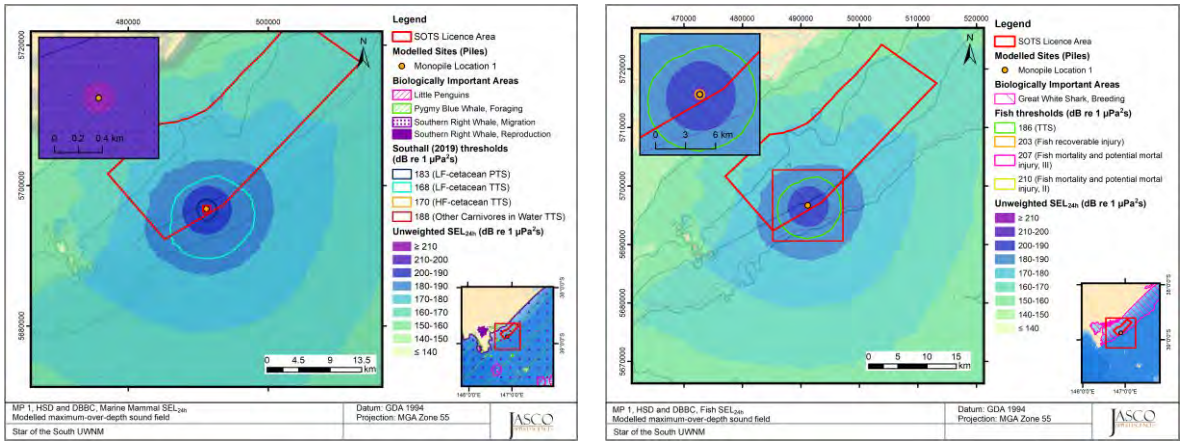


Figure 76. *HSD and DBBC, MP 1.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

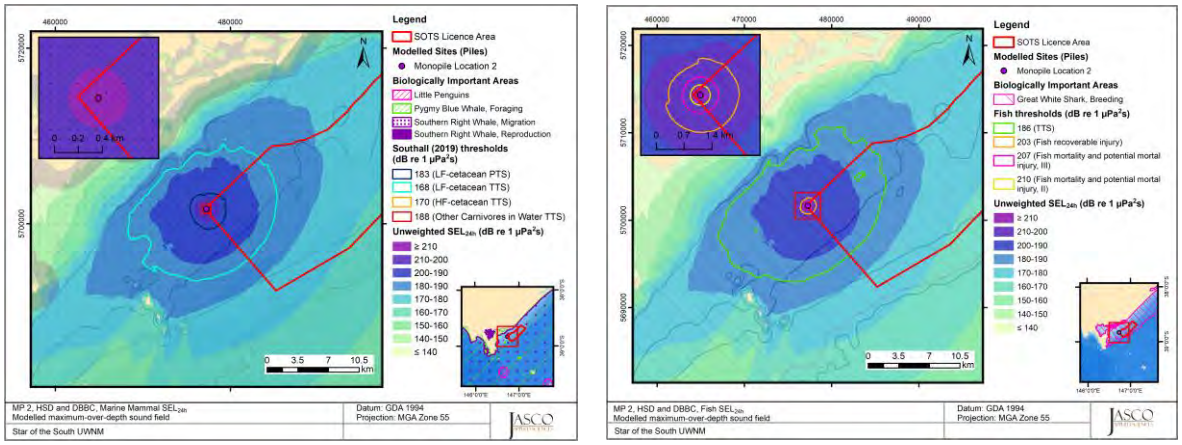


Figure 77. *HSD and DBBC, MP 2.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals. Thresholds omitted here were not reached or not large enough to display graphically.

4.1.2.8. Scenario 8 – Unmitigated (Fourth Modelling Round)

4.1.2.8.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented in the following tables. Results are presented in terms of per–strike SPL, SEL, PK sound fields and per–strike particle motion field results.

Table 76. *Monopile 1, Unmitigated, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 1									
	Penetration depth (m)									
	11.2		15.3		19.5		23.6		27.8	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.04	0.04	0.03	0.03	0.06	0.05	0.12	0.12	0.09	0.09
180	0.30	0.28	0.25	0.24	0.47	0.44	0.82	0.78	0.80	0.77
170	1.61	1.51	1.41	1.27	2.22	2.06	3.20	2.95	3.09	2.87
162[a]	4.01	3.72	3.71	3.42	5.14	4.68	6.52	5.94	6.44	5.92
160	4.75	4.46	4.50	4.13	5.96	5.49	7.58	6.94	7.56	6.94
150	11.2	9.99	10.3	9.25	13.7	12.0	18.9	16.3	19.4	16.8
140	48.7	29.6	29.5	25.6	48.9	36.8	83.0	49.1	82.9	49.9
130	85.4	77.9	83.8	68.4	>90.0	/	>90.0	/	>90.0	/

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 77. *Monopile 2, Unmitigated, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 2									
	Penetration depth (m)									
	14.6		18.2		21.9		25.5		29.1	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.03	0.03	0.03	0.03	0.06	0.06	0.09	0.08	0.10	0.10
180	0.23	0.23	0.23	0.22	0.37	0.34	0.54	0.48	0.82	0.78
170	1.42	1.32	1.42	1.33	2.22	2.08	2.83	2.65	3.74	3.49
162[a]	4.23	3.92	4.36	4.04	6.00	5.64	7.26	6.78	9.15	8.48
160	5.28	4.94	5.45	5.10	7.54	6.98	8.94	8.32	11.2	10.4
150	14.4	13.2	15.3	14.0	20.4	18.8	24.3	22.3	29.8	27.2
140	33.7	30.9	43.2	34.8	50.9	46.8	78.2	54.5	78.5	63.3
130	78.6	67.4	86.7	78.5	>90.0	/	>90.0	/	>90.0	/

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 78. *Monopile 3, Unmitigated, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 3									
	Penetration depth (m)									
	16.3		22.7		29.0		35.4		41.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.02	0.02	0.03	0.03	0.09	0.09	0.09	0.09	0.12	0.12
180	0.17	0.16	0.22	0.22	0.39	0.37	0.47	0.45	0.68	0.66
170	1.04	1.00	1.24	1.19	2.03	1.93	2.24	2.15	2.87	2.73
162[a]	2.96	2.81	3.39	3.23	4.71	4.48	5.11	4.86	6.19	5.81
160	3.63	3.44	4.08	3.91	5.66	5.34	6.14	5.78	7.39	6.87
150	8.62	7.95	9.61	8.86	12.5	11.6	13.4	12.5	15.6	14.3
140	17.1	15.8	19.6	18.0	26.5	24.2	28.8	26.3	32.8	29.9
130	33.7	30.7	38.5	35.2	68.1	46.0	68.5	51.2	68.7	59.0

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 79. *Monopile 4, Unmitigated, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Monopile 4									
	Penetration depth (m)									
	13.0		19.0		24.9		30.9		36.9	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.09	0.09	0.11	0.11	0.13	0.13	0.15	0.14	0.15	0.15
180	0.42	0.40	0.50	0.47	0.68	0.63	0.92	0.88	1.03	0.97
170	2.02	1.92	2.59	2.43	3.02	2.90	3.56	3.41	3.74	3.56
162[a]	4.88	4.61	5.73	5.40	6.49	6.11	7.39	6.88	7.50	7.05
160	5.84	5.50	6.73	6.35	7.64	7.14	8.84	8.04	8.72	8.17
150	12.9	11.9	13.9	13.1	15.7	14.5	17.7	16.3	17.1	15.9
140	25.1	23.5	27.0	25.2	31.2	27.9	42.6	31.4	42.6	31.5
130	47.6	42.5	64.1	45.3	64.6	52.1	70.6	61.0	72.7	62.5

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 80. *Monopile 1, Unmitigated, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1									
	Penetration depth (m)									
	11.2		15.3		19.5		23.6		27.8	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.03	0.03	0.03	0.03	0.05	0.05	0.08	0.08	0.09	0.09
190	0.24	0.24	0.19	0.19	0.44	0.42	0.68	0.65	0.66	0.62
180	1.32	1.22	1.15	1.09	1.89	1.75	2.63	2.44	2.53	2.39
170	4.03	3.78	3.73	3.46	4.90	4.56	6.28	5.79	6.36	5.88
160	9.43	8.43	8.66	7.79	11.3	10.0	14.0	12.0	13.8	12.0
150	27.4	23.9	24.0	20.6	48.6	28.1	82.4	38.8	49.0	40.5
145[a]	49.0	41.8	48.8	35.6	82.6	46.8	83.8	66.4	83.5	62.6
140	83.6	63.5	82.8	54.1	83.9	71.0	90.0	/	>90.0	/

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 81. *Monopile 2, Unmitigated, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 2									
	Penetration depth (m)									
	14.6		18.2		21.9		25.5		29.1	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.07	0.09	0.09
190	0.16	0.16	0.18	0.18	0.28	0.27	0.37	0.36	0.69	0.67
180	1.14	1.09	1.15	1.09	1.84	1.75	2.30	2.11	2.90	2.68
170	3.72	3.48	3.72	3.52	5.05	4.66	5.89	5.49	7.84	7.24
160	9.10	8.35	10.1	9.21	14.1	13.0	17.1	15.6	20.8	19.0
150	22.6	20.7	28.4	25.9	43.3	35.9	44.2	40.3	50.6	46.3
145[a]	34.6	31.3	44.1	40.7	78.1	53.9	78.6	63.9	79.1	72.9
140	53.5	49.1	78.3	59.9	86.9	78.6	>90.0	/	>90.0	/

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 82. *Monopile 3, Unmitigated, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 3									
	Penetration depth (m)									
	16.3		22.7		29.0		35.4		41.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	0.07	0.07	0.09	0.09	0.12	0.11	0.13	0.13	0.14	0.14
190	0.31	0.30	0.43	0.42	0.59	0.57	0.84	0.72	0.80	0.77
180	1.64	1.58	2.04	1.96	2.43	2.30	2.80	2.64	2.96	2.80
170	4.50	4.23	5.24	4.88	5.79	5.39	6.52	6.07	6.57	6.15
160	10.4	9.48	11.6	10.6	12.5	11.6	13.2	12.3	13.2	12.1
150	21.8	20.2	22.8	21.3	25.1	23.2	31.1	26.9	31.1	26.5
145[a]	31.1	27.4	31.2	28.1	42.7	32.0	42.8	36.6	42.8	36.0
140	42.8	36.7	42.9	38.2	64.1	44.2	64.5	49.0	64.7	50.1

[a] Human health assessment threshold derived from Parvin (2005).

Table 83. *Monopile 4, Unmitigated, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 4									
	Penetration depth (m)									
	13.0		19.0		24.9		30.9		36.9	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	0.02	0.02	0.07	0.07	0.09	0.09	0.11	0.11
190	0.12	0.12	0.15	0.14	0.34	0.34	0.37	0.36	0.53	0.51
180	0.95	0.79	1.05	1.01	1.63	1.57	1.82	1.74	2.27	2.18
170	2.92	2.76	3.13	2.98	4.35	4.08	4.67	4.37	5.64	5.28
160	6.49	5.99	7.39	6.77	10.2	9.34	10.9	10.0	12.3	11.3
150	13.6	12.5	16.4	15.0	22.8	20.7	24.2	22.1	28.6	25.8
145[a]	19.3	17.5	24.3	22.2	31.5	28.7	35.3	32.3	39.7	36.4
140	28.9	26.2	34.1	31.1	43.2	39.4	47.4	43.8	68.3	48.7

[a] Human health assessment threshold derived from Parvin (2005).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 84. *Monopile 1, Unmitigated, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1									
		Penetration depth (m)									
		11.2		15.3		19.5		23.6		27.8	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	2.53	2.34	2.31	2.14	3.10	2.88	4.12	3.83	4.23	3.95
Sea turtle behavioural response [a]	166	5.63	5.22	5.18	4.84	6.85	6.27	8.60	7.74	8.67	7.81
Marine mammal behavioural response [b]	160	9.43	8.43	8.66	7.79	11.3	10.0	14.0	12.0	13.8	12.0
LF-cetacean weighted behavioural response [c]	160	5.56	5.22	5.27	4.91	6.81	6.27	8.16	7.48	8.22	7.57
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	82.0	43.1	48.8	35.5	82.9	49.0	84.7	76.1	83.8	67.3
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 85. *Monopile 2, Unmitigated, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 2									
		Penetration depth (m)									
		14.6		18.2		21.9		25.5		29.1	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	2.36	2.20	2.36	2.20	3.06	2.91	3.62	3.42	4.63	4.26
Sea turtle behavioural response [a]	166	5.32	4.90	5.63	5.12	7.54	6.95	9.33	8.56	11.7	10.8
Marine mammal behavioural response [b]	160	9.10	8.35	10.1	9.21	14.1	13.0	17.1	15.6	20.8	19.0
LF-cetacean weighted behavioural response [c]	160	5.36	5.05	5.82	5.46	8.33	7.71	10.0	9.25	12.1	11.1
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	32.3	29.7	43.5	37.1	78.1	51.6	78.6	63.4	78.9	72.5
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 86. *Monopile 3, Unmitigated, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 3									
		Penetration depth (m)									
		16.3		22.7		29.0		35.4		41.7	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	2.83	2.68	3.48	3.27	3.82	3.61	4.30	4.06	4.55	4.22
Sea turtle behavioural response [a]	166	6.32	5.88	6.96	6.52	8.32	7.30	9.41	8.50	9.05	8.24
Marine mammal behavioural response [b]	160	10.4	9.48	11.6	10.6	12.5	11.6	13.2	12.3	13.2	12.1
LF-cetacean weighted behavioural response [c]	160	6.17	5.80	6.97	6.55	8.43	7.54	9.65	8.68	9.25	8.54
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	26.0	24.4	26.8	25.2	42.6	29.5	42.8	35.4	42.8	35.4
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 87. *Monopile 4, Unmitigated, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 4									
		Penetration depth (m)									
		13.0		19.0		24.9		30.9		36.9	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	1.74	1.65	1.92	1.85	2.80	2.64	3.01	2.86	3.62	3.43
Sea turtle behavioural response [a]	166	4.05	3.82	4.51	4.18	6.20	5.72	6.64	6.14	7.93	7.32
Marine mammal behavioural response [b]	160	6.49	5.99	7.39	6.77	10.2	9.34	10.9	10.0	12.3	11.3
LF-cetacean weighted behavioural response [c]	160	3.83	3.64	4.34	4.16	6.11	5.72	6.79	6.35	8.27	7.61
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	17.7	15.6	21.3	19.4	29.0	26.4	33.6	30.4	38.7	35.6
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	74.4	66.5	78.7	69.1	>90.0	/	>90.0	/	>90.0	/

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 88. *Monopiles, Unmitigated, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1					Monopile 2					Monopile 3					Monopile 4				
		Penetration depth (m)					Penetration depth (m)					Penetration depth (m)					Penetration depth (m)				
		11.2	15.3	19.5	23.6	27.8	14.6	18.2	21.9	25.5	29.1	16.3	22.7	29.0	35.4	41.7	13.0	19.0	24.9	30.9	36.9
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS/AUD INJ																					
LF cetaceans	222	–	–	–	0.02	0.02	–	–	–	–	–	–	–	–	–	0.02	–	–	–	–	–
HF cetaceans	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Otariid seals	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sea turtles	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Penguins	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
TTS																					
LF cetaceans	216	0.03	0.03	0.04	0.06	0.06	–	–	0.05	0.06	0.09	0.03	0.07	0.09	0.13	0.13	–	–	0.06	0.08	0.11
HF cetaceans	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Otariid seals	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sea turtles	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Penguins	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury																					
Fish I	213	0.05	0.04	0.06	0.09	0.09	0.04	0.05	0.09	0.10	0.12	0.09	0.12	0.13	0.15	0.16	0.02	0.05	0.10	0.12	0.14
Fish II, III Fish eggs and larvae	207	0.18	0.17	0.20	0.26	0.26	0.09	0.11	0.23	0.26	0.28	0.24	0.28	0.31	0.41	0.43	0.09	0.12	0.23	0.25	0.30

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 89. *Monopiles, Unmitigated, winter, PK–PK thresholds: Maximum (R_{max}) horizontal distances (m) from each monopile to modelled seafloor peak–peak pressure level (PK–PK) thresholds for invertebrates for each penetration depth.*

Marine Fauna	PK–PK threshold (L_{pkpk}; dB re 1 µPa)	Monopile 1					Monopile 2					Monopile 3					Monopile 4				
		Penetration depth (m)					Penetration depth (m)					Penetration depth (m)					Penetration depth (m)				
		11.2	15.3	19.5	23.6	27.8	14.6	18.2	21.9	25.5	29.1	16.3	22.7	29.0	35.4	41.7	13.0	19.0	24.9	30.9	36.9
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Crustaceans [a]	202	432	331	587	950	861	367	370	490	659	834	472	645	825	882	899	358	427	674	790	>1000 *

[a] Payne et al. (2008), lobster

* Maximum modelling range is 1 km, see Section 3.1.1

Table 90. *Monopiles winter, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from four monopiles to modelled seafloor peak acceleration magnitude level (m/s^2) thresholds for benthic invertebrates for each penetration depth.

Marine Fauna	Marine fauna Peak acceleration magnitude (m/s^2)	Monopile 1					Monopile 2					Monopile 3					Monopile 4				
		Penetration depth (m)					Penetration depth (m)					Penetration depth (m)					Penetration depth (m)				
		11.2	15.3	19.5	23.6	27.8	14.6	18.2	21.9	25.5	29.1	16.3	22.7	29.0	35.4	41.7	13.0	19.0	24.9	30.9	36.9
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Benthic invertebrates [b]	35.75	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] Day et al. (2016a) – Crustaceans and bivalves

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.1.2.8.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 91. *Monopiles, unmitigated, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS)/auditory injury and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
PTS/AUD INJ									
LF cetaceans	183	12.1	323.4	17.4	598.5	14.9	522.4	11.8	335.8
HF cetaceans	193	0.06	0.01	0.03	*	0.13	0.05	0.03	0.00
Otariid seals	185	0.08	0.02	0.09	0.02	0.16	0.08	0.12	0.05
Sea turtles	184	9.56	227.2	13.2	382.8	12.5	373.5	9.85	238.6
Penguins	185	0.08	0.02	0.09	0.02	0.16	0.08	0.12	0.05
TTS									
LF cetaceans	168	83.6	3834.0	78.6	6966.0	42.9	3018.0	36.0	2304.0
HF cetaceans	178	0.89	2.26	0.66	1.18	1.35	5.48	0.76	1.71
Otariid seals	170	1.43	6.11	1.21	3.98	2.20	13.8	1.25	4.66
Sea turtles	169	83.4	2912.0	78.2	4445.0	42.7	2123.0	28.3	1541.0
Penguins	170	1.43	6.11	1.21	3.98	2.20	13.8	1.25	4.66

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
An asterisk indicates that the area was smaller than 0.0013 km²

Table 92. *Monopiles, unmitigated, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
Mortality and potential mortal injury									
I	219	0.29	0.27	0.26	0.21	0.59	1.04	0.32	0.30
II, Fish eggs and fish larvae	210	1.47	6.27	1.38	5.45	2.50	18.3	1.52	7.00
III	207	2.19	13.8	2.22	13.8	3.45	36.5	2.25	15.3
Fish recoverable injury									
I	216	0.54	0.90	0.48	0.55	1.01	3.07	0.53	0.88
II, III	203	3.46	34.1	3.78	40.7	5.14	77.0	3.50	37.2
Fish temporary threshold shift (TTS)									
I, II, III	186	15.1	448.7	22.6	950.2	18.1	733.1	14.4	475.2

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.8.3. Sound field maps

The following presents the sound field maps.

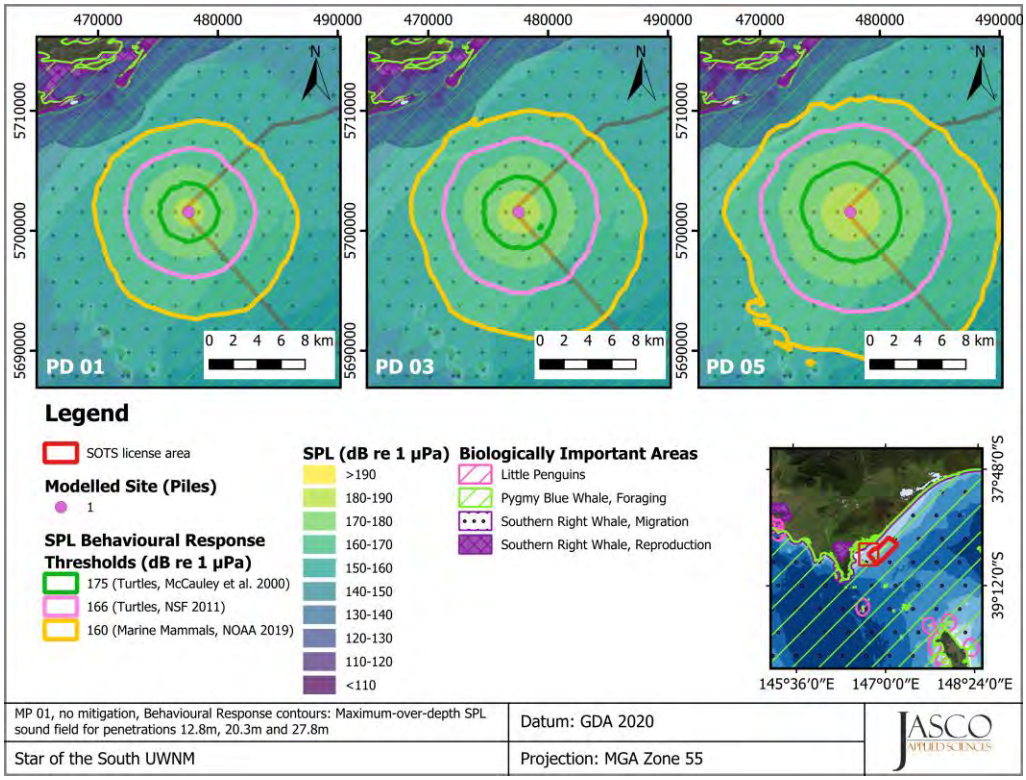


Figure 78. Monopile 1, unmitigated, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

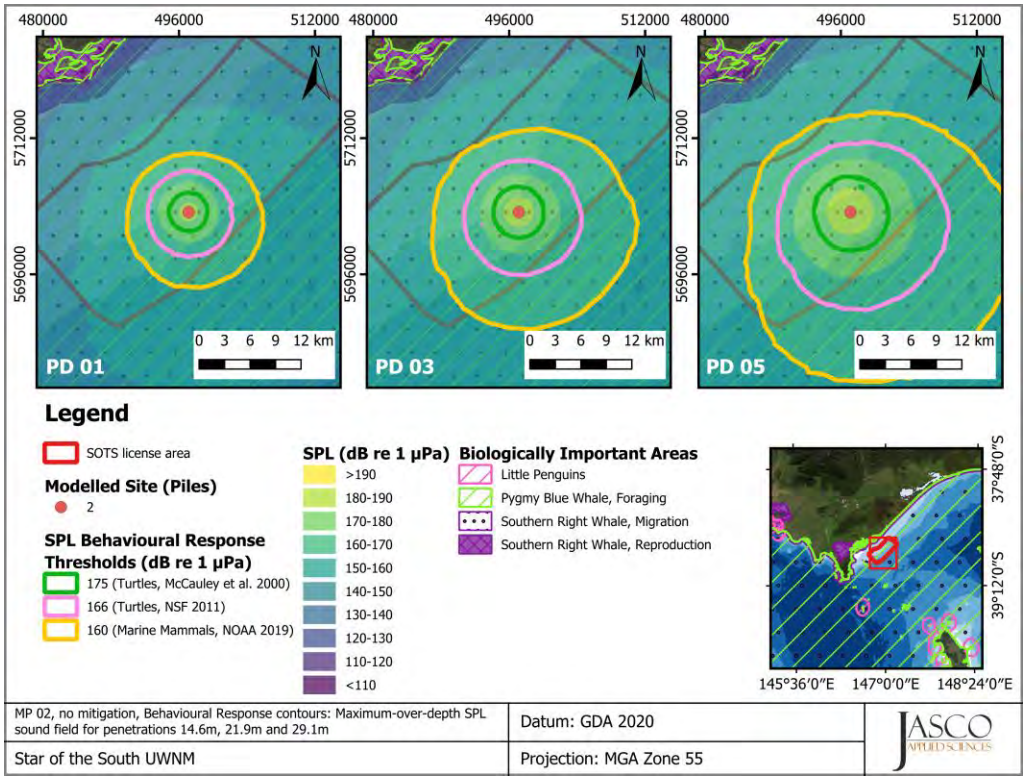


Figure 79. Monopile 2, unmitigated, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

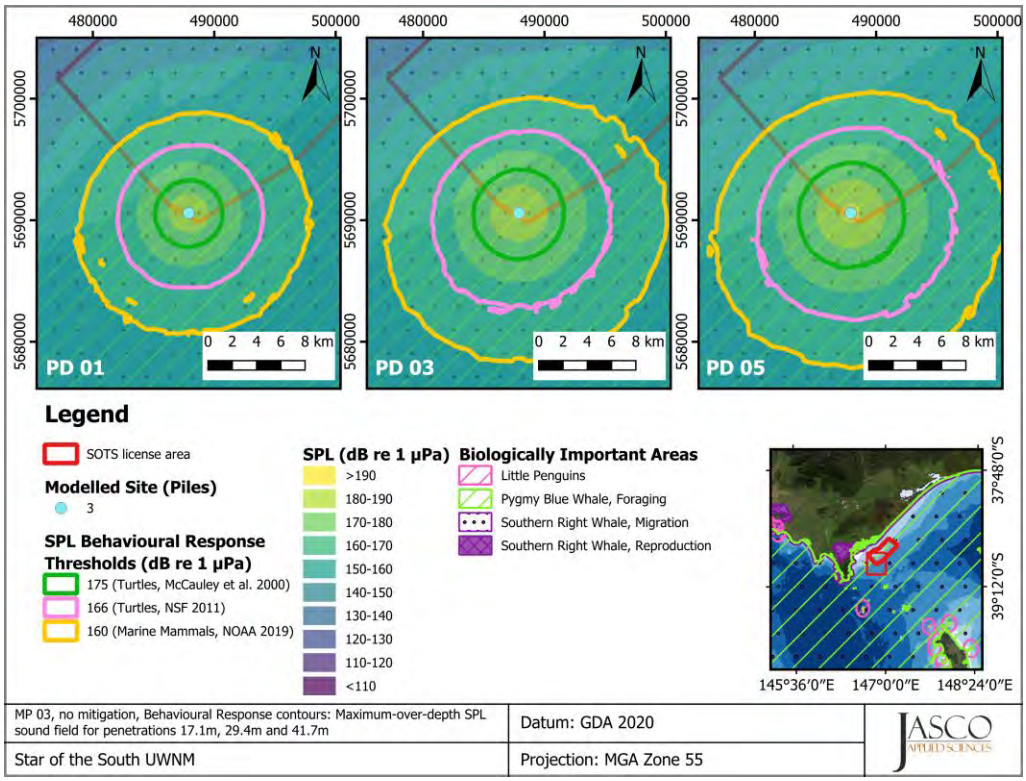


Figure 80. Monopile 3, unmitigated, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

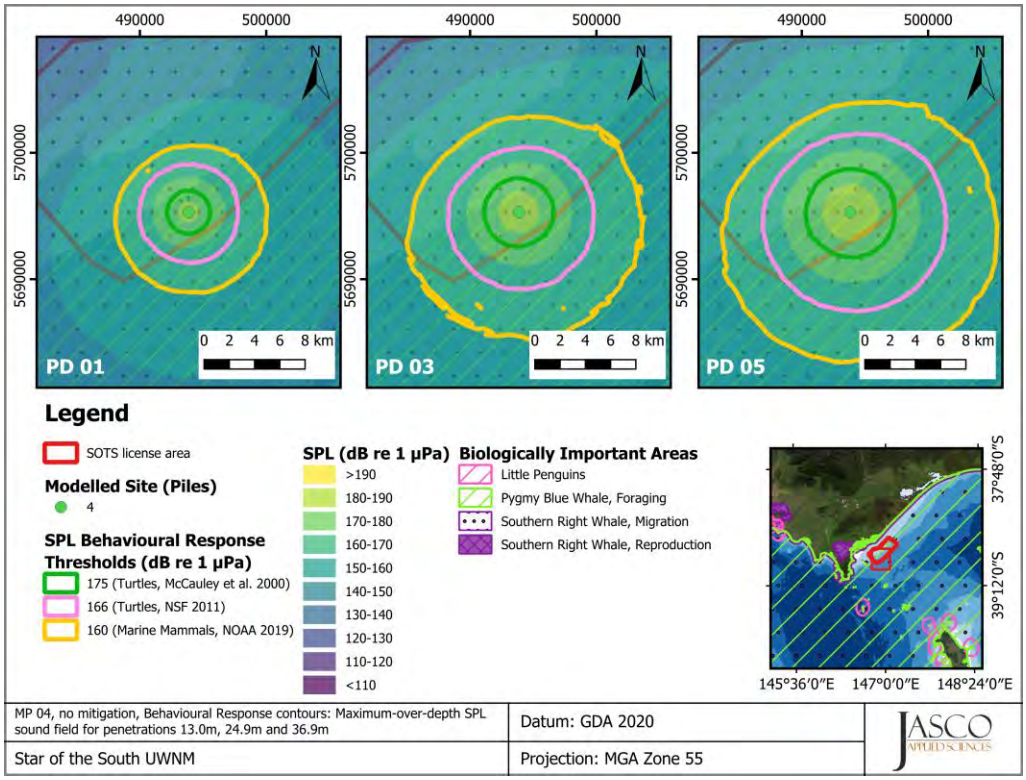


Figure 81. Monopile 4, unmitigated, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

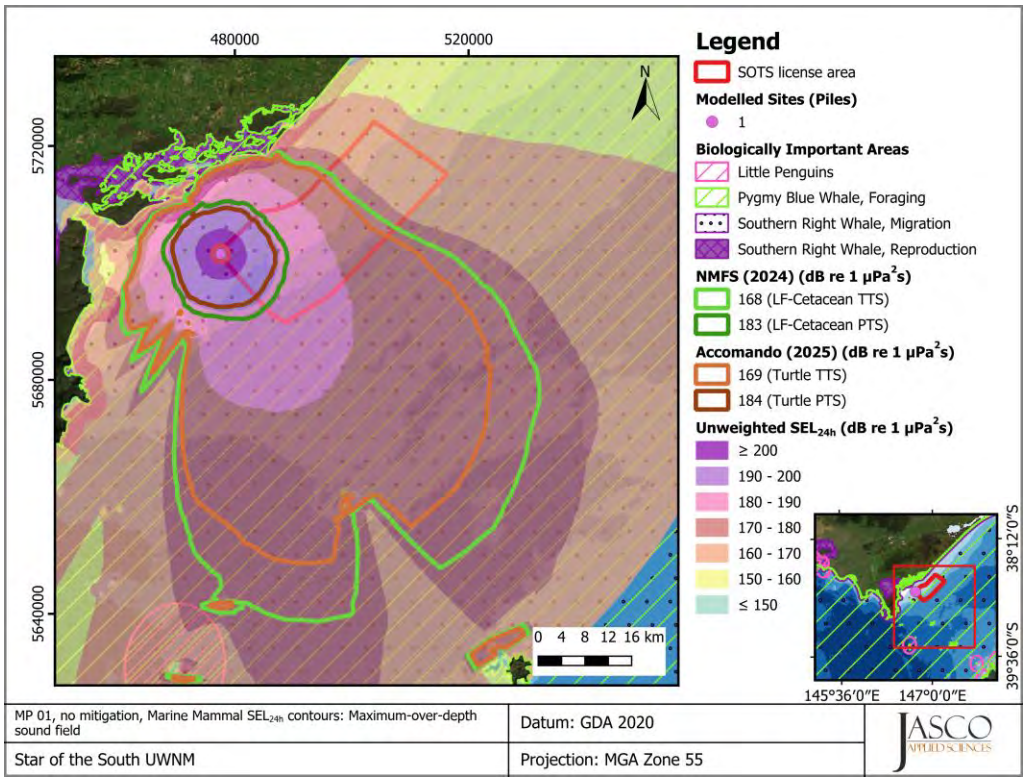


Figure 82. Monopile 1, unmitigated, *accumulated SEL_{24h}*: Sound level contour map showing maximum-over-depth SEL_{24h} results (unweighted/flat), along with frequency weighted isopleths for PTS and TTS in low-frequency cetaceans and sea turtles.

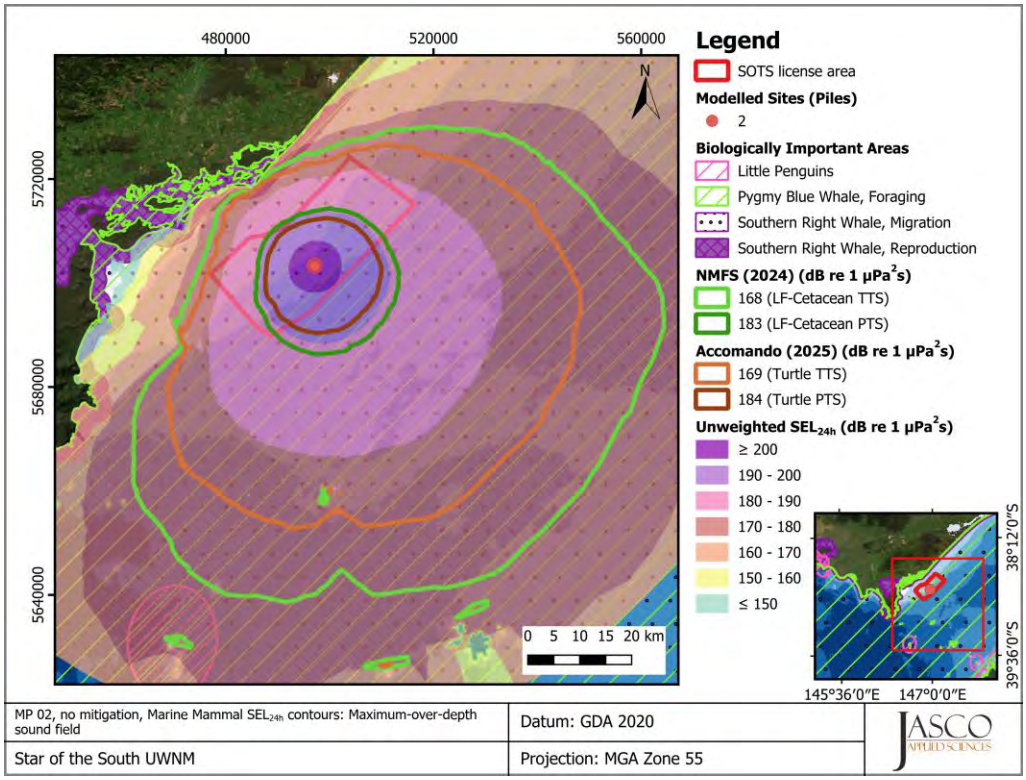


Figure 83. Monopile 2, unmitigated, accumulated SEL24h: Sound level contour map showing maximum-over-depth SEL24h results (unweighted/flat), along with frequency weighted isopleths for PTS and TTS in low-frequency cetaceans and sea turtles.

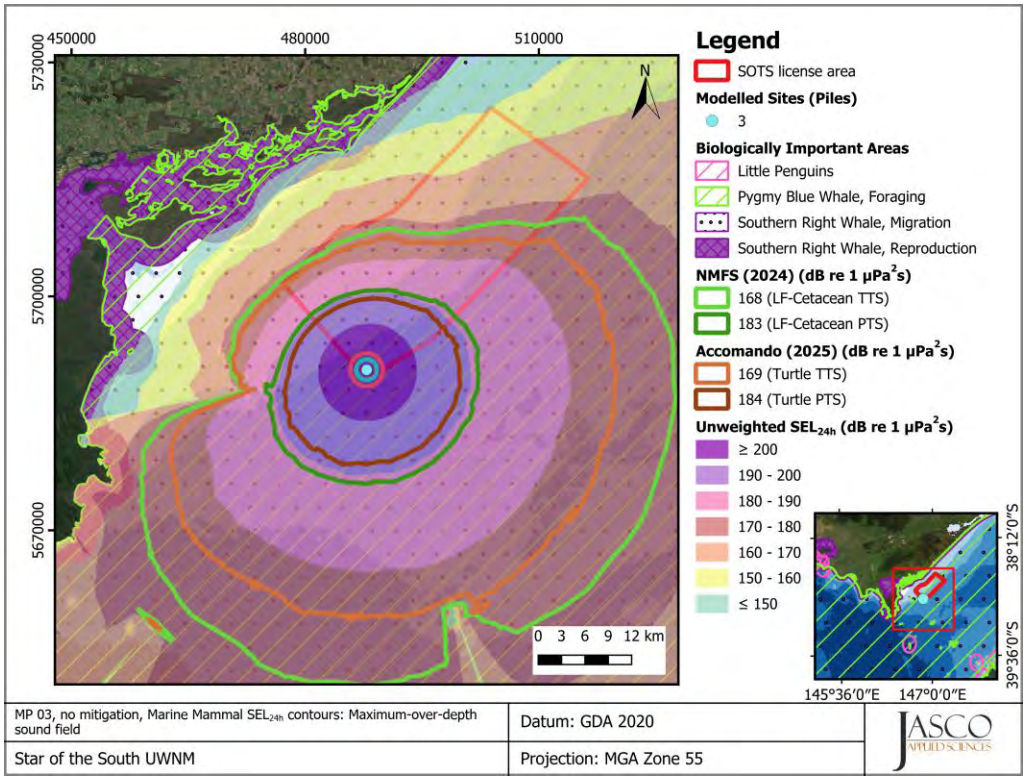


Figure 84. Monopile 3, unmitigated, *accumulated SEL_{24h}*: Sound level contour map showing maximum-over-depth SEL_{24h} results (unweighted/flat), along with frequency weighted isopleths for PTS and TTS in low-frequency cetaceans and sea turtles.

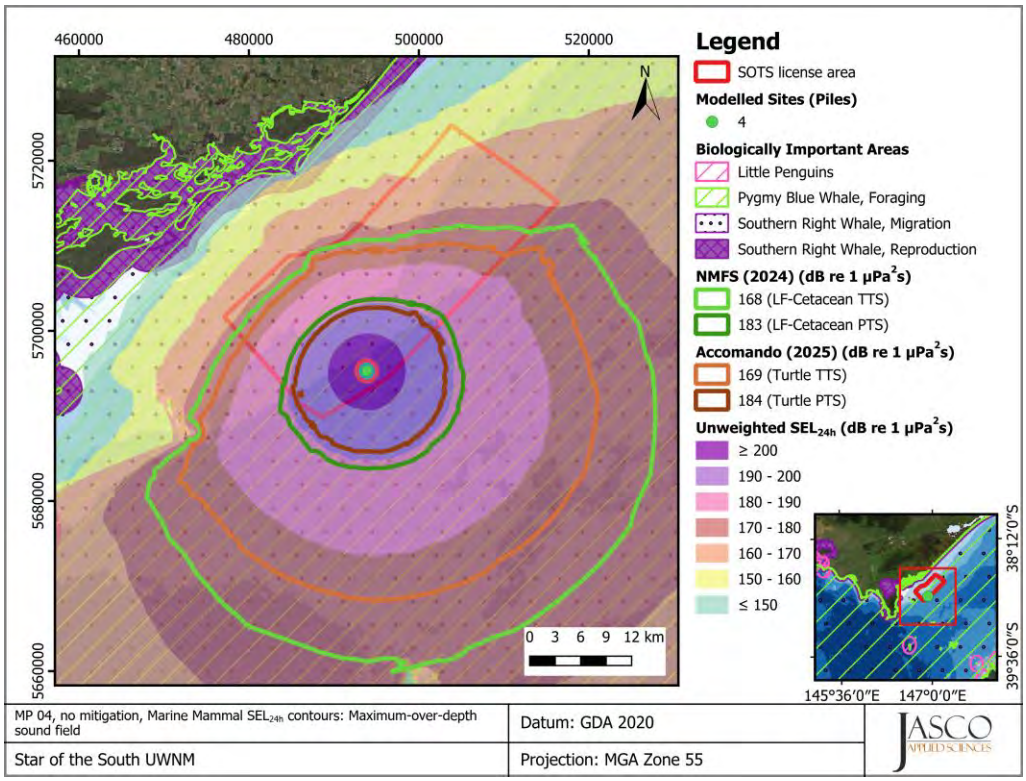


Figure 85. Monopile 4, unmitigated, accumulated SEL_{24h}: Sound level contour map showing maximum-over-depth SEL_{24h} results (unweighted/flat), along with frequency weighted isopleths for PTS and TTS in low-frequency cetaceans and sea turtles.

4.1.2.9. Scenario 9 – PULSE + DBBC + HSD (Fourth Modelling Round)

4.1.2.9.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented in the following tables.

Table 93. *Monopile 1, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Penetration depth (m)									
	12.8		16.5		20.3		24.0		27.8	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	–	–	–	–
180	–	–	0.02	0.02	0.06	0.06	0.07	0.07	0.06	0.06
170	0.07	0.06	0.09	0.09	0.19	0.13	0.31	0.29	0.29	0.27
162[a]	0.12	0.12	0.31	0.29	1.29	1.16	1.83	1.63	1.75	1.52
160	0.24	0.23	0.43	0.41	1.99	1.81	2.62	2.41	2.50	2.29
150	1.89	1.73	3.31	3.05	8.62	7.74	10.6	9.20	10.4	9.04
140	7.83	7.16	11.4	10.2	20.4	17.3	22.6	19.2	22.6	19.1
130	19.2	16.3	23.8	20.5	35.1	28.9	38.7	30.7	38.6	30.7

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 94. *Monopile 2, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Penetration depth (m)									
	14.6		18.2		21.9		25.5		29.1	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	–	–	–	–
180	0.05	0.05	0.03	0.03	0.03	0.03	0.05	0.05	0.05	0.05
170	0.13	0.13	0.10	0.10	0.12	0.12	0.13	0.13	0.20	0.20
162[a]	0.86	0.82	0.46	0.43	0.54	0.51	0.91	0.86	1.11	1.05
160	1.26	1.20	0.71	0.67	0.80	0.76	1.32	1.26	1.63	1.54
150	5.75	5.32	3.93	3.65	4.36	4.06	6.06	5.57	6.80	6.31
140	14.6	13.1	11.4	10.5	12.2	11.2	15.3	13.6	16.6	14.7
130	26.0	23.4	22.3	20.1	23.5	21.1	26.9	24.1	28.7	25.5

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 95. *Monopile 3, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Penetration depth (m)									
	17.1		23.3		29.4		35.6		41.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	–	–	–	–
180	–	–	0.03	0.03	0.03	0.03	0.04	0.04	0.05	0.05
170	0.07	0.07	0.09	0.09	0.09	0.09	0.11	0.11	0.12	0.12
162[a]	0.12	0.12	0.20	0.20	0.18	0.18	0.38	0.38	0.47	0.45
160	0.13	0.13	0.36	0.35	0.28	0.28	0.48	0.47	0.69	0.66
150	0.86	0.83	1.89	1.81	1.82	1.71	2.80	2.56	3.42	3.21
140	3.42	3.24	6.11	5.68	5.89	5.46	7.91	7.39	9.32	8.69
130	8.69	8.10	13.4	12.4	13.2	12.3	16.6	15.2	19.9	17.3

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 96. *Monopile 4, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Penetration depth (m)									
	13.0		19.0		24.9		30.9		36.9	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	–	–	–	–
180	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04
170	0.09	0.09	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13
162[a]	0.13	0.13	0.43	0.42	0.46	0.45	0.51	0.49	0.62	0.61
160	0.22	0.21	0.63	0.61	0.67	0.65	0.75	0.72	0.88	0.86
150	1.33	1.28	2.83	2.71	3.05	2.91	3.31	3.13	3.86	3.67
140	4.30	4.08	7.20	6.73	7.74	7.19	8.34	7.65	9.60	8.64
130	9.62	8.78	14.6	12.8	15.4	13.7	16.6	14.6	18.8	15.9

[a] Startle response level for squid (Fewtrell and McCauley 2012).

Table 97. *Monopile 1, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Penetration depth (m)									
	12.8		16.5		20.3		24.0		27.8	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	–	–	–	–	–	–	–	–
190	–	–	–	–	0.05	0.05	0.06	0.06	0.06	0.06
180	0.06	0.06	0.09	0.08	0.13	0.13	0.23	0.22	0.22	0.21
170	0.13	0.13	0.35	0.33	1.20	1.07	1.61	1.37	1.42	1.26
160	1.22	1.11	2.09	1.84	4.73	4.26	5.64	5.07	5.45	4.90
150	4.55	4.07	6.10	5.51	11.0	10.1	13.5	11.6	13.3	11.5
145[a]	7.02	6.32	9.05	8.32	17.2	14.6	20.3	16.8	20.2	16.8
140	10.2	9.34	14.3	12.4	25.0	21.2	28.4	23.3	28.5	23.3

[a] Human health assessment threshold derived from Parvin (2005).

Table 98. *Monopile 2, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Penetration depth (m)									
	14.6		18.2		21.9		25.5		29.1	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	–	–	–	–	–	–	–	–
190	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
180	0.13	0.13	0.09	0.09	0.09	0.09	0.13	0.13	0.13	0.13
170	0.98	0.93	0.54	0.52	0.64	0.61	1.02	0.96	1.22	1.16
160	4.47	4.22	3.01	2.86	3.30	3.13	4.55	4.31	5.18	4.89
150	11.4	10.6	9.03	8.41	9.65	8.95	11.7	11.0	12.7	11.9
145[a]	15.8	14.6	13.0	12.1	13.7	12.7	16.2	15.1	17.3	16.2
140	20.1	18.5	17.8	16.3	18.5	16.9	21.0	18.8	22.2	20.6

[a] Human health assessment threshold derived from Parvin (2005).

Table 99. *Monopile 3, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Penetration depth (m)									
	17.1		23.3		29.4		35.6		41.7	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	–	–	–	–	–	–	–	–
190	–	–	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03
180	0.06	0.06	0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.11
170	0.13	0.13	0.23	0.23	0.21	0.20	0.41	0.40	0.49	0.47
160	0.67	0.65	1.52	1.47	1.37	1.33	2.01	1.87	2.37	2.23
150	2.70	2.59	4.27	4.06	4.06	3.85	5.12	4.79	5.76	5.42
145[a]	4.25	4.05	6.23	5.84	6.01	5.61	7.55	6.93	8.64	7.88
140	6.11	5.76	8.89	8.14	8.71	7.91	10.5	9.64	12.8	11.1

[a] Human health assessment threshold derived from Parvin (2005).

Table 100. *Monopile 4, NAS – PULSE+DBBC+HSD, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Penetration depth (m)									
	13.0		19.0		24.9		30.9		36.9	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	–	–	–	–	–	–	–	–
190	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
180	0.09	0.09	0.10	0.10	0.11	0.10	0.12	0.11	0.12	0.12
170	0.15	0.14	0.51	0.49	0.57	0.54	0.60	0.58	0.68	0.67
160	1.09	1.05	2.22	2.16	2.34	2.26	2.43	2.33	2.72	2.60
150	3.45	3.33	5.44	5.12	5.63	5.28	5.80	5.42	6.36	5.92
145[a]	5.19	4.91	7.45	7.01	7.75	7.23	8.01	7.43	8.93	8.07
140	7.12	6.70	9.88	9.09	10.4	9.41	11.0	9.72	12.2	10.7

[a] Human health assessment threshold derived from Parvin (2005).

Table 101. *Monopile 1, NAS – PULSE+HSD+DBBC, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1									
		Penetration depth (m)									
		12.8		16.5		20.3		24.0		27.8	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	0.09	0.09	0.12	0.12	0.47	0.44	0.62	0.58	0.58	0.55
Sea turtle behavioural response [a]	166	0.39	0.37	0.72	0.68	2.34	2.08	2.95	2.61	2.82	2.42
Marine mammal behavioural response [b]	160	1.22	1.11	2.09	1.84	4.73	4.26	5.64	5.07	5.45	4.90
LF-cetacean weighted behavioural response [c]	160	0.09	0.09	0.09	0.09	0.37	0.34	0.51	0.47	0.50	0.42
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	2.29	2.12	3.23	2.99	6.13	5.67	7.17	6.60	6.97	6.38
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	15.9	13.7	21.2	17.9	32.1	27.2	36.6	29.3	36.2	29.1

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).

Table 102. *Monopile 2, NAS – PULSE+HSD+DBBC, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 2									
		Penetration depth (m)									
		14.6		18.2		21.9		25.5		29.1	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	0.36	0.34	0.14	0.14	0.22	0.21	0.37	0.36	0.46	0.44
Sea turtle behavioural response [a]	166	1.95	1.85	1.15	1.09	1.32	1.25	2.03	1.90	2.35	2.22
Marine mammal behavioural response [b]	160	4.47	4.22	3.01	2.86	3.30	3.13	4.55	4.31	5.18	4.89
LF-cetacean weighted behavioural response [c]	160	0.18	0.18	0.12	0.12	0.13	0.13	0.19	0.18	0.31	0.30
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	5.63	5.27	4.10	3.79	4.59	4.24	5.73	5.37	6.37	5.95
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	22.2	20.6	19.1	18.0	19.7	18.6	22.8	21.3	24.0	22.5

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).

Table 103. *Monopile 3, NAS – PULSE+HSD+DBBC, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 3									
		Penetration depth (m)									
		17.1		23.3		29.4		35.6		41.7	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	0.09	0.09	0.13	0.13	0.12	0.12	0.13	0.13	0.17	0.17
Sea turtle behavioural response [a]	166	0.19	0.19	0.61	0.59	0.47	0.46	0.87	0.83	1.12	1.08
Marine mammal behavioural response [b]	160	0.67	0.65	1.52	1.47	1.37	1.33	2.01	1.87	2.37	2.23
LF-cetacean weighted behavioural response [c]	160	0.09	0.09	0.12	0.12	0.11	0.11	0.13	0.13	0.13	0.13
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	0.92	0.88	2.13	2.00	2.01	1.80	2.83	2.54	3.21	2.94
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	8.53	7.91	11.8	11.0	11.6	10.8	13.8	12.8	16.2	14.4

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).

Table 104. *Monopile 4, NAS – PULSE+HSD+DBBC, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 4									
		Penetration depth (m)									
		13.0		19.0		24.9		30.9		36.9	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	0.10	0.10	0.17	0.17	0.19	0.19	0.21	0.21	0.28	0.27
Sea turtle behavioural response [a]	166	0.39	0.38	1.02	0.99	1.08	1.05	1.14	1.10	1.34	1.28
Marine mammal behavioural response [b]	160	1.09	1.05	2.22	2.16	2.34	2.26	2.43	2.33	2.72	2.60
LF-cetacean weighted behavioural response [c]	160	0.09	0.09	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	1.46	1.40	2.71	2.54	2.85	2.68	3.01	2.80	3.17	2.98
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	9.59	8.70	12.0	10.7	12.6	11.0	13.3	11.6	13.9	12.2

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).

Table 105. *Monopiles, NAS – PULSE+HSD+DBBC, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Monopile 1					Monopile 2					Monopile 3					Monopile 4				
		Penetration depth (m)					Penetration depth (m)					Penetration depth (m)					Penetration depth (m)				
		12.8	16.5	20.3	24.0	27.8	14.6	18.2	21.9	25.5	29.1	17.1	23.3	29.4	35.6	41.7	13.0	19.0	24.9	30.9	36.9
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS/AUD INJ																					
LF cetaceans	222	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HF cetaceans	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Otariid seals	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sea turtles	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Penguins	230	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
TTS																					
LF cetaceans	216	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
HF cetaceans	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Otariid seals	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sea turtles	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Penguins	224	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury																					
Fish I	213	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fish II, III Fish eggs and larvae	207	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 106. *Monopiles winter, NAS – PULSE+HSD+DBBC, winter, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from four monopiles to modelled seafloor peak acceleration magnitude level (m/s^2) thresholds for benthic invertebrates for each penetration depth.

Marine Fauna	Marine fauna Peak acceleration magnitude (m/s^2)	Monopile 1					Monopile 2					Monopile 3					Monopile 4				
		Penetration depth (m)					Penetration depth (m)					Penetration depth (m)					Penetration depth (m)				
		11.2	15.3	19.5	23.6	27.8	14.6	18.2	21.9	25.5	29.1	16.3	22.7	29.0	35.4	41.7	13.0	19.0	24.9	30.9	36.9
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Benthic invertebrates [b]	35.75	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] Day et al. (2016a) – Crustaceans and bivalves
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.1.2.9.2. Multiple–strike sound fields in winter

The multiple–strike sound fields for the modelling sites are presented below.

Table 107. *Monopiles, NAS – PULSE+HSD+DBBC, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
PTS									
LF cetaceans	183	0.77	1.49	0.41	0.51	0.18	0.10	0.36	0.38
HF cetaceans	193	–	*	–	*	–	*	–	*
Otariid seals	185	–	*	–	*	–	*	–	*
Sea turtles	184	0.09	0.03	0.09	0.03	0.09	0.03	0.09	0.03
Penguins	185	–	*	–	*	–	*	–	*
TTS									
LF cetaceans	168	8.61	175	5.48	81.0	3.30	25.4	3.56	34.2
HF cetaceans	178	–	*	–	*	–	*	–	*
Otariid seals	170	–	*	–	*	–	*	–	*
Sea turtles	169	1.14	2.79	0.75	1.25	0.36	0.40	0.39	0.47
Penguins	170	–	*	–	*	–	*	–	*

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
An asterisk indicates that the area was smaller than 0.0013 km²

Table 108. *Monopiles, NAS – PULSE+HSD+DBBC, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
Mortality and potential mortal injury									
I	219	0.03	0.00	0.02	0.00	0.03	0.00	0.03	0.00
II, Fish eggs and fish larvae	210	0.09	0.03	0.09	0.03	0.09	0.03	0.09	0.03
III	207	0.13	0.05	0.13	0.05	0.11	0.04	0.13	0.05
Fish recoverable injury									
I	216	0.05	0.01	0.04	0.01	0.05	0.01	0.06	0.01
II, III	203	0.35	0.35	0.30	0.28	0.13	0.06	0.24	0.18
Fish temporary threshold shift (TTS)									
I, II, III	186	7.82	148.2	5.63	86.1	3.05	26.5	3.74	40.5

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.1.2.9.3. Sound field maps

The following presents the sound field maps.

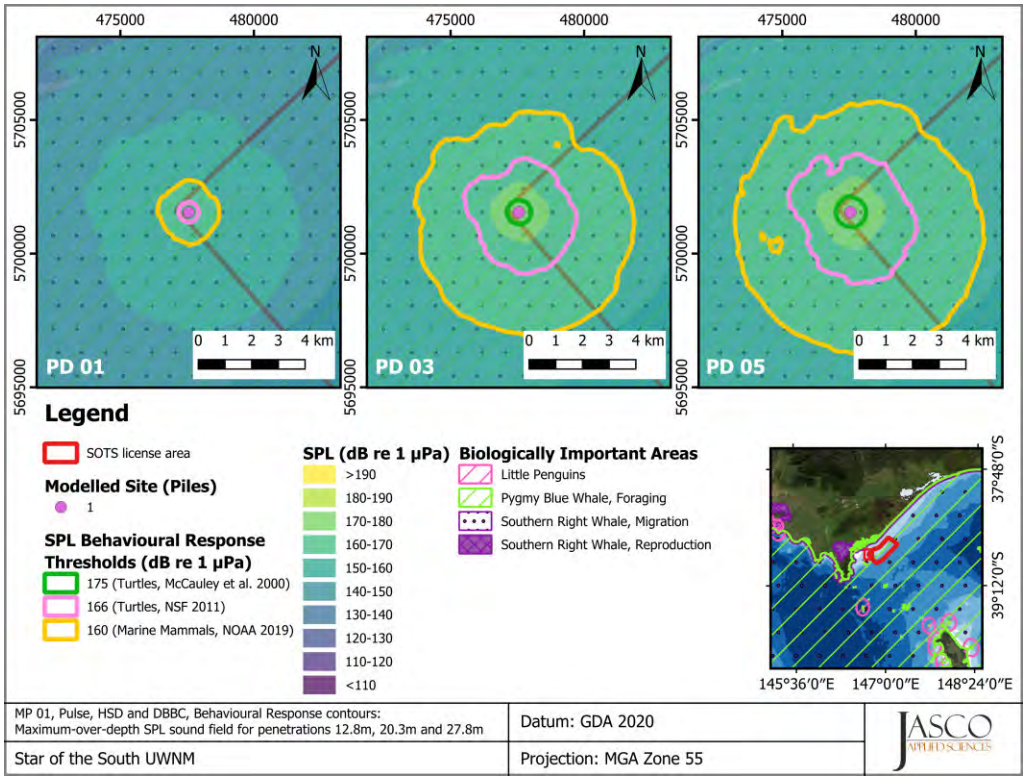


Figure 86. Monopile 1, PULSE+HSD+DBBC, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

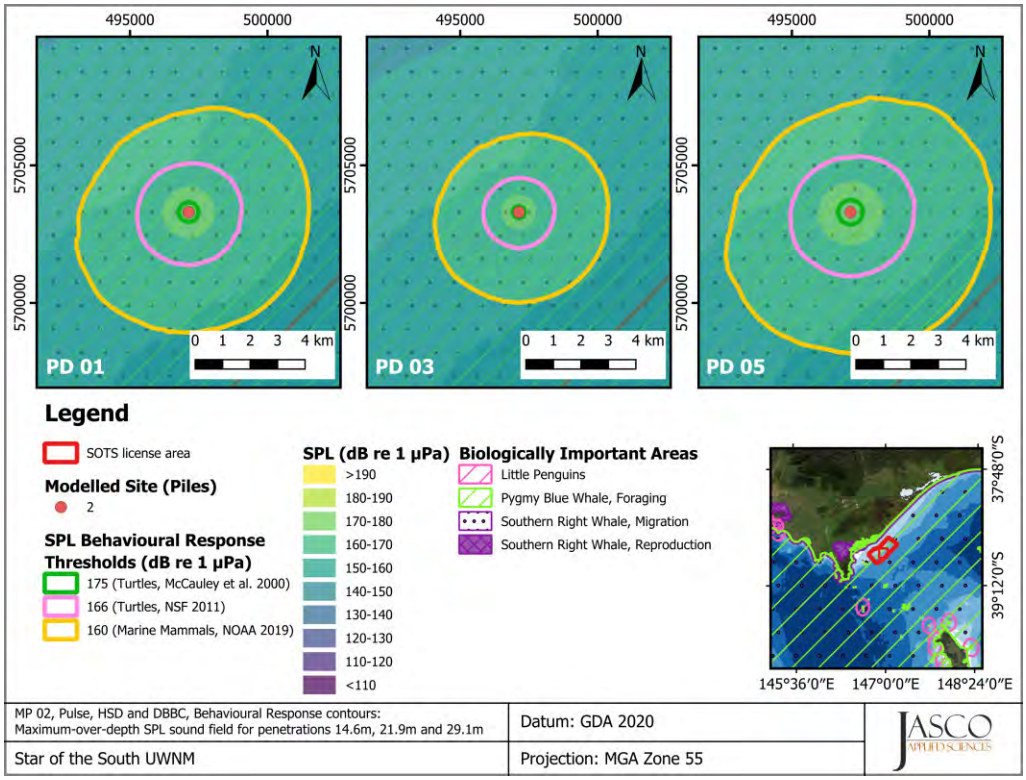


Figure 87. Monopile 2, PULSE+HSD+DBBC, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

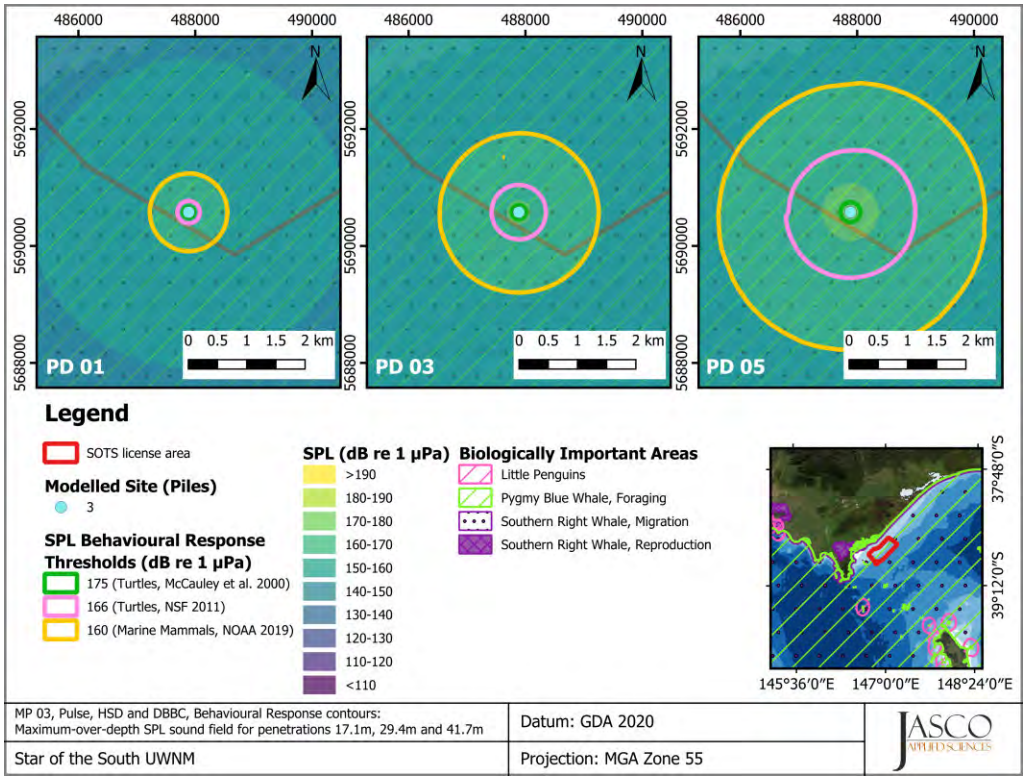


Figure 88. Monopile 3, PULSE+HSD+DBBC, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

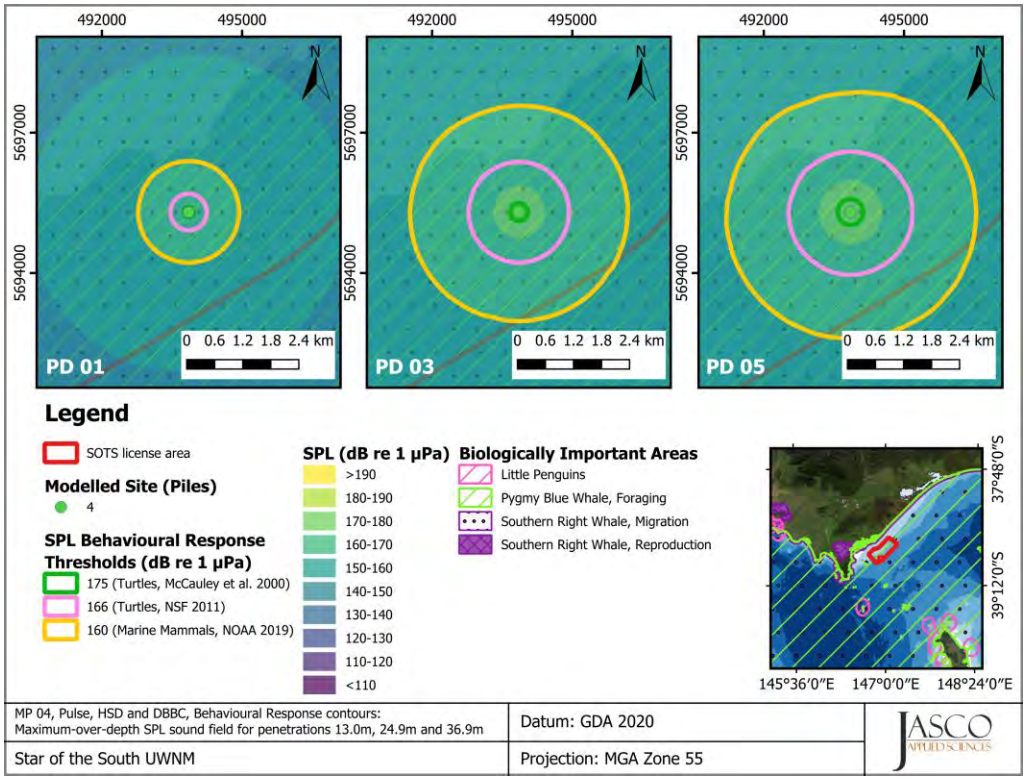


Figure 89. Monopile 4, PULSE+HSD+DBBC, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

Multiple strike maps are presented below:

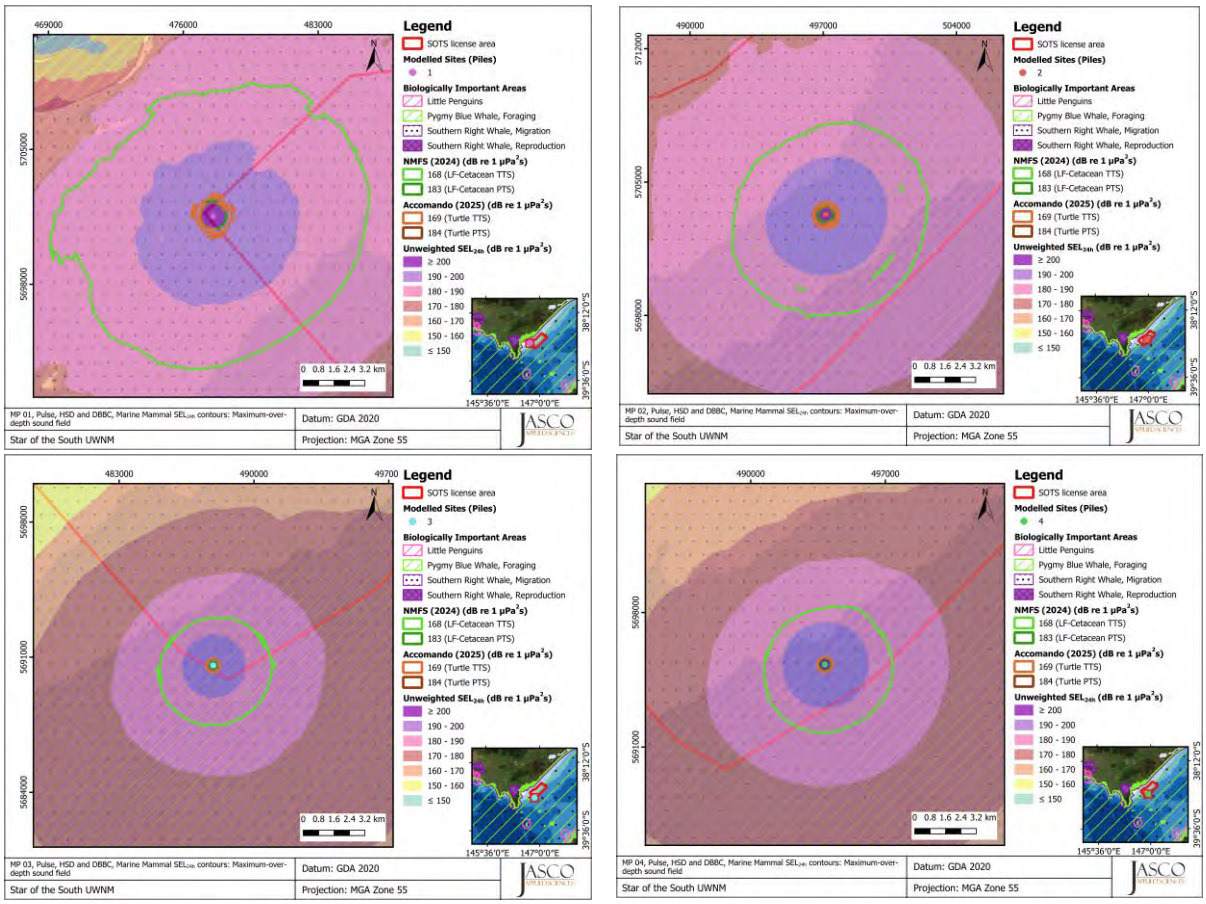


Figure 90. PULSE+HSD+DBBC, Monopile 1 (top left), Monopile 2 (top right), Monopile 3 (bottom left), Monopile 4 (bottom right), *accumulated SEL$_{24h}$*: Sound level contour map showing maximum-over-depth SEL$_{24h}$ results (unweighted/flat), along with frequency weighted isopleths for PTS and TTS in low-frequency cetaceans and sea turtles.

4.1.3. Results: Animal Movement Modelling

4.1.3.1. Scenario 2 – DBBC (First Modelling Round)

Exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) were calculated for pygmy blue, humpback, minke and southern right whales. A summary of radial distances to exposure thresholds for modelled species, along with probability of exposure for each monopile are included assuming the frequency dependent performance of a DBBC in the tables below. Note that dashes indicate that no animats were exposed above threshold. In addition, histograms of CPA ranges to SEL_{24h} PTS and TTS (Southall et al. 2021), NOAA (2019) SPL behavioural threshold and the Wood et al. (2012a) 50% behavioural threshold for migrating mysticetes (>140 d B re 1 µPa) at each site assuming a DBBC NAS are shown in Appendix E.1.1.1 for female pygmy blue whales, mother and calf humpback whale pairs, minke whales and mother and calf southern right whale pairs. Note that no female pygmy blue whale animats were exposed above threshold for PTS at Monopile 3. Additionally, Monopile 3 was located in water which was shallower than the minimum preferred depth for this species, resulting in CPA ranges that were > 1.5 km at these sites.

Table 109. *Winter, single pile SEL, advanced mitigation*: Exposure ranges ($ER_{95\%}$) in km from Monopiles 1 and 3 to permanent threshold shift (PTS) and temporary threshold shift (TTS) low-frequency marine mammal thresholds and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Species	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS				
Pygmy blue whale, female	0.55	81	–	–
Pygmy blue whale, male	0.54	78	–	–
Pygmy blue whale, migrating northbound	0.60	54	–	–
Pygmy blue whale, migrating southbound	0.61	58	–	–
Humpback whale, female nursing a calf	0.96	47	0.93	40
Humpback whale, no calf	1.02	29	0.94	41
Minke whale	0.67	67	0.70	77
Southern right whale, female nursing a calf	1.29	21	0.60	57
Southern right whale, no calf	0.69	40	0.54	55
TTS				
Pygmy blue whale, female	4.64	71	3.72	83
Pygmy blue whale, male	4.56	71	3.63	63
Pygmy blue whale, migrating northbound	4.99	61	0	0
Pygmy blue whale, migrating southbound	4.77	53	4.29	72
Humpback whale, female nursing a calf	5.35	51	3.79	65
Humpback whale, no calf	5.19	57	3.86	62
Minke whale	5.00	72	3.78	76
Southern right whale, female nursing a calf	5.18	56	3.85	66
Southern right whale, no calf	3.83	62	3.21	63

Table 110. *Winter, single pile PK, advanced mitigation*: Exposure ranges ($ER_{95\%}$) in km from Monopiles 1 and 3 to permanent threshold shift (PTS) and temporary threshold shift (TTS) low-frequency marine mammal thresholds and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Species	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS				
Pygmy blue whale, female	0.08	36	–	–
Pygmy blue whale, male	0.07	50	–	–
Pygmy blue whale, migrating northbound	0.02	50	–	–
Pygmy blue whale, migrating southbound	<0.01	100	–	–
Humpback whale, female nursing a calf	–	–	–	–
Humpback whale, no calf	0.02	50	–	–
Minke whale	0.03	60	<0.01	100
Southern right whale, female nursing a calf	–	–	–	–
Southern right whale, no calf	0.04	100	–	–
TTS				
Pygmy blue whale, female	0.09	67	–	–
Pygmy blue whale, male	0.07	75	–	–
Pygmy blue whale, migrating northbound	0.04	60	–	–
Pygmy blue whale, migrating southbound	0.05	40	–	–
Humpback whale, female nursing a calf	0.05	25	–	–
Humpback whale, no calf	0.03	33	–	–
Minke whale	0.06	83	0.08	67
Southern right whale, female nursing a calf	0.05	100	–	–
Southern right whale, no calf	0.06	50	0.07	33

Table 111. *Winter, single unweighted SPL, advanced mitigation*: Exposure ranges ($ER_{95\%}$) in km from Monopiles 1 and 3 to the NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal threshold and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Species	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy blue whale, female	6.22	87	6.11	98
Pygmy blue whale, male	6.19	90	6.00	91
Pygmy blue whale, migrating northbound	5.40	81	6.21	70
Pygmy blue whale, migrating southbound	4.99	88	5.75	92
Humpback whale, female nursing a calf	5.84	86	5.70	81
Humpback whale, no calf	5.84	89	5.92	76
Minke whale	5.83	87	5.67	83
Southern right whale, female nursing a calf	5.02	89	5.26	83
Southern right whale, no calf	5.10	85	5.30	85

Table 112. *Winter, non-migrating, single pile LF-weighted SPL, advanced mitigation*: Exposure ranges ($ER_{95\%}$) in km from Monopiles 1 and 3 to the Wood et al. (2012a) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa) and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Species	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy blue whale, female	1.53	83	–	–
Pygmy blue whale, male	1.57	83	–	–
Pygmy blue whale, migrating northbound	1.63	78	–	–
Pygmy blue whale, migrating southbound	1.50	81	–	–
Humpback whale, female nursing a calf	1.49	81	1.67	92
Humpback whale, no calf	1.39	82	1.60	87
Minke whale	1.40	84	1.56	89
Southern right whale, female nursing a calf	1.54	79	1.63	80
Southern right whale, no calf	1.49	73	1.53	90

Table 113. *Winter, migrating, single pile LF-weighted SPL, advanced mitigation*: Exposure ranges ($ER_{95\%}$) in km from Monopiles 1 and 3 to the Wood et al. (2012a) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa) and probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp} (%)) are provided.

Species	Monopile 1 (DBBC)		Monopile 3 (DBBC)	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy blue whale, female	8.39	79	8.24	92
Pygmy blue whale, male	8.12	84	8.30	93
Pygmy blue whale, migrating northbound	7.54	59	8.46	81
Pygmy blue whale, migrating southbound	7.17	86	8.17	84
Humpback whale, female nursing a calf	7.83	76	8.01	67
Humpback whale, no calf	7.60	79	8.07	66
Minke whale	7.48	80	7.65	81
Southern right whale, female nursing a calf	7.62	75	8.03	65
Southern right whale, no calf	7.21	76	7.92	68

4.1.3.2. Scenario 5 – DBBC (Second Modelling Round)

Exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) were calculated for pygmy blue, humpback, minke and southern right whales. A summary of radial distances to exposure thresholds for modelled species, along with probability of exposure for each monopile are included assuming the frequency dependent performance of a DBBC in the tables below. Note that dashes indicate that no animats were exposed above threshold. In addition, histograms for this scenario are presented in Appendix E.1.1.2.

Table 114. *Monopile installation, DBBC attenuation, LF-weighted SEL_{24h}*: Exposure ranges ($ER_{95\%}$) in km from each Site to permanent threshold shift (PTS) and temporary threshold shift (TTS) low-frequency marine mammal thresholds.

Species	Site 1 - Monopile 1		Site 2 - Monopile 2	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS				
Pygmy blue whale, female	0.22	90	–	–
Pygmy blue whale, male	0.26	68	–	–
Humpback whale, female nursing a calf	0.44	80	1.12	39
Humpback whale, no calf	0.56	39	1.05	44
Southern right whale, female nursing a calf	0.48	42	0.90	54
Southern right whale, no calf	0.15	>99	0.58	71
Pygmy blue whale, migrating northbound	0.17	62	–	–
Pygmy blue whale, migrating southbound	0.12	92	–	–
Minke whale	0.11	>99	0.52	73
TTS				
Pygmy blue whale, female	3.57	73	4.75	8
Pygmy blue whale, male	3.41	78	4.90	22
Humpback whale, female nursing a calf	3.23	66	4.06	71
Humpback whale, no calf	3.35	60	3.86	71
Southern right whale, female nursing a calf	2.83	67	4.01	66
Southern right whale, no calf	2.46	72	3.45	80
Pygmy blue whale, migrating northbound	2.95	77	5.08	13
Pygmy blue whale, migrating southbound	3.14	69	–	–
Minke whale	2.38	77	3.47	83

Table 115. *Monopile installation, DBBC attenuation, unweighted PK*: Exposure ranges ($ER_{95\%}$) in km from each Site to permanent threshold shift (PTS) and temporary threshold shift (TTS) low-frequency marine mammal thresholds.

Species	Site 1 - Monopile 1		Site 2 - Monopile 2	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS				
Pygmy blue whale, female	–	–	–	–
Pygmy blue whale, male	0.06	33	–	–
Humpback whale, female nursing a calf	–	–	–	–
Humpback whale, no calf	–	–	–	–
Southern right whale, female nursing a calf	–	–	–	–
Southern right whale, no calf	–	–	–	–
Pygmy blue whale, migrating northbound	–	–	–	–
Pygmy blue whale, migrating southbound	<0.01	>99	–	–
Minke whale	<0.01	>99	–	–
TTS				
Pygmy blue whale, female	0.06	80	–	–
Pygmy blue whale, male	0.07	>99	–	–
Humpback whale, female nursing a calf	–	–	–	–
Humpback whale, no calf	–	–	–	–
Southern right whale, female nursing a calf	<0.01	>99	–	–
Southern right whale, no calf	–	–	–	–
Pygmy blue whale, migrating northbound	0.02	>99	–	–
Pygmy blue whale, migrating southbound	<0.01	>99	–	–
Minke whale	0.08	33	0.05	75

Table 116. *Monopile installation, DBBC attenuation, unweighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each Site to the NOAA (2019) 160 dB re 1 µPa behavioural response marine mammal threshold.

Species	Site 1 - Monopile 1		Site 2 - Monopile 2	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy blue whale, female	4.58	91	6.06	72
Pygmy blue whale, male	4.67	88	6.02	78
Humpback whale, female nursing a calf	4.20	80	5.50	78
Humpback whale, no calf	4.03	87	5.52	76
Southern right whale, female nursing a calf	3.45	91	5.15	81
Southern right whale, no calf	3.62	87	5.19	81
Pygmy blue whale, migrating northbound	3.61	94	5.87	72
Pygmy blue whale, migrating southbound	3.67	92	5.98	44
Minke whale	4.16	92	5.39	83

Table 117. *Monopile installation, DBBC attenuation, non-migrating, LF-weighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each Site to the Wood et al. (2012a) 50% behavioural response threshold for non-migrating mysticetes (>160 dB re 1 µPa).

Species	Site 1 - Monopile 1		Site 2 - Monopile 2	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy blue whale, female	0.89	95	–	–
Pygmy blue whale, male	0.98	91	–	–
Humpback whale, female nursing a calf	1.05	75	1.63	80
Humpback whale, no calf	0.93	88	1.52	87
Southern right whale, female nursing a calf	0.97	82	1.53	84
Southern right whale, no calf	0.94	88	1.49	89
Pygmy blue whale, migrating northbound	0.92	93	–	–
Pygmy blue whale, migrating southbound	0.95	83	–	–
Minke whale	0.82	90	1.54	86

Table 118. *Monopile installation, DBBC attenuation, migrating, LF-weighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each Site to the Wood et al. (2012a) 50% behavioural response threshold for migrating mysticetes (>140 dB re 1 µPa).

Species	Site 1 - Monopile 1		Site 2 - Monopile 2	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy blue whale, female	6.45	81	7.02	83
Pygmy blue whale, male	6.45	81	7.05	83
Humpback whale, female nursing a calf	6.09	78	6.45	88
Humpback whale, no calf	6.11	76	6.57	85
Southern right whale, female nursing a calf	6.04	74	6.09	90
Southern right whale, no calf	5.80	79	6.16	89
Pygmy blue whale, migrating northbound	5.80	82	6.58	81
Pygmy blue whale, migrating southbound	5.67	86	6.55	71
Minke whale	5.56	86	6.70	88

4.1.3.3. Scenario 9 – PULSE + DBBC + HSD (Fourth Modelling Round)

Exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) were calculated for pygmy blue, humpback, minke and southern right whales. A summary of radial distances to exposure thresholds for modelled species, along with probability of exposure for each monopile are included assuming the frequency dependent performance of a DBBC+HSD+PULSE in the tables below. Note that dashes indicate that no animats were exposed above threshold. In addition, histograms for this scenario are presented in Appendix E.1.1.3.

Table 119. *Monopile installation – NAS, PULSE+DBBC+HSD, LF-weighted SEL_{24h}*: Exposure ranges ($ER_{95\%}$) in km from each Site to permanent threshold shift (PTS) and temporary threshold shift (TTS) low-frequency marine mammal thresholds.

Species	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS								
Pygmy Blue Whale, Feeding	–	–	0.03	14	0.04	25	0.06	15
Pygmy Blue Whale, Northbound Migrating	–	–	–	–	–	–	–	–
Pygmy Blue Whale, Southbound Migrating	–	–	–	–	–	–	–	–
Humpback Whale, Migrating with Calf	–	–	–	–	–	–	–	–
Humpback Whale, Migrating without Calf	0.20	5	–	–	0.02	>99	–	–
Minke Whale, Migrating	–	–	–	–	–	–	–	–
Southern Right Whale, Migrating with Calf	–	–	–	–	0.05	17	–	–
Southern Right Whale, Migrating without Calf	–	–	–	–	–	–	–	–
TTS								
Pygmy Blue Whale, Feeding	4.60	53	2.28	82	1.34	74	0.86	61
Pygmy Blue Whale, Northbound Migrating	4.21	2	1.21	71	0.43	59	0.35	55
Pygmy Blue Whale, Southbound Migrating	–	–	1.22	64	0.47	51	0.49	34
Humpback Whale, Migrating with Calf	4.27	25	2.45	20	1.48	14	1.43	11
Humpback Whale, Migrating without Calf	4.13	22	2.37	17	1.33	14	1.33	10
Minke Whale, Migrating	1.42	58	0.57	61	0.27	22	0.08	74
Southern Right Whale, Migrating with Calf	1.49	58	0.84	40	0.44	24	0.37	30
Southern Right Whale, Migrating without Calf	1.32	49	0.50	58	0.16	59	0.28	31

Table 120. *Monopile installation – NAS, PULSE+HSD+DBBC, unweighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each site to the NOAA (2019) 160 dB re 1 µPa behavioural response marine mammal threshold.

Species	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)

Pygmy Blue Whale, Feeding	5.20	74	4.65	84	2.38	91	2.08	74
Pygmy Blue Whale, Northbound Migrating	4.86	64	3.49	78	1.88	71	1.43	63
Pygmy Blue Whale, Southbound Migrating	5.16	20	3.35	84	1.83	75	1.53	63
Humpback Whale, Migrating with Calf	4.70	73	4.23	76	2.24	77	1.77	74
Humpback Whale, Migrating without Calf	4.79	71	4.33	82	2.20	81	1.84	73
Minke Whale, Migrating	4.68	73	4.40	89	2.29	87	1.83	74
Southern Right Whale, Migrating with Calf	4.27	72	3.37	88	1.74	84	1.48	65
Southern Right Whale, Migrating without Calf	4.49	73	3.56	91	1.86	83	1.46	69

Table 121. *Monopile installation – NAS, PULSE+HSD+DBBC, LF-weighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each site to the Wood et al. (2012a) 50% chance of behavioural response for non-migrating (> 160 dB re 1 µPa) and migrating (> 140 dB re 1 µPa) mysticetes.

Species	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Non-migrating								
Pygmy Blue Whale, Feeding	–	–	0.27	65	0.12	94	0.12	69
Pygmy Blue Whale, Northbound Migrating	–	–	0.13	43	0.10	71	0.09	74
Pygmy Blue Whale, Southbound Migrating	–	–	0.15	54	0.08	90	0.10	75
Humpback Whale, Migrating with Calf	0.40	54	0.09	80	0.10	80	0.10	25
Humpback Whale, Migrating without Calf	0.42	71	0.15	58	0.11	42	0.08	40
Minke Whale, Migrating	0.44	65	0.21	75	0.10	90	0.09	82
Southern Right Whale, Migrating with Calf	0.40	54	0.11	79	0.07	>99	0.08	75
Southern Right Whale, Migrating without Calf	0.31	64	0.11	73	0.06	88	0.09	61
Migrating								
Pygmy Blue Whale, Feeding	6.57	81	5.58	91	2.77	90	2.75	72
Pygmy Blue Whale, Northbound Migrating	5.84	76	4.49	88	2.29	83	2.32	69
Pygmy Blue Whale, Southbound Migrating	6.30	40	4.53	87	2.34	82	2.43	68
Humpback Whale, Migrating with Calf	6.14	80	5.07	85	2.35	90	2.58	75
Humpback Whale, Migrating without Calf	6.33	78	5.13	90	2.36	89	2.52	79
Minke Whale, Migrating	6.27	79	5.20	95	2.49	89	2.41	77
Southern Right Whale, Migrating with Calf	5.68	82	4.55	91	2.35	85	2.41	70
Southern Right Whale, Migrating without Calf	5.95	83	4.69	93	2.31	87	2.35	74

4.2. Jacket Pile Installation Operations

The table below provides a summary of the different scenarios included in Sections 4.2.2 and 4.2.3.

Table 122. Summary of the modelled impact piling (jacket pile) scenarios presented in the sections below. OSS: Offshore substation

Scenario	Operation	Mitigation	Modelling round	Site description (water depth)	Max. pile diameter	Hammer model	Season	Results presented	Sound source parameters	Noise effect threshold
1	Impact piling: Jacket Pile	None	First	OSS centre (24 m)	3.25 m	IHC S-2300	Winter	Acoustic	Appendix C.2.3.1	Southall et al. 2019
2		DBBC	First	OSS centre (24 m)		IHC S-2300		Acoustic	Appendix C.2.3.1	Southall et al. 2019
3		None	Second	OSS (30 m)		MHU 3500S		Acoustic	Appendix C.2.3.1	Southall et al. 2019
4		DBBC	Second	OSS (30 m)		MHU 3500S		Acoustic	Appendix C.2.3.1	Southall et al. 2019
5		DBBC + PULSE	Fourth	OSS (30 m)		MHU 3500S		Acoustic, Animat	Appendix C.2.3.1 Appendix C.2.3.3	NMFS 2024

4.2.1. Parameterisation and Methodology: Jacket Piles

The impact hammers considered for the studies were selected to match the driveability study provided by Star of the South and was used for the OSS jacket pile installation modelling scenarios. Tables summarising the general specifications of the jacket piles extracted from the driveability study as pertaining to the modelled pile driving site are presented in Appendix C.2.3 for each modelling round. Like the monopiles, the parameters for a seabed with strong mechanical resistance were selected for acoustic modelling as part of a likely worst-case and conservative modelling approach.

For the OSS jacket piles, the hammer penetration/hammering values used in this acoustic modelling study was developed in considering the driveability study provided by the Star of the South, which included number the strikes and applied hammer energy per metre of the pile drive. The same approach as described above was employed to determine the penetration depth, strike count and hammer energy used for acoustic modelling, which are presented in Appendix C.2.3, along with tables presenting the pile geometry used by GRLWEAP, PDSM, and figures of the hammer forcing function for the hammers from GRLWEAP.

4.2.2. Results: Acoustic Modelling

Received levels at 10 m – Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. The figures below show the decidecade–band levels for the receiver with the highest SEL at a horizontal range of 10 m, for the considered pile and for each of the modelled penetrations per modelling round. The levels above 1500 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of impact pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports and literature, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

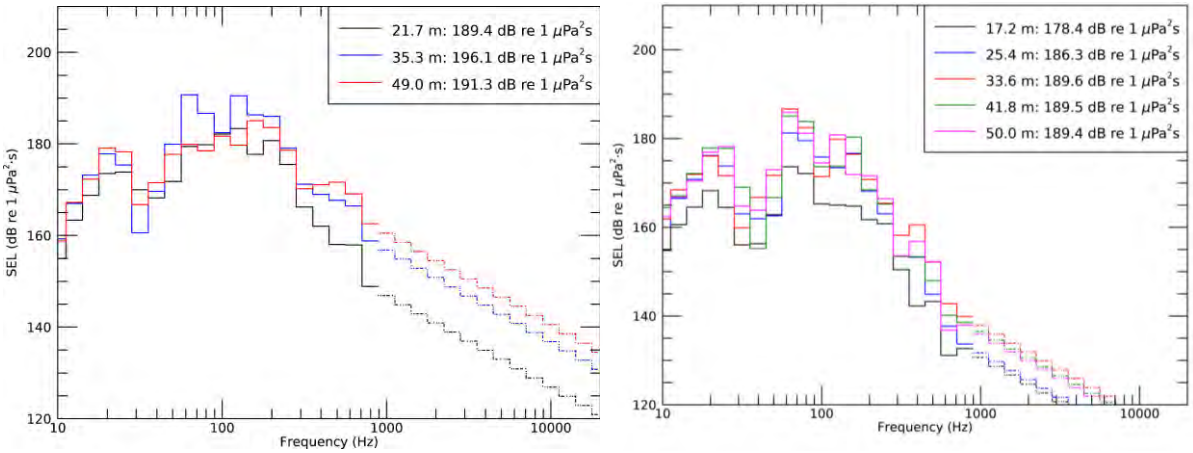


Figure 91. *Jacket Pile 1, winter, first modelling round (left) and second modelling round (right)*: Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the IHC S2300 hammer, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 μPa²·s.

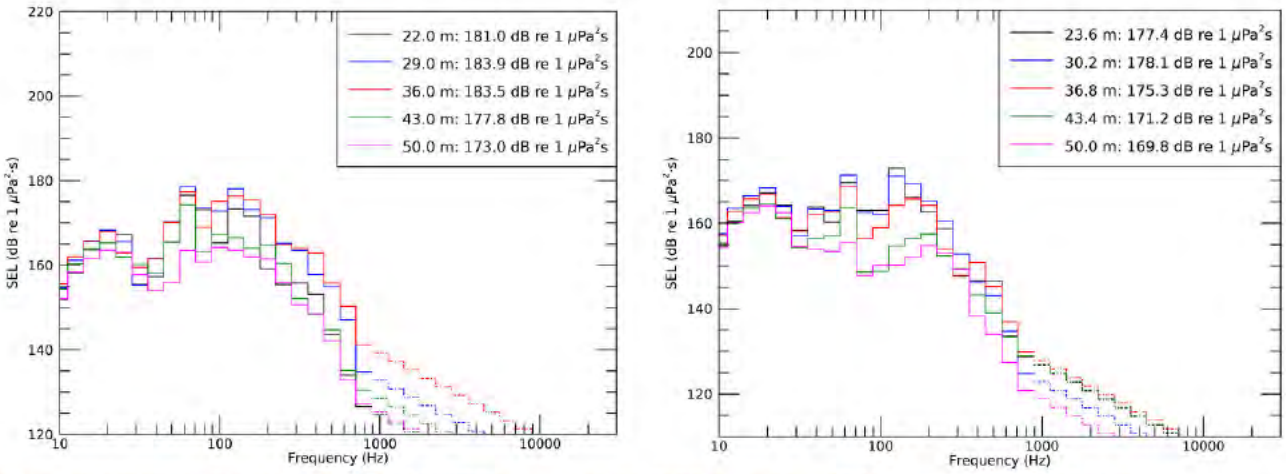


Figure 92. *OSS Jacket Pile using* MHU 3500S hammer (left), *OSS Jacket Pile* IQ4 hammer with the PULSE hammer (right), *winter, fourth modelling round:* Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for impact pile driving using the, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 µPa²·s.

4.2.2.1. Scenario 1 – Unmitigated (First Modelling Round)

4.2.2.1.1. Per–strike sound fields in winter

The modelled per–strike sound fields are presented below. The results are presented in terms of per–strike SPL, SEL and PK sound fields.

Vertical slice plots of the SPL sound field are presented in Appendix F.1.1.1 for a jacket pile considering all penetration depths. The orientation of the slice transects are such that the first bearing listed in the caption corresponds with the positive distance and the second bearing corresponds with the negative distances.

Table 123. *Sub–station jacket pile, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Single Jacket Pile					
	Penetration depth (m)					
	21.7		35.3		49.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	0.03	0.03	0.04	0.04
180	0.09	0.09	0.23	0.23	0.17	0.17
170	0.62	0.61	1.17	1.14	1.00	0.95
162[a]	1.96	1.88	3.32	3.19	2.76	2.62
160	2.42	2.31	4.14	3.95	3.34	3.17
150	5.91	5.63	10.76	9.76	7.20	6.81
140	14.3	12.7	49.2	32.8	14.0	12.5
130	51.3	40.4	90.0	86.3	49.6	33.1

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 124. *Sub–station jacket pile, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from a pile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Single Jacket Pile					
	Penetration depth (m)					
	21.7		35.3		49.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	0.03	0.03	0.02	0.02
190	0.07	0.07	0.17	0.17	0.16	0.15
180	0.52	0.51	1.00	0.98	0.75	0.72
170	2.00	1.90	3.36	3.21	2.48	2.33
160	4.72	4.48	8.62	8.06	5.52	5.25
150	10.9	9.80	29.6	26.7	9.84	9.24
145[a]	18.6	16.6	51.9	45.5	16.2	14.5
140	49.1	31.7	86.1	74.9	29.2	26.0
130	>90.0	/	>90.0	/	87.1	79.4

[a] Human health assessment threshold derived from Parvin (2005).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 125. *Sub–station jacket pile, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from a pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL; dB threshold (L_p; re 1 µPa)	Single Jacket Pile					
		Penetration depth (m)					
		21.7		35.3		49.0	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	1.07	1.04	1.87	1.81	1.46	1.37
Sea turtle behavioural response [a]	166	2.70	2.59	5.00	4.78	3.52	3.33
Marine mammal behavioural response [c]	160	4.72	4.48	8.62	8.06	5.52	5.25
LF-cetacean weighted behavioural response [d]	160	2.82	2.71	4.98	4.74	2.83	2.66
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	18.6	16.6	53.0	48.4	14.5	12.6
Penguin behavioural response [e]	120	10.7	9.5	29.3	26.4	14.4	12.6

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 126. Sub–station jacket pile, winter, PTS and TTS PK thresholds: Maximum (Rmax) horizontal distances (km) from a pile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Single Jacket Pile		
		Penetration depth (m)		
		21.7	35.3	49.0
		R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS				
LF cetaceans	219	–	–	–
HF cetaceans	230	–	–	–
Otariid seals	232	–	–	–
Sea turtles	232	–	–	–
Penguins	232	–	–	–
TTS				
LF cetaceans	213	0.02	0.03	0.02
HF cetaceans	224	–	–	–
Otariid seals	226	–	–	–
Sea turtles	226	–	–	–
Penguins	226	–	–	–
Mortality and potential mortal injury / recoverable injury				
Fish I	213	0.02	0.03	0.02
Fish II, III Fish eggs and larvae	207	0.06	0.10	0.06

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.2.2.1.2. Multiple–strike sound fields in winter

The modelled multiple–strike sound fields are presented below.

Table 127. *Sub–station jacket pile, winter, accumulated SEL*: Maximum (*Rmax*) and 95% ($R95_{\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		4 Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	8.06	7.55	16.0	14.2
HF cetaceans	185	–	–	0.02	0.02
Otariid seals	203	–	–	0.04	0.04
Sea turtles	204	1.62	1.49	3.05	2.91
Penguins	203	–	–	0.04	0.04
TTS					
LF cetaceans	168	53.3	47.5	>90.0	85.4
HF cetaceans	170	0.13	0.13	0.40	0.37
Otariid seals	188	0.23	0.22	0.61	0.60
Sea turtles	189	7.05	6.59	13.1	11.8
Penguins	188	0.23	0.22	0.61	0.60

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 128. *Sub–station jacket pile, winter, fish, accumulated SEL*: Maximum (*Rmax*) and 95% ($R95_{\%}$) horizontal distances (in km) from each pile to SEL24h based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		4 Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.22	0.21	0.60	0.58
II, Fish eggs and fish larvae	210	1.00	0.96	2.15	2.05
III	207	1.40	1.35	2.93	2.79
Fish recoverable injury					
I	216	0.37	0.36	1.00	0.96
II, III	203	2.35	2.25	4.27	4.08
Fish temporary threshold shift (TTS)					
I, II, III	186	10.5	9.74	20.0	18.0

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.1.3. Sound field maps

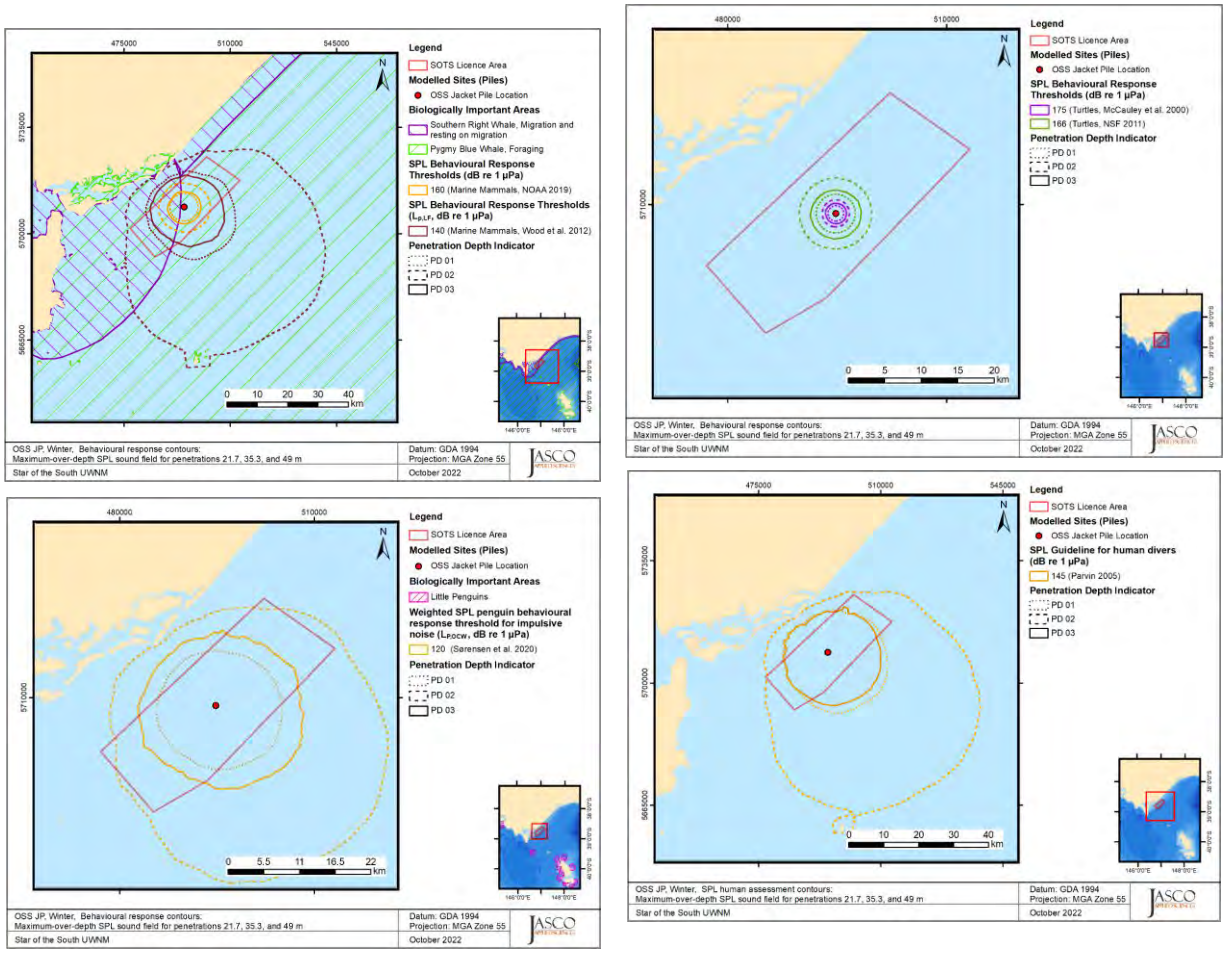


Figure 93. *OSS Jacket Pile, winter, marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL: Sound level contour map showing maximum–over–depth results for all penetration depths*.

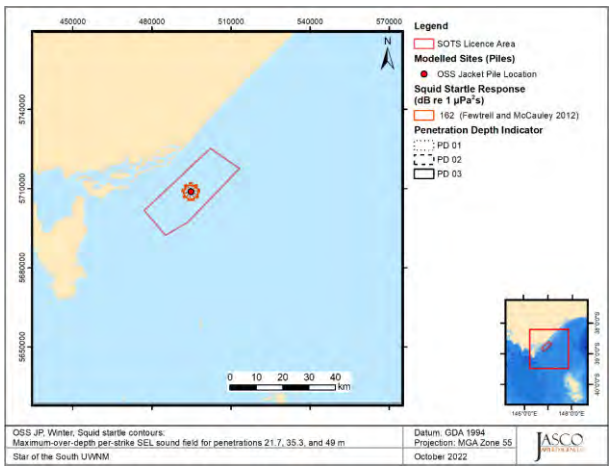


Figure 94. *OSS Jacket Pile, winter, squid* startle response criteria*, per–strike SEL*: *Sound level contour map showing maximum–over–depth results for all penetration depths*.

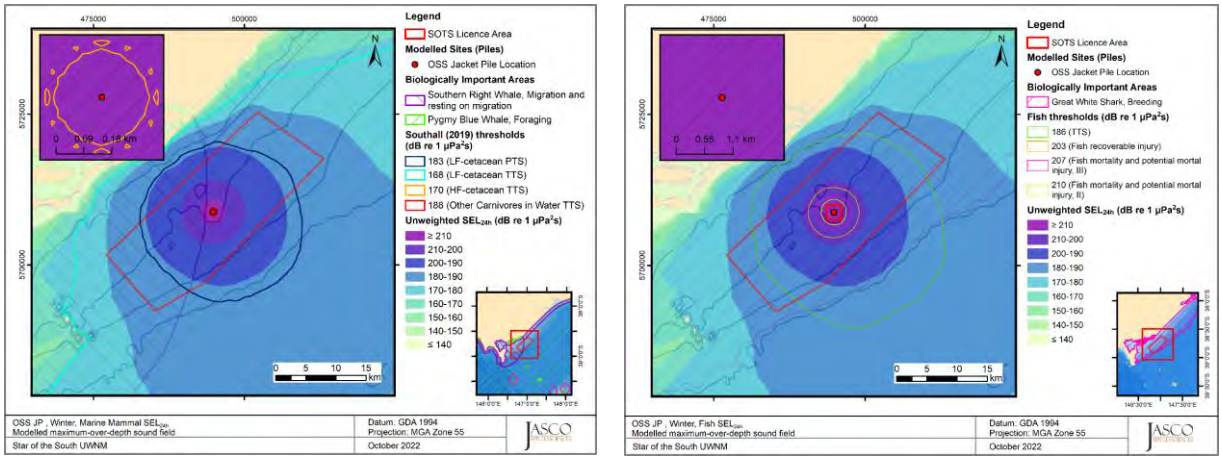


Figure 95. *OSS Jacket Pile, winter, marine mammals (left) and fish (right), SEL_{24h}*: Contour map showing maximum–over–depth unweighted SEL_{24h} isopleths.

4.2.2.2. Scenario 2 – DBBC (First Modelling Round)

4.2.2.2.1. Per–strike sound fields in winter

The modelled per–strike sound fields are presented below. The results are presented in terms of per–strike SPL, SEL, and PK sound fields.

Table 129. *Sub–station jacket pile, NAS – DBBC, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa^2·s)	Single Jacket Pile (DBBC)					
	Penetration depth (m)					
	21.7		35.3		49.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	0.03	0.03	0.04	0.04
180	0.09	0.09	0.10	0.1	0.11	0.11
170	0.12	0.12	0.28	0.27	0.31	0.3
162[a]	0.27	0.27	0.99	0.95	1.03	0.99
160	0.36	0.34	1.25	1.19	1.35	1.29
150	1.61	1.51	3.68	3.48	3.85	3.64
140	4.58	4.27	7.21	6.84	7.48	7.09
130	8.58	8.03	12.3	11.3	12.6	11.6

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 130. *Sub–station jacket pile, NAS – DBBC, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from a pile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Single Jacket Pile (DBBC)					
	Penetration depth (m)					
	21.7		35.3		49.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	0.03	0.03	0.02	0.02
190	0.07	0.07	0.10	0.09	0.10	0.10
180	0.12	0.12	0.26	0.26	0.29	0.28
170	0.29	0.28	1.00	0.97	0.97	0.94
160	1.20	1.15	2.92	2.76	2.75	2.52
150	3.46	3.23	6.28	5.87	6.01	5.61
145[a]	5.07	4.75	8.22	7.66	8.12	7.53
140	7.04	6.56	10.3	9.54	10.4	9.56
130	12.0	10.8	16.3	14.8	17.0	15.3

[a] Human health assessment threshold derived from Parvin (2005).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 131. *Sub–station jacket pile, NAS – DBBC, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from a pile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL; dB threshold (L_p; re 1 µPa)	Single Jacket Pile (DBBC)					
		Penetration depth (m)					
		21.7		35.3		49.0	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.13	0.13	0.48	0.47	0.58	0.56
Sea turtle behavioural response [a]	166	0.60	0.58	1.49	1.44	1.47	1.42
Marine mammal behavioural response [c]	160	1.20	1.15	2.92	2.76	2.75	2.52
LF-cetacean weighted behavioural response [d]	160	0.40	0.38	1.07	1.03	1.19	1.13
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	3.37	3.06	5.89	5.52	5.53	5.08
Penguin behavioural response [e]	120	1.57	1.50	2.79	2.61	2.85	2.54

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 132. *Sub–station jacket pile, NAS – DBBC, winter*, PTS and TTS PK thresholds: Maximum (Rmax) horizontal distances (km) from a pile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Single Jacket Pile (DBBC)		
		Penetration depth (m)		
		21.7	35.3	49.0
		R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS				
LF cetaceans	219	–	–	–
HF cetaceans	230	–	–	–
Otariid seals	232	–	–	–
Sea turtles	232	–	–	–
Penguins	232	–	–	–
TTS				
LF cetaceans	213	0.02	0.03	0.04
HF cetaceans	224	–	–	–
Otariid seals	226	–	–	–
Sea turtles	226	–	–	–
Penguins	226	–	–	–
Mortality and potential mortal injury / recoverable injury				
Fish I	213	0.02	0.03	0.04
Fish II, III Fish eggs and larvae	207	0.06	0.09	0.08

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.2.2.2.2. Multiple–strike sound fields in winter

The modelled multiple–strike sound fields are presented below.

Table 133. *Sub–station jacket pile, winter, NAS – DBBC, accumulated SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile (DBBC)		4 Jacket Piles (DBBC)	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	2.72	2.40	4.31	3.86
HF cetaceans	185	–	–	0.02	0.02
Otariid seals	203	–	–	0.04	0.04
Sea turtles	204	0.58	0.58	1.20	0.93
Penguins	203	–	–	0.04	0.04
TTS					
LF cetaceans	168	7.21	6.70	9.87	9.12
HF cetaceans	170	0.09	0.09	0.09	0.09
Otariid seals	188	0.09	0.09	0.13	0.13
Sea turtles	189	2.59	2.32	4.18	3.83
Penguins	188	0.09	0.09	0.13	0.13

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 134. *Sub–station jacket pile, winter, NAS – DBBC, fish, accumulated SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile (DBBC)		4 Jacket Piles (DBBC)	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.09	0.09	0.19	0.19
II, Fish eggs and fish larvae	210	0.29	0.28	0.68	0.66
III	207	0.39	0.38	0.95	0.92
Fish recoverable injury					
I	216	0.13	0.13	0.29	0.28
II, III	203	0.86	0.68	1.58	1.53
Fish temporary threshold shift (TTS)					
I, II, III	186	4.78	4.48	6.96	6.59

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.2.3. Sound field maps

The following presents the contour maps:

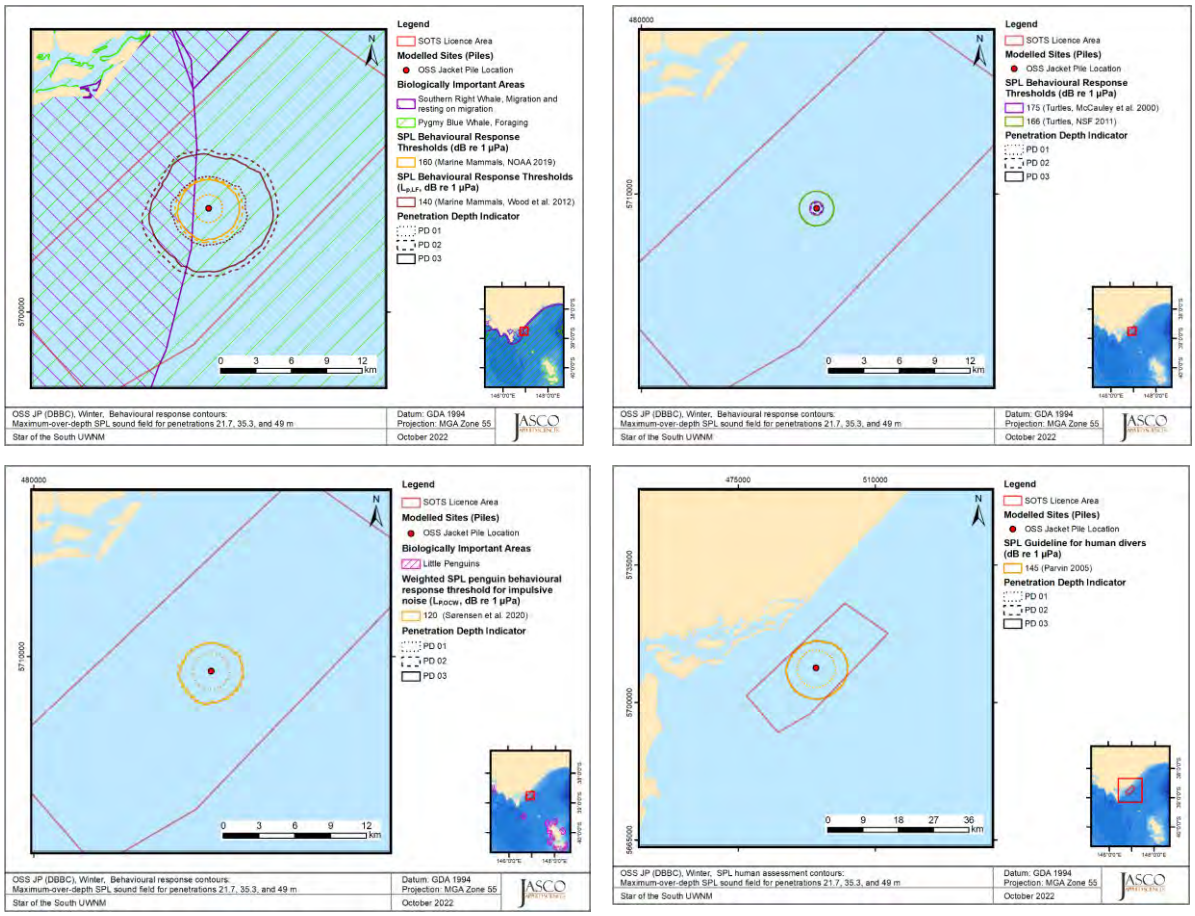


Figure 96. *OSS Jacket Pile, DBBC, winter, , marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL:* Sound level contour map showing maximum–over–depth results for all penetration depths.

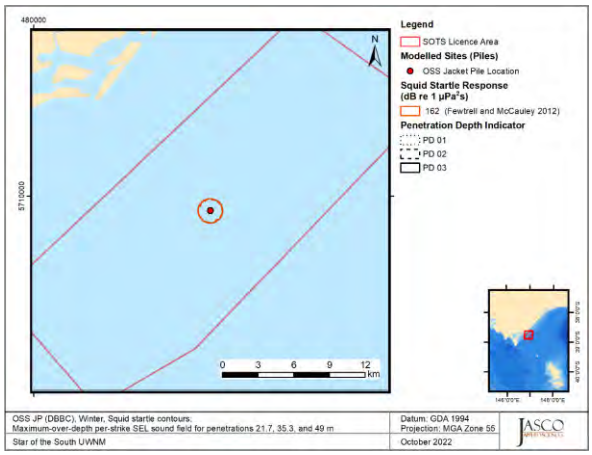


Figure 97. *OSS Jacket Pile, DBBC, winter, squid* startle response criteria*, per–strike SEL: Sound level contour map showing maximum–over–depth results for all penetration depths.*

4.2.2.3. Scenario 3 – Unmitigated (Second Modelling Round)

4.2.2.3.1. Per–strike sound fields in winter

The modelled per–strike sound fields are presented below. The results are presented in terms of per–strike SPL, SEL and PK sound fields.

Table 135. *Sub–station jacket pile, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	-	-	-	-	-	-	-	-	-	-
180	-	-	0.03	0.03	0.05	0.05	0.03	0.03	-	-
170	0.09	0.08	0.34	0.33	0.49	0.46	0.29	0.27	0.13	0.12
162[a]	0.48	0.41	1.39	1.24	1.56	1.44	1.1	1.03	0.52	0.48
160	0.66	0.58	1.84	1.69	2.02	1.89	1.46	1.37	0.74	0.67
150	2.68	2.55	5.63	5.28	6.43	5.97	4.57	4.33	2.98	2.66
140	7.23	6.72	16.12	14.44	20.01	18.22	12.67	11.32	7.21	6.62
130	19.13	17.32	41.81	34.95	53.96	49.65	41.92	35.25	15.74	13.17

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 136. *Sub–station jacket pile, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	-	-	-	-	-	-	-	-	-	-
190	-	-	0.03	0.03	0.03	0.03	0.02	0.02	-	-
180	0.07	0.07	0.33	0.26	0.36	0.34	0.24	0.19	0.12	0.11
170	0.55	0.51	1.42	1.3	1.47	1.36	1.11	1.03	0.58	0.52
160	1.86	1.78	4.49	4.03	5.01	4.59	3.16	2.97	2.11	1.98
150	5.45	4.9	12.9	11.59	15.37	13.98	9.54	8.57	5.42	5.05
145[a]	9.27	8.41	20.41	18.46	41.58	22.65	16.7	15.03	7.84	7.16
140	16.21	14.69	30.1	27.6	45.22	41.47	41.72	29.21	10.31	9.32
130	33.64	31.4	71.93	55.52	90	86.47	82.9	75.57	21.73	17.35

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 137. *Sub–station jacket pile, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Single Jacket Pile									
		Penetration depth (m)									
		17.20		25.40		33.60		41.80		50.00	
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
Sea turtle behavioural disturbance [b]	175	0.22	0.22	0.71	0.61	0.82	0.74	0.52	0.5	0.28	0.26
Sea turtle behavioural response [a]	166	1.02	0.92	2.24	2.06	2.34	2.2	1.73	1.58	0.96	0.91
Marine mammal behavioural response [c]	160	1.86	1.78	4.49	4.03	5.01	4.59	3.16	2.97	2.11	1.98
LF-cetacean weighted behavioural response [d]	160	0.71	0.65	1.81	1.62	1.83	1.71	1.36	1.28	0.7	0.61
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	6.38	5.86	15.79	14.24	41.53	21.16	15.08	13.49	5.24	4.66
Penguin OCW-weighted behavioural response [e]	120	3.72	3.42	7.01	6.4	9.04	8.28	6.67	5.96	2.22	2.02

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020), OCW weighted.

Table 138. *Sub–station jacket pile, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Single Jacket Pile				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS						
LF cetaceans	219	-	-	-	-	-
HF cetaceans	230	-	-	-	-	-
Otariid seals	232	-	-	-	-	-
Sea turtles	232	-	-	-	-	-
Penguins	232	-	-	-	-	-
TTS						
LF cetaceans	213	-	-	-	-	-
HF cetaceans	224	-	-	-	-	-
Otariid seals	226	-	-	-	-	-
Sea turtles	226	-	-	-	-	-
Penguins	226	-	-	-	-	-
Mortality and potential mortal injury / recoverable injury						
Fish I	213	-	-	-	-	-
Fish II, III Fish eggs and larvae	207	-	-	0.02	-	-

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.3.2. Multiple–strike sound fields in winter

The modelled multiple–strike sound fields are presented below.

Table 139. *Sub–station jacket piles, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		4 Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	3.61	3.4	7.29	6.74
HF cetaceans	185	-	-	-	-
Otariid seals	203	-	-	-	-
Sea turtles	204	0.37	0.34	1.06	0.99
Penguins	203	-	-	-	-
TTS					
LF cetaceans	168	22.27	20.3	43.72	40.22
HF cetaceans	170	-	-	0.02	0.02
Otariid seals	188	0.02	0.02	0.06	0.06
Sea turtles	189	3.41	3.19	6.82	6.29
Penguins	188	0.02	0.02	0.06	0.06

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 140. *Sub–station jacket piles, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		4 Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.03	0.03	0.11	0.11
II, Fish eggs and fish larvae	210	0.2	0.18	0.63	0.6
III	207	0.36	0.34	1.07	1
Fish recoverable injury					
I	216	0.06	0.06	0.2	0.18
II, III	203	0.79	0.73	1.91	1.78
Fish temporary threshold shift (TTS)					
I, II, III	186	6.41	5.97	12.25	11.05

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.3.3. Sound Field Maps

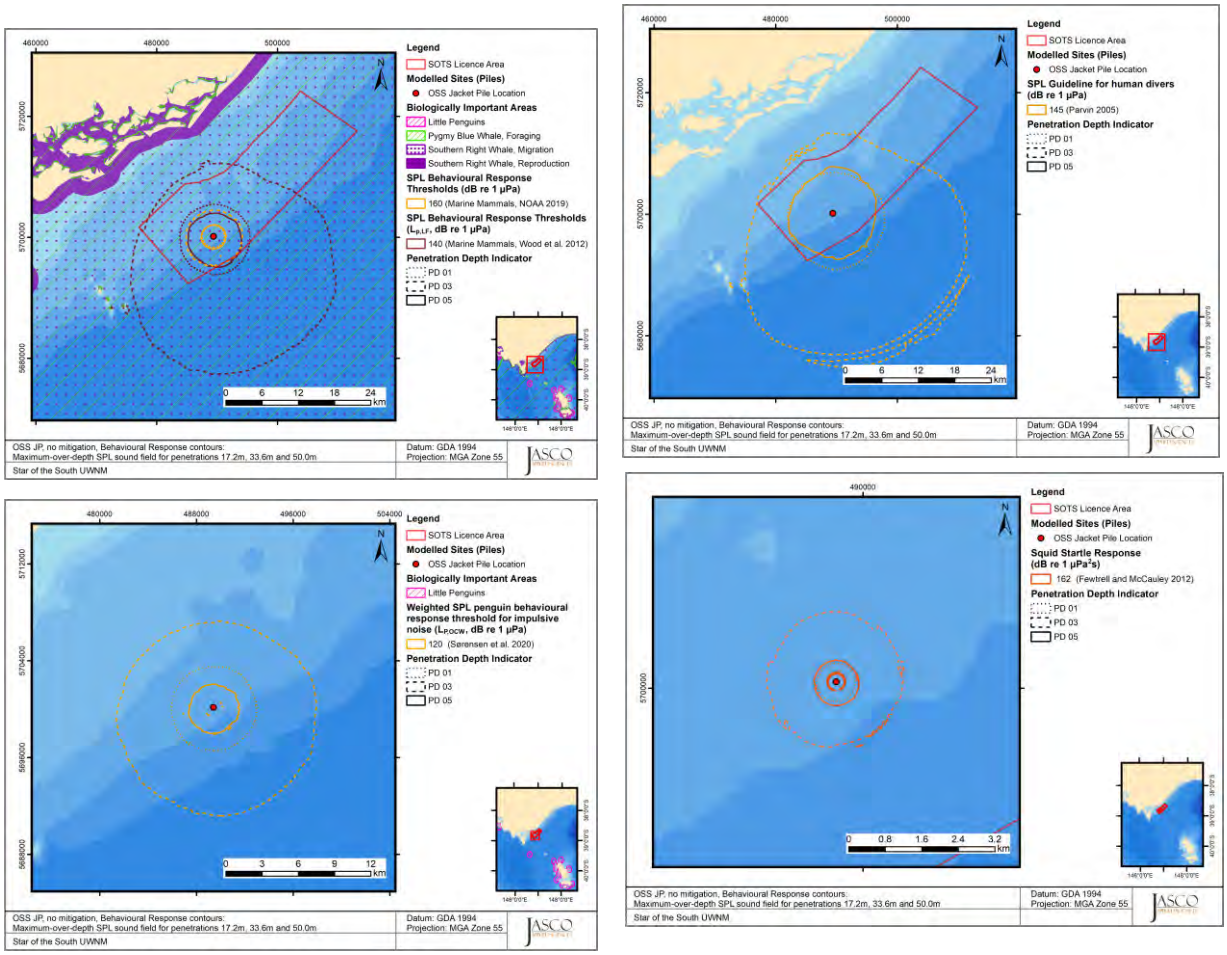


Figure 98. *Unmitigated per-strike sound fields for JP,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), human (top right), penguin (bottom left), squid (bottom right).

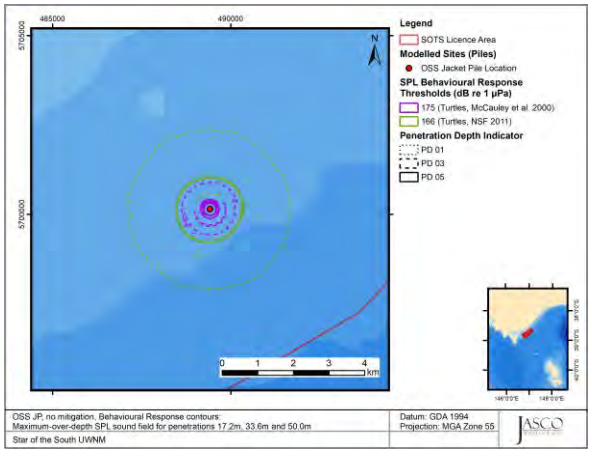


Figure 99. *Unmitigated per-strike sound fields for JP,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

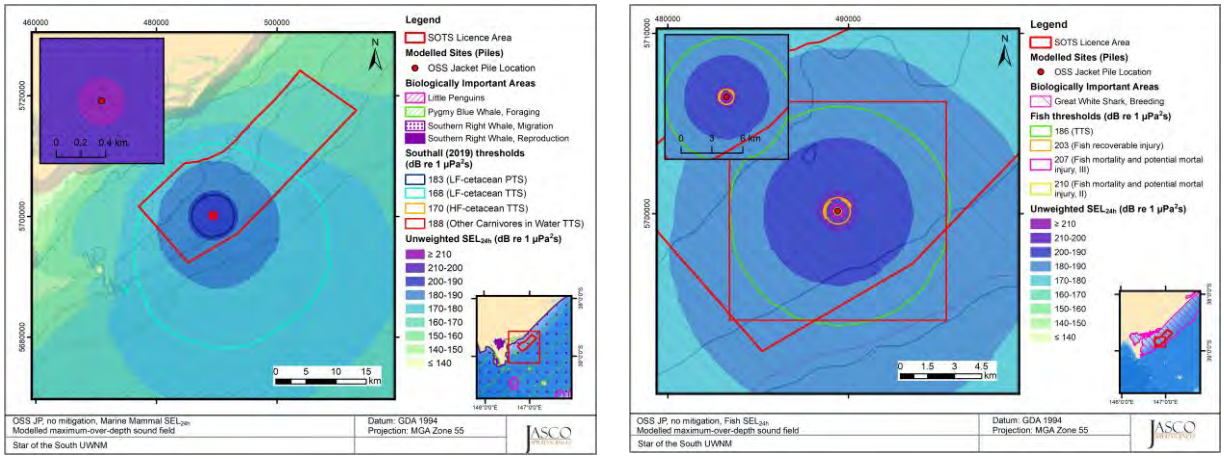


Figure 100. *Unmitigated, JP.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

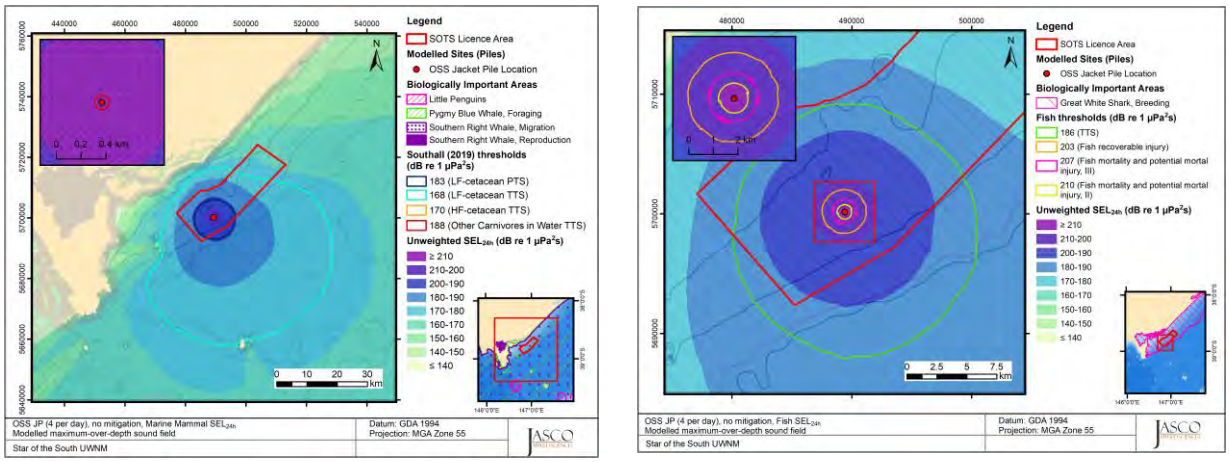


Figure 101. *Unmitigated, 4 JP per day.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

4.2.2.4. Scenario 4 – DBBC (Second Modelling Round)

4.2.2.4.1. Per–strike sound fields in winter

The modelled per–strike sound fields are presented below. The results are presented in terms of per–strike SPL, SEL, and PK sound fields.

Table 141. *Sub–station jacket pile, NAS – DBBC, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	-	-	-	-	-	-	-	-	-	-
180	-	-	0.03	0.03	0.05	0.05	0.03	0.03	-	-
170	0.09	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
162[a]	0.09	0.09	0.23	0.22	0.28	0.26	0.25	0.24	0.24	0.22
160	0.13	0.11	0.29	0.28	0.42	0.39	0.32	0.31	0.36	0.26
150	0.67	0.64	1.79	1.7	2.14	2.01	1.93	1.75	1.65	1.47
140	3.08	2.88	5.95	5.39	6.73	5.88	5.72	5.34	5.64	4.84
130	8.93	7.82	13.78	12.02	15.34	12.88	14.31	11.91	12.27	10.22

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 142. *Sub–station jacket pile, NAS – DBBC, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	-	-	-	-	-	-	-	-	-	-
190	-	-	0.03	0.03	0.03	0.03	0.02	0.02	-	-
180	0.07	0.07	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
170	0.1	0.1	0.25	0.24	0.29	0.27	0.27	0.26	0.25	0.24
160	0.51	0.48	1.36	1.3	1.59	1.49	1.4	1.27	1.14	1.02
150	2.42	2.29	4.54	4.24	4.99	4.63	4.45	4.1	3.82	3.51
145[a]	4.18	3.89	7.08	6.32	7.48	6.76	6.64	5.79	5.97	5.33
140	6.44	5.61	9.59	8.66	10.18	9.06	9.56	8.38	8.55	7.61
130	13.92	11.14	20.49	15.23	21.45	16.36	21.05	15.91	18.8	14.18

[a] Human health assessment threshold derived from Parvin (2005).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 143. *Sub–station jacket pile, NAS – DBBC, winter, marine mammal, sea turtle and penguin behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Single Jacket Pile									
		Penetration depth (m)									
		17.20		25.40		33.60		41.80		50.00	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [b]	175	0.09	0.09	0.13	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Sea turtle behavioural response [a]	166	0.13	0.13	0.54	0.47	0.62	0.58	0.51	0.48	0.49	0.42
Marine mammal behavioural response [c]	160	0.51	0.48	1.36	1.3	1.59	1.49	1.4	1.27	1.14	1.02
LF-cetacean weighted behavioural response [d]	160	0.09	0.09	0.21	0.2	0.26	0.25	0.3	0.28	0.34	0.25
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	1.14	1.05	2.91	2.56	4	3.43	3.82	3.38	3.9	3.2
Penguin OCW-weighted behavioural response [e]	120	0.28	0.26	0.91	0.77	1.29	1.09	1.51	1.36	1.3	1.05

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020), OCW weighted.

Table 144. *Sub–station jacket pile, NAS – DBBC, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Single Jacket Pile				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS						
LF cetaceans	219	-	-	-	-	-
HF cetaceans	230	-	-	-	-	-
Otariid seals	232	-	-	-	-	-
Sea turtles	232	-	-	-	-	-
Penguins	232	-	-	-	-	-
TTS						
LF cetaceans	213	-	-	-	-	-
HF cetaceans	224	-	-	-	-	-
Otariid seals	226	-	-	-	-	-
Sea turtles	226	-	-	-	-	-
Penguins	226	-	-	-	-	-
Mortality and potential mortal injury / recoverable injury						
Fish I	213	-	-	-	-	-
Fish II, III Fish eggs and larvae	207	-	-	0.02	-	-

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.4.2. Multiple–strike sound fields in winter

The modelled multiple–strike sound fields are presented below.

Table 145. *Sub–station jacket piles, winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		4 Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS					
LF cetaceans	183	0.72	0.64	1.77	1.57
HF cetaceans	185	-	-	-	-
Otariid seals	203	-	-	-	-
Sea turtles	204	0.09	0.09	0.2	0.2
Penguins	203	-	-	-	-
TTS					
LF cetaceans	168	4.72	4.06	7.22	6.36
HF cetaceans	170	-	-	0.02	0.02
Otariid seals	188	0.02	0.02	0.06	0.06
Sea turtles	189	0.68	0.58	1.74	1.52
Penguins	188	0.02	0.02	0.06	0.06

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 146. *Sub–station jacket piles, winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		4 Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Mortality and potential mortal injury					
I	219	0.03	0.03	0.09	0.09
II, Fish eggs and fish larvae	210	0.09	0.09	0.13	0.13
III	207	0.09	0.09	0.23	0.22
Fish recoverable injury					
I	216	0.06	0.06	0.09	0.09
II, III	203	0.13	0.13	0.45	0.42
Fish temporary threshold shift (TTS)					
I, II, III	186	2.59	2.4	4.99	4.67

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.4.3. Sound field maps

The following presents the contour maps:

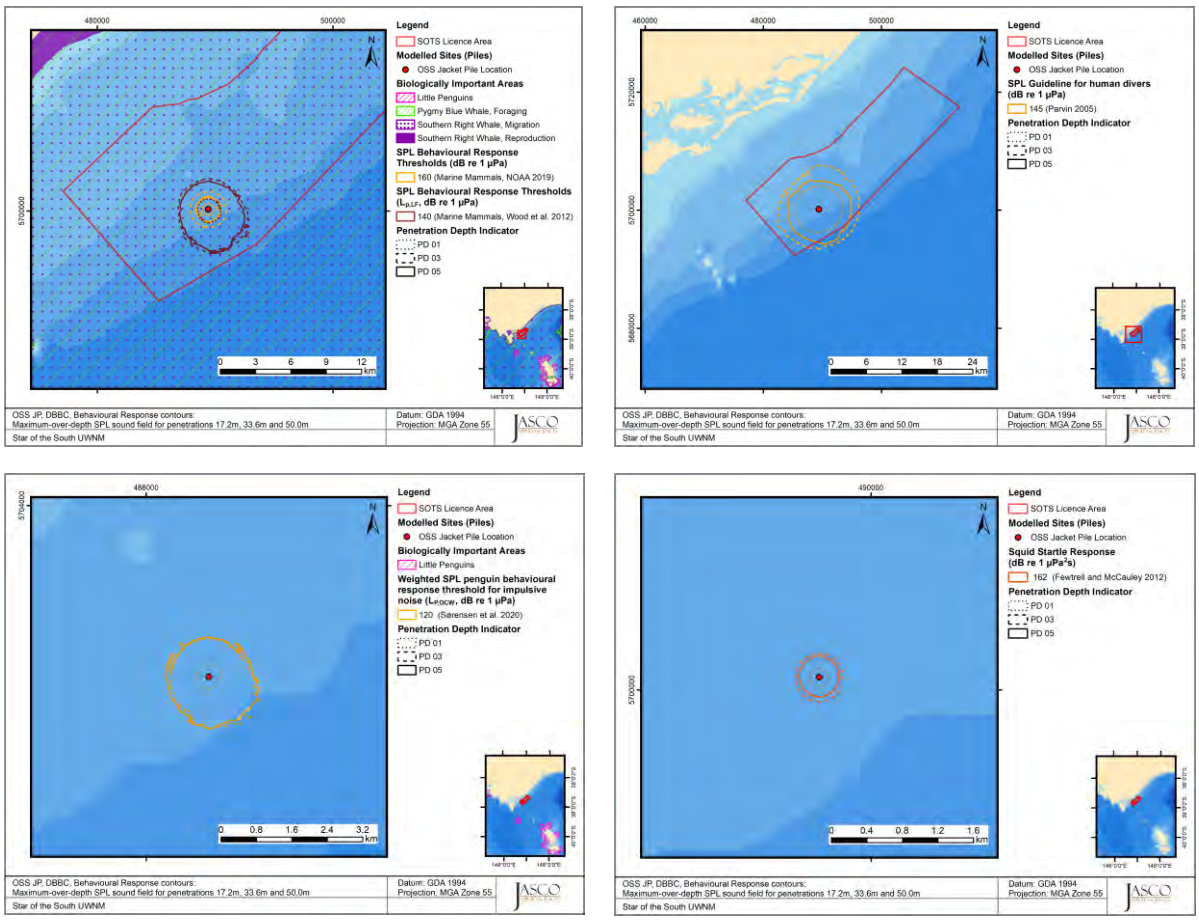


Figure 102. *DBBC per-strike sound fields for JP,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for marine mammals (top left), human (top right), penguin (bottom left), squid (bottom right).

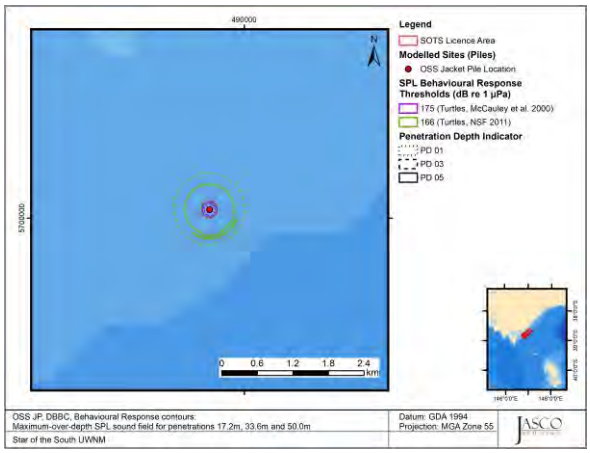


Figure 103. *DBBC per-strike sound fields for JP,* SPL. Sound level contour map of unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response to thresholds for turtles.

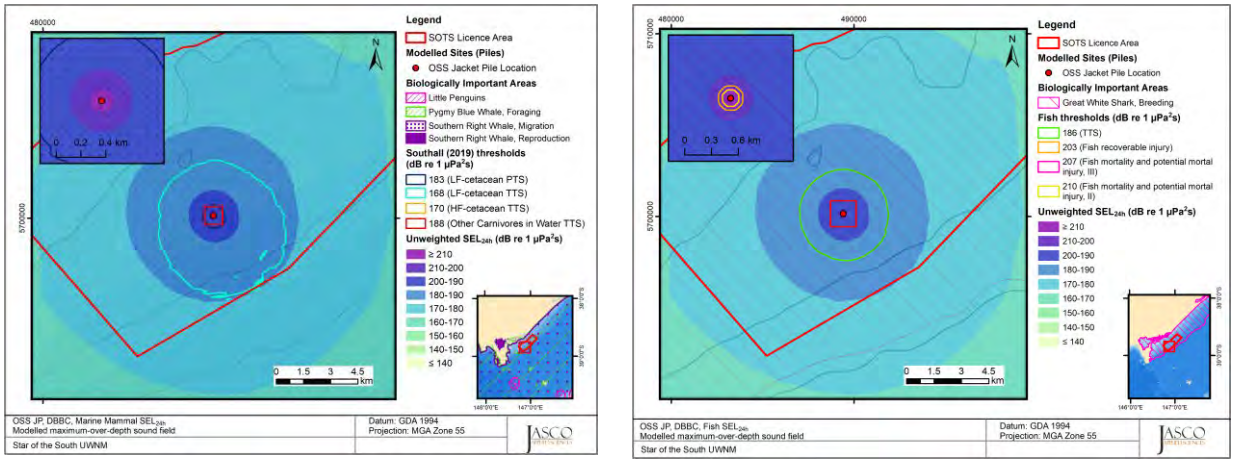


Figure 104. *DBBC, JP.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

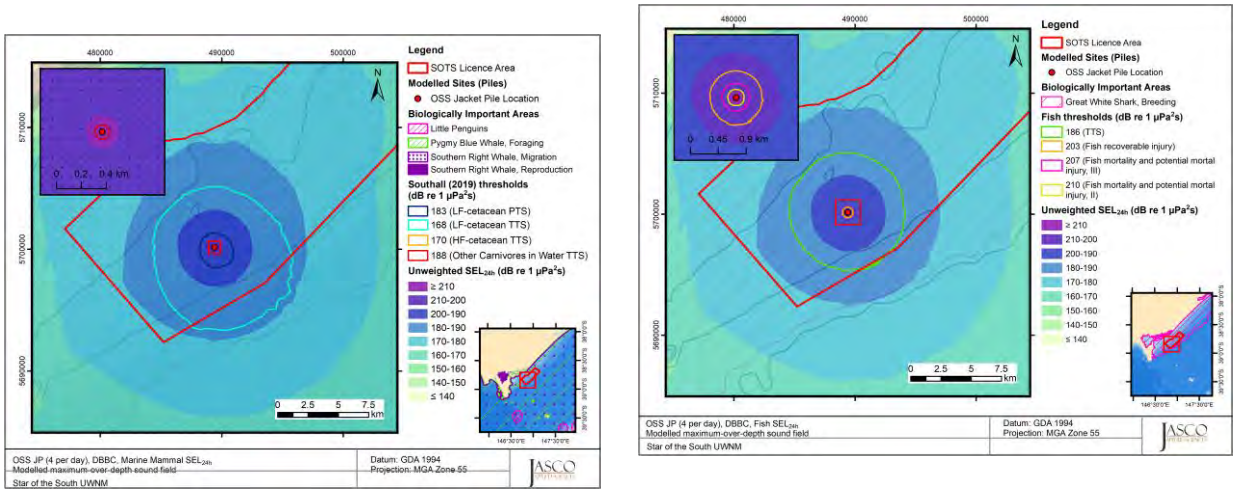


Figure 105. *DBBC, 4 JP per day.* Sound level contour map of weighted maximum-over-depth SEL_{24h} results, along with isopleths for marine mammals (left) and fish (right). Thresholds omitted here were not reached or not large enough to display graphically.

4.2.2.5. Scenario 5 – Unmitigated (Fourth Modelling Round)

4.2.2.5.1. Per–strike sound fields in winter

The per–strike sound fields for the modelling sites are presented in the following tables. Results are presented in terms of per–strike SPL, SEL, PK sound fields and per–strike particle motion field results.

Table 147. *Sub–station jacket pile, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa²·s)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	–	–	–	–
180	–	–	0.04	0.04	0.05	0.05	0.03	0.03	–	–
170	0.15	0.14	0.28	0.28	0.50	0.48	0.33	0.32	0.11	0.11
162[a]	0.86	0.74	1.27	1.18	1.71	1.60	1.32	1.22	0.53	0.52
160	1.13	1.08	1.81	1.66	2.32	2.19	1.81	1.69	0.82	0.70
150	4.80	4.53	6.63	6.20	8.28	7.63	6.47	5.98	3.62	3.42
140	13.5	12.2	21.0	18.4	27.6	24.6	17.4	15.6	10.1	9.32
130	36.2	32.5	56.3	52.0	82.4	69.2	51.8	47.5	23.2	20.6

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 148. *Sub–station jacket pile, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	–	–	–	–	–	–	–	–
190	–	–	0.03	0.03	0.03	0.03	0.03	0.03	–	–
180	0.10	0.10	0.21	0.21	0.35	0.34	0.21	0.20	0.10	0.10
170	0.98	0.90	1.45	1.37	1.83	1.66	1.40	1.28	0.58	0.54
160	3.60	3.38	5.30	4.96	6.57	6.18	4.17	3.87	2.70	2.42
150	9.46	8.70	15.9	14.1	19.5	17.2	12.8	11.4	6.68	6.02
145[a]	16.2	14.4	25.1	22.4	49.1	29.3	20.7	17.9	10.5	8.92
140	29.1	25.1	49.2	35.2	57.6	52.8	49.2	33.6	15.6	13.3
130	59.2	54.6	>90.0	/	>90.0	/	>90.0	/	49.1	32.0

[a] Human health assessment threshold derived from Parvin (2005).

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 149. *Sub–station jacket pile, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Single Jacket Pile									
		Penetration depth (m)									
		17.20		25.40		33.60		41.80		50.00	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	0.38	0.31	0.60	0.58	0.96	0.84	0.60	0.58	0.20	0.19
Sea turtle behavioural response [a]	166	1.80	1.67	2.56	2.37	3.21	2.93	2.14	2.02	1.22	1.10
Marine mammal behavioural response [b]	160	3.60	3.38	5.30	4.96	6.57	6.18	4.17	3.87	2.70	2.42
LF-cetacean weighted behavioural response [c]	160	1.76	1.64	2.50	2.34	2.87	2.70	2.21	2.04	1.01	0.88
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	14.4	12.7	22.2	20.1	49.1	28.5	19.1	17.0	8.26	7.50
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	83.1	75.4	>90.0	/	>90.0	/	>90.0	/	52.7	48.5

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Threshold for sea turtle behavioural response to impulsive noise (McCauley et al. 2000a)
[c] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 150. *Sub–station jacket pile, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Single Jacket Pile				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{emix} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS/AUD INJ						
LF cetaceans	222	–	–	–	–	–
HF cetaceans	230	–	–	–	–	–
Otariid seals	230	–	–	–	–	–
Sea turtles	230	–	–	–	–	–
Penguins	230	–	–	–	–	–
TTS						
LF cetaceans	216	–	–	–	–	–
HF cetaceans	224	–	–	–	–	–
Otariid seals	224	–	–	–	–	–
Sea turtles	224	–	–	–	–	–
Penguins	224	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury						
Fish I	213	–	–	–	–	–
Fish II, III Fish eggs and larvae	207	–	–	0.02	–	–

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 151. *Sub–station jacket pile, unmitigated, winter, PK–PK thresholds: Maximum (R_{max}) horizontal distances (m) from a single jacket pile to modelled seafloor peak–peak pressure level (PK–PK) thresholds for invertebrates for each penetration depth.*

Marine Fauna	PK–PK threshold (L_{pkpk}; dB re 1 µPa)	Single Jacket Pile				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Crustaceans [a]	202	49	62	53	33	11

[a] Payne et al. (2008), lobster

Table 152. *Sub–station jacket pile, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from a single jacket pile to modelled seafloor peak acceleration magnitude level (m/s^2) thresholds for benthic invertebrates for each penetration depth.

Marine Fauna	Marine fauna Peak acceleration magnitude (m/s^2)	Monopile 1				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Benthic invertebrates [b]	35.75	–	–	–	–	–

[a] Day et al. (2016a) – Crustaceans and bivalves
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.2.2.5.2. Multiple–strike sound fields in winter

The SEL 24-hour sound fields for the modelling sites are presented in the following tables in relation to relevant noise effect criteria for marine fauna. Results are presented for 1, 2, 3 and 4 jacket pile installations per day.

Table 153. *Sub–station Jacket Piles, winter, single and multiple piles SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 $\mu Pa^2 \cdot s$)	Jacket Pile		Jacket Pile x2		Jacket Pile x3		Jacket Pile x4	
		R_{max} (km)	*Area* (km^2)	R_{max} (km)	*Area* (km^2)	R_{max} (km)	*Area* (km^2)	R_{max} (km)	*Area* (km^2)
PTS/AUD INJ									
LF cetaceans	183	5.32	82.3	7.35	151.9	8.86	214.0	10.1	273.4
HF cetaceans	193	–	*	–	*	–	*	0.02	*
Otariid seals	185	–	*	0.02	0.00	0.03	*	0.05	0.01
Sea turtles	184	3.69	40.6	5.30	80.8	6.46	115.9	7.29	148.1
Penguins	185	–	*	0.02	*	0.03	*	0.05	0.01
TTS									
LF cetaceans	168	49.1	1611.0	49.3	2883.0	53.0	3967.0	59.9	4919.0
HF cetaceans	178	0.12	0.04	0.17	0.09	0.23	0.16	0.33	0.34
Otariid seals	170	0.18	0.10	0.33	0.35	0.56	0.66	0.60	1.11
Sea turtles	169	21.2	884.0	49.2	1670.0	49.3	2403.0	49.4	3107.0
Penguins	170	0.18	0.10	0.33	0.35	0.56	0.66	0.60	1.11

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
An asterisk indicates that the area was smaller than 0.0013 km^2

Table 154. *Sub–station Jacket Piles, winter, fish, multiple piles SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Jacket Pile		Jacket Pile x2		Jacket Pile x3		Jacket Pile x4	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
Mortality and potential mortal injury									
I	219	0.03	0.00	0.05	0.01	0.06	0.01	0.09	0.03
II, Fish eggs and fish larvae	210	0.19	0.12	0.34	0.37	0.50	0.67	0.58	1.03
III	207	0.34	0.37	0.58	1.03	0.87	2.04	1.06	3.09
Fish recoverable injury									
I	216	0.05	0.01	0.09	0.03	0.16	0.06	0.19	0.12
II, III	203	0.73	1.53	1.22	4.53	1.68	8.30	2.04	12.2
Fish temporary threshold shift (TTS)									
I, II, III	186	7.94	176.0	10.9	311.2	13.3	430.1	15.3	538.6

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

4.2.2.5.3. Sound field maps

The per–strike sound field maps for the jacket pile modelling site are presented below along with the SEL 24-hour sound field maps for the jacket pile modelling site for the installation of 1, 2, 3 or 4 jacket piles per day.

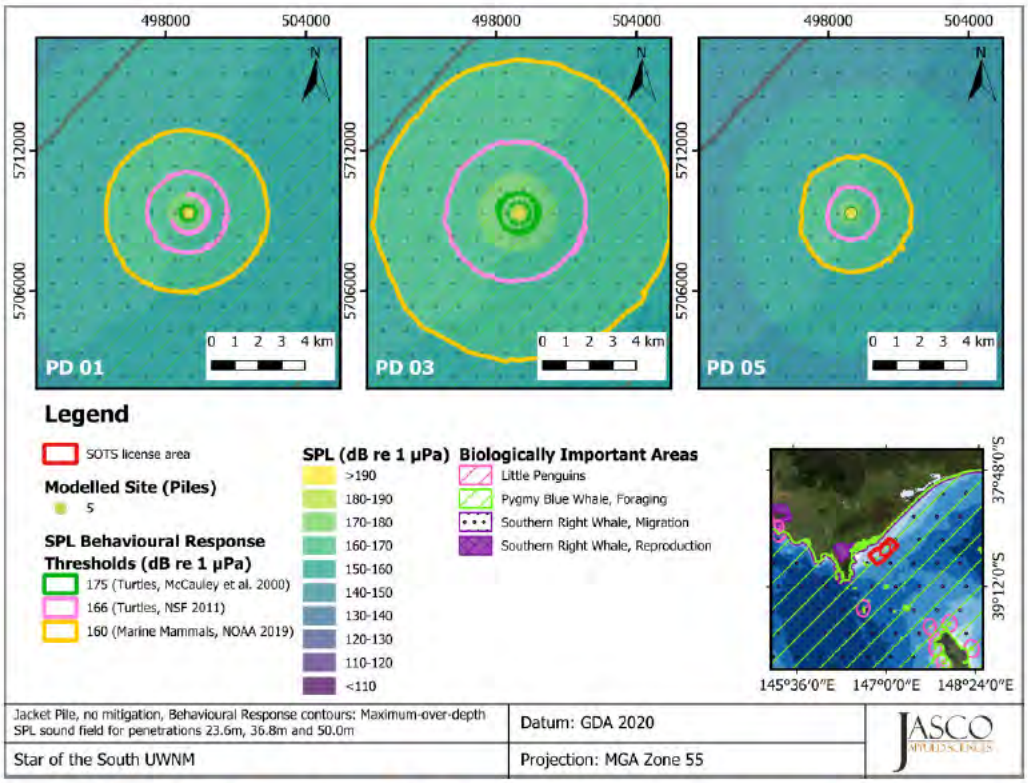


Figure 106. Jacket pile, unmitigated, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals and turtles.

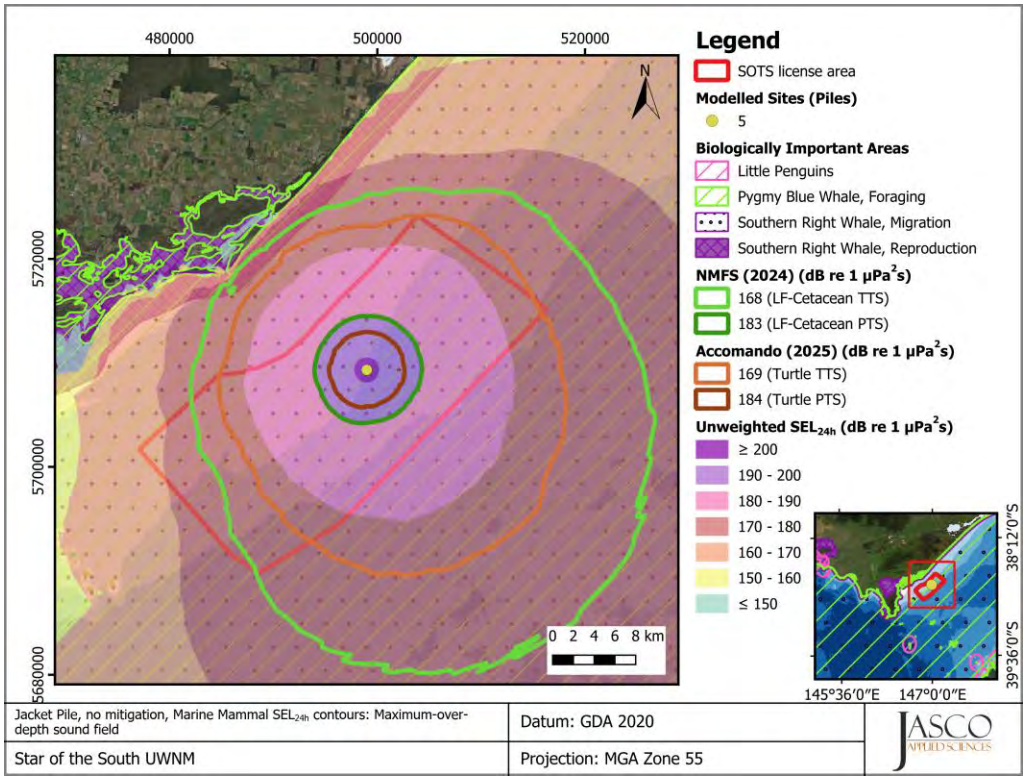


Figure 107. Jacket pile, 1 per day, unmitigated, *accumulated SEL_{24h}*: Sound level contour map showing maximum-over-depth SEL_{24h} results (unweighted/flat), along with frequency weighted isopleths for TTS in low-frequency cetaceans, and sea turtles.

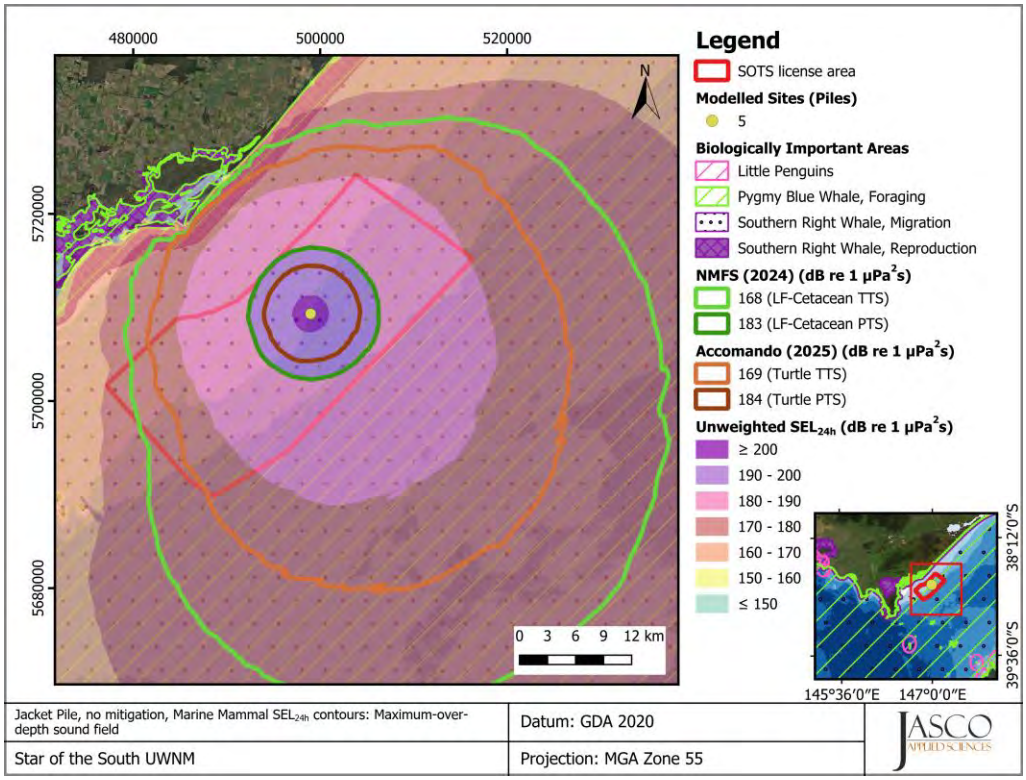


Figure 108. Jacket pile, 2 per day, unmitigated, accumulated SEL24h: Sound level contour map showing maximum-over-depth SEL24h results (unweighted/flat), along with frequency weighted isopleths for TTS in low-frequency cetaceans, and sea turtles.

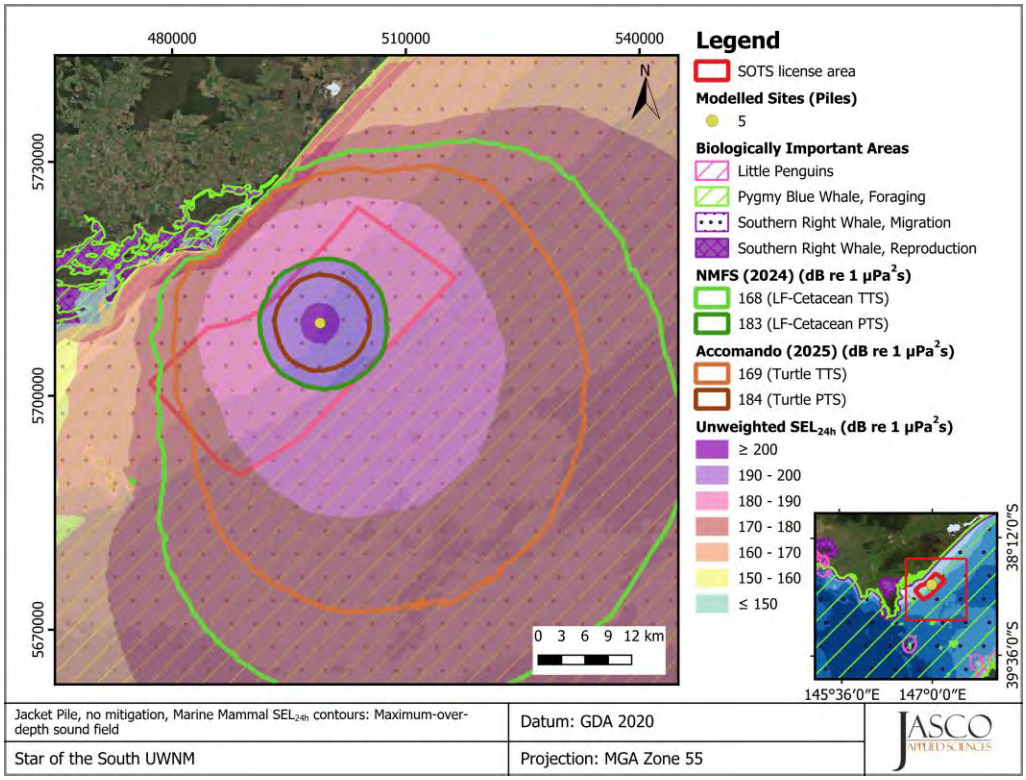


Figure 109. Jacket pile, 3 per day, unmitigated, *accumulated SEL_{24h}*: Sound level contour map showing maximum-over-depth SEL_{24h} results (unweighted/flat), along with frequency weighted isopleths for TTS in low-frequency cetaceans, and sea turtles.

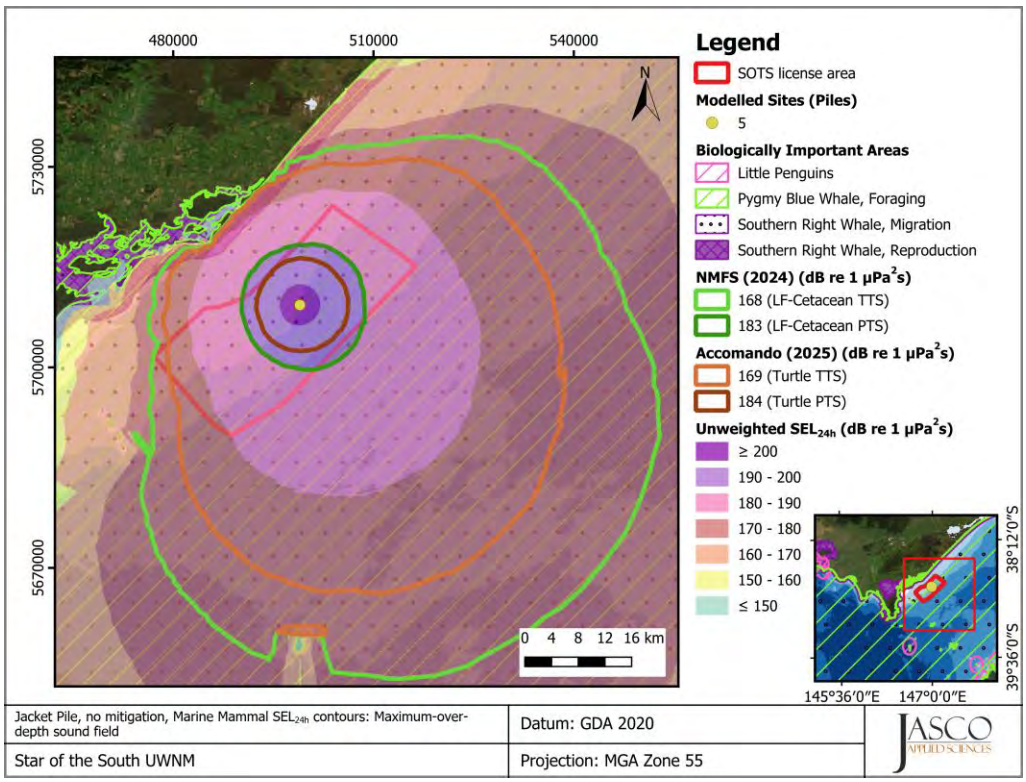


Figure 110. Jacket pile, 4 per day, unmitigated, *accumulated SEL_{24h}*: Sound level contour map showing maximum-over-depth SEL_{24h} results (unweighted/flat), along with frequency weighted isopleths for TTS in low-frequency cetaceans, and sea turtles.

4.2.2.6. Scenario 6 – PULSE + DBBC (Fourth Modelling Round)

4.2.2.6.1. Per–strike sound fields in winter

The modelled per–strike sound fields are presented below. The results are presented in terms of per–strike SPL, SEL, PK sound fields.

Table 155. *Sub–station Jacket Pile, NAS – PULSE+DBBC, winter, modelled maximum–over–depth per–strike SEL isopleths*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

Per–strike SEL (L_E; dB re 1 µPa^2·s)	Single Jacket Pile									
	Penetration depth (m)									
	17.20		25.40		33.60		41.80		50.00	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	–	–	–	–	–	–	–	–	–	–
180	–	–	–	–	–	–	–	–	–	–
170	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.03	0.03
162[a]	0.45	0.44	0.42	0.40	0.37	0.36	0.32	0.22	0.20	0.20
160	0.63	0.61	0.66	0.57	0.66	0.53	0.37	0.36	0.33	0.31
150	3.23	3.06	3.33	3.15	3.11	2.93	2.58	2.32	2.06	1.88
140	9.68	9.03	10.4	9.69	9.89	9.25	8.20	7.69	7.37	6.90
130	25.7	22.8	30.5	27.0	28.3	25.3	19.5	17.6	16.6	15.6

[a] Startle response level for squid (Fewtrell and McCauley 2012).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 156. *Sub–station Jacket Pile, NAS – PULSE+DBBC, winter, modelled maximum–over–depth per–strike SPL isopleths for each pile per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Single Jacket Pile									
	Penetration depth (m)									
	23.6		30.2		36.8		43.4		50.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
200	–	–	–	–	–	–	–	–	–	–
190	–	–	–	–	–	–	–	–	–	–
180	0.06	0.06	0.06	0.06	0.05	0.05	0.03	0.03	0.02	0.02
170	0.47	0.45	0.56	0.54	0.50	0.49	0.34	0.33	0.22	0.22
160	2.60	2.39	2.56	2.40	2.23	2.09	1.71	1.63	1.53	1.38
150	6.28	5.85	7.14	6.70	6.51	6.13	5.46	4.87	5.11	4.68
145[a]	10.0	9.06	12.2	11.0	11.3	10.1	8.74	7.99	8.65	7.88
140	16.7	14.7	20.6	18.2	19.1	16.7	13.5	12.2	13.3	12.2

[a] Human health assessment threshold derived from Parvin (2005).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

Table 157. *Sub–station Jacket Pile, NAS – PULSE+DBBC, winter, marine mammal and sea turtle behavioural response thresholds, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from the monopile to modelled maximum–over–depth isopleths per penetration depth.

Fauna group	SPL threshold (L_p; re 1 µPa)	Single Jacket Pile									
		Penetration depth (m)									
		17.20		25.40		33.60		41.80		50.00	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
Sea turtle behavioural disturbance [a]	175	0.17	0.16	0.19	0.19	0.18	0.18	0.09	0.09	0.10	0.10
Sea turtle behavioural response [a]	166	1.08	1.00	1.11	1.00	1.01	0.88	0.69	0.66	0.51	0.48
Marine mammal behavioural response [b]	160	2.60	2.39	2.56	2.40	2.23	2.09	1.71	1.63	1.53	1.38
LF-cetacean weighted behavioural response [c]	160	1.10	0.95	0.93	0.83	0.69	0.66	0.42	0.34	0.18	0.17
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	9.67	8.89	9.50	8.72	8.17	7.52	5.44	5.05	3.83	3.59
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	61.4	56.3	86.5	78.3	>90.0	/	49.4	40.0	25.8	22.0

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 158. *Sub–station jacket pile, winter, PTS and TTS PK thresholds*: Maximum (R_{max}) horizontal distances (km) from each monopile to modelled maximum–over–depth peak pressure level (PK) thresholds for marine mammals, fish, sea turtles, and penguins for each penetration depth.

Fauna group	PK threshold (L_{pk}; dB re 1 µPa)	Single Jacket Pile				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)	R_{max} (km)
PTS						
LF cetaceans	222	–	–	–	–	–
HF cetaceans	230	–	–	–	–	–
Otariid seals	230	–	–	–	–	–
Sea turtles	230	–	–	–	–	–
Penguins	230	–	–	–	–	–
TTS						
LF cetaceans	216	–	–	–	–	–
HF cetaceans	224	–	–	–	–	–
Otariid seals	224	–	–	–	–	–
Sea turtles	224	–	–	–	–	–
Penguins	224	–	–	–	–	–
Mortality and potential mortal injury / recoverable injury						
Fish I	213	–	–	–	–	–
Fish II, III Fish eggs and larvae	207	–	–	–	–	–

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Table 159. *Sub–station jacket pile, winter, particle motion thresholds*: Maximum (R_{max}) horizontal distances (m) from a single jacket pile to modelled seafloor peak acceleration magnitude level (m/s^2) thresholds for benthic invertebrates for each penetration depth.

Marine Fauna	Marine fauna Peak acceleration magnitude (m/s^2)	Monopile 1				
		Penetration depth (m)				
		17.20	25.40	33.60	41.80	50.00
		R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)	R_{max} (m)
Benthic invertebrates [b]	35.75	–	–	–	–	–

[a] Day et al. (2016a) – Crustaceans and bivalves
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.2.2.6.2. Multiple–strike sound fields in winter

The modelled multiple–strike sound fields are presented below.

Table 160. *Jacket Piles, NAS – Pulse+DBBC, winter, single and multiple piles SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from jacket pile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Jacket Pile		Jacket Pile x2		Jacket Pile x3		Jacket Pile x4	
		*R*max (km)	*Area* (km²)	*R*max (km)	*Area* (km²)	*R*max (km)	*Area* (km²)	*R*max (km)	*Area* (km²)
PTS/AUD INJ									
LF cetaceans	183	1.93	10.6	3.00	25.6	3.71	40.0	4.30	53.9
HF cetaceans	193	–	*	–	*	–	*	–	*
Otariid seals	185	–	*	–	*	–	*	–	*
Sea turtles	184	1.37	4.99	2.14	12.7	2.72	20.8	3.14	28.8
Penguins	185	–	*	–	*	–	*	–	*
TTS									
LF cetaceans	168	11.4	321.2	15.6	550.2	19.2	755.9	22.4	947.7
HF cetaceans	178	0.02	*	0.05	0.01	0.06	0.01	0.06	0.01
Otariid seals	170	0.05	0.01	0.06	0.01	0.11	0.03	0.16	0.06
Sea turtles	169	8.71	196.1	12.0	340.9	14.4	467.3	16.5	589.9
Penguins	170	0.05	0.01	0.06	0.01	0.11	0.03	0.16	0.06

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
An asterix indicates that the area was smaller than 0.0013 km²

Table 161. *Jacket Piles, NAS – PULSE+DBBC, winter, fish, multiple piles SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from jacket pile to SEL_{24h} based fish criteria.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Jacket Pile		Jacket Pile x4	
		*R*max (km)	*Area* (km²)	*R*max (km)	*Area* (km²)
Mortality and potential mortal injury					
I	219	–	*	0.02	*
II, Fish eggs and fish larvae	210	0.05	0.01	0.17	0.10
III	207	0.07	0.02	0.23	0.17
Fish recoverable injury					
I	216	–	*	0.05	0.01
II, III	203	0.19	0.12	0.62	1.15
Fish temporary threshold shift (TTS)					
I, II, III	186	3.90	44.8	7.74	170.3

Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
An asterisk indicates that the area was smaller than 0.0013 km²

4.2.2.6.3. Sound field maps

The per–strike sound field maps for the jacket pile modelling site are presented in Figure 111 and the SEL 24-hour sound field maps for the jacket pile modelling site are presented in Figure 112 for the installation of 1 or 4 jacket piles per day.

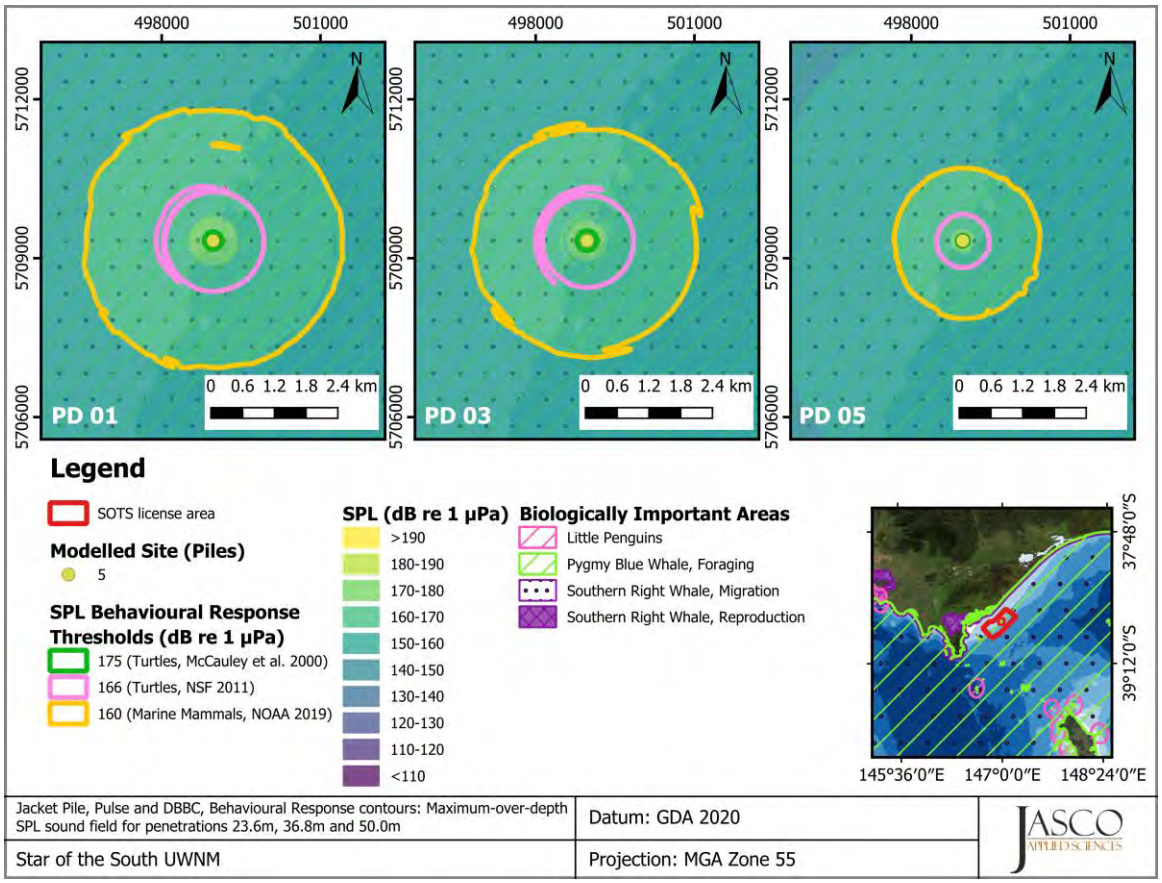


Figure 111. Jacket pile, PULSE+DBBC, *SPL*: Sound level contour map showing the unweighted maximum-over-depth sound field in 10 dB steps, and the isopleths for behavioural response threshold for marine mammals.

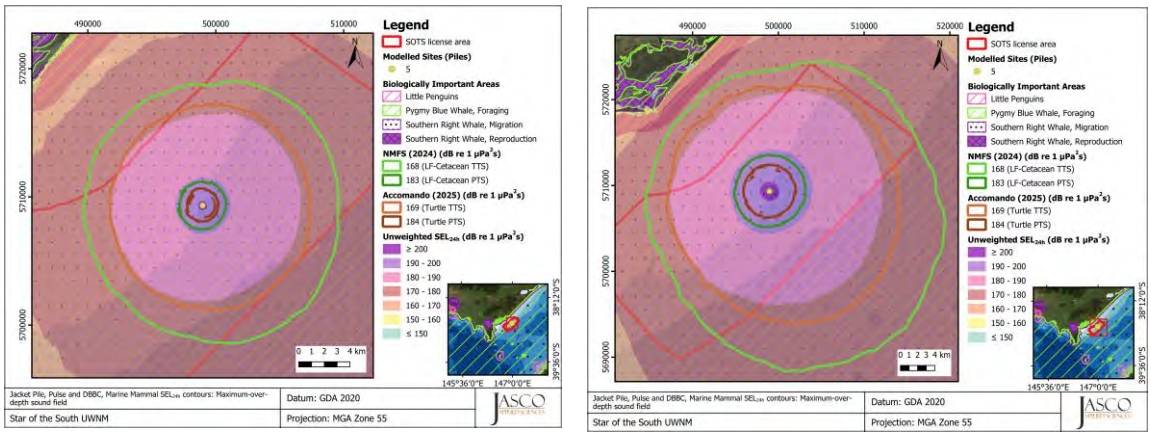


Figure 112. Jacket pile, 1 per day (left) and 4 per day (right), PULSE+DBBC, *accumulated SEL$_{24h}$*: Sound level contour map showing maximum-over-depth SEL$_{24h}$ results (unweighted/flat), along with frequency weighted isopleths for TTS in low-frequency cetaceans, and sea turtles.

4.2.3. Results: Animal Movement Modelling

4.2.3.1. Scenario 6 – PULSE + DBBC (Fourth Modelling Round)

Exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) were calculated for pygmy blue, humpback, minke and southern right whales. A summary of radial distances to exposure thresholds for modelled species, along with probability of exposure for each monopile are included assuming the frequency dependent performance of a DBBC+PULSE in the tables below. Note that dashes indicate that no animats were exposed above threshold. In addition, histograms for 1 per day and 4 per day scenarios are presented in Appendix E.1.2.1 .

Table 162. *Jacket pile installation – NAS, PULSE+DBBC, LF-weighted SEL_{24h}*: Exposure ranges ($ER_{95\%}$) in km from each site to permanent threshold shift (PTS) and temporary threshold shift (TTS) low-frequency marine mammal thresholds.

Species	1 per day		2 per day		3 per day		4 per day	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS/AUD INJ								
Pygmy Blue Whale, Feeding	0.62	46	0.81	53	0.93	61	1.08	65
Pygmy Blue Whale, Northbound Migrating	0.21	38	0.25	39	0.26	36	0.26	36
Pygmy Blue Whale, Southbound Migrating	0.24	34	0.26	32	0.25	35	0.24	36
Humpback Whale, Migrating with Calf	0.78	21	1.05	18	1.25	24	1.54	19
Humpback Whale, Migrating without Calf	0.69	15	1.35	9	1.43	9	1.67	8
Minke Whale, Migrating	–	–	<0.02	8	0.02	13	0.02	23
Southern Right Whale, Migrating with Calf	0.51	23	0.86	24	1.03	25	1.46	22
Southern Right Whale, Migrating without Calf	0.39	36	0.39	26	0.39	24	0.38	22
TTS								
Pygmy Blue Whale, Feeding	6.61	88	8.30	91	9.55	90	10.5	91
Pygmy Blue Whale, Northbound Migrating	5.55	76	6.55	79	6.85	82	6.94	85
Pygmy Blue Whale, Southbound Migrating	5.37	75	6.48	80	6.92	84	7.05	86
Humpback Whale, Migrating with Calf	6.26	59	7.87	60	8.45	63	8.97	65
Humpback Whale, Migrating without Calf	6.25	56	7.68	58	8.36	59	8.74	61
Minke Whale, Migrating	3.40	75	3.96	82	4.34	84	4.66	85
Southern Right Whale, Migrating with Calf	4.73	75	5.87	75	6.89	72	7.65	70
Southern Right Whale, Migrating without Calf	4.29	77	4.99	77	5.35	81	5.49	84

Table 163. *Jacket pile installation – NAS, PULSE+DBBC, unweighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each site to the NOAA (2019) 160 dB re 1 µPa behavioural response marine mammal threshold.

Species	1 per day		2 per day		3 per day		4 per day	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy Blue Whale, Feeding	2.27	83	2.21	89	2.17	91	2.15	92
Pygmy Blue Whale, Northbound Migrating	2.01	78	2.00	82	2.04	81	2.07	80
Pygmy Blue Whale, Southbound Migrating	1.99	78	1.99	82	1.98	84	1.97	85
Humpback Whale, Migrating with Calf	2.22	80	2.30	84	2.29	86	2.28	86
Humpback Whale, Migrating without Calf	2.27	81	2.28	88	2.26	88	2.25	89
Minke Whale, Migrating	2.24	85	2.21	90	2.19	90	2.16	92
Southern Right Whale, Migrating with Calf	2.14	79	2.17	82	2.14	85	2.13	88
Southern Right Whale, Migrating without Calf	2.10	79	2.11	80	2.09	85	2.11	86

Table 164. *Jacket pile installation – NAS, PULSE+DBBC, LF-weighted SPL*: Exposure ranges ($ER_{95\%}$) in km from each Site to the Wood et al. (2012a) 50% chance of behavioural response for non-migrating (> 160 dB re 1 µPa) and migrating (> 140 dB re 1 µPa) mysticetes.

Species	1 per day		2 per day		3 per day		4 per day	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Non-migrating								
Pygmy Blue Whale, Feeding	0.91	69	0.91	70	0.88	75	0.87	77
Pygmy Blue Whale, Northbound Migrating	0.79	66	0.77	68	0.78	69	0.78	67
Pygmy Blue Whale, Southbound Migrating	0.83	63	0.80	64	0.79	65	0.79	65
Humpback Whale, Migrating with Calf	0.81	68	0.81	67	0.76	72	0.81	70
Humpback Whale, Migrating without Calf	0.81	72	0.81	69	0.84	68	0.81	70
Minke Whale, Migrating	0.82	62	0.81	70	0.82	70	0.83	70
Southern Right Whale, Migrating with Calf	0.83	65	0.81	70	0.81	70	0.82	71
Southern Right Whale, Migrating without Calf	0.76	64	0.77	68	0.77	69	0.77	69
Migrating								
Pygmy Blue Whale, Feeding	8.63	88	8.62	91	8.59	93	8.58	94
Pygmy Blue Whale, Northbound Migrating	8.24	74	8.13	82	8.06	86	7.98	88
Pygmy Blue Whale, Southbound Migrating	8.03	76	8.00	85	7.98	89	7.96	91
Humpback Whale, Migrating with Calf	8.43	85	8.42	90	8.40	91	8.36	93
Humpback Whale, Migrating without Calf	8.48	82	8.42	88	8.37	90	8.37	92
Minke Whale, Migrating	8.26	82	8.19	86	8.15	90	8.10	91
Southern Right Whale, Migrating with Calf	8.21	85	8.21	90	8.22	93	8.23	94
Southern Right Whale, Migrating without Calf	8.10	83	8.13	87	8.15	90	8.15	92

4.3. Concurrent Pile Driving Operations

The table below provides a summary of the different scenarios included in Sections 4.3.1 and 4.3.2.

Table 165. Summary of the modelled concurrent impact piling scenarios presented in the sections below. MP: monopile. OSS: Offshore substation

Scenario	Operation	Mitigation	Modelling round	Site	Site description (water depth)	Max. pile diameter	Hammer model	Season	Results presented	Sound source parameters	Noise effect threshold
1	Impact Piling: Concurrent Monopiles	None	First	1,1a	Deep SE (42 m)	12.5 m	IHC S-4000	Winter	Acoustic	Appendix C.2.3.1	Southall et al. 2019
2	Impact Piling: Concurrent Monopile and Jacket Pile	None	First	1 4	Deep SE (42 m) and OSS centre (24 m)	12.5 m and 3.25 m	IHC S-4000 IHC S-2300	Winter	Acoustic	Appendix C.2.3.1 Appendix C.2.3.1	Southall et al. 2019

4.3.1. Concurrent Monopile Installation

4.3.1.1. Scenario 1 – Unmitigated (First Modelling Round)

The sound field results are presented for the considered concurrent pile driving scenario. Results have been presented for two piles being installed at the same time in an offshore location of the OWF and the concurrent modelling represents a simultaneous hammer strike at each location.

4.3.1.1.1. Tabulated results

The tabulated isopleth distances presented below show a side-by-side comparison of the distances to effect criteria and simultaneous strike equivalent. Distances are presented in-terms of R_{max} for comparison worst-case predictions.

Table 166. *Monopile 1, aggregate piling, Winter, modelled maximum–over–depth per–strike SEL threshold*: Maximum (R_{max}) horizontal distances (in km) from the operational centroid for the worst–case penetration depth for unmitigated.

Threshold	Per–strike SEL (L_E; dB re 1 µPa²·s)	Unmitigated	
		Simultaneous strike	Independent strike
Squid and octopus startle response [a]	162[a]	16.65	13.20

[a] Startle response level for squid and octopus (Fewtrell and McCauley 2012).

Table 167. *Monopile 1, aggregate piling, Winter, modelled maximum–over–depth per–strike SPL thresholds*: Maximum (R_{max}) horizontal distances (in km) from the operational centroid for the worst–case penetration depth for simultaneous strikes and independent strikes for unmitigated.

Threshold	SPL (L_p; dB re 1 µPa)	Unmitigated	
		Simultaneous strike	Independent strike
Turtle behavioural response [a]	175	9.59	7.13
Turtle behavioural disturbance [b]	166	18.6	15.4
Marine mammal behavioural response [c]	160	31.3	23.8
LF-cetacean weighted behavioural response [d]	160	16.0	12.8
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	88.8	73.0
Penguin behavioural response [e]	120	44.8	33.2
Human health assessment [f]	145	>90.0	82.8

[a] Threshold for turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).
[f] Human health assessment threshold derived from Parvin (2005).

Table 168. *Monopiles, aggregate piling, Winter, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds for unmitigated.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Unmitigated	
		Simultaneous strike	Independent strike
PTS			
LF cetaceans	183	39.1	25.2
HF cetaceans	185	–	–
Otariid seals	203	–	–
Sea turtles	204	9.01	6.69
Penguins	203	–	–
TTS			
LF cetaceans	168	>90.0	89.9
HF cetaceans	170	0.14	0.14
Otariid seals	188	0.44	0.43
Sea turtles	189	31.7	24.7
Penguins	188	0.44	0.43

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} is smaller than the modelling resolution (20 m).

Table 169. *Monopiles, aggregate piling, Winter, fish, single pile SEL*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each pile to SEL_{24h} based fish criteria for temporary threshold shift (TTS). Fish I–No swim bladder; Fish II–Swim bladder not involved with hearing; Fish III–Swim bladder involved with hearing.

Fauna group	Threshold for SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	Unmitigated	
		Independent strike	Simultaneous strike
Fish I, II, III	186	45.3	40.1

Fish I–No swim bladder.
Fish II–Swim bladder not involved with hearing.
Fish III–Swim bladder involved with hearing.
An asterisk indicates that the threshold was not reached.

4.3.1.1.2. Sound field maps

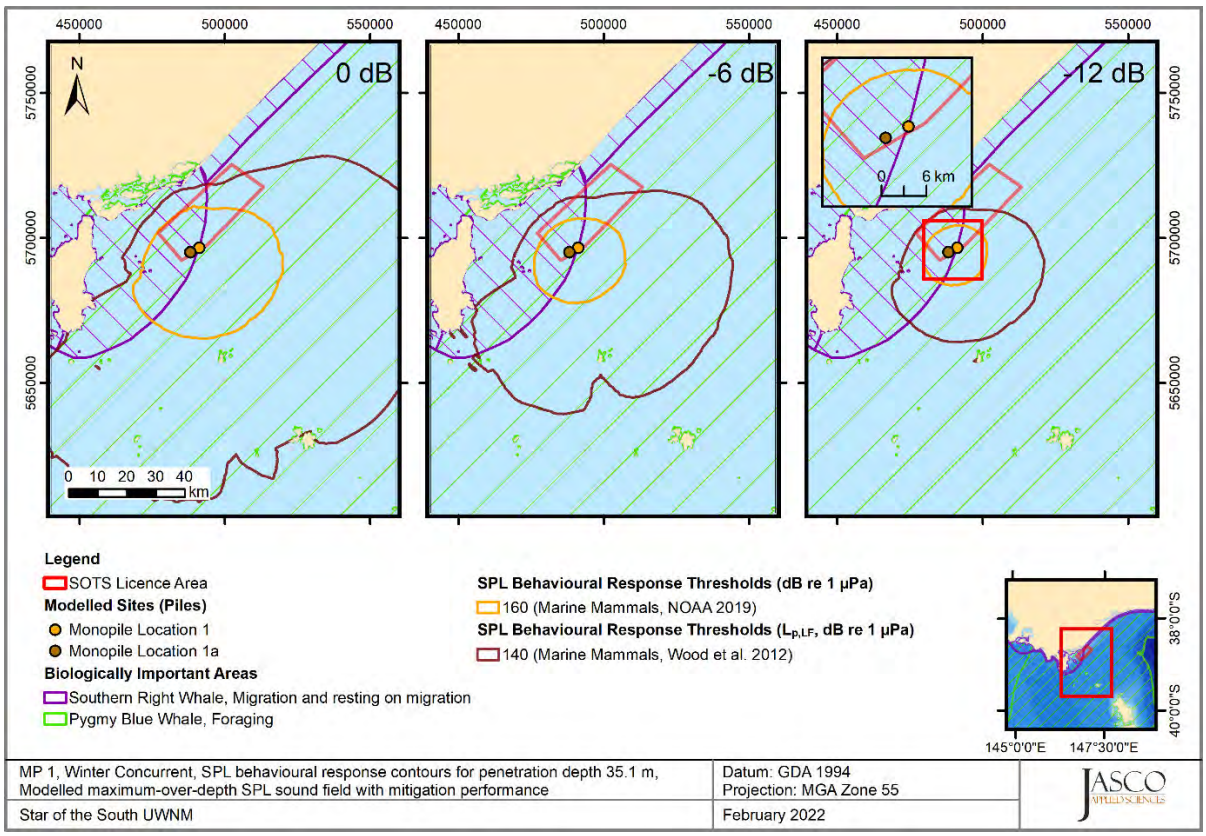


Figure 113. *Monopile 1, aggregate piling, winter, marine mammal behavioural criteria, SPL*: Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

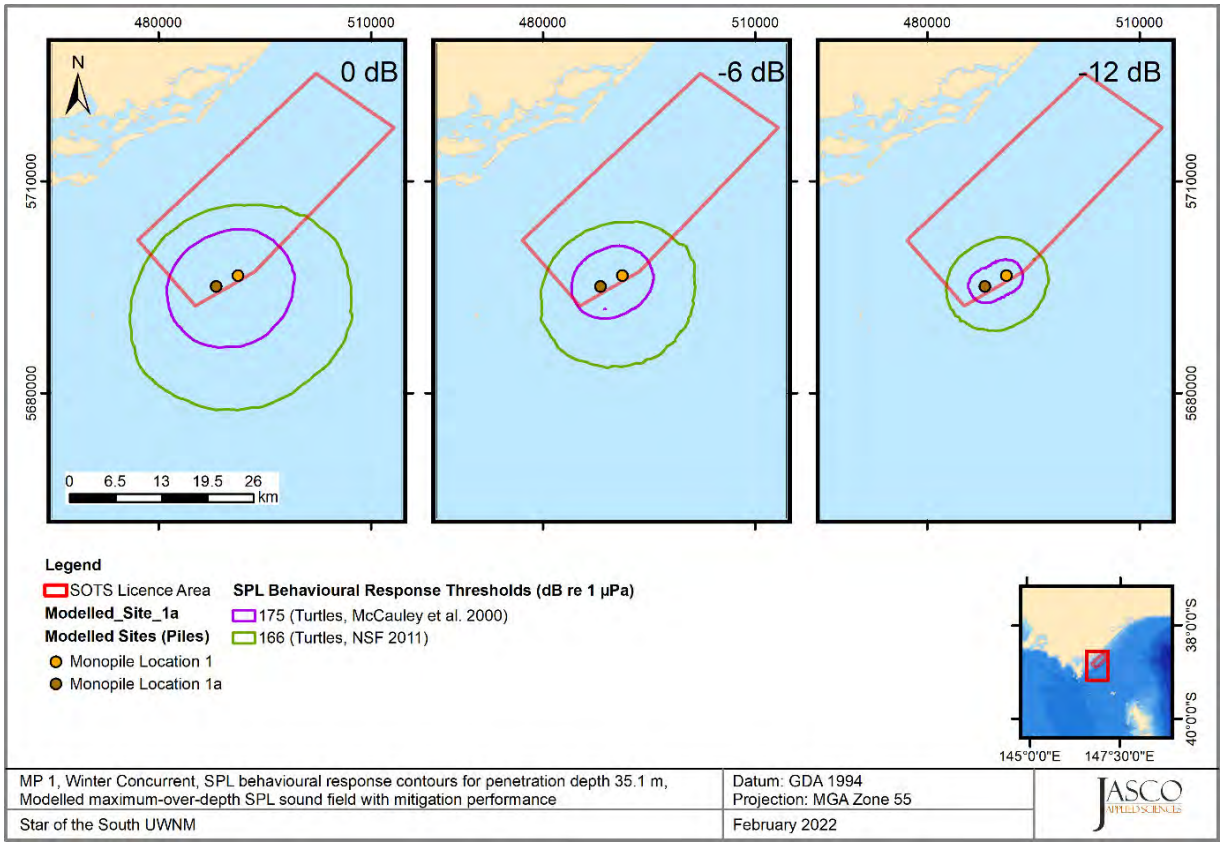


Figure 114. *Monopile 1, aggregate piling, winter, sea turtle behavioural criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

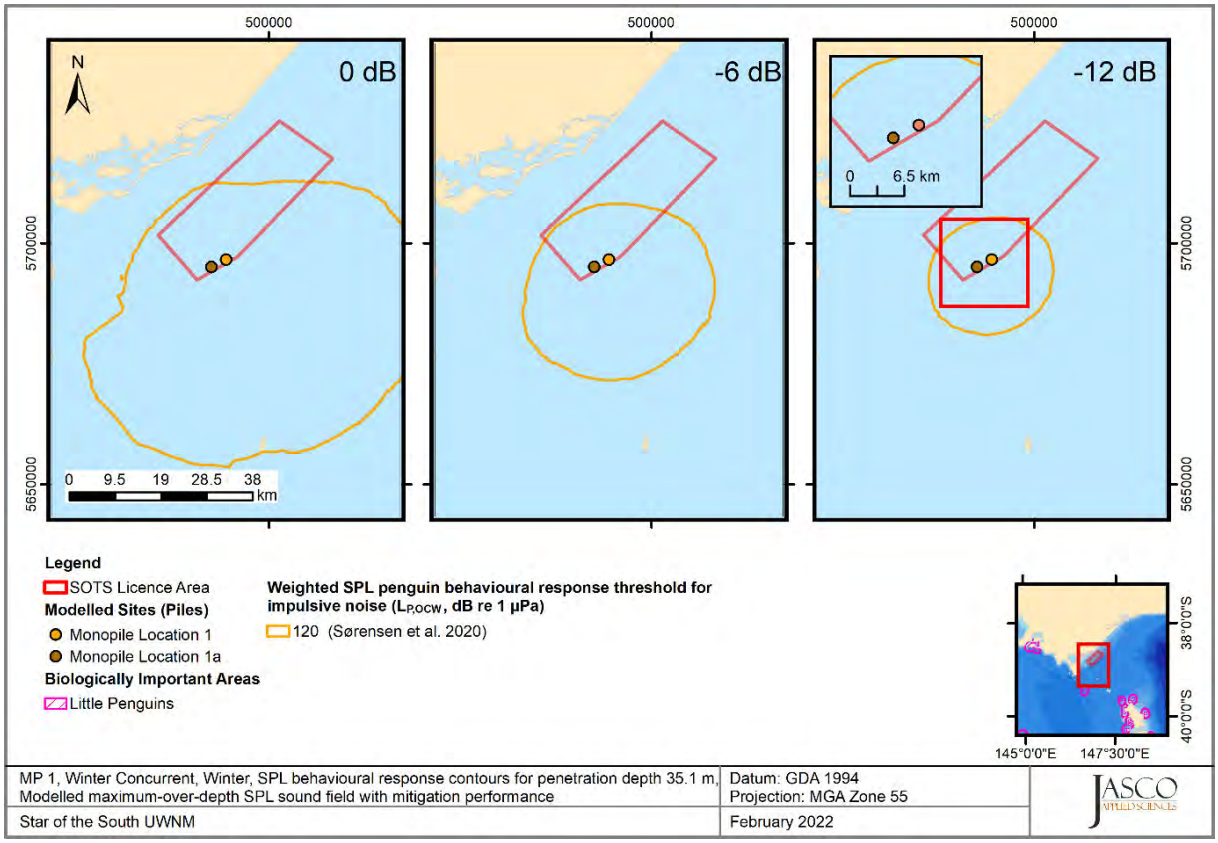


Figure 115. *Monopile 1, aggregate piling, winter, penguin behavioural criteria, SPL*: Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

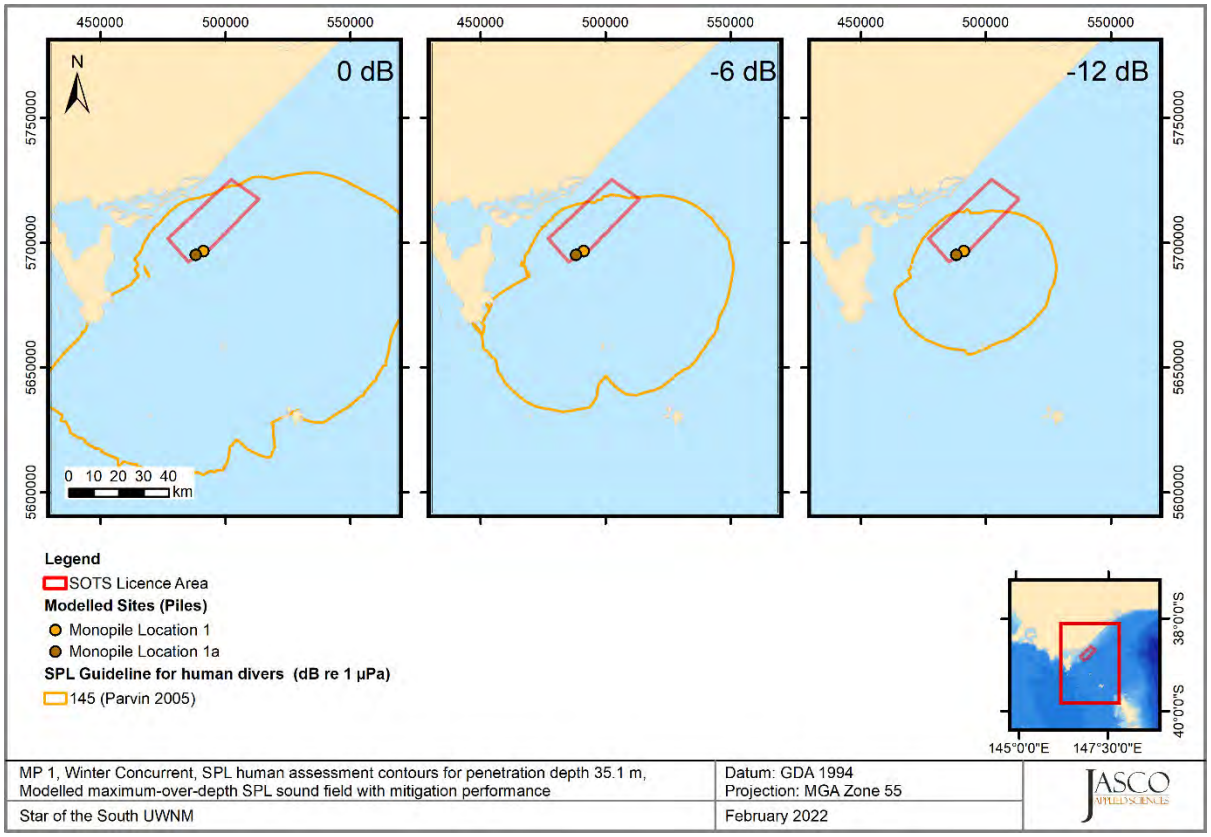


Figure 116. *Monopile 1, aggregate piling, winter, human health assessment criteria, SPL:* Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

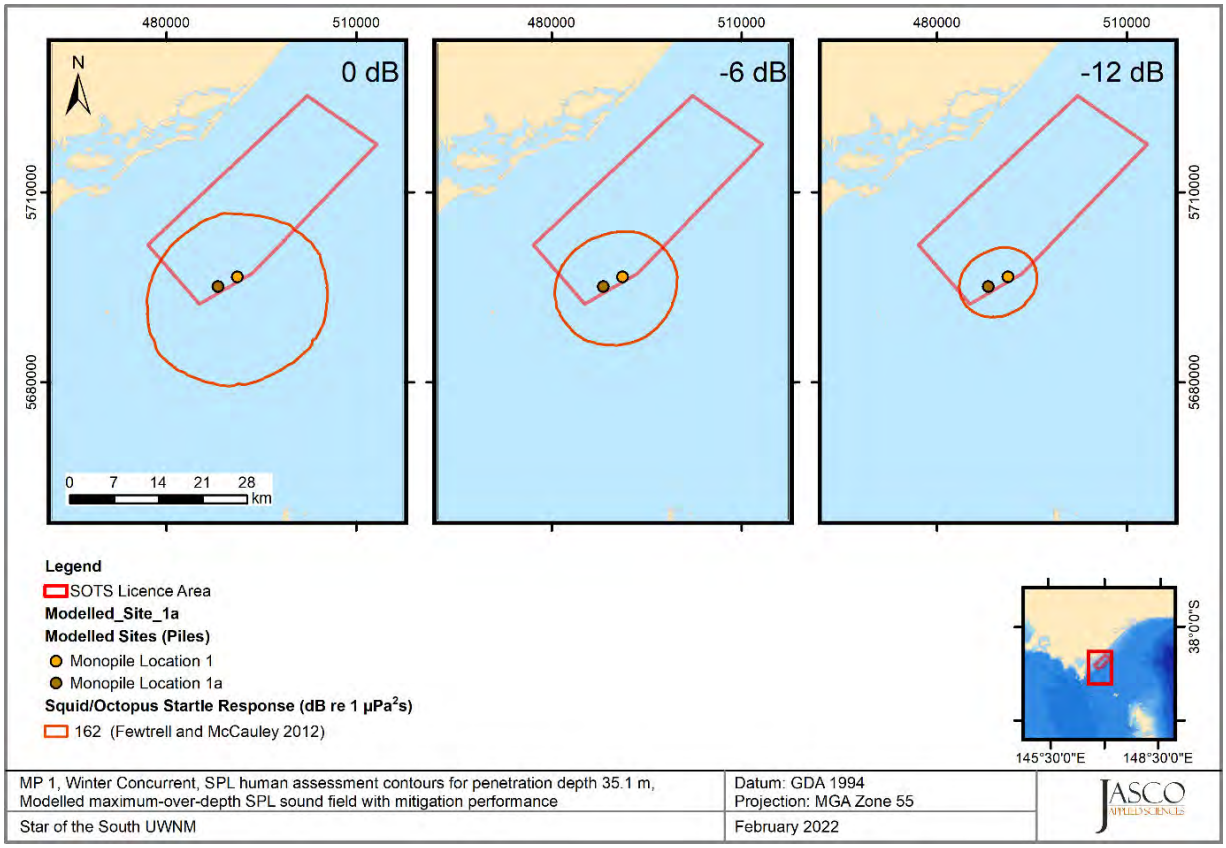


Figure 117. *Monopile 1, aggregate piling, winter, squid/octopus* startle response criteria*, per–strike SEL*: Sound level contour map showing maximum-over-depth SPL results for the third penetration depth. Panels from left to right showing unmitigated (left), 6 dB of mitigation (centre), 12 dB of mitigation sound level contours.

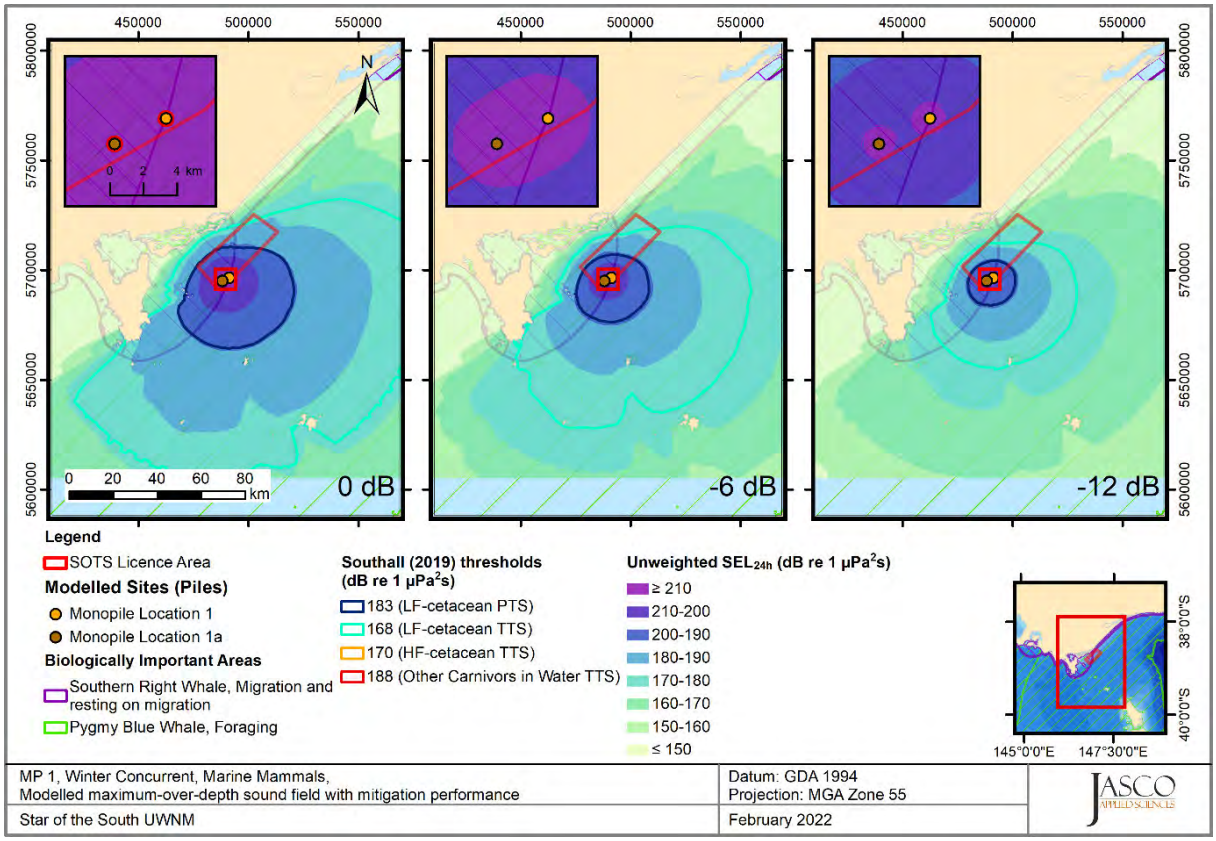


Figure 118. Monopile 1, aggregate piling, winter, marine mammals, SEL_{24h}: Contour map showing maximum–over–depth unweighted SEL24h isopleths. Panels from left to right showing unmitigated (Left), 6 dB of mitigation (Centre), 12 dB of mitigation (Right) sound level contours. Thresholds omitted here were not reached or not large enough to display graphically.

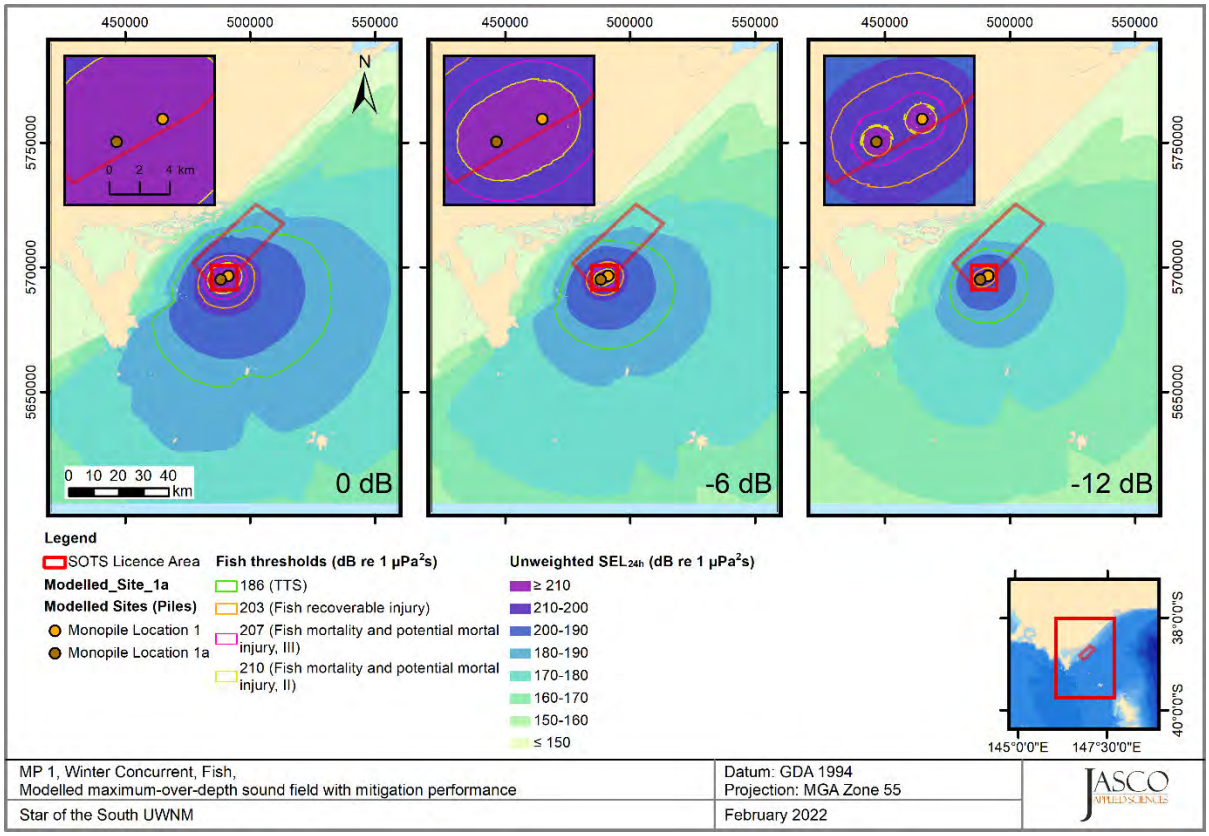


Figure 119. Monopile 1, aggregate piling, winter, fish, SEL_{24h}: Contour map showing maximum–over–depth unweighted SEL24h isopleths. Panels from left to right showing unmitigated (Left), 6 dB of mitigation (Centre), 12 dB of mitigation (Right) sound level contours. Thresholds omitted here were not reached or not large enough to display graphically.

4.3.2. Concurrent Monopile and Jacket Pile Installation

4.3.2.1. Scenario 2 – Unmitigated (First Modelling Round)

The sound field results are presented for the considered concurrent pile driving scenario. Results have been presented for two piles (a monopile and an OSS jacket pile) being installed at the same time in an offshore location of the OWF and the concurrent modelling represents a simultaneous hammer strike at each location.

4.3.2.1.1. Tabulated results

The tabulated isopleth distances presented below show a side-by-side comparison of the distances to effect criteria and simultaneous strike equivalent. Distances are presented in-terms of R_{max} for comparison worst-case predictions.

Table 170. *Monopile 1 and sub–station jacket pile, winter, marine mammal, sea turtle and penguin behavioural* response thresholds, SPL: Maximum (R_{max}) horizontal distances (in km) from the operational centroid for the worst–case penetration depth for simultaneous strikes and independent strikes.

Fauna group	SPL; dB threshold (L_p; re 1 µPa)	Monopile 1 + OSS Jacket Pile		
		Simultaneous strike	Monopile 1 Independent strike	Jacket Independent strike
Sea turtle behavioural disturbance [b]	175	13.4	7.13	1.87
Sea turtle behavioural response [a]	166	21.5	15.4	5.00
Marine mammal behavioural response [c]	160	29.8	23.8	8.62
LF-cetacean weighted behavioural response [d]	160	18.9	12.8	4.98
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	140	80.2	73.0	53.0
Penguin behavioural response [e]	120	46.1	33.2	29.3
Human health assessment threshold	145	88.5	82.2	51.1

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000b).
[b] Threshold for sea turtle behavioural response to impulsive noise (NSF 2011).
[c] Marine mammal behavioural threshold for impulsive sound sources (NOAA 2019).
[d] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)
[e] Penguin behavioural response threshold for impulsive noise (Sørensen et al. 2020).

Table 171. *Monopile 1 and sub–station jacket pile, winter, accumulated SEL:* Maximum (R_{max}) horizontal distances (in km) to permanent threshold shift (PTS) and temporary threshold shift (TTS) thresholds.

Fauna group	Weighted SEL thresholds ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1 + 4 Jacket Piles		
		Simultaneous Drive	Monopile 1	4 Jacket Piles
PTS				
LF cetaceans	183	32.6	25.2	16.0
HF cetaceans	185	–	–	–
Otariid seals	203	–	–	–
Sea turtles	204	12.9	6.69	3.05
Penguins	203	–	–	–
TTS				
LF cetaceans	168	>90.0	>90.0	>90.0
HF cetaceans	170	0.14	0.14	0.40
Otariid seals	188	0.43	0.43	0.61
Sea turtles	189	31.6	24.7	13.1
Penguins	188	0.43	0.43	0.61
Fish temporary threshold shift (TTS)				
I, II, III	186	46.1	40.1	20.0

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.3.2.1.2. Sound field maps

The following presents the contour maps:

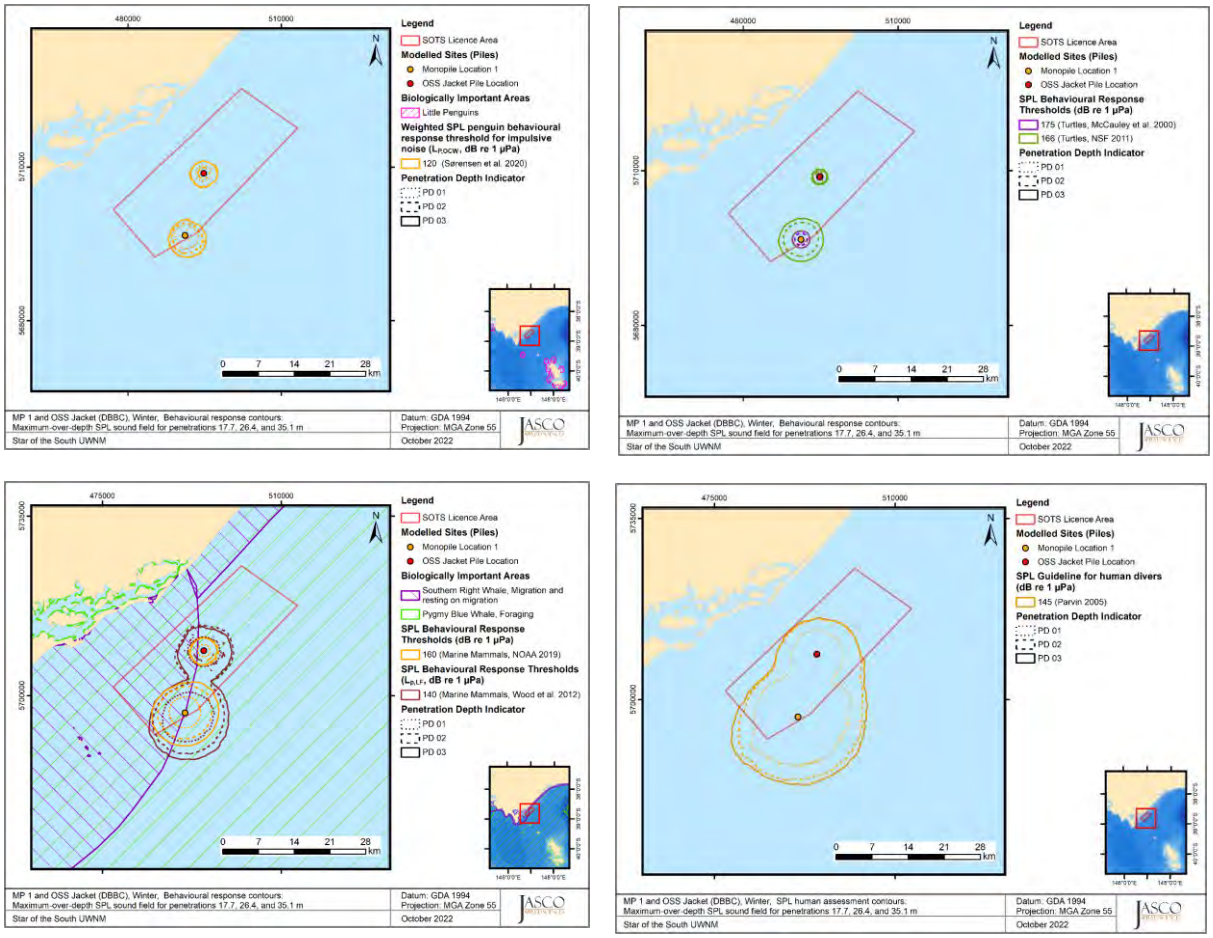


Figure 120 *Monopile 1 and sub–station jacket pile, DBBC, winter marine mammal behavioural criteria (top left), sea turtle behavioural criteria (top right), penguin behavioural criteria (bottom left), human health assessment criteria (bottom right), SPL: Sound level contour map showing maximum–over–depth results for all penetration depths.*

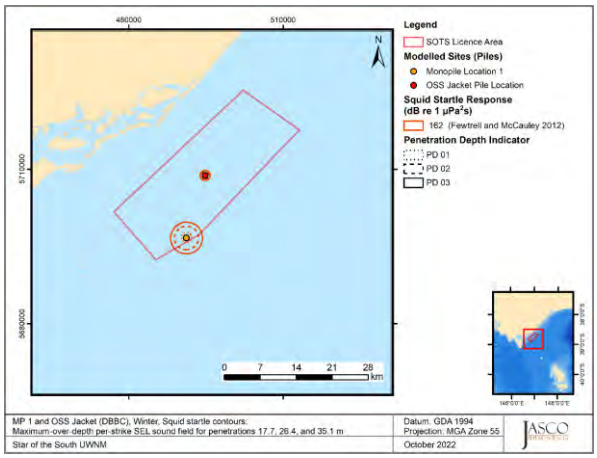


Figure 121. *Monopile 1 and sub–station jacket pile, DBBC, winter, squid* startle response criteria*, per–strike SEL*: *Sound level contour map showing maximum–over–depth results for all penetration depths.*

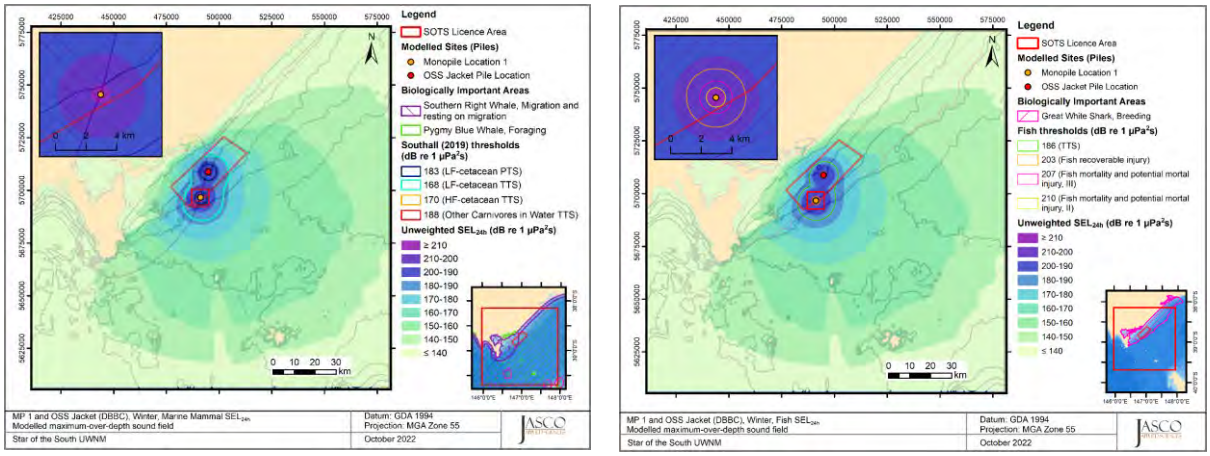


Figure 122. *Monopile 1 and sub–station jacket pile, DBBC, winter, marine mammals (left) and fish (right), SEL$_{24h}$*: Contour map showing maximum–over–depth unweighted SEL$_{24h}$ isopleths. Thresholds omitted here were not reached or not large enough to display graphically.

4.4. Summary: Impact Pile Driving

4.4.1. Monopiles

The latest modelling study predicted underwater sound levels associated with impact piling monopiles under a variety of mitigation or NAS (Noise attenuation system) scenarios. The PULSE hammer damping mechanism, double big bubble curtain (DBBC) and hydro sound damper (HSD) systems were considered for frequency dependent attenuation NAS modelling (Section 3.4).

The noise generated from monopile foundation installation at four locations within the Licence Area were modelled and considered the specifications for each pile and five pile sediment penetrations / energies over the duration of the drive.

Noise emissions from pile driving were considered here to be cylindrically isotropic (i.e., omnidirectional in the horizontal plane). As such, variations in noise that propagates across azimuths are attributed to the bathymetry or seabed layering. When the hammer strikes the pile, noise propagates into the water as a downward Mach cone (see Appendix B.1). A portion of the energy from the strike is also reflected at the pile bottom, generating an upward Mach cone. This cycle of downward propagation, reflection, and upward propagation occurs multiple times per strike. At close range from the pile, noise levels are determined by the summation of Mach cones, which might add constructively (i.e., their summation results in a total wave with higher amplitude than the original ones) or destructively (i.e., wavefronts can cancel each other, resulting in low amplitudes). The way in which Mach cones combine with each other is strongly dependent on their frequency content of the signal, which in turn are determined by the hammer forcing function and the pile dimensions. Due to the relation between the speed of sound in steel (~5000 m/s) relative to the speed of sound in the water (~1500 m/s at the depth of the pile), the Mach cone propagates away from the pile and impinges the seabed at an angle of ~17°, as shown in Figure 123 for example.

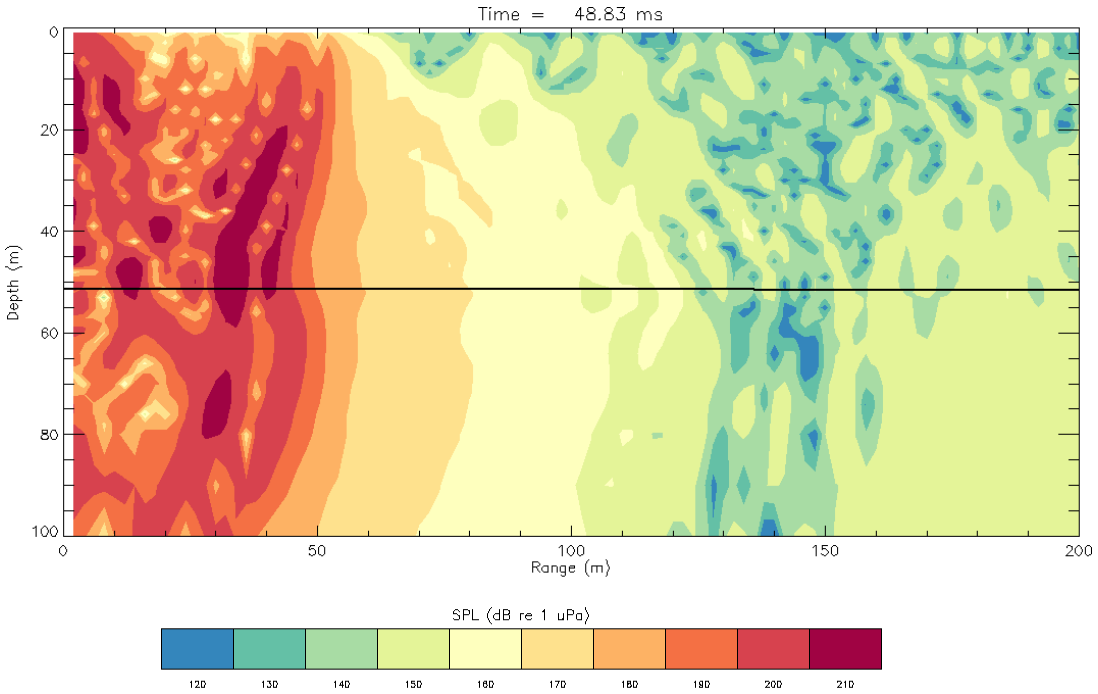


Figure 123. Monopile 3, winter, IQ4, third penetration depth (25.8 m) unweighted SPL sound field time snapshot slice showing the Mach cone propagation. The black line indicates the seafloor interface.The extents of the per-strike sound fields depend significantly on parameterisation of the source, particularly the driveability profile and applied hammer energy. Hammer energy is one of the main factors influencing acoustic isopleth extents, particularly the higher applied energies as a pile is embedded deeper into the seabed. The higher strike energies correlate to larger per-strike sound field extents. The representation of the entire piling operation for each pile, i.e. accumulated sound fields, involves accounting for each strike and its associated footprint as well as repeated strikes. The high hammer energies and many strikes are two main factors influencing accumulated sound energy isopleth extents.

The modelling of the five penetration depths for each pile provides a detailed quantification of the associated sound levels for different portions of the pile drive. The distances to per-strike isopleths are generally farthest when most of the pile is in the water column and when a pile is struck with the highest energy. For the modelled monopiles the pile will always span the entire water column, as such the hammer energy is most influential on the radiated noise emissions.

It is not possible to compare the “source levels” of different piles because they are distributed sources; however, it is possible to compare levels at a close range to the pile. The decidecade–band levels at the receiver with the highest SEL at a horizontal range of 10 m can be used for comparison purposes. The broadband sound energy for the IQ4 hammer at each penetration depth ranged from 198.7–203.6 dB re 1 $\mu Pa^2 \cdot s$ with the highest amount of sound energy concentrated in the frequency range 40 to 200 Hz.

For the specific frequency dependent attenuation of an NAS, the overall performance depends on several parameters. These include factors like the dominant frequency produced by the pile when driven and the mechanical properties of the hammer, pile, helmet, and soil during a pilling strike. These ultimately determine the sound level and frequency content of noise produced by the driven pile. Variability and uncertainty in modelling parameters could result in frequency shifts to higher or lower frequencies and this could result in overlap with frequencies where the bubble curtains are more or less effective (Section 3.4.4.1).

The considered mitigation systems, like the DBBC, HSD and their combination, are only good at mitigating noise that is generated in the water column. Since all piles extend through the water column

and the seabed, the performance of these systems may be degraded due to energy returning from within the seabed.

The incorporation of the PULSE mitigation NAS is particularly relevant in this context. The PULSE system reduces underwater noise emissions during impact piling; by increasing the duration of the hammer's forcing function. PULSE spreads the energy of each strike over a longer time interval. This reduces peak sound pressure levels and shifts the dominant frequency content to lower ranges. This temporal elongation modifies the stress wave that travels down the length of the pile, which in turn alters how sound waves are generated both in the water column and within the seabed. These changes can reduce the intensity and frequency of seabed-borne energy that may otherwise propagate beneath noise attenuation systems (NASs) such as double big bubble curtains (DBBC) and hydro sound dampers (HSD).

The broadband sound energy for the IQ4 hammer with the PULSE system, ranged from 179.9–192.3 dB re 1 μPa^2·s with the highest amount of sound energy concentrated in the frequency range 20 to 40 Hz. Figure 124 provides a comparable example to Figure 123, (this contain a scenario with the PULSE and a DBBC); it shows the a Mach cone generated when a pile is struck but the relative amplitude is lower than the corresponding unmitigated example. These changes in the propagating waves can also be seen within the seabed.

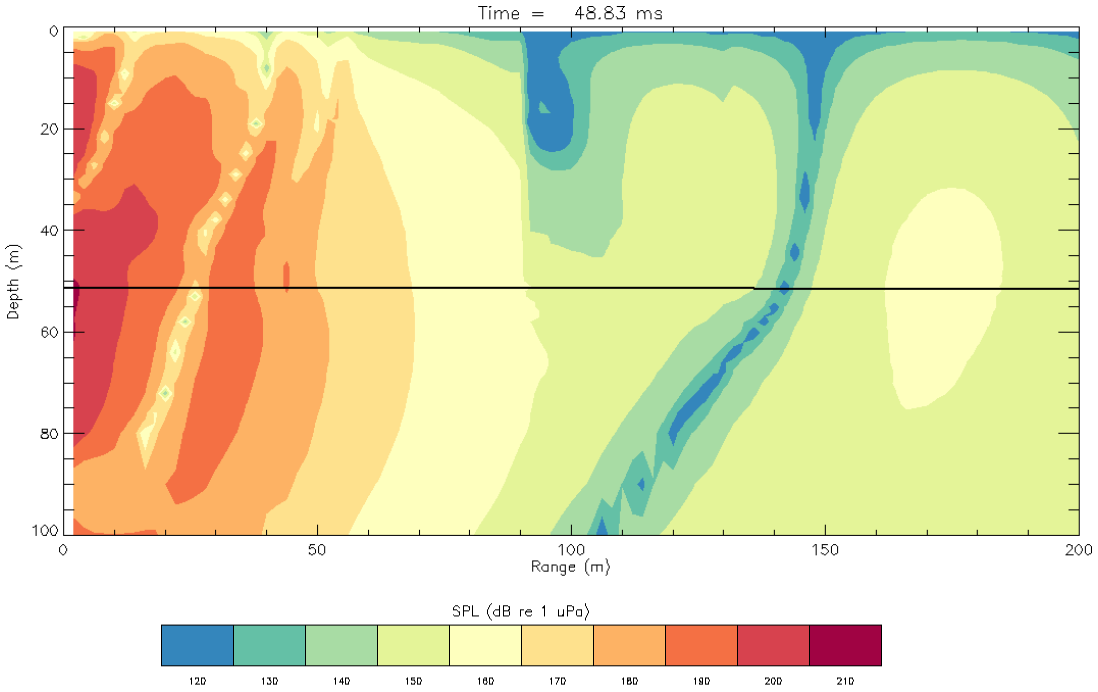


Figure 124. Monopile 3, winter, IQ4+*PULSE+DBBC*, third penetration depth (29.4 m) unweighted SPL sound field time snapshot slice showing the Mach cone propagation.The black line indicates the seafloor interface.In general, for all monopile modelling there is also uncertainty in the seabed geoacoustic properties resulting in uncertainty in sound propagating in the seabed; these uncertainties could result in shifted spectral content, levels, and/or distances where sound recouples from the substrate.

For criteria based on SEL_{24h} metrics, the ranges above must be considered in context of the duration of operations. One monopile will be driven per day; therefore, the corresponding sound level is denoted as SEL_{24h}. However, the estimated time for driving a single pile was ~2–3 h within a 24 hour period for a monopile. The SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within the driving period and assumes that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure since. More realistically, marine fauna such as marine mammals,

sea turtles, and penguins would not stay in the same location or at the same range for an extended period, however site attached fish and invertebrates might. Therefore, a reported radius associated with the accumulated SEL criteria does not mean that any animal travelling within this radius of the source *will* be injured, but rather that it *could* be injured if it remained in that range for the entire period of driving. The animat modelling was completed to provide additional context to these results for humpback, southern right and pygmy blue whales, as it allows receivers to move throughout the modelling region while being exposed to pulses emitted from pile driving.

Table 172 summarises the largest distance to behavioural response criteria for marine mammals and sea turtles considered in this study. A key example of the performance of NASs and the attenuation at higher frequencies when applying the HSD+DBBC system with the PULSE system can be seen in the significant reduction in ranges for LF-cetacean behavioural response for the single-strike ranges to the frequency weighted 140 dB, which has reduced from a maximum of 82.9 km to a minimum of 6.13 km for monopile 1.

Table 173 summarises the largest distance to injury thresholds for marine mammals, turtles and diving birds considered in this study, which in all cases corresponded to the SEL_{24h} metric. This table allows easy comparison of the distance reduction as a result of applying different NAS combinations.

Table 172. *Monopiles summary of marine mammal and sea turtle behavioural response thresholds*: distances (R_{max} in km) to SPL acoustic behavioural response thresholds for unmitigated and mitigated impact piling. Distances at the penetration depth that results in the farthest ranges are presented.

Fauna group	SPL threshold (L_p; re 1 µPa)	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
		None	PULSE+HSD+ DBBC	None	PULSE+HSD+ DBBC	None	PULSE+HSD+ DBBC	None	PULSE+HSD+ DBBC
Sea turtle behavioural disturbance [a]	175	4.23	0.62	4.63	0.46	4.55	0.17	3.62	0.28
Sea turtle behavioural response [a]	166	8.67	2.95	11.7	2.35	9.41	1.12	7.93	1.34
Marine mammal behavioural response [b]	160	14.0	5.64	20.8	5.18	13.2	2.37	12.3	2.72
LF-cetacean weighted behavioural response [c]	160	8.22	0.51	12.1	0.31	9.65	0.13	8.27	0.13
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	84.7	7.17	78.9	6.37	42.8	3.21	38.7	3.17
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	>90.0	36.6	>90.0	24.0	>90.0	16.2	>90.0	13.9

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).

Table 173. *Monopiles summary of permanent threshold shift (PTS)/auditory injury and temporary threshold shift (TTS) thresholds:* distances (R_{max} in km) to SEL_{24h} acoustic thresholds for marine mammals, fish, and sea turtles, for unmitigated and mitigated impact piling.

Hearing group	$L_{E,24h}$ threshold	Monopile 1		Monopile 2		Monopile 3		Monopile 4	
		None	PULSE+HSD+ DBBC	None	PULSE+HSD+ DBBC	None	PULSE+HSD+ DBBC	None	PULSE+HSD+ DBBC
PTS/AUD INJ									
LF cetaceans	183	12.1	0.77	17.4	0.41	14.9	0.18	11.8	0.36
HF cetaceans	193	0.06	–	0.03	–	0.13	–	0.03	–
Otariid seals	185	0.08	–	0.09	–	0.16	–	0.12	–
Sea turtles	184	9.56	0.09	13.2	0.09	12.5	0.09	9.85	0.09
Penguins	185	0.08	–	0.09	–	0.16	–	0.12	–
TTS									
LF cetaceans	168	83.6	8.61	78.6	5.48	42.9	3.30	36.0	3.56
HF cetaceans	178	0.89	–	0.66	–	1.35	–	0.76	–
Otariid seals	170	1.43	–	1.21	–	2.20	–	1.25	–
Sea turtles	169	83.4	1.14	78.2	0.75	42.7	0.36	28.3	0.39
Penguins	170	1.43	–	1.21	–	2.20	–	1.25	–
Fish	186	15.1	7.82	22.6	5.63	18.1	3.05	14.4	3.74

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.4.2. Jacket Piles

The latest modelling study predicted underwater sound levels associated with impact piling jacket piles for an Offshore Sub-Station (OSS), under a variety of mitigation or NAS (Noise attenuation system) scenarios. The PULSE hammer damping mechanism and double big bubble curtain (DBBC) systems were considered for frequency dependent attenuation NAS modelling (Section 3.4).

Jacket piles were considered for the OSS foundations, installed through impact piling. Table 12 presents the location where the site was modelled considering the specifications for the jacket pile and three pile sediment penetrations / energies over the course of the drive. The broadband sound energy at 10 m for each penetration depth ranged from 173.0–183.5 dB re 1 $\mu Pa^2 \cdot s$ with the peak sound energy concentrated in the frequency range 50 to 300 Hz, refer to Figure 92. The broadband sound energy for the IQ4 hammer with the PULSE system, ranged from 169.8–178.1 dB re 1 $\mu Pa^2 \cdot s$ with the highest amount of sound energy concentrated in the frequency range 20 to 100 Hz, refer to Figure 92.

Compared to the monopiles, the numerical results indicate that the inclusion of the PULSE system results in a less substantial drop in received levels. This is apparent when comparing levels and spectra between Figure 92 and Figure 130. The shape of the forcing function for the jacket pile (see Figure C-11) with and without the PULSE system have not changed as significantly as those of the monopiles. Therefore, the damping effect of the PULSE system appears to be less effective with the combination of the jacket piles and IQ4 hammer and the PULSE system. A possible explanation might be that the IQ4 hammer is oversized for the smaller jacket piles.

For the OSS jacket foundation modelled in this study, the piles do not always fully span the entire water column, and at the completion of the drive only approximately 2 m of the pile will remain protruding above the seabed. A subsea hammer is proposed to be used to accomplish this. The maximum distances to per-strike isopleths generally occur in the middle of the drive when there is still 26 m of the pile spanning the water column, 36 m within the sediment, and the hammer is operating at a higher energy. For jacket piles installed with this method, the largest acoustic ranges will likely occur when the pile is struck with a high energy and when the majority of the pile is exposed to the water column. Conversely the distances are shortest at the end of piling when most of the pile is buried in the sediment. The amount of the pile within the water column limits the energy emitted into the water column despite the pile approaching refusal and the highest hammer energies being applied the final stages of driving.

The extents of the per-strike sound fields depend significantly on parameterisation of the source, particularly the driveability profile and applied hammer energy. For the seabed considered here, which is mechanically resistive to pile driving, the applied hammer energies coupled with the number of strikes required (7201) over the majority of the pile drive are the main factors influencing acoustic isopleth extents for the full-pile SEL metrics.

For criteria based on SEL_{24h} metrics, the ranges above must be considered in context of the duration of operations. Up to four jacket piles will be driven per day; therefore, the corresponding sound level is denoted as SEL_{24h}. However, the estimated time for driving a single pile was 3.75 h. The total time to consecutively install four jacket piles, which is the operationally nominated amount, is 15 h. The distances to thresholds based on SEL_{24h} metrics for one jacket pile versus four jacket piles increase due to the additional accumulated energy of four piles compared to a single pile. The accumulated energy from four piles is equivalent to increasing all levels of a single by a factor of $10\log_{10}(4) = 6.02$ dB to account for the additional strikes for additional piles. Received levels generally follow a logarithmic decay trend as a function of distance from the source, and because of this decay, received levels typically decay more rapidly near the source compared to further away. Therefore, for a receiver is a far distance from the pile a small change in level can have a comparably larger change in the isopleth distance, as seen by the four versus single jacket pile comparison.

As discussed for the monopiles, SEL_{24h} is a cumulative metric that reflects the dosimetric impact of noise levels within the driving period and assumes that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure since. More realistically, marine fauna such as marine mammals, sea turtles, and penguins would not stay in the same location or at the same range for an extended period, however site attached fish and invertebrates might. Therefore, a reported radius associated with the accumulated SEL criteria does not mean that any animal travelling within this radius of the source *will* be injured, but rather that it *could* be injured if it remained in that range for the entire period of driving.

Table 174 summarises the largest distance to behavioural response criteria for marine mammals and turtles considered in this study. Table 175 summarises the largest distance to injury thresholds for marine mammals, turtles and diving birds considered in this study, which in all cases corresponded to the SEL_{24h} metric. This table allows easy comparison of the distance reduction as a result of applying mitigations.

Table 174. *Jacket pile, summary of marine mammal and sea turtle behavioural response thresholds*: distance (R_{max} in km) to SPL acoustic behavioural response thresholds for unmitigated and mitigated piling. Distances at the penetration depth that results in the farthest ranges are presented.

Fauna group	SPL (L_p; dB re 1 µPa)	Single Jacket Pile Mitigation Scenarios	
		None	PULSE+DBBC
Sea turtle behavioural disturbance [a]	175	0.96	0.19
Sea turtle behavioural response [a]	166	3.21	1.11
Marine mammal behavioural response [b]	160	6.57	2.60
LF-cetacean weighted behavioural response [c]	160	2.87	1.10
LF-cetacean weighted behavioural response (migrating mysticetes) [c]	140	49.1	9.67
LF-cetacean weighted behavioural response (migrating mysticetes) [d]	120	>90	>90

[a] Threshold for sea turtle behavioural disturbance from impulsive noise (McCauley et al. 2000a)
[b] Marine mammal behavioural threshold for impulsive sound sources NOAA (2024).
[c] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[d] Behavioural response weighted threshold for a 10% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).

Table 175. *Jacket piles, summary of permanent threshold shift (PTS)/auditory injury and temporary threshold shift (TTS)* distance (R_{max} in km) to SEL_{24h} acoustic thresholds for marine mammals, fish, and sea turtles, for unmitigated and mitigated piling.

Hearing group	$L_{E,24h}$ threshold	Single Jacket Pile Mitigation Scenarios		Jacket Pile x2 Mitigation Scenarios		Jacket Pile x3 Mitigation Scenarios		Jacket Pile x4 Mitigation Scenarios	
		None	PULSE+DBBC	None	PULSE+DBBC	None	PULSE+DBBC	None	PULSE+DBBC
PTS									
LF cetaceans	183	5.32	1.93	7.35	3.00	8.86	3.71	10.1	4.30
HF cetaceans	193	–	–	–	–	–	–	0.02	–
Otariid seals	185	–	–	0.02	–	0.03	–	0.05	–
Sea turtles	184	3.69	1.37	5.30	2.14	6.46	2.72	7.29	3.14
Penguins	185	–	–	0.02	–	0.03	–	0.05	–
TTS									
LF cetaceans	168	49.1	11.4	49.3	15.6	53.0	19.2	59.9	22.4
HF cetaceans	178	0.12	0.02	0.17	0.05	0.23	0.06	0.33	0.06
Otariid seals	170	0.18	0.05	0.33	0.06	0.56	0.11	0.60	0.16
Sea turtles	169	21.2	8.71	49.2	12.0	49.3	14.4	49.4	16.5
Penguins	170	0.18	0.05	0.33	0.06	0.56	0.11	0.60	0.16
Fish	186	7.94	3.90	10.9	5.65	13.3	6.86	15.3	7.74

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

4.4.3. Concurrent Pile Driving

Concurrent piling operations were modelled in the first modelling round, and the potential increase in sound per-strike energy for two equivalent sources is at most 3 dB at any receiver location. This would represent a doubling of energy at any location. Considering the different pile sizes and hammers used, it is more likely that combination of levels would result in less than a doubling of energy. Different rates propagation loss from the two sources also results in a further difference in level as they combine at a given receiver. The main consequence in this instance is that one source is likely to dominate the sound file extents over the other. The installation of a monopile would dominate the sound field isopleths in the considered concurrent scenario. In all case concurrent operations resulted in equal or larger distances to criteria/threshold compared to those for a single monopile (i.e., Monopile 1).

5. Vibro Pile Driving

Table 176 presents the overview of the modelling round, the type(s) of results being presented, a reference to find the sound source parameter and main noise effect threshold reference. Details can be found in the corresponding result sections.

Table 176. Overview of vibro pile driving result presentation

Scenario (operation)	Mitigation	Modelling round	Results presented	Sound source parameters	Noise effect threshold
1 (Monopile)	None	Third	Acoustic	Appendix C.2.3.1 Appendix C.2.3.3	NMFS 2024
1 (Jacket Pile)	None	Third	Acoustic	Appendix C.2.3.1 Appendix C.2.3.3	NMFS 2024

5.1. Monopile Installation Operations

The table below provides a summary of the scenario included in Section 5.1.2.

Table 177. Summary of the modelled vibro piling scenarios presented in the sections below. MP: monopile.

Scenario	Operation	Mitigation	Modelling round	Site	Site description (water depth)	Max. pile diameter	Hammer model	Season	Results presented	Sound source parameters	Noise effect threshold
1	Vibro Piling: monopile	None	Third	MP1	Shallow NW (21 m)	9.2 m	GIANT4000	Winter	Acoustic	Appendix C.2.3.1 Appendix C.2.3.3	NMFS 2024
				MP2	Intermediate (34.7 m)	11.0 m					
				MP3	Deepest SW (51.3 m)	11.8 m					

5.1.1. Parameterisation and Methodology: Monopiles

JASCO's pile driving source model (PDSM, MacGillivray 2014) was used in conjunction with the GRLWEAP 2010 wave equation model (Pile Dynamics 2010) to predict source levels associated with pile driving activities.

GRLWEAP, which includes a database of commercial impact hammers, was used to model a forcing function at the top of the pile. PDSM computes the underwater vibration and sound radiation of a pile using a finite difference scheme which utilises the forcing function of the hammer at the top of the pile and the mechanical resistance of the seabed at the base of the pile. See Appendix B.1 for more detail. Given that piles are distributed sources (Appendix B.1), they cannot be accurately approximated by a point source. As such, the sound radiating from the pile itself is simulated using a vertical array of discrete point sources, as described in Appendix B.1.

The hammer penetration rates values used in this acoustic modelling study was developed in considering the driveability information provided by the Star of the South, which included number of penetrations rate per metre of the pile drive. The drive was divided into five depth intervals, each with a different pile penetration depth and average penetrations rate. This was done to represent the different portions of the pile drive while maintaining computation efficiency. Table presents the parameters that were used for acoustic modelling is presented in Appendix C.2.3.3.

5.1.2. Results: Acoustic Modelling

Received Levels at 10 m – Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. The figures below show the decidecade–band levels for the receiver with the highest SEL at a horizontal range of 10 m, for each of the modelled penetrations. The levels above 1000 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports and literature, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

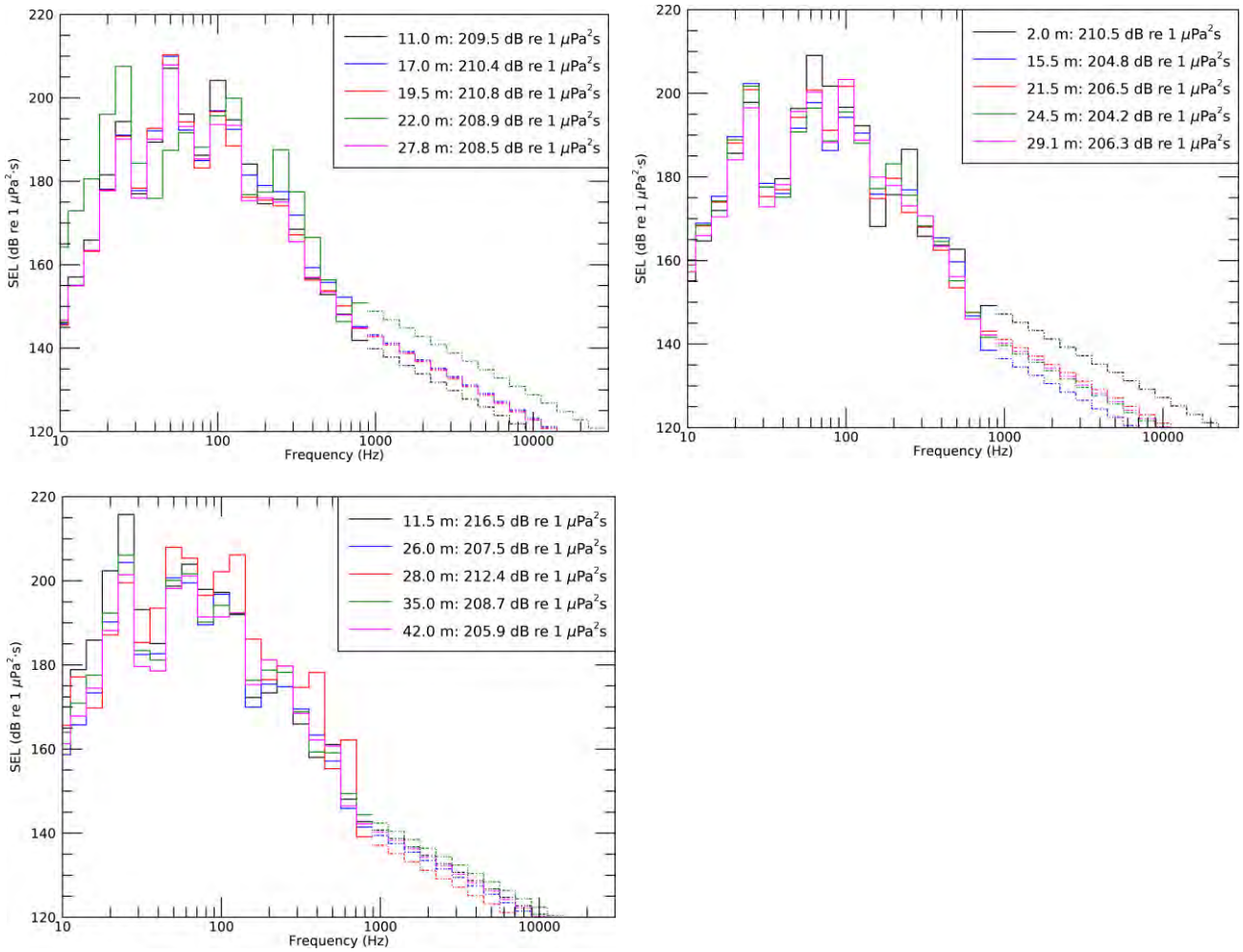


Figure 125. *Monopile 1 (top left), Monopile 2 (top right), Monopile 3 (bottom left), winter, third modelling round,* Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for vibro piling using the GIANT 4000 hammer, after high–frequency extrapolation(dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 µPa

Scenario 1 – Unmitigated (Third Modelling Round)

The SPL sound fields for the modelling sites are presented in the following section. The results are presented in terms of average instantaneous SPL as well as Accumulated SEL over the duration of the pile drive but within the assessment time frame of 24 hours. Hence results are referenced with respect to an SEL_{24h} metric.

5.1.2.1.1. Tabulated results

Table 178. *Monopile 1, modelled maximum–over–depth SPL isopleths for per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 1									
	Penetration depth (m)									
	11.0		17.0		19.5		22.0		27.8	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.43	0.41	0.57	0.55	0.72	0.70	0.34	0.31	0.51	0.39
180	2.32	2.09	2.72	2.46	2.83	2.63	2.65	2.40	2.31	2.07
170[a]	5.90	5.35	6.18	5.88	6.43	6.13	8.75	7.84	5.58	5.31
160	12.1	10.4	12.5	10.9	13.1	11.3	17.7	15.2	11.6	10.0
158[b]	14.1	11.9	14.6	12.4	15.1	12.8	19.6	17.0	13.4	11.4
150	28.8	24.3	25.5	21.9	26.0	22.8	29.6	24.0	23.2	19.8
140	82.4	57.4	48.8	39.9	48.7	39.8	49.0	39.5	48.8	38.5
130	>90.0	/	84.5	73.4	83.4	64.7	>90.0	/	>90.0	/
120[c]	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 179. *Monopile 2, modelled maximum–over–depth SPL isopleths for per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 2									
	Penetration depth (m)									
	2.0		15.5		21.5		24.5		29.1	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.80	0.74	0.46	0.42	0.56	0.53	0.34	0.33	0.66	0.54
180	4.11	3.76	2.81	2.42	3.41	2.73	2.30	2.05	3.53	2.77
170[a]	14.5	12.9	8.03	7.18	9.02	7.68	7.21	6.64	9.45	7.90
160	43.2	36.1	17.6	15.2	20.2	17.3	15.5	13.9	21.0	18.4
158[b]	45.2	41.9	20.1	17.5	23.6	20.4	17.9	16.0	25.1	21.7
150	78.8	71.4	34.6	30.0	48.6	43.8	30.6	27.8	49.4	44.7
140	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/
130	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/
120[c]	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 180. *Monopile 3, modelled maximum–over–depth SPL isopleths for per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	Monopile 3									
	Penetration depth (m)									
	11.5		26.0		28.0		35.0		42.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	1.61	1.54	0.42	0.40	1.40	1.30	0.66	0.64	0.58	0.56
180	4.93	4.55	2.34	2.16	4.71	4.08	3.11	2.74	2.54	2.33
170[a]	9.73	9.08	5.88	5.37	10.1	9.20	6.83	6.29	6.23	5.68
160	17.7	16.3	11.6	10.6	20.6	18.6	12.9	11.7	11.5	10.4
158[b]	19.6	18.0	13.7	12.1	22.3	20.6	14.5	13.2	12.8	11.5
150	28.1	25.8	23.5	21.1	42.5	31.7	25.7	23.1	22.0	19.3
140	42.8	38.3	42.7	36.0	64.7	55.2	43.6	39.1	42.6	34.3
130	77.5	63.5	70.4	58.7	>90.0	/	75.5	62.8	67.0	56.5
120[c]	>90.0	/	>90.0	/	>90.0	/	>90.0	/	>90.0	/

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 181. *Monopiles, SEL_{24h}:* Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on NMFS (2024) and Accomando et al. (2025b).

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	Monopile 1		Monopile 2		Monopile 3	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS							
LF cetaceans	197	11.1	10.0	5.82	4.79	21.1	18.2
HF cetaceans	201	0.06	0.06	–	–	0.41	0.40
Otariid Seals	199	0.04	0.04	–	–	0.23	0.23
Sea turtles	198	7.25	6.32	3.51	2.58	17.3	14.6
Penguins	199	0.04	0.04	–	–	0.23	0.23
TTS							
LF cetaceans	177	83.5	58.0	37.0	33.3	68.7	58.4
HF cetaceans	181	2.90	2.48	0.38	0.36	6.45	5.48
Otariid Seals	179	2.20	1.77	0.18	0.17	5.00	4.28
Sea turtles	178	83.2	49.4	25.5	21.3	64.4	46.2
Penguins	179	2.20	1.77	0.18	0.17	5.00	4.28

A dash indicates the level was not reached within the limits of the modelled resolution (20 m).

5.1.2.1.2. Sound field maps

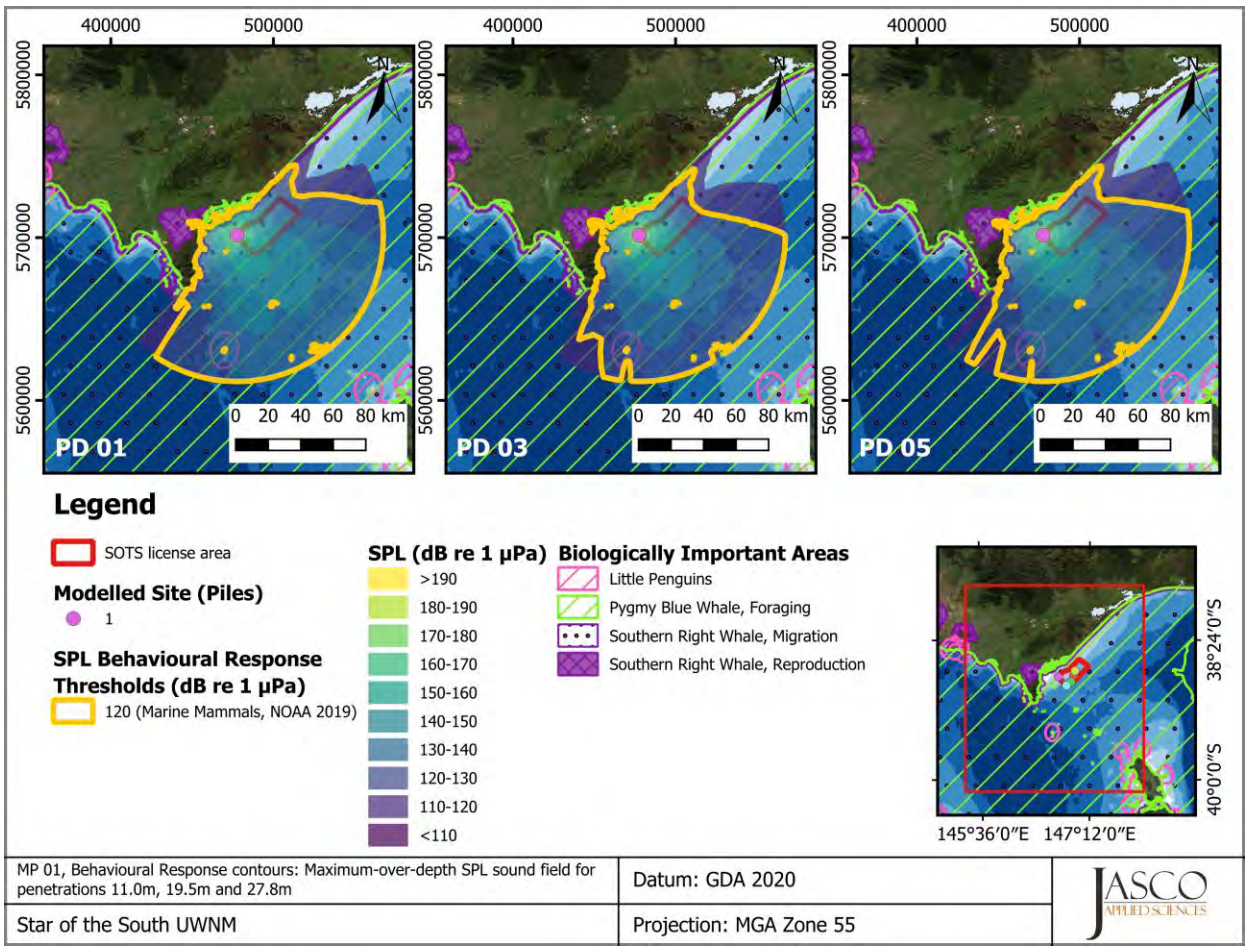


Figure 126. *Vibro Piling Monopile 1, Penetration Depths 01, 03 and 05, SPL:* Sound level contour map, showing unweighted maximum-over-depth SPL results for marine mammal (120 dB re 1 µPa).

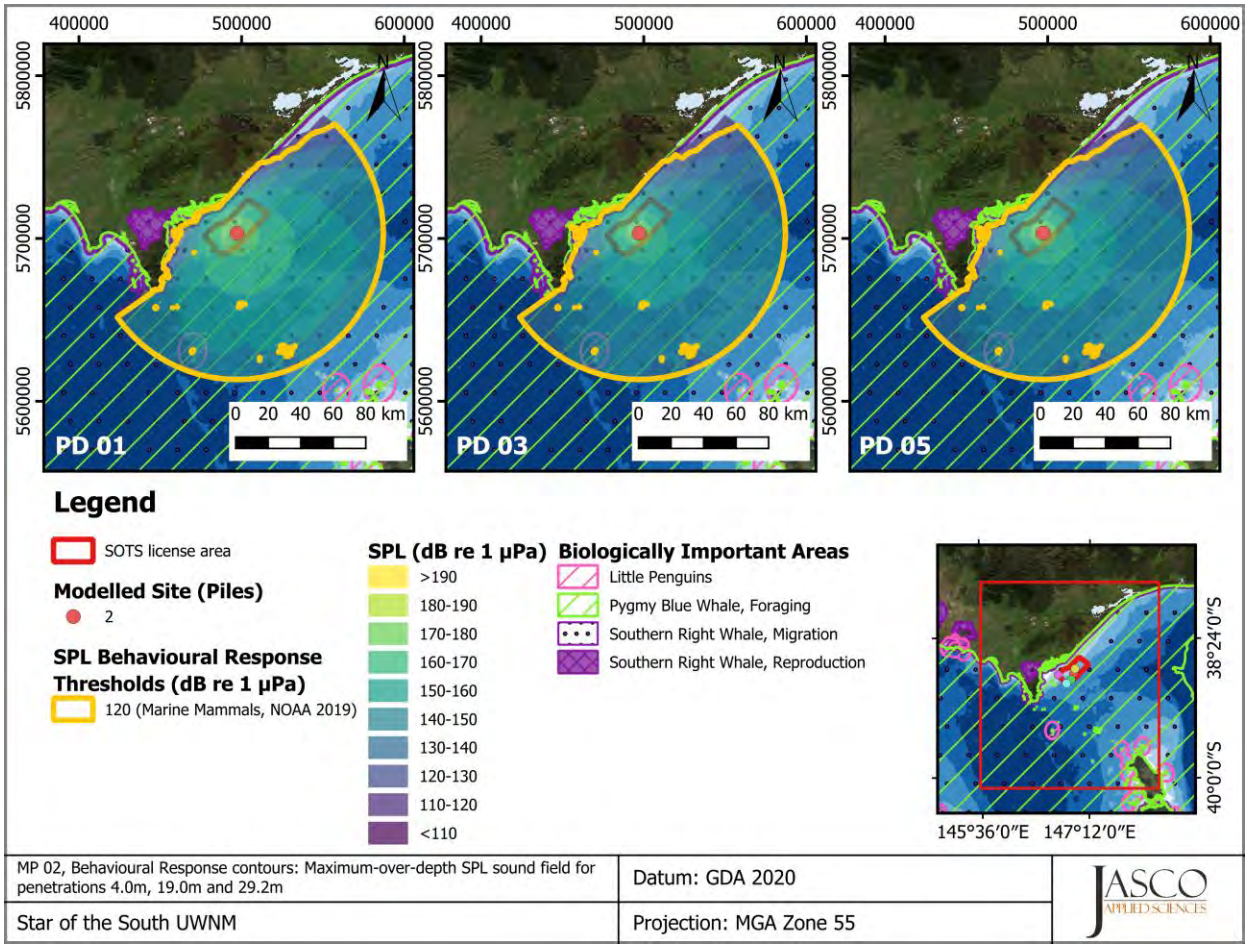


Figure 127. *Vibro Piling Monopile 2, Penetration Depths 01, 03 and 05, SPL:* Sound level contour map, showing unweighted maximum-over-depth SPL results for marine mammal (120 dB re 1 µPa).

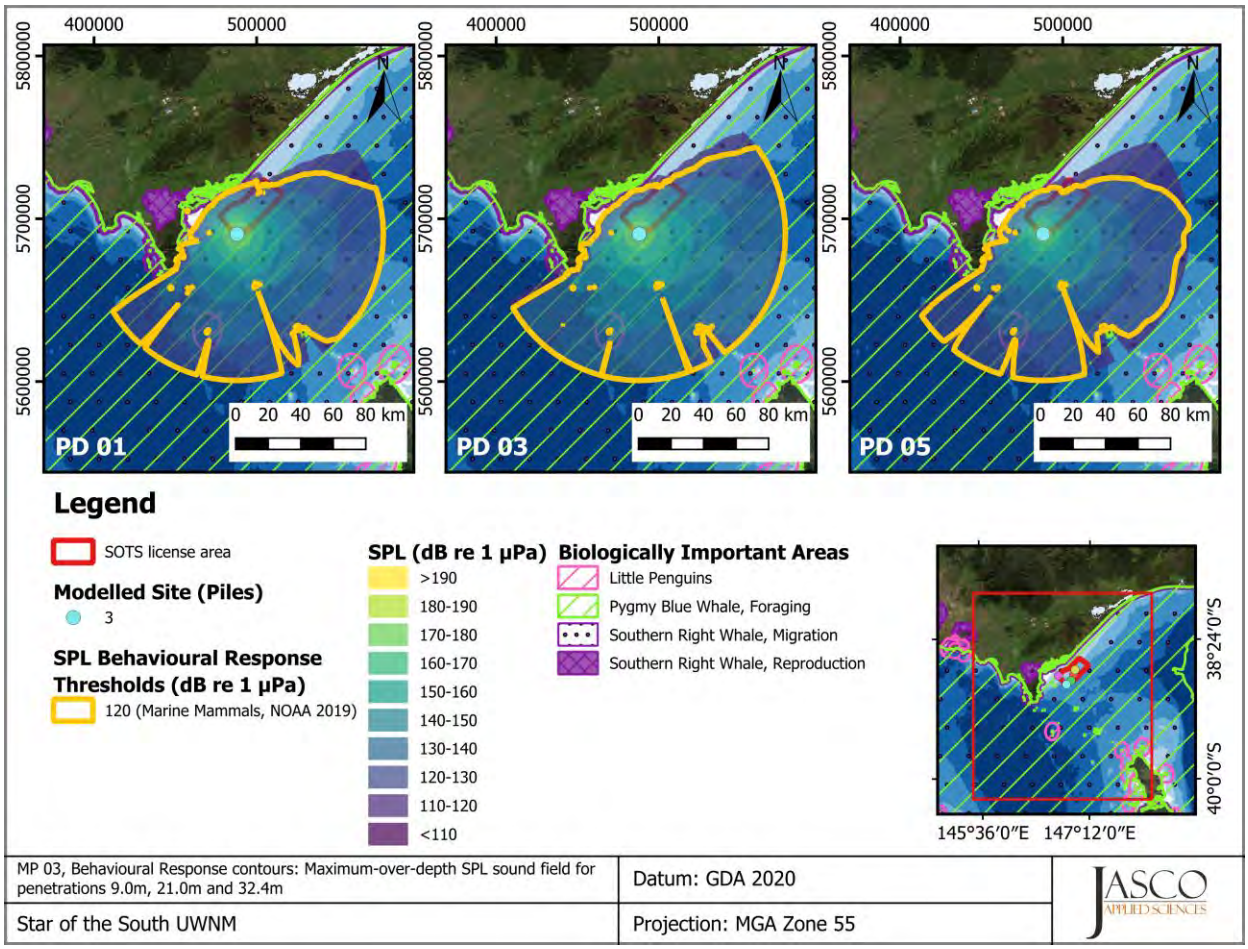
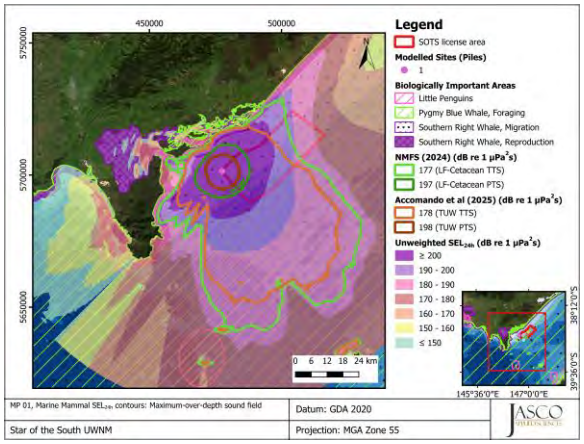
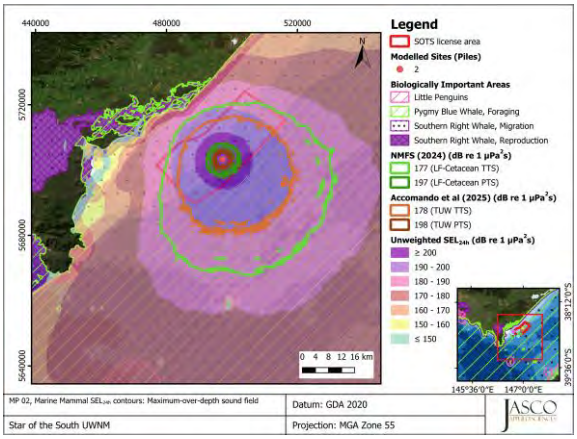


Figure 128. *Vibro Piling Monopile 3, Penetration Depths 01, 03 and 05*, SPL: Sound level contour map, showing unweighted maximum-over-depth SPL results for marine mammal (120 dB re 1 µPa).





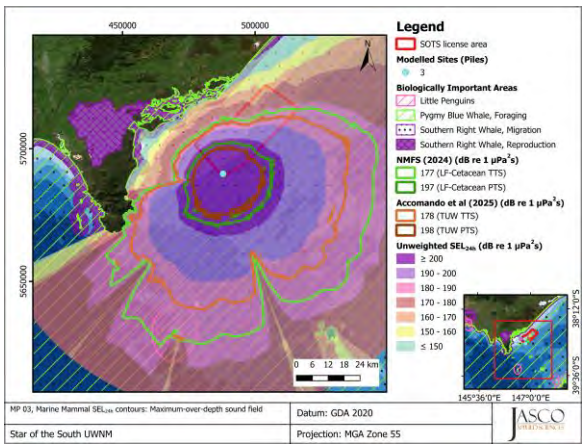


Figure 129. *Vibro Piling Monopile 1(top left), Monopile 2 (top right), Monopile 3 (bottom left),* SEL_{24h}*: Sound level contour map of weighted maximum-over-dept.*

5.2. Jacket Pile Installation Operations

The table below provides a summary of the scenario included in Section 5.2.2.

Table 182. Summary of the modelled vibro piling scenarios presented in the sections below. MP: monopile.

Scenario	Operation	Mitigation	Modelling round	Site	Site description (water depth)	Max. pile diameter	Hammer model	Season	Results presented	Sound source parameters	Noise effect threshold
1	Vibro Piling: Jacket Pile	None	Third	OSS	29.6	3.25	GIANT4000	Winter	Acoustic	Appendix C.2.3.1 Appendix C.2.3.3	NMFS 2024

5.2.1. Parameterisation and Methodology: Jacket Piles

JASCO's pile driving source model (PDSM, MacGillivray 2014) was used in conjunction with the GRLWEAP 2010 wave equation model (Pile Dynamics 2010) to predict source levels associated with pile driving activities.

GRLWEAP, which includes a database of commercial impact hammers, was used to model a forcing function at the top of the pile. PDSM computes the underwater vibration and sound radiation of a pile using a finite difference scheme which utilises the forcing function of the hammer at the top of the pile and the mechanical resistance of the seabed at the base of the pile. See Appendix B.1 for more detail. Given that piles are distributed sources (Appendix B.1), they cannot be accurately approximated by a point source. As such, the sound radiating from the pile itself is simulated using a vertical array of discrete point sources, as described in Appendix B.1.

The hammer penetration rates values used in this acoustic modelling study was developed in considering the driveability information provided by the Star of the South, which included number of penetrations rate per metre of the pile drive. The drive was divided into five depth intervals, each with a different pile penetration depth and average penetrations rate. This was done to represent the different portions of the pile drive while maintaining computation efficiency. Table presents the parameters that were used for acoustic modelling is presented in Appendix C.2.3.3.

5.2.2. Results: Acoustic Modelling

Received Levels at 10 m – Since piles are distributed and directional sources, they cannot be accurately approximated by a point source with corresponding source levels. It is possible to compare the maximum modelled levels at short distances from the piles. The figure below show the decidecade–band levels for the receiver with the highest SEL at a horizontal range of 10 m, for each of the modelled penetrations. The levels above 1000 Hz were extrapolated using a 20 dB/decade decay rate to match acoustic measurements of pile driving of similarly sized piles (Illingworth & Rodkin 2007, Matuschek and Betke 2009). The modelled results at a distance of 10 m are included to provide results comparable to other pile driving reports and literature, such as Illingworth & Rodkin (2007), and Denes et al. (2016).

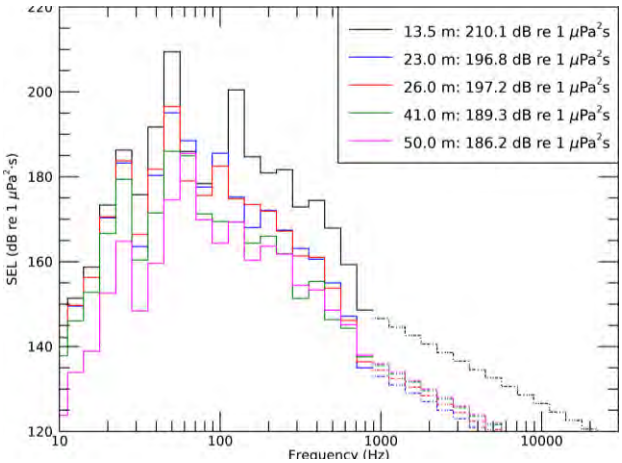


Figure 130. *OSS Jacket Pile*, *winter, third modelling round,* Decidecade–band levels for the receiver with highest SEL at 10 m horizontal range for vibro piling using the GIANT 4000 hammer, after high–frequency extrapolation (dashes indicate extrapolated portion of the spectrum). Legend items indicate the modelled pile penetration and the broadband SEL in dB re 1 μPa²·s.

5.2.2.1. Scenario 1 – Unmitigated (Third Modelling Round)

5.2.2.1.1. Tabulated results

Table 183. *Sub–station jacket pile, modelled maximum–over–depth SPL isopleths for per penetration depth*: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) from each monopile and for each penetration depth.

SPL (L_p; dB re 1 µPa)	OSS Jacket Pile									
	Penetration depth (m)									
	11.5		26.0		28.0		35.0		42.0	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
190	0.77	0.75	0.06	0.06	0.08	0.08	0.03	0.03	–	–
180	4.00	3.71	0.55	0.54	0.65	0.63	0.35	0.34	0.26	0.26
170[a]	11.6	10.4	3.52	3.00	3.80	3.28	2.80	2.08	2.30	1.80
160	29.7	26.4	10.1	8.52	10.6	9.46	8.44	7.30	8.06	7.07
158[b]	34.1	30.8	11.7	10.2	13.0	11.3	9.81	8.54	9.30	8.26
150	53.3	48.9	24.3	21.4	27.1	23.8	18.6	15.5	15.1	13.5
140	90.0	/	49.8	45.2	51.2	46.7	43.1	37.2	34.4	26.9
130	90.0	/	85.6	78.7	82.4	75.4	77.3	69.2	63.1	53.8
120[c]	90.0	/	90.0	/	90.0	/	90.0	/	90.0	/

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (90 km).

Table 184. *Sub–station jacket pile, SEL_{24h}:* Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS/AUD INJ and TTS thresholds based on NMFS (2024) and Accomando et al. (2025a).

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	Single Jacket Pile		Four Jacket Piles	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS/AUD INJ					
LF cetaceans	197	1.11	1.00	3.01	2.66
HF cetaceans	201	–	–	–	–
Otariid Seals	199	–	–	–	–
Sea turtles	198	0.38	0.38	1.21	1.01
Penguins	199	–	–	–	–
TTS					
LF cetaceans	177	13.2	11.8	24.5	21.5
HF cetaceans	181	0.05	0.05	0.11	0.11
Otariid Seals	179	–	–	0.07	0.07
Sea turtles	178	7.26	6.16	13.1	11.2
Penguins	179	–	–	0.07	0.07

A dash indicates the level was not reached within the limits of the modelled resolution (20 m).

5.2.2.1.2. Sound field maps

The following presents the contour maps:

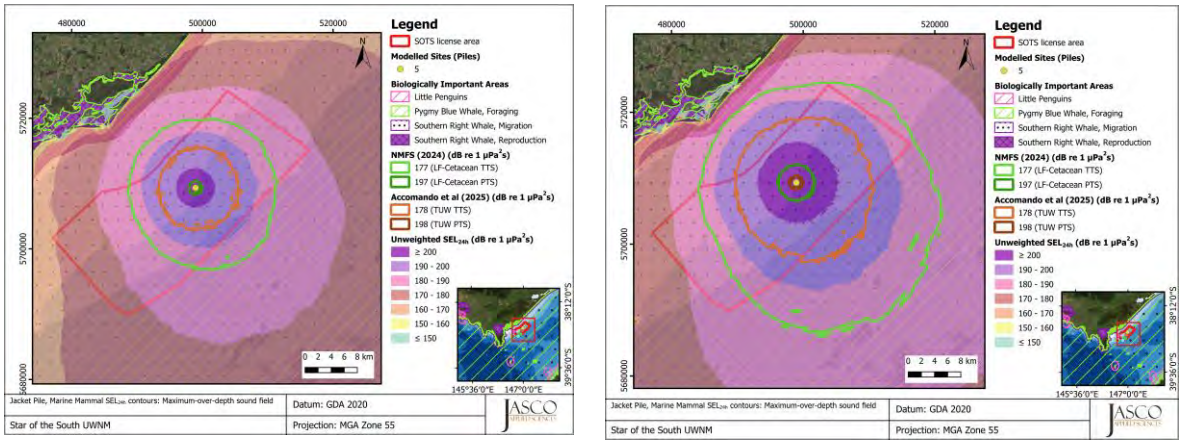


Figure 131. *Vibro Piling OSS Jacket Pile (left) and 4 OSS Jacket Piles (right),* SEL_{24h} *Sound level contour map of weighted maximum-over-depth.*

5.3. Summary: Vibro Pile Driving

From the latest study, the GIANT 4000 vibratory hammer was selected as the representative vibratory piling equipment, it has a nominal fundamental frequency of 23 Hz and is capable of installing large-diameter piles. Predicted underwater sound levels associated with vibratory piling activities at three representative monopile locations within the Licence Area (refer to Table 12). The modelling incorporates pile specifications (Table C-11. and Table C-15.) and five sediment penetration depths with variable penetration rates throughout the piling process.

The broadband sound energy at 10 m for each penetration depth ranged from 204.2 to 216.5 dB re 1 $\mu Pa^2 \cdot s$ with the highest amount of sound energy concentrated in the frequency range 20 to 100 Hz. This frequency range encompasses the fundamental operating frequency of the GIANT 4000 vibratory hammer.

Vibro piling generates a tonal acoustic signature characterized by a dominant fundamental frequency corresponding to the hammer's operating rate along with a series of harmonics. These harmonics occur at integer multiples of the fundamental frequency and contribute to the overall spectral energy distribution. The presence and relative intensity of these harmonics depend on factors such as pile geometry, sediment type, and coupling efficiency between the pile and substrate.

Noise emissions from pile driving were considered here to be cylindrically isotropic (i.e., omnidirectional in the horizontal plane). As such, variations in noise that propagates across azimuths are attributed to the bathymetry or seabed layering. In similarity to impact piling, when a vibratory hammer vibrates the pile, noise propagates into the water as a downward Mach cone (see Appendix B.1). A portion of the energy from the strike is also reflected at the pile bottom, generating an upward Mach cone. Due to the relation between the speed of sound in steel (~5000 m/s) relative to the speed of sound in the water (~1500 m/s at the depth of the pile), the Mach cone propagates away from the pile and impinges the seabed at an angle of ~17°, as shown in Figure 132 for example.

Under vibratory excitation, the pile experiences a continuous sequence of stress waves and Mach cones that propagate along its length. Unlike impact piling, where discrete stress pulses produce isolated wavefronts, vibratory piling results in a sustained and periodic excitation, with energy being continuously emitted both into the surrounding water column and the seabed. Figure 132 an example of several time snap shots showing the evolution of the sound field, highlighting continuous noise generation characteristics of vibratory piling.

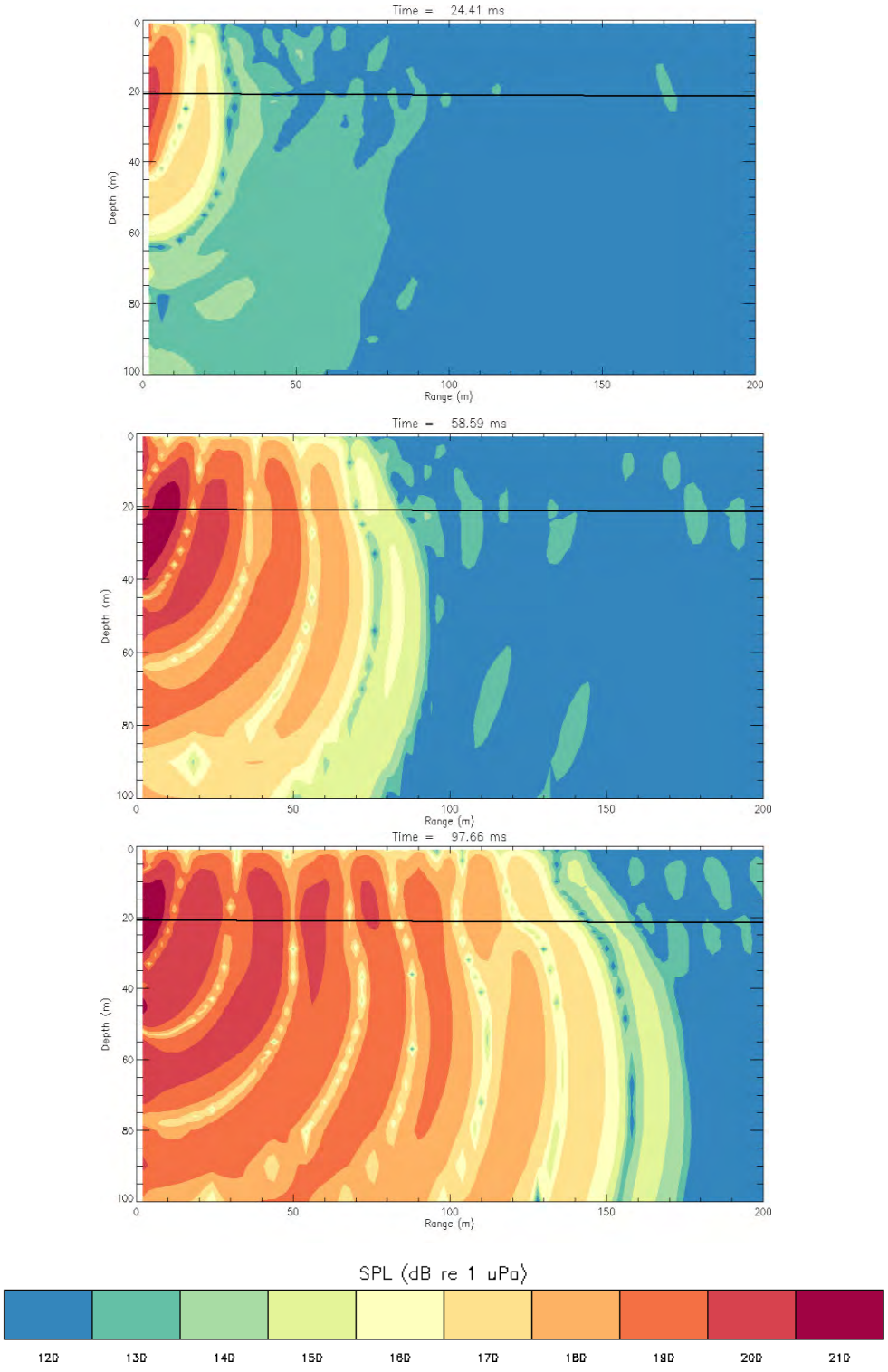


Figure 132. Monopile 1, winter, third penetration depth (19.5 m) unweighted SPL sound field time snapshot slice showing the Mach cone propagation. The black line indicates the seafloor interface.

In contrast to impact piling, vibratory piling produces energy at higher frequencies than the fundamental driving frequency. Whilst considered a quieter alternative, modelling indicates that vibratory piling can generate higher sound pressure levels near the source than unmitigated impact piling. This elevated source level, combined with the continuous nature of vibratory noise, results in larger distances to behavioural isopleths. The increased spatial extent is primarily due to the lower

thresholds for continuous noise exposure, which, when coupled with high source levels, can lead to large areas of potential behavioural disturbance.

Within the modelling study, there were some instances where the seabed driveability resulted in a very slow penetration rate. The greater period of time required to drive the pile in these areas leads to greater accumulation of sound energy and therefore contributes towards the extended TTS ranges for some of the monopiles (Table 186). In reality, vibro pile driving may be halted with such drivability, but that would be a decision that is ultimately made by the foundations engineering team on site.

Table 185 summarises the largest distance to behavioural response criteria for marine mammals and fish considered in this study.

Table 186 summarises the largest distance to injury thresholds for marine mammals, turtles and diving birds considered in this study, which in all cases corresponded to the SEL_{24h} metric.

Table 185. Monopile foundation (GIANT 4000 hammer): distance (R_{max} in km) to SPL acoustic behavioural response thresholds for vibro piling. Maximum distances across all penetration depths are presented.

Fauna group	SPL (L_p; dB re 1 µPa)	Monopile 1	Monopile 2	Monopile 3	OSS Jacket Pile
Fish recoverable injury [a]	170	8.75	14.5	10.1	11.6
Fish TTS [b]	158	19.6	45.2	22.3	34.1
Marine mammal behavioural response [c]	120	>90.0	>90.0	>90.0	>90.0

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).

Table 186. Monopile foundation (GIANT 4000 hammer): distance (R_{max} in km) to SEL_{24h} acoustic thresholds for marine mammals, fish, and sea turtles, for vibro piling.

Hearing group	$L_{E,24h}$ threshold	Monopile 1	Monopile 2	Monopile 3	Single Jacket Pile	Four Jacket Piles
PTS						
LF cetaceans	197	11.1	5.82	21.1	1.11	3.01
HF cetaceans	201	0.06	–	0.41	–	–
Otariid seals	199	0.04	–	0.23	–	–
Sea turtles	198	7.25	3.51	17.3	0.38	1.21
Penguins	199	0.04	–	0.23	–	–
TTS						
LF cetaceans	177	83.5	37.0	68.7	13.2	24.5
HF cetaceans	181	2.90	0.38	6.45	0.05	0.11
Otariid seals	179	2.20	0.18	5.00	–	0.07
Sea turtles	178	83.2	25.5	64.4	7.26	13.1
Penguins	179	2.20	0.18	5.00	–	0.07

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

6. Vessel noise

Table 187 presents the overview of the modelling round, the type(s) of results being presented, a reference to find the sound source parameters and main noise effect threshold reference. Details can be found in the corresponding result sections.

Table 187. Overview of vessel noise result presentation

Scenario (Operation)	Mitigation	Modelling round	Results presented	Sound source parameters	Noise effect threshold
Intermediate Shallow: WTGIV + PLV + CLV	None	Third	Acoustic Animat	Section 3.2.1 and Section 6.2	NMFS 2024
Deep: WTGIV + PLV + CLV					

6.1. Vessel Operations

The following sections were defined based on the project envelope as defined by Star of the South as well as a vessel candidate and activity duration list also provided by the Star of the South.

The Bokalift-1 has been proposed as a candidate vessel for the WTGIV. As there are no publicly available measurements of the sound produced by the Bokalift-1, JASCO considered the *Skandi Feinstein* as a potential proxy sound source for the Bokalift-1.

6.2. Parameterisation and Methodology: Vessel Noise

Underwater sound that radiates from vessels is produced mainly by propeller and thruster cavitation, with a smaller fraction of noise produced by sound transmitted through the hull, such as by engines, gearing, and other mechanical systems. Sound levels tend to be the highest when thrusters are used to position the vessel and/or when the vessel is transiting at high speeds. A vessel's sound signature depends on the vessel's size, power output, propulsion system and the design characteristics of the vessels drive system (e.g., blade shape and size). Vessels typically produce broadband acoustic energy with most of the energy emitted below a few kilohertz.

For the vessel and associated scenarios, the subsections below present the source specific considerations for underwater noise emission. Vessels were modelled as point sources, with an associated source level, source spectrum and source depth. The source level and decidecade source spectra characterise the free-field acoustic levels of a source at a standard reference distance of 1 metre from the acoustic centre. Source levels are a measure of how loud a source is in the absence environmental interaction. For the considered vessels, the depth of the equivalent point sources were based on the approximate location of cavitation, and was selected based on 0.7 times vessel draft in line ([ISO] International Organization for Standardization 2019). Table 188 presents three nominal candidates based on the project envelope and vessel summary list which represent the likely type of vessel to be involved with the construction program.

Table 188 Nominal vessel selection and specifications for modelled scenarios.

Vessel Type	Vessel Name	Length (m)	Draft (m)	Width (m)	Power (MCR) (kW)	Source Depth (m)
WTGIV	Bokalift-1	216.0	9.0	43.0	26,900	6.0
PSV	VOS Shine	60.0	4.6	15.0	5,010	3.0
CLV	Seaway Phoenix	130.0	6.6	28.0	12,000	4.5

MCR: Maximum Continuous Rating
WTGIV: Wind Turbine Generator Install Vessel
PSV: Platform Support/Supply Vessel
CLV: Cable Lay Vessel

At this stage, the exact vessel selection is not known as vessel operators have not been contracted, thus specifications are also unknown. Based on the specifications discussed above, peer-reviewed literature and Jasco's experience in modelling and measuring underwater noise from offshore development activities, the source levels were estimated from surrogate vessels considering, operational activity, MCR power, number of thrusters, and overall vessel size. Section 3.2.2 presents the details of the estimation for sound source level of the vessels used as input for the modelling.

6.3. Results: Acoustic Modelling

6.3.1. Scenario 1 – WTGIV + PSV + CLV (Third Modelling Round)

6.3.1.1.1. Tabulated results

For the considered scenarios, the results below report the distances to isopleths/thresholds from either the centroid of several sources or from the most dominant single source. When an isopleth completely envelopes multiple sources, the centroid was used. When several closed isopleths exist, the most dominant source was used.

Table 189. Vessel scenarios: Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to sound pressure level (SPL).

SPL (L_p; dB re 1 µPa)	Intermediate Shallow: WTGIV, PSV and CLV		Deep: WTGIV, PSV and CLV	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
180	–	–	–	–
170[a]	–	–	0.02	0.02
160	–	–	0.02	0.02
158[b]	0.02	0.02	0.02	0.02
150	0.08	0.08	0.06	0.06
140	1.34	1.17	0.71	0.64
130	6.78	6.12	7.77	6.59
120[c]	15.6	14.1	12.0	10.9
110	60.2	52.9	33.6	30.1

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise (NOAA 2019).
A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that $R_{95\%}$ radius to threshold is not reported when the R_{max} was greater than the modelling extent (100 km).

Table 190. Vessel scenarios: Maximum (R_{max}) horizontal distances (in km) to frequency-weighted SEL_{24h} PTS and TTS thresholds based on NMFS (2024) and Finneran et al. (2017) from the most appropriate location for considered sources per scenario, and ensonified area (km²).

Hearing group	Frequency-weighted SEL_{24h} threshold ($L_{E,24h}$; dB re 1 µPa²·s)	Intermediate Shallow: WTGIV, PSV and CLV		Deep: WTGIV, PSV and CLV	
		R_{max} (km)	Area (km²)	R_{max} (km)	Area (km²)
PTS					
Low-Frequency (LF) cetaceans	197	0.08	0.26	0.07	0.23
High-frequency (HF) cetaceans	201	–	/	0.02	/
Otariid seals	199	–	/	0.02	/
Sea Turtles	198	0.04	0.02	0.04	0.02
Penguins	199	–	/	0.02	/
TTS					
Low-Frequency (LF) cetaceans	177	9.16	104	6.35	72.5
High-frequency (HF) cetaceans	181	0.16	0.32	0.10	0.25
Otariid seals	179	0.14	0.30	0.09	0.24
Sea Turtles	178	7.05	18.47	4.8	9.69
Penguins	179	0.14	0.30	0.09	0.24

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).
A slash indicates that the area is less than an area associated with the modelled resolution (0.0013 km²)

6.3.1.1.2. Sound field maps

The following presents the contour maps:

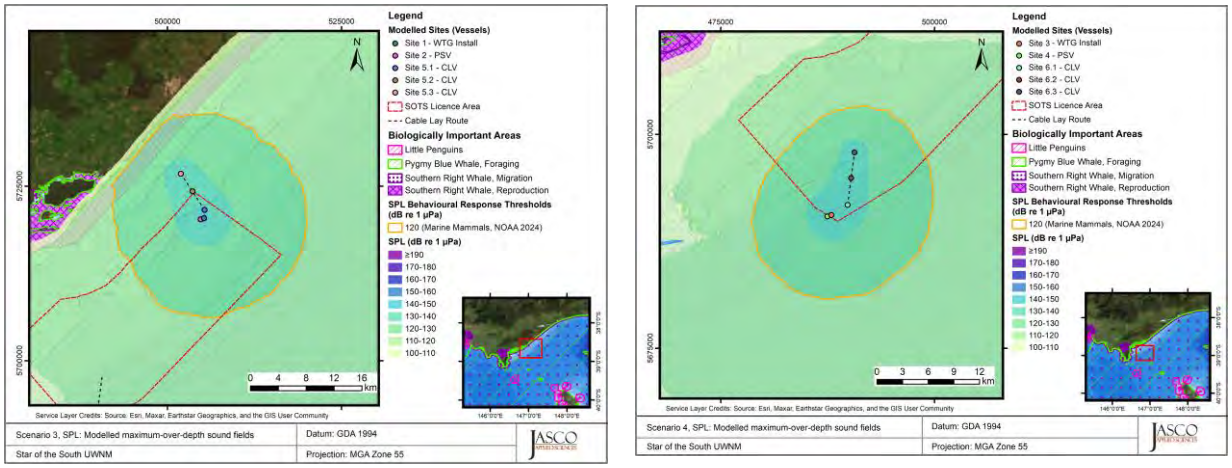


Figure 133. *Vessel Scenarios, Intermediate Shallow (left) and Deep (right), SPL: Sound level contour map of weighted maximum-over-depth.*

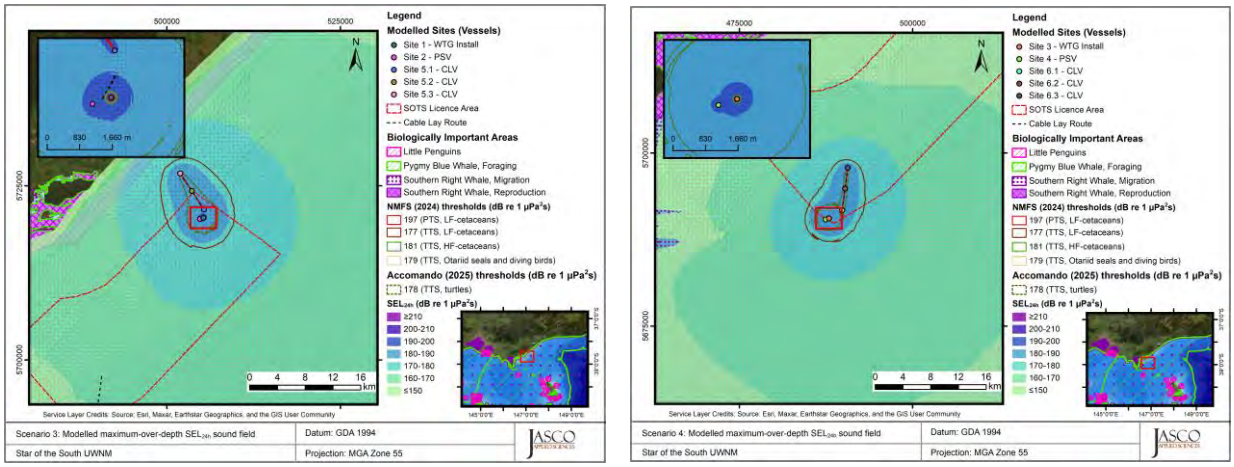


Figure 134. *Vessel Scenario, WTGIV Intermediate Shallow (left) and Deep (right), SEL_{24h}: Sound level contour map of weighted maximum-over-depth.*

6.4. Results: Animal Movement Modelling

Exposure ranges ($ER_{95\%}$) and the probability of exposure within $ER_{95\%}$ (P_{exp}) were calculated for pygmy blue, humpback, minke and southern right whales. A summary of radial distances to exposure thresholds for modelled species, along with probability of exposure for the vessel scenarios are included below. Note that dashes indicate that no animats were exposed above threshold. In addition, histograms are presented in Appendix E.2.

6.4.1. Scenario 1 – WTGIV + PSV + CLV (Third Modelling Round)

Table 191. *Vessel scenarios:* Exposure ranges ($ER_{95\%}$) in km to permanent threshold shift (PTS)/auditory injury (AUD INJ) and temporary threshold shift (TTS) low-frequency marine mammal thresholds.

Species	Intermediate Shallow: WTGIV, PSV and CLV		Deep: WTGIV, PSV and CLV	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
PTS/AUD INJ				
Pygmy Blue Whale, Feeding	–	–	–	–
Pygmy Blue Whale, Northbound Migrating	–	–	–	–
Pygmy Blue Whale, Southbound Migrating	–	–	–	–
Humpback Whale, Migrating with Calf	–	–	–	–
Humpback Whale, Migrating without Calf	–	–	–	–
Minke Whale, Migrating	–	–	–	–
Southern Right Whale, Migrating with Calf	–	–	–	–
Southern Right Whale, Migrating without Calf	–	–	–	–
TTS				
Pygmy Blue Whale, Feeding	0.21	35	0.15	10
Pygmy Blue Whale, Northbound Migrating	0.02	84	0.02	71
Pygmy Blue Whale, Southbound Migrating	0.02	71	0.02	78
Humpback Whale, Migrating with Calf	0.77	16	0.83	11
Humpback Whale, Migrating without Calf	0.32	15	0.60	10
Minke Whale, Migrating	0.02	98	0.02	85
Southern Right Whale, Migrating with Calf	1.09	13	1.00	13
Southern Right Whale, Migrating without Calf	0.04	55	0.02	>99

Table 192. *Vessel scenarios, SPL*: Exposure ranges ($ER_{95\%}$) in km to the unweighted NOAA (2024) 120 dB re 1 µPa marine mammal behavioural response threshold.

Species	Intermediate Shallow: WTGIV, PSV and CLV		Deep: WTGIV, PSV and CLV	
	$ER_{95\%}$ (km)	P_{exp} (%)	$ER_{95\%}$ (km)	P_{exp} (%)
Pygmy Blue Whale, Feeding	11.6	99	7.70	95
Pygmy Blue Whale, Northbound Migrating	10.9	>99	7.76	84
Pygmy Blue Whale, Southbound Migrating	10.8	>99	7.79	86
Humpback Whale, Migrating with Calf	10.7	90	7.82	87
Humpback Whale, Migrating without Calf	10.8	90	7.74	90
Minke Whale, Migrating	10.8	97	7.20	94
Southern Right Whale, Migrating with Calf	10.8	89	7.87	86
Southern Right Whale, Migrating without Calf	10.5	94	7.81	90

6.5. Summary: Vessels

Similar points as discussed in relation to pile driving about acoustic propagation and the environment also apply to vessel noise emissions. In particular, the influence of changes in received levels on isopleths that extend tens of kilometres away from considered activities. The main source of uncertainty for vessel noise modelling is the source levels considered, particularly for the WTGIV. The estimation of SPL isopleths for vessels, is based on instantaneous received level and over the course of construction it is surmisable that levels from vessel activities will fluctuate. Small shifts in this source level could result in large changes for distances to effects criteria, like those for marine mammals.

As is the case for driven piles, the sand seabed is expected to have very low bottom loss (i.e., acoustically reflective) at shallow grazing angles, which can result in higher levels persisting to longer ranges from the source. This reflectivity likely led to large isopleths for low level thresholds at long range. When combined with a high source level, the reflectivity of the seabed is most evident for the marine mammal behavioural threshold of 120 dB re 1 µPa (SPL) for non-impulsive sound sources.

Similar to pile driving, the cumulative metric for vessel noise reflects the dosimetric impact of noise levels within that period, based on the assumption that an animal is consistently exposed to such noise levels at a fixed position. The radii that correspond to SEL_{24h} typically represent an unlikely worst-case scenario for SEL-based exposure since, more realistically, marine animals would not stay in the same location for 24 hours (especially in the absence of location-specific habitat) but rather a shorter period, depending on the animal's behaviour and the source's proximity and movements. Therefore, a reported radius for SEL_{24h} criteria does not mean that any animal travelling within this radius from the source *will* be injured, but rather that it *could* be injured if it remained within that range for the entire duration of vessel activity. Accordingly, the animal movement modelling results that incorporate realistic animal behaviour provide a more realistic estimate for the noise effect radii.

7. Summary

7.1. Modelling Approach and Methodology

JASCO Applied Sciences (JASCO) performed multiple rounds of modelling studies over the years to understand potential effect ranges for marine fauna based on underwater sound levels associated with construction activities for the Star of the South (Star of the South) offshore wind farm (OWF). The underwater noise modelling considered a number of sources and scenarios:

- Wind turbine generator (WTG) foundations consisting of monopiles were modelled as being installed using impact piling.
- Wind turbine generator (WTG) foundations, consisting of monopiles were modelled as being installed using vibro piling.
- Jacket structures were considered for Offshore Sub-Station (OSS) foundations, installed using impact piling and vibro piling.
- Mitigation was considered for the impact piling activities. The mitigation systems that have been considered in the latest (fourth) round of modelling comprise:
    - No mitigation.
    - Specific frequency dependent attenuation curves to represent the application of a double big bubble curtain (DBBC) system.
    - Specific frequency dependent attenuation curves to represent the application of a hydro sound damper (HSD).
    - Adjusted impact hammer forcing functions for the application of a hydraulic damping mechanism to represent the application of the PULSE noise mitigation system.
- Vessel operations associated with the OWF at two representative locations within the License Area (Intermediate Shallow, and Deep). The considered types of operations include:
    - A Wind Turbine Generator Installation Vessel (WTGIV) stationary under dynamic positioning (DP).
    - A Platform Support Vessel (PSV) holding position under DP deploying some type of pile driving noise mitigation, e.g., a bubble curtain.
    - A single cable lay vessel moving along a cable lay path using DP during cable laying operations.

The objective of these modelling studies was to predict the ranges to acoustic thresholds that may result in injury to or behavioural disruption of marine fauna near the construction area. The corresponding thresholds used in the studies represented the best available science at the time of performance for behavioural response or disturbance, temporary threshold shift (TTS), and permanent threshold shift (PTS/AUD INJ) or injury depending upon the fauna group. The fauna considered included low- and high-frequency cetaceans, sea turtles, fish including fish larvae and eggs, penguins, and invertebrates. A human health assessment threshold for divers was also considered.

The basic modelling approach was to characterise the sound sources and then determine how the sounds propagated at specific locations considering the environmental properties that influence the propagation of underwater sound. A winter sound speed profile was considered.

The modelling methodology considered the dynamics of pile driving, source levels of vessels and range-dependent environmental properties. Estimated underwater acoustic levels are presented as

sound pressure levels (SPL, L_p); zero-to-peak pressure levels (PK, L_{pk}); peak-to-peak pressure levels (PK-PK; $L_{pk\text{-}pk}$); particle acceleration (ms^{-2}); and either single-strike (i.e., per-strike) or accumulated sound exposure levels (SEL, L_E) as appropriate for different noise effect criteria and noise sources. In this report, the duration period for SEL accumulation is defined as a 24-hour period over which sound energy is integrated; the level is specified with the abbreviation SEL_{24h}.

SEL_{24h} is a cumulative metric that reflects the dosimetric effect of noise levels within 24 hours, based on the assumption that a receiver (e.g., an animal) is consistently exposed to such noise levels at a fixed position. More realistically, marine animals would not stay in the same location for 24 hours (especially in the absence of location-specific habitat) but rather a shorter period, depending on the animal's behaviour and the source's proximity and movements. Therefore, a reported radius for the SEL_{24h} criteria does not mean that marine fauna travelling within this radius of the source will be impaired, but rather that an animal could be exposed to the sound level associated with impairment (either PTS/AUD INJ or TTS) if it remained within the ensonified area for 24 hours.

A more realistic representation of the potential exposures for pygmy blue, southern right, humpback and minke whales was undertaken using animal movement modelling ('animat modelling'), with the results presented separately below. While acoustic modelling inherently assumes static animals, the JASCO Animal Simulation Model Including Noise Exposure (JASMINE) combines modelled sound fields with realistic animal movements to predict how animals might be impacted through sound exposure. JASMINE provides a framework for understanding and predicting sound exposure for species of interest and for calculating ranges to relevant regulatory thresholds with ranges estimated using JASMINE also referred to as exposure ranges. The distribution of distances of animats predicted to be exposed to sound levels above relevant thresholds was used to calculate the 95th percentile exposure range ($ER_{95\%}$), and the probability of animats being exposed above threshold within the $ER_{95\%}$ (P_{exp}).

7.2. Results Summary

A summary of the latest acoustic modelling round results for impact pile driving installation of monopiles for turbines and jacket piles for the offshore sub-station for all marine fauna and humans are provided in Tables 193 to 195. Vibro piling results are presented in Tables 196 and 197.

A summary of the latest acoustic modelling results for vessel operational scenarios are presented in Tables 198 and 199, focusing on the maximum distances to the NOAA (2024) marine mammal behavioural response criterion and low-frequency cetacean permanent and temporary threshold shift, using the criteria from NMFS (2024).

A summary of the latest animal movement modelling results for the installation of monopiles for turbines and jacket piles for the offshore sub-station for marine mammals are provided in Tables 200 and 201 including modelling with mitigation systems. Additionally, Table 202 summarises animal movement results for the considered vessel scenarios.

7.2.1. Impact Piling Operations

Table 193. *Monopile foundation summary (Monopiles 1 and 2), no mitigation, and PULSE+DBBC+HSD*: ranges (R_{max} in km) to acoustic thresholds for marine fauna and humans for each monopile at the penetration depth that results in the farthest ranges. Since $L_{E,24h}$ accounts for the accumulation of all hammer strikes required to drive a single pile, the distances to the corresponding thresholds encompass all the hammer energy settings. A dash (-) indicates that the acoustic threshold was not reached.

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 1		Monopile 2	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Low-frequency (LF) cetaceans	PTS [a]	$L_{E,24h}$	183	12.1	0.77	17.4	0.41
	TTS [a]	$L_{E,24h}$	168	83.6	8.61	78.6	5.48
	Weighted behavioural response [h]	L_p	160	8.22	0.51	12.1	0.31
	Weighted behavioural response (migrating mysticetes) [h]	L_p	140	84.7	7.17	78.9	6.37
High-frequency (HF) cetaceans	PTS [a]	$L_{E,24h}$	193	0.06	–	0.03	–
	TTS [a]	$L_{E,24h}$	178	0.89	–	0.66	–
Otariid seals	PTS [a]	$L_{E,24h}$	185	0.08	–	0.09	–
	TTS [a]	$L_{E,24h}$	170	1.43	–	1.21	–
All marine mammal groups	Behavioural Response [b]	L_p	160	14.0	5.64	20.8	5.18
Fish without swim bladder	Mortality and Potential mortal injury [c]	$L_{E,24h}$	219	0.29	0.03	0.26	0.02
	Recoverable injury [c]	$L_{E,24h}$	216	0.54	0.05	0.48	0.04
	TTS [c]	$L_{E,24h}$	186	15.1	7.82	22.6	5.63
	Recoverable injury [c]	L_{pk}	213	0.09	–	0.12	–
Fish with swim bladder not involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	210	1.47	0.09	1.38	0.09
	Recoverable injury [c]	$L_{E,24h}$	203	3.46	0.35	3.78	0.3
	TTS [c]	$L_{E,24h}$	186	15.1	7.82	22.6	5.63
	Recoverable injury [c]	L_{pk}	207	0.26	–	0.28	–

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 1		Monopile 2	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Fish with swim bladder involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	207	2.19	0.13	2.22	0.13
	Recoverable injury [c]	$L_{E,24h}$	203	3.46	0.35	3.78	0.3
	TTS [c]	$L_{E,24h}$	186	15.1	7.82	22.6	5.63
	Recoverable injury [c]	L_{pk}	207	0.26	–	0.28	–
Sea turtles	PTS [d]	$L_{E,24h}$	184	9.56	0.09	13.2	0.09
	TTS [d]	$L_{E,24h}$	169	83.4	1.14	78.2	0.75
	Behavioural disturbance [e]	L_p	175	4.23	0.62	4.63	0.46
	Behavioural response [e]	L_p	166	8.67	2.95	11.7	2.35
Penguins	PTS [a]	$L_{E,24h}$	185	0.08	–	0.09	–
	TTS [a]	$L_{E,24h}$	170	1.43	–	1.21	–
Humans	Human health assessment threshold [f]	L_p	145	83.8	20.3	79.1	17.3
Squid	Startle response [g]	L_E	162	6.52	1.83	9.15	1.11
Benthic invertebrates	Peak acceleration magnitude [i]	m/s^2	35.75	–	–	–	–

L_{pk}= unweighted peak sound pressure level (dB re 1 µPa).
L_p= unweighted sound pressure level (dB re 1 µPa).
L_E= sound exposure level for single strike (dB re 1 μPa^2 s).
$L_{E,24h}$= sound exposure level over 24 hours (dB re 1 μPa^2 s), unweighted for fish and frequency weighted for all other groups.
[a] NMFS (2024) criteria for marine fauna.
[b] NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
[c] Popper et al. (2014).
[d] Accomando et al. (2025a).
[e] McCauley et al. (2000).
[f] Human health assessment threshold derived from Parvin (2005).
[g] Fewtrell and McCauley (2012).
[h] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[i] Day et al (2016a).

Table 194. *Monopile foundation summary (Monopiles 3 and 4), no mitigation, and PULSE+DBBC+HSD*: ranges (R_{max} in km) to acoustic thresholds for marine fauna and humans for each monopile at the penetration depth that results in the farthest ranges. Since $L_{E,24h}$ accounts for the accumulation of all hammer strikes required to drive a single pile, the distances to the corresponding thresholds encompass all the hammer energy settings. A dash (-) indicates that the acoustic threshold was not reached.

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 3		Monopile 4	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Low-frequency (LF) cetaceans	PTS [a]	$L_{E,24h}$	183	14.9	0.18	11.8	0.36
	TTS [a]	$L_{E,24h}$	168	42.9	3.30	36.0	3.56
	Weighted behavioural response [h]	L_p	160	9.65	0.13	8.27	0.13
	Weighted behavioural response (migrating mysticetes) [h]	L_p	140	42.8	3.21	38.7	3.17
High-frequency (HF) cetaceans	PTS [a]	$L_{E,24h}$	193	0.13	–	0.03	–
	TTS [a]	$L_{E,24h}$	178	1.35	–	0.76	–
Otariid seals	PTS [a]	$L_{E,24h}$	185	0.16	–	0.12	–
	TTS [a]	$L_{E,24h}$	170	2.20	–	1.25	–
All marine mammal groups	Behavioural Response [b]	L_p	160	13.2	2.37	12.3	2.72
Fish without swim bladder	Mortality and Potential mortal injury [c]	$L_{E,24h}$	219	0.59	0.03	0.32	0.03
	Recoverable injury [c]	$L_{E,24h}$	216	1.01	0.05	0.53	0.06
	TTS [c]	$L_{E,24h}$	186	18.1	3.05	14.4	3.74
	Recoverable injury [c]	L_{pk}	213	0.16	–	0.14	–
Fish with swim bladder not involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	210	2.50	0.09	1.52	0.09
	Recoverable injury [c]	$L_{E,24h}$	203	5.14	0.13	3.50	0.24
	TTS [c]	$L_{E,24h}$	186	18.1	3.05	14.4	3.74
	Recoverable injury [c]	L_{pk}	207	0.43	–	0.30	–

Fauna group / Receiver	Threshold	Metric	Threshold	Monopile 3		Monopile 4	
				Unmitigated	PULSE+DBBC +HSD	Unmitigated	PULSE+DBBC +HSD
Fish with swim bladder involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	207	3.45	0.11	2.25	0.13
	Recoverable injury [c]	$L_{E,24h}$	203	5.14	0.13	3.50	0.24
	TTS [c]	$L_{E,24h}$	186	18.1	3.05	14.4	3.74
	Recoverable injury [c]	L_{pk}	207				
Sea turtles	PTS [d]	$L_{E,24h}$	184	12.5	0.09	9.85	0.09
	TTS [d]	$L_{E,24h}$	169	42.7	0.36	28.3	0.39
	Behavioural disturbance [e]	L_p	175	4.55	0.17	3.62	0.28
	Behavioural response [e]	L_p	166	9.41	1.12	7.93	1.34
Penguins	PTS [a]	$L_{E,24h}$	185	0.16	–	0.12	–
	TTS [a]	$L_{E,24h}$	170	2.20	–	1.25	–
Humans	Human health assessment threshold [f]	L_p	145	42.8	8.64	39.7	8.93
Squid	Startle response [g]	L_E	162	6.19	0.47	7.50	0.62
Benthic invertebrates	Peak acceleration magnitude [i]	m/s^2	35.75	–	–	–	–

L_{pk}= unweighted peak sound pressure level (dB re 1 µPa).
L_p= unweighted sound pressure level (dB re 1 µPa).
L_E= sound exposure level for single strike (dB re 1 μPa^2 s).
$L_{E,24h}$= sound exposure level over 24 hours (dB re 1 μPa^2 s), unweighted for fish and frequency weighted for all other groups.
[a] NMFS (2024) criteria for marine fauna.
[b] NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
[c] Popper et al. (2014).
[d] Accomando et al. (2025a).
[e] McCauley et al. (2000).
[f] Human health assessment threshold derived from Parvin (2005).
[g] Fewtrell and McCauley (2012).
[h] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[i] Day et al (2016a).

Table 195. Sub-station Jacket Piles, no mitigation and PULSE+DBBC: ranges (R_{max} in km) to acoustic thresholds for marine fauna and humans for each monopile at the penetration depth that results in the farthest ranges. Since $L_{E,24h}$ accounts for the accumulation of all hammer strikes required to drive four piles, the distances to the corresponding thresholds encompass all the hammer energy settings. A dash (-) indicates that the acoustic threshold was not reached.

Fauna group / Receiver	Threshold	Metric	Threshold	Jacket Piles (x4)	
				Unmitigated	PULSE+DBBC
Low-frequency (LF) cetaceans	PTS [a]	$L_{E,24h}$	183	10.1	4.30
	TTS [a]	$L_{E,24h}$	168	59.9	22.4
	Weighted behavioural response [h]	L_p	160	2.87	1.10
	Weighted behavioural response (migrating mysticetes) [h]	L_p	140	49.1	9.67
High-frequency (HF) cetaceans	PTS [a]	$L_{E,24h}$	193	0.02	–
	TTS [a]	$L_{E,24h}$	178	0.33	0.06
Otariid seals	PTS [a]	$L_{E,24h}$	185	0.05	–
	TTS [a]	$L_{E,24h}$	170	0.60	0.16
All marine mammal groups	Behavioural Response [b]	L_p	160	6.57	2.60
Fish without swim bladder	Mortality and Potential mortal injury [c]	$L_{E,24h}$	219	0.09	0.02
	Recoverable injury [c]	$L_{E,24h}$	216	0.19	0.05
	TTS [c]	$L_{E,24h}$	186	15.3	7.74
	Recoverable injury [c]	L_{pk}	213	–	–
Fish with swim bladder not involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	210	0.58	0.17
	Recoverable injury [c]	$L_{E,24h}$	203	2.04	0.62
	TTS [c]	$L_{E,24h}$	186	15.3	7.74
	Recoverable injury [c]	L_{pk}	207	0.02	–
Fish with swim bladder involved in hearing	Mortality and Potential mortal injury [c]	$L_{E,24h}$	207	1.06	0.23
	Recoverable injury [c]	$L_{E,24h}$	203	2.04	0.62
	TTS [c]	$L_{E,24h}$	186	15.3	7.74
	Recoverable injury [c]	L_{pk}	207	0.02	–
Sea turtles	PTS [d]	$L_{E,24h}$	184	7.29	3.14
	TTS [d]	$L_{E,24h}$	169	49.4	16.5
Penguins	PTS [a]	$L_{E,24h}$	185	0.05	–
	TTS [a]	$L_{E,24h}$	170	0.60	0.16
Humans	Human health assessment threshold [f]	L_p	145	49.1	12.2
Squid	Startle response [g]	L_E	162	1.71	0.45
Benthic invertebrates	Peak acceleration magnitude [i]	m/s^2	35.75	–	–

L_{pk}= unweighted peak sound pressure level (dB re 1 µPa).
L_p= unweighted sound pressure level (dB re 1 µPa).
L_E= sound exposure level for single strike (dB re 1 µPa^2 s).
$L_{E,24h}$= sound exposure level over 24 hours (dB re 1 µPa^2 s), unweighted for fish and frequency weighted for all other groups.
[a] NMFS (2024) criteria for marine fauna.
[b] NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
[c] Popper et al. (2014).
[d] Accomando et al. (2025a).
[e] McCauley et al. (2000).
[f] Human health assessment threshold derived from Parvin (2005).
[g] Fewtrell and McCauley (2012).
[h] Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)).
[i] Day et al (2016a).

7.2.2. Vibro Piling Operations

Table 196. Monopile foundation (GIANT 4000 hammer): distance (R_{max} in km) to SPL acoustic behavioural response thresholds for vibro piling. Maximum distances over penetration depth are presented.

Fauna group	SPL (L_p; dB re 1 µPa)	Monopile 1	Monopile 2	Monopile 3	OSS Jacket Pile
Fish recoverable injury [a]	170	8.75	14.5	10.1	11.6
Fish TTS [b]	158	19.6	45.2	22.3	34.1
Marine mammal behavioural response [c]	120	>90.0	>90.0	>90.0	>90.0

[a] 48 h threshold for recoverable injury for fish with a swim bladder involved in hearing (Popper et al. 2014).
[b] 12 h threshold for TTS for fish with a swim bladder involved in hearing (Popper et al. 2014).
[c] Threshold for marine mammal behavioural response to non-impulsive noise NOAA (2024).

Table 197. Monopile foundation (GIANT 4000 hammer): distance (R_{max} in km) to SEL_{24h} acoustic thresholds for marine mammals, fish, and sea turtles, for vibro piling.

Hearing group	$L_{E,24h}$ threshold	Monopile 1	Monopile 2	Monopile 3	Single Jacket Pile	Four Jacket Piles
PTS						
LF cetaceans	197	11.1	5.82	21.1	1.11	3.01
HF cetaceans	201	0.06	–	0.41	–	–
Otariid seals	199	0.04	–	0.23	–	–
Sea turtles	198	7.25	3.51	17.3	0.38	1.21
Penguins	199	0.04	–	0.23	–	–
TTS						
LF cetaceans	177	83.5	37.0	68.7	13.2	24.5
HF cetaceans	181	2.90	0.38	6.45	0.05	0.11
Otariid seals	179	2.20	0.18	5.00	–	0.07
Sea turtles	178	83.2	25.5	64.4	7.26	13.1
Penguins	179	2.20	0.18	5.00	–	0.07

A dash indicates the threshold was not reached within the limits of the modelling resolution (20 m).

7.2.3. Vessel Operations

Table 198. Maximum (R_{max}) and 95% ($R_{95\%}$) horizontal distances (in km) to the NOAA (2024) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) from the most appropriate location for considered sources per scenario.

Scenario Description	R_{max} (km)	$R_{95\%}$ (km)
Intermediate Shallow; WTGIV, PSV and CLV	15.6	14.1
Deep; WTGIV B, PSV and CLV	12.0	10.9

Table 199. Summary: Maximum (R_{max}) horizontal distances (in km) and ensonified area (km²) for the NMFS (2024) frequency-weighted LF-cetacean SEL_{24h} TTS thresholds from the most appropriate location for the considered scenario.

Scenario Description	R_{max} (km)	Area (km²)
Intermediate Shallow; WTGIV B, PSV and CLV	9.16	104
Deep; WTGIV B, PSV and CLV	6.35	72.5

7.2.4. Animal Movement Modelling

In this study, the moving receivers ('animats') were set to simulate the real-world movements of pygmy blue whales, humpback whales, southern right whales, and minke whales.

Table 200. *Monopiles*: Summary of animat simulation results indicating the maximum of the 95th percentile exposure ranges ($ER_{95\%}$) (in km) for each species at each modelled site for the monopiles. A dash (-) indicates that no animat was exposed above the threshold.

Species	PULSE+DBBC+HSD			
	Monopile 1	Monopile 2	Monopile 3	Monopile 4
PTS SEL_{24h} (183 dB re 1 µPa² s) [a]				
Pygmy blue whale	–	0.03	0.04	0.06
Humpback whale	0.20	–	0.02	–
Southern right whale	–	–	0.05	–
Minke whale	–	–	–	–
TTS SEL_{24h} (168 dB re 1 µPa² s) [a]				
Pygmy blue whale	4.60	2.28	1.34	0.86
Humpback whale	4.27	2.45	1.48	1.43
Southern right whale	1.49	0.84	0.44	0.37
Minke whale	1.42	0.57	0.27	0.08
Behavioural response SPL (160 dB re 1 µPa) [b]				
Pygmy blue whale	5.20	4.65	2.38	2.08
Humpback whale	4.79	4.33	2.24	1.84
Southern right whale	4.49	3.56	1.86	1.48
Minke whale	4.68	4.40	2.29	1.83
Behavioural response SPL ('Other' mysticetes, low-frequency weighted 160 dB re 1 µPa) [c]				
Pygmy blue whale	–	0.27	0.12	0.12
Humpback whale	0.42	0.15	0.11	0.10
Southern right whale	0.40	0.11	0.07	0.09
Minke whale	0.44	0.21	0.10	0.09
Behavioural response SPL (Migrating mysticetes, low-frequency weighted 140 dB re 1 µPa) [c]				
Pygmy blue whale	6.57	5.58	2.77	2.75
Humpback whale	6.33	5.13	2.36	2.58
Southern right whale	5.95	4.69	2.35	2.41
Minke whale	6.27	5.20	2.49	2.41

a NMFS (2024) criteria for marine fauna.
b NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
c Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)

Table 201. *Sub-station Jacket Piles*: Summary of animat simulation results indicating the maximum of the 95th percentile exposure ranges ($ER_{95\%}$) (in km) for each species for the OSS Jacket Pile.

Species	Sub-station Jacket Piles x4
	PULSE+DBBC
PTS SEL_{24h} (183 dB re 1 µPa² s) [a]	
Pygmy blue whale	1.08
Humpback whale	1.67
Southern right whale	1.46
Minke whale	0.02
TTS SEL_{24h} (168 dB re 1 µPa² s) [a]	
Pygmy blue whale	10.5
Humpback whale	8.97
Southern right whale	7.65
Minke whale	4.66
Behavioural response SPL (160 dB re 1 µPa) [b]	
Pygmy blue whale	2.15
Humpback whale	2.28
Southern right whale	2.13
Minke whale	2.16
Behavioural response SPL ('Other' mysticetes, low-frequency weighted 160 dB re 1 µPa) [c]	
Pygmy blue whale	0.87
Humpback whale	0.81
Southern right whale	0.82
Minke whale	0.83
Behavioural response SPL (Migrating mysticetes, low-frequency weighted 140 dB re 1 µPa) [c]	
Pygmy blue whale	8.58
Humpback whale	8.37
Southern right whale	8.23
Minke whale	8.10

a NMFS (2024) criteria for marine fauna.
b NOAA (2024) recommended unweighted behavioural threshold for marine mammals.
c Behavioural response weighted threshold for a 50% probability of response for impulsive sound sources (adapted from Wood et al. (2012a)

Table 202. *Vessel operations:* Summary of animat simulation results indicating the maximum of the 95th percentile exposure ranges ($ER_{95\%}$) (in km) for each species for each modelled vessel scenario. A dash (-) indicates that no animat was exposed above the threshold.

Species	Intermediate Shallow: WTGIV, PSV and CLV	Deep: WTGIV, PSV and CLV
PTS SEL_{24h} (199 dB re 1 μPa^2 s) [a]		
Pygmy blue whale	–	–
Humpback whale	–	–
Minke whale	–	–
Southern right whale	–	–
TTS SEL_{24h} (179 dB re 1 μPa^2 s) [a]		
Pygmy blue whale	0.21	0.15
Humpback whale	0.77	0.83
Minke whale	0.02	0.02
Southern right whale	1.09	1.00
Behavioural response SPL (120 dB re 1 µPa) [b]		
Pygmy blue whale	11.6	7.79
Humpback whale	10.8	7.82
Minke whale	10.8	7.20
Southern right whale	10.8	7.87

a NMFS (2024) criteria for marine fauna.
b NOAA (2024) recommended unweighted behavioural threshold for marine mammals.

Glossary

Unless otherwise stated in an entry, these definitions are consistent with ISO 80000-3 (2017b).

1/3-octave

One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec).

1/3-octave-band

Frequency band whose bandwidth is one one-third octave. *Note*: The bandwidth of a one-third octave-band increases with increasing centre frequency.

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

acoustic impedance

The ratio of the sound pressure in a medium to the volume flow rate of the medium through a specified surface due to the sound wave.

acoustic noise

Sound that interferes with an acoustic process.

attenuation

The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

auditory frequency weighting

The process of applying an auditory frequency weighting function. In human audiometry, C-weighting is the most commonly used function, an example for marine mammals are the auditory frequency weighting functions published by Southall et al. (2007).

auditory frequency weighting function

Frequency weighting function describing a compensatory approach accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity. Example hearing groups are low-, mid-, and high-frequency cetaceans, phocid and otariid pinnipeds.

azimuth

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation it is also called bearing.

bandwidth

The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI R2010).

bar

Unit of pressure equal to 100 kPa, which is approximately equal to the atmospheric pressure on Earth at sea level. 1 bar is equal to 10^5 Pa or 10^{11} µPa.

broadband level

The total level measured over a specified frequency range.

cetacean

Any animal in the order Cetacea. These are aquatic species and include whales, dolphins, and porpoises.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period. A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade

One tenth of a decade (ISO 2017b). Note: An alternative name for decidecade (symbol ddec) is “one-tenth decade”. A decidecade is approximately equal to one third of an octave (1 ddec ≈ 0.3322 oct) and for this reason is sometimes referred to as a “one-third octave”.

decidecade band

Frequency band whose bandwidth is one decidecade. Note: The bandwidth of a decidecade band increases with increasing centre frequency.

decibel (dB)

Unit of level used to express the ratio of one value of a power quantity to another on a logarithmic scale. Unit: dB.

ensonified

Exposed to sound.

far field

The zone where, to an observer, sound originating from an array of sources (or a spatially distributed source) appears to radiate from a single point.

Fourier transform (or Fourier synthesis)

A mathematical technique which, although it has varied applications, is referenced in the context of this report as a method used in the process of deriving a spectrum estimate from time-series data (or the reverse process, termed the inverse Fourier transform). A computationally efficient numerical algorithm for computing the Fourier transform is known as fast Fourier transform (FFT).

flat weighting

Term indicating that no frequency weighting function is applied. Synonymous with unweighted.

frequency

The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: *f*. 1 Hz is equal to 1 cycle per second.

frequency weighting

The process of applying a frequency weighting function.

frequency-weighting function

The squared magnitude of the sound pressure transfer function. For sound of a given frequency, the frequency weighting function is the ratio of output power to input power of a specified filter, sometimes expressed in decibels. Examples include the following:

- *Auditory frequency weighting function*: compensatory frequency weighting function accounting for a species' (or functional hearing group's) frequency-specific hearing sensitivity.
- *System frequency weighting function*: frequency weighting function describing the sensitivity of an acoustic acquisition system, typically consisting of a hydrophone, one or more amplifiers, and an analogue to digital converter.

geoacoustic

Relating to the acoustic properties of the seabed.

hearing group

Category of animal species when classified according to their hearing sensitivity and to the susceptibility to sound. Examples for marine mammals include very low-frequency (VLF) cetaceans, low-frequency (LF) cetaceans, mid-frequency (MF) cetaceans, high-frequency (HF) cetaceans, very high-frequency (VHF) cetaceans, otariid pinnipeds in water (OPW), phocid pinnipeds in water (PPW), sirenians (SI), other marine carnivores in air (OCA), and other marine carnivores in water (OCW). See **auditory frequency weighting functions**, which are often applied to these groups (Accomando et al. 2025a), NMFS (2024), Southall et al. (2019) and NMFS (2018) Examples for fish include species for which the swim bladder is involved in hearing, species for which the swim bladder is not involved in hearing, and species without a swim bladder (Popper et al. 2014).

hearing threshold

The sound pressure level for any frequency of the hearing group that is barely audible for a given individual for specified background noise during a specific percentage of experimental trials.

hertz (Hz)

A unit of frequency defined as one cycle per second.

high-frequency (HF) cetacean

See **hearing group**.

intermittent sound

A sound whose level abruptly drops below the background noise level several times during an observation period.

impulsive sound

Qualitative term meaning sounds that are typically transient, brief (less than 1 second), broadband, with rapid rise time and rapid decay. They can occur in repetition or as a single event. Examples of impulsive sound sources include explosives, seismic airguns, and impact pile drivers.

level

A measure of a quantity expressed as the logarithm of the ratio of the quantity to a specified reference value of that quantity. Examples include sound pressure level, sound exposure level, and peak sound pressure level. For example, a value of sound exposure level with reference to 1 μPa^2 s can be written in the form *x* dB re 1 μPa^2 s.

low-frequency (LF) cetacean

See **hearing group**.

mysticete

A suborder of cetaceans that use baleen plates to filter food from water. Members of this group include rorquals (Balaenopteridae), right whales (Balaenidae), and grey whales (*Eschrichtius robustus*).

non-impulsive sound

Sound that is not an impulsive sound. A non-impulsive sound is not necessarily a continuous sound.

octave

The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

odontocete

The presence of teeth, rather than baleen, characterizes these whales. Members of the Odontoceti are a suborder of cetaceans, a group comprised of whales, dolphins, and porpoises. The skulls of toothed whales are mostly asymmetric, an adaptation for their echolocation. This group includes sperm whales, killer whales, belugas, narwhals, dolphins, and porpoises.

otariid

A common term used to describe members of the Otariidae, eared seals, commonly called sea lions and fur seals. Otariids are adapted to a semi-aquatic life; they use their large fore flippers for propulsion. Their ears distinguish them from phocids. Otariids are one of the three main groups in the superfamily Pinnipedia; the other two groups are phocids and walrus.

other marine carnivores in water (OCW)

See **hearing group**.

parabolic equation method

A computationally efficient solution to the acoustic wave equation that is used to model propagation loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of propagation loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

phocid

A common term used to describe all members of the family Phocidae. These true/earless seals are more adapted to in-water life than are otariids, which have more terrestrial adaptations. Phocids use their hind flippers to propel themselves. Phocids are one of the three main groups in the superfamily Pinnipedia; the other two groups are otariids and walrus.

phocid pinnipeds in water (PPW)

See **hearing group**.

pinniped

A common term used to describe all three groups that form the superfamily Pinnipedia: phocids (true seals or earless seals), otariids (eared seals or fur seals and sea lions), and walrus.

point source

A source that radiates sound as if from a single point.

pressure, acoustic

The deviation from the ambient pressure caused by a sound wave. Also called sound pressure. Unit: pascal (Pa).

propagation loss (PL)

Difference between a source level (SL) and the level at a specified location, PL(x) = SL − L(x). Also see **transmission loss**.

received level

The level measured (or that would be measured) at a defined location. The type of level should be specified.

reference values

Standard underwater references values used for calculating sound **levels**, e.g., the reference value for expressing sound pressure level in decibels is 1 µPa.

Quantity	Reference value
Sound pressure	1 µPa
Sound exposure	1 μPa^2 s
Sound particle displacement	1 pm
Sound particle velocity	1 nm/s
Sound particle acceleration	1 $\mu m/s^2$

rms

abbreviation for root-mean-square.

sound

A time-varying disturbance in the pressure, stress, or material displacement of a medium propagated by local compression and expansion of the medium.

sound exposure

Time integral of squared sound pressure over a stated time interval. The time interval can be a specified time duration (e.g., 24 hours) or from start to end of a specified event (e.g., a pile strike, an airgun pulse, a construction operation). Unit: Pa^2 s.

sound exposure level

The level (L_E) of the sound exposure (E). Unit: decibel (dB). Reference value (E_0) for sound in water: 1 μPa^2 s.

$$L_E := 10 \log_{10}(E/E_0)\,\text{dB} = 20 \log_{10}\left(E^{1/2}/E_0^{1/2}\right)\,\text{dB}$$

The frequency band and integration time should be specified. Abbreviation: SEL.

sound field

Region containing sound waves.

sound intensity

Product of the sound pressure and the sound particle velocity. The magnitude of the sound intensity is the sound energy flowing through a unit area perpendicular to the direction of propagation per unit time.

sound pressure

The contribution to total pressure caused by the action of sound.

sound pressure level (rms sound pressure level)

The level ($L_{p,\text{rms}}$) of the time-mean-square sound pressure (p^2_{rms}). Unit: decibel (dB). Reference value (p_0^2) for sound in water: 1 μPa^2.

$$L_{p,\text{rms}} := 10 \log_{10}(p^2_{\text{rms}}/p_0^2)\,\text{dB} = 20 \log_{10}(p_{\text{rms}}/p_0)\,\text{dB}$$

The frequency band and averaging time should be specified. Abbreviation: SPL or Lrms.

sound speed profile

The speed of sound in the water column as a function of depth below the water surface.

source level (SL)

A property of a sound source obtained by adding to the sound pressure level measured in the far field the propagation loss from the acoustic centre of the source to the receiver position. Unit: decibel (dB). Reference value: 1 μPa^{2}m^2.

spectrum

An acoustic signal represented in terms of its power, energy, mean-square sound pressure, or sound exposure distribution with frequency.

temporary threshold shift (TTS)

Reversible loss of hearing sensitivity. TTS can be caused by noise exposure.

transmission loss (TL)

The difference between a specified level at one location and that at a different location, TL(x1,x2) = L(x1) − L(x2). Also see **propagation loss**.

unweighted

Term indicating that no frequency weighting function is applied. Synonymous with flat weighting.

very high-frequency (VHF) cetacean

See **hearing group**.

wavelength

Distance over which a wave completes one cycle of oscillation. Unit: metre (m). Symbol: λ.

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Appendix A. Acoustic Metrics and Noise Effect Criteria

This section describes in detail the acoustic metrics, impact criteria, and frequency weighting relevant to the modelling study.

A.1. Pressure Related Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 µPa. Because the perceived loudness of sound, especially pulsed sound such as from seismic airguns, pile driving, and sonar, is not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate sound and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow International Organization for Standardization definitions and symbols for sound metrics (e.g., ISO 2017a, ANSI S1.1-2013).

The zero-to-peak sound pressure, or peak sound pressure (PK or $L_{p,pk}$; dB re 1 µPa), is the decibel level of the maximum instantaneous acoustic pressure in a stated frequency band attained by an acoustic pressure signal, $\mathrm{p(t)}$:

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \tag{A-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of an acoustic event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure (PK-PK or $L_{p,pk\text{-}pk}$; dB re 1 µPa) is the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $\mathrm{p(t)}$:

$$L_{p,\mathrm{pk\text{-}pk}} = 10\log_{10}\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2} \tag{A-2}$$

The sound pressure level (SPL or L_p; dB re 1 µPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that SPL always refers to an rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt/p_0^2\right)\ \mathrm{dB} \tag{A-3}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying SPL function. For short acoustic events, such as sonar pulses and marine mammal vocalizations, it is important to choose an appropriate time window that matches the duration of the signal. For in-air studies, when evaluating the perceived loudness of sounds with rapid amplitude variations in time, the time weighting function $\mathrm{g(t)}$ is often set to a decaying exponential function that emphasizes more recent pressure signals. This function mimics the leaky integration nature of mammalian hearing. For example, human-based fast time-weighted SPL ($L_{p,fast}$) applies an exponential function with time constant 125 ms. A related simpler approach used in underwater acoustics sets $\mathrm{g(t)}$ to a boxcar (unity amplitude) function of width 125 ms; the results can be referred to as $L_{p,boxcar\ 125ms}$. Another approach, historically used to evaluate SPL of impulsive signals underwater, defines $\mathrm{g(t)}$ as a boxcar function with edges set to the times corresponding to 5% and 95% of the cumulative square pressure function encompassing the

duration of an impulsive acoustic event. This calculation is applied individually to each impulse signal, and the results are referred to as 90% SPL ($L_{p,90\%}$).

The sound exposure level (SEL or L_E; dB re 1 µPa^2·s) is the time-integral of the squared acoustic pressure over a duration (T):

$$L_E = 10 \log_{10} \left(\int_T p^2(t)\, dt / T_0 p_0^2 \right) \text{ dB} \tag{A-4}$$

where T_0 is a reference time interval of 1 s. SEL continues to increase with time when non-zero pressure signals are present. It is a dose-type measurement, so the integration time applied must be carefully considered for its relevance to impact to the exposed recipients.

SEL can be calculated over a fixed duration, such as the time of a single event or a period with multiple acoustic events. When applied to pulsed sounds, SEL can be calculated by summing the SEL of the N individual pulses. For a fixed duration, the square pressure is integrated over the duration of interest. For multiple events, the SEL can be computed by summing (in linear units) the SEL of the N individual events:

$$L_{E,N} = 10 \log_{10} \left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}} \right) \text{ dB}. \tag{A-5}$$

If applied, the frequency weighting of an acoustic event should be specified, as in the case of weighted SEL (e.g., $L_{E,LFC,24h}$; Appendix A.5). The use of fast, slow, or impulse exponential-time-averaging or other time-related characteristics should also be specified.

A.2. Decidecade Band Analysis

The distribution of a sound's power with frequency is described by the sound's spectrum. The sound spectrum can be split into a series of adjacent frequency bands. Splitting a spectrum into 1 Hz wide bands, called passbands, yields the power spectral density of the sound. This splitting of the spectrum into passbands of a constant width of 1 Hz, however, does not represent how animals perceive sound.

Because animals perceive exponential increases in frequency rather than linear increases, analysing a sound spectrum with passbands that increase exponentially in size better approximates real-world scenarios. In underwater acoustics, a spectrum is commonly split into decidecade bands, which are one tenth of a decade wide. A decidecade is sometimes referred to as a "1/3 octave" because one tenth of a decade is approximately equal to one third of an octave. Each decade represents a factor 10 in sound frequency. Each octave represents a factor 2 in sound frequency. The centre frequency of the ith band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}} \text{ kHz} \tag{A-6}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith decade band are defined as:

$$f_{lo,i} = 10^{\frac{-1}{20}} f_c(i) \quad \text{and} \quad f_{hi,i} = 10^{\frac{1}{20}} f_c(i) \tag{A-7}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure A-1). The acoustic modelling spans from band 10 (f_c (10) = 10 Hz) to band 44 ($f_c(44)$ = 25 kHz).

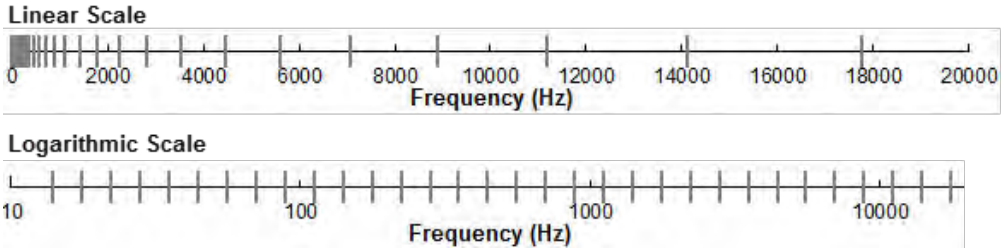


Figure A-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{\mathrm{lo},i}$ and $f_{\mathrm{hi},i}$:

$$L_{p,i} = 10\,log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\,\mathrm{d}f \ \ \mathrm{dB} \tag{A-8}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\text{Broadband SPL} = 10\log_{10} \sum_{i} 10^{\frac{L_{p,i}}{10}} \ \mathrm{dB} \tag{A-9}$$

Figure A-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient sound signal. Because the decidecade bands are wider than 1 Hz, the decidecade band SPL is higher than the spectral levels at higher frequencies. Acoustic modelling of decidecade bands requires less computation time than 1 Hz bands and still resolves the frequency-dependence of the sound source and the propagation environment.

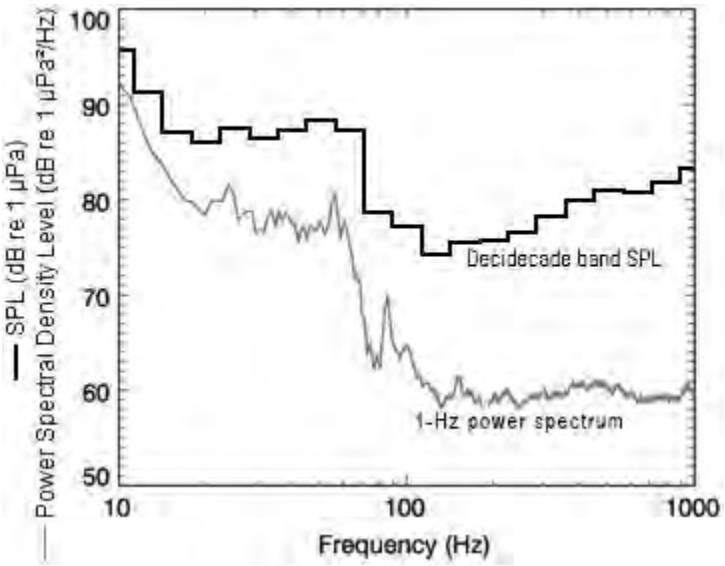


Figure A-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale.Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum.

A.3. Noise Effect Criteria (First and Second Modelling Rounds)

A.3.1. Impulsive Noise

Impact pile driving activities were assessed as impulsive noise source as consistent with the considered thresholds and guidelines.

A.3.1.1. Marine Mammals

The criteria applied in these studies to assess possible effects of impulsive noise sources on marine mammals are summarised in Table A-1; cetaceans and otariid seals were identified as the hearing groups requiring assessment. Details on frequency weighting explained in detail in Appendix A.5. Whilst Southall et al. (2021) provided recommendations and discussed the nuances of assessing behavioural response, the paper did not recommend new numerical thresholds for onset of behavioural responses for marine mammals. The criterion from the U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) was applied.

Table A-1. Acoustic effects of impulsive noise on marine mammals: Unweighted SPL, SEL_{24h}, and PK thresholds.

Hearing group	NOAA (2019)	Southall et al. (2019)			
	Behaviour	PTS onset thresholds* (received level)		TTS onset thresholds* (received level)	
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)
Low–Frequency (LF) cetaceans	160	183	219	168	213
High–frequency (HF) cetaceans		185	230	170	224
Otariid seals		203	232	188	226

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non–impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.

L_p denotes sound pressure level.

$L_{pk,flat}$ denotes peak sound pressure is flat weighted or unweighted.

L_E denotes cumulative sound exposure over a 24 h period.

To assist in the assessment of potential behavioural responses by migrating whales, a graded probability of response for impulsive sounds using a frequency weighted SPL metric, as described in Wood et al. (2012a), has been applied. Wood et al. (2012a) defined behavioural response categories for sensitive species (including harbor porpoise and beaked whales), for migrating mysticetes, and for all other species. Both the migrating mysticete category and the category for all other species have been applied in this analysis to all whale species, for comparative purposes (Table A-2). This analysis considers distances to the levels related to probabilistic response of 50% or above i.e. 140 dB re 1 µPa for 'migrating', and 160 dB re 1 µPa for 'other' whales. The Wood et al. (2012a) approach has been updated to consider the frequency weighting from Southall et al. (2019) for low-frequency cetaceans as opposed to that from Southall et al. (2007).

Table A-2. Acoustic sound pressure level (SPL) thresholds used to evaluate potential behavioural impacts to marine mammals. Probabilities are not additive. Adapted from Wood et al. (2012).

Marine mammal group	Frequency weighted probabilistic response (L_p; dB re 1 µPa)			
	120	140	160	180
Beaked whales and harbor porpoises	50%	90%		
Migrating mysticete whales	10%	50%	90%	
All other species		10%	50%	90%

A.3.1.2. Fish

In 2006, the Working Group on the Effects of Sound on Fish and Sea Turtles was formed to continue developing noise exposure criteria for fish and sea turtles, work begun by a NOAA panel two years earlier. The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death,
- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. However, as these depend upon activity–based subjective ranges, these effects are not addressed in this report and are included in Table A-3 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish's susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Sea turtles, fish eggs, and fish larvae are considered separately.

Impulsive noise from pile driving is assessed in this study based on the relevant effects thresholds from Popper et al. (2014) listed in Table A-3. In general, whether an impulsive sound adversely effects fish behaviour depends on the species, the state of the individual exposed, and other factors.

The SEL metric integrates noise intensity over some period of exposure. Because the period of integration for regulatory assessments is not well defined for sounds that do not have a clear start or end time, or for very long–lasting exposures, an exposure evaluation time must be defined. Southall et al. (2007) defines the exposure evaluation time as the greater of 24 h or the duration of the activity. Popper et al. (2014) recommend a standard period of the duration of the activity; however, the publication also includes caveats about considering the actual exposure times if fish move.

Table A-3. Criteria for pile driving noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	

Fish: No swim bladder (particle motion detection)	> 219 dB SEL_{24h} or > 213 dB PK	> 216 dB SEL_{24h} or > 213 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	210 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	186 dB SEL_{24h}	Pile driving: (N, I) High (F) Moderate	(N, I) High (F) Moderate
Fish eggs and fish larvae (relevant to plankton)	> 210 dB SEL_{24h} or > 207 dB PK	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	Pile driving: (N) Moderate (I, F) Low	(N) Moderate (I, F) Low

Peak sound pressure level: dB re 1 µPa; SEL_{24h} dB re 1µPa^2·s.
All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

A.3.1.3. Sea Turtles

The thresholds for sea turtles are shown in Table A-4.

Table A-4. Acoustic effects of impulsive noise on sea turtles: Unweighted sound pressure level (SPL), 24-hour sound exposure level (SEL_{24h}), and peak pressure (PK) thresholds

Effect type	Criterion	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)	PK (L_{pk}; dB re 1 µPa)
Behavioural response	NSF (2011)	166	NA	
Behavioural disturbance	McCauley et al. (2000a)	175		
PTS onset thresholds[1] (received level)	Finneran et al. (2017)	NA	204	232
TTS onset thresholds[1] (received level)			189	226

[1] Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS and TTS onset. If a non–impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.
L_p denotes sound pressure level period and has a reference value of 1 µPa.
$L_{pk,flat}$ denotes peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^2s.

A.3.1.4. Diving Seabirds

There are no regulatory thresholds with regard to onset of hearing impairment for penguins, any other bird species, or phylogenetically or anatomically related species. The only scientifically robust thresholds in this context exist for marine mammals. To allow for assessing the noise–induced impact and injury risk of impulsive pile driving signals on penguins, the marine mammal hearing group, other carnivores in water (OCW), from both Southall et al. (2019) and NMFS (2024), is recommended as a proxy. This hearing group has been selected due to similar hearing sensitivity in the frequency band of underwater hearing for diving birds and otariid pinnipeds, which are included in the OCW group. This may provide a conservative approach, as otariids are considered more sensitive to underwater sound at higher frequencies than penguins.

There are also no regulatory thresholds or criteria established to assess potential behavioural responses by penguins or flying seabirds to underwater noise. To allow for assessing the potential for such impacts was chosen based on information from Sørensen et al. (2020). A study undertaken by Sørensen et al. (2020) exposed gentoo penguins (*Pygoscelis papua*) in a controlled exposure experiment to underwater noise bursts (impulsive signals) and demonstrated that the animals show a graded reaction depending on received sound levels. Based on the outcome of this study, an onset criterion for behavioural responses of penguins and flying seabirds of 120 dB re 1 µPa (SPL) for impulsive sources has been suggested and was utilised in earlier modelling rounds. However, upon further review it was decided that given the limitations of this study, it is not appropriate for this threshold to be applied to all seabirds and contexts at this stage. Consequently, there is no robust threshold or criteria to assess potential behavioural responses for penguins and flying seabirds.

A.3.1.5. Invertebrates

Although the study of effects of sound on invertebrates (e.g., crustaceans, cephalopods, and bivalves) is in its nascency, it is evident that invertebrates are sensitive to particle motion (as opposed to pressure) (Popper and Hawkins 2018) and that they can detect vibrations in the sea bed (Roberts et al. 2015, Roberts and Breithaupt 2016, Roberts and Elliott 2017). While there are currently no agreed upon metrics or clearly defined levels (in terms of sound pressure or particle motion) for assessing the effects or impacts of sound on invertebrates (Hawkins and Popper 2017), levels reported in literature can in some cases be used to guide assessments. This is primarily possible for impulsive sound sources. Overall, while there are preliminary indications of potential impacts of vessel noise on some invertebrates, most research has been conducted in a laboratory setting, where tank boundaries may affect the acoustic field and observed behavioural response (Rogers et al. 2016, Popper and Hawkins 2018). Further, nearly all studies measured sound pressure rather than particle motion (Jesus et al. (2020). Although high-intensity noise may produce high sound pressure levels and high levels of particle motion concurrently, it is impossible to determine this relationship without proper measurements (Popper and Hawkins 2018). Therefore, levels in this study have not been assessed for comparison to literature for vessels and non-impulsive noise sources.

A.3.1.6. Benthic Invertebrates (Crustaceans and Bivalves)

Research is ongoing into the relationship between sound and its effects on crustaceans, including the relevant metrics for both effect and impact. Available literature suggests particle motion, rather than sound pressure, is a more important factor for crustacean and bivalve hearing. The majority of work has been completed for seismic survey sources, where water depth and seismic source size are related to the particle motion levels at the seafloor, with larger arrays and shallower water being related to higher particle motion levels, more likely relevant to effects on crustaceans and bivalves.

At the seafloor interface, crustaceans and bivalves are subject to particle motion stimuli from several acoustic or acoustically–induced waves. These include the particle motion associated with an impinging sound pressure wave in the water column (the incident, reflected, and transmitted portions), substrate acoustic waves, and interface waves of the Scholte type. However, it is unclear which aspect(s) of these waves is/are most relevant to the animals, either when they normally sense the environment or their physiological responses to loud sounds so there is not enough information to establish similar criteria and thresholds as done for marine mammals and fish. Including recent research, such as Day et al. (2016b), current literature does not clearly define an appropriate metric or identify relevant levels (pressure or particle motion) for an assessment. This includes the consideration of what particle motion levels lead to a behavioural response, or mortality. Therefore, at this stage, we cannot propose authoritative thresholds to inform the impact assessment. However, levels can be determined for pressure metrics presented in literature to assist the assessment.

The pressure and acceleration examples provided in Figures 11 and 12 of Day et al. (2016a) indicate that the acceleration and pressure signals occurred simultaneously, which was interpreted as an indication that the waterborne sounds were responsible for the accelerations measured by the geophones. For clarity, it is important to distinguish that the acceleration from waterborne sound energy is *not* ground roll, which Day et al. (2016a) correctly define as the sound that propagates along the interface at a speed lower than the shear wave speed of the sediment. However, the report subsequently uses ground roll for all further discussions of particle acceleration. While Day et al. (2016a) discuss that they chose the simplest measure of ground roll, it should have been referring to as 'the acceleration from waterborne sound energy', or 'waterborne acceleration' for short.

For crustaceans, a PK–PK sound level of 202 dB re 1 µPa (Payne et al. 2008) is considered to be associated with no effect, and therefore applied in the assessment.

Literature does not present a sound level associated with no impact. Particle motion is the more relevant metric, and recent work by Jézéquel et al. (2022) has investigated the potential effects on scallops using this metric. They investigated behavioural responses of scallops to piling across three life-stages, and found juveniles to be most sensitive, and that responses were range (or level) dependent. They also found that scallops did not habituate to pile driving events, unlike squid (Section A.3.1.7). The levels presented in Jézéquel et al. (2022), Table A-5, have not been assessed in this report. The results are also presented to allow comparison against the results in Table 7 of Day et al. (2016a), in which the maximum particle acceleration assessed for scallops was 37.57 ms^{-2}.

Table A-5. Mean substrate-borne vibrations' features from the impact hammer presented in Jézéquel et al. (2022)

Distance (m)	Acceleration peaks (dB re 1 µm·s^{-2})	Single strike exposure (dB re (1 µm·s^{-2})^2·s)	Cumulative strike exposure (dB re (1 µm·s^{-2})^2·s)
8	109.95 [a]	94.39 [a]	115.67 [c]
50	87.08 [b]	72.48 [b]	93.13 [d]

[a] Calculated on 536 strikes, [b] Calculated on 315 strikes, [c] Calculated from 115 strikes, [d] Calculated from 129 strikes

A.3.1.7. Squid

The responses of squid to airgun signals were investigated by Fewtrell and McCauley (2012). The authors conducted a number of experiments and examined the received per–pulse SEL for caged squid. They found that in one trial, where the received level of the first airgun impulse was 162 dB re 1 µPa²·s, the squid inked. This response was not observed again within this trial, however the authors stated that it was unknown if this was due to depleted ink reserves or habituation. In two other trials, the initial received levels were lower (132 and 146 dB re 1 µPa²·s per–pulse SEL), and although the received levels did exceed 162 dB re 1 µPa²s, no inking behaviour was observed. The authors hypothesised that the results also suggest that a gradual increase in received levels and prior exposure to air gun impulses decreases the severity of the alarm responses in this species. This aligns with findings of general habituation in response to predators in squid (Long et al. 1989). Recent work (Jones et al. 2020) supports these findings as well, indicating potential rapid, short–term habituation by squid to impulsive noise, however, similar response rates were seen 24 h later, which indicated that squid might re–sensitise to the noise.

The results presented in by Fewtrell and McCauley (2012) were stated by the authors to be preliminary, and while they stated that while it is possible that noise levels greater than 147 dB re 1 µPa²·s are required to induce avoidance behaviour, the level associated with inking, of 162 dB re 1 µPa²·s per–pulse SEL, has been considered as a startle response level for squid.

A.3.1.8. Human Health Assessment Threshold

Underwater, the human ear is about 20 dB less sensitive than it is in air at low frequencies (20 Hz), increasing to 40 dB at mid–frequencies (less than 1 kHz), and increasing to 70–80 dB less sensitive at higher frequencies (Parvin 1998). Divers who wear neoprene hoods have even higher hearing thresholds (lower sensitivity) above 500 Hz because the hood material absorbs high–frequency sounds (Sims et al. 1999). Exposure studies related to divers have typically focused on military sonar exposure, with little information on pile driving noise, and as such care is required when considering thresholds for recreational divers and swimmers, particularly for impulsive sounds such as pile driving (Ainslie 2008).

The auditory threshold of hearing under water was lowest at 1 kHz (70 dB re 1 µPa SPL) and increased for lower and higher frequencies to around 120 dB re 1 µPa at 20 Hz and at 20 kHz (Parvin 1998). Fothergill et al. (2000) and Fothergill et al. (2001) conducted controlled acoustic exposure experiments on military divers under fully controlled conditions at a US Ocean Simulation Facility and an US Open water test facility; in all tests, the diver were covered with soft or hard shell dive suits and their position and distance relative to sound source, signal characteristics and received levels were controlled and documented (Pestorius et al. 2009). A total of 89 male Navy divers were exposed to pure tone signals and sweeps between 160–320 Hz at SPLs up to 160 dB re 1 µPa. The divers were exposed to these sounds over 100 seconds at depths from 10 to 40 metres. The divers rated the sounds on a severity scale. For frequencies between 100 and 500 Hz, at a received SPL of 130 dB re 1 µPa, divers and swimmers detected body vibration. None of the divers tested rated levels of 140 dB re 1 µPa as “very severe”; however, at 157 dB re 1 µPa, sound was rated as “very severe” 19 per cent of the time. No physiological damage was observed at the highest levels tested: 160 dB re 1 µPa (Fothergill et al. 2001). In a subsequent study, recreational divers were exposed to tonal signals or 30 Hz–sweeps at frequencies between 100 and 500 Hz at received levels of 130–157 dB re 1 µPa (Pestorius et al. 2009). Each exposure lasted for seven seconds. Nine female and 17 male scuba divers were tested, all wearing full body neoprene wetsuits. Diver aversion and perception of body vibration were used as test parameters. The results showed no sex–specific differences. The results differed as a function of frequency – while test results showed a strong overall variation between subjects, signals at 100 Hz elicited the strongest aversion in all tests and even at 148 dB a few diver ratings indicated extreme aversion. Due to this and the strong variation between test subjects, the following exposure limit for both military and recreational divers was suggested as a conservative measure: For frequencies between 100 and 500 Hz, the maximum SPL should be 145 dB re 1 µPa over a maximum continuous exposure of 100 seconds or with a maximum duty cycle of 20 per cent and a maximum daily cumulative total of three hours. The trading relation between the maximum SPL and duration was 4 dB per doubling of duration (e.g. 141 dB SPL for a 200 second exposure) (Pestorius et al. 2009).

Considering only frequencies between 100 and 500 Hz, Parvin (2005) suggested 145 dB re 1 µPa as a safety criterion for recreational divers and swimmers. Piling impulses are broadband sources, and therefore, to be precautionary, the 145 dB re 1 µPa SPL suggested by Fothergill et al. (2001) and Parvin (2005) has been applied in this study as a broadband SPL and as a human health assessment threshold for recreational divers and swimmers. This does not imply that this level is associated with the onset of injury.

A.3.2. Non-impulsive Noise

Vessel activities have been assessed as non-impulsive noise source as consistent with the considered thresholds and guidelines.

A.3.2.1. Marine Mammals

The criteria applied in this study to assess possible effects of non–impulsive sources on marine mammals are summarised in Table A-6; cetaceans and otariid seals were identified as the hearing groups requiring assessment. Detail on frequency weighting explained in detail in Appendix A.5. While Southall et al. (2021) provided recommendations and discussed the nuances of assessing behavioural response, the paper did not recommend new numerical thresholds for onset of behavioural responses for marine mammals. The criterion from the U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) was applied.

Table A-6. Criteria for effects of non–impulsive noise exposure, including vessel noise, for marine mammals: Unweighted SPL and SEL_{24h} thresholds.

Hearing group	NOAA (2019)	Southall et al. (2019)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 $µPa^2 \cdot s$)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 $µPa^2 \cdot s$)
Low–Frequency (LF) cetaceans	120	199	179
High–frequency (HF) cetaceans		198	178
Otariid seals		219	199

L_p denotes sound pressure level period and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 $µPa^2 \cdot s$.

A.3.2.2. Fish, Sea turtles, Fish Eggs, and Fish Larvae

Non-impulsive noise from vessels is assessed in this study based on the relevant effects thresholds from Popper et al. (2014). The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death,
- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Table A-7 lists the relevant effects thresholds from Popper et al. (2014) for vessel noise. Some evidence suggests that fish sensitive to acoustic pressure show a recoverable loss in hearing sensitivity, or injury when exposed to high levels of noise (Scholik and Yan 2002, Amoser and Ladich 2003, Smith et al. 2006); this is reflected in the SPL thresholds for fish with a swim bladder involved in hearing. Finneran et al. (2017) presented revised thresholds for turtle injury, considering frequency weighted SEL, which have been applied in this study for vessels (Table A-8).

Table A-7. Criteria for non–impulsive (vessels noise) noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Sound pressure level dB re 1 µPa.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

Table A-8. Acoustic effects of non–impulsive noise on sea turtles, weighted SEL_{24h}, Finneran et al. (2017).

PTS onset thresholds (received level)	TTS onset thresholds (received level)
220	200

A.4. Noise Effect Criteria (Third and Fourth Modelling Rounds)

The following thresholds and guidelines for the third and fourth modelling round studies were chosen because they represent the best available science, and sound levels presented in literature for fauna with no defined thresholds.

The following sections (along with Appendix A.5), expand on the thresholds, guidelines and sound levels for all marine fauna.

A.4.1. Marine Mammals

It has been long recognised that marine mammals can be adversely affected by underwater anthropogenic noise. For example, Payne and Webb (1971) suggested that communication distances of fin whales are reduced by shipping sounds. Subsequently, similar concerns arose regarding effects of other underwater noise sources and the possibility that impulsive sources—primarily airguns used in seismic surveys—could cause auditory injury. This led to a series of workshops held in the late 1990s, conducted to address acoustic mitigation requirements for seismic surveys and other underwater noise sources (NMFS 1998, ONR 1998, Nedwell and Turnpenny 1998, HESS 1999, Ellison and Stein 1999). In the years since these early workshops, a variety of thresholds have been proposed for both injury and disturbance. The following sections summarize the recent development of thresholds; however, this field remains an active research topic.

A.4.1.1. Auditory Impairment

In recognition of shortcomings of the SPL-only based injury criteria, in 2005 NMFS sponsored the Noise Criteria Group to review literature on marine mammal hearing to propose new noise exposure criteria. Some members of this expert group published a landmark paper (Southall et al. 2007) that suggested assessment methods similar to those applied for humans. The resulting recommendations introduced dual acoustic injury criteria for impulsive sounds that included peak pressure level thresholds and SEL_{24h} thresholds, where the subscripted 24h refers to the accumulation period for calculating SEL. The peak pressure level criterion is not frequency weighted whereas the SEL_{24h} is frequency weighted according to one of four marine mammal species hearing groups: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively) and Pinnipeds in Water (PINN). These weighting functions are referred to as M-weighting filters (analogous to the A-weighting filter for humans; Appendix A.5). The SEL_{24h} thresholds were obtained by extrapolating measurements of onset levels of Temporary Threshold Shift (TTS) in belugas by the amount of TTS required to produce Permanent Threshold Shift (PTS) in chinchillas. The Southall et al. (2007) recommendations do not specify an exchange rate, which suggests that the thresholds are the same regardless of the duration of exposure (i.e., it implies a 3 dB exchange rate).

Wood et al. (2012b) refined Southall et al. (2007)'s thresholds, suggesting lower injury values for LF and HF cetaceans while retaining the filter shapes. Their revised thresholds were based on TTS-onset levels in harbour porpoises from Lucke et al. (2009), which led to a revised impulsive sound PTS threshold for HF cetaceans of 179 dB re 1 $\mu Pa^2 \cdot s$. Because there were no data available for baleen whales, Wood et al. (2012b) based their recommendations for LF cetaceans on results obtained from MF cetacean studies. In particular they referenced Finneran and Schlundt (2010) research, which found mid-frequency cetaceans are more sensitive to non-impulsive sound exposure than Southall et al. (2007) assumed. Wood et al. (2012b) thus recommended a more conservative TTS-onset level for LF cetaceans of 192 dB re 1 $\mu Pa^2 \cdot s$.

As of present, an optimal approach is not apparent. There is consensus in the research community that an SEL-based method is preferable either separately or in addition to an SPL-based approach to assess the potential for injuries. In August 2016, after substantial public and expert input into three draft versions and based largely on the above-mentioned literature (NOAA 2013, 2015, 2016), NMFS finalised technical guidance for assessing the effect of anthropogenic sound on marine mammal hearing (NMFS 2016). The guidance describes injury criteria with new thresholds and frequency weighting functions for the five hearing groups described by Finneran and Jenkins (2012). Further revisions were published by NMFS in 2018 (NMFS, 2018). Southall et al. (2019) revisited the interim criteria published in 2007. All noise exposure criteria in NMFS (2018) and Southall et al. (2019) are identical (for impulsive and non-impulsive sounds); however, the mid- and high-frequency cetaceans groups from NMFS (2018) were renamed high- and very high-frequency cetaceans, respectively, in Southall et al. (2019).

The latest revision to noise exposure criteria was published by NMFS in 2024 (NMFS 2024), and these criteria are applied in the current report. In both of these publications, the term auditory injury (represented by either AUD INJ or AINJ) is used to encompass auditory injury with and without PTS, however for consistency with historic assessments the term PTS is used within this report.

A.4.1.2. Behavioural response

Numerous studies on marine mammal behavioural responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioural reactions. However, it is recognised that the context in which the sound is received affects the nature and extent of responses to a stimulus (Ellison and Frankel 2012, Southall et al. 2016).

For impulsive noise, NMFS currently uses a step function threshold of 160 dB re 1 µPa SPL (unweighted) to assess and regulate noise-induced behavioural impacts for marine mammals (NOAA 2018, NOAA 2019). The threshold for impulsive sound is derived from the High-Energy Seismic Survey (HESS) panel (HESS 1999) report that, in turn, is based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1984). The HESS team recognised that behavioural responses to sound may occur at lower levels, but significant responses were only likely to occur above a SPL of 140 dB re 1 µPa. Southall et al. (2007) found varying responses for most marine mammals between a SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions.

A.4.2. Diving Birds

A.4.2.1. Auditory Impairment

There are no regulatory thresholds with regard to onset of hearing impairment for penguins, any other bird species, or phylogenetically or anatomically related species. The only scientifically robust thresholds in this context exist for marine mammals.

Studies which have been conducted on birds have not resulted in any thresholds with regard to onset of hearing impairment for penguins, any other bird species, or phylogenetically or anatomically related species. Auditory measurements of in-air hearing capabilities of terrestrial and marine birds indicate that birds generally have best in-air hearing sensitivity between 1 and 4 kHz . Very few can hear below 20 Hz, most have an upper frequency hearing limit of 10 kHz, and none exhibit hearing at frequencies higher than 15 kHz (Dooling and Popper 2000, Dooling 2002, Beason 2004). This information was supposed by finite-element-modelling for Little Penguins (*Eudyptula minor*), in which the lowest predicted underwater threshold was approximately 83 dB re 1 µPa at approximately 1.5 kHz with the region of best sensitivity being approximately 200–6000 Hz (Wei and Erbe 2024). These modelled results are similar to that of the great cormorants as shown in Larsen et al. (2020), although they indicate a slightly lower sensitivity (and a slightly higher sensitive frequency range).

Using information available since 2020, all modelling for assessing the noise–induced impact and injury risk of impulsive pile driving signals on penguins applied the approach of using the marine mammal hearing group ‘other carnivores in water (OCW)’ from NMFS (2018) and then NMFS (2024), as a proxy. This hearing group was selected due to similar hearing sensitivity in the frequency band of underwater hearing for diving birds and otariid pinnipeds, which are included in the OCW group. This was considered to potentially provide a conservative approach, as otariids are considered more sensitive to underwater sound at higher frequencies than penguins. This approach has remained unchanged throughout the entire scope of work as no valid alternative exists.

A.4.2.2. Behavioural response

There are no regulatory thresholds or criteria established to assess potential behavioural responses by penguins or flying seabirds to underwater noise. Few published studies are available, however, Sørensen et al. (2020) did consider captive gentoo penguins (*Pygoscelis papua*) and endeavoured to understand behavioural responses to pulsed sounds in a tank environment. In their controlled exposure experiment, gentoo penguins were exposed to underwater noise bursts and demonstrated a graded reaction depending on received sound levels. They reported a sound level of 120 dB re 1 µPa (SPL) for the pulsed sources as an example of a behavioural response in penguins and may be considered for other diving birds. Further study is required to establish more robust criteria for behavioural response. Initial work for this project applied the 120 dB re 1 µPa (SPL) from Sørensen et al. (2020) to assess behavioural response, and for consistency with the approach to assess PTS and TTS, it was applied as OCW weighted.

Further detailed investigation into this approach determined that Sørensen et al. (2020) alone is not robust enough to underpin behavioural response thresholds. This accounts for fact that the ambient noise floor in the captive study was very low while free-ranging animals are permanently exposed to natural ambient sound at levels clearly exceeding the experimental conditions. Moreover, the received levels were not measured at the position of the observed animals but calculated for an acoustically confined space. Due to the limited availability of data relating to noise effects on marine avifauna, a precautionary approach to the management of underwater noise is recommended, but despite this, no behavioural response thresholds, or auditory frequency weighting function for behavioural response is currently recommended or applied.

A.4.3. Impulsive Noise

Impact pile driving activities have been assessed as impulsive noise source as consistent with the considered thresholds and guidelines.

A.4.3.1. Marine Mammals

The criteria applied in this study to assess possible effects of impulsive noise sources on marine mammals are summarised in Table A-9; low-frequency (LF) cetaceans, high-frequency (HF) cetaceans and otariid seals were identified as the hearing groups requiring assessment.

There are two categories of auditory threshold shifts or hearing loss: temporary threshold shift (TTS), a temporary reduction in an animal's hearing sensitivity as the result of receptor hair cells in the cochlea becoming fatigued; and permanent threshold shift (PTS), a physical injury to an animal's hearing organs. As discussed within NMFS (2024), intense noise exposures can cause auditory injury (represented by either AUD INJ or AINJ) without PTS occurring. In this report, the terms PTS and auditory injury can be considered to be used interchangeably, however it is acknowledged that auditory injury may occur without PTS.

Details on thresholds related to auditory threshold shifts or hearing loss and behavioural response are provided in Appendix A.4.1, with frequency weighting explained in detail in Appendix A.5. The behavioural response criterion from the U.S. National Oceanic and Atmospheric Administration (NOAA) (2019) has been applied.

Table A-9. Acoustic effects of impulsive noise on marine mammals: Unweighted SPL, SEL_{24h}, and PK thresholds. In this report, PTS is used interchangeably with auditory injury (AUD INJ).

Hearing group	NOAA (2019)	NMFS (2024)			
	Behaviour	TTS onset thresholds* (received level)		PTS onset thresholds* (received level)	
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²·s)	PK (L_{pk}; dB re 1 µPa)
Low–Frequency (LF) cetaceans	160	168	216	183	222
High–frequency (HF) cetaceans		178	224	193	230
Otariid Seals		170	224	185	230

* Dual metric (SEL_{24h} and PK) acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating TTS and PTS onset.
L_p denotes sound pressure level and has a reference value of 1 µPa.
L_{pk} denotes peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa.
$L_{E,24h}$ denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa²s.

To assist in the assessment of potential behavioural responses by migrating whales, a graded probability of response for impulsive sounds using a frequency weighted SPL metric, as described in Wood et al. (2012a), has been applied. Wood et al. (2012a) defined behavioural response categories for sensitive species (including harbor porpoise and beaked whales), for migrating mysticetes, and for all other species. Both the migrating mysticete category and the category for all other species have been applied in this analysis to all whale species, for comparative purposes (Table A-10). This analysis considers distances to the levels related to probabilistic response of 50% or above i.e. 140 dB re 1 µPa for 'migrating', and 160 dB re 1 µPa for 'other' whales. The Wood et al. (2012a) approach has been updated to consider the frequency weighting from NMFS (2024) for low-frequency cetaceans as opposed to that from Southall et al. (2007).

Table A-10. Acoustic sound pressure level (SPL) thresholds used to evaluate potential behavioural impacts to marine mammals. Probabilities are not additive. Adapted from Wood et al. (2012).

Marine mammal group	Frequency weighted probabilistic response (L_p; dB re 1 µPa)			
	120	140	160	180
Beaked whales and harbor porpoises	50%	90%		
Migrating mysticete whales	10%	50%	90%	
All other species		10%	50%	90%

A.4.3.2. Fish

In 2006, the Working Group on the Effects of Sound on Fish and Sea Turtles was formed to continue developing noise exposure criteria for fish and sea turtles, work begun by a NOAA panel two years earlier. The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death,

- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Masking and behavioural effects can be assessed qualitatively, by assessing relative risk rather than by specific sound level thresholds. However, as these depend upon activity–based subjective ranges, these effects are not addressed in this report and are included in Table A-3 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish's susceptibility to injury from noise exposure depends on the species and the presence and possible role of a swim bladder in hearing. Thus, different thresholds were proposed for fish without a swim bladder (also appropriate for sharks and applied to whale sharks in the absence of other information), fish with a swim bladder not used for hearing, and fish that use their swim bladders for hearing. Sea turtles, fish eggs, and fish larvae are considered separately.

Impulsive noise from pile driving is assessed in this study based on the relevant effects thresholds from Popper et al. (2014) listed in Table A-3. In general, whether an impulsive sound adversely effects fish behaviour depends on the species, the state of the individual exposed, and other factors.

The SEL metric integrates noise intensity over some period of exposure. Because the period of integration for regulatory assessments is not well defined for sounds that do not have a clear start or end time, or for very long–lasting exposures, an exposure evaluation time must be defined. Southall et al. (2007) defines the exposure evaluation time as the greater of 24 h or the duration of the activity. Popper et al. (2014) recommend a standard period of the duration of the activity; however, the publication also includes caveats about considering the actual exposure times if fish move.

Table A-11. Criteria for pile driving noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	> 219 dB SEL_{24h} or > 213 dB PK	> 216 dB SEL_{24h} or > 213 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	210 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	>> 186 dB SEL_{24h}	Pile driving: (N) Moderate (I, F) Low	(N) High (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL_{24h} or > 207 dB PK	203 dB SEL_{24h} or > 207 dB PK	186 dB SEL_{24h}	Pile driving: (N, I) High (F) Moderate	(N, I) High (F) Moderate
Fish eggs and fish larvae (relevant to plankton)	> 210 dB SEL_{24h} or > 207 dB PK	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	Pile driving: (N) Moderate (I, F) Low	(N) Moderate (I, F) Low

Peak sound pressure level: dB re 1 µPa; SEL_{24h} dB re 1µPa^2·s.
All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

A.4.3.3. Sea Turtles

The thresholds for sea turtles are shown in Table A-12.

Table A-12. Acoustic effects of impulsive noise on sea turtles: Unweighted sound pressure level (SPL), 24-hour sound exposure level (SEL_{24h}), and peak pressure (PK) thresholds. In this report, PTS is used interchangeably with auditory injury (AUD INJ).

Effect type	Reference	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^2·s)	PK (L_{pk}; dB re 1 µPa)
Behavioural response	McCauley et al. (2000a)	166	NA	
Behavioural disturbance		175		
PTS onset thresholds[1] (received level)	Accomando et al. (2025a)	NA	184	230
TTS onset thresholds[1] (received level)			169	224

[1] Dual metric (SEL_{24h} and PK) acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS and TTS onset.

L_p denotes sound pressure level and has a reference value of 1 µPa.

L_{pk} denotes peak sound pressure is flat weighted or unweighted and has a reference value of 1 µPa.

$L_{E,24h}$ denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

A.4.3.4. Diving Birds

There are no regulatory thresholds with regard to onset of hearing impairment for penguins, any other bird species, or phylogenetically or anatomically related species. The only scientifically robust thresholds in this context exist for marine mammals. Using information available since 2020, all modelling for assessing the noise–induced impact and injury risk of impulsive pile driving signals on penguins applied the approach of using the marine mammal hearing group 'other carnivores in water (OCW)' from NMFS (2018) and then NMFS (2024), as a proxy. This hearing group was selected due to similar hearing sensitivity in the frequency band of underwater hearing for diving birds and otariid pinnipeds, which are included in the OCW group. This was considered to potentially provide a conservative approach, as otariids are considered more sensitive to underwater sound at higher frequencies than penguins. This approach has remained unchanged throughout the entire scope of work as no valid alternative exists.

Due to the limited availability of data relating to noise effects on marine avifauna, a precautionary approach to the management of underwater noise is recommended, but despite this, no behavioural response thresholds, or auditory frequency weighting function for behavioural response is currently recommended or applied.

A.4.3.5. Invertebrates

Although the study of effects of sound on invertebrates (e.g., crustaceans, cephalopods, and bivalves) is in its nascency, it is evident that invertebrates are sensitive to particle motion (as opposed to pressure) (Popper and Hawkins 2018) and that they can detect vibrations in the sea bed (Roberts et al. 2015, Roberts and Breithaupt 2016, Roberts and Elliott 2017). While there are currently no agreed upon metrics or clearly defined levels (in terms of sound pressure or particle motion) for assessing the effects or impacts of sound on invertebrates (Hawkins and Popper 2017), levels reported in literature can in some cases be used to guide assessments. This is primarily possible for impulsive sound sources. Overall, while there are preliminary indications of potential impacts of vessel noise on some invertebrates, most research has been conducted in a laboratory setting, where tank boundaries may affect the acoustic field and observed behavioural response (Rogers et al. 2016, Popper and Hawkins 2018). Further, nearly all studies measured sound pressure rather than particle motion (Jesus et al. (2020). Although high-intensity noise may produce high sound pressure levels and high levels of particle motion concurrently, it is impossible to determine this relationship without proper measurements (Popper and Hawkins 2018). Therefore, levels in this study have not been assessed for comparison to literature for vessels and non-impulsive noise sources.

A.4.3.6. Benthic Invertebrates (Crustaceans and Bivalves)

Research is ongoing into the relationship between sound and its effects on crustaceans, including the relevant metrics for both effect and impact. Available literature suggests particle motion, rather than sound pressure, is a more important factor for crustacean and bivalve hearing. The majority of work has been completed for seismic survey sources, where water depth and seismic source size are related to the particle motion levels at the seafloor, with larger arrays and shallower water being related to higher particle motion levels, more likely relevant to effects on crustaceans and bivalves.

At the seafloor interface, crustaceans and bivalves are subject to particle motion stimuli from several acoustic or acoustically–induced waves. These include the particle motion associated with an impinging sound pressure wave in the water column (the incident, reflected, and transmitted portions), substrate acoustic waves, and interface waves of the Scholte type. However, it is unclear which aspect(s) of these waves is/are most relevant to the animals, either when they normally sense the environment or their physiological responses to loud sounds so there is not enough information to establish similar criteria and thresholds as done for marine mammals and fish. Including recent research, such as Day et al. (2016b), current literature does not clearly define an appropriate metric or identify relevant levels (pressure or particle motion) for an assessment. This includes the consideration of what particle motion levels lead to a behavioural response, or mortality. Therefore, at this stage, we cannot propose authoritative thresholds to inform the impact assessment. However, levels can be determined for pressure metrics presented in literature to assist the assessment.

The pressure and acceleration examples provided in Figures 11 and 12 of Day et al. (2016a) indicate that the acceleration and pressure signals occurred simultaneously, which was interpreted as an indication that the waterborne sounds were responsible for the accelerations measured by the geophones. For clarity, it is important to distinguish that the acceleration from waterborne sound energy is *not* ground roll, which Day et al. (2016a) correctly define as the sound that propagates along the interface at a speed lower than the shear wave speed of the sediment. However, the report subsequently uses ground roll for all further discussions of particle acceleration. While Day et al. (2016a) discuss that they chose the simplest measure of ground roll, it should have been referring to as 'the acceleration from waterborne sound energy', or 'waterborne acceleration' for short.

For crustaceans, a PK–PK sound level of 202 dB re 1 µPa (Payne et al. 2008) is considered to be associated with no effect, and therefore applied in the assessment.

Literature does not present a sound level associated with no impact. Particle motion is the more relevant metric, and recent work by Jézéquel et al. (2022) has investigated the potential effects on scallops using this metric. They investigated behavioural responses of scallops to piling across three life-stages, and found juveniles to be most sensitive, and that responses were range (or level) dependent. They also found that scallops did not habituate to pile driving events, unlike squid (Section A.3.1.7). The levels presented in Jézéquel et al. (2022), Table A-5, have not been assessed in this report. The results are also presented to allow comparison against the results in Table 7 of Day et al. (2016a), in which the maximum particle acceleration assessed for scallops was 37.57 ms^{-2}.

Table A-13. Mean substrate-borne vibrations' features from the impact hammer presented in Jézéquel et al. (2022)

Distance (m)	Acceleration peaks (dB re 1 $\mu m \cdot s^{-2}$)	Single strike exposure (dB re (1 $\mu m \cdot s^{-2})^2 \cdot s$)	Cumulative strike exposure (dB re (1 $\mu m \cdot s^{-2})^2 \cdot s$)
8	109.95 [a]	94.39 [a]	115.67 [c]
50	87.08 [b]	72.48 [b]	93.13 [d]

[a] Calculated on 536 strikes, [b] Calculated on 315 strikes, [c] Calculated from 115 strikes, [d] Calculated from 129 strikes

A.4.3.7. Squid

The responses of squid to airgun signals were investigated by Fewtrell and McCauley (2012). The authors conducted a number of experiments and examined the received per–pulse SEL for caged squid. They found that in one trial, where the received level of the first airgun impulse was 162 dB re 1 µPa²·s, the squid inked. This response was not observed again within this trial, however the authors stated that it was unknown if this was due to depleted ink reserves or habituation. In two other trials, the initial received levels were lower (132 and 146 dB re 1 µPa²·s per–pulse SEL), and although the received levels did exceed 162 dB re 1 µPa^{2}s, no inking behaviour was observed. The authors hypothesised that the results also suggest that a gradual increase in received levels and prior exposure to air gun impulses decreases the severity of the alarm responses in this species. This aligns with findings of general habituation in response to predators in squid (Long et al. 1989). Recent work (Jones et al. 2020) supports these findings as well, indicating potential rapid, short–term habituation by squid to impulsive noise, however, similar response rates were seen 24 h later, which indicated that squid might re–sensitise to the noise.

The results presented in by Fewtrell and McCauley (2012) were stated by the authors to be preliminary, and while they stated that while it is possible that noise levels greater than 147 dB re 1 µPa²·s are required to induce avoidance behaviour, the level associated with inking, of 162 dB re 1 µPa²·s per–pulse SEL, has been considered as a startle response level for squid.

A.4.3.8. Human Health Assessment Threshold

Underwater, the human ear is about 20 dB less sensitive than it is in air at low frequencies (20 Hz), increasing to 40 dB at mid–frequencies (less than 1 kHz), and increasing to 70–80 dB less sensitive at higher frequencies (Parvin 1998). Divers who wear neoprene hoods have even higher hearing thresholds (lower sensitivity) above 500 Hz because the hood material absorbs high–frequency sounds (Sims et al. 1999). Exposure studies related to divers have typically focused on military sonar exposure, with little information on pile driving noise, and as such care is required when considering thresholds for recreational divers and swimmers, particularly for impulsive sounds such as pile driving (Ainslie 2008).

The auditory threshold of hearing under water was lowest at 1 kHz (70 dB re 1 µPa SPL) and increased for lower and higher frequencies to around 120 dB re 1 µPa at 20 Hz and at 20 kHz (Parvin 1998). Fothergill et al. (2000) and Fothergill et al. (2001) conducted controlled acoustic exposure experiments on military divers under fully controlled conditions at a US Ocean Simulation Facility and an US Open water test facility; in all tests, the diver were covered with soft or hard shell dive suits and their position and distance relative to sound source, signal characteristics and received levels were controlled and documented (Pestorius et al. 2009). A total of 89 male Navy divers were exposed to pure tone signals and sweeps between 160–320 Hz at SPLs up to 160 dB re 1 µPa. The divers were exposed to these sounds over 100 seconds at depths from 10 to 40 metres. The divers rated the sounds on a severity scale. For frequencies between 100 and 500 Hz, at a received SPL of 130 dB re 1 µPa, divers and swimmers detected body vibration. None of the divers tested rated levels of 140 dB re 1 µPa as “very severe”; however, at 157 dB re 1 µPa, sound was rated as “very severe” 19 per cent of the time. No physiological damage was observed at the highest levels tested: 160 dB re 1 µPa (Fothergill et al. 2001). In a subsequent study, recreational divers were exposed to tonal signals or 30 Hz–sweeps at frequencies between 100 and 500 Hz at received levels of 130–157 dB re 1 µPa (Pestorius et al. 2009). Each exposure lasted for seven seconds. Nine female and 17 male scuba divers were tested, all wearing full body neoprene wetsuits. Diver aversion and perception of body vibration were used as test parameters. The results showed no sex–specific differences. The results differed as a function of frequency – while test results showed a strong overall variation between subjects, signals at 100 Hz elicited the strongest aversion in all tests and even at 148 dB a few diver ratings indicated extreme aversion. Due to this and the strong variation between test subjects, the

following exposure limit for both military and recreational divers was suggested as a conservative measure: For frequencies between 100 and 500 Hz, the maximum SPL should be 145 dB re 1 µPa over a maximum continuous exposure of 100 seconds or with a maximum duty cycle of 20 per cent and a maximum daily cumulative total of three hours. The trading relation between the maximum SPL and duration was 4 dB per doubling of duration (e.g. 141 dB SPL for a 200 second exposure) (Pestorius et al. 2009).

Considering only frequencies between 100 and 500 Hz, Parvin (2005) suggested 145 dB re 1 µPa as a safety criterion for recreational divers and swimmers. Piling impulses are broadband sources, and therefore, to be precautionary, the 145 dB re 1 µPa SPL suggested by Fothergill et al. (2001) and Parvin (2005) has been applied in this study as a broadband SPL and as a human health assessment threshold for recreational divers and swimmers. This does not imply that this level is associated with the onset of injury.

A.4.4. Non-Impulsive

A.4.4.1. Marine Mammals

The criteria applied in this study to assess possible effects of non–impulsive sources on marine mammals are summarised in Table A-14.

Table A-14. Criteria for effects of non–impulsive noise exposure, including vessel noise, for marine mammals: Unweighted SPL and SEL_{24h} thresholds.

Hearing group	NOAA (2024)	NMFS (2024)	
	Behaviour	PTS onset thresholds (received level)	TTS onset thresholds (received level)
	SPL (L_p; dB re 1 µPa)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 $\mu Pa^2 \cdot s$)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 $\mu Pa^2 \cdot s$)
Low–Frequency (LF) cetaceans	120	197	177
High–frequency (HF) cetaceans		201	181
Otariid seals		199	161

L_p denotes sound pressure level period and has a reference value of 1 µPa.
L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 $\mu Pa^2 \cdot s$.

A.4.4.2. Fish, Sea Turtles, Fish Eggs and Fish Larvae

Non-impulsive noise from vessels is assessed in this study based on the relevant effects thresholds from Popper et al. (2014). The Working Group developed guidelines with specific thresholds for different levels of effects for several species groups (Popper et al. 2014). The guidelines define quantitative thresholds for three types of immediate effects:

- Mortality, including injury leading to death,
- Recoverable injury, including injuries unlikely to result in mortality, such as hair cell damage and minor haematoma, and
- TTS.

Table A-15 lists the relevant effects thresholds from Popper et al. (2014) for vessel noise. Some evidence suggests that fish sensitive to acoustic pressure show a recoverable loss in hearing

sensitivity, or injury when exposed to high levels of noise (Scholik and Yan 2002, Amoser and Ladich 2003, Smith et al. 2006); this is reflected in the SPL thresholds for fish with a swim bladder involved in hearing.

Table A-15. Criteria for non–impulsive (vessels noise) noise exposure for fish, adapted from Popper et al. (2014).

Type of animal	Mortality and Potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	170 dB SPL for 48 h	158 dB SPL for 12 h	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) High (I) Moderate (F) Low
Fish eggs and fish larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Sound pressure level dB re 1 µPa.
Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

The criteria applied in this study to assess possible effects of non–impulsive sources on sea turtles are summarised in Table A-16, which are revised thresholds from Accomando et al. (2025b)..

Table A-16. Acoustic effects of non–impulsive noise on sea turtles, weighted SEL_{24h}, Accomando et al. (2025b).

PTS onset thresholds (received level)	TTS onset thresholds (received level)
198	178

A.5. Marine Mammal Frequency Weighting

The potential for noise to affect animals depends on how well the animals can hear it. Noises are less likely to disturb or injure an animal if they are at frequencies that the animal cannot hear well. An exception occurs when the sound pressure is so high that it can physically injure an animal by non-auditory means (i.e., barotrauma). For sound levels below such extremes, the importance of sound components at particular frequencies can be scaled by frequency weighting relevant to an animal's sensitivity to those frequencies (Nedwell and Turnpenny 1998, Nedwell et al. 2007).

A.5.1. Marine Mammal Frequency Weighting Functions

In 2015, a US Navy technical report by Finneran (2015) recommended new auditory weighting functions. The overall shape of the auditory weighting functions is similar to human A-weighting functions, which follows the sensitivity of the human ear at low sound levels. The new frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^{2}\right]^{a}\left[1+(f/f_{hi})^{2}\right]^{b}}\right)\right] \quad \text{(A-10)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid- and high-frequency cetaceans (LF, MF, and HF cetaceans, respectively), phocid pinnipeds, and otariid pinnipeds. The parameters for these frequency-weighting functions were further modified the following year (Finneran 2016) and were adopted in NOAA's technical guidance that assesses acoustic impacts on marine mammals (NMFS 2018), Southall (2019) for first and second modelling rounds and the latest guidance by NMFS (2024) for the third and fourth modelling rounds. The updates did not affect the content related to either the definitions of frequency-weighting functions or the threshold values, however, the terminology for mid- and high-frequency cetaceans was changed to high- and very high-frequency cetaceans, respectively. Table A-17 lists the frequency-weighting parameters for each hearing group relevant to this assessment, and Figure A-4 shows the resulting frequency-weighting curves.

Table A-17. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2024). The 'flo' and 'fhi' parameters used by Finneran (2015) are now referred to as 'f1' and 'f2' in the latest guidance.

Southall (2019) (First and Second Modelling Rounds)					
Hearing group	**a**	**b**	**flo (Hz)**	**fhi (Hz)**	***K* (dB)**
Low-frequency cetaceans (baleen whales)	1.0	2	200	19,000	0.13
High-frequency cetaceans (most dolphins, plus sperm, beaked, and bottlenose whales)	1.6	2	8,800	110,000	1.20
Very-high-frequency cetaceans (true porpoises, *Kogia*, river dolphins, *Cephalorhynchus* spp., *Lagenorhynchus cruciger* and *L. australis*)	1.8	2	12,000	140,000	1.36
NMFS (2024) (Third and Fourth Round Modellings)					
Hearing group	**a**	**b**	**flo (kHz)**	**fhi (kHz)**	**C (dB) ***
Low-frequency cetaceans (baleen whales)	0.99	5	0.168	26.6	0.12
High-frequency cetaceans (most dolphins, plus sperm, beaked, and bottlenose whales)	1.55	5	1.73	129	0.32
Otariid Seals in water	1.58	5	2.53	43.8	1.37

* The 'C' parameter in NMFS (2024) is equivalent to the 'K' parameter in Finneran (2015).

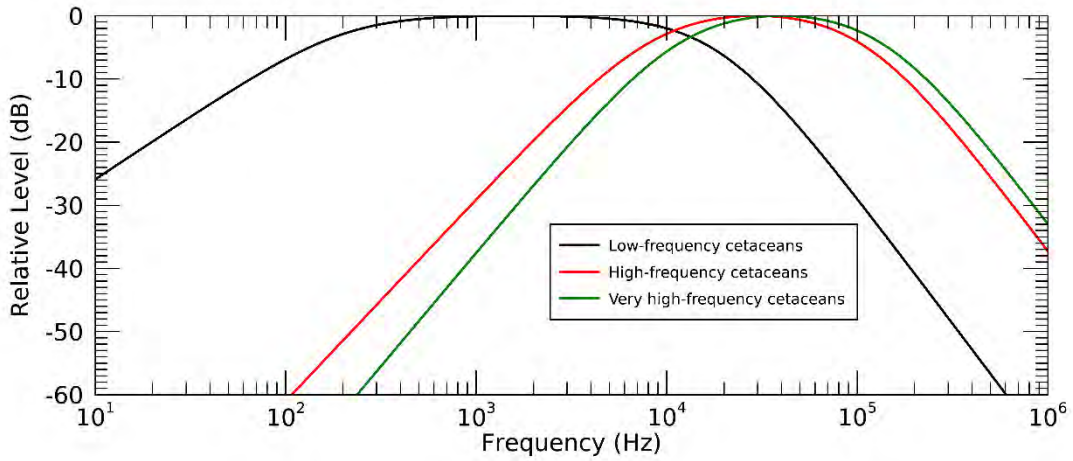


Figure A-3. Auditory weighting functions for functional marine mammal hearing groups used in this project as recommended by Southall et al. (2019).

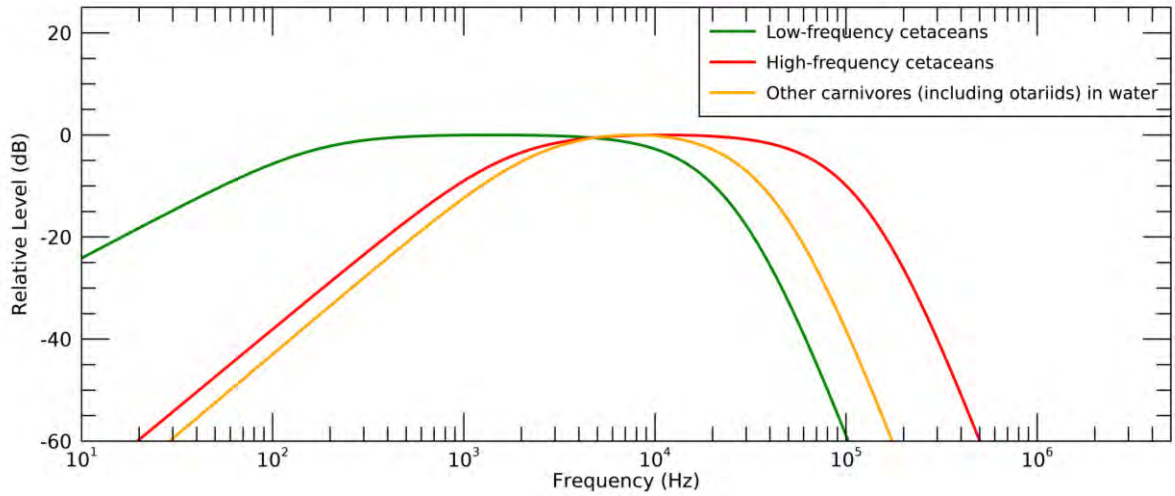


Figure A-4. Auditory weighting functions for functional marine mammal hearing groups used in this project as recommended by NMFS (2024).

Appendix B. Acoustic Source Model

B.1. Acoustic Source Model – Pile Driving

B.1.1. Source Properties

For most projects involving pile driving, there is potential for direct transmission from the sound source to biological receivers, and there are reflected sound paths from the water's surface and bottom that may be perceived by marine fauna. Normally, ground-radiated sound is dominated by low frequencies that cannot propagate efficiently through shallow water. When pile driving is the sound source, there is the potential for substrate-borne sound caused by the hammer's action on the pile to be re-radiated back into the water where it may reach a biological receiver. For pile driving, energy transmission through water depends on the following factors (Christopherson and Lundberg 2013):

- Direct contact between the pile and the water
- The depth of the water column
- The size of the pile
- The type of hammer
- The hammer energy
- The addition of re-radiation of substrate-borne sound

The way sound propagates in water is affected by obstructions (barges, breakwater walls, other piles, etc.) and the bathymetric characteristics (Buehler et al. 2015). Figure B-1 illustrates these basic propagation concepts.

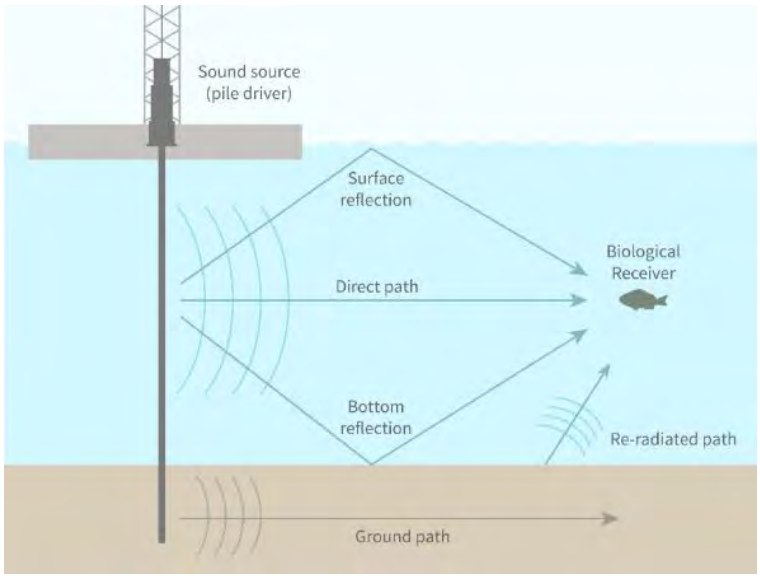


Figure B-1 Underwater sound propagation paths associated with pile driving (Buehler et al. 2015).

B.1.2. Source Model

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a

cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile, as shown in Figure B-2. Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretised using the finite difference (FD) method and are solved on a discrete time and depth mesh.

To model the sound emissions from the piles, the force of the pile driving hammers also had to be modelled. The force at the top of each pile was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010), which includes a large database of simulated hammers—both impact and vibratory—based on the manufacturer's specifications. The forcing functions from GRLWEAP were used as inputs to the FD model to compute the resulting pile vibrations.

The sound radiating from the pile itself is simulated using a vertical array of discrete point sources. The point sources are centred on the pile axis. Their amplitudes are derived using an inverse technique, such that their collective particle velocity, calculated using a near-field wave-number integration model, matches the particle velocity in the water at the pile wall. The sound field propagating away from the vertical source array is then calculated using a time-domain acoustic propagation model (FWRAM, Appendix C.2.2). MacGillivray (2014) describes the theory behind the physical model in more detail.

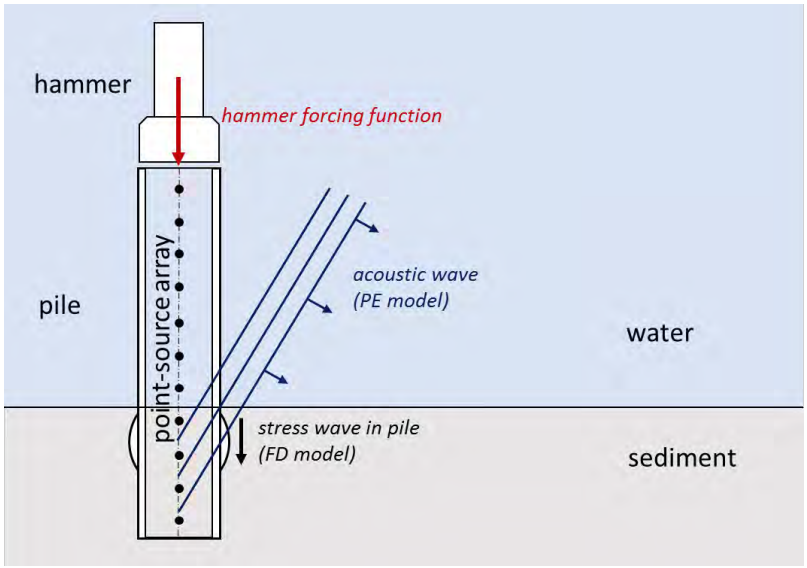


Figure B-2. Physical model geometry for impact driving of a cylindrical pile(vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.

Appendix C. Methods and Parameters

C.1. Environmental Parameters

C.1.1. Bathymetry (All Modelling Rounds)

Water depths throughout the modelled area were extracted from Australian Bathymetry and Topography Grid, a 9 arc-second grid rendered for Australian waters (Whiteway 2009). Bathymetry data was extracted and re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 51) with a regular grid spacing of 150 × 150 m to generate the bathymetry in Figure C-1.

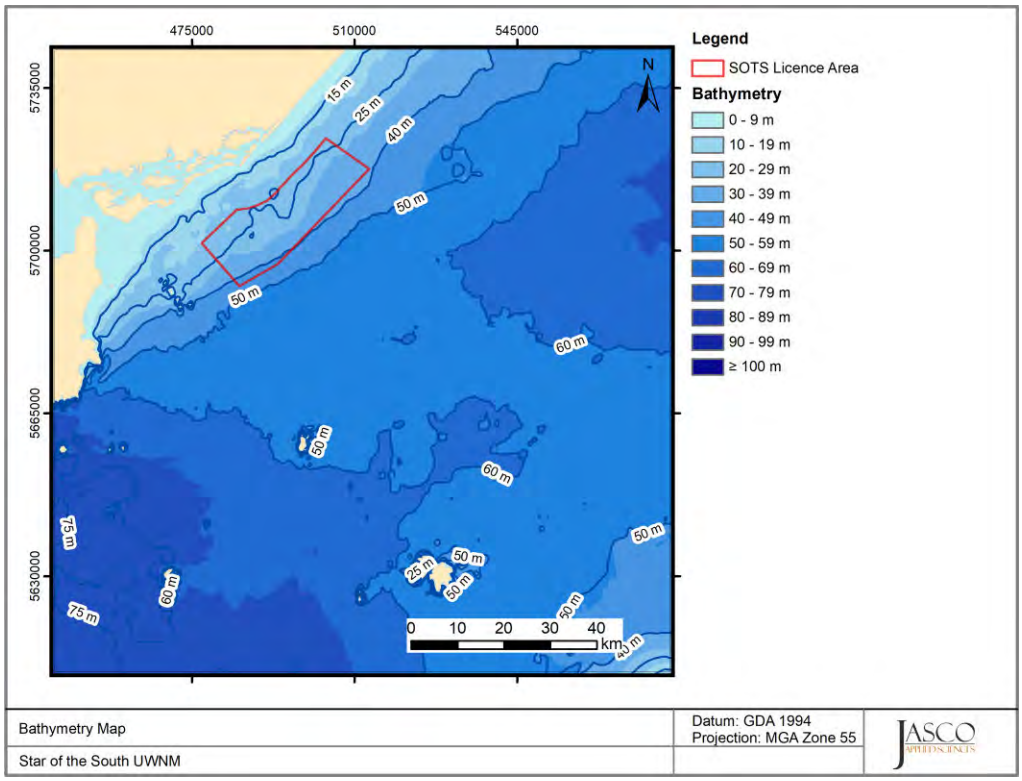


Figure C-1. Bathymetry map of the modelled area for the Star of the South offshore wind farm.

C.1.2. Sound Speed Profile (All Modelling Rounds)

The sound speed profiles for the modelled sites were derived from temperature and salinity profiles from the US Naval Oceanographic Office's Generalized Digital Environmental Model V 3.0 (GDEM; Teague et al. 1990, Carnes 2009). GDEM provides an ocean climatology of temperature and salinity for the world's oceans on a latitude-longitude grid with 0.25° resolution, with a temporal resolution of one month, based on global historical observations from the US Navy's Master Oceanographic Observational Data Set (MOODS). The climatology profiles include 78 fixed depth points to a maximum depth of 6800 m (where the ocean is that deep). The GDEM temperature-salinity profiles were converted to sound speed profiles according to Coppens (1981).

Mean monthly sound speed profiles were derived from the GDEM profiles within a 100 km box radius from the centre of the license area. To determine the sound speed profile that is expected to be most favourable to longer-range sound propagation during the proposed survey time frame, each month within the summer and winter periods were assessed to determine which may lead to the furthest

propagation within that season. As such, June and January were selected for the first round of sound propagation modelling to represent winter and summer, respectively. The modelling work determined that the winter month would be more likely to result in sound travelling further and June was selected for sound propagation modelling within all later modelling rounds to ensure precautionary estimates of distances to received sound level thresholds. Figure C-3 and Figure C-4 show the profiles used as input to the sound propagation modelling.

Refraction is the mechanism by which the direction propagating sound waves can bend when the properties of the medium change in a continuous manner. Downward refraction is mechanism by which upward propagating energy can be redirected downward and upward refraction is the mechanism by which downward propagating energy redirected upward (see the diagram in Figure C-2). The influence is that an upward refracting sounds speed profile can focus slightly more energy into the water column, and a downward refracting profile can focus more energy onto and into the seabed. The strength of refraction depends on the gradient by which sound speed and density change within the water column.

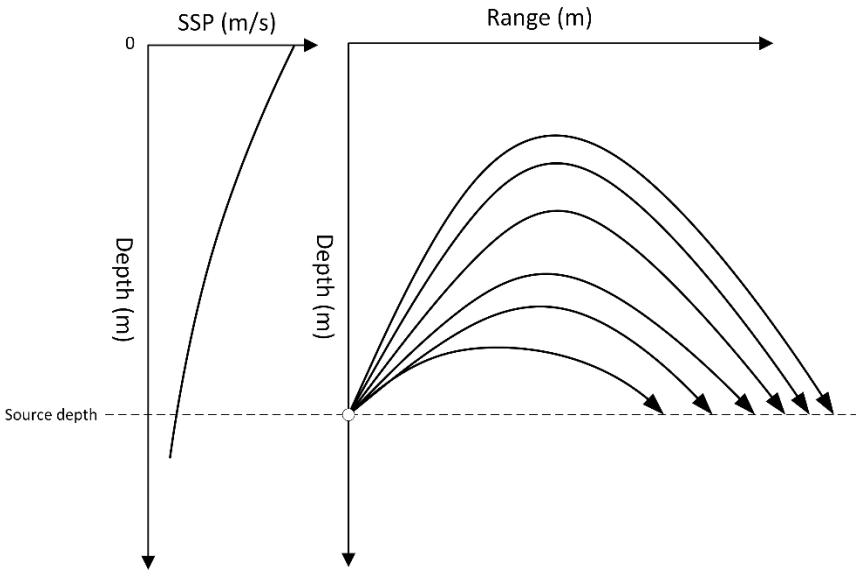


Figure C-2. Simplified ray diagram to illustrate downward refraction.

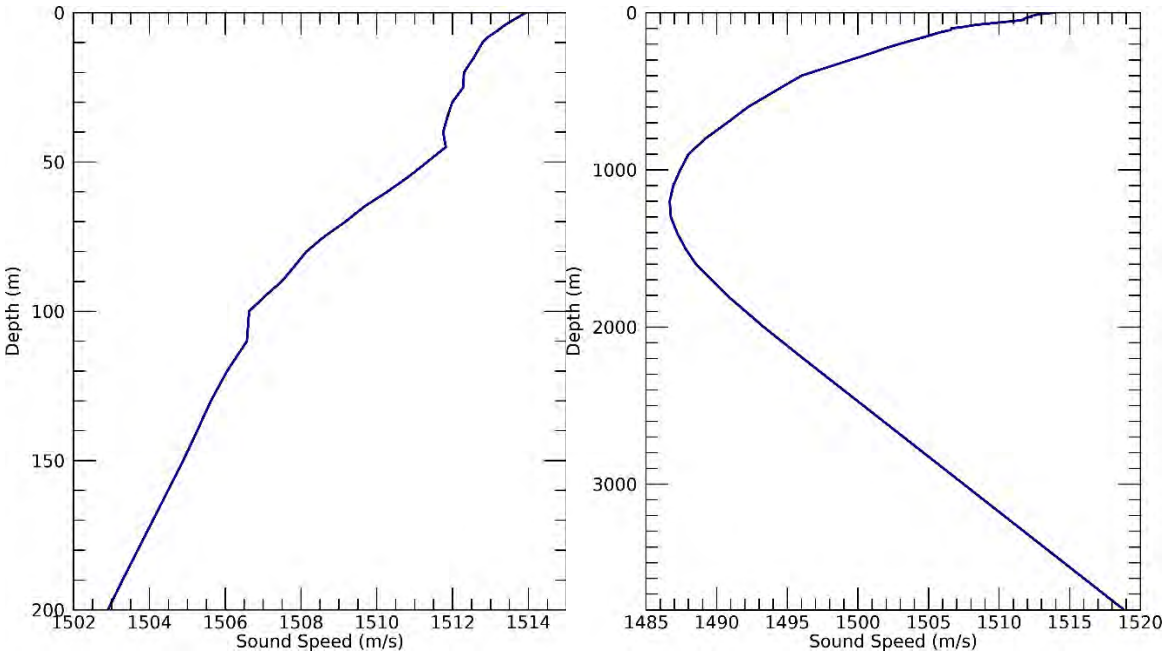


Figure C-3. The sound speed profile for summer used for the first modelling round showing the entire water column (right) and the top 200 m within the profile (left). Profiles are calculated from temperature and salinity profiles from GDEM V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

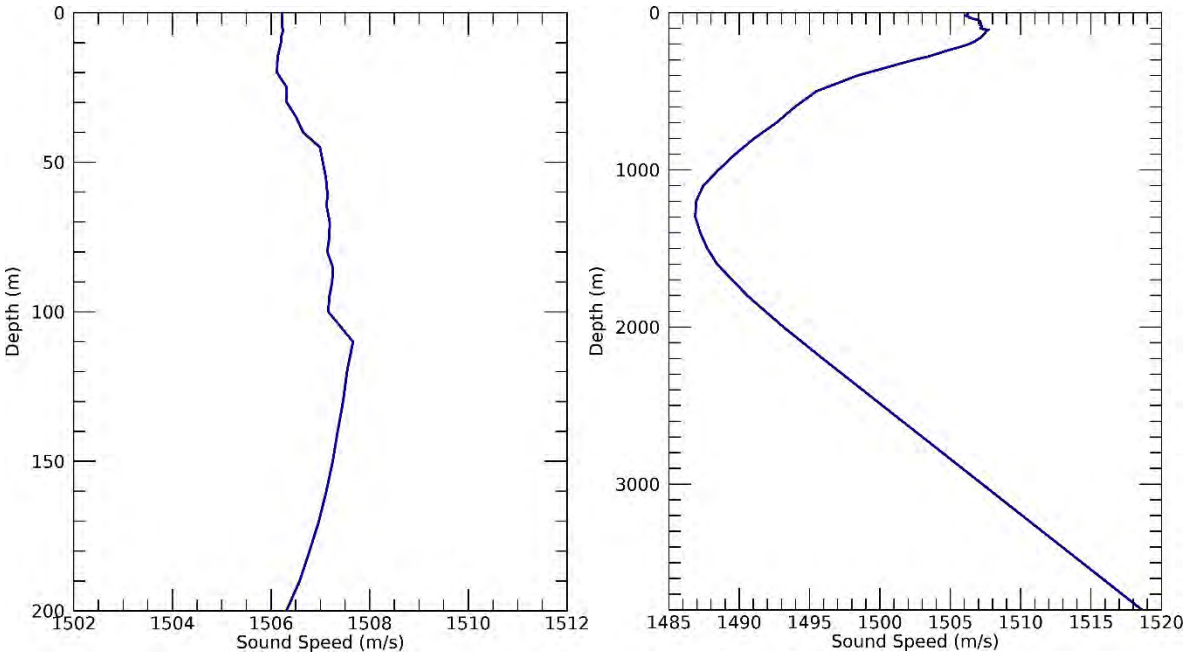


Figure C-4. The sound speed profile for winter used for all modelling rounds showing the entire water column (right) and the top 200 m within the profile (left). Profiles are calculated from temperature and salinity profiles from GDEM V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

C.1.3. Geoacoustics (First and Second Modelling Rounds)

Within the Licence Area of the OWF, the geophysical and acoustic propagation loss studies indicate that the seabed likely consists of a coarse unconsolidated layered sediments underlain by a more cemented horizon (Fitzallen 2020, McCauley 2021). Detailed geotechnical information such as porosity and grain size measurement with depth below the seafloor were not available at the time of this study. As such the seabed geoacoustic model was based on that provided in McCauley (2021),

and pre-modelling sensitivity such that a stable numerical prediction which aligned with measurements could be achieved.

Table C-1. Geoacoustic profile for modelled site – inshore continental shelf.

Depth below seafloor (m)	Predicted lithology	Density (g/cm³)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–20	Coarse Sand	2.2	1975.0	0.15	330	0.5
20	Cemented Limestone	2.4	2820.5			

C.1.4. Geoacoustics (Third and Fourth Modelling Rounds)

Within the Licence Area of the OWF, the geophysical and acoustic propagation loss studies indicate that the seabed likely consists of a coarse unconsolidated layered sediments underlain by a more cemented horizon (Fitzallen 2020, McCauley 2021). In addition, geotechnical site investigations and borehole data have also been gathered for Star of the South. These three data sources were considered together to define four geoacoustic profiles, each of which correspond to a different water depth regime (Figure C-5).

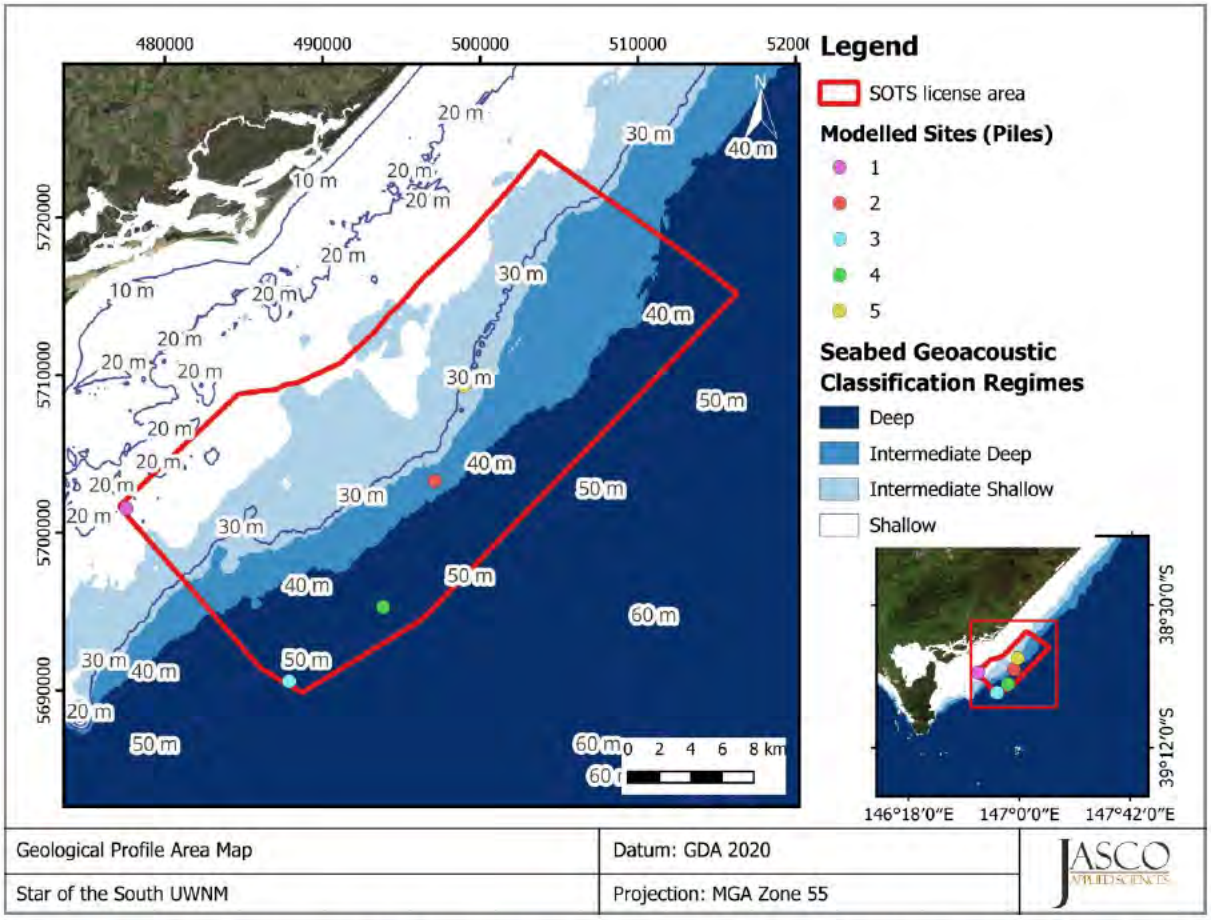


Figure C-5. Seabed geoacoustic classification map of the within the license area for the Star of the South offshore wind farm.

Sediment grainsize distributions, porosities and bulk densities from the geotechnical site investigations were used in defining these regimes. Data were used in combination with the grain-shearing model by Buckingham (2005) to estimate the geoacoustic parameters for each water depth regime. The general procedure for incorporating geotechnical data was conducted following these steps:

1. Four depth regimes were defined which correlate to the foundation driveability data used (Figure C-5).
2. Sediment grainsize, porosities and bulk density data were grouped by the borehole within each regime. All data where interpolated to a 1 m depth bin, up to a maximum depth of 60 m below the seafloor. For values not constrained by data, typical and the beginning or end of interpolated array, the last value present was used.
3. The interpolated grainsize, porosity and density data were averaged across all boreholes within the regime.
4. The interpolated and averaged grainsize, porosity and density data were used as inputs into the grain-shearing model Buckingham (2005) to calculate geoacoustic parameters in 1 m depth bins and up to a maximum depth of 60 m below the seafloor. This was done for each regime to produce four geoacoustic profiles.

These profiles are generally consistent with unconsolidated sediments that increase in consolidation with depth. The exact depth of a cemented layer was not defined but is expected to vary over the licences area due to variable sediment cover (Fitzallen 2020, McCauley 2021). However, the deeper geoacoustic parameters are consistent with a more compact material and are considered to be representative. These geoacoustic profiles were used to compare the outputs of a propagation model to the airgun propagation loss measurement study from McCauley (2021). JASCO's AASM model was used with FWRAM to compare the measured airgun data to the predictions of and acoustic model to validate the geoacoustic model.

Adjustments to the shear wave speed and compressional wave and shear wave attenuations from the grain-shearing model were implemented to yield better agreement with the propagation loss data (Figure C-6).

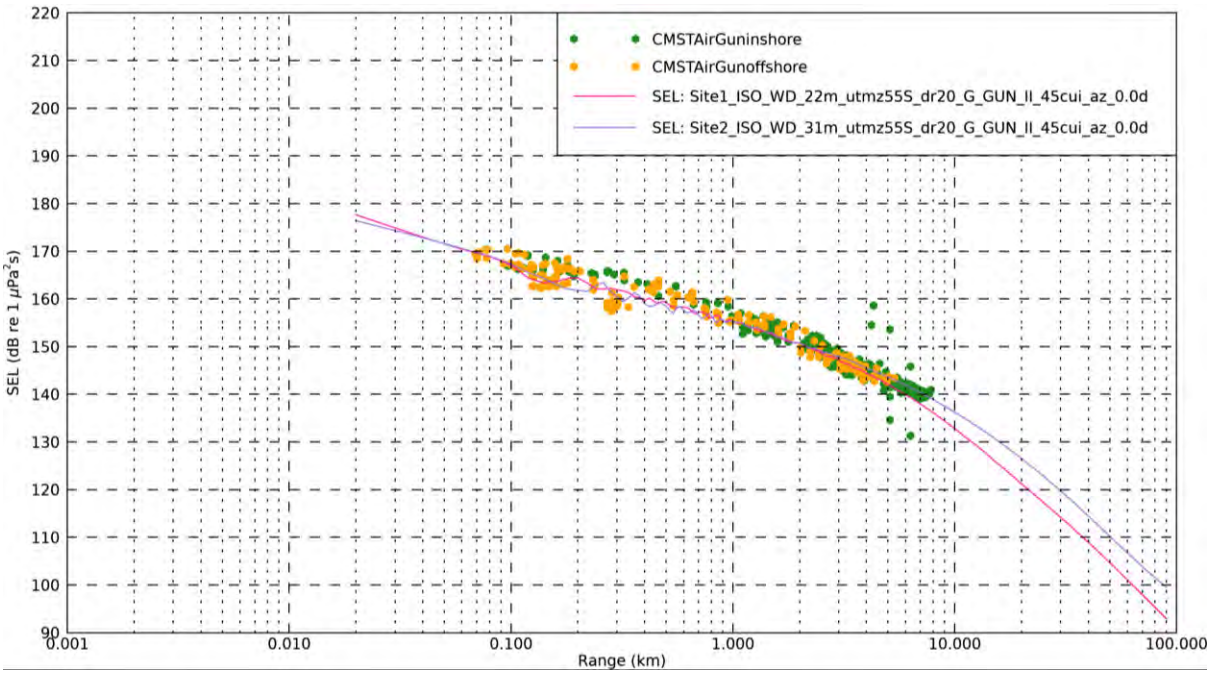


Figure C-6. Comparison of modelled and measured airgun (45 in^3) data using JASCO's AASM and FWRAM and the data from McCauley (2021).

Table C-2 to C-5 presents the resultant geoacoustic profiles and Figure C-5 shows the water depth regimes, boreholes and pile modelling sites.

Table C-2. Geoacoustic profile for modelled "Shallow" classification regime

Depth below seafloor (m)	Density (g/cm^3)	Compressional wave		Shear wave	
		Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0	1.99	1608.8	0.10	318.2	0.50
1	1.96	1685.8			
2	1.91	1697.6			
3	1.89	1715.5			
4	1.89	1733.7			
6	1.91	1765.6			
8	1.92	1794.7			
10	1.94	1826.5			
15	2.02	1912.6			
20	1.97	1938.3			
25	2.01	1996.0			
30	2.07	2055.0			
40	2.05	2103.7			
50	2.10	2193.6			
>60	2.11	2242.8			

Parameters vary linearly between depth bins. A subset of parameters presented but a 1 m depth increment was used in the as input to propagation models.

Table C-3. Geoacoustic profile for modelled "Intermediate shallow" classification regime.

Depth below seafloor (m)	Density (g/cm³)	Compressional wave		Shear wave	
		Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0	1.97	1594.7	0.10	273.1	0.50
1	1.96	1665.1			
2	1.96	1684.6			
3	1.95	1701.7			
4	1.95	1720.1			
6	1.96	1759.4			
8	1.99	1806.6			
10	2.02	1852.5			
15	2.10	1966.1			
20	2.14	2062.0			
25	2.14	2070.7			
30	2.12	2050.8			
40	2.12	2098.3			
50	2.12	2139.3			
>60	2.12	2175.9			

Parameters vary linearly between depth bins. A subset of parameters presented but a 1 m depth increment was used in the as input to propagation models.

Table C-4. Geoacoustic profile for modelled "Intermediate Deep" classification regime.

Depth below seafloor (m)	Density (g/cm³)	Compressional wave		Shear wave	
		Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0	2.08	1663.3	0.10	299.8	0.50
1	2.07	1761.3			
2	2.05	1773.5			
3	2.03	1764.7			
4	2.02	1773.7			
6	2.01	1786.4			
8	1.99	1797.0			
10	1.98	1805.1			
15	1.97	1833.8			
20	1.96	1898.9			
25	1.95	1962.4			
30	1.98	2164.0			
40	1.98	2190.5			
50	1.98	2196.0			
>60	1.97	2227.3			

Parameters vary linearly between depth bins. A subset of parameters presented but a 1 m depth increment was used in the as input to propagation models.

Table C-5. Geoacoustic profile for modelled "Deep" classification regime.

Depth below seafloor (m)	Density (g/cm³)	Compressional wave		Shear wave	
		Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0	1.89	1570.6	0.10	400.0	0.50
1	1.90	1712.2			
2	1.92	1774.7			
3	1.94	1825.5			
4	1.96	1871.0			
6	2.00	1954.0			
8	2.01	1995.8			
10	1.99	2011.3			
15	1.95	2029.4			
20	1.93	2037.1			
25	1.93	2084.9			
30	1.94	2128.0			
40	1.95	1905.7			
50	1.99	2086.5			
60	1.99	2124.5			

Parameters vary linearly between depth bins. A subset of parameters presented but a 1 m depth increment was used in the as input to propagation models.

C.2. Impulsive Noise

C.2.1. Propagation Loss

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic energy source level (ESL), expressed in dB re 1 $\mu Pa^2 \cdot s\ m^2$, and propagation loss (PL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 $\mu Pa^2 \cdot s$ by:

$$RL = SL - PL. \quad \text{(C-1)}$$

C.2.2. Full Waveform Range-dependent Acoustic Model: FWRAM

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required for calculating SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterise vertical directivity effects in the near-field zone.

For this study, synthetic pressure waveforms were computed using the Full Waveform Range-dependent Model (FWRAM), which is a time-domain acoustic model based on the wide-angle parabolic equation (PE) algorithm (Collins 1993). FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments, and it takes bathymetry, water sound speed profile, and seabed geoacoustic profile, as environmental inputs. FWRAM computes pressure waveforms via Fourier synthesis of the modelled acoustic transfer function in closely spaced frequency bands.

FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012). Synthetic pressure waveforms were modelled over the frequency range 10 – 1024 Hz, inside a 1 s window. These waveforms are post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

C.2.3. Estimating Sound Fields from Piling

C.2.3.1. Additional Monopiles Parameterisation and Methodology (First Modelling Round)

The IHC S-4000 impact hammer considered for this study was selected based on the project requirements/assumptions considered in the driveability study and defined by Star of the South. This hammer was used for the WTG foundation monopile modelling scenarios.

Table C-6. Pile specifications for driven cylindrical steel piles.

Site	Number of piles per day	Pile description	Hammer model	Dimension			Final penetration depth (m)
				Length (m)	Diameter range (m)	Wall thickness (cm) [i]	
1	1	MP 1	IHC S-4000	81.1	10 – 12.5	10.5	35.1
2		MP 2		60.7		9.7	28.7
3		MP 3					

MP: Monopile

[i] Median thickness provided here for cylindrical piles refer pile for detail in Section 4.1.

Table C-7. Hammer energy and modelled number of strikes at each energy setting, for monopile foundations driven by an impact hammer IHC S-4000. The table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Hammer Energy (kJ)	Strike count	Sediment penetration (m)	Total number of strikes	Strike rate (bpm)	Installation time (h)
MP 1	2131.2	1150	17.7	6883	36.0	3.19
	3999.8	1660	26.4			
	3999.8	4073	35.1			
MP 2*	1197.4	701	14.2	3731		1.73
	3670.8	1200	21.4			
	3999.8	1830	28.7			
MP 3*	1197.4	701	14.2	3731		1.73
	3670.8	1200	21.4			
	3999.8	1830	28.7			

*MP 2 and MP 3 were modelled with the same driveability profile

Table C-8. Parameters for the pile geometry used in the impact piling modelling scenarios

Pile type	MP 1			MP 2 and MP 3		
	Section Length (m)	Diameter (m)	Wall Thickness (cm)	Section Length (m)	Diameter (m)	Wall Thickness (cm)
Tapered cylindrical steel	0.2	10.0	10.5	0.2	10.0	9.1
	0.1	10.0	10.6	0.1	10.0	9.1
	3.5	10.0	11.0	3.5	10.0	9.2
	2.4	10.0	10.8	2.4	10.0	8.4
	4.1	10.0	10.4	3.9	10.0	8.4
	4.2	10.6	9.9	3.6	10.5	8.8
	4.2	11.2	9.6	3.2	11.0	8.9
	3.0	11.7	9.7	2.4	11.5	9.2
	2.4	12.2	9.7	2.4	11.8	9.4
	4.2	12.5	9.8	2.4	12.2	9.7
	4.2	12.5	10.2	2.8	12.5	9.7
	4.2	12.5	10.6	2.7	12.5	9.7
	4.2	12.5	10.9	2.8	12.5	9.7
	4.1	12.5	11.3	2.8	12.5	9.7
	4.0	12.5	11.6	2.8	12.5	9.7
	4.0	12.5	11.6	2.8	12.5	9.7
	4.0	12.5	11.2	2.8	12.5	9.7
	4.2	12.5	10.3	2.8	12.5	9.7
	4.2	12.5	9.7	2.4	12.5	9.7
	4.2	12.5	9.7	2.4	12.5	9.7
	4.2	12.5	9.7	2.4	12.5	9.7
	2.6	12.5	10.7	2.4	12.5	9.7
	2.4	12.5	13.2	2.4	12.5	9.7
	2.3	12.5	10.5	2.2	12.5	10.7
	–	–	–	0.1	12.5	13.2
Total	81.1			60.7		

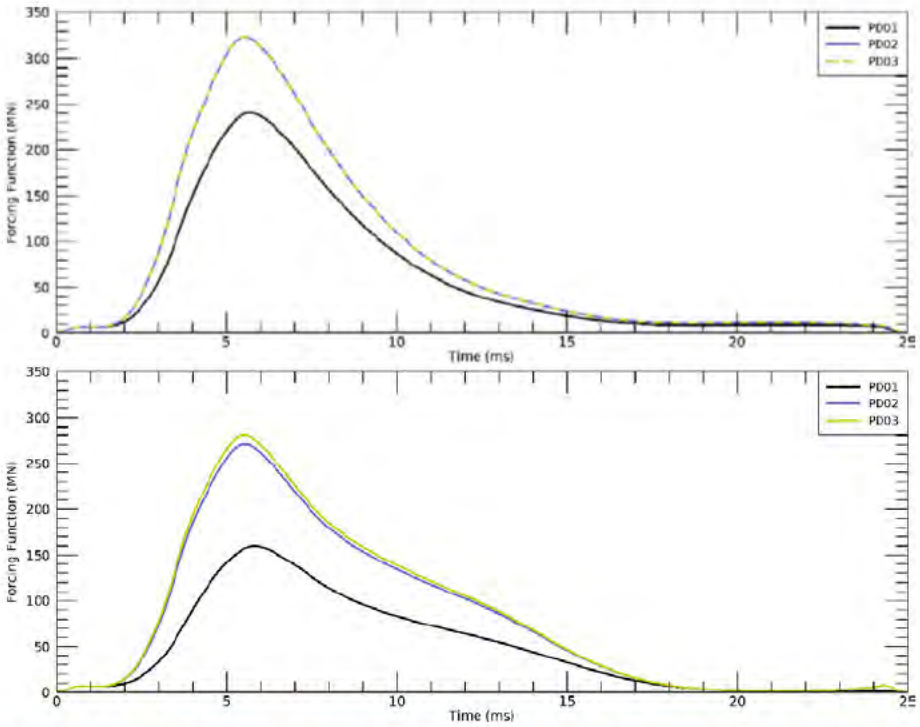


Figure C-7. Force (in meganewtons) at the top of the pile, corresponding to impact pile driving of monopile MP 1 (top panel). Note: the forcing functions for PD02 and PD03 were the same. Force at the top of the pile, corresponding to impact pile driving of monopiles MP 2 and MP 3 (bottom panel) for the three penetration depth/hammer energy combinations Computations were performed using the GRLWEAP 2010 wave equation model for the IHC S-4000 impact hammer.

C.2.3.2. Additional Monopiles Parameterisation and Methodology (Second Modelling Round)

The IHC S-4000 impact hammer considered for this study was selected based on the project requirements/assumptions considered in the driveability study and defined by Star of the South. This hammer was used for the WTG foundation monopile modelling scenarios.

Table C-9. Pile specifications for driven cylindrical steel piles.

Site	Number of piles per day	Pile description	Hammer model	Dimension			Final penetration depth (m)
				Length (m)	Diameter range (m)	Wall thickness (cm)[i]	
1	1	Cylindrical - Tapered	IHC S-4000	85.9	8.0-11.8	9.9	36.4
2	1			57.8		10.3	31.1

MP: Monopile
[i] Median thickness provided here for cylindrical piles refer pile for detail in Section 4.1.

The tables below present the penetration depths, strike count and hammer energy used for acoustic modelling, and the pile geometry used by GRLWEAP and PDSM. The hammer forcing functions from GRLWEAP are shown in Figure C-8.

Table C-10. Hammer energy and modelled number of strikes at each energy setting, for monopile foundations driven by an impact hammer IHC S-4000. The table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Hammer Energy (kJ)	Strike count	Sediment penetration (m)	Total number of strikes	Strike rate (bpm)	Installation time (h)
MP 1	1546.8	952	15.3	5350	36	2.5
	1332.3	1200	20.5			
	1359.1	999	25.8			
	1771.0	1000	31.8			
	2194.4	1200	36.4			
MP 2	930.7	550	10.4	4945		2.3
	1168.3	999	15.8			
	1597.2	998	21.3			
	2414.6	1199	26.7			
	2362.1	1200	32.1			

Table C-11. Parameters for the pile geometry used in the impact piling modelling scenarios.

Pile type	MP 1			MP 2		
	Section Length (m)	Diameter (m)	Wall Thickness (cm)	Section Length (m)	Diameter (m)	Wall Thickness (cm)
Tapered cylindrical steel	0.32	8.0	15.0	0.32	8.0	13.1
	4.03	8.0	15.0	4.03	8.0	13.1
	2.50	8.0	14.4	2.50	8.0	14.4
	2.59	8.0	14.3	2.59	8.0	16.9
	3.50	8.5	14.3	1.00	8.3	16.9
	3.50	9.8	13.7	3.00	9.3	14.4
	3.50	9.5	12.8	3.50	10.5	11.9
	3.00	9.9	11.9	3.85	11.8	10.3
	3.00	10.3	11.1	4.14	11.8	10.3
	3.50	10.8	10.3	4.00	11.8	9.1
	3.50	11.3	9.6	4.00	11.8	9.1
	3.67	11.8	9.9	4.00	11.8	9.1
	4.00	11.8	9.3	3.50	11.8	9.1
	4.00	11.8	9.1	3.50	11.8	9.1
	3.72	11.8	9.3	3.50	11.8	9.1
	4.00	11.8	9.1	3.50	11.8	9.1
	4.00	11.8	9.1	3.48	11.8	10
	4.00	11.8	9.1	3.38	11.8	12.5
	4.00	11.8	9.1			
	4.00	11.8	9.1			
	3.50	11.8	9.1			
	3.50	11.8	9.1			
	3.50	11.8	9.1			
	3.73	11.8	10.0			
	3.38	11.8	12.5			
Total	85.9			57.8		

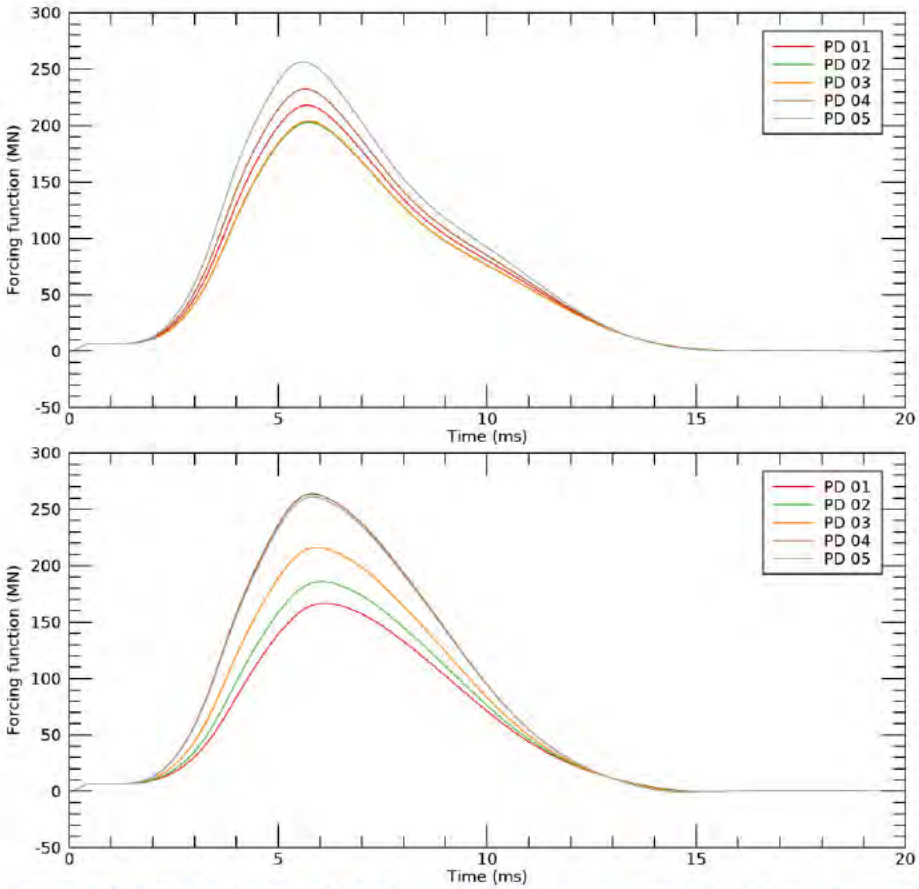


Figure C-8. Force at the top of the pile, corresponding to impact pile driving of monopiles for the five-penetration depths/hammer energy combinations. Computations were performed using the GRLWEAP 2010 wave equation model for the IHC S-4000 impact hammer. Top panel – MP1. Bottom panel – MP2.

C.2.3.3. Additional Impact Pile Parameterisation and Methodology (Fourth Modelling Round)

The IQ4 and IQ4 + PULSE impact hammer considered for this study was selected based on the project requirements/assumptions considered in the driveability study and defined by Star of the South. This hammer was used for the WTG foundation monopile modelling scenarios.

Table C-12. Pile specifications for driven cylindrical steel piles.

Site	Number of piles per day	Pile description	Hammer model	Dimension		Final penetration depth (m)
				Length (m)	Max Diameter (m)	
1	1	Cylindrical – Tapered	IQ4 and IQ4 + PULSE	50.7	9.2	27.8
2	1			67.1	11	29.11
3	1			97.8	11.8	36.91
4	1			88.5	11.8	41.7

MP: Monopile
[i] Median thickness provided here for cylindrical piles refer pile for detail in Section 4.1.

Table C-13. Hammer energy and modelled number of strikes at each energy setting, for pile foundations. Monopile foundations were driven by the IQ4 impact hammer. This table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Sediment penetration (m)	Hammer Energy (kJ)	Strike count	Total number of strikes	Strike rate (bpm)
MP1	11.2	641.5	498	3738	36
	15.3	511.3	648		
	19.5	1108.8	798		
	23.6	1417.2	797		
	27.8	1369.2	998		
MP2	14.6	633.4	600	3797	
	18.2	639.6	795		
	21.9	711.1	601		
	25.5	896.4	800		
	29.1	1201.7	1000		
MP3	16.3	1069.9	1150	6345	
	22.7	975.5	1201		
	29.0	1166.5	1399		
	35.4	1449.8	1197		
	41.7	2011.0	1399		
MP4	13.0	217.4	649	5550	
	19.0	652.6	1100		
	24.9	858.3	1199		
	30.9	1120.8	1201		
	36.9	1567.9	1401		

Table C-14. Hammer energy and modelled number of strikes at each energy setting, for monopile foundations driven by an impact hammer IQ4 with the PULSE system. This table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Sediment penetration (m)	Hammer Energy (kJ)	Strike count	Total number of strikes	Strike rate (bpm)
MP1	12.8	500.0	800	3996	36
	16.5	554.3	798		
	20.3	1523.2	800		
	24.0	1969.0	799		
	27.8	2035.7	800		
MP2	14.6	559.7	799	3995	
	18.2	697.2	799		
	21.9	750.9	600		
	25.5	881.1	800		
	29.1	1178.8	997		
MP3	17.1	758.8	1397	6393	
	23.3	828.1	1200		
	29.4	1023.6	1200		
	35.6	1332.3	1197		
	41.7	2041.9	1400		
MP4	13.0	134.2	800	5800	
	19.0	676.2	1199		
	24.9	912.0	1199		
	30.9	1144.0	1205		
	36.9	1304.6	1398		

Table C-15. Parameters for the tapered monopile geometry used in the impact piling modelling scenarios.

MP 1			MP 2			MP 3			MP 4		
Section Length (m)	Diameter (cm)	Wall Thickness (cm)	Section Length (m)	Diameter (cm)	Wall Thickness (cm)	Section Length (m)	Diameter (cm)	Wall Thickness (cm)	Section Length (m)	Diameter (cm)	Wall Thickness (cm)
0.3	800.0	12.6	0.3	800.0	13.6	0.32	800.0	15.0	0.3	800.0	13.3
4.0	800.0	12.6	4.0	800.0	13.6	4.13	800.0	15.0	4.0	800.0	13.3
2.5	800.0	12.1	2.5	800.0	13.1	2.70	800.0	14.4	2.5	800.0	12.8
2.6	800.0	12.3	2.6	800.0	13.1	2.29	800.0	14.3	2.6	800.0	12.9
2.5	835.0	12.3	2.5	835.0	13.1	3.50	848.9	14.3	3.5	848.9	12.9
3.0	876.9	11.8	3.0	876.9	12.6	3.50	897.9	13.7	3.5	897.9	12.2
3.1	920.0	11.1	3.0	918.9	11.9	3.50	946.8	12.8	3.5	946.8	11.4
4.1	920.0	10.8	3.0	960.8	11.1	3.50	995.8	11.9	3.0	988.8	10.6
4.0	920.0	10.3	3.0	1002.8	10.3	3.20	1040.6	11.0	3.0	1030.8	9.9
4.0	920.0	10.2	3.5	1051.7	9.6	3.20	1085.3	10.2	3.5	1079.7	9.2
4.0	920.0	10.1	3.5	1100.0	9.8	3.30	1131.5	9.5	3.5	1128.7	8.8
4.0	920.0	9.8	4.1	1100.0	9.1	3.47	1180.0	9.9	3.7	1180.0	9.1
4.0	920.0	8.9	4.0	1100.0	8.6	4.20	1180.0	9.3	3.0	1180.0	9.1
3.0	920.0	7.2	4.0	1100.0	8.5	3.70	1180.0	9.7	3.5	1180.0	9.1
2.9	920.0	7.4	3.5	1100.0	8.5	3.40	1180.0	10.3	3.7	1180.0	9.1
2.6	920.0	9.9	3.5	1100.0	8.5	3.44	1180.0	10.7	4.0	1180.0	9.1
			3.5	1100.0	8.5	4.18	1180.0	11.3	4.0	1180.0	9.1
			3.5	1100.0	8.5	4.20	1180.0	11.1	4.0	1180.0	9.1
			3.5	1100.0	8.5	4.20	1180.0	11.2	4.0	1180.0	9.1
			3.4	1100.0	9.2	4.20	1180.0	11.2	4.0	1180.0	9.1
			3.2	1100.0	11.7	4.20	1180.0	11.0	4.0	1180.0	9.1
						4.20	1180.0	10.9	3.5	1180.0	9.1
						4.20	1180.0	10.7	3.5	1180.0	9.1
						3.50	1180.0	9.5	3.5	1180.0	9.1
						3.40	1180.0	9.1	3.8	1180.0	10.0
						3.40	1180.0	9.1	3.4	1180.0	12.5
						3.38	1180.0	10.0			
						3.38	1180.0	12.5			

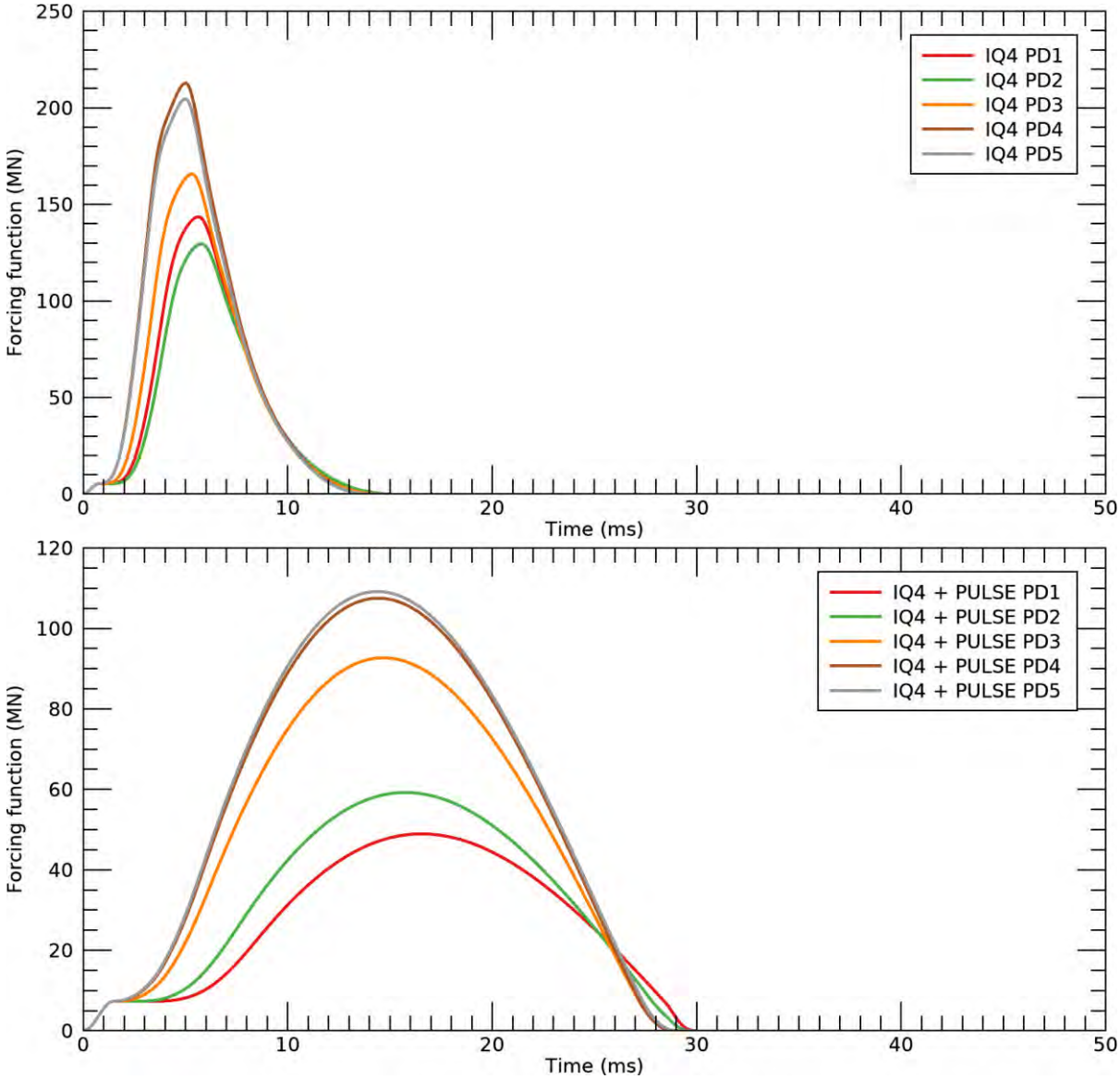


Figure C-9. Monopile 1: Force at the top of the pile, corresponding to impact pile driving of monopiles for five-penetration depths/hammer energy combinations. Top panel – IQ4. Bottom panel – IQ4+PULSE.

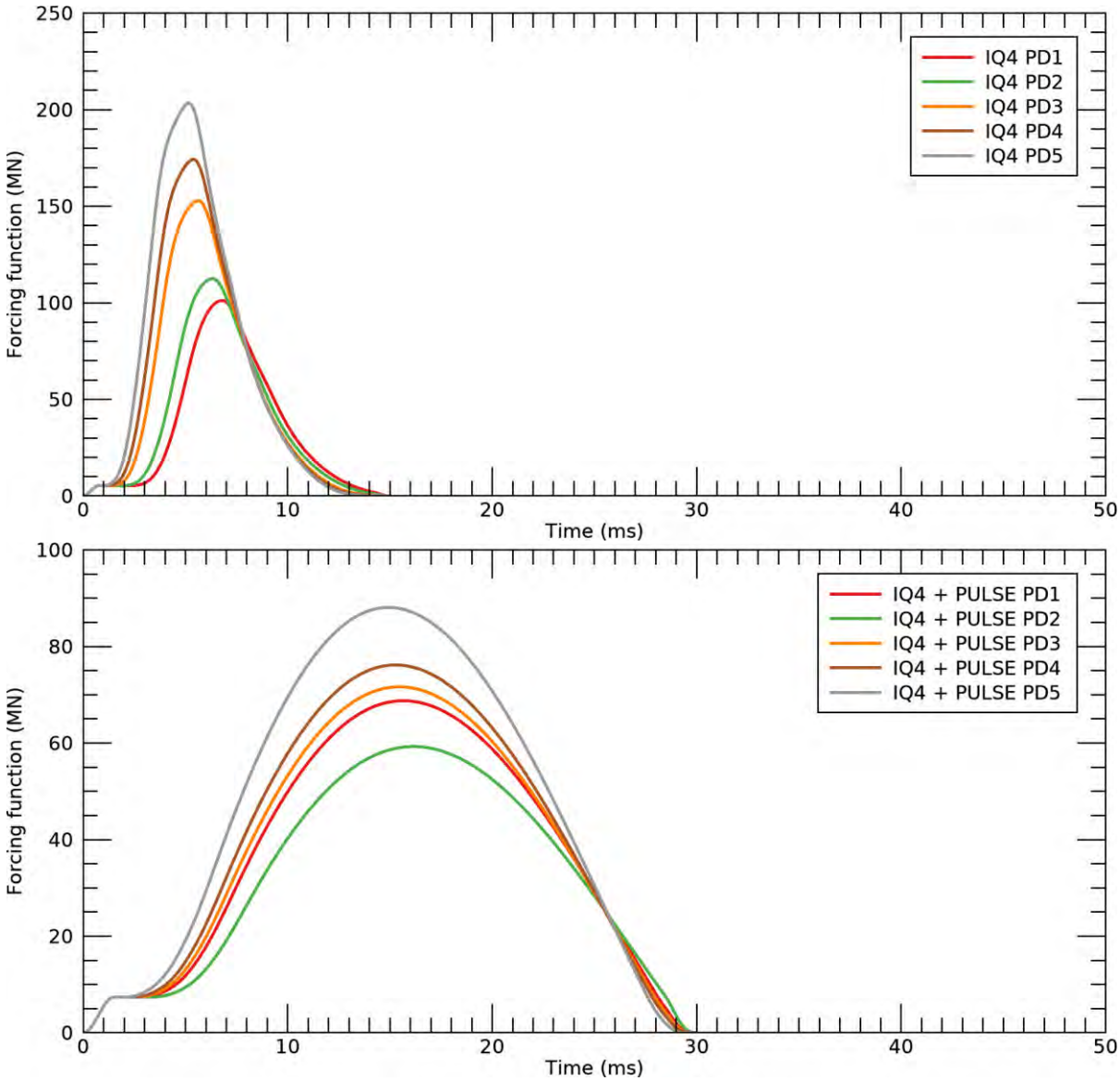


Figure C-10. Monopile 2: Force at the top of the pile, corresponding to impact pile driving of monopiles for five-penetration depths/hammer energy combinations. Top panel – IQ4. Bottom panel – IQ4+PULSE.

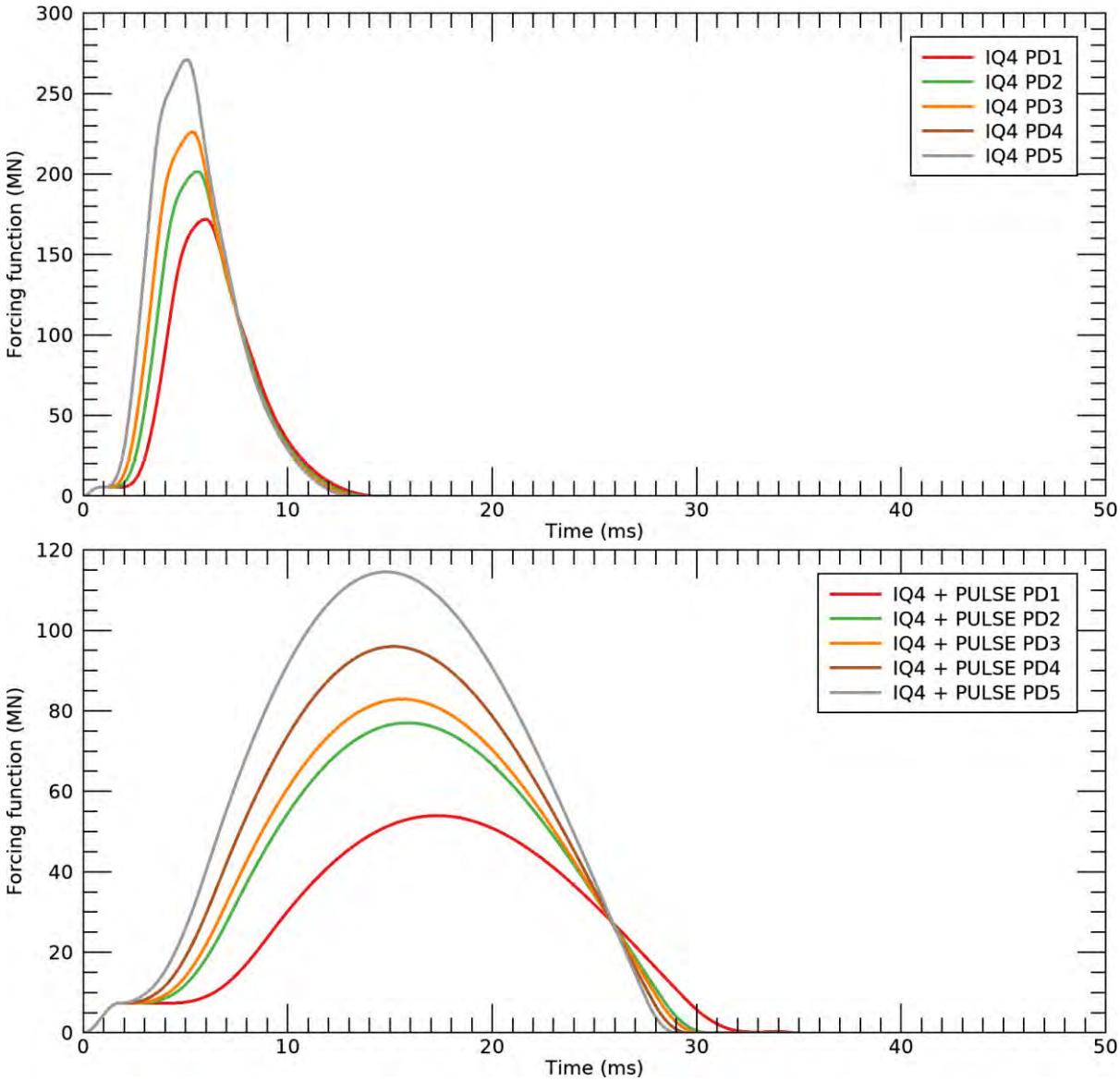


Figure C-11. Monopile 3: Force at the top of the pile, corresponding to impact pile driving of monopiles for five-penetration depths/hammer energy combinations. Top panel – IQ4. Bottom panel – IQ4+PULSE.

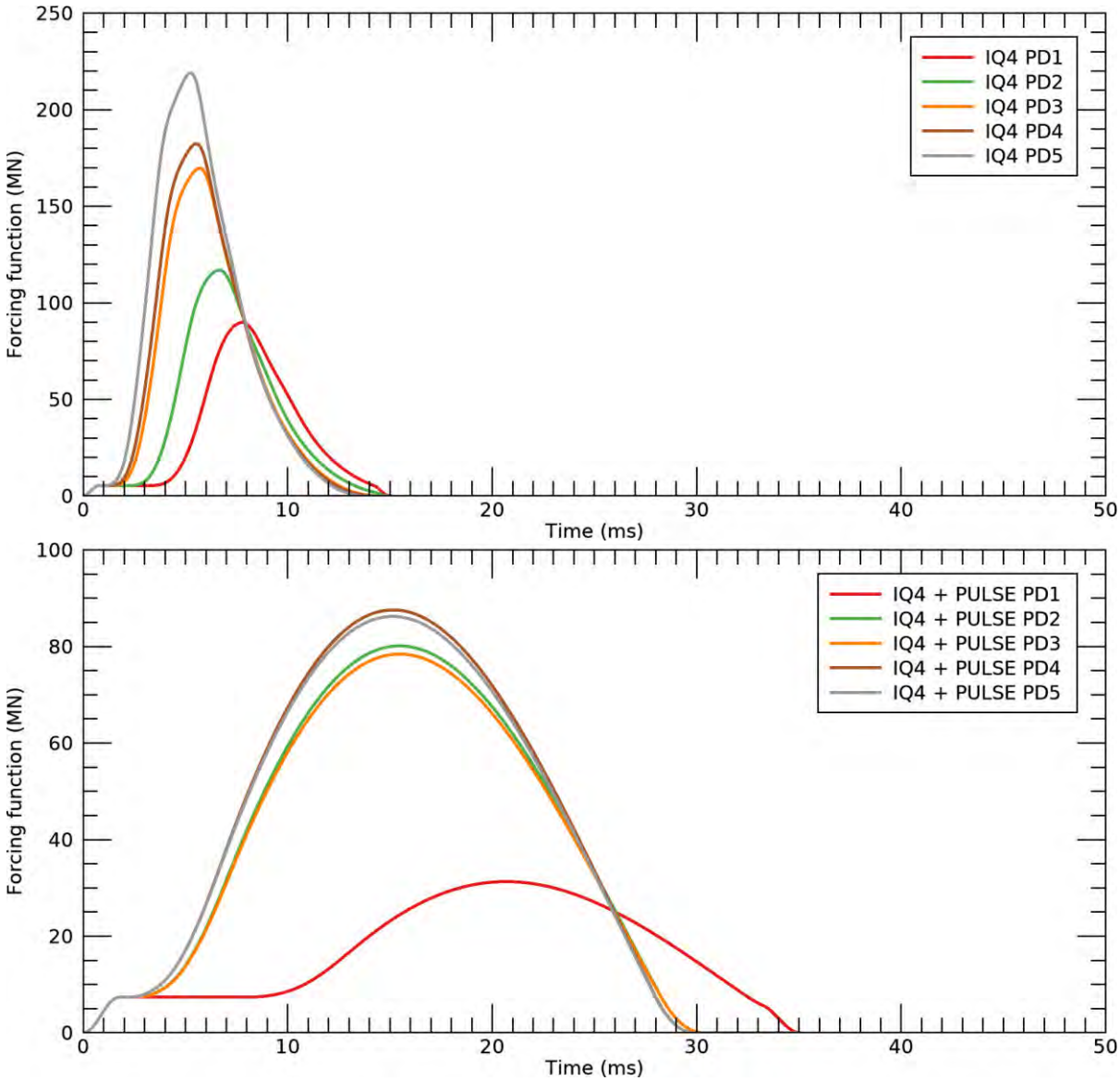


Figure C-12. Monopile 4: Force at the top of the pile, corresponding to impact pile driving of monopiles for five-penetration depths/hammer energy combinations. Top panel – IQ4. Bottom panel – IQ4+PULSE.

C.2.3.1. Additional Jacket Pile Parametrisation and Methodology (First Modelling Round)

The IHC S-2300 impact hammer considered for this study was selected to match the driveability study provided by Star of the South and was used for the OSS jacket pile installation modelling scenarios. Table C-16 summarises the general specifications of the jacket piles extracted from the driveability study as pertain to the modelled pile driving site. Similar to the monopiles, the parameters for a seabed with strong mechanical resistance were selected for acoustic modelling as part of a likely worst-case and conservative modelling approach.

Table C-16. Pile specifications for driven cylindrical steel jacket piles.

Site	Number of piles per day	Pile Description	Hammer Model	Dimension			Final penetration depth (m)
				Length (m)	Diameter Range (m)	Wall thickness (cm)[i]	
4	4	OSS JP	IHC S-2300	52	3.25	6.5	49

OSS JP: Offshore sub-station jacket pile
[i] Median thickness provided here for cylindrical piles refer pile for detail in Section 4.2.

For the OSS jacket piles, the hammer penetration/hammering values used in this acoustic modelling study was developed in considering the driveability study provided by the client, which included number the strikes and applied hammer energy per metre of the pile drive. The same approach as described above was employed to determine the resulting the penetration depth, strike count and hammer energy used for acoustic modelling (Table C-17). Table C-18 presents the pile geometry used by GRLWEAP and PDSM, while the hammer forcing function for the IHC S-2300 from GRLWEAP is shown in Figure C-13.

Table C-17. Hammer energy and modelled number of strikes at each energy setting, for monopile foundations driven by an impact hammer IHC S-2300. The table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Hammer Energy (kJ)	Strike count	Sediment penetration (m)	Pile in water column (m)	Total number of strikes	Strike rate (bpm)	Installation time (h)
OSS JP	499.7	2050	21.7	24 (full water column)	9565	30	5.31
	1371.7	2599	35.3	16.7			
	2280.7	4916	49.0	3			

Table C-18. Parameters for the pile geometry used in the impact piling modelling scenarios.

Pile type		OSS JP	
	Section Length (m)	Diameter (m)	Wall Thickness (cm)
Cylindrical steel	3.0	3.3	7.0
	3.0	3.3	7.0
	3.0	3.3	7.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	3.0	3.3	6.0
	4.0	3.3	6.0
Total	52	–	–

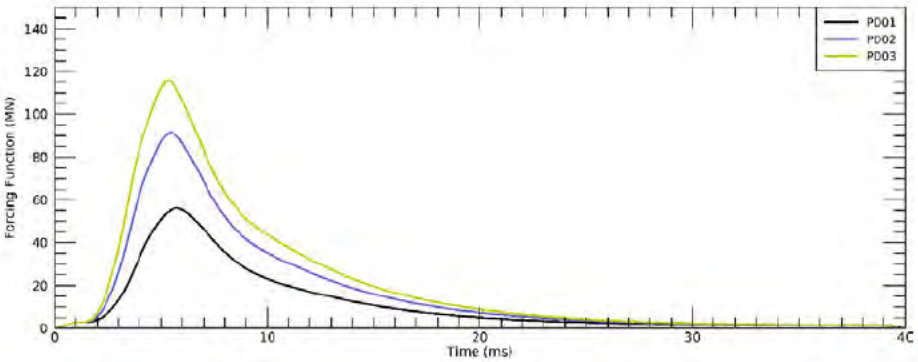


Figure C-13. Force (in meganewtons) at the top of the pile, corresponding to impact pile driving of OSS Jacket Pile for the three penetration depth/hammer energy combinations, computed using the GRLWEAP 2010 wave equation model for the IHC S-2300 impact hammer.

C.2.3.2. Additional Jacket Pile Parametrisation and Methodology (Second Modelling Round)

The MHU 3500S impact hammer considered for this study was selected to match the driveability study provided by Star of the South and was used for the OSS jacket pile installation modelling scenarios. Table C-19 summarises the general specifications of the jacket piles extracted from the driveability study as pertain to the modelled pile driving site. As for the monopiles the parameters for a seabed with strong mechanical resistance were selected for acoustic modelling as part of a likely worst-case and conservative modelling approach.

Table C-19. Pile specifications for driven cylindrical steel jacket piles.

Site	Number of piles per day	Pile Description	Hammer Model	Dimension			Final penetration depth (m)
				Length (m)	Diameter Range (m)	Wall thickness (cm)[i]	
4	4	OSS JP	MHU 3500S	52	3.25	6.5	49

OSS JP: Offshore sub-station jacket pile

[i] Median thickness provided here for cylindrical piles refer pile for detail in Section 4.2.

For the OSS jacket piles, the hammer penetration/hammering values used in this acoustic modelling study was developed in considering the driveability study provided by the Star of the South, which included number the strikes and applied hammer energy per metre of the pile drive. The same approach as described above was employed to determine the resulting the penetration depth, strike count and hammer energy used for acoustic modelling (Table C-20). Table C-21 presents the pile geometry used by GRLWEAP and PDSM, while the hammer forcing function for the MHU 3500S from GRLWEAP is shown in Figure C-14.

Table C-20. Hammer energy and modelled number of strikes at each energy setting, for jacket pile foundations driven by an impact hammer MHU 3500S. The table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Hammer Energy (kJ)	Strike count	Sediment penetration (m)	Pile in water column (m)	Total number of strikes	Strike rate (bpm)	Installation time (h)
OSS JP	150.5	1449	17.2	30 (full water column	8052	35	3.83
	592.1	1598	25.4	26.6			
	964.7	1799	33.6	18.4			
	1007.6	1607	41.8	10.2			
	956.0	1599	50.0	2.0			

Table C-21. Parameters for the pile geometry used in the impact piling modelling scenarios.

Pile type	OSS JP		
	Section Length (m)	Diameter (m)	Wall Thickness (cm)
Cylindrical steel	3	3.25	7
	3	3.25	7
	3	3.25	7
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	3	3.25	6
	4	3.25	6
Total	52	–	–

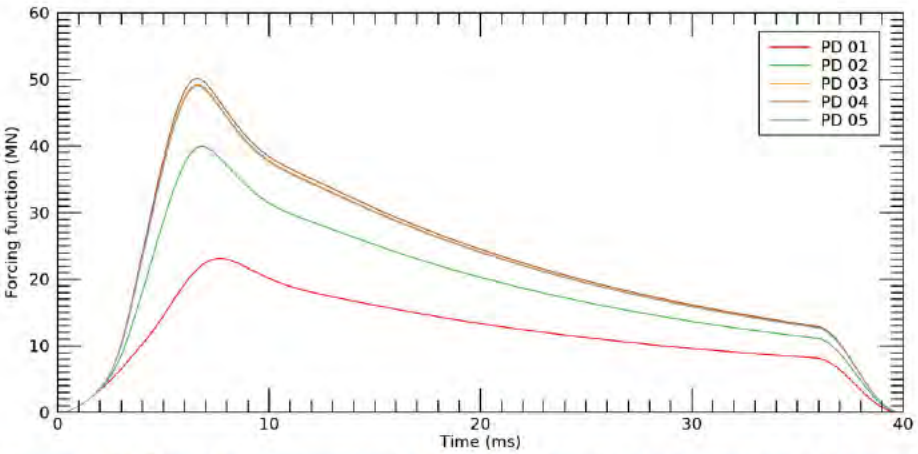


Figure C-14. Force (in meganewtons) at the top of the pile, corresponding to impact pile driving of OSS Jacket Pile for the five penetration depth/hammer energy combinations, computed using the GRLWEAP 2010 wave equation model for the MHU 3500S impact hammer.

C.2.3.3. Additional Jacket Pile Parameterisation and Methodology (Fourth Modelling Round)

The MHU 3500S and IQ4 + PULSE impact hammers were considered for this study, selected based on the project requirements/assumptions considered in the driveability study and defined by Star of the South.

Table C-22. Pile specifications for driven cylindrical steel piles.

Site	Number of piles per day	Pile description	Hammer model	Dimension		Final penetration depth (m)
				Length (m)	Max Diameter (m)	
5	4	Cylindrical	MHU 3500S and IQ4 + PULSE	52.0	3.25	50.0

[i] Median thickness provided here for cylindrical piles refer pile for detail in Section 4.1.

Table C-23. Hammer energy and modelled number of strikes at each energy setting, for pile foundations. Jacket foundations were driven by the MHU-3500S impact hammer. This table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Sediment penetration (m)	Hammer Energy (kJ)	Strike count	Total number of strikes	Strike rate (bpm)
JP	22.0	237.1	1599	7201	32
	29.0	384.6	1400		
	36.0	527.2	1405		
	43.0	586.3	1399		
	50.0	545.7	1399		

Table C-24. Hammer energy and modelled number of strikes at each energy setting, for jacket pile foundations driven by an impact hammer IQ4 with the PULSE system. This table provides the modelled pile sediment penetration corresponding to each energy setting.

Site Description	Sediment penetration (m)	Hammer Energy (kJ)	Strike count	Total number of strikes	Strike rate (bpm)
JP	23.6	213.0	1400	6795	36
	30.2	395.2	1397		
	36.8	501.3	1199		
	43.4	570.7	1399		
	50.0	586.5	1400		

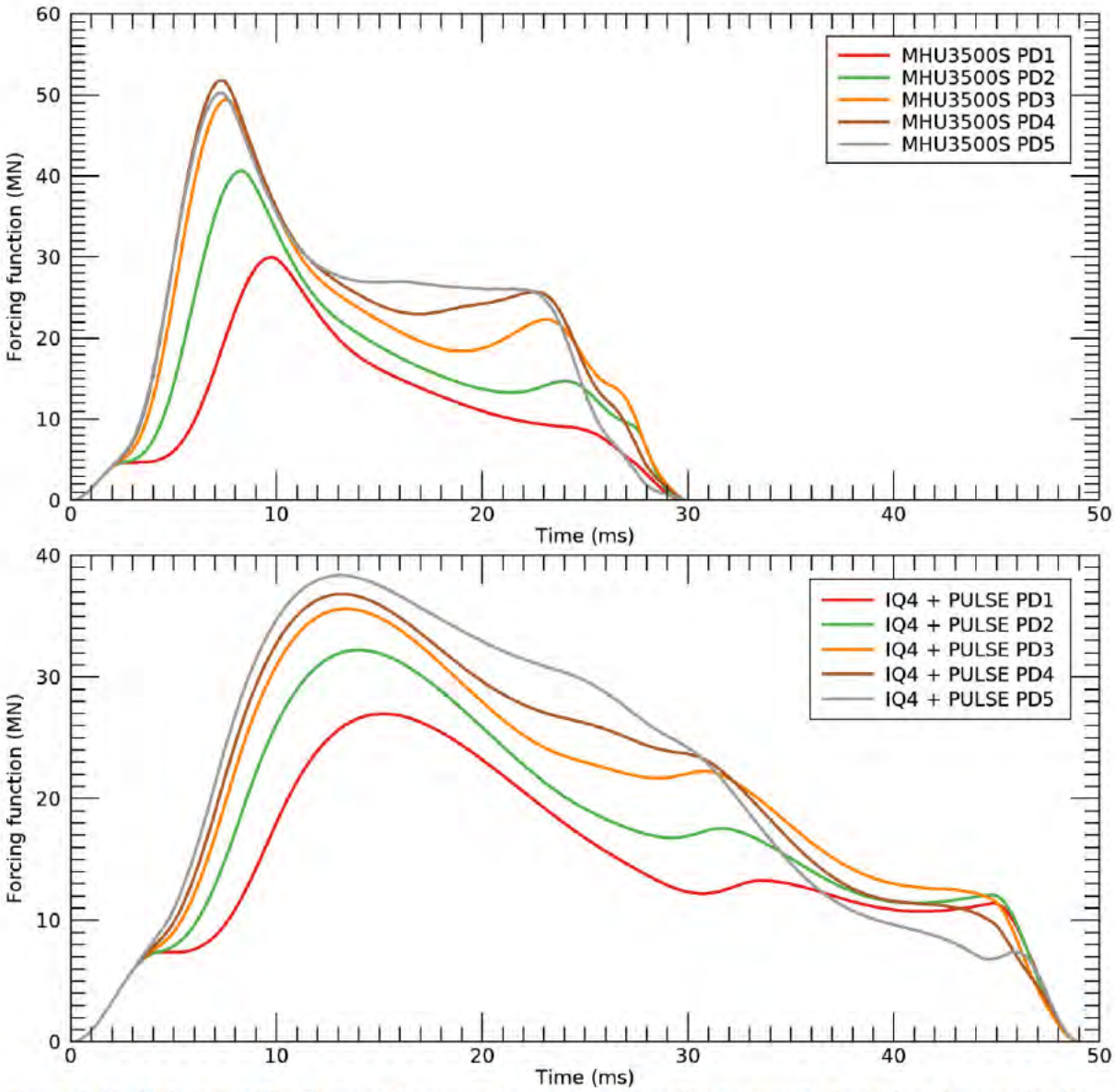


Figure C-15. OSS Jacket Pile: Force at the top of the pile, corresponding to impact pile driving of monopiles for five-penetration depths/hammer energy combinations for the jacket pile foundation. Top panel – MHU 3500S. Bottom panel – IQ4+PULSE.

C.2.3.1. Additional Vibro Pile Parametrisation and Methodology (Third Modelling Round)

Table C-25. Hammer energy and modelled number of strikes at each energy setting, for monopile and jacket pile foundations driven by a vibro hammer, the GIANT 4000. The table below provides the modelled pile sediment penetration rates, interval times and total modelled installation times.

Site Description	Hammer Frequency (Hz)	Sediment penetration (m)	Penetration Rate (mm/s)	Drive Time Per Interval (min)	Total Time (min)	Total Time (hr)
MP 1	23.3	11.0	48.44	3.8	433.8	7.2
		17.0	22.52	4.4		
		19.5	22.63	1.8		
		22.0	0.10	416.6		
		27.8	13.24	7.1		
MP 2		2.0	98.06	0.3	22.0	0.4
		15.5	32.12	7.0		
		21.5	14.25	7.0		
		24.5	25.74	1.9		
		29.1	12.95	5.7		
MP 3		11.5	175.17	1.1	356.9	5.9
		26.0	17.54	13.8		
		28.0	0.10	333.3		
		35.0	27.61	4.2		
		42.0	25.81	4.5		
JP OSS		13.5	316.23	0.7	10.7	0.2
		23	79.26	2.0		
		26	77.72	0.6		
		41	53.61	4.7		
		50	55.53	2.7		

C.3. Non-Impulsive Noise

C.3.1. Propagation Loss

The propagation of sound through the environment was modelled by predicting the acoustic propagation loss—a measure, in decibels, of the decrease in sound level between a source and a receiver some distance away. Geometric spreading of acoustic waves is the predominant way by which propagation loss occurs. Propagation loss also happens when the sound is absorbed and scattered by the seawater, and absorbed scattered, and reflected at the water surface and within the seabed. Propagation loss depends on the acoustic properties of the ocean and seabed; its value changes with frequency.

If the acoustic energy source level (ESL), expressed in dB re 1 $\mu Pa^2 \cdot s\ m^2$, and propagation loss (PL), in units of dB, at a given frequency are known, then the received level (RL) at a receiver location can be calculated in dB re 1 $\mu Pa^2 \cdot s$ by:

$$RL = SL - PL. \quad \text{(C-2)}$$

C.3.2. MONM-BELLHOP

Long-range sound fields were computed using JASCO's Marine Operations Noise Model (MONM). While other models may be more accurate for steep-angle propagation in high-shear environment, MONM is well suited for effective longer-range estimation. This model computes sound propagation at frequencies of 10 Hz to 1.6 kHz via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). MONM computes sound propagation at frequencies > 1.6 kHz via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed, which results from partial conversion of incident compressional waves to shear waves at the seabed and sub-bottom interfaces, and it includes wave attenuations in all layers. MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modelled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

MONM computes acoustic fields in three dimensions by modelling propagation loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D. These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ number of planes (Figure C-16).

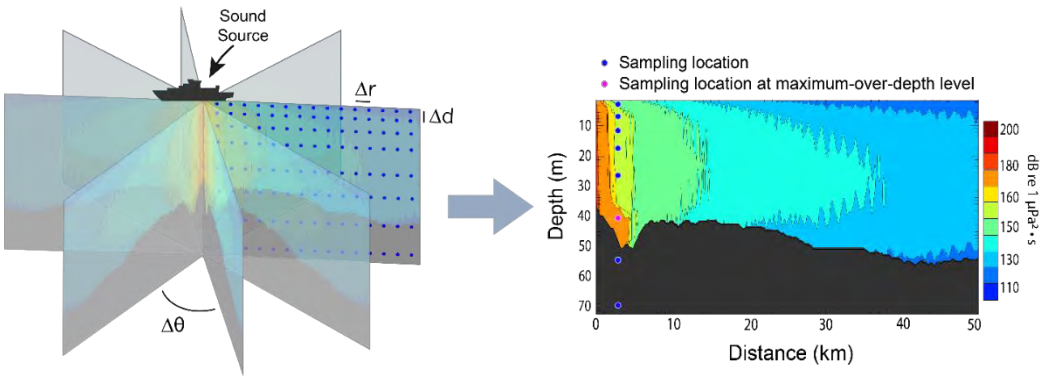


Figure C-16. The N×2-D and maximum-over-depth modelling approach used by MONM.

MONM treats frequency dependence by computing acoustic propagation loss at the centre frequencies of decidecade bands. Sufficiently many decidecade frequency-bands, starting at 10 Hz, are modelled to include most of the acoustic energy emitted by the source. At each centre frequency, the propagation loss is modelled within each of the N vertical planes as a function of depth and range from the source. The decidecade received per-second SEL are computed by subtracting the band propagation loss values from the directional source level in that frequency band. Composite broadband received per-second SEL are then computed by summing the received decidecade levels.

The received 1-s SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface. The step sizes are chosen to provide increased coverage near the depth of the source and at depths of interest in terms of the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received per-second SEL at a surface sampling location is taken as the maximum value that occurs over all

samples within the water column, i.e., the maximum-over-depth received per-second SEL. These maximum-over-depth per-second SEL are presented as colour contours around the source.

C.3.3. Wavenumber Integration Model: VSTACK

Particle velocity for vibrations due to pile driving were modelled using JASCO's VSTACK wavenumber integration model. VSTACK computes the vertical and horizontal particle velocity versus time at specific depths and ranges from the pile for arbitrarily layered, range-independent, acoustic environments using the wavenumber integration approach to solving the exact (range-independent) acoustic wave equation. This model is valid over the full angular range of the wave equation and can fully account for the elasto-acoustic properties of the sub-bottom. Wavenumber integration methods are extensively used in the fields of underwater acoustics and seismology where they are often referred to as reflectivity methods or discrete wavenumber methods.

VSTACK computes sound propagation in arbitrarily stratified water and seabed layers by decomposing the outgoing field into a continuum of outward-propagating plane cylindrical waves. Seabed reflectivity in the model is dependent on the seabed layer properties: compressional and shear wave speeds, attenuation coefficients, and layer densities.

VSTACK accurately predicts steep-angle propagation in the proximity of the source but it is computationally slow at predicting sound pressures at large distances due to the need for smaller wavenumber steps with increasing distance. Additionally, VSTACK assumes range-invariant bathymetry with a horizontally stratified medium (i.e. a range-independent environment) that is azimuthally symmetric about the source. VSTACK is thus best suited to modelling the sound field near the source.

C.3.4. Estimating Sound Fields from Moving Vessels

During vessel transit, new sound energy is constantly being introduced to the environment. The noise footprint for the transiting vessels considered in this report were estimated by modelling the 1-s maximum over depth SEL footprints for the vessel at one location, and by translating and summing these footprints along the vessel transit routes. The vessel locations along the tracks were spaced uniformly, with an approximate step of $\Delta s \approx 10$ m.

The SEL sound field at any given point along the track is dependent upon the time duration within each 10 m segment of the track. When the track segment spacing is fixed, the duration of exposure depends upon the speed of the vessel during each segment of the transit. The 1-s SEL footprint at each vessel location (i) was therefore scaled based on the speed of the vessel following:

$$\mathrm{SEL}_i = \mathrm{SEL}_{1s} + 10 \log_{10} \left(\frac{\Delta s}{v} \right) . \qquad \text{(C-3)}$$

where v represents the vessel speed in m/s.

The present method acceptably reflects large-scale sound propagation features, primarily dependent on water depth, which dominate the cumulative field and is thus considered to provide a meaningful estimate of the SEL_{24h} field.

C.4. Estimating Range to Thresholds Levels

Sound level contours were calculated based on the underwater sound fields predicted by the propagation models, sampled by taking the maximum value over all modelled depths above the sea floor for each location in the modelled region. The predicted distances to specific levels were

computed from these contours. Two distances relative to the source are reported for each sound level: 1) R_{max}, the maximum range to the given sound level over all azimuths, and 2) $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure C-17).

The $R_{95\%}$ is used because sound field footprints are often irregular in shape. In some cases, a sound level contour might have small protrusions or anomalous isolated fringes. This is demonstrated in the image in Figure C-17(a). In cases such as this, where relatively few points are excluded in any given direction, R_{max} can misrepresent the area of the region exposed to such effects, and $R_{95\%}$ is considered more representative. In strongly asymmetric cases such as shown in Figure C-17(b), on the other hand, $R_{95\%}$ neglects to account for significant protrusions in the footprint. In such cases R_{max} might better represent the region of effect in specific directions. Cases such as this are usually associated with bathymetric features affecting propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

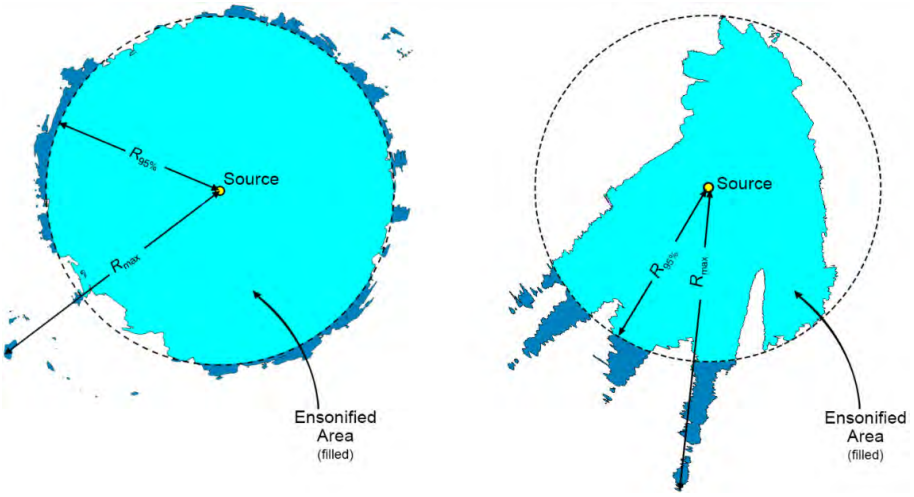


Figure C-17. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ ranges shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

C.5. Model Validation Information

Predictions from JASCO's propagation models (MONM, FWRAM, and VSTACK) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including programs in the United States and Canadian Arctic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities that have included internal validation of the modelling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016, Austin et al. 2018, Beach Energy Limited 2020).

Appendix D. Animal Movement and Exposure Modelling

Animal movement and exposure modelling considers the movement of both sound sources and animals over time. Acoustic source and propagation modelling are used to generate 3-D sound fields that vary as a function of distance to source, depth, and azimuth. Sound sources are modelled at representative sites and the resulting sound fields are assigned to source locations using the minimum Euclidean distance. The sound received by an animal at any given time depends on its location relative to the source. Because the true locations of the animals within the sound fields are unknown, realistic animal movements are simulated using repeated random sampling of various behavioural parameters. The Monte Carlo method of simulating many animals within the operations area is used to estimate the sound exposure history of the population of simulated animals (animats).

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more simulated animats, the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practical allowing for computation time. Typically, the animat density is much higher than the real-world density to ensure good representation of the PDF. The resulting PDF can be scaled using the real-world density if it is available.

Several models for marine mammal movement have been developed (Ellison et al. 1987, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behaviour. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth ranges can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source marine mammal movement and behaviour model (3MB, Houser 2006) and used to predict the exposure of animats to sound arising from the anthropogenic activities. Animats are programmed to behave like the species likely to be present in the survey area. The parameters used for forecasting realistic behaviours (e.g., diving, foraging, aversion, surface times, etc.) are determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modelled sound exposure levels are summed over the total simulation duration to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as 3MB (Houser, 2006), but has been extended to be directly compatible with JASCO's Marine Operations Noise Model (MONM) and Full Waveform Range-dependent Acoustic Model acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioural states based on time and space dependent modelled variables such as received levels for aversion behaviour, although aversion was not considered in this study.

D.1. Animal Movement Parameters

JASMINE uses previously measured behaviour to forecast behaviour in new situations and locations. The parameters used for forecasting realistic behaviour are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behaviour of a species are available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behaviour states. The probability of an animat starting out in or transitioning into a given behaviour state can in turn be defined in terms of the animat's current behavioural state, depth, and the time of day. In addition, each travel parameter and behavioural state has a termination function that governs how long the parameter value or overall behavioural state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. The parameters relating to travel in these two planes are briefly described below.

Travel sub-models

- **Direction**– determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to range from strongly biased to undirected. A random walk model can be used for behaviours with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006) and Houser and Cross (1999).
- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behaviour is used to emulate the foraging behaviour of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

D.1.1.1. Pygmy Blue Whale Parameter Tables

Table D-1. *Feeding pygmy blue whales*: Data references input in JASMINE to create diving behaviour.

Behaviour	Variable	Reference
Feeding	Travel direction	Approximated
	Perturbation value	Approximated
	Termination coefficient	Approximated
	Travel rate (m/s)	Möller et al. (2020a)
	Ascent rate (m/s)	Thums et al. (2025)
	Descent rate (m/s)	Thums et al. (2025)
	Average depth (m)	Thums et al. (2025)
	Bottom following	Approximated – blue whale (Goldbogen et al. 2011)
	Reversals	Approximated - Thums et al. (2025)
	Probability of reversals	Approximated - Thums et al. (2025)
	Reversal ascent dive rate (m/s)	Thums et al. (2025)
	Reversal descent dive rate (m/s)	Thums et al. (2025)
	Time in reversal (s)	Approximated – blue whale (Goldbogen et al. 2011)
	Surface interval (s)	Thums et al. (2025)
	Bout duration (s)	Thums et al. (2025)
	Transition probability	Thums et al. (2025)
Resting	Travel direction	Approximated
	Perturbation value	Approximated
	Termination coefficient	Approximated
	Travel rate (m/s)	Möller et al. (2020a)
	Ascent rate (m/s)	Thums et al. (2025)
	Descent rate (m/s)	Thums et al. (2025)
	Average depth (m)	Thums et al. (2025)
	Bottom following	Approximated - (Owen et al. 2016)
	Reversals	Approximated - Thums et al. (2025)
	Probability of reversals	Approximated - Thums et al. (2025)
	Reversal ascent dive rate (m/s)	Thums et al. (2025)
	Reversal descent dive rate (m/s)	Thums et al. (2025)
	Time in reversal (s)	Approximated - Thums et al. (2025)
	Surface interval (s)	Thums et al. (2025)
	Bout duration (s)	Thums et al. (2025)
	Transition probability	Approximated - (Möller et al. 2020a)
General	Shore following (m)	Double et al. (2014), Gill (2015)
	Depth limit on seeding (m)	Double et al. (2014), Gill (2015)

Approximated: Value based on the best fit for diving profile or known behaviour. Those values were unavailable from literature, but they were estimated to produce a diving profile similar to D-tag results, for example, based on either the reference provided or in JASMINE if no reference is provided.

Table D-2. *Migrating pygmy blue whales*: Data references input in JASMINE to create diving behaviour.

Behaviour	Variable	Reference
Exploratory	Travel direction	Approximated
	Perturbation value	Approximated
	Termination coefficient	Approximated
	Travel rate (m/s)	Möller et al. (2020a)
	Ascent rate (m/s)	Thums et al. (2025)
	Descent rate (m/s)	Thums et al. (2025)
	Average depth (m)	Thums et al. (2025)
	Bottom following	Approximated - Thums et al. (2025)
	Reversals	Approximated - Thums et al. (2025)
	Surface interval (s)	Thums et al. (2025)
	Bout duration (s)	Approximated - Thums et al. (2025)
	Transition probability	Approximated - (Owen et al. 2016)
Migrating	Travel direction	Approximated
	Perturbation value	Approximated
	Termination coefficient	Approximated
	Travel rate (m/s)	Möller et al. (2020a)
	Ascent rate (m/s)	Thums et al. (2025)
	Descent rate (m/s)	Thums et al. (2025)
	Average depth (m)	Thums et al. (2025)
	Bottom following	Approximated - Thums et al. (2025)
	Reversals	Approximated - Thums et al. (2025)
	Probability of reversals	Approximated - Thums et al. (2025)
	Reversal ascent dive rate (m/s)	Thums et al. (2025)
	Reversal descent dive rate (m/s)	Thums et al. (2025)
General	Time in reversal (s)	Approximated - Thums et al. (2025)
	Surface interval (s)	Thums et al. (2025)

Approximated: Value based on the best fit for diving profile or known behaviour. Those values were unavailable from literature, but they were estimated to produce a diving profile similar to D-tag results, for example, based on either the reference provided or in JASMINE if no reference is provided.

D.1.1.2. Humpback Whale Parameter Table

Table D-3. *Migrating and feeding humpback whales*: Data references input in JASMINE to create diving behaviour.

Behaviour	Variable	Reference
Resting	Travel direction	Approximated (Kavanagh 2014)
	Perturbation value	Approximated (Kavanagh 2014)
	Termination coefficient	Approximated (Kavanagh 2014)
	Travel rate (m/s)	Kavanagh (2014)
	Ascent rate (m/s)	Szesciorka (2015)
	Descent rate (m/s)	Szesciorka (2015)
	Average depth (m)	Bejder et al. (2019)
	Bottom following	Approximated
	Reversals	Approximated
	Surface interval (s)	Szesciorka (2015)
	Bout duration (s)	Approximated (Friedlaender et al. 2013)
	Transition probability	Approximated (Kavanagh 2014)
Migrating	Travel direction	Approximated (Kavanagh 2014, Andrews-Goff et al. 2018)
	Perturbation value	Approximated (Kavanagh 2014)
	Bias arc step	Approximated (Kavanagh 2014)
	Bias direction (project specific)	Approximated (Andrews-Goff et al. 2018)
	Bias factor	Approximated (Kavanagh 2014)
	Termination coefficient	Approximated (Kavanagh 2014)
	Travel rate (m/s)	Noad and Cato (2007), Garrigue et al. (2015)
	Ascent rate (m/s)	Goldbogen et al. (2008)

Behaviour	Variable	Reference
	Descent rate (m/s)	Goldbogen et al. (2008)
	Average depth (m)	Friedlaender et al. (2013)
	Bottom following	Approximated
	Reversals	Approximated
	Surface interval (s)	Kavanagh et al. (2017)
	Bout duration (s)	Approximated – pygmy blue whales (Owen et al. 2016)
	Transition probability	Approximated (Kavanagh 2014, Owen et al. 2015)
Feeding –Shallow	Travel direction	Approximated (Owen et al. 2015)
	Perturbation value	Approximated (Owen et al. 2015)
	Termination coefficient	Approximated (Owen et al. 2015)
	Travel rate (m/s)	Lagerquist et al. (2008)
	Ascent rate (m/s)	Goldbogen et al. (2008)
	Descent rate (m/s)	Goldbogen et al. (2008)
	Average depth (m)	Owen et al. (2015)
	Bottom following	Approximated
	Reversals	Approximated (Goldbogen et al. 2008, Ware et al. 2011)
	Probability of reversals	Approximated (Goldbogen et al. 2008, Ware et al. 2011)
	Reversal ascent dive rate (m/s)	Goldbogen et al. (2008)
	Reversal descent dive rate (m/s)	Goldbogen et al. (2008)
	Time in reversal (s)	Ware et al. (2011)
	Surface interval (s)	Dolphin (1987a)
	Bout duration (s)	Approximated (D'Vincent et al. 1985) (Dolphin 1987b)
	Transition probability	Owen et al. (2015)
Feeding – Surface	Travel direction	Approximated (Owen et al. 2015)
	Termination coefficient	Approximated (Owen et al. 2015)
	Travel rate (m/s)	Lagerquist et al. (2008)
	Ascent rate (m/s)	Goldbogen et al. (2008)
	Descent rate (m/s)	Goldbogen et al. (2008)
	Average depth (m)	Owen et al. (2015)
	Bottom following	Approximated
	Reversals	Approximated (Goldbogen et al. 2008, Ware et al. 2011)
	Probability of reversals	Approximated (Goldbogen et al. 2008, Ware et al. 2011)
	Reversal ascent dive rate (m/s)	Goldbogen et al. (2008)
	Reversal descent dive rate (m/s)	Goldbogen et al. (2008)
	Time in reversal (s)	Ware et al. (2011)
	Surface interval (s)	Dolphin (1987a)
	Bout duration (s)	Approximated (D'Vincent et al. 1985) (Dolphin 1987b)
	Transition probability	Owen et al. (2015)
General	Shore following (m)	Halpin et al. (2009)
	Depth limit on seeding (m)	Halpin et al. (2009), Garrigue et al. (2015)

Approximated: Value based on the best fit for diving profile or known behaviour. Those values were unavailable from literature, but they were estimated to produce a diving profile similar to D-tag results, for example, based on either the reference provided or in JASMINE if no reference is provided.

D.1.1.3. Minke Whale Parameter Table

Table D-4. *Migrating minke whales*: Data references input in JASMINE to create diving behaviour.

Behaviour	Variable	Reference
Migrating	Travel direction	Approximated
	Perturbation value	Approximated
	Termination coefficient	Approximated
	Travel rate (m/s)	Approximated – common minke whale (Risch et al. 2014a)
	Ascent rate (m/s)	Approximated – common minke whale (Risch et al. 2014a, Gough et al. 2021)
	Descent rate (m/s)	Approximated – common minke whale (Risch et al. 2014a, Gough et al. 2021)
	Average depth (m)	Approximated – common minke whale (Blix and Folkow 1995b)
	Bottom following	Approximated
	Reversals	Approximated – common minke whale (Blix and Folkow 1995b)
	Surface interval (s)	Approximated – common minke whale (Christiansen et al. 2011a)
	Bout duration (s)	Approximated – common minke whale (Blix and Folkow 1995b)
	Transition probability	Approximated
General	Shore following (m)	Halpin et al. (2009)
	Depth limit on seeding (m)	Hoelzel et al. (1989), Halpin et al. (2009)

Approximated: Value based on the best fit for diving profile or known behaviour. Those values were unavailable from literature, but they were estimated to produce a diving profile similar to D-tag results, for example, based on either the reference provided or in JASMINE if no reference is provided.

D.1.1.4. Southern Right Whale Parameter Table

Table D-5. *Migrating and resting southern right whales*: Data references input in JASMINE to create diving behaviour.

Behaviour	Variable	Reference
Resting	Travel direction	Approximated – humpback whales (Kavanagh 2014)
	Perturbation value	Approximated – humpback whales (Kavanagh 2014)
	Termination coefficient	Approximated – humpback whales (Kavanagh 2014)
	Travel rate (m/s)	Approximated – North Atlantic right whales (Hain et al. 2013)
	Ascent rate (m/s)	Approximated – North Atlantic right whales (Dombroski et al. 2021)
	Descent rate (m/s)	Approximated – North Atlantic right whales (Dombroski et al. 2021)
	Average depth (m)	Approximated – North Atlantic right whales (Dombroski et al. 2021)
	Bottom following	Approximated
	Reversals	Approximated
	Surface interval (s)	Approximated – North Atlantic right whales (Dombroski et al. 2021)
	Bout duration (s)	Approximated – North Atlantic right whales (Hain et al. 2013)
	Transition probability	Approximated – humpback whales (Kavanagh 2014)
Migrating	Travel direction	Approximated – North Atlantic right whales (Mayo and Marx 1990)
	Perturbation value	Approximated – North Atlantic right whales (Mayo and Marx 1990)
	Bias arc step	Approximated – North Atlantic right whales (Mayo and Marx 1990)
	Bias direction (project specific)	Approximated
	Bias factor	Approximated – North Atlantic right whales (Mayo and Marx 1990)
	Termination coefficient	Approximated – North Atlantic right whales (Mayo and Marx 1990)
	Travel rate (m/s)	Mackay et al. (2020)
	Ascent rate (m/s)	Approximated – North Atlantic right whales (Baumgartner and Mate 2003)
	Descent rate (m/s)	Approximated – North Atlantic right whales (Baumgartner and Mate 2003)
	Average depth (m)	Approximated – North Atlantic right whales (Nousek McGregor 2010)
	Bottom following	Approximated
	Reversals	Approximated
	Surface interval (s)	Approximated – North Atlantic right whales (Baumgartner and Mate 2003)
	Bout duration (s)	Approximated – North Atlantic right whales (Mayo and Marx 1990)
	Transition probability	Approximated – humpback whales (Kavanagh 2014)
General	Shore following (m)	Halpin et al. (2009)
	Depth limit on seeding (m)	Halpin et al. (2009), De Rock et al. (2019)

Approximated: Value based on the best fit for diving profile or known behaviour. Those values were unavailable from literature, but they were estimated to produce a diving profile similar to D-tag results, for example, based on either the reference provided or in JASMINE if no reference is provided.

D.2. Exposure Integration Time

The interval over which acoustic exposure (L_E) should be integrated and maximal exposure (L_p) determined is not well defined. NMFS (2024) recommend a 24 hour baseline accumulation period, but state that there may be situations where this is not appropriate. Resetting the integration after 24 hours can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behaviour collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. For this study, a representative 24-hour period was simulated.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that could approach the source during an operation is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited. In the simulation, every animat that reaches a border is replaced by another animat entering at the opposing border—e.g., an animat crossing the northern border of the simulation is replaced by one entering the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a

depth suited to its species definition. The exposures of all animats (including those leaving the simulation and those entering) are kept for analysis. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.

D.3. Seeding Density and Scaling

Seeding density refers to the spatial sample rate, in units of animats/km^2, used in the simulation. It is not related to the real-world animal density, but rather is a model parameter that controls the how samples are drawn from the model space. The minimum required seeding density for any given project depends on several factors such as bathymetry, source characteristics, and the behavioural profile of the animats, with the main constraint being computation time and resources. Seeding density is adjusted as needed based on model conditions specific to a project or project area.

In the present study, the exposure criteria for impulsive sounds were used to determine the number of animats exceeding exposure thresholds. To generate statistically reliable probability density functions, all simulations were seeded with an animat density of 4 animat/km^2 over the entire simulation area. Due to insufficient density data availability, the modelling results are not related to real-world density estimates for the modelled species.

Appendix E. Additional Results: Animal Movement Modelling Histograms

E.1. Impact Pile Driving

E.1.1. Monopile

E.1.1.1. Scenario 2 – DBBC (First Modelling Round)

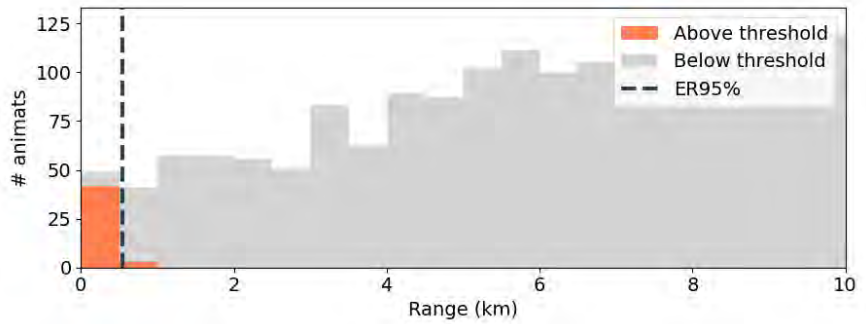


Figure E-1. *Monopile 1, pygmy blue whale, female, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

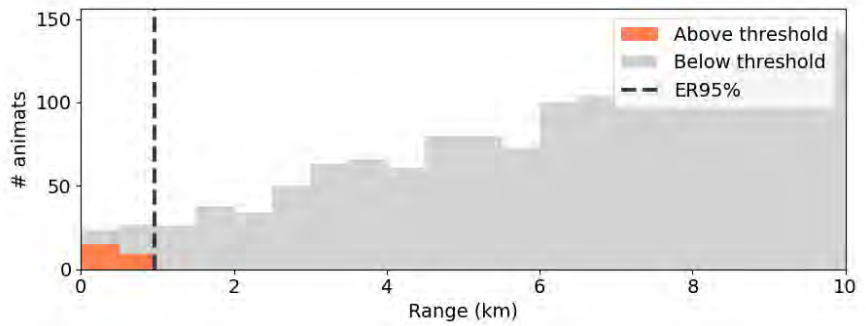


Figure E-2. *Monopile 1, humpback whale, mother & calf, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

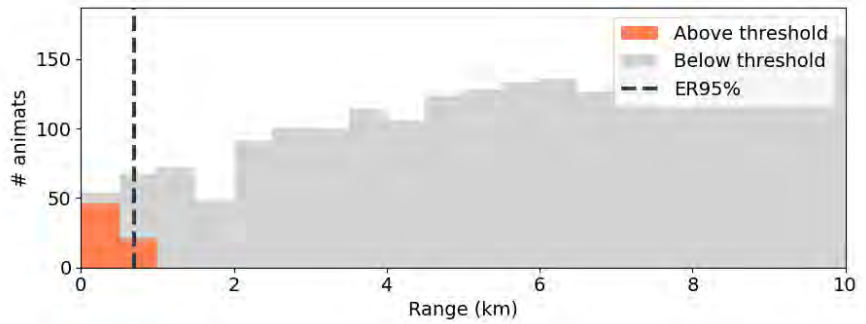


Figure E-3. *Monopile 1, minke whale, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

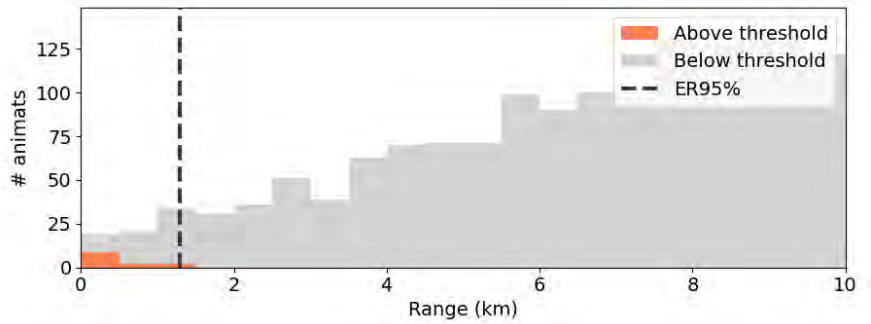


Figure E-4. *Monopile 1, southern right whale, mother & calf, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

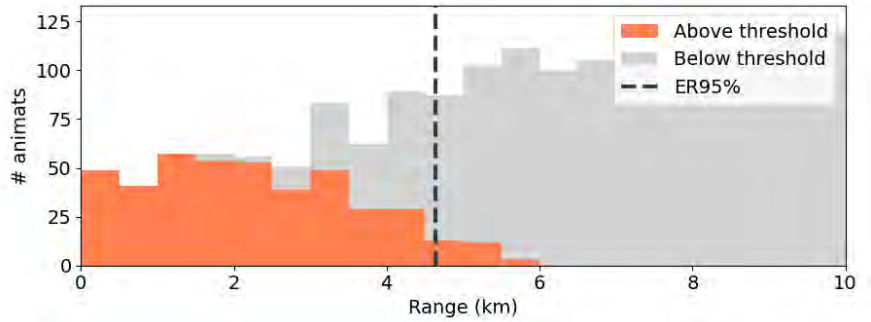


Figure E-5. *Monopile 1, pygmy blue whale, female, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

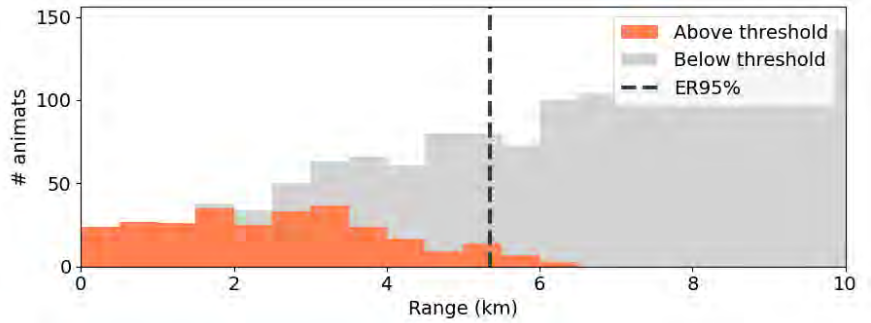


Figure E-6. *Monopile 1, humpback whale, mother & calf, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

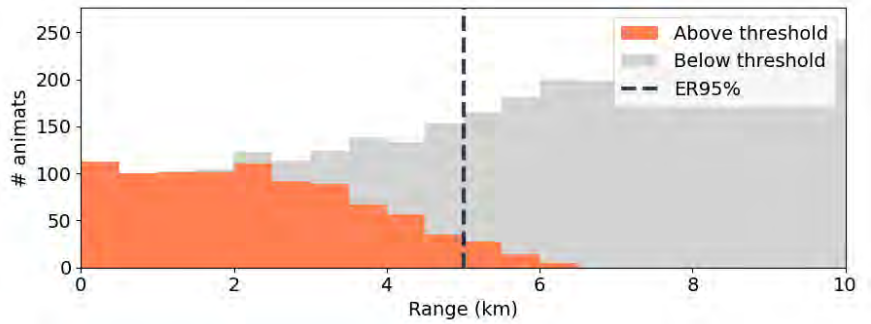


Figure E-7. *Monopile 1, minke whale, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

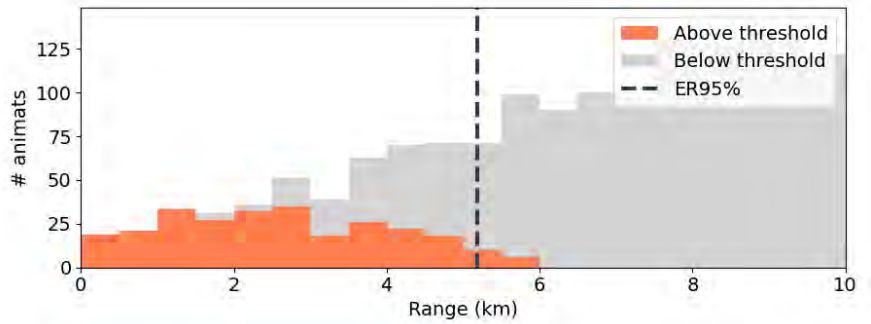


Figure E-8. *Monopile 1, southern right whale, mother & calf, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

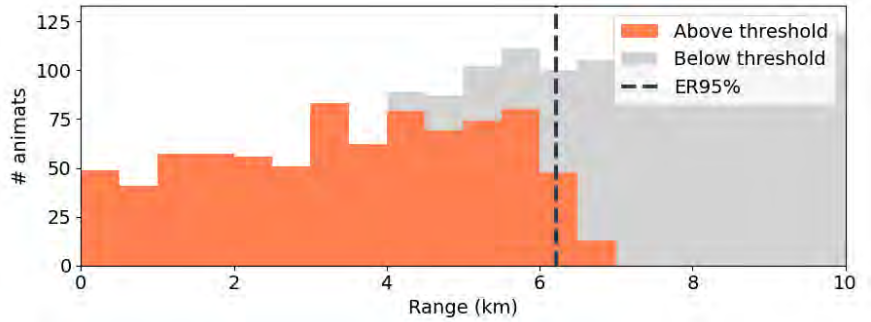


Figure E-9. *Monopile 1, pygmy blue whale, female,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

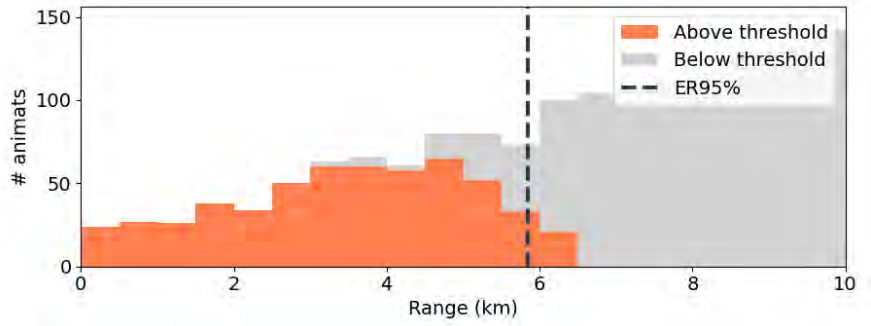


Figure E-10. *Monopile 1, humpback whale, mother & calf,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

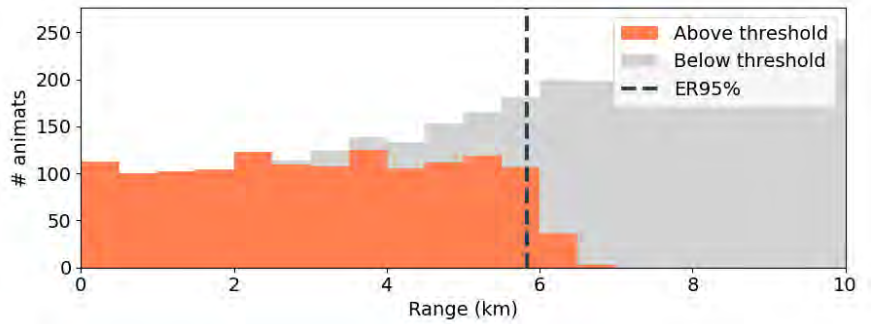


Figure E-11. *Monopile 1, minke whale,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

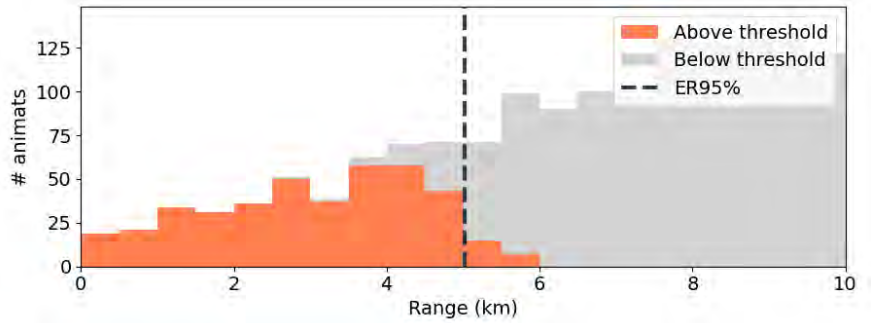


Figure E-12. *Monopile 1, southern right whale, mother & calf,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

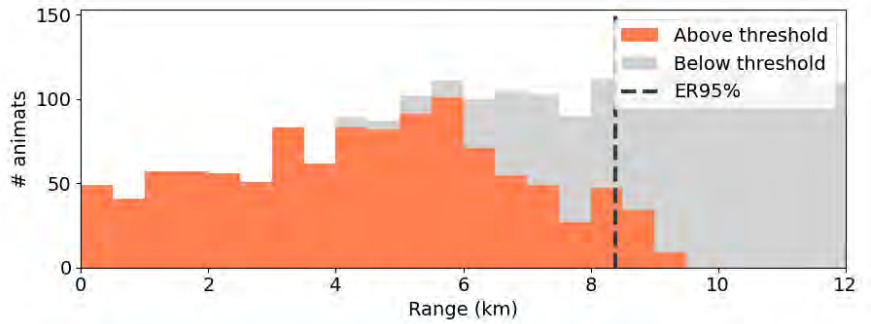


Figure E-13. *Monopile 1, pygmy blue whale, female, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

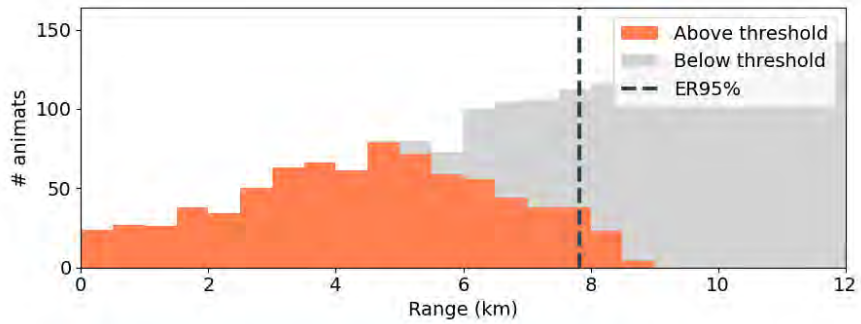


Figure E-14. *Monopile 1, humpback whale, mother & calf, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

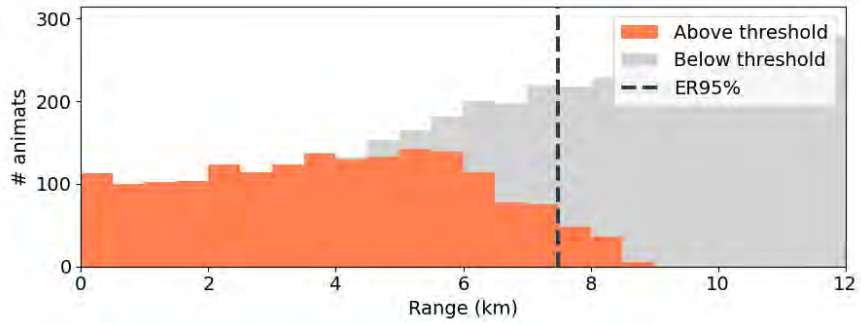


Figure E-15. *Monopile 1, minke whale, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

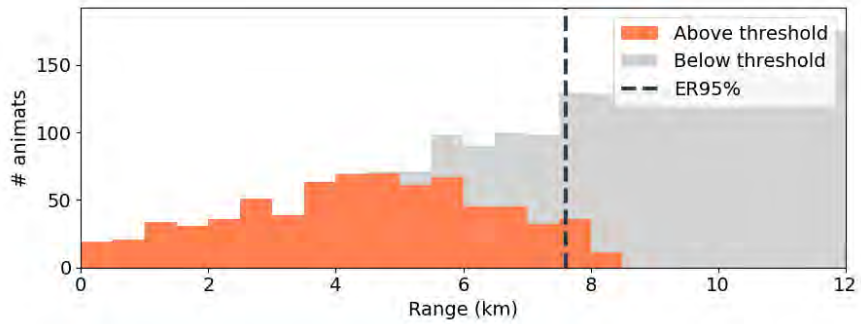


Figure E-16. *Monopile 1, southern right whale, mother & calf, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 1. Bar colours indicate whether the animats exceeded the threshold.

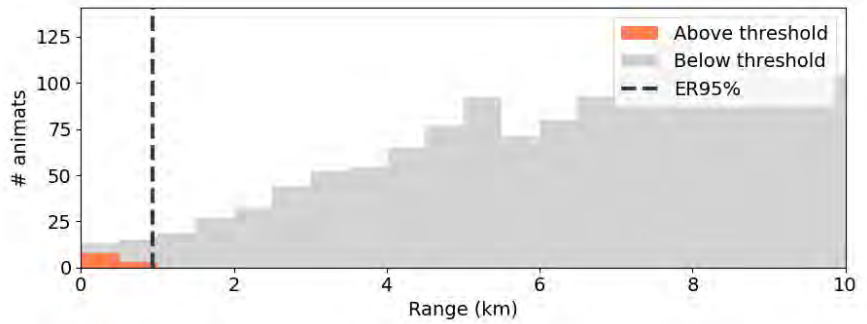


Figure E-17. *Monopile 3, humpback whale, mother & calf, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

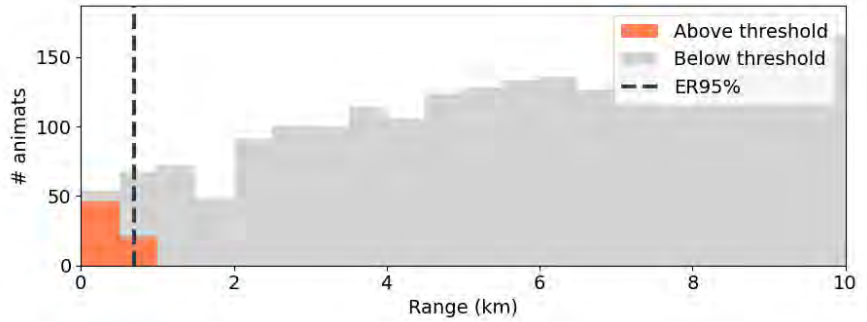


Figure E-18. *Monopile 3, minke whale, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

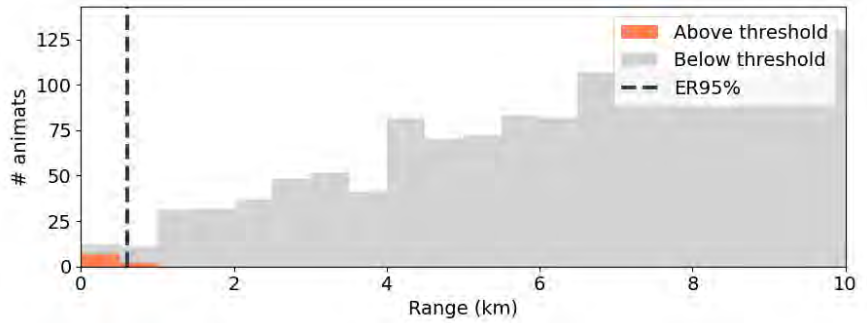


Figure E-19. *Monopile 3, southern right whale, mother & calf, SEL_{24h} PTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

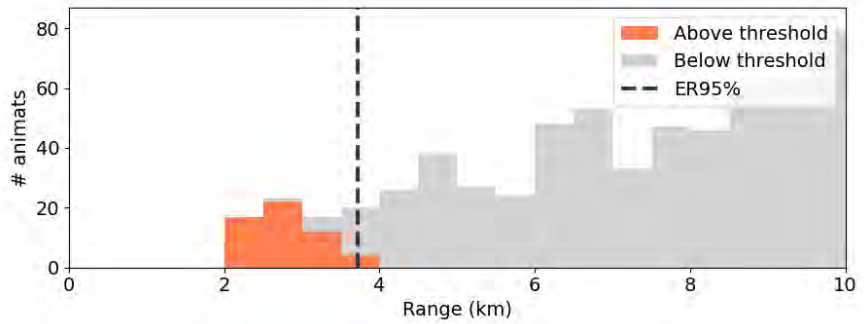


Figure E-20. *Monopile 3, pygmy blue whale, female, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

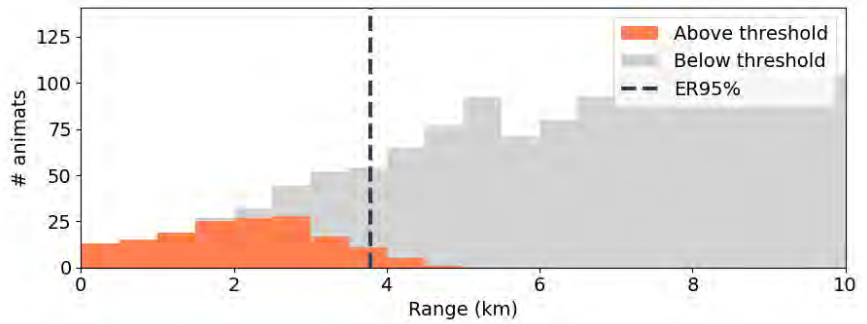


Figure E-21. *Monopile 3, humpback whale, mother & calf, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

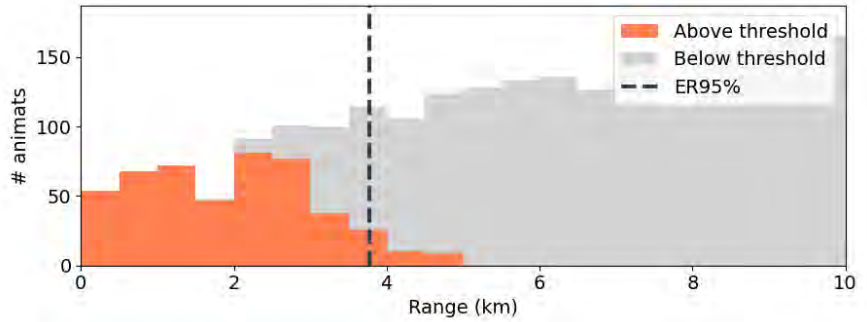


Figure E-22. *Monopile 3, minke whale, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

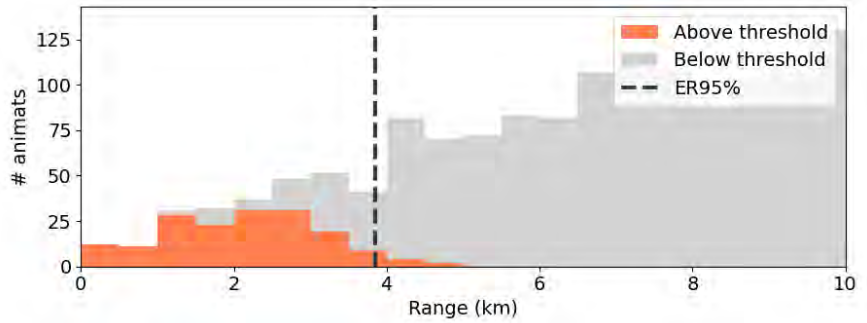


Figure E-23. *Monopile 3, southern right whale, mother & calf, SEL_{24h} TTS threshold, DBBC, winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

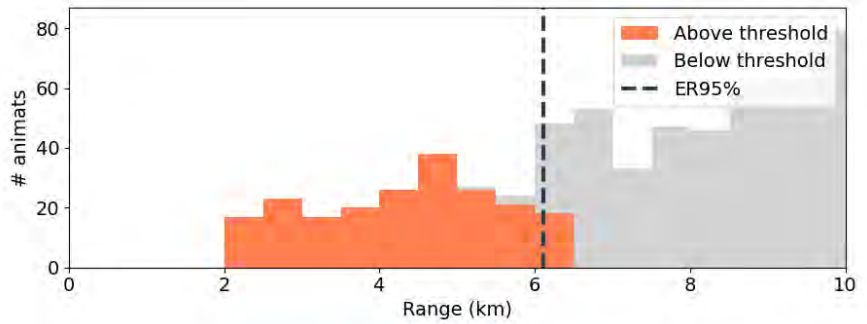


Figure E-24. *Monopile 3, pygmy blue whale, female,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

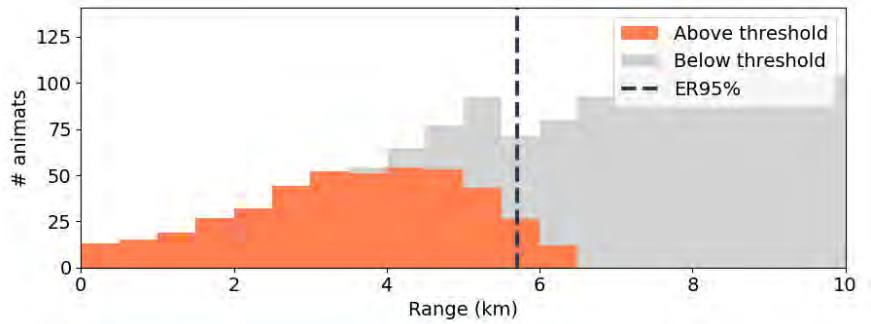


Figure E-25. *Monopile 3, humpback whale, mother & calf,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

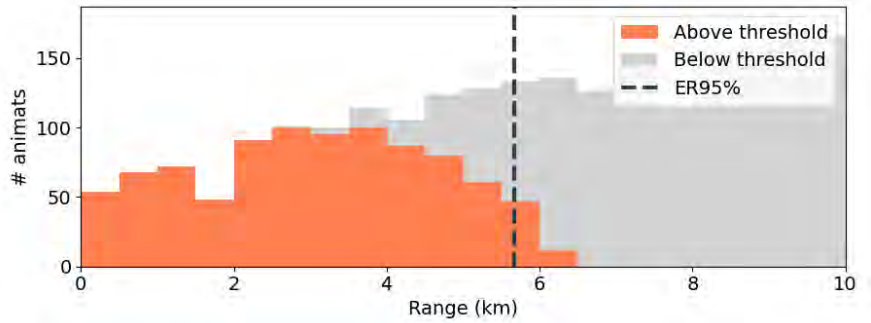


Figure E-26. *Monopile 3, minke whale,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

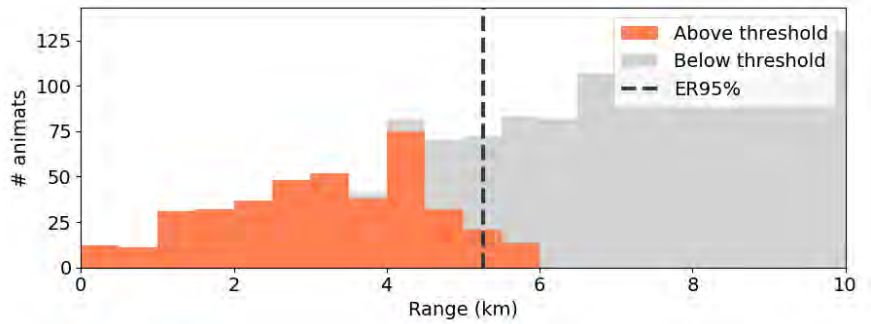


Figure E-27. *Monopile 3, southern right whale, mother & calf,* NOAA (2019) 160 dB re 1 µPa behavioural low-frequency marine mammal thresholds, winter: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

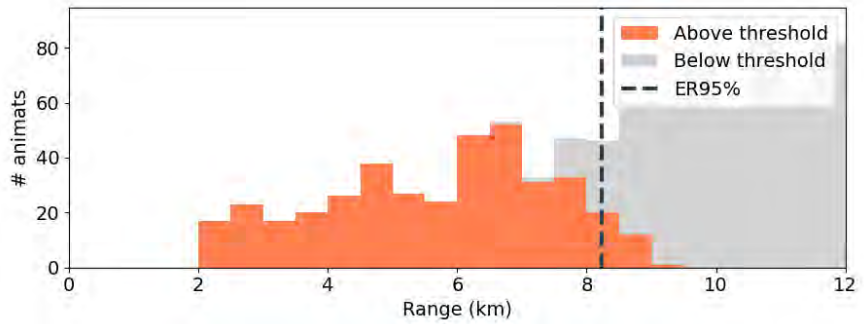


Figure E-28. *Monopile 3, pygmy blue whale, female, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

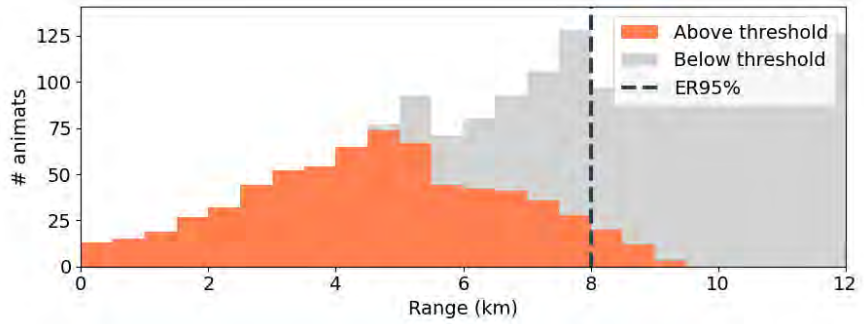


Figure E-29. *Monopile 3, humpback whale, mother & calf, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

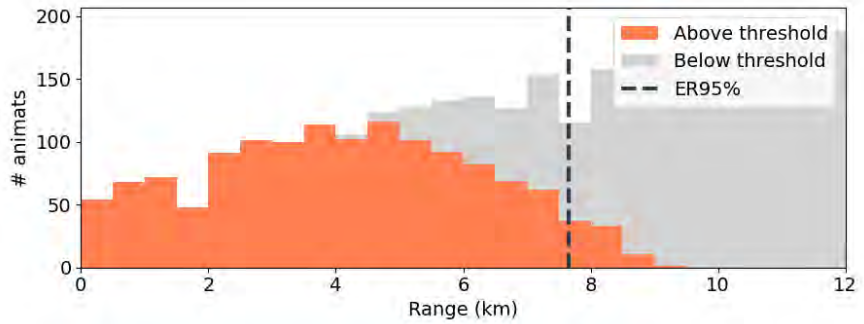


Figure E-30. *Monopile 3, minke whale, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

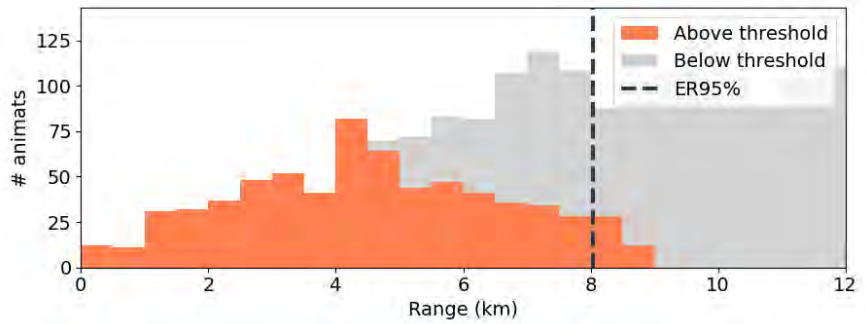


Figure E-31. *Monopile 3, southern right whale, mother & calf, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL), winter*: CPA range histogram for animats to Monopile 3. Bar colours indicate whether the animats exceeded the threshold.

E.1.1.2. Scenario 5 – DBBC (Second Modelling Round)

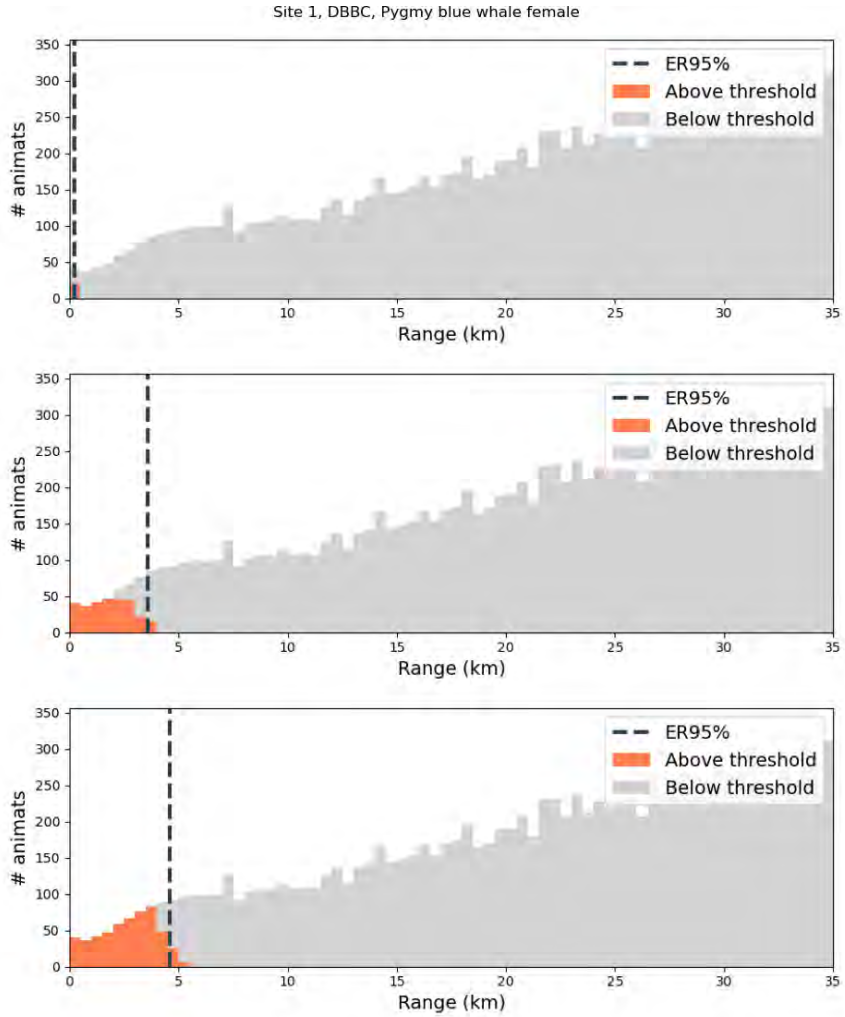


Figure E-32. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, female, SEL*$_{24h}$ *PTS (top), SEL*$_{24h}$ *TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

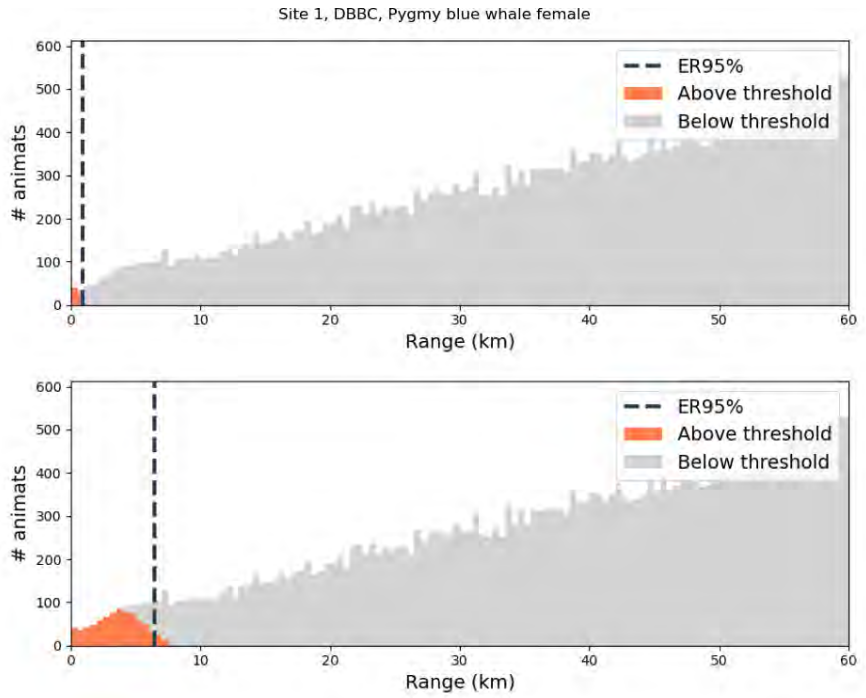


Figure E-33. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, female, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

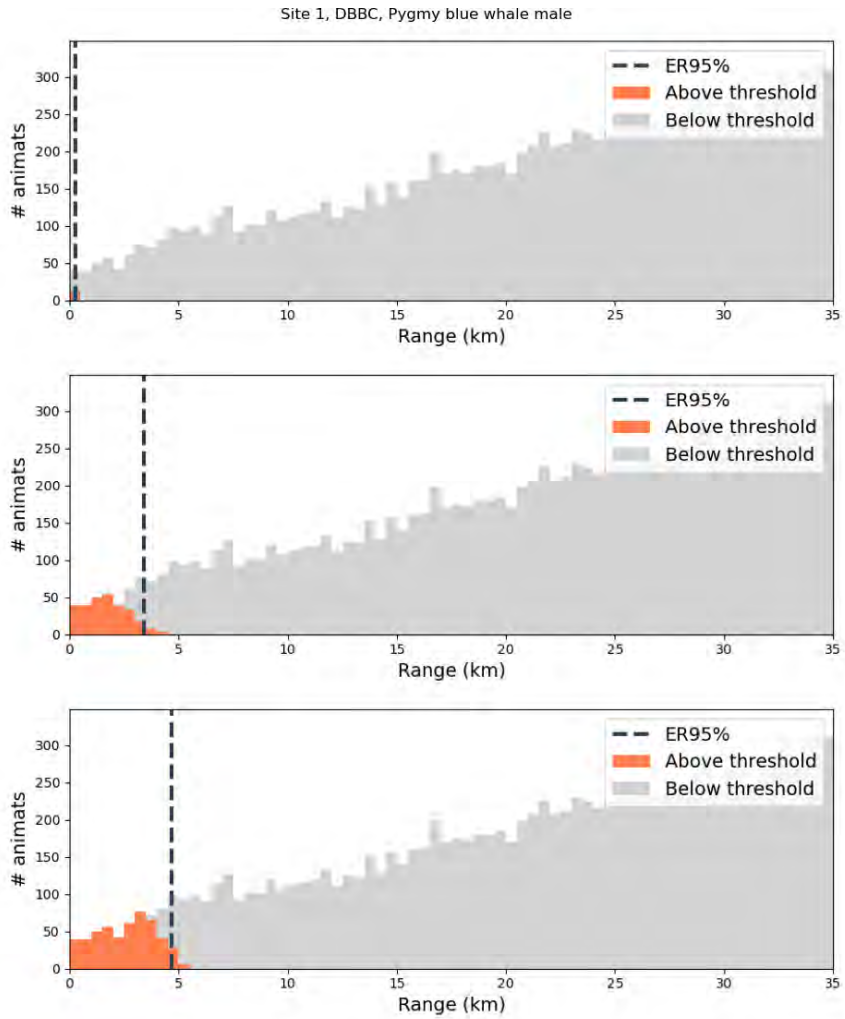


Figure E-34. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, male, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

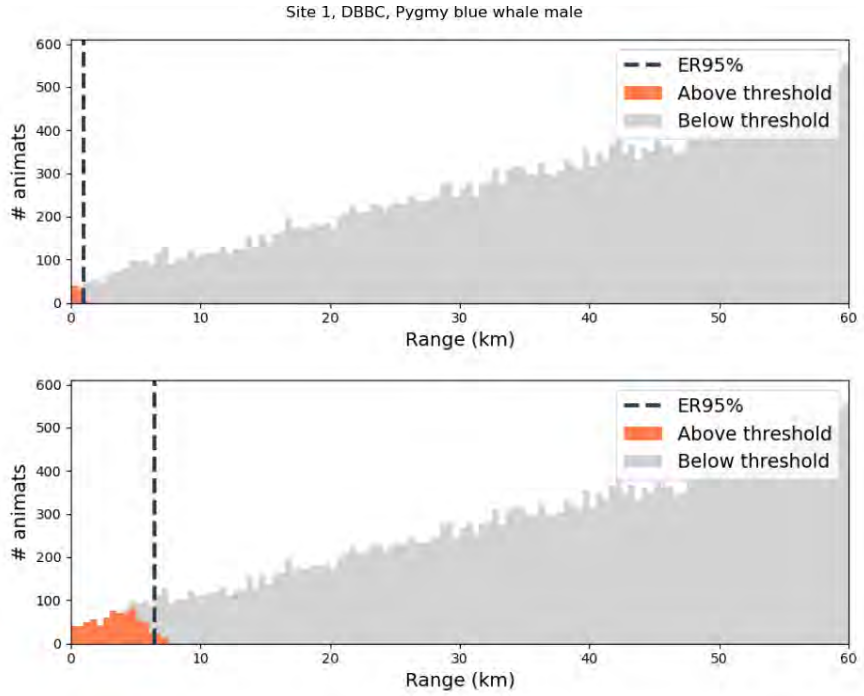


Figure E-35. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, male, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

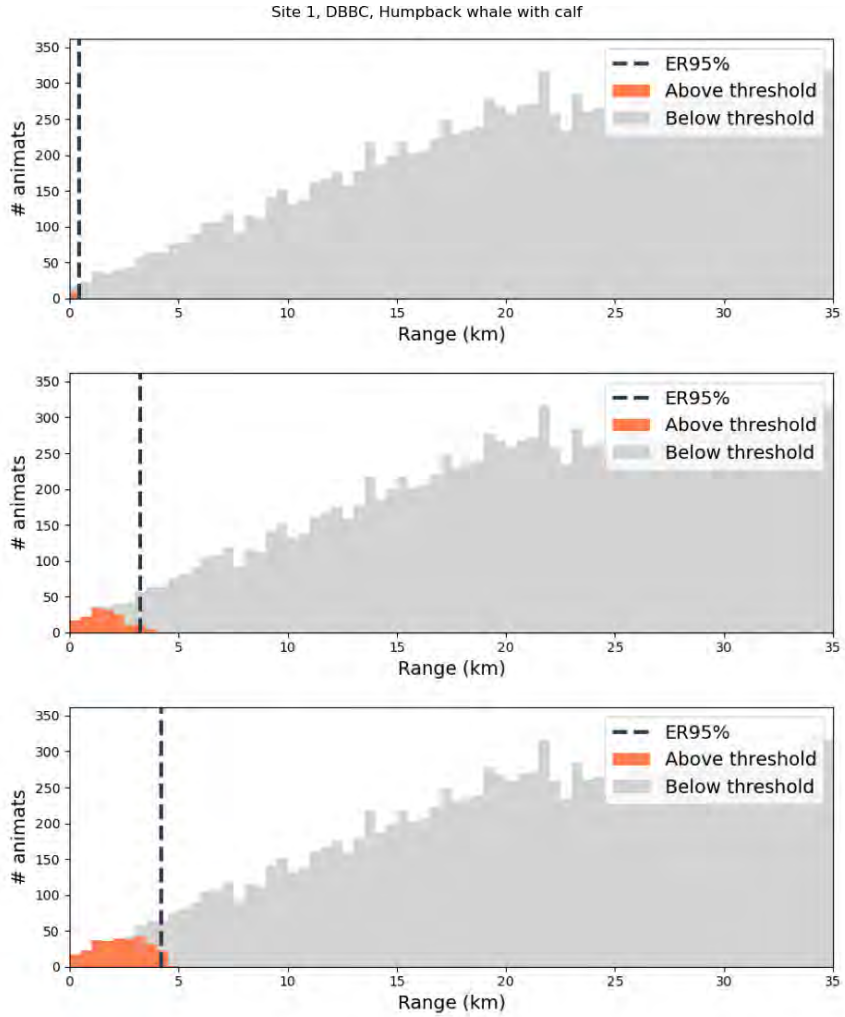


Figure E-36. *Site 1 - Monopile 1, DBBC attenuation, humpback whale with calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

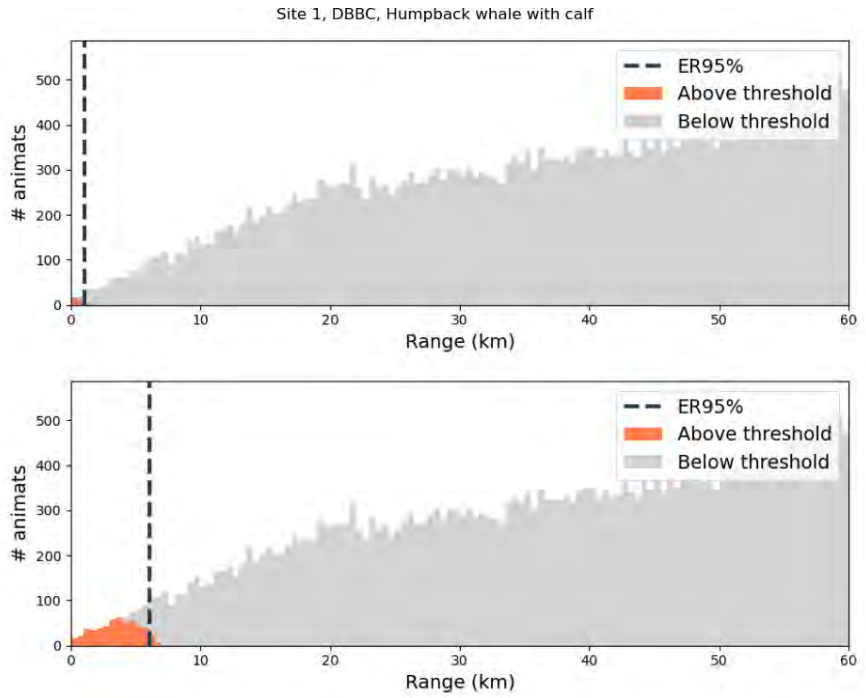


Figure E-37. *Site 1 - Monopile 1, DBBC attenuation, humpback whale with calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

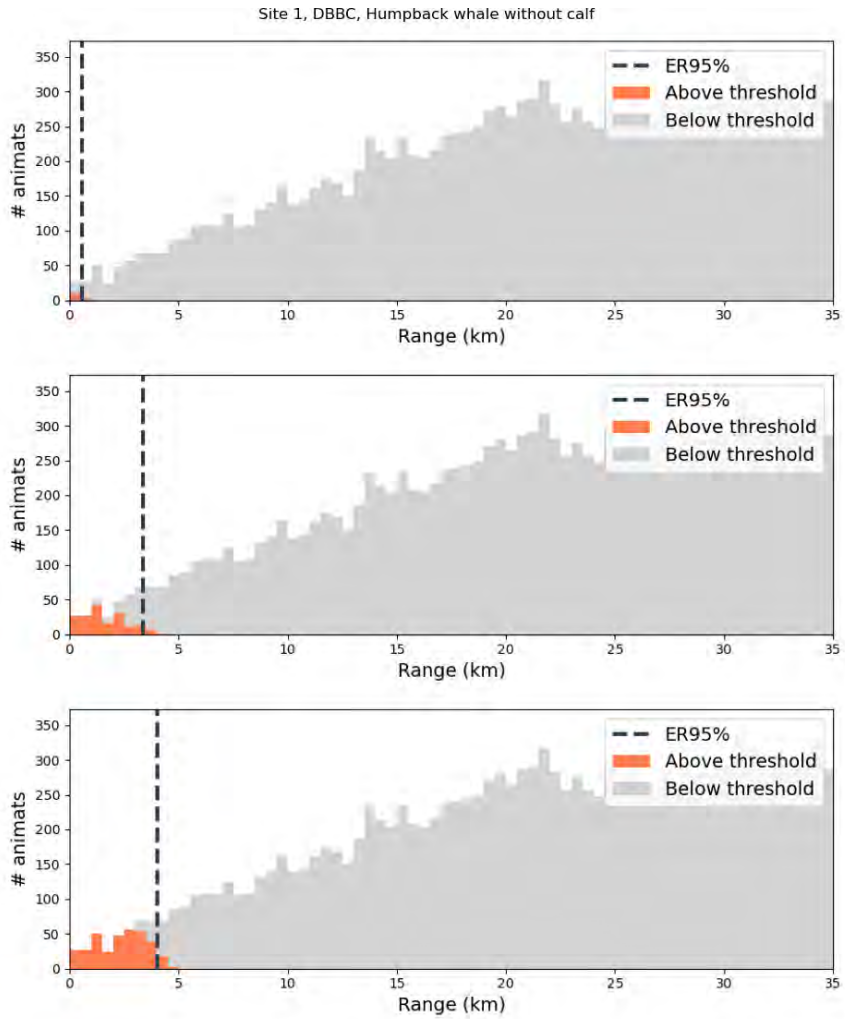


Figure E-38. *Site 1 - Monopile 1, DBBC attenuation, humpback whale without calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

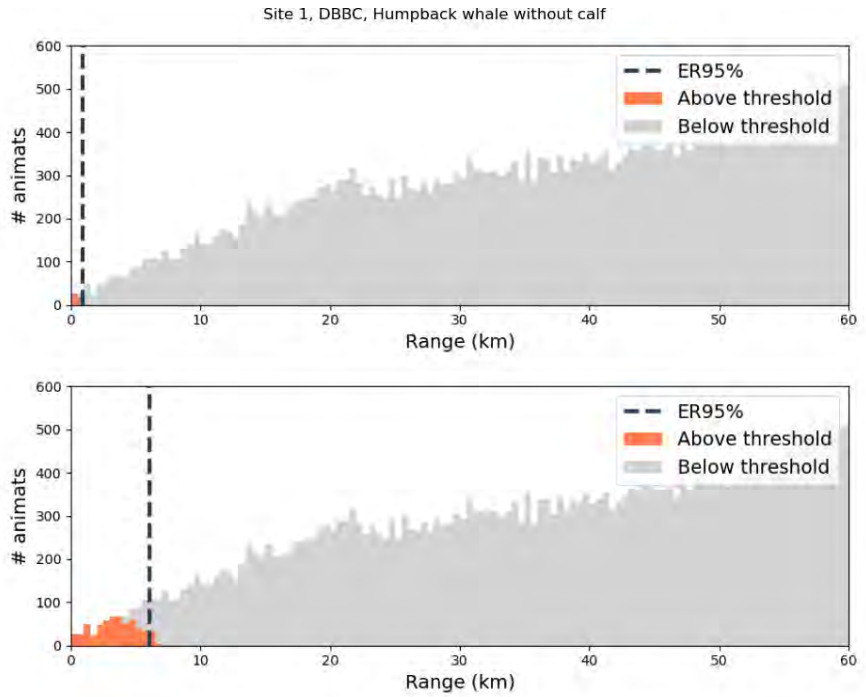


Figure E-39. *Site 1 - Monopile 1, DBBC attenuation, humpback whale without calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

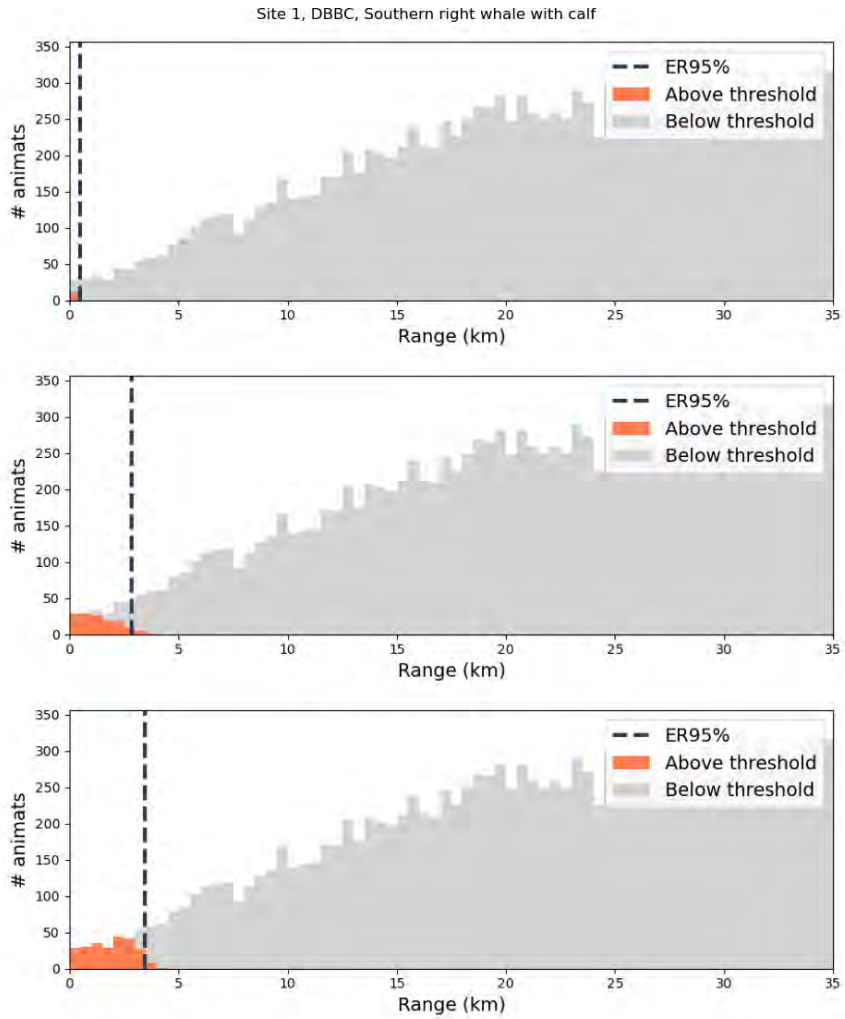


Figure E-40. *Site 1 - Monopile 1, DBBC attenuation, southern right whale with calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

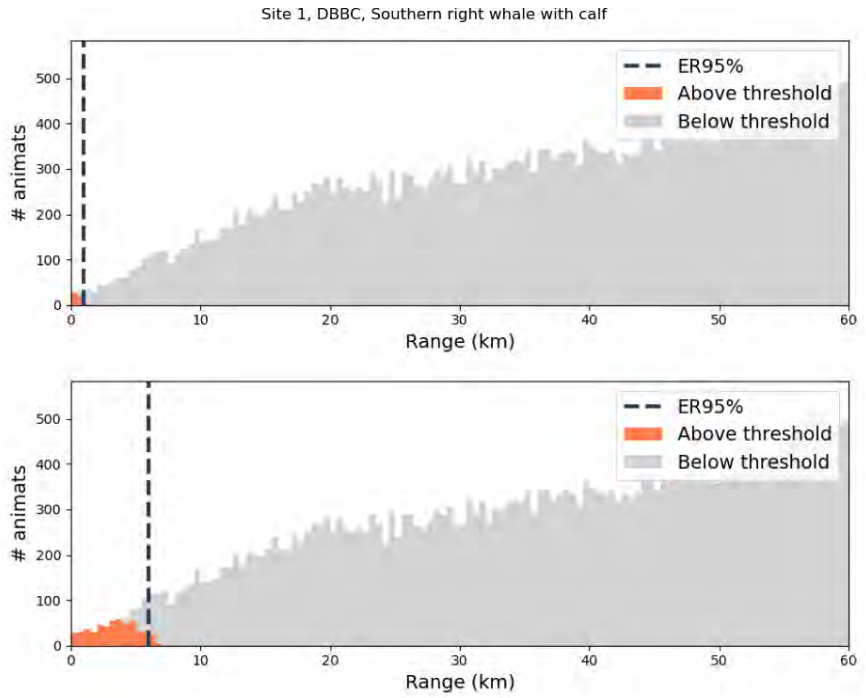


Figure E-41. *Site 1 - Monopile 1, DBBC attenuation, southern right whale with calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

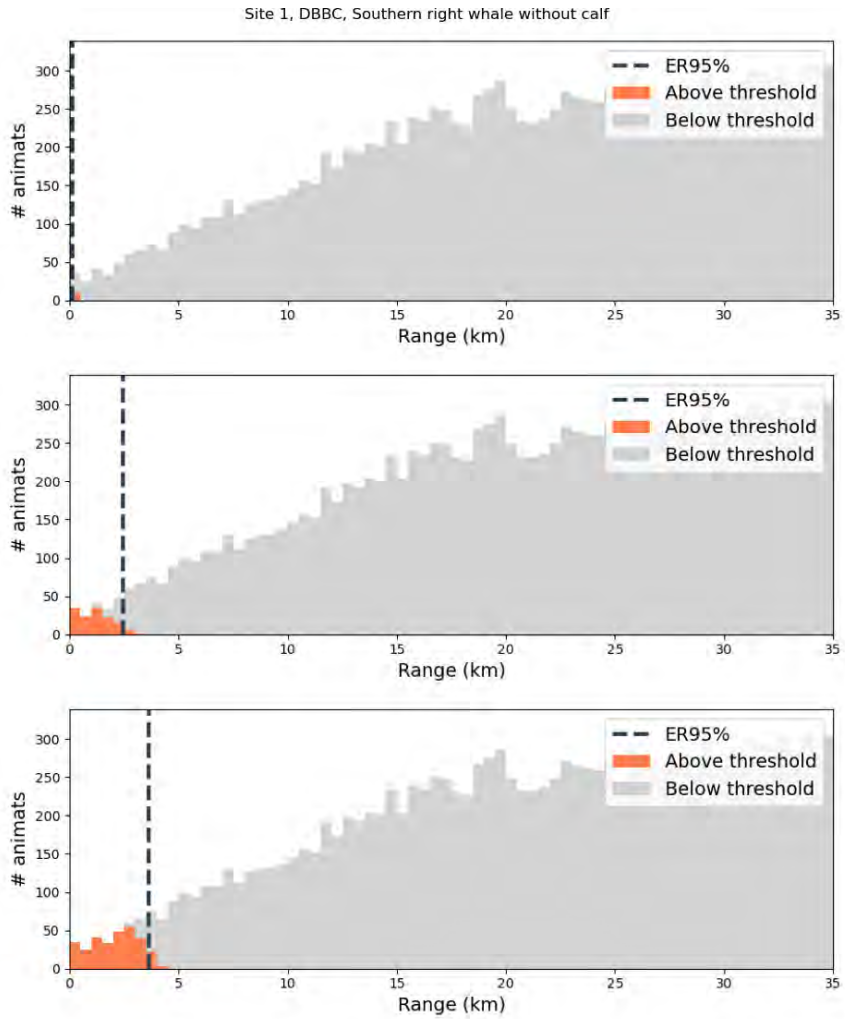


Figure E-42. *Site 1 - Monopile 1, DBBC attenuation, southern right whale without calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

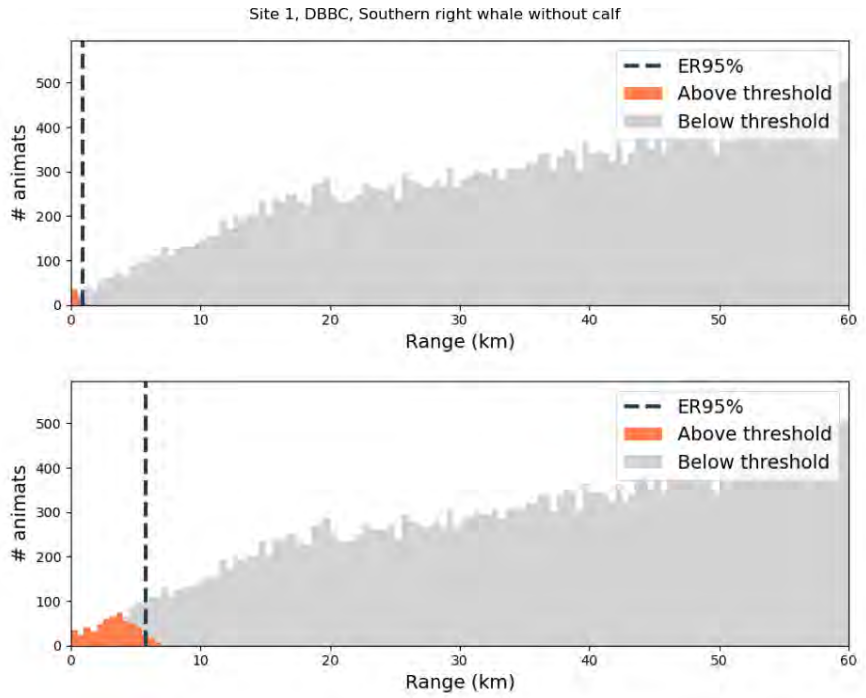


Figure E-43. *Site 1 - Monopile 1, DBBC attenuation, southern right whale without calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

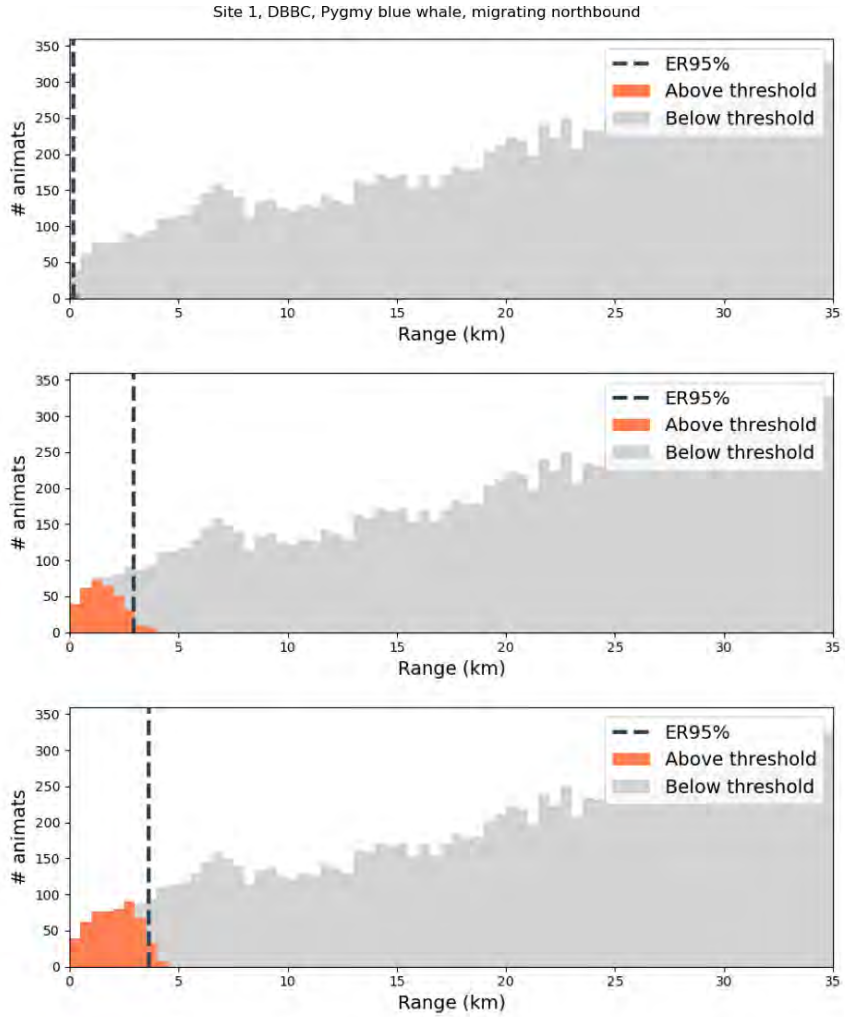


Figure E-44. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, migrating northbound, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

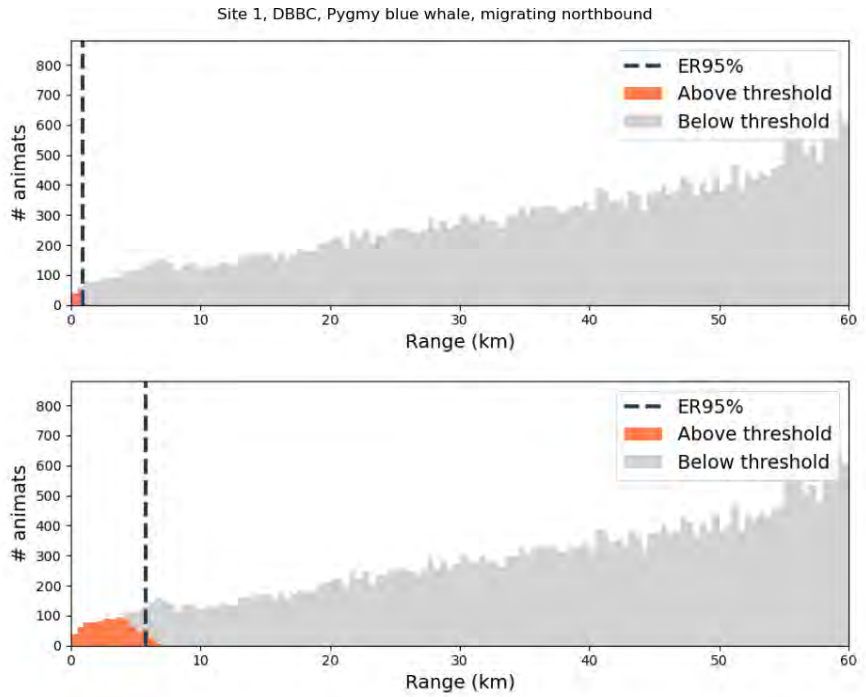


Figure E-45. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, migrating northbound, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

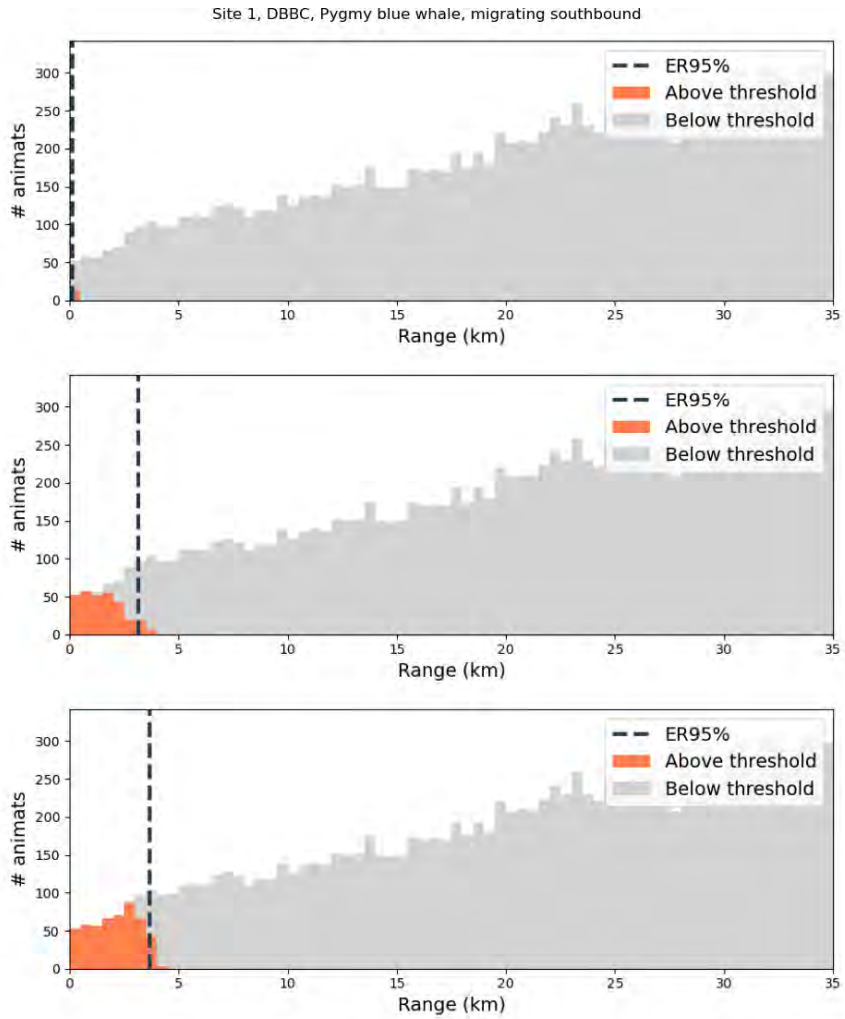


Figure E-46. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, migrating southbound, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

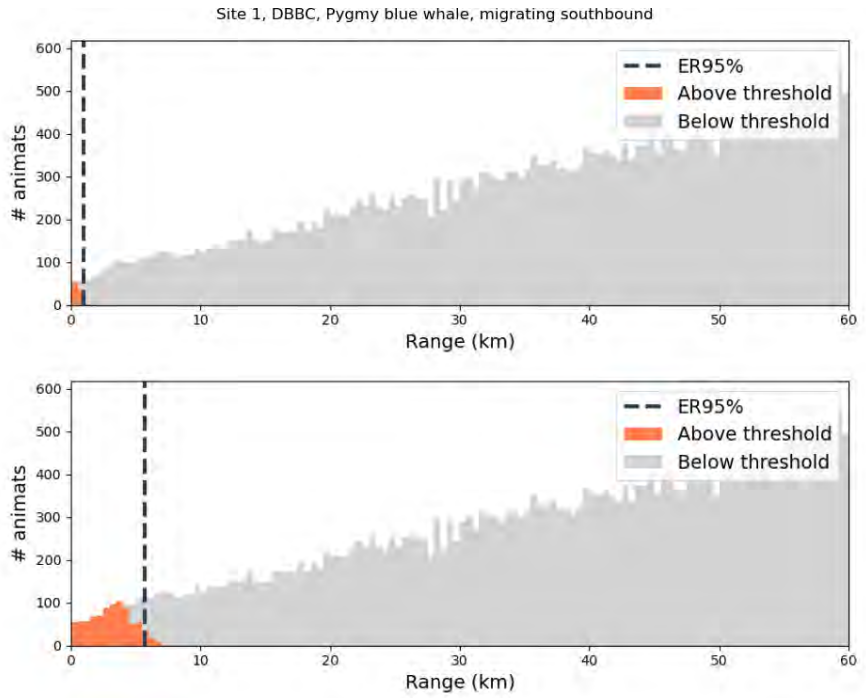


Figure E-47. *Site 1 - Monopile 1, DBBC attenuation, pygmy blue whale, migrating southbound, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

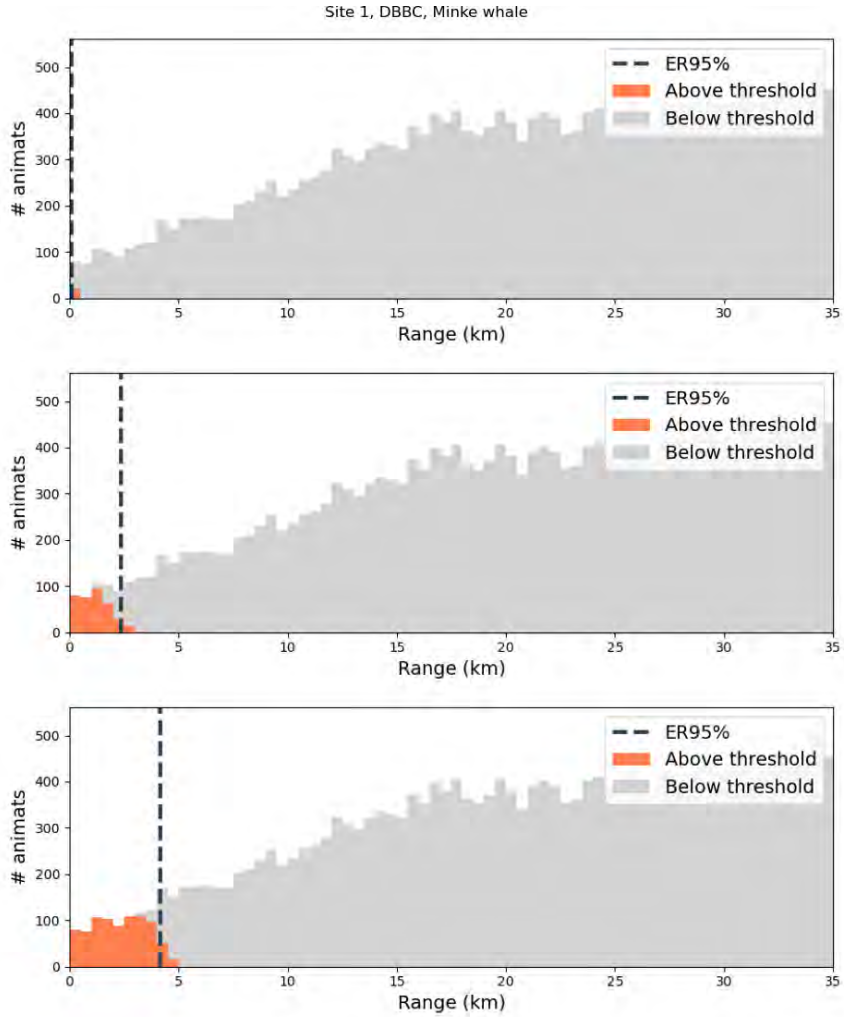


Figure E-48. *Site 1 - Monopile 1, DBBC attenuation, minke whale, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

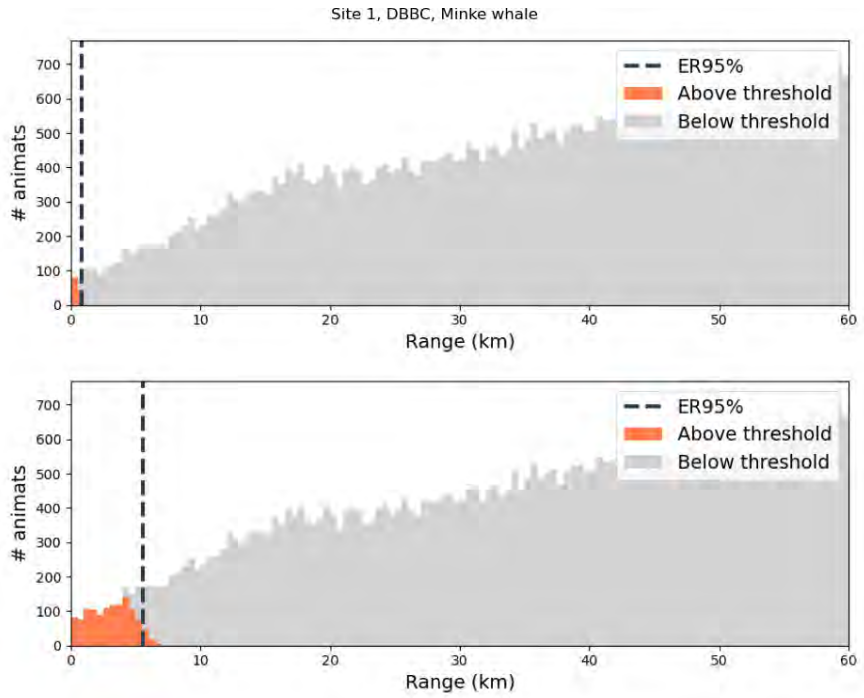


Figure E-49. *Site 1 - Monopile 1, DBBC attenuation, minke whale, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

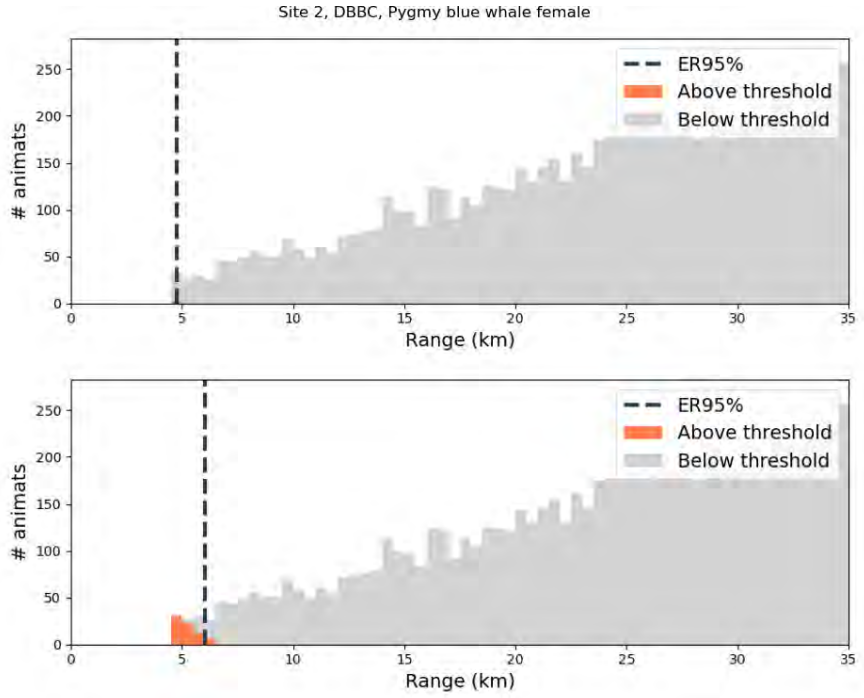


Figure E-50. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, female, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

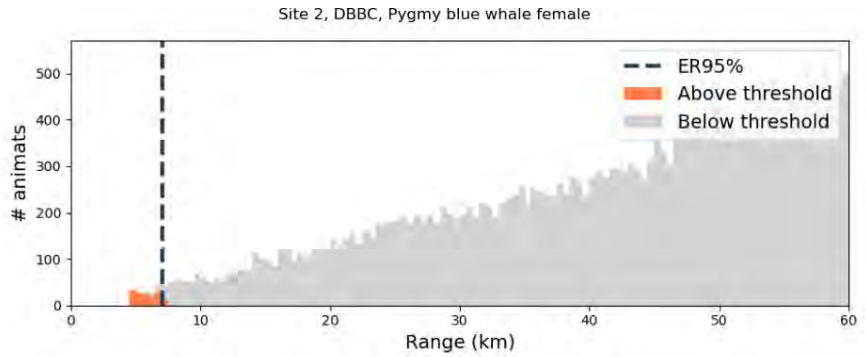


Figure E-51. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, female, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

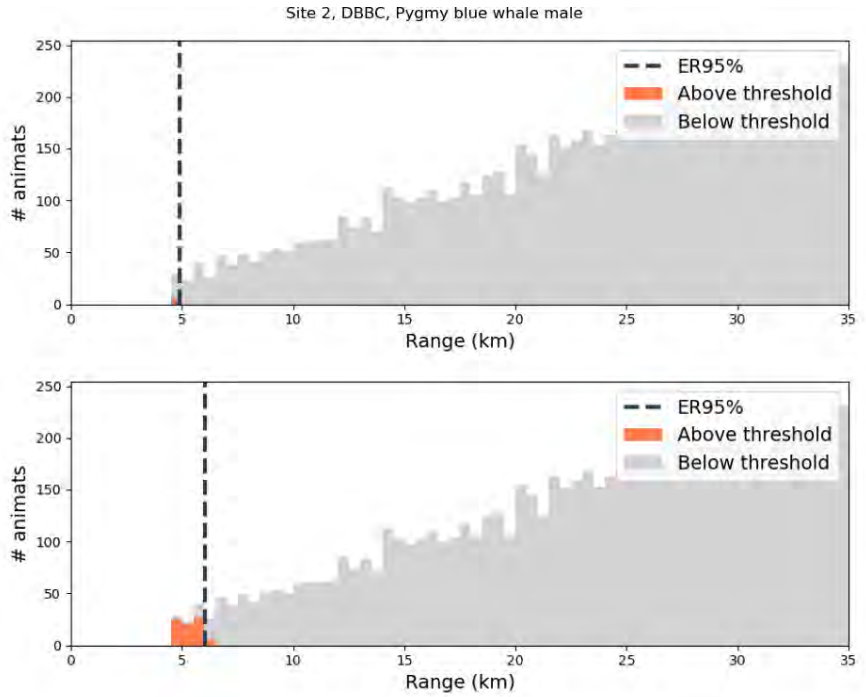


Figure E-52. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, male, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

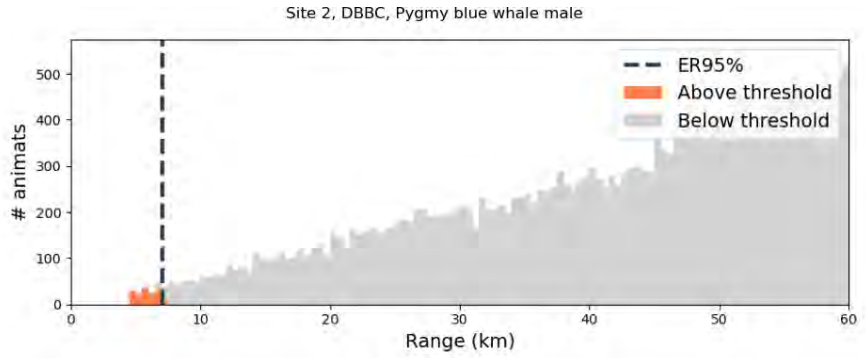


Figure E-53. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, male, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

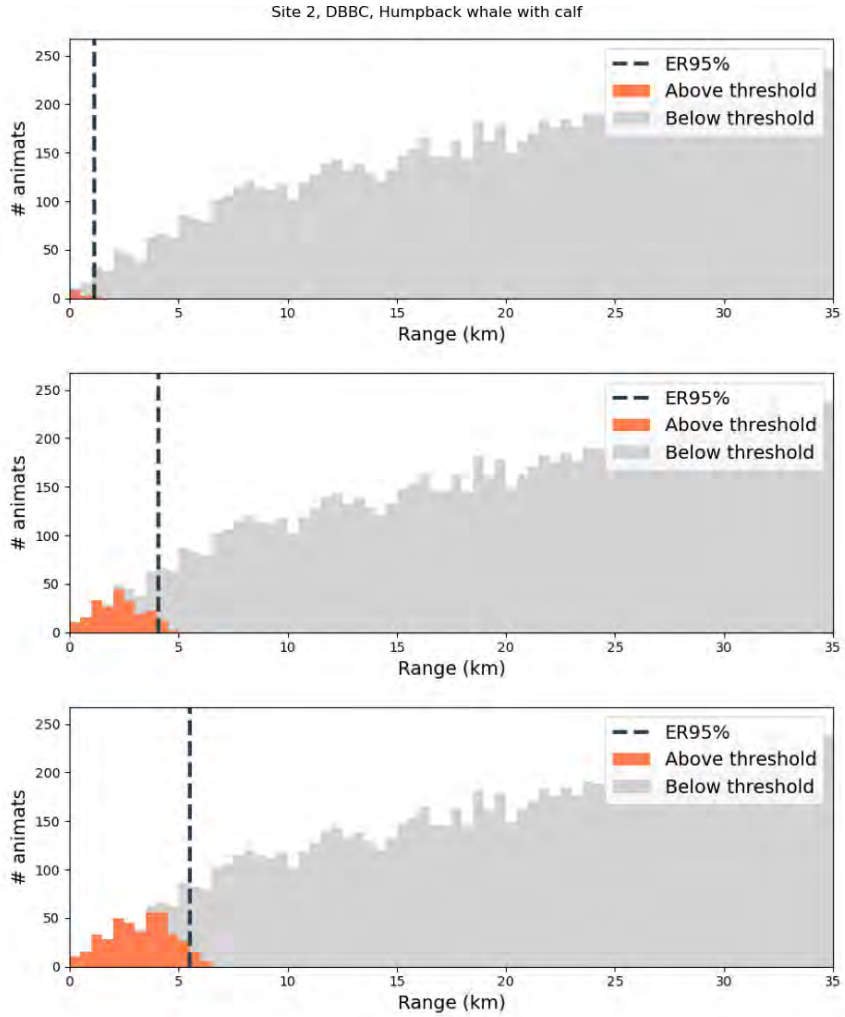


Figure E-54. *Site 2 - Monopile 2, DBBC attenuation, humpback whale with calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

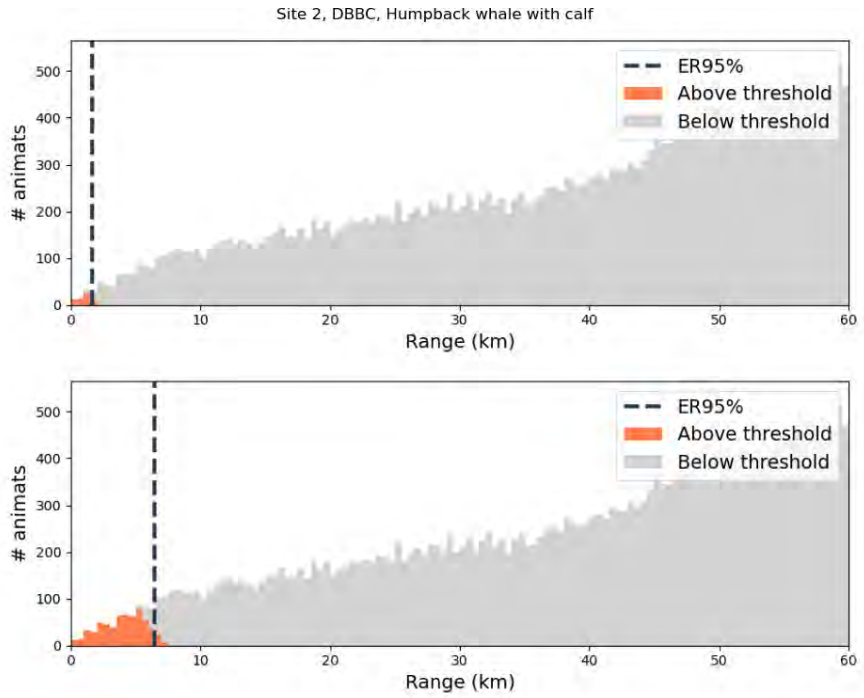


Figure E-55. *Site 2 - Monopile 2, DBBC attenuation, humpback whale with calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

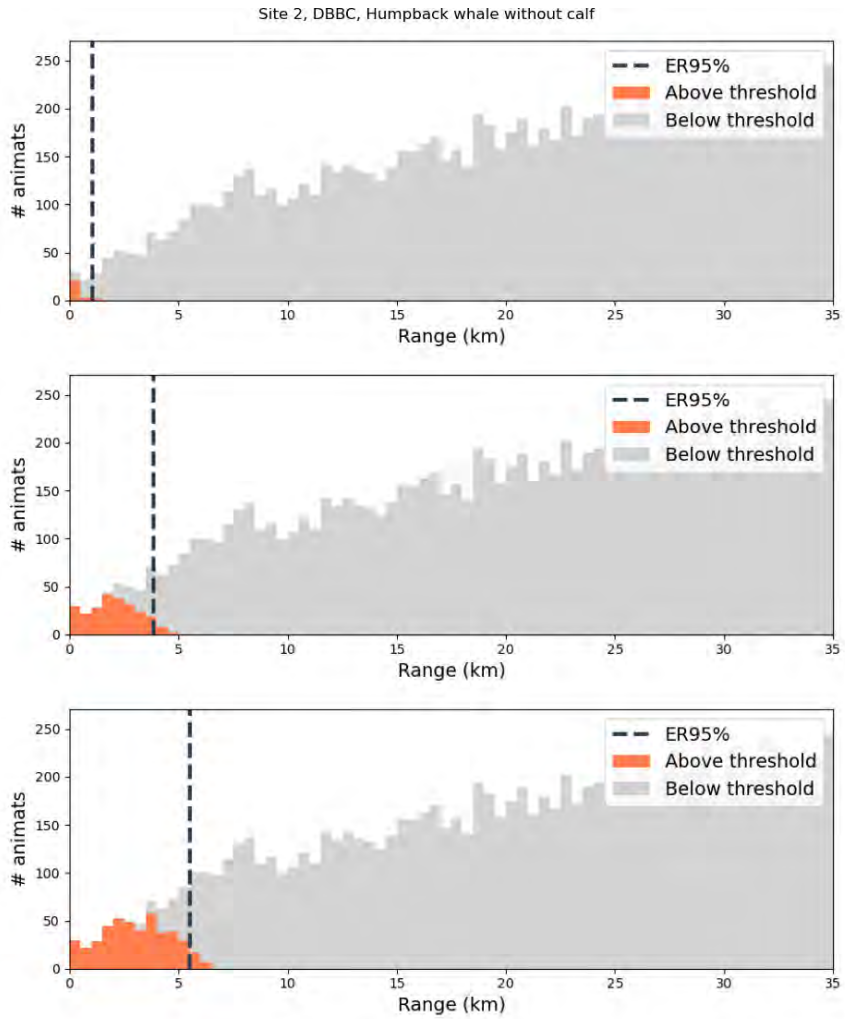


Figure E-56. *Site 2 - Monopile 2, DBBC attenuation, humpback whale without calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 1. Bar colours indicate whether the animats exceeded the threshold.

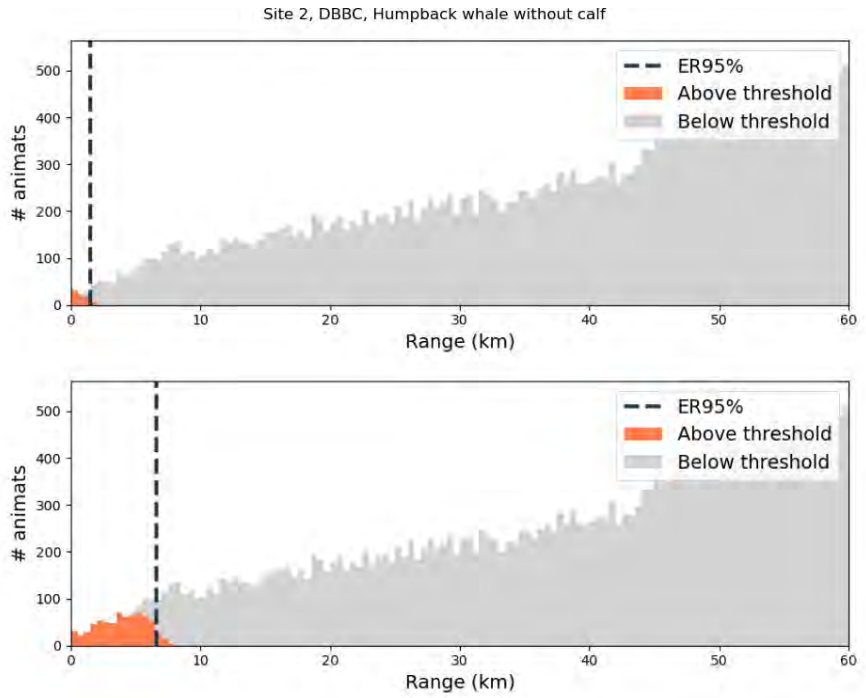


Figure E-57. *Site 2 - Monopile 2, DBBC attenuation, humpback whale without calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

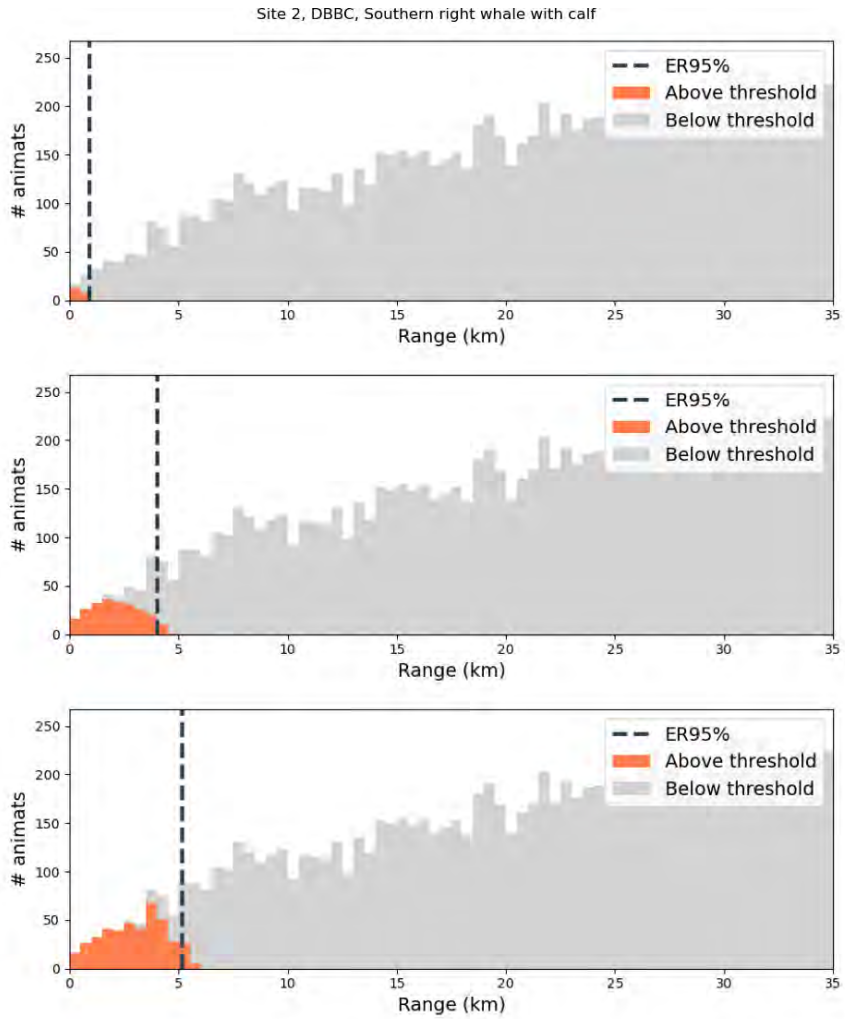


Figure E-58. *Site 2 - Monopile 2, DBBC attenuation, southern right whale with calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

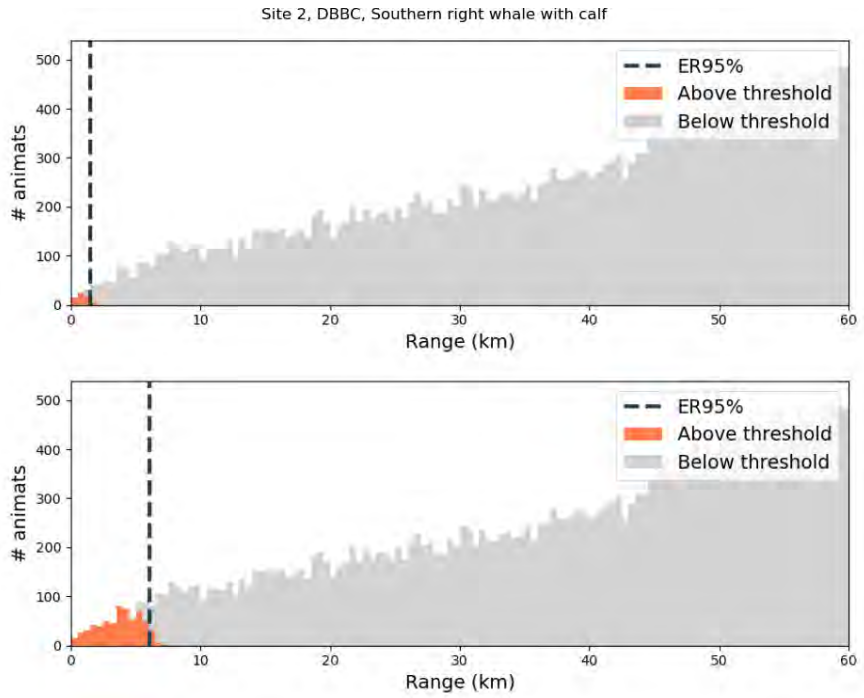


Figure E-59. *Site 2 - Monopile 2, DBBC attenuation, southern right whale with calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

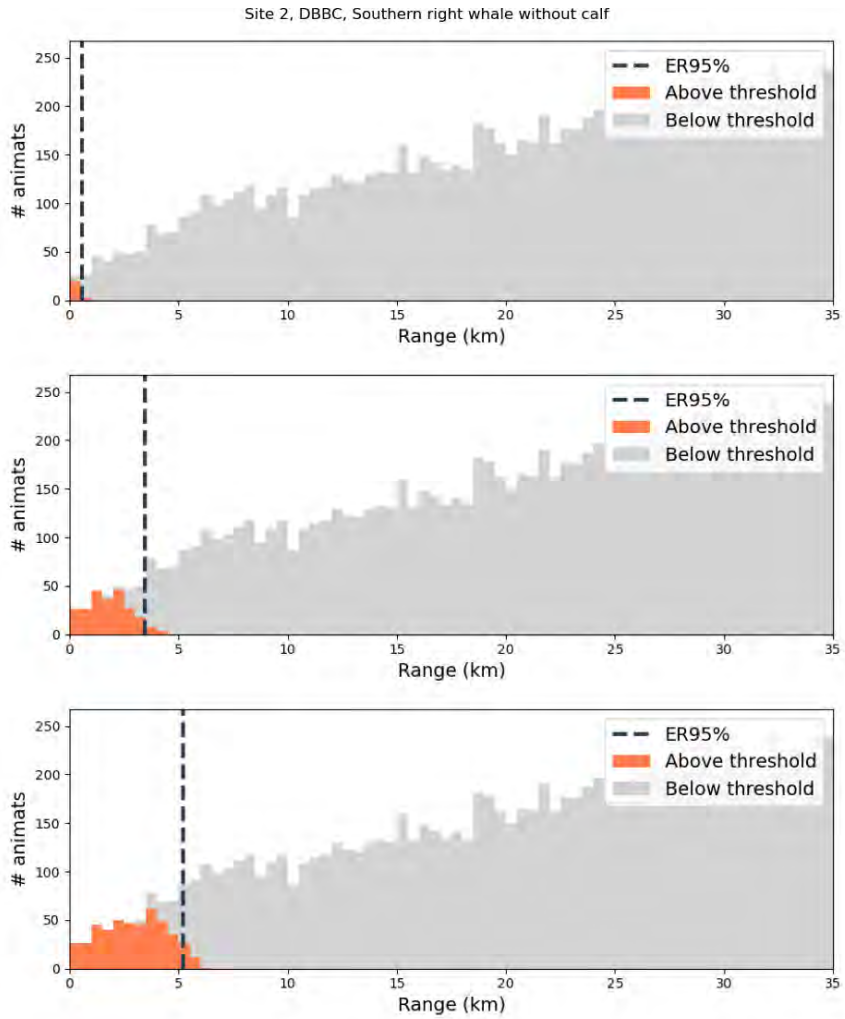


Figure E-60. *Site 2 - Monopile 2, DBBC attenuation, southern right whale without calf, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

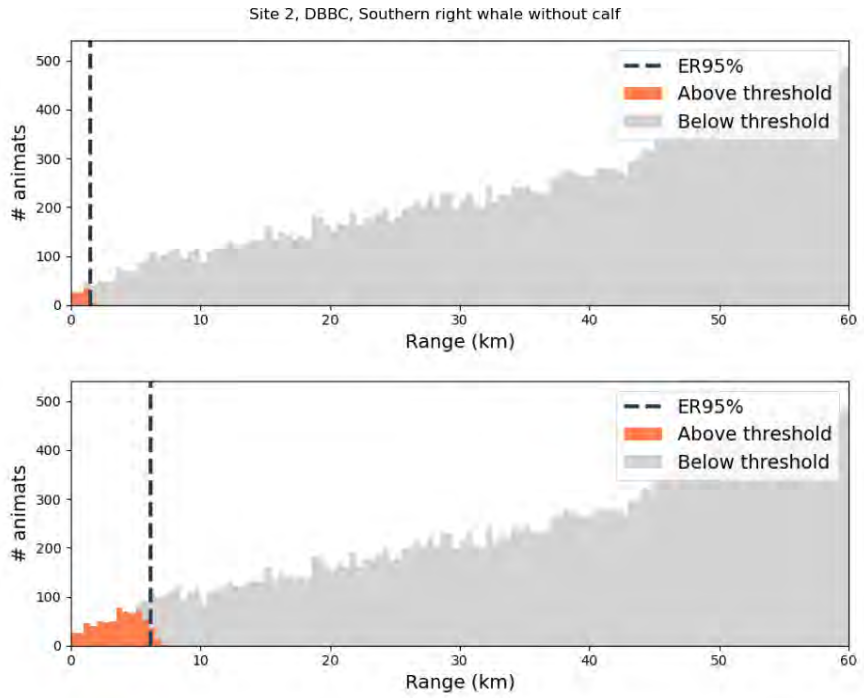


Figure E-61. *Site 2 - Monopile 2, DBBC attenuation, southern right whale without calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

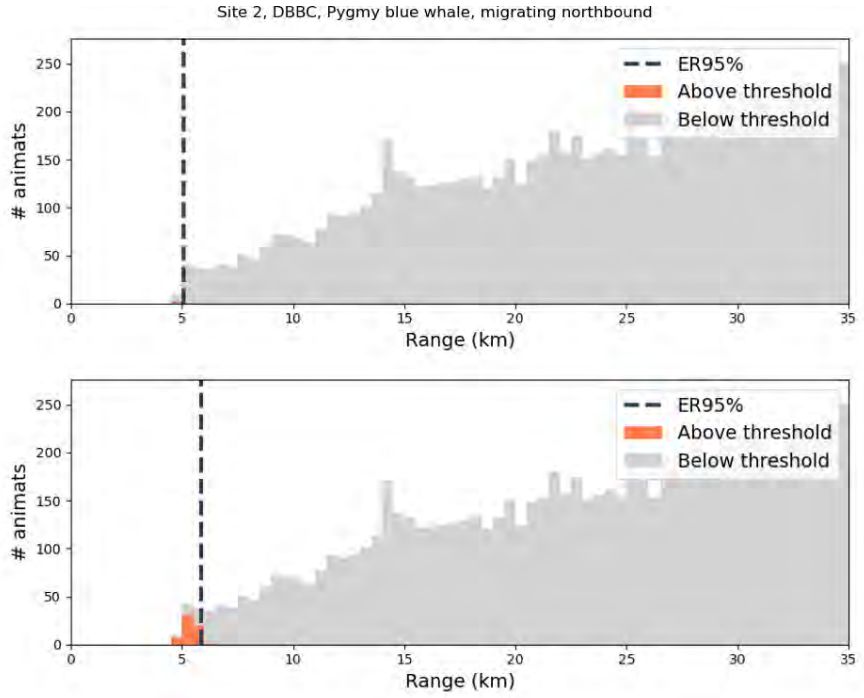


Figure E-62. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, migrating northbound, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

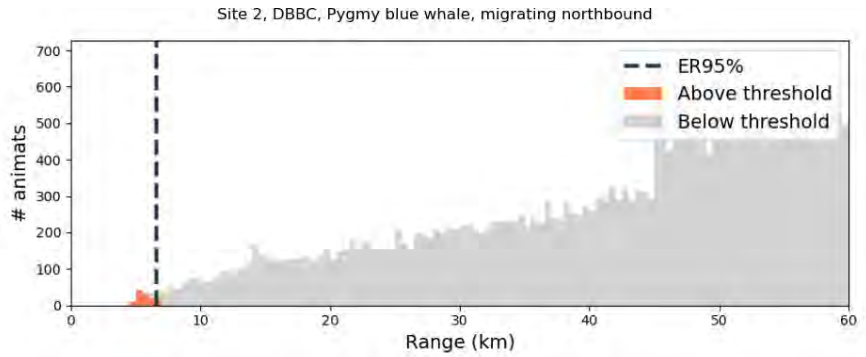


Figure E-63. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, migrating northbound, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

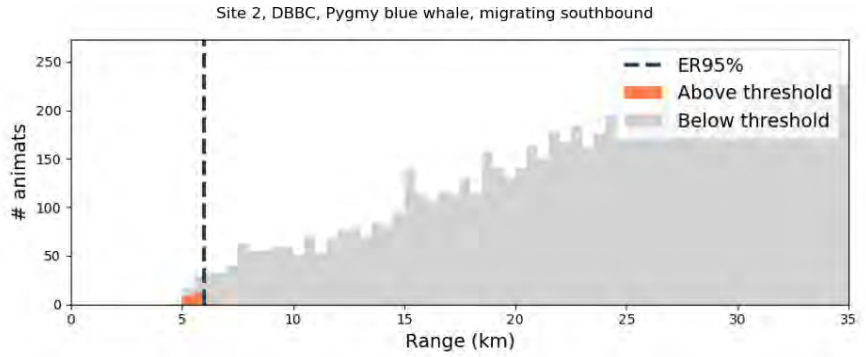


Figure E-64. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, migrating southbound, SPL behavioural response threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

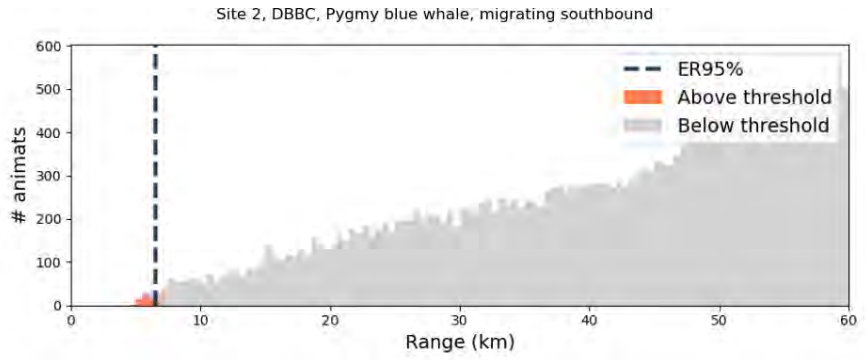


Figure E-65. *Site 2 - Monopile 2, DBBC attenuation, pygmy blue whale, migrating southbound, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

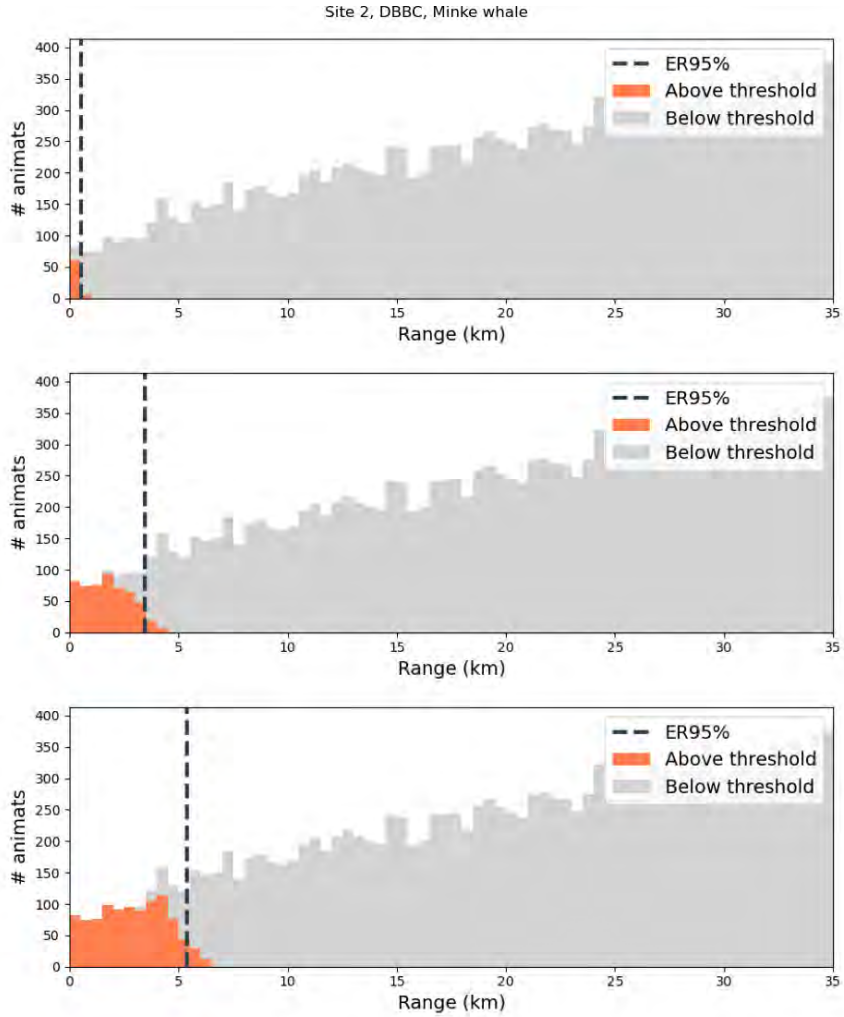


Figure E-66. *Site 2 - Monopile 2, DBBC attenuation, minke whale, SEL_{24h} PTS (top), SEL_{24h} TTS (middle) and SPL behavioural response (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

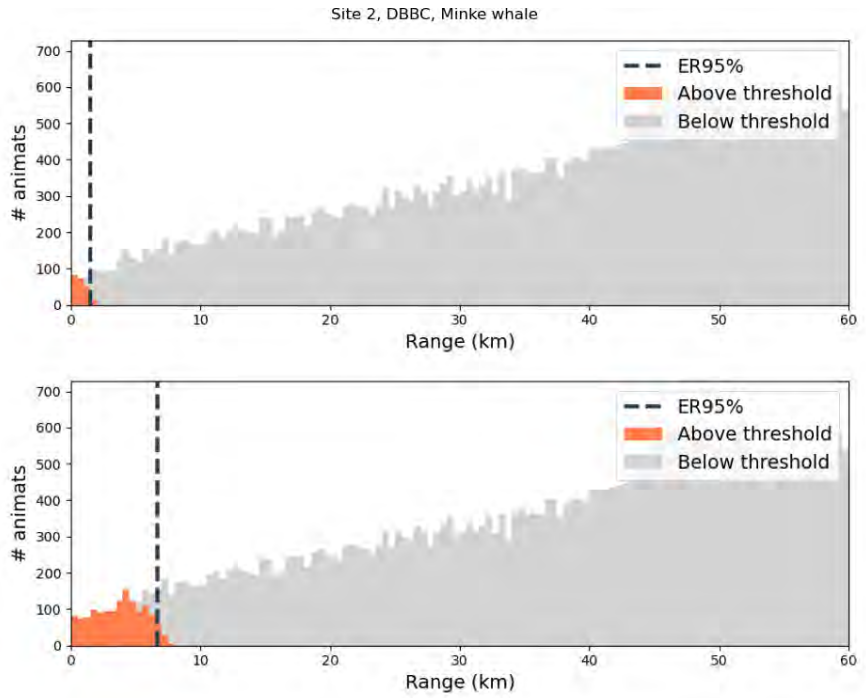


Figure E-67. *Site 2 - Monopile 2, DBBC attenuation, minke whale, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160* dB re 1 µPa *weighted SPL) (top), and Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140* dB re 1 µPa *weighted SPL) (bottom) threshold*: CPA range histogram for animats to Site 2. Bar colours indicate whether the animats exceeded the threshold.

E.1.1.3. Scenario 9 – PULSE + DBBC + HSD (Fourth Modelling Round)

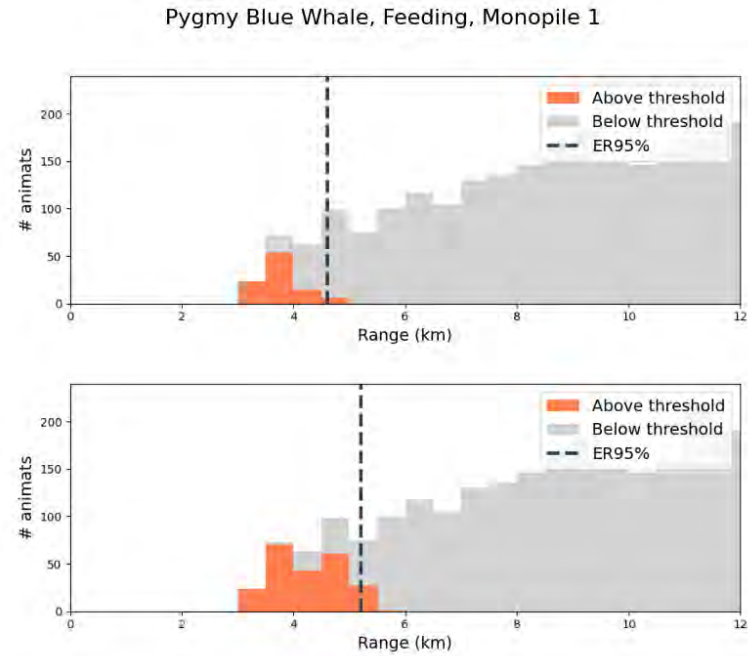


Figure E-68. Monopile 1, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

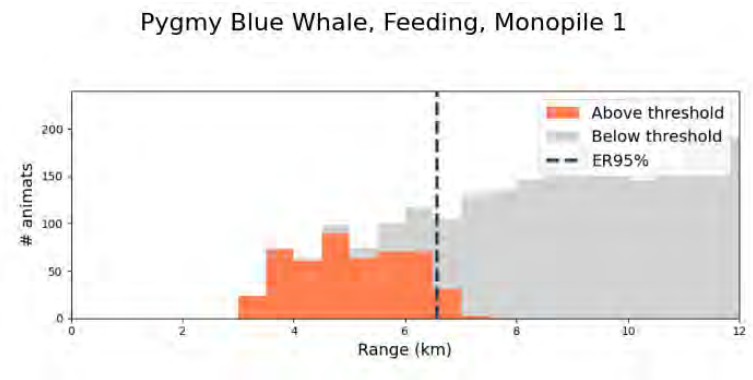


Figure E-69. Monopile 1, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, Wood et al. (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

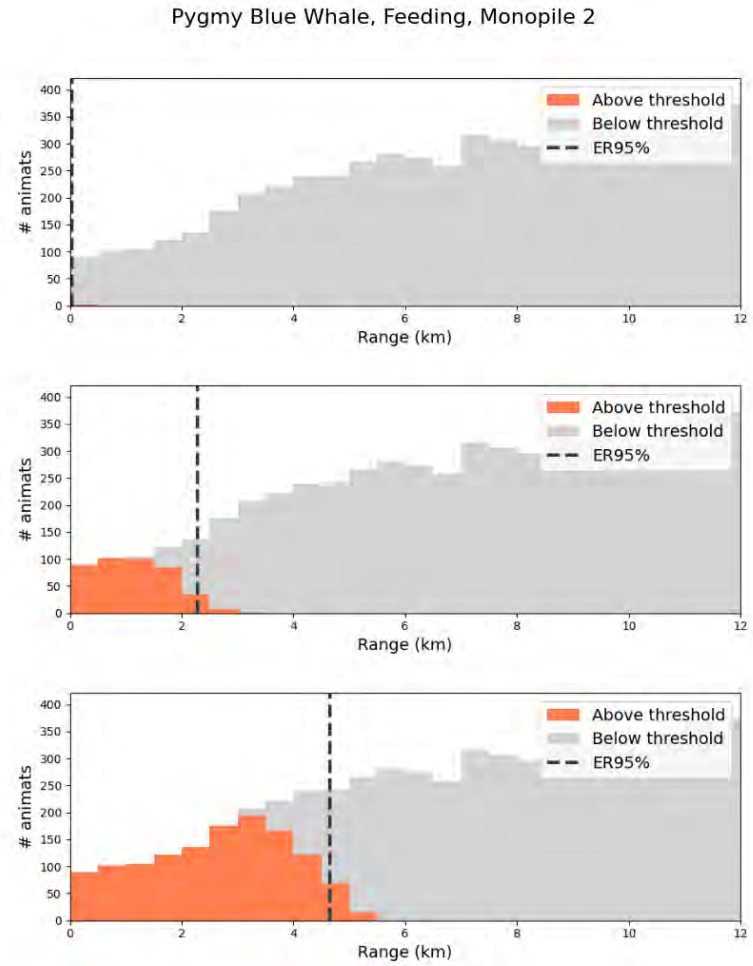


Figure E-70. Monopile 2, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

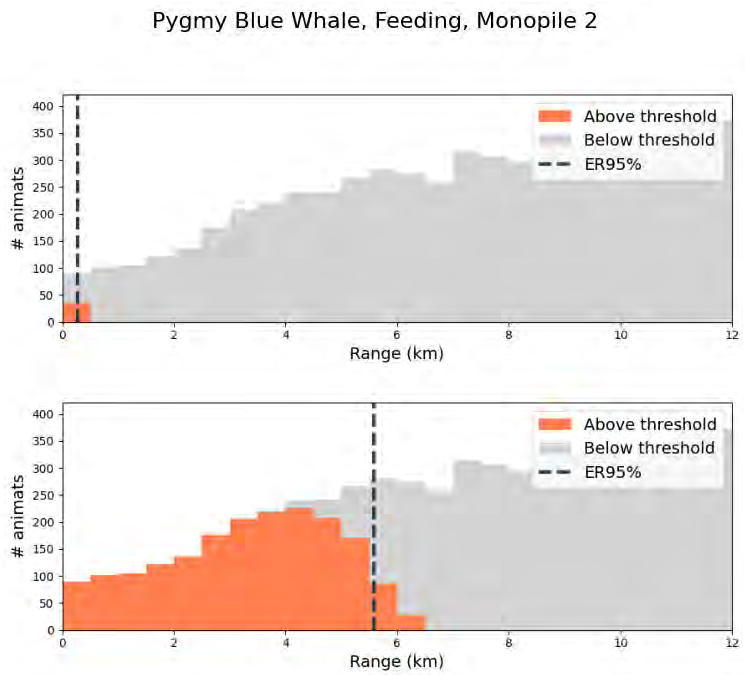


Figure E-71. Monopile 2, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

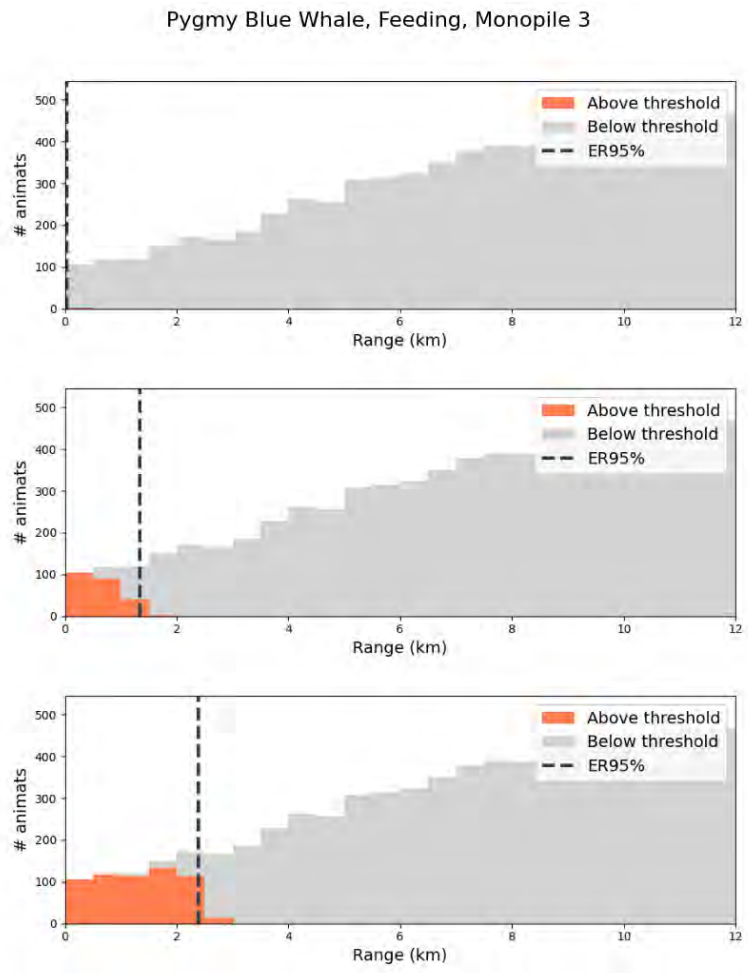


Figure E-72. Monopile 3, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

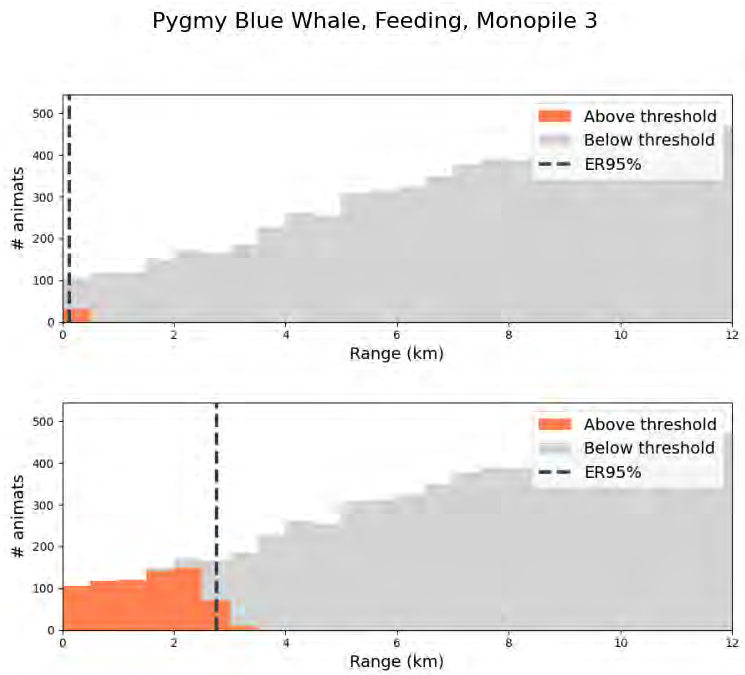


Figure E-73. Monopile 3, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

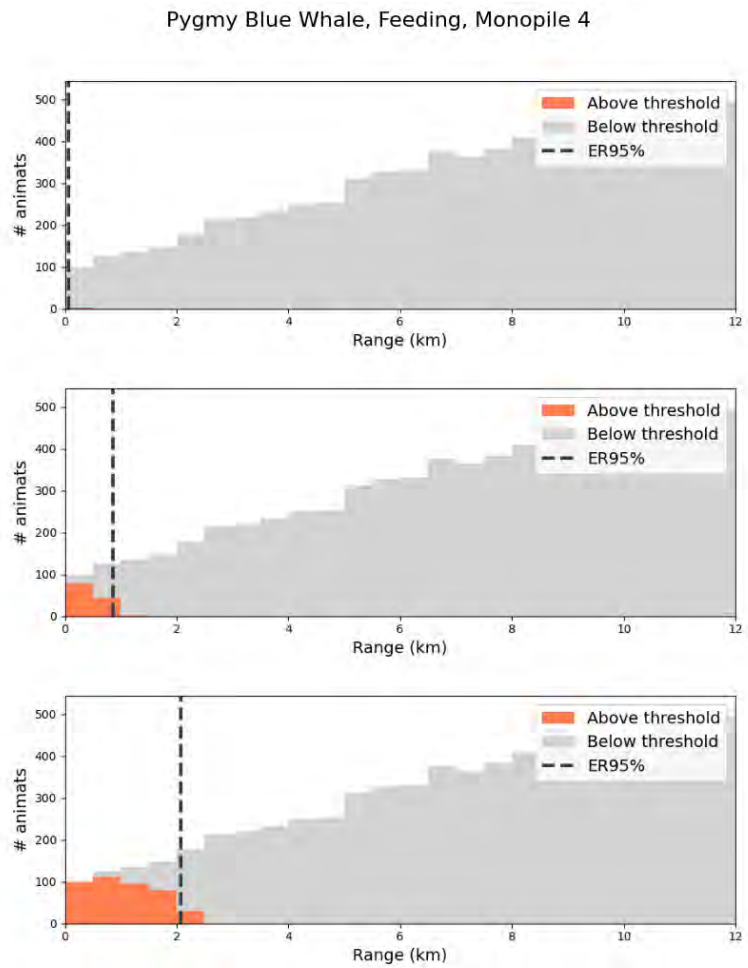


Figure E-74. Monopile 4, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

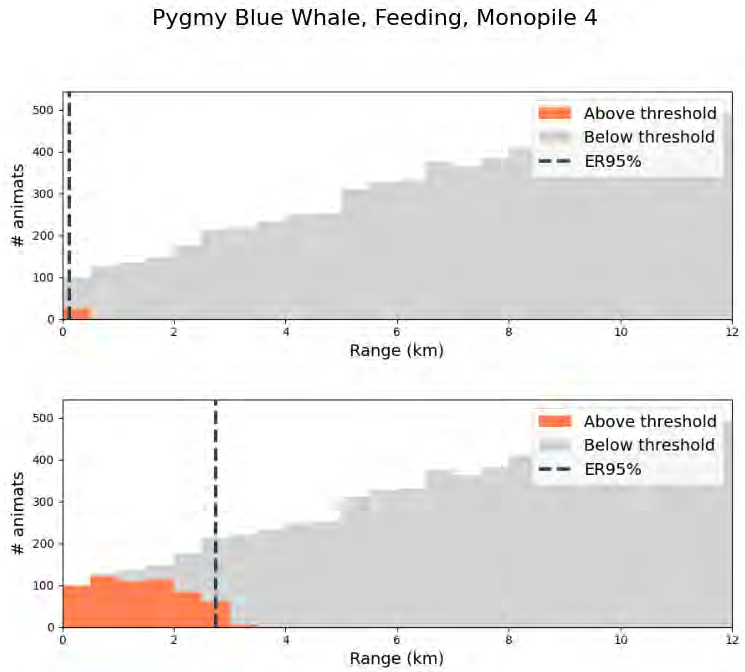


Figure E-75. Monopile 4, PULSE+HSD+DBBC, Pygmy Blue Whale, Feeding, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

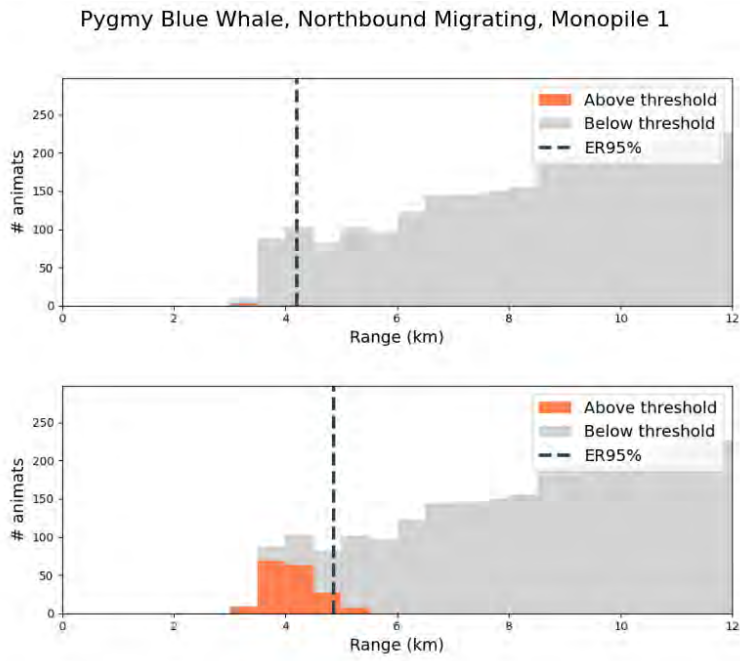


Figure E-76. Monopile 1, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

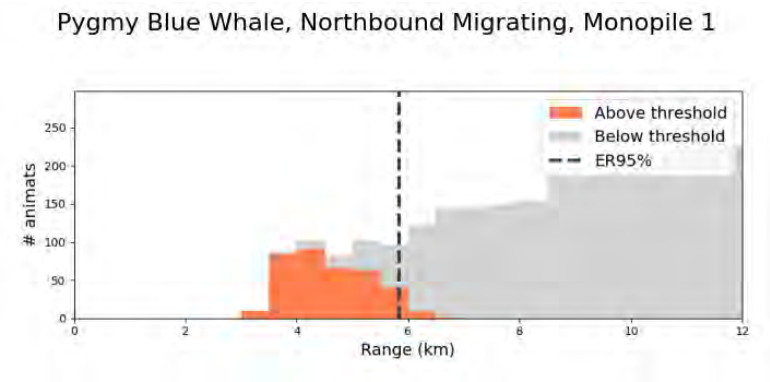


Figure E-77. Monopile 1, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

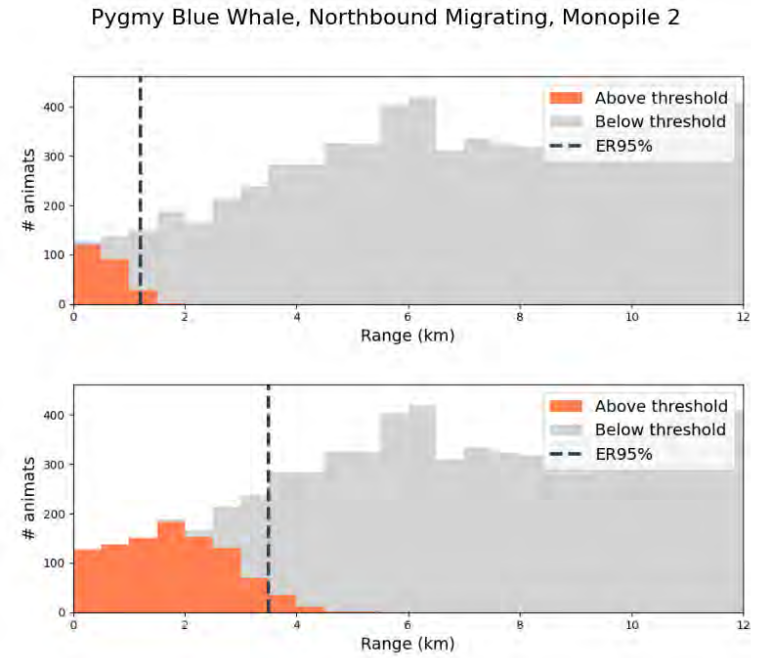


Figure E-78. Monopile 2, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

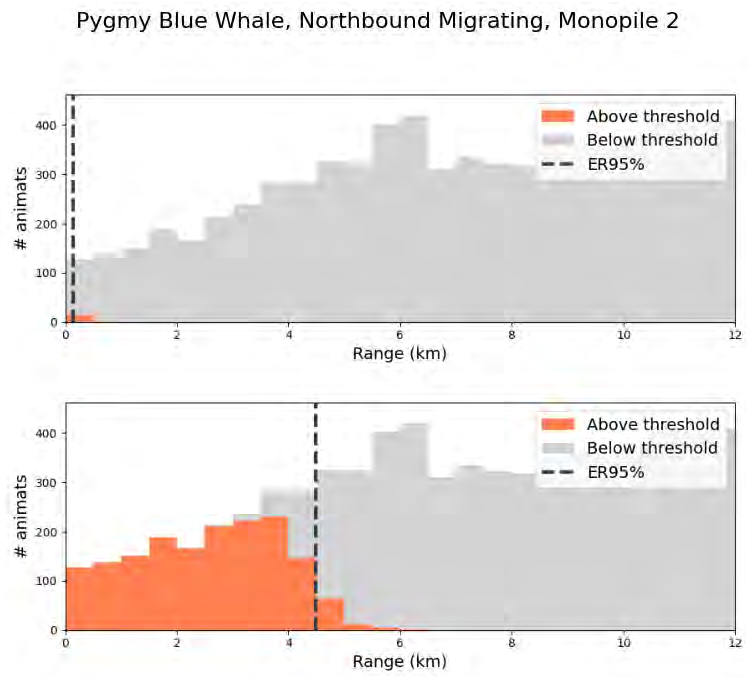


Figure E-79. Monopile 2, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

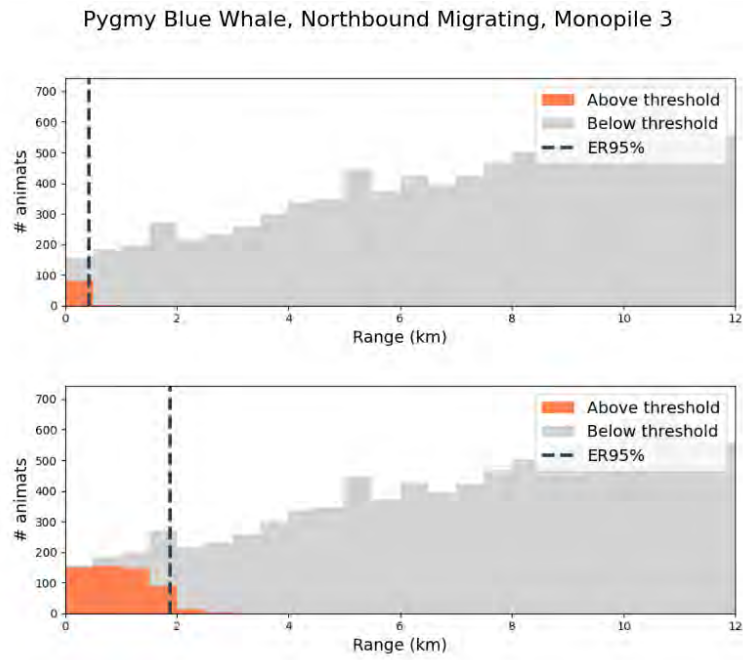


Figure E-80. Monopile 3, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

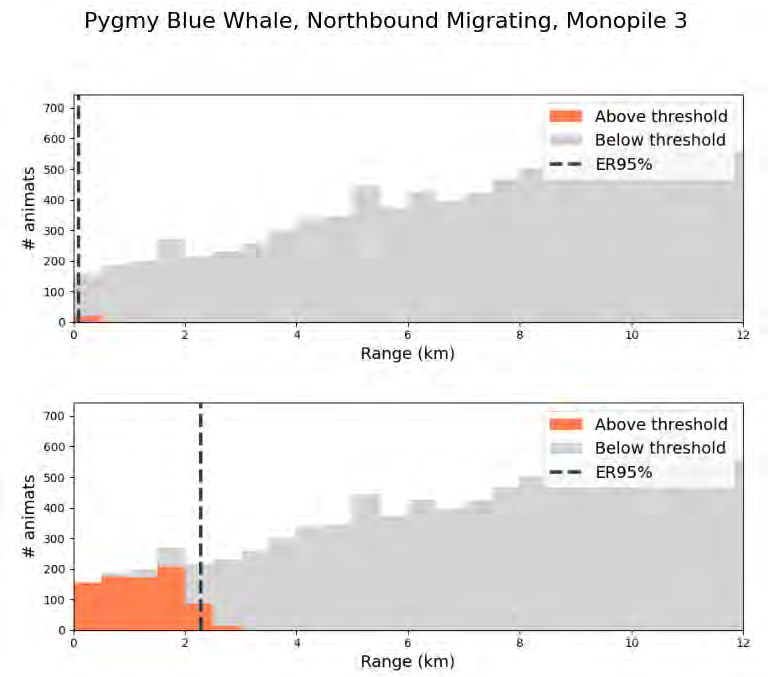


Figure E-81. Monopile 3, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

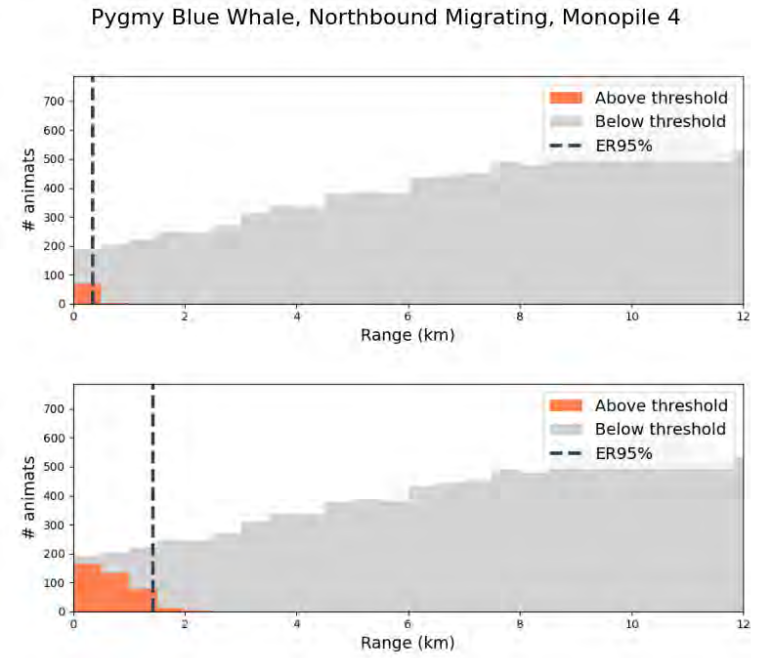


Figure E-82. Monopile 4, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

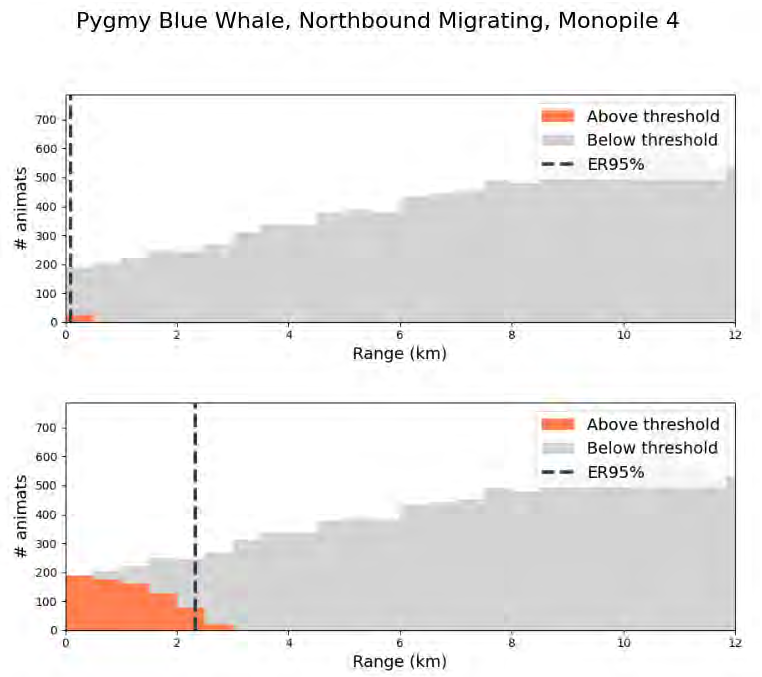


Figure E-83. Monopile 4, PULSE+HSD+DBBC, Pygmy Blue Whale, Northbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

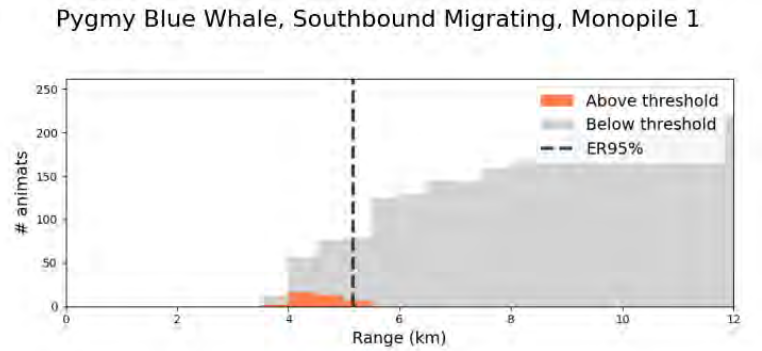


Figure E-84. Monopile 1, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, SPL behavioural response threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

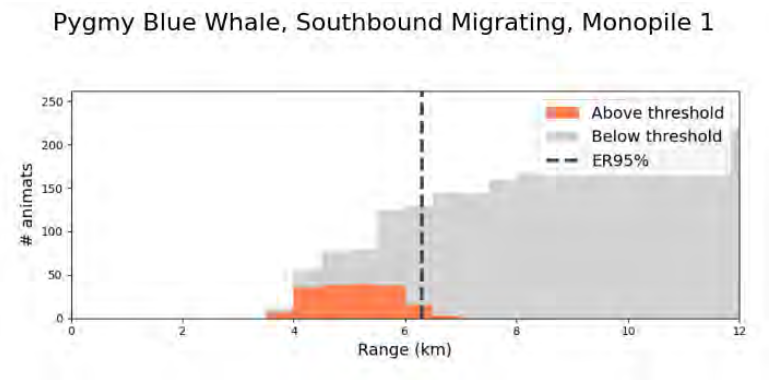


Figure E-85. Monopile 1, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

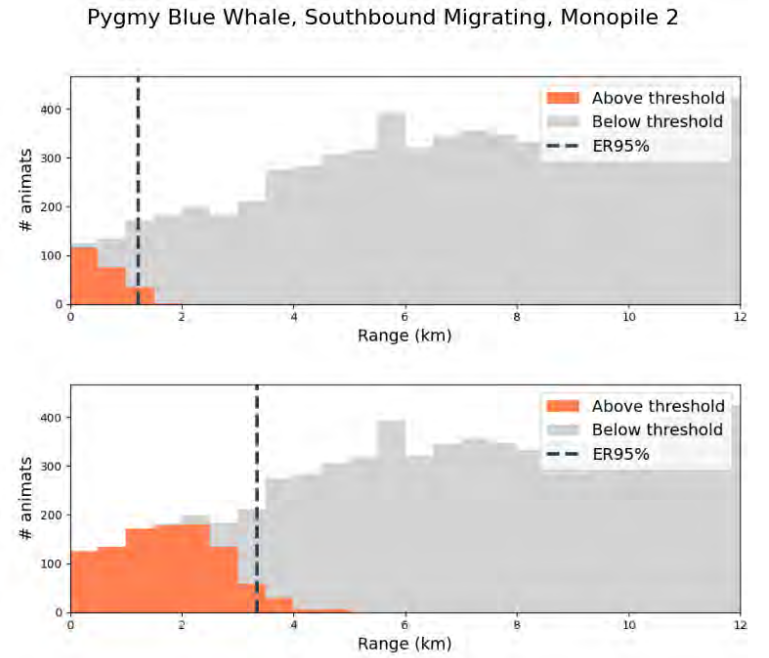


Figure E-86. Monopile 2, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

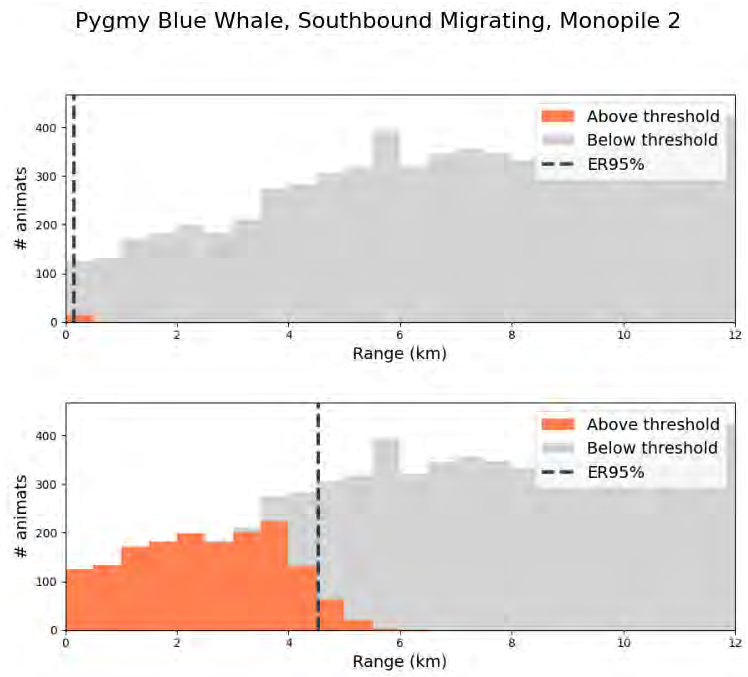


Figure E-87. Monopile 2, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

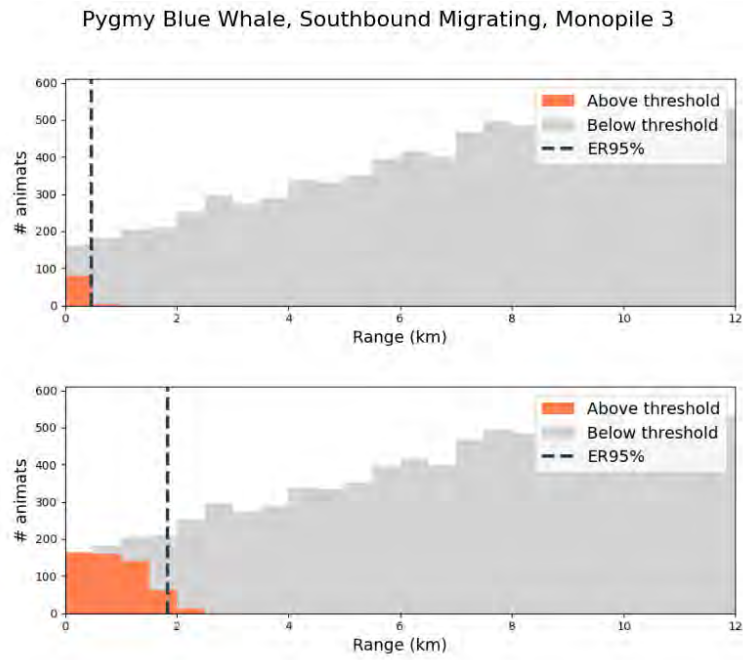


Figure E-88. Monopile 3, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

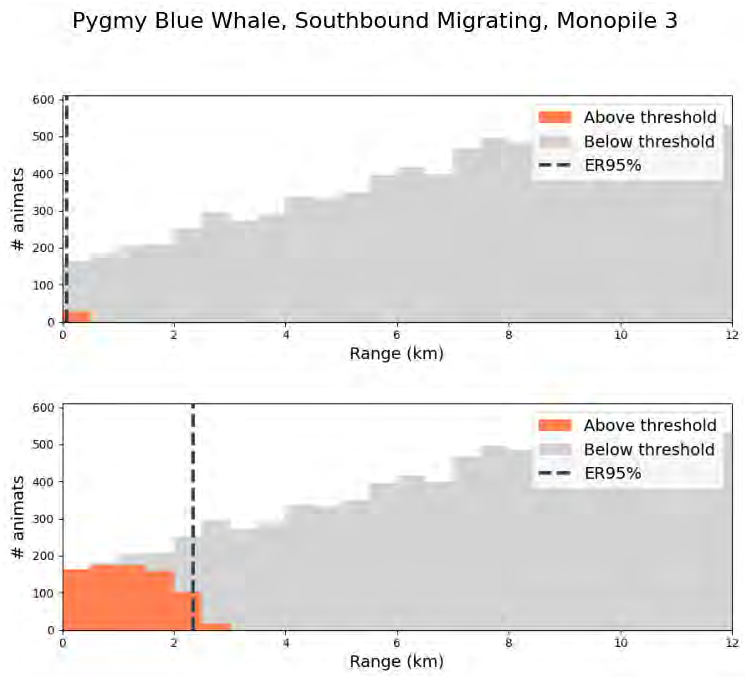


Figure E-89. Monopile 3, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

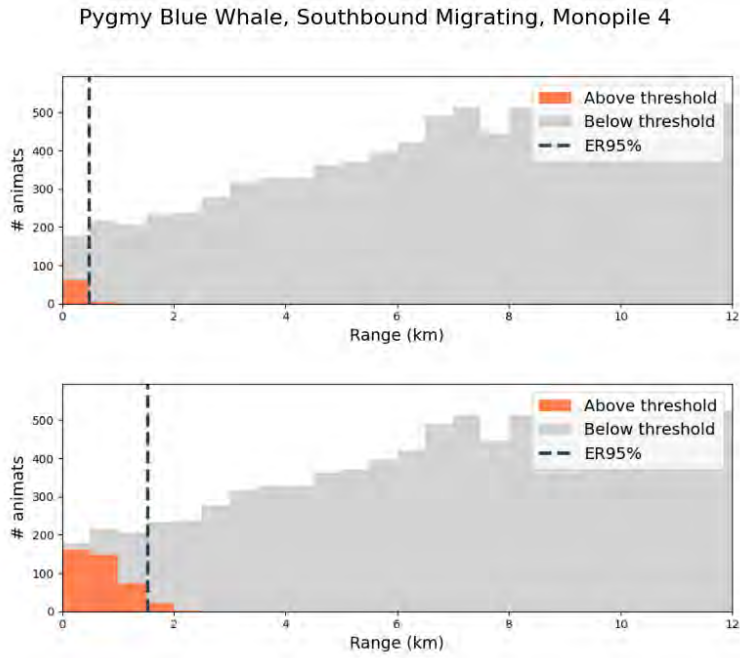


Figure E-90. Monopile 4, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

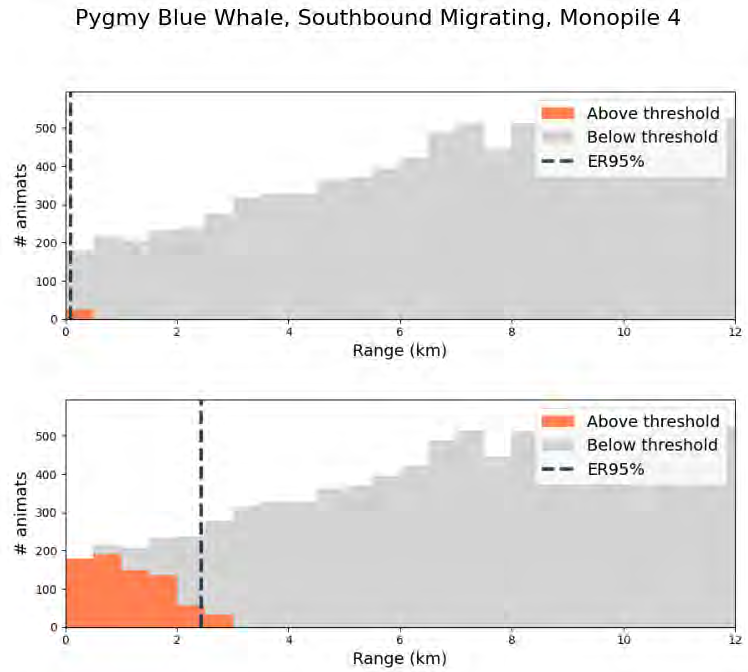


Figure E-91. Monopile 4, PULSE+HSD+DBBC, Pygmy Blue Whale, Southbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

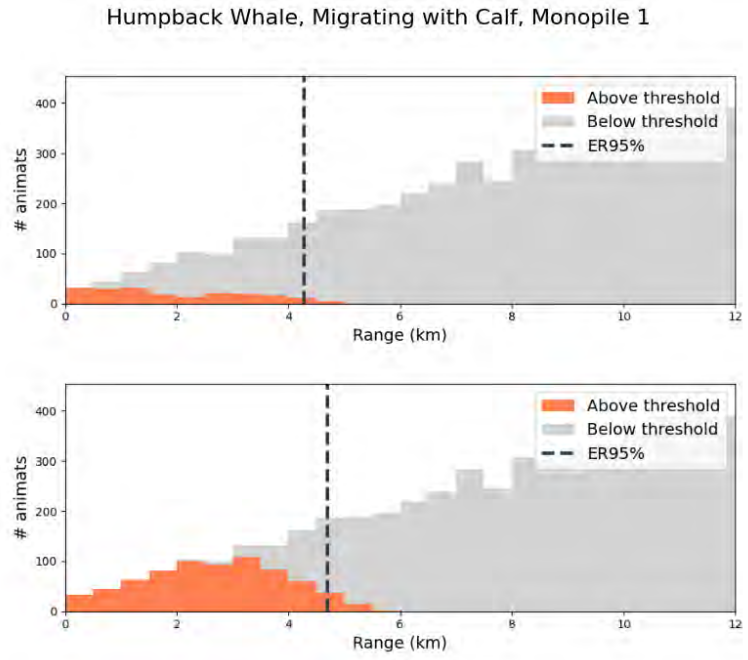


Figure E-92. Monopile 1, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

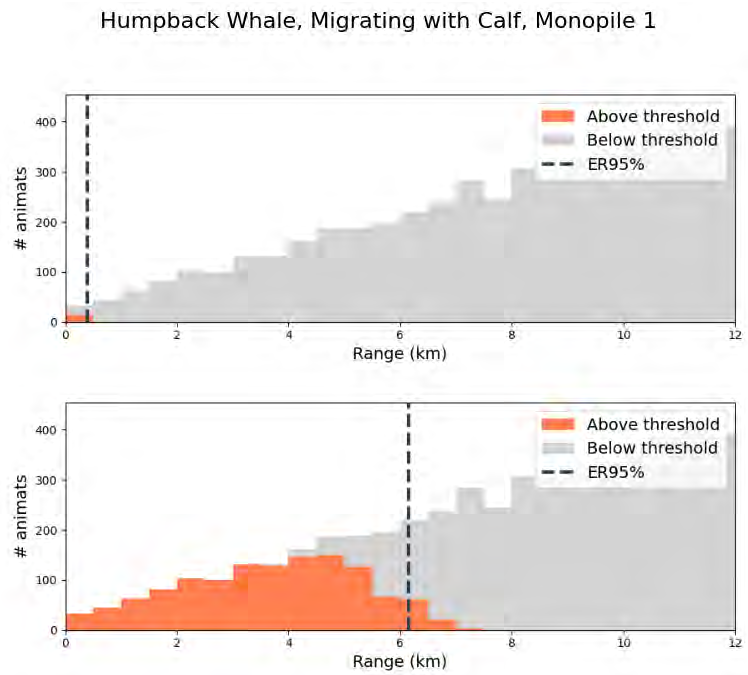


Figure E-93. Monopile 1, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

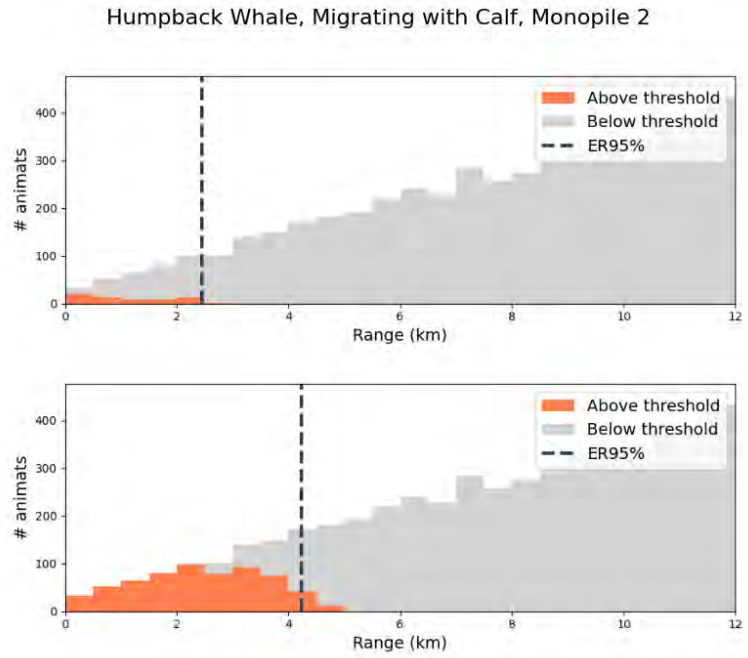


Figure E-94. Monopile 2, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

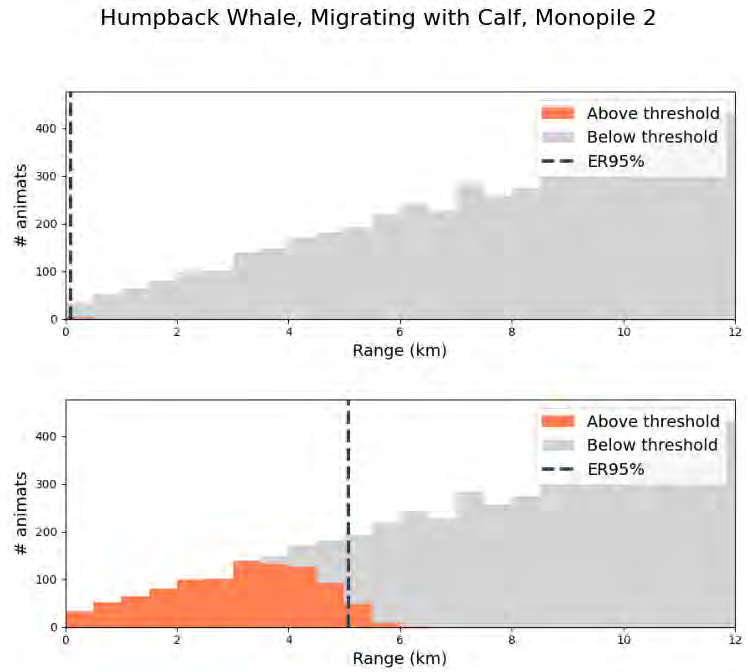


Figure E-95. Monopile 2, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

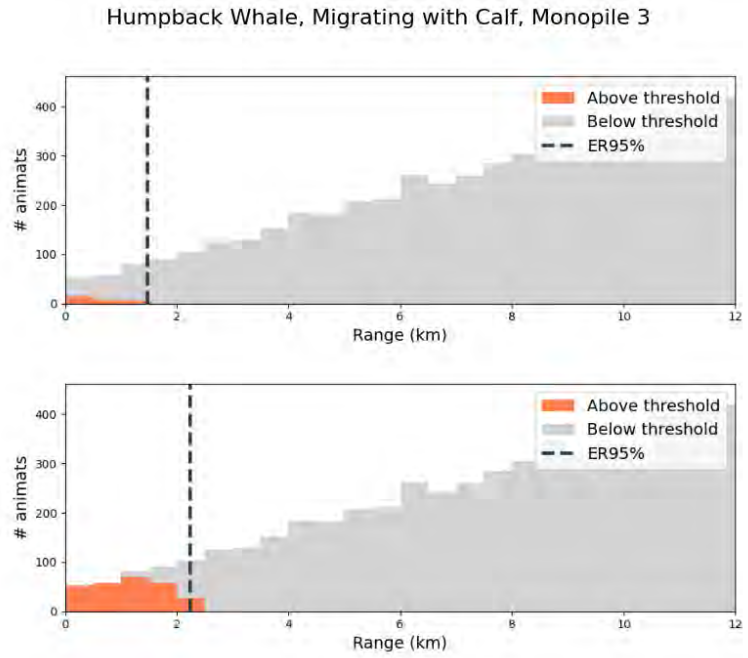


Figure E-96. Monopile 3, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

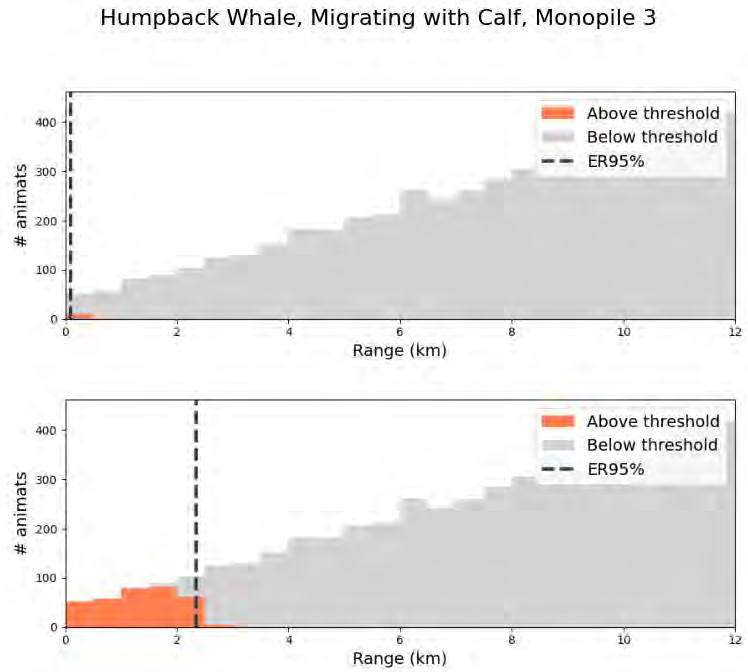


Figure E-97. Monopile 3, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

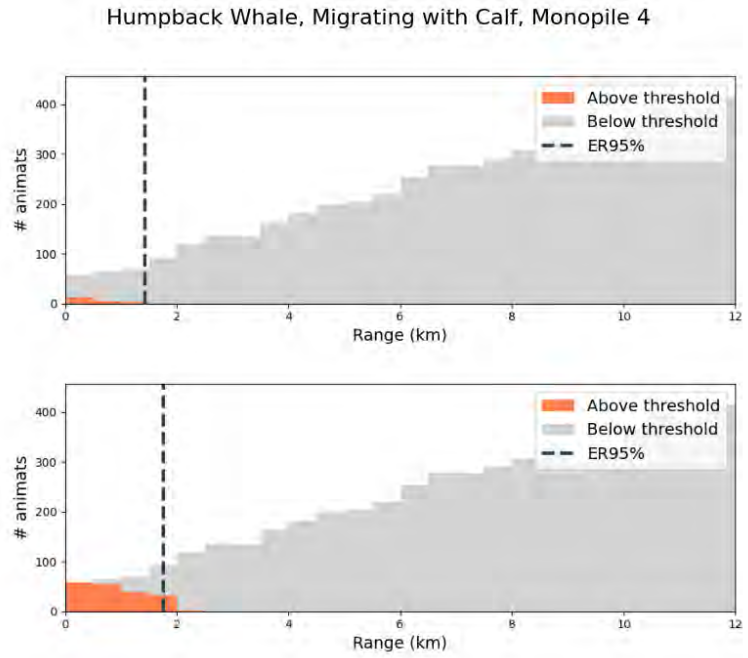


Figure E-98. Monopile 4, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

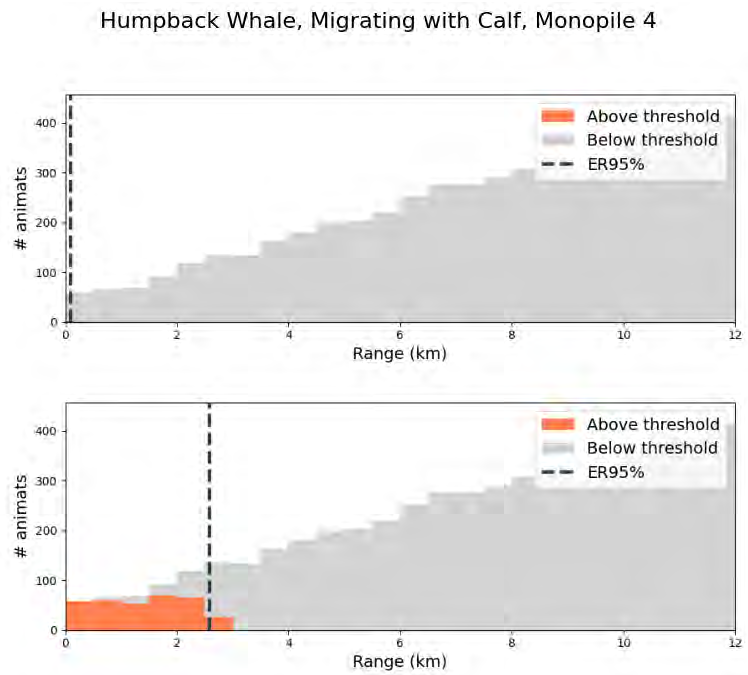


Figure E-99. Monopile 4, PULSE+HSD+DBBC, Humpback Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

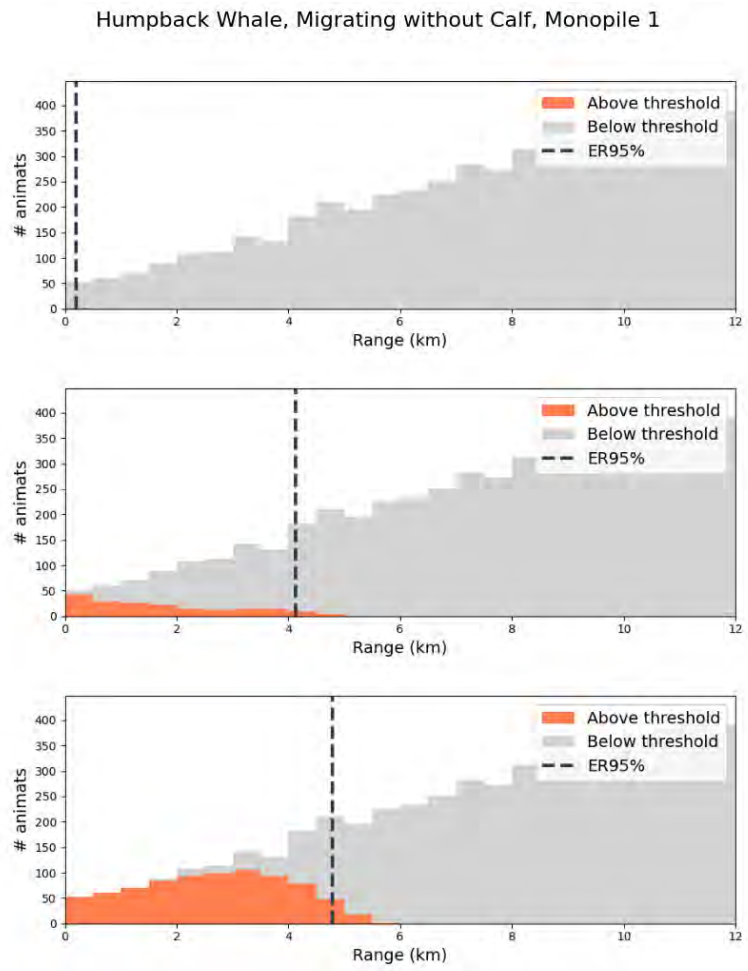


Figure E-100. Monopile 1, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

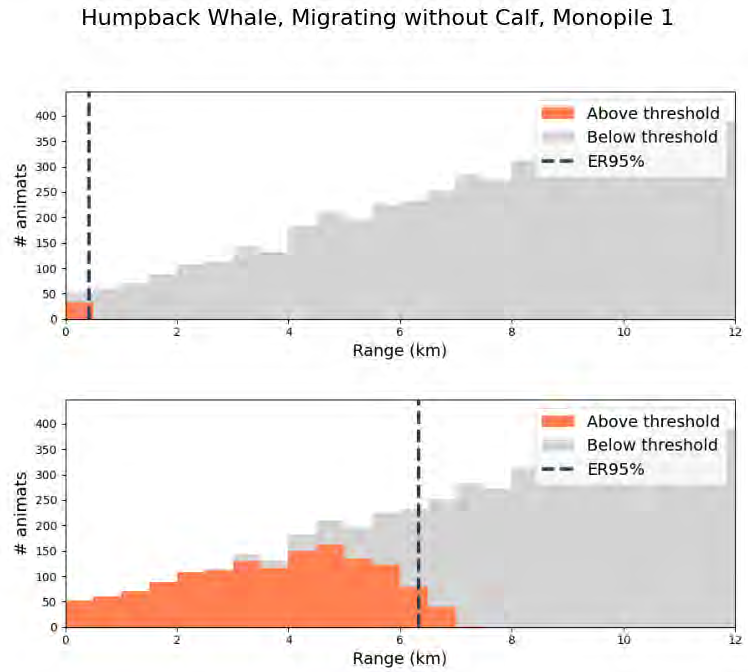


Figure E-101. Monopile 1, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

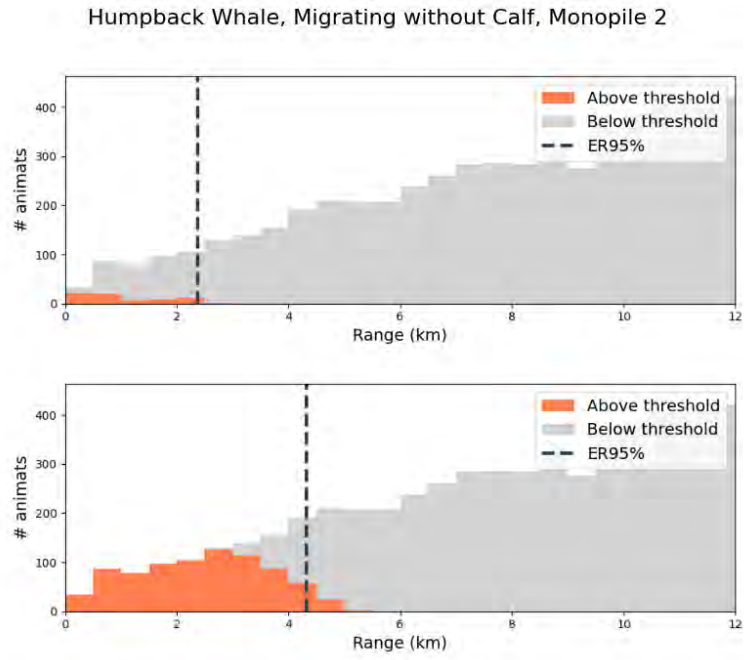


Figure E-102. Monopile 2, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

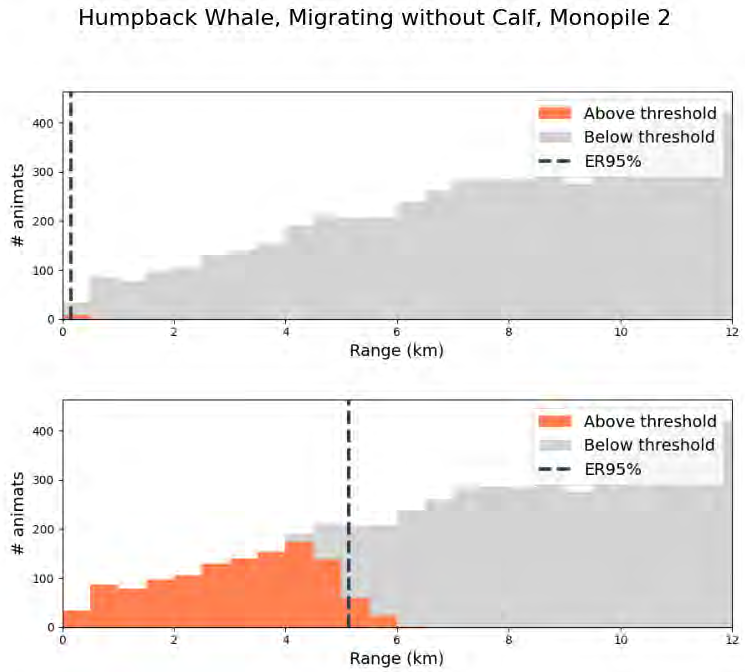


Figure E-103. Monopile 2, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

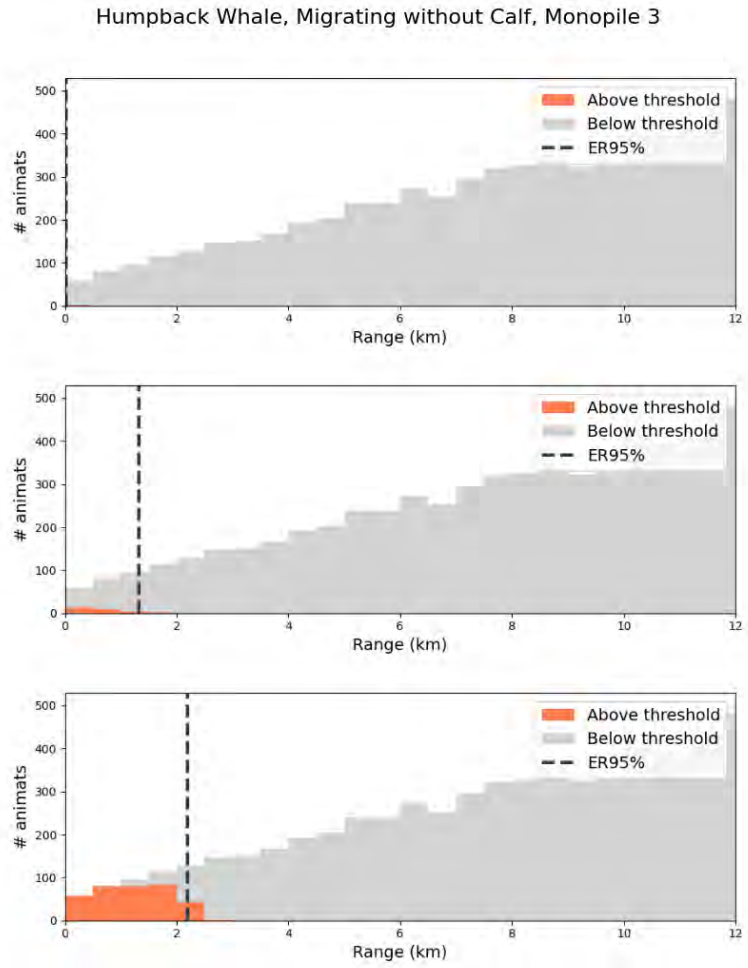


Figure E-104. Monopile 3, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

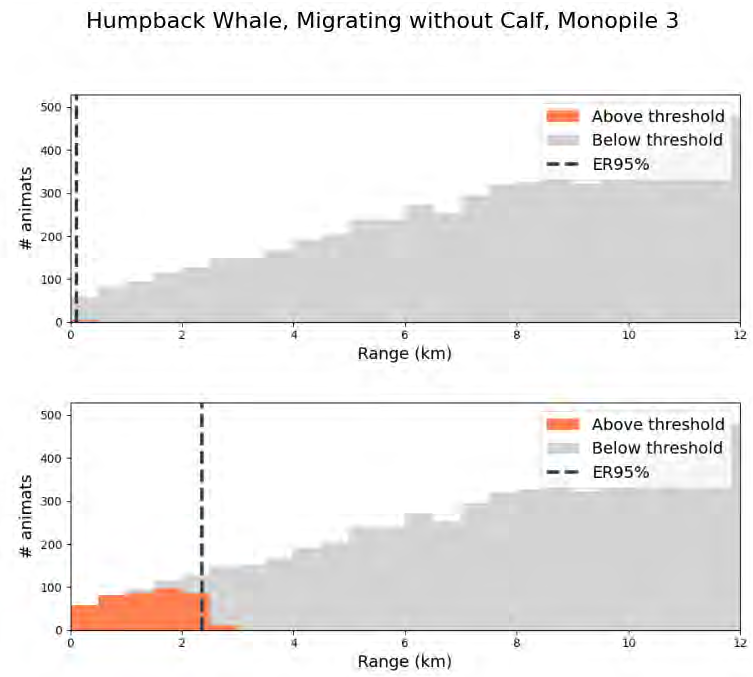


Figure E-105. Monopile 3, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

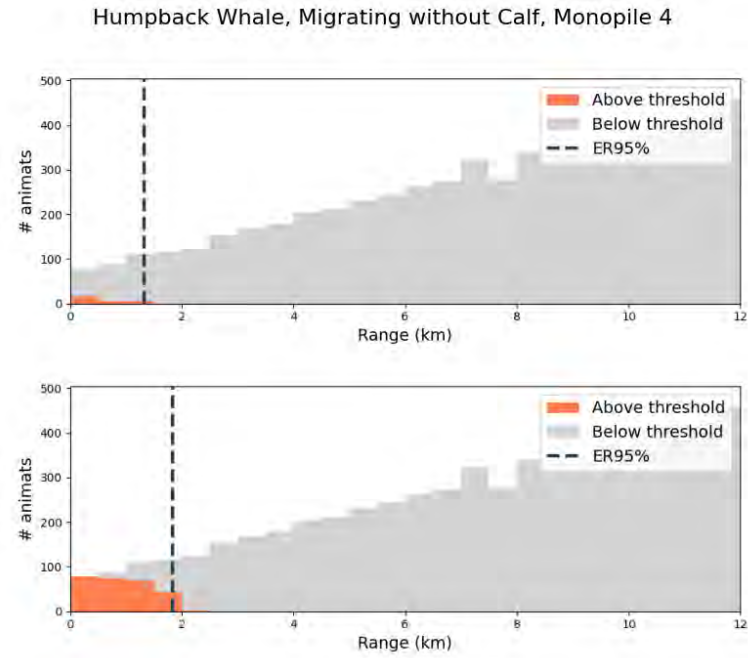


Figure E-106. Monopile 4, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

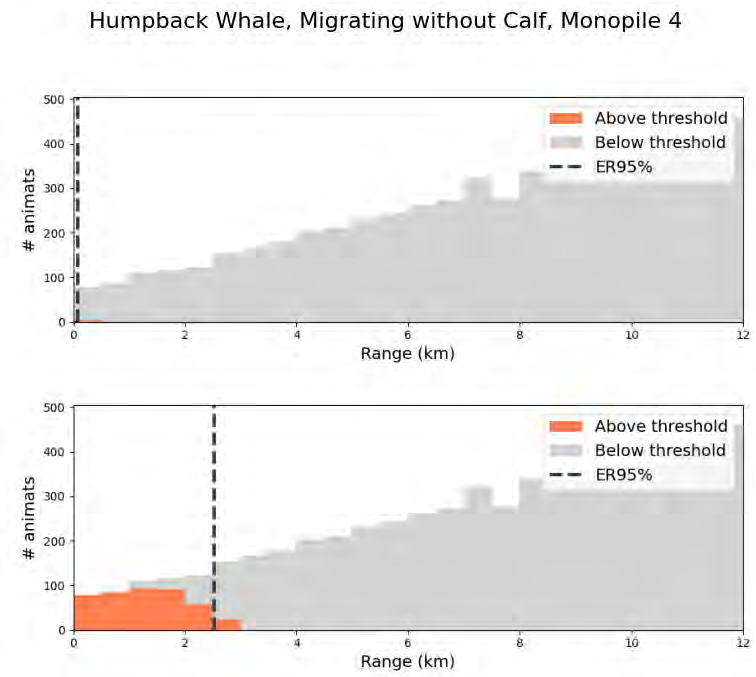


Figure E-107. Monopile 4, PULSE+HSD+DBBC, Humpback Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

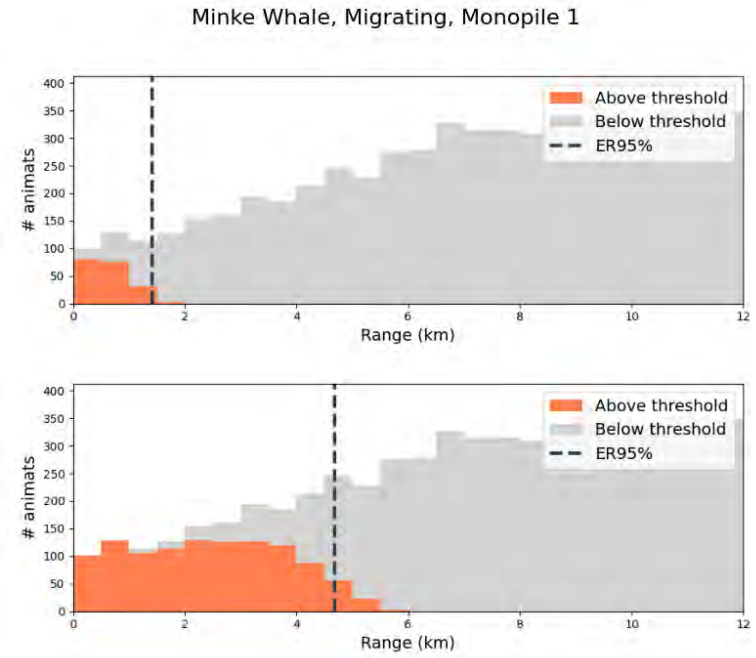


Figure E-108. Monopile 1, PULSE+HSD+DBBC, Minke Whale, Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

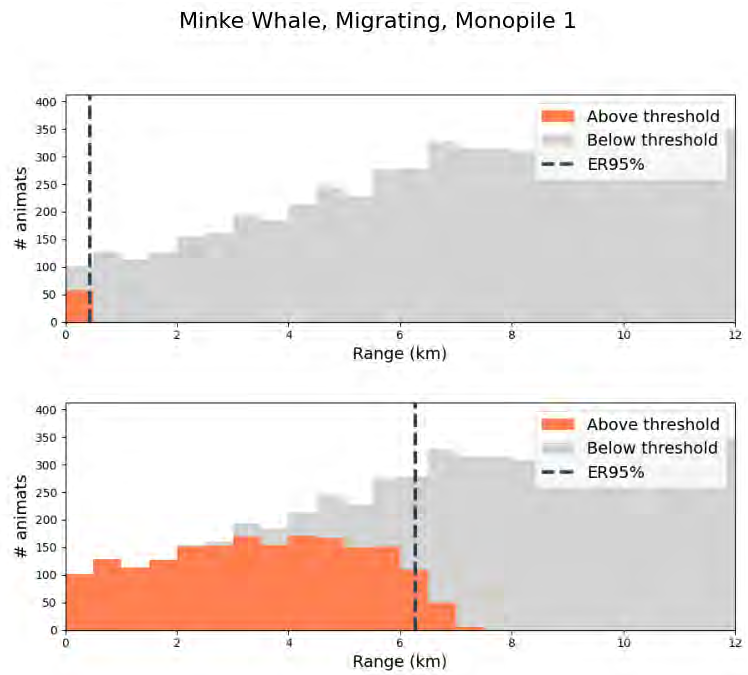


Figure E-109. Monopile 1, PULSE+HSD+DBBC, Minke Whale, Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

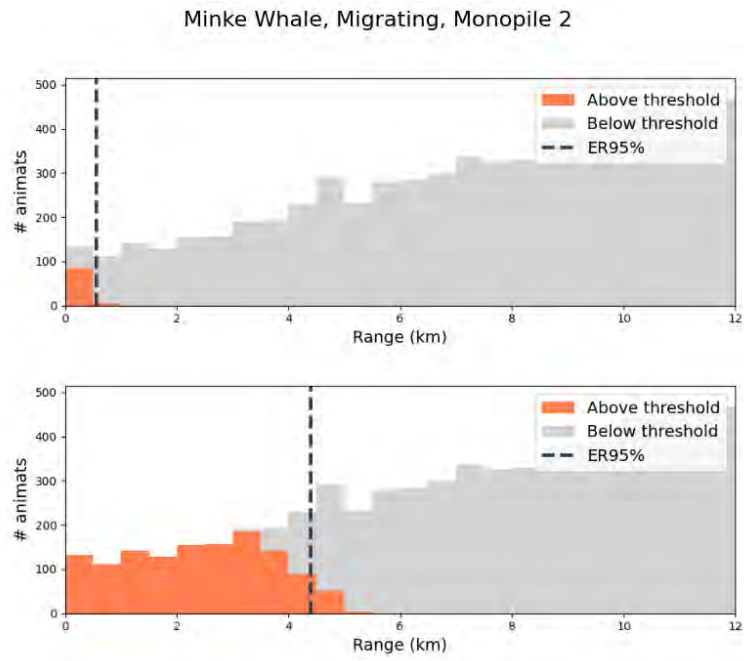


Figure E-110. Monopile 2, PULSE+HSD+DBBC, Minke Whale, Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

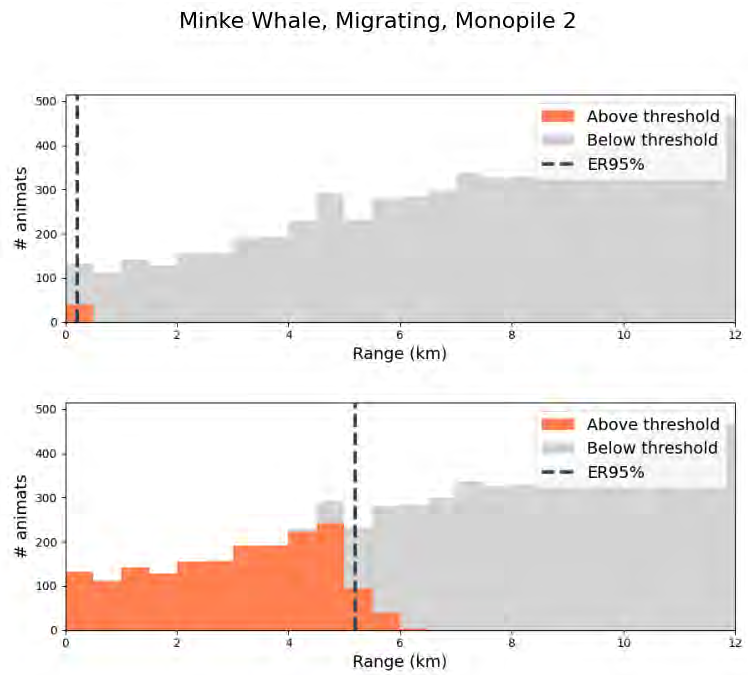


Figure E-111. Monopile 2, PULSE+HSD+DBBC, Minke Whale, Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

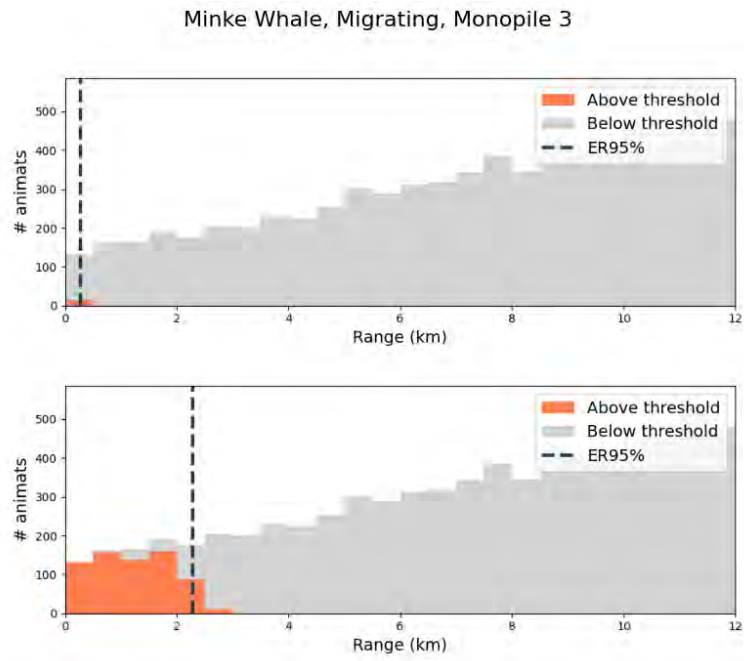


Figure E-112. Monopile 3, PULSE+HSD+DBBC, Minke Whale, Migrating, TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

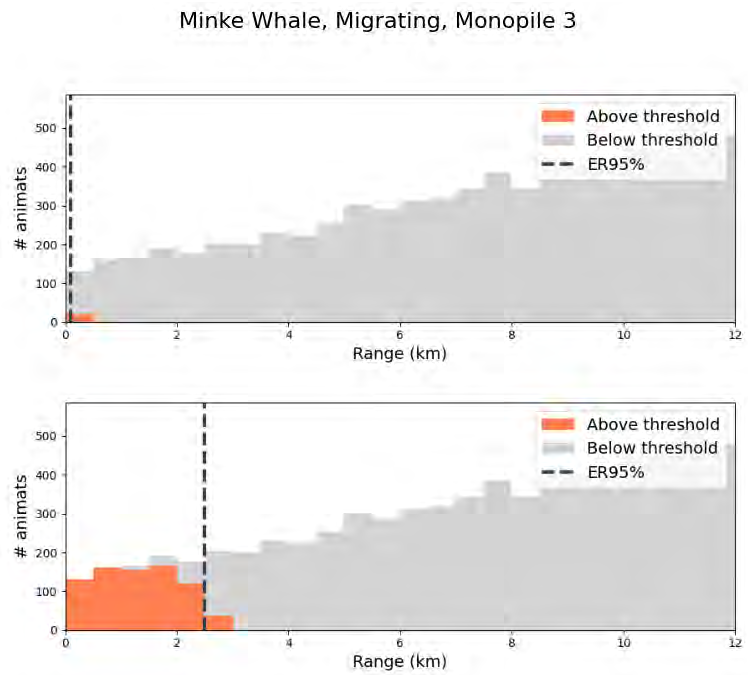


Figure E-113. Monopile 3, PULSE+HSD+DBBC, Minke Whale, Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

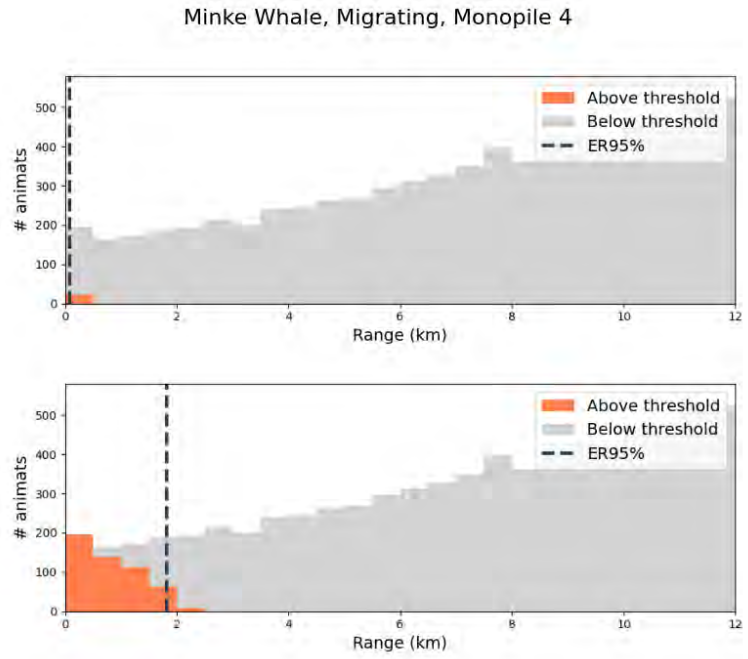


Figure E-114. Monopile 4, PULSE+HSD+DBBC, Minke Whale, Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

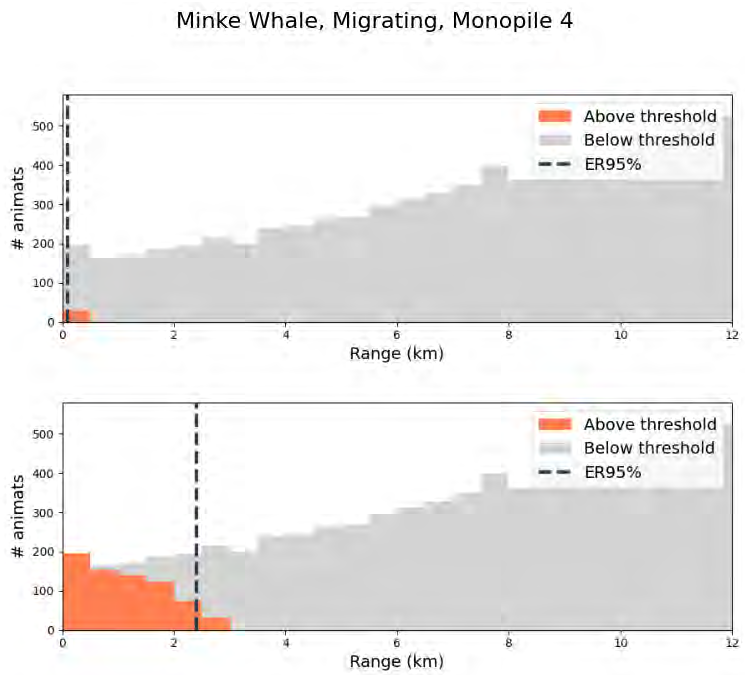


Figure E-115. Monopile 4, PULSE+HSD+DBBC, Minke Whale, Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

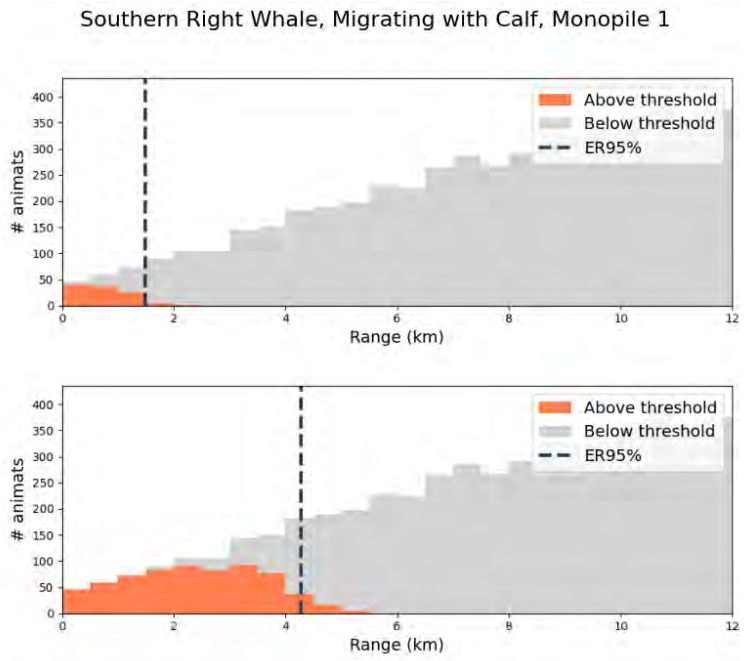


Figure E-116. Monopile 1, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

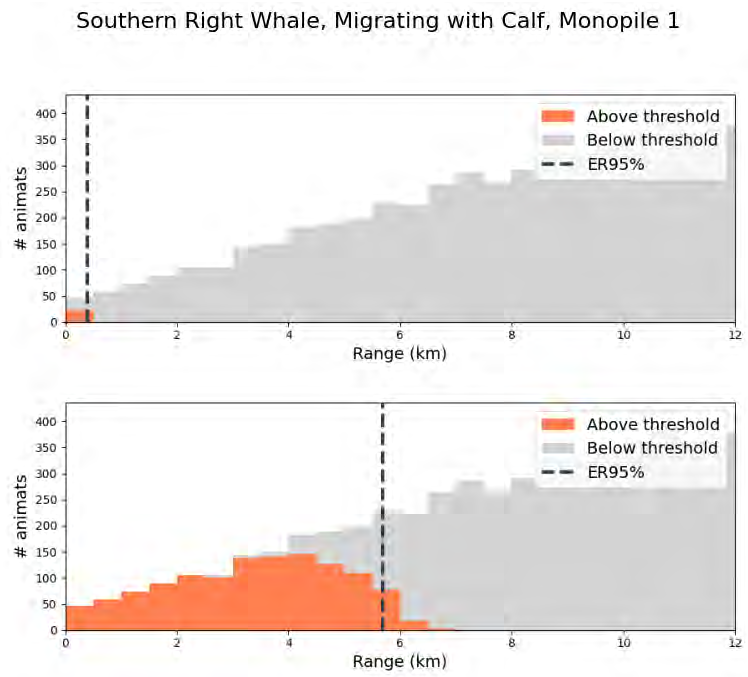


Figure E-117. Monopile 1, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

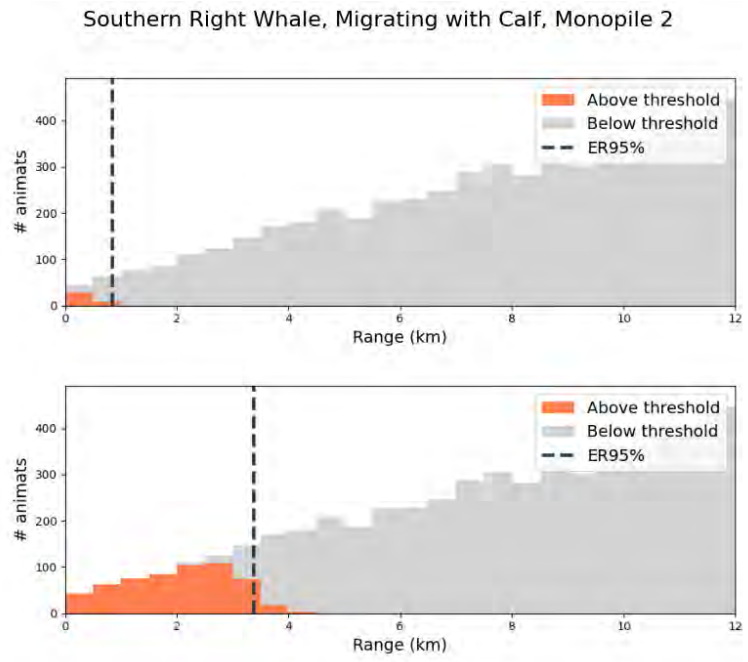


Figure E-118. Monopile 2, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

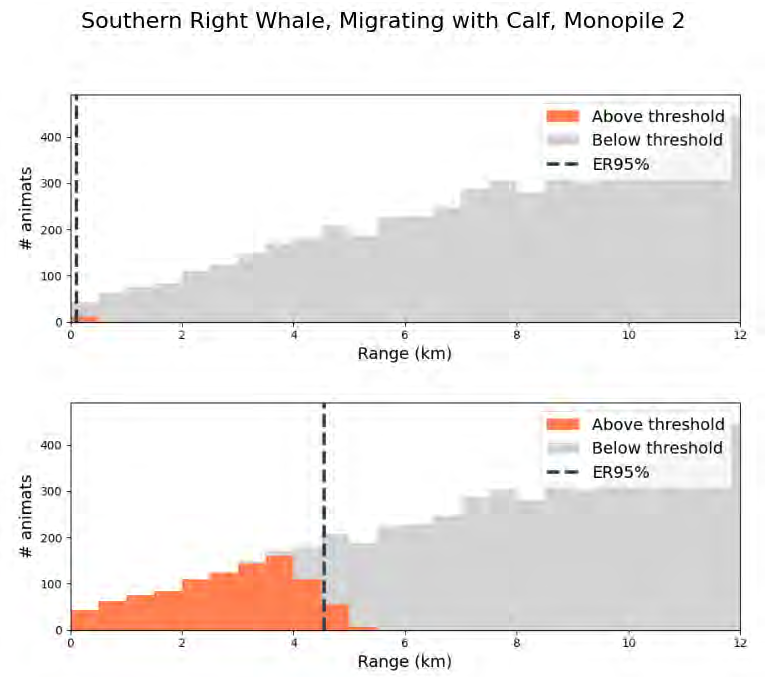


Figure E-119. Monopile 2, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

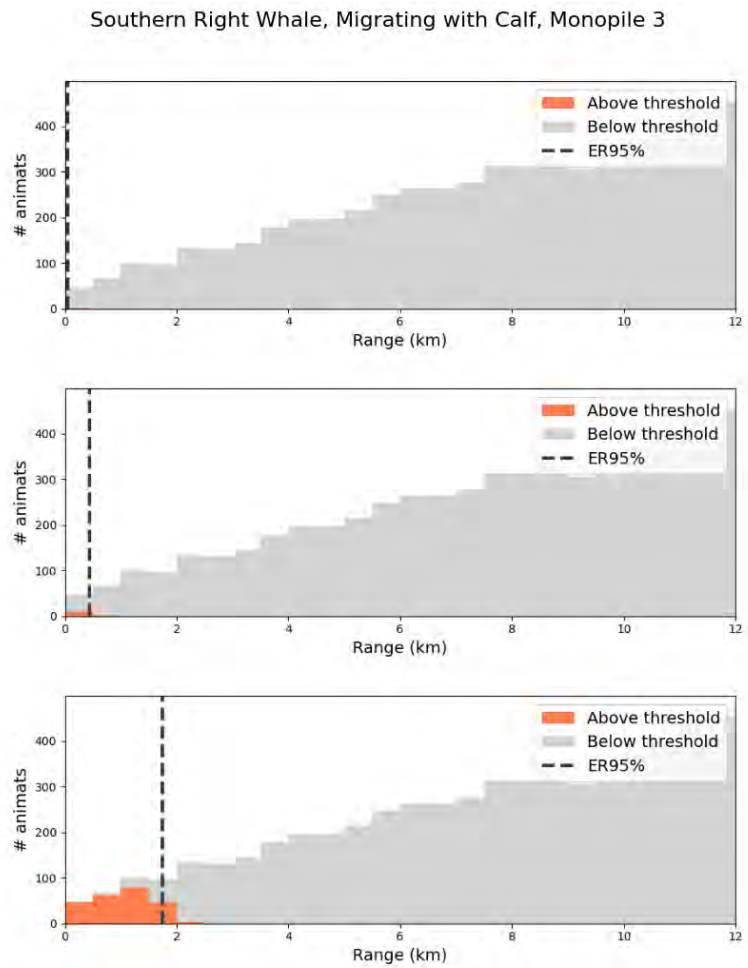


Figure E-120. Monopile 3, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

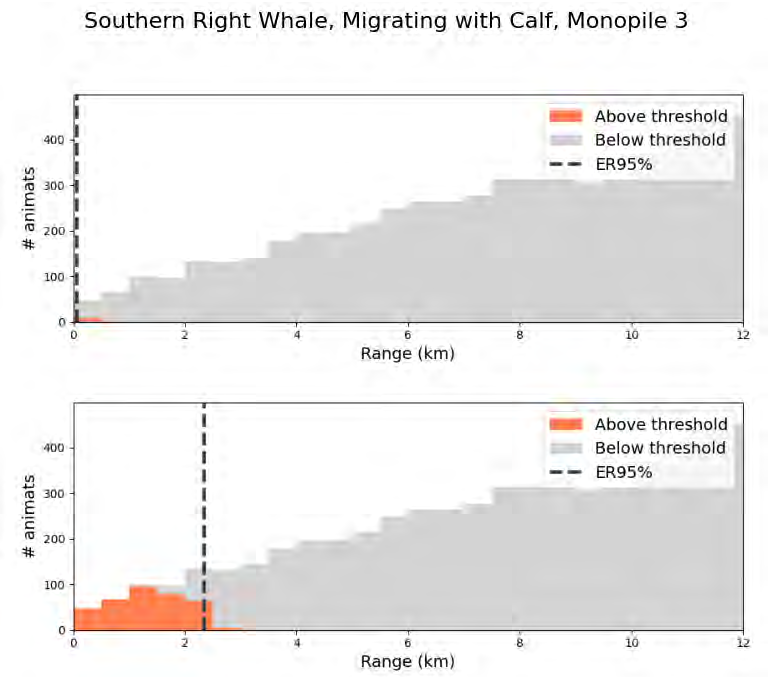


Figure E-121. Monopile 3, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

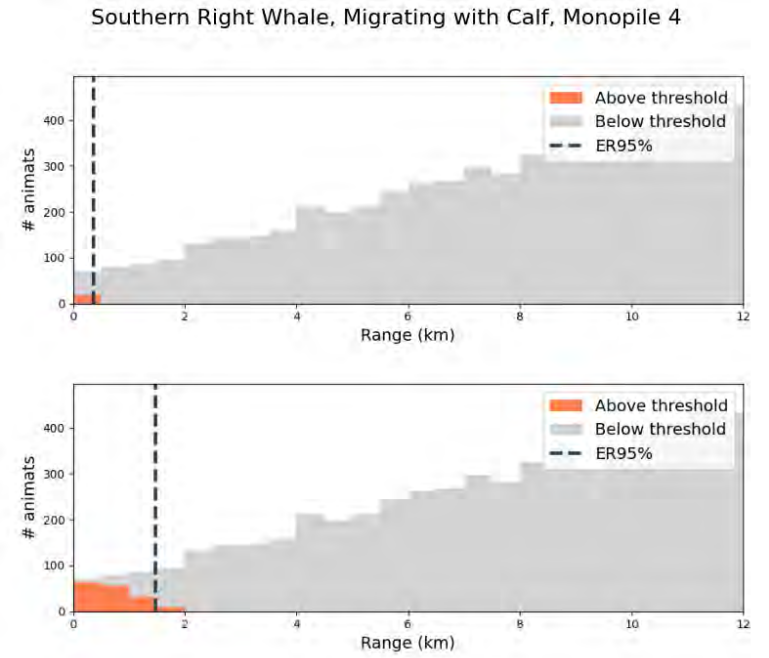


Figure E-122. Monopile 4, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

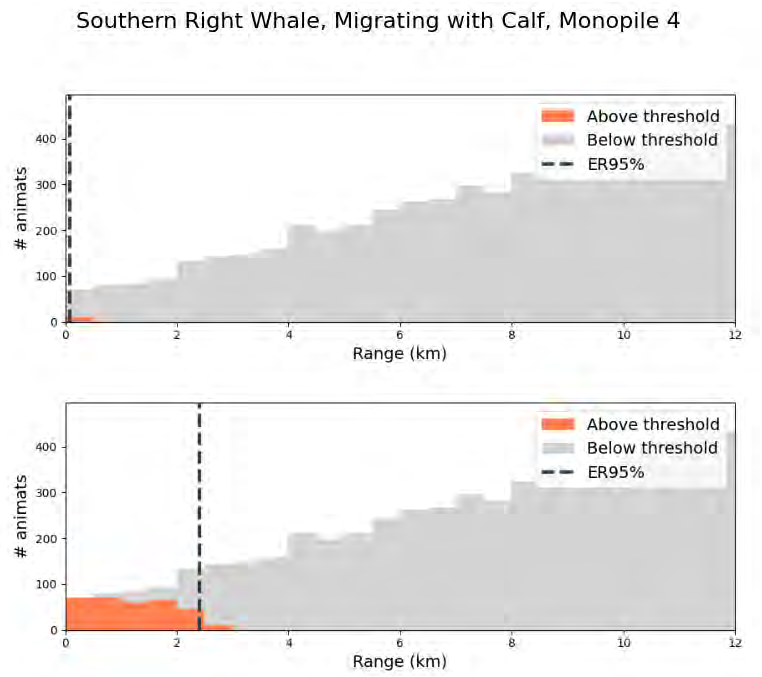


Figure E-123. Monopile 4, PULSE+HSD+DBBC, Southern Right Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

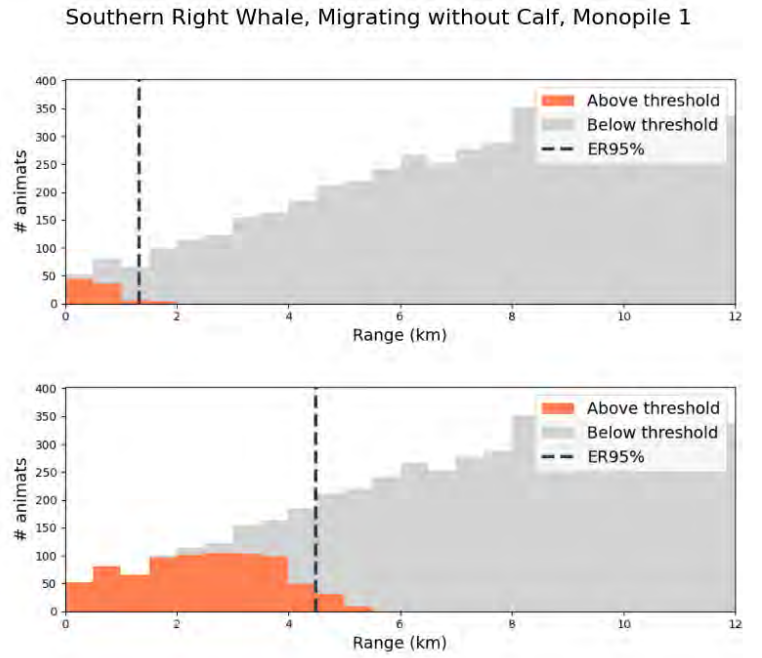


Figure E-124. Monopile 1, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

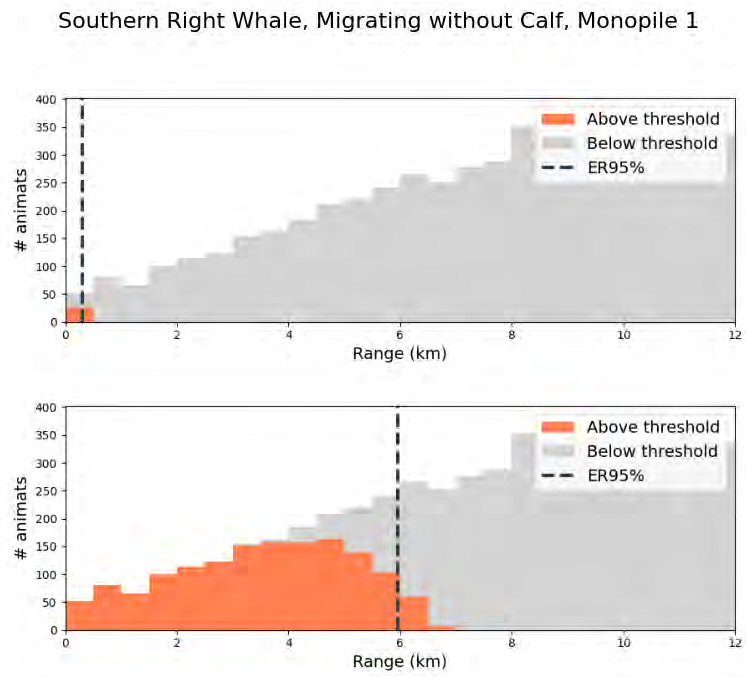


Figure E-125. Monopile 1, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

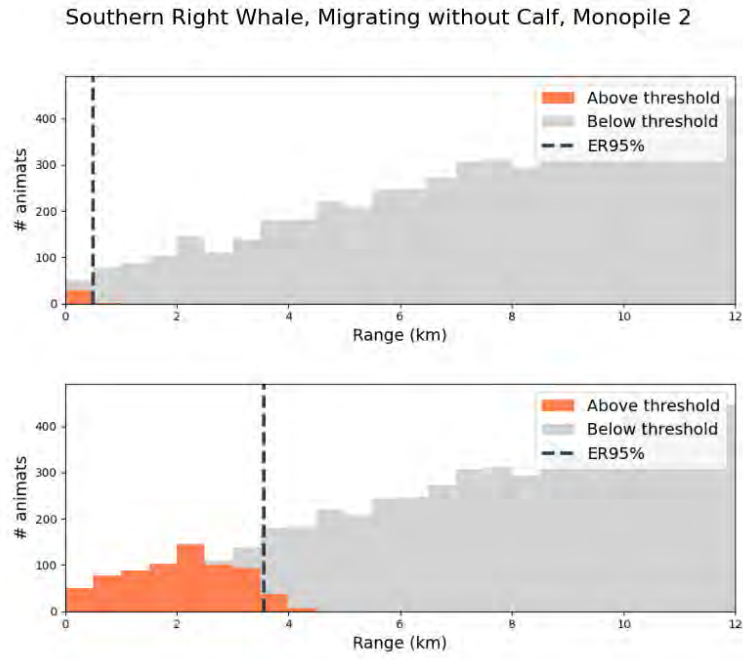


Figure E-126. Monopile 2, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

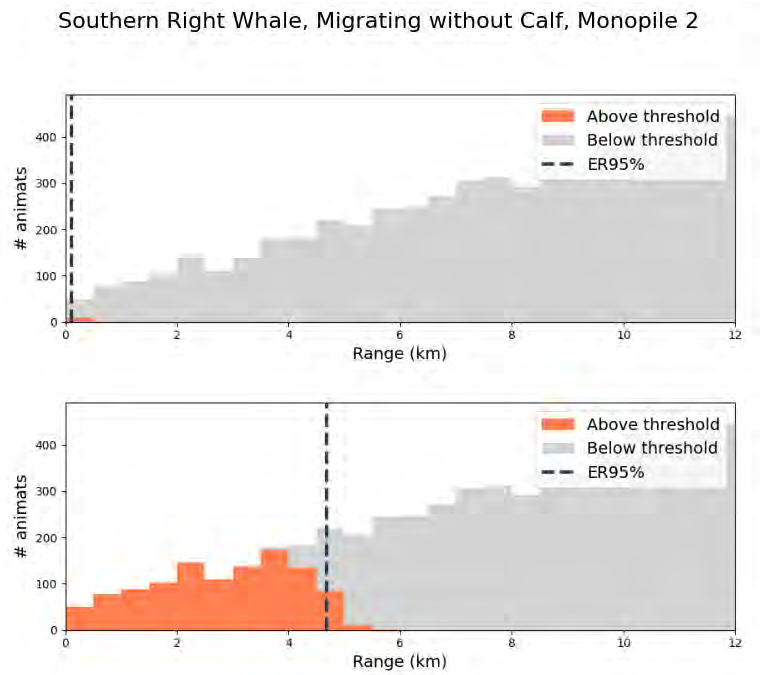


Figure E-127. Monopile 2, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

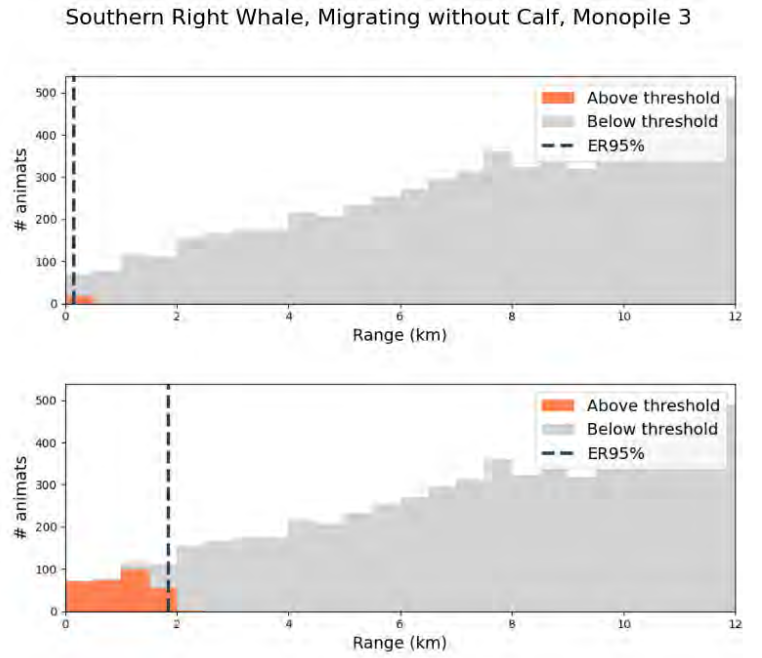


Figure E-128. Monopile 3, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

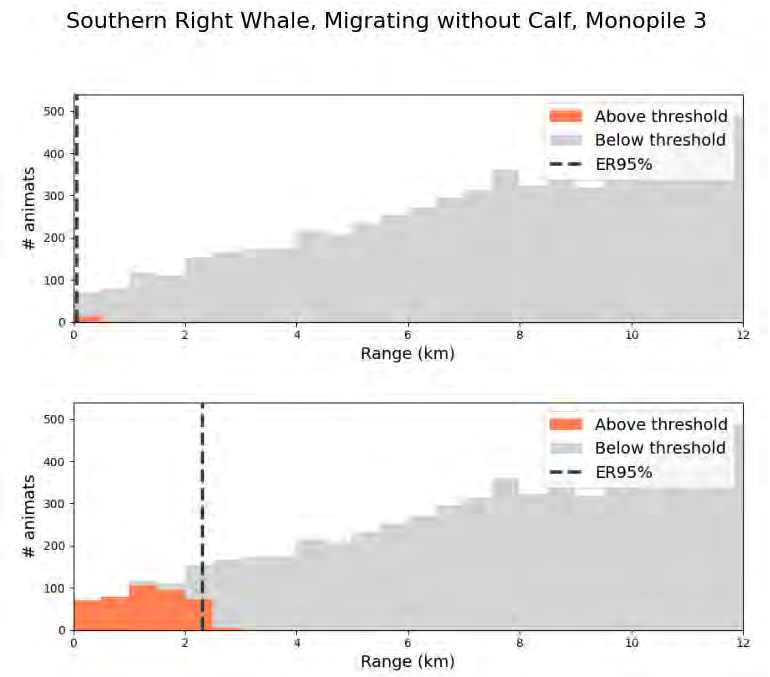


Figure E-129. Monopile 3, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

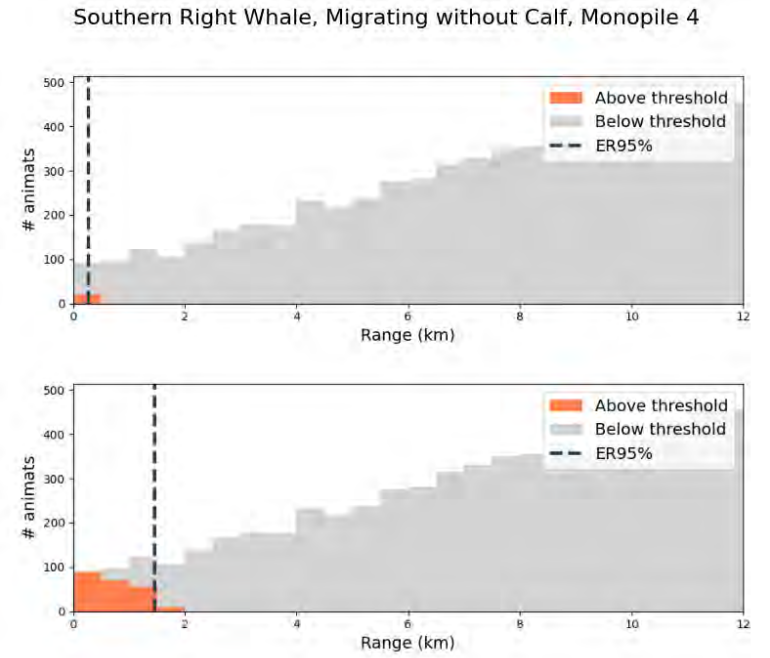


Figure E-130. Monopile 4, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

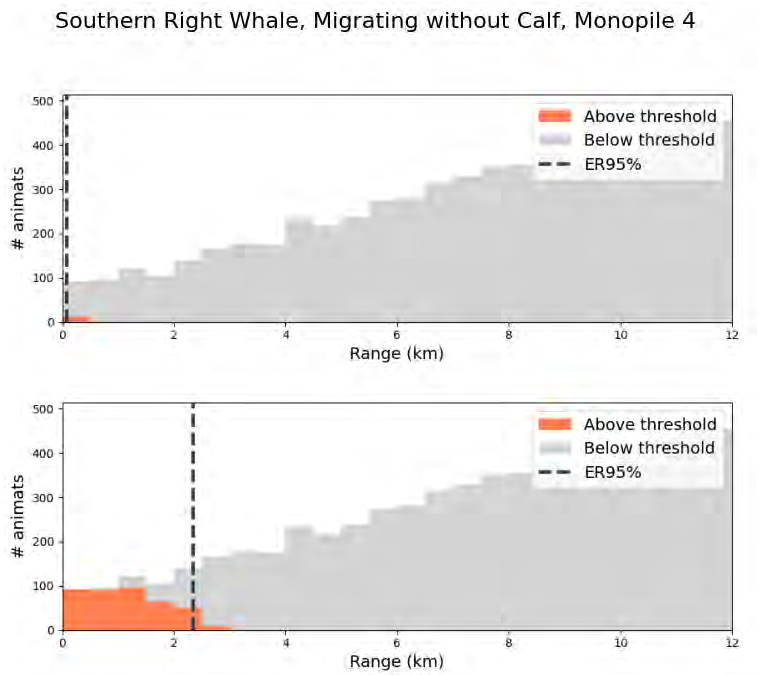


Figure E-131. Monopile 4, PULSE+HSD+DBBC, Southern Right Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the monopile. Bar colours indicate whether the animats exceeded the threshold.

E.1.2. Jacket Pile

E.1.2.1. Scenario 6 – DBBC + PULSE (Fourth Modelling Round)

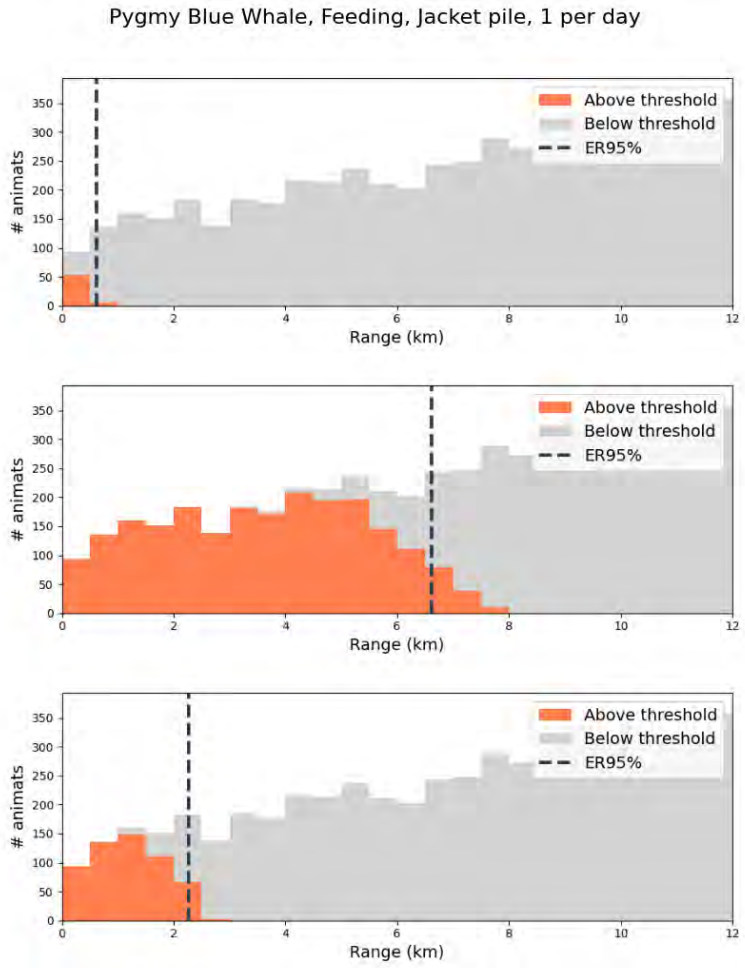


Figure E-132. Jacket pile, 1 per day, PULSE+DBBC, Pygmy Blue Whale, Feeding, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

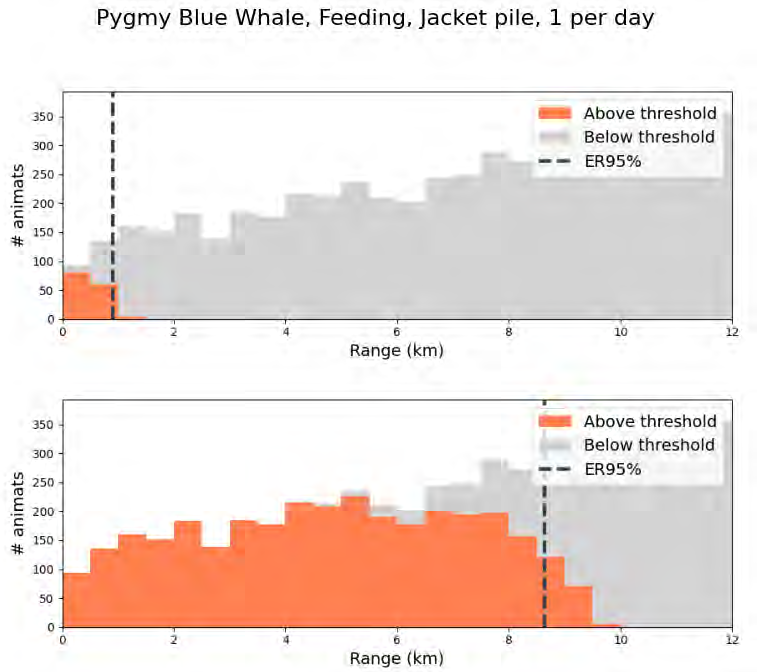


Figure E-133. Jacket pile, 1 per day, PULSE+DBBC, Pygmy Blue Whale, Feeding, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

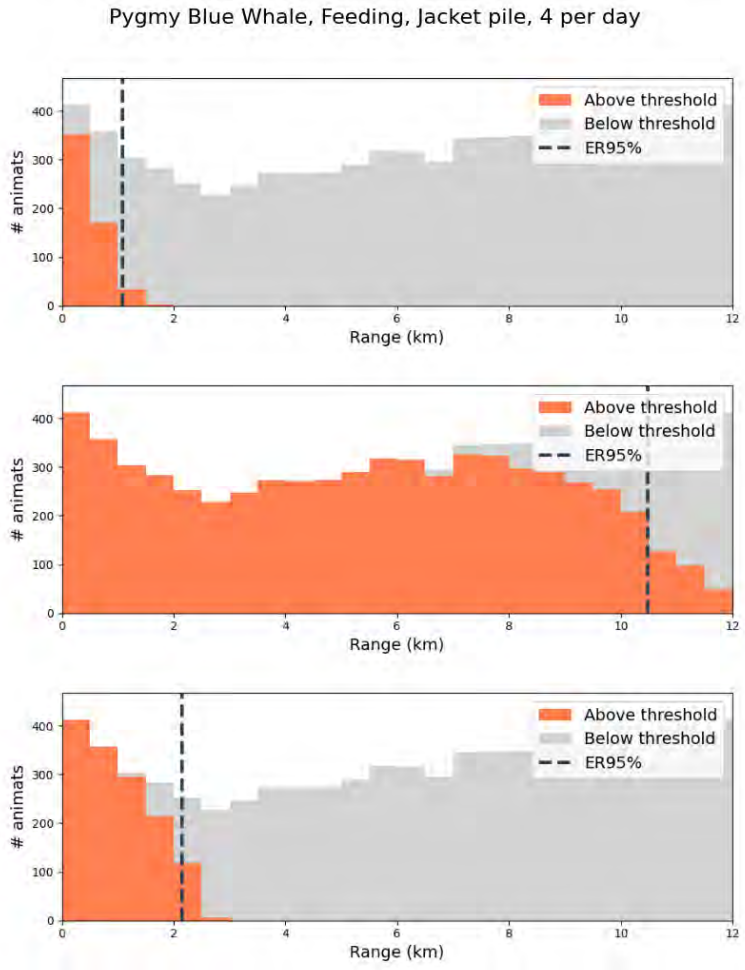


Figure E-134. Jacket pile, 4 per day, PULSE+DBBC, Pygmy Blue Whale, Feeding, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

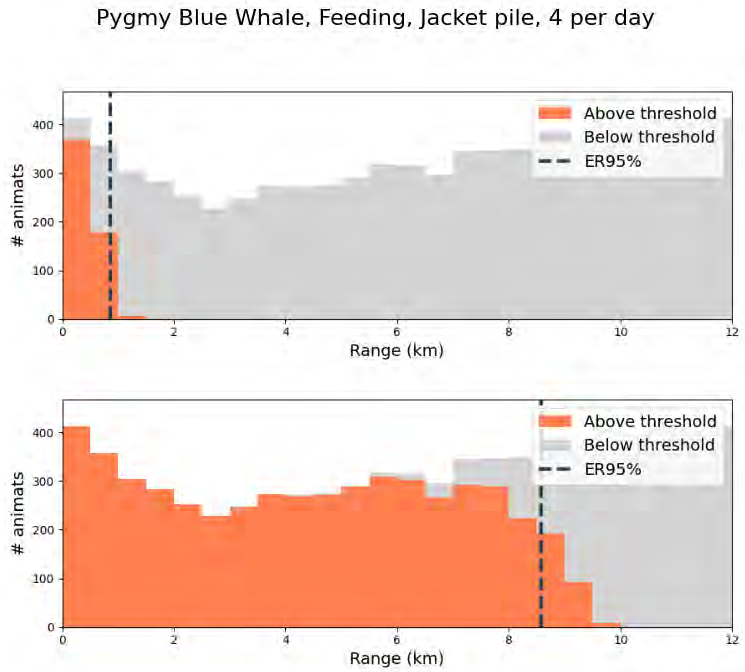


Figure E-135. Jacket pile, 4 per day, PULSE+DBBC, Pygmy Blue Whale, Feeding, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

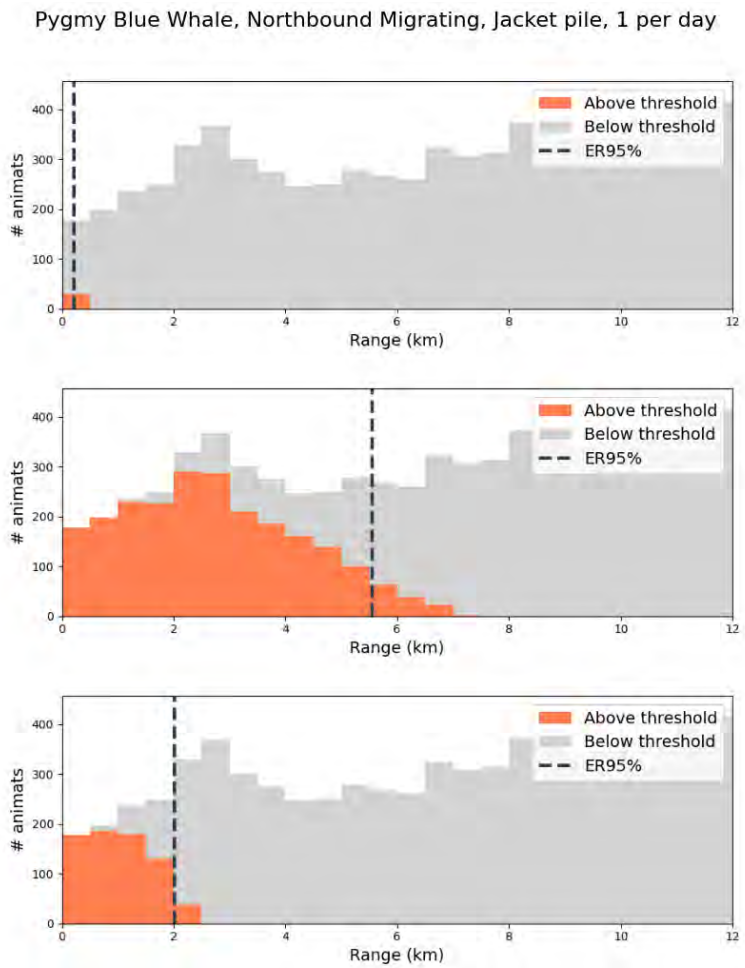


Figure E-136. Jacket pile, 1 per day, PULSE+DBBC, Pygmy Blue Whale, Northbound Migrating, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

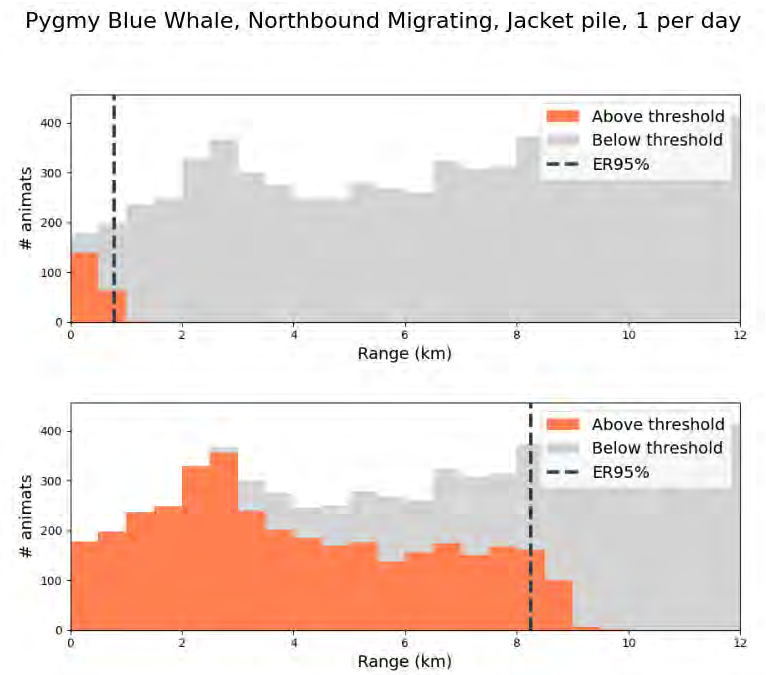


Figure E-137. Jacket pile, 1 per day, PULSE+DBBC, Pygmy Blue Whale, Northbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

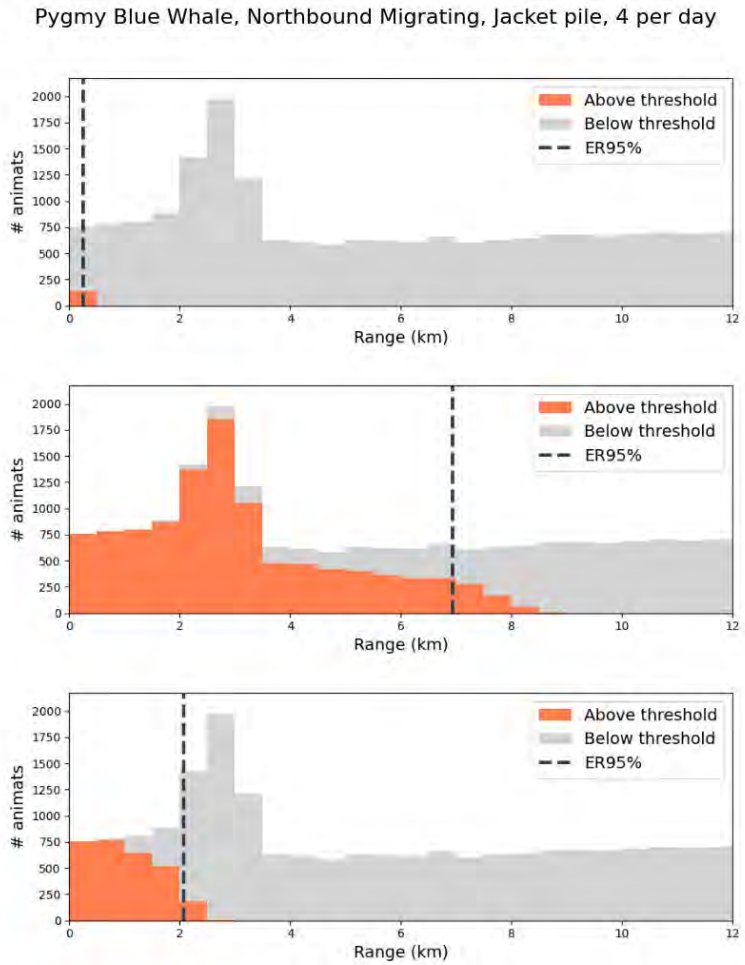


Figure E-138. Jacket pile, 4 per day, PULSE+DBBC, Pygmy Blue Whale, Northbound Migrating, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

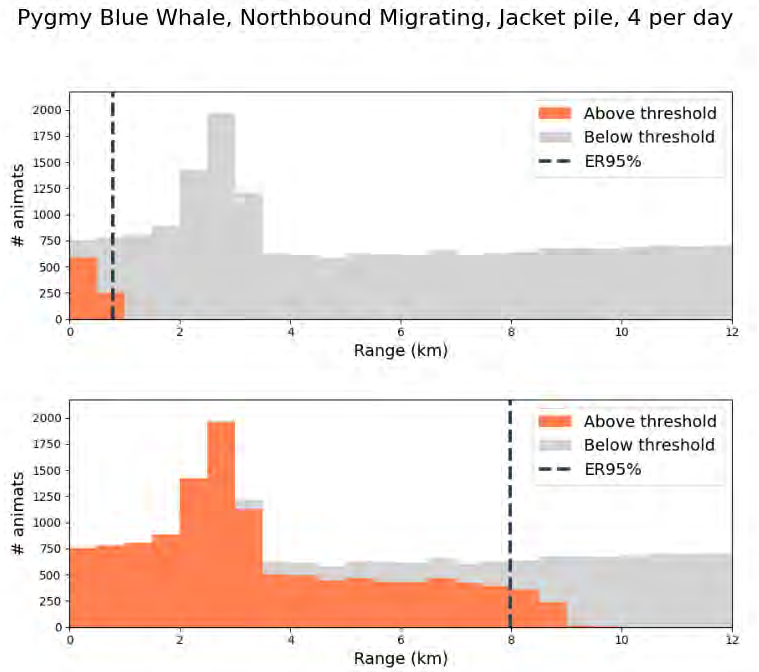


Figure E-139. Jacket pile, 4 per day, PULSE+DBBC, Pygmy Blue Whale, Northbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

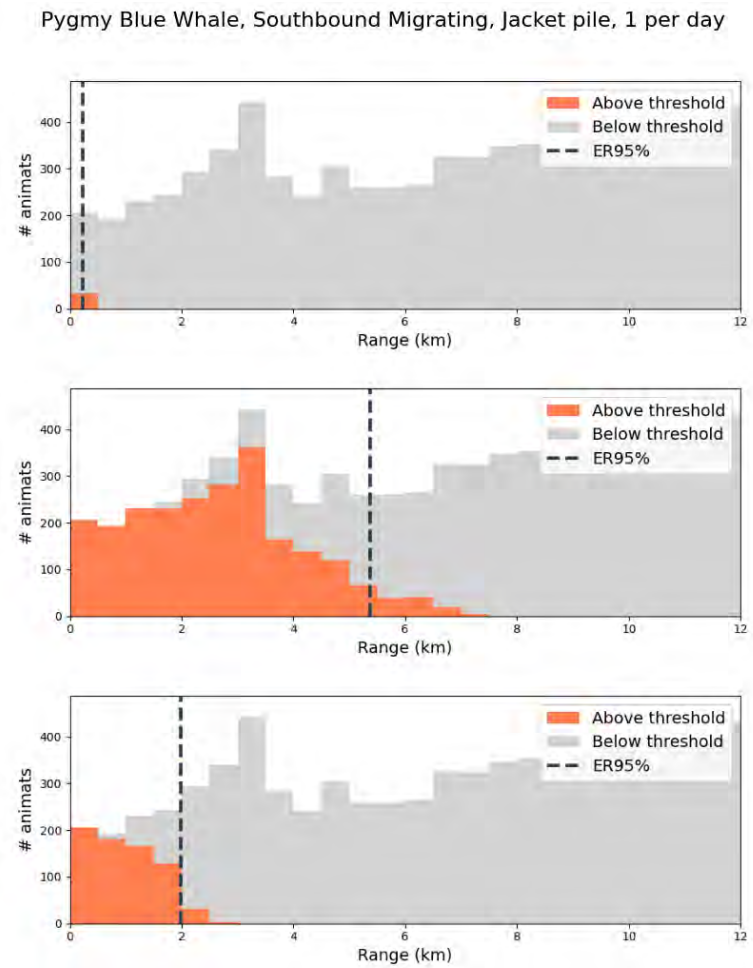


Figure E-140. Jacket pile, 1 per day, PULSE+DBBC, Pygmy Blue Whale, Southbound Migrating, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

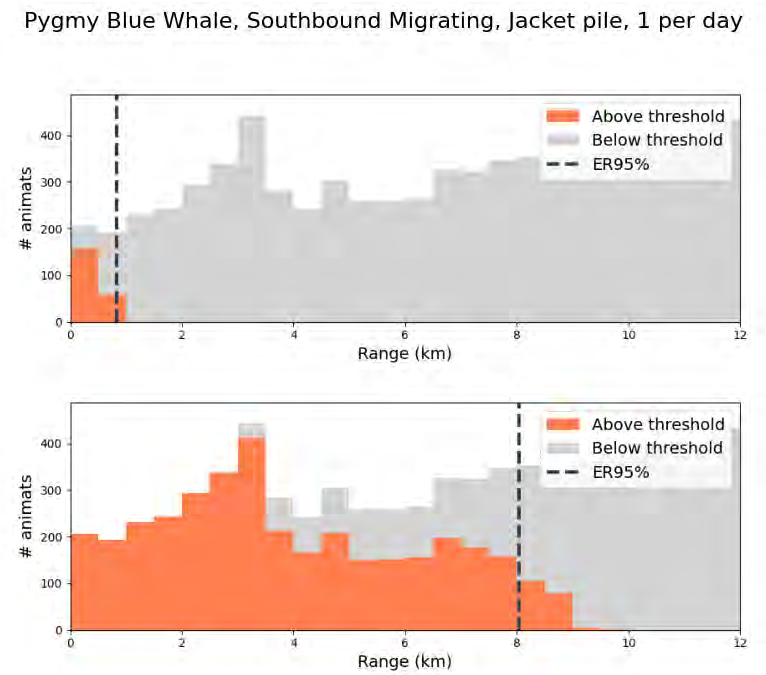


Figure E-141. Jacket pile, 1 per day, PULSE+DBBC, Pygmy Blue Whale, Southbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

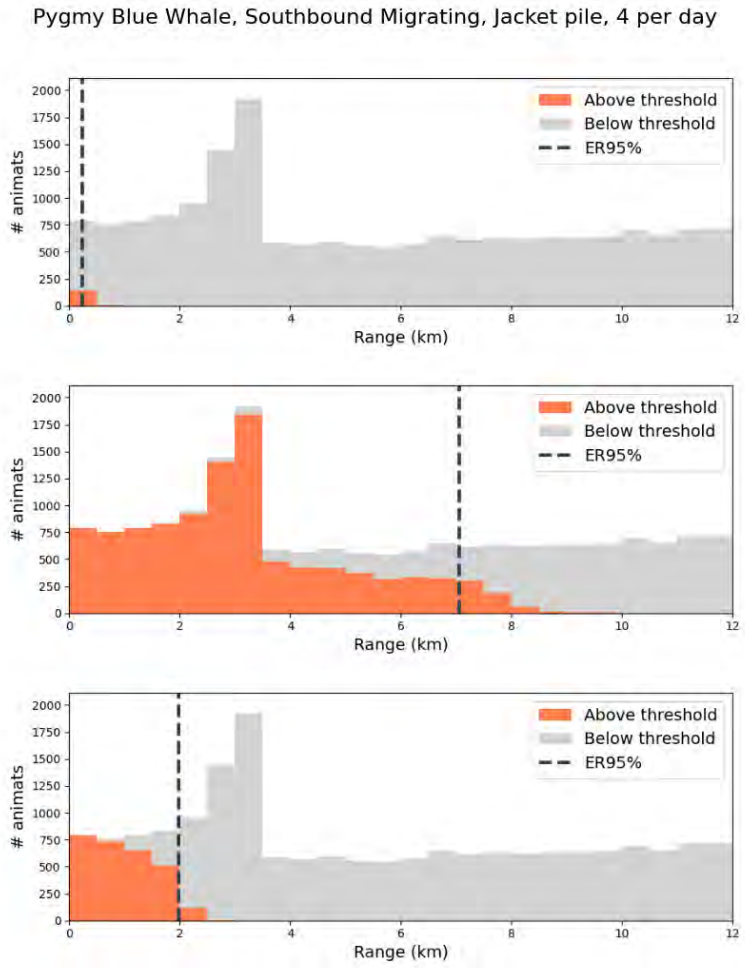


Figure E-142. Jacket pile, 4 per day, PULSE+DBBC, Pygmy Blue Whale, Southbound Migrating, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

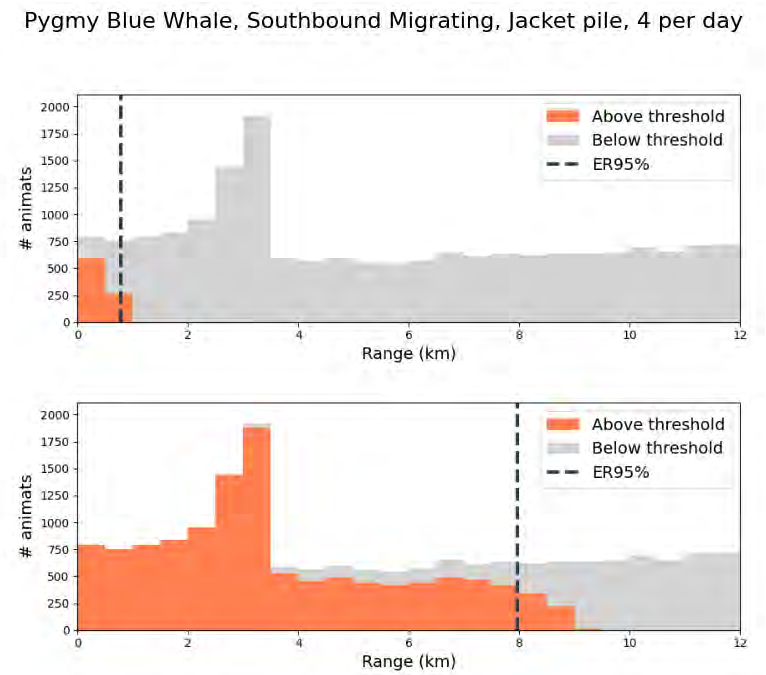


Figure E-143. Jacket pile, 4 per day, PULSE+DBBC, Pygmy Blue Whale, Southbound Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

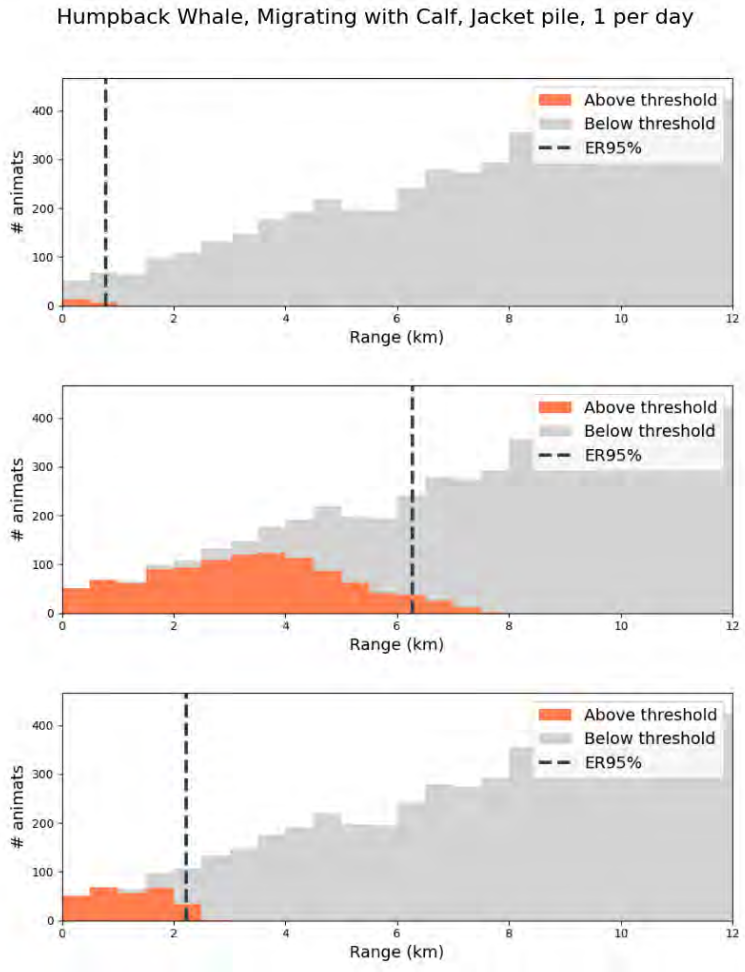


Figure E-144. Jacket pile, 1 per day, PULSE+DBBC, Humpback Whale, Migrating with Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

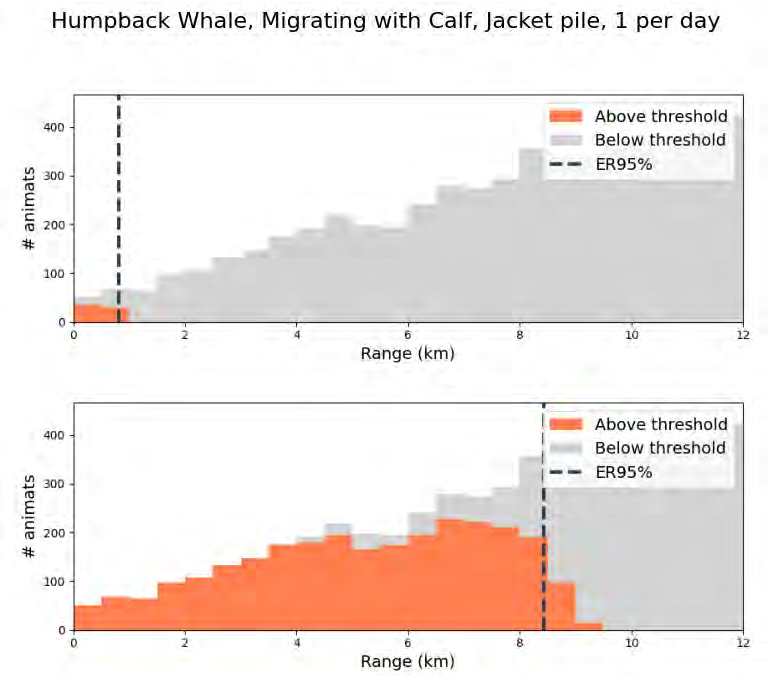


Figure E-145. Jacket pile, 1 per day, PULSE+DBBC, Humpback Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

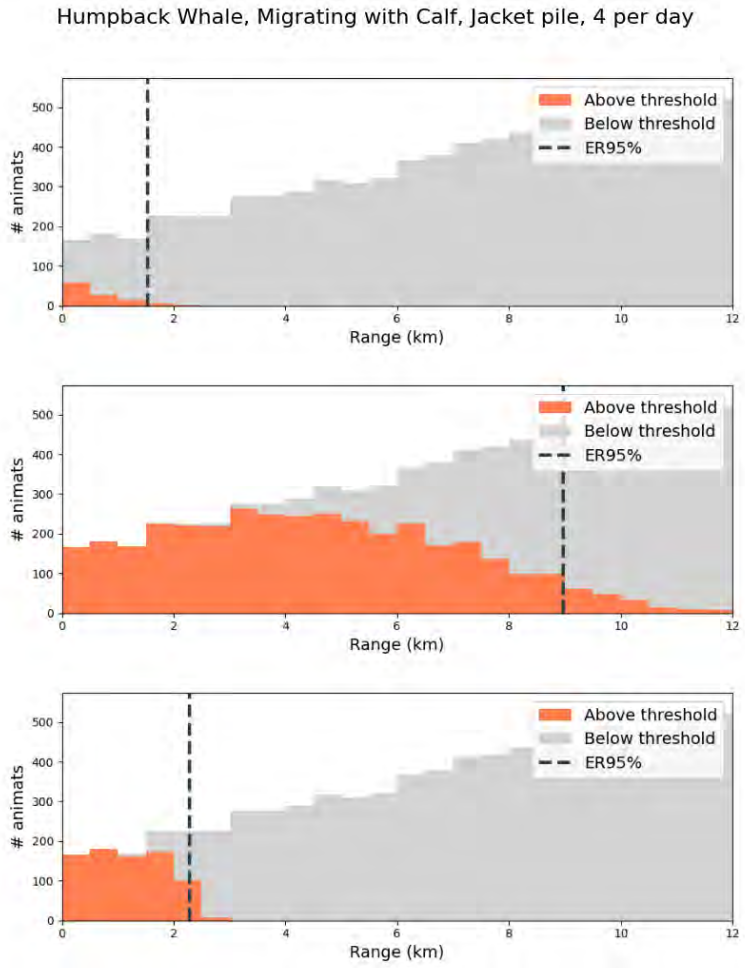


Figure E-146. Jacket pile, 4 per day, PULSE+DBBC, Humpback Whale, Migrating with Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

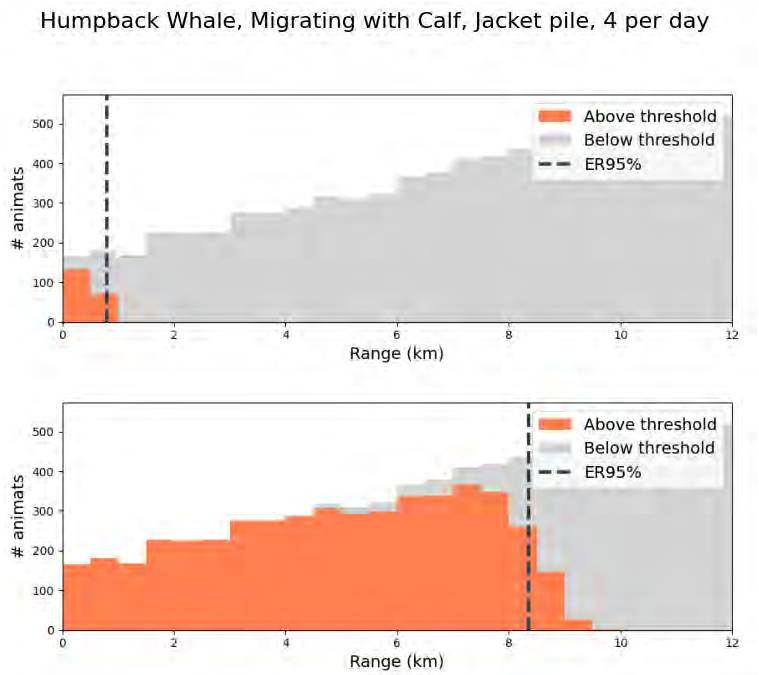


Figure E-147. Jacket pile, 4 per day, PULSE+DBBC, Humpback Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

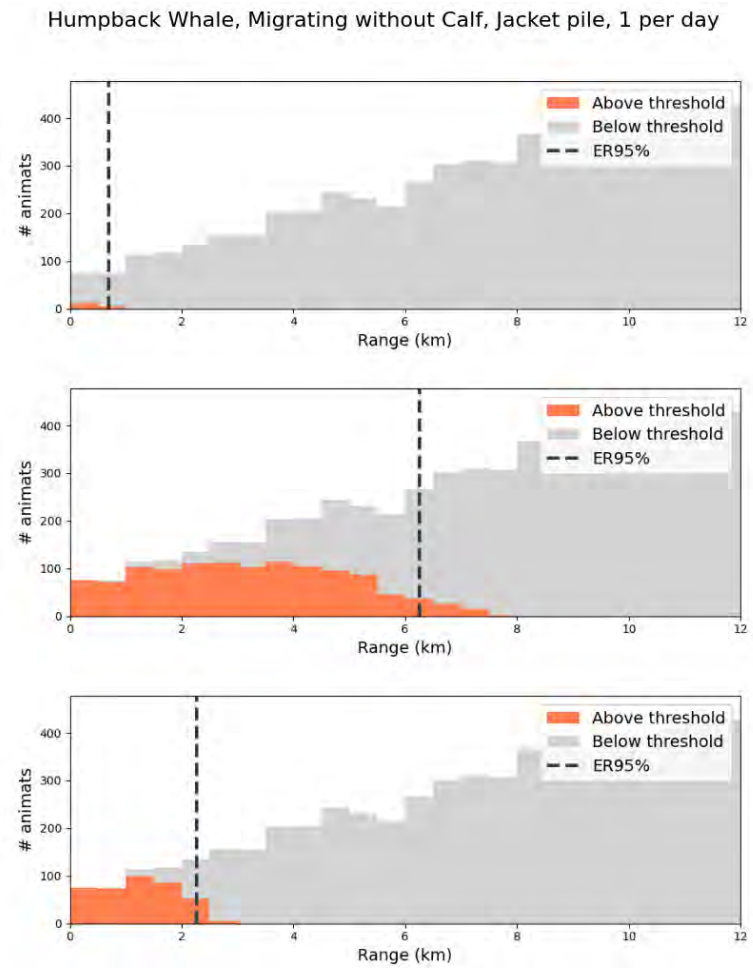


Figure E-148. Jacket pile, 1 per day, PULSE+DBBC, Humpback Whale, Migrating without Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

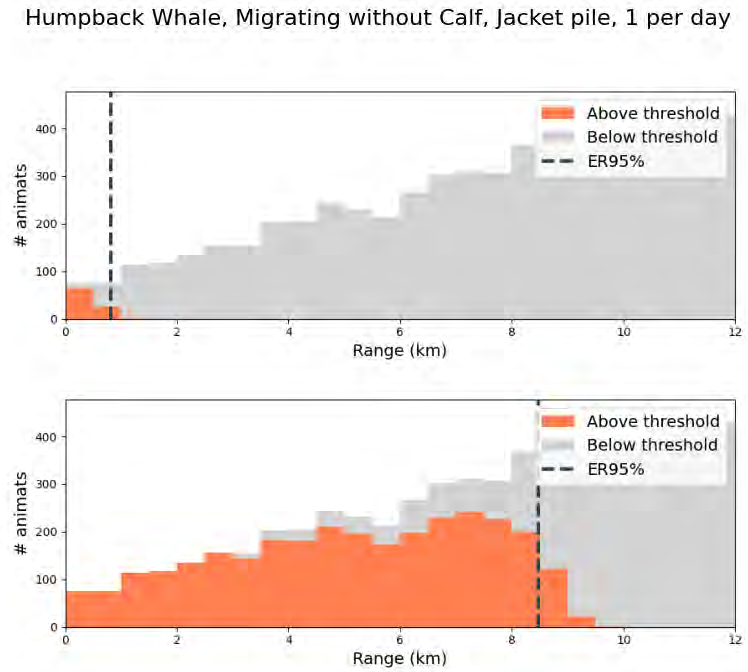


Figure E-149. Jacket pile, 1 per day, PULSE+DBBC, Humpback Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

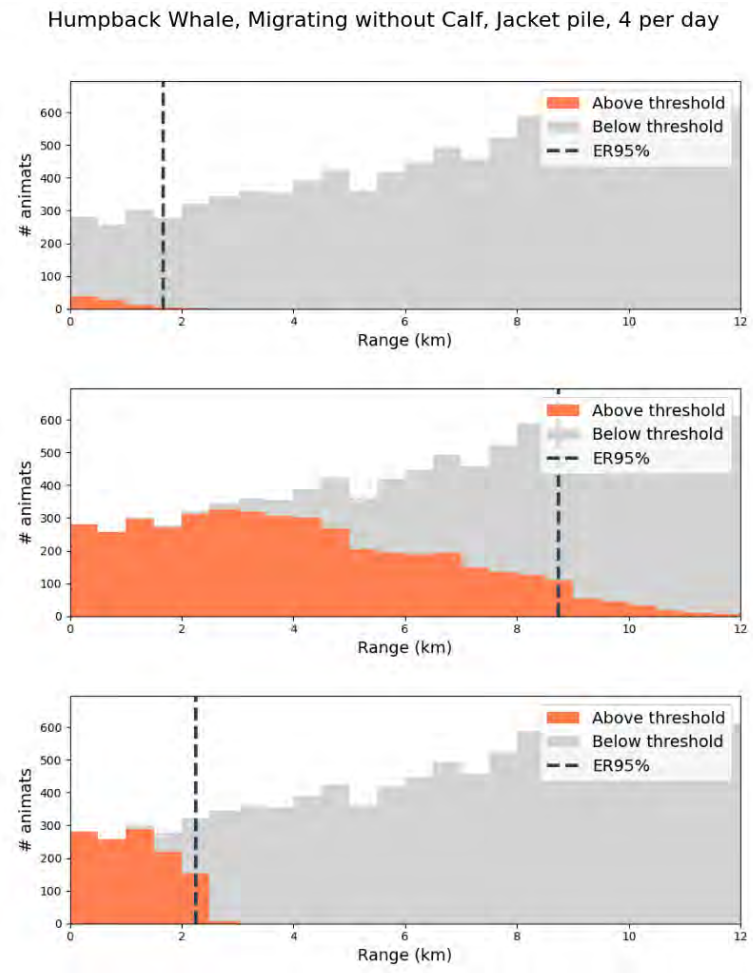


Figure E-150. Jacket pile, 4 per day, PULSE+DBBC, Humpback Whale, Migrating without Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

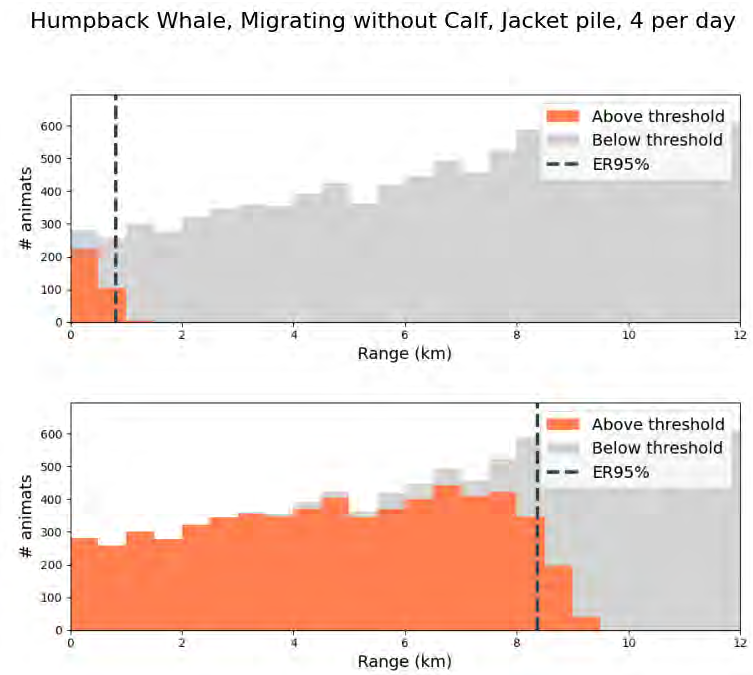


Figure E-151. Jacket pile, 4 per day, PULSE+DBBC, Humpback Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

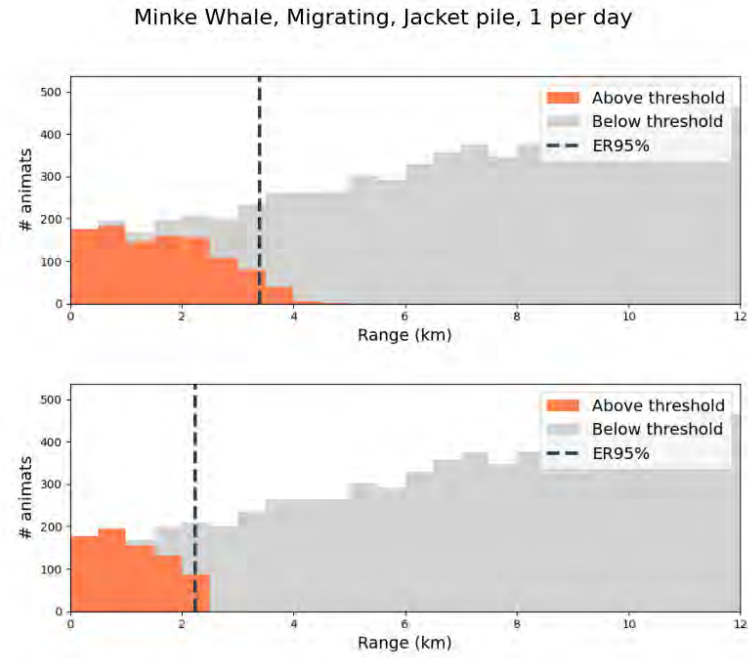


Figure E-152. Jacket pile, 1 per day, PULSE+DBBC, Minke Whale, Migrating, TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

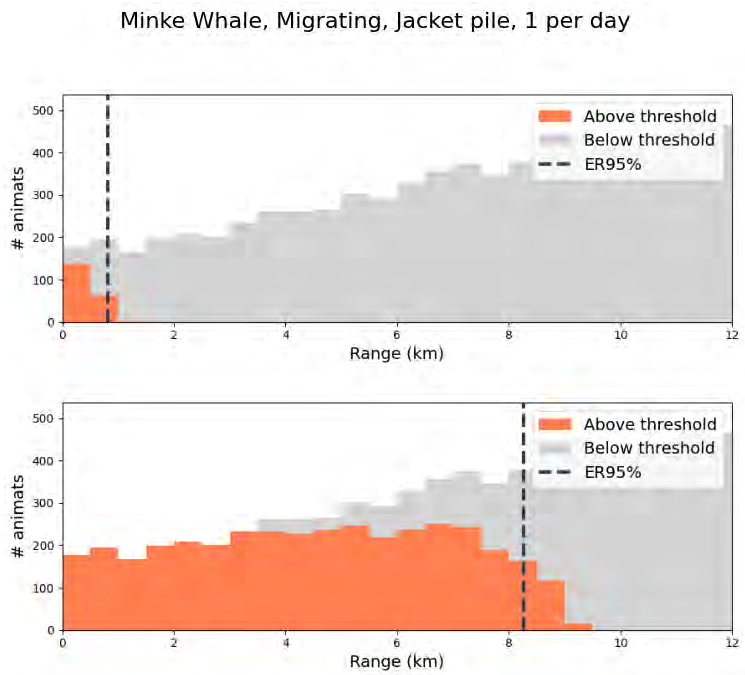


Figure E-153. Jacket pile, 1 per day, PULSE+DBBC, Minke Whale, Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

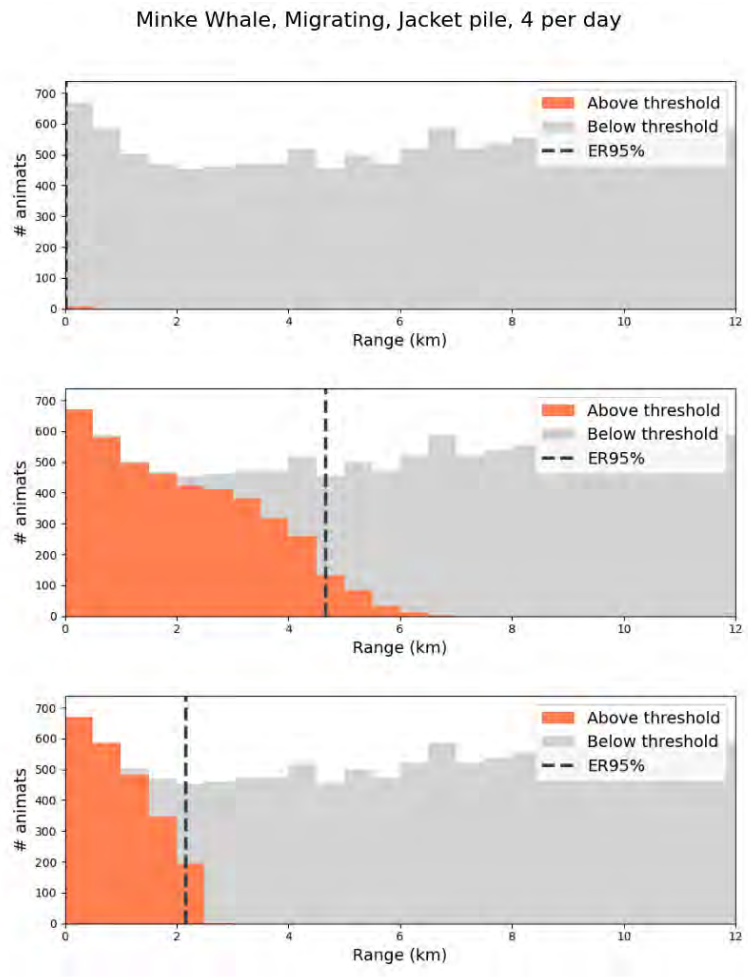


Figure E-154. Jacket pile, 4 per day, PULSE+DBBC, Minke Whale, Migrating, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

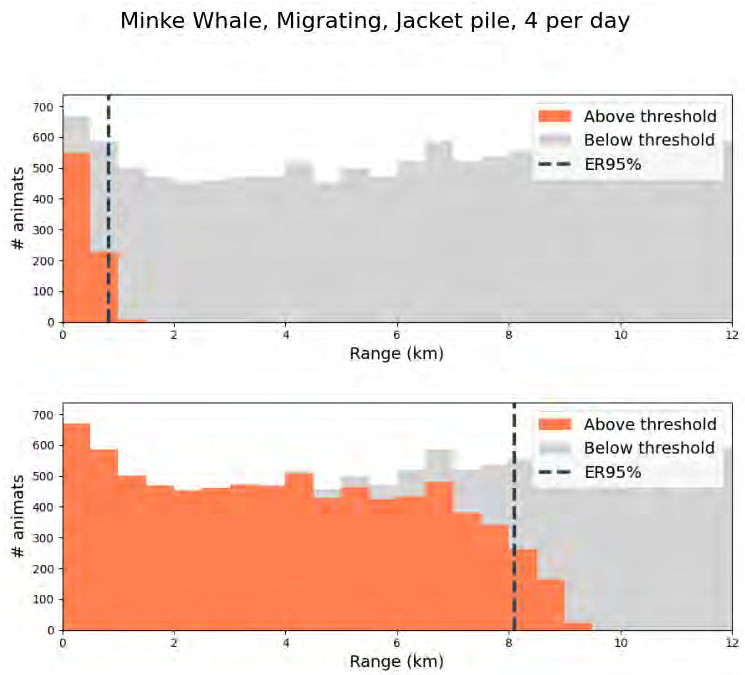


Figure E-155. Jacket pile, 4 per day, PULSE+DBBC, Minke Whale, Migrating, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

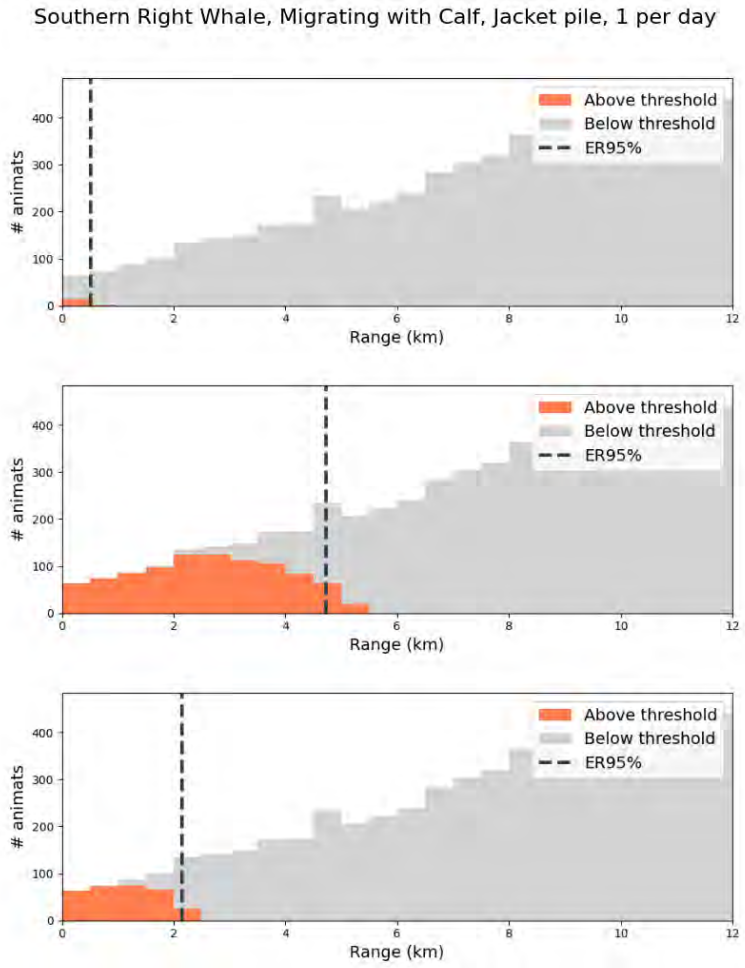


Figure E-156. Jacket pile, 1 per day, PULSE+DBBC, Southern Right Whale, Migrating with Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

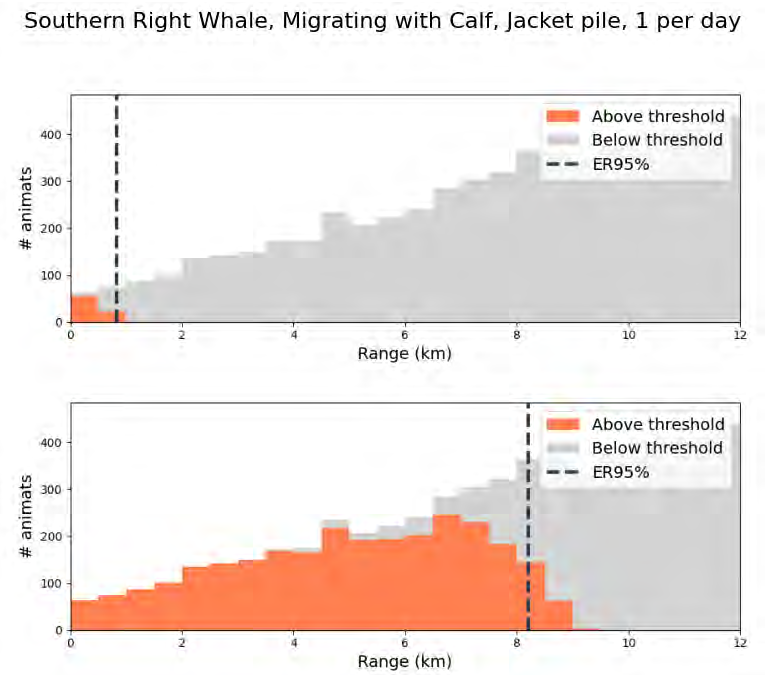


Figure E-157. Jacket pile, 1 per day, PULSE+DBBC, Southern Right Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

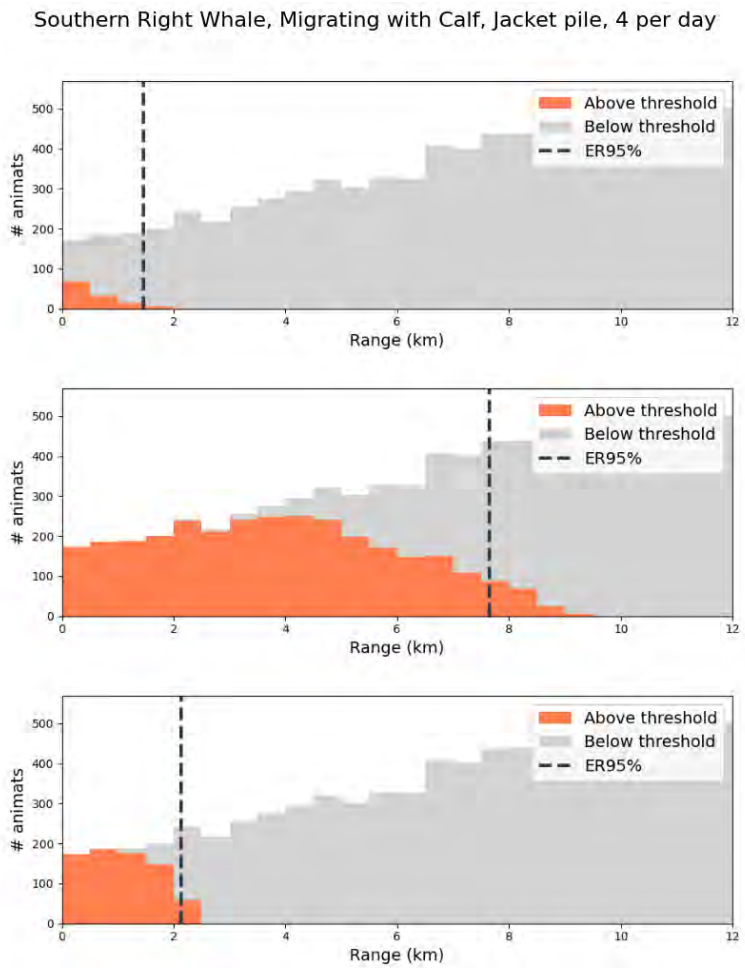


Figure E-158. Jacket pile, 4 per day, PULSE+DBBC, Southern Right Whale, Migrating with Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

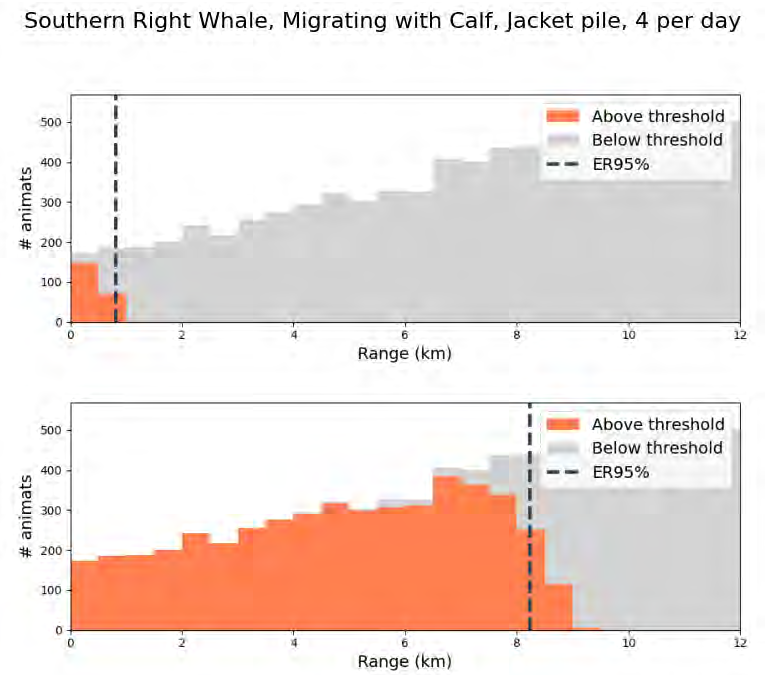


Figure E-159. Jacket pile, 4 per day, PULSE+DBBC, Southern Right Whale, Migrating with Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

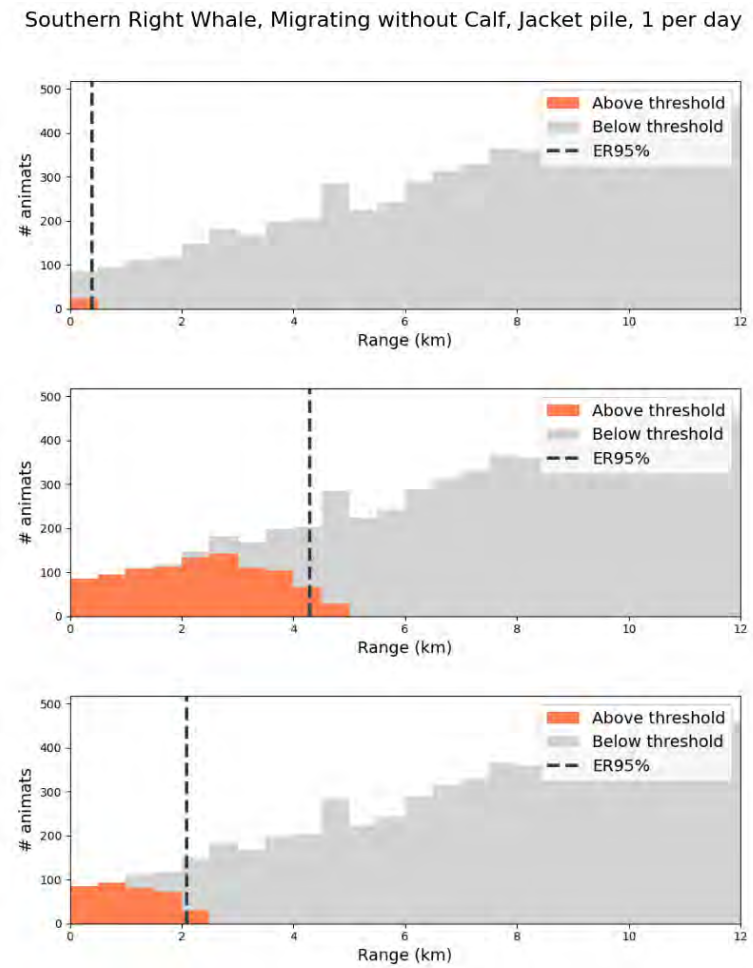


Figure E-160. Jacket pile, 1 per day, PULSE+DBBC, Southern Right Whale, Migrating without Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

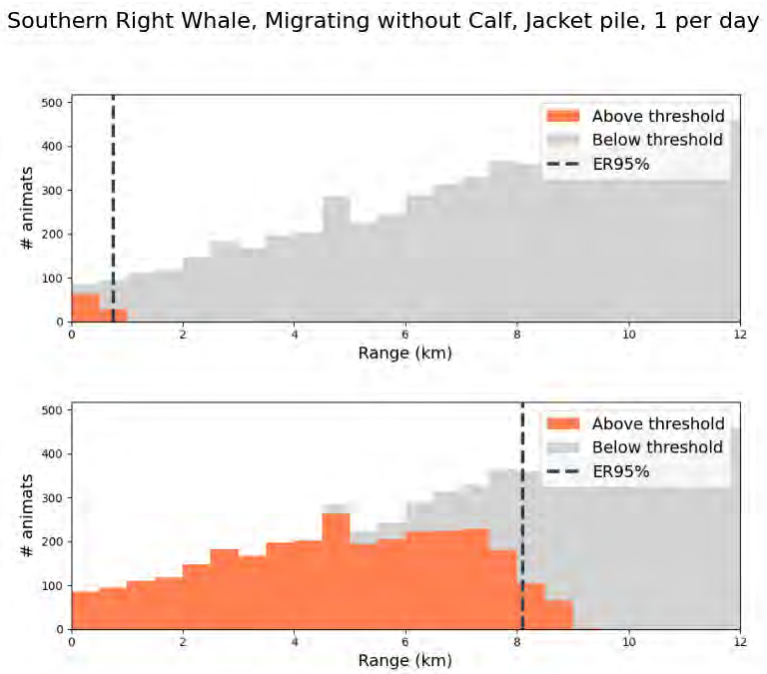


Figure E-161. Jacket pile, 1 per day, PULSE+DBBC, Southern Right Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

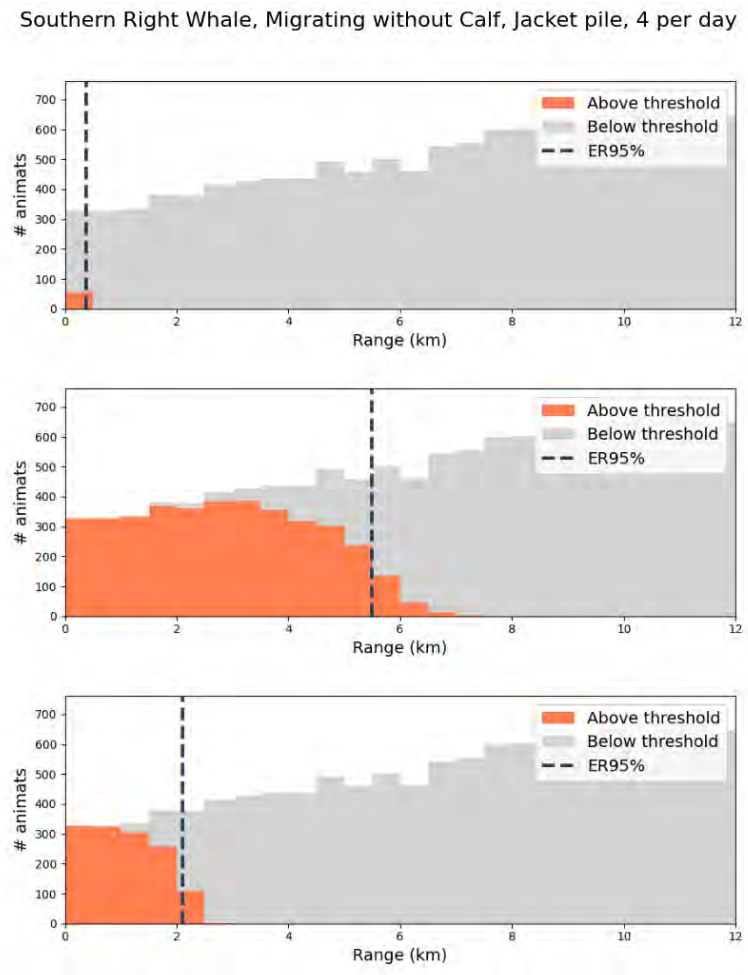


Figure E-162. Jacket pile, 4 per day, PULSE+DBBC, Southern Right Whale, Migrating without Calf, PTS (top), TTS (middle) and SPL behavioural response (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

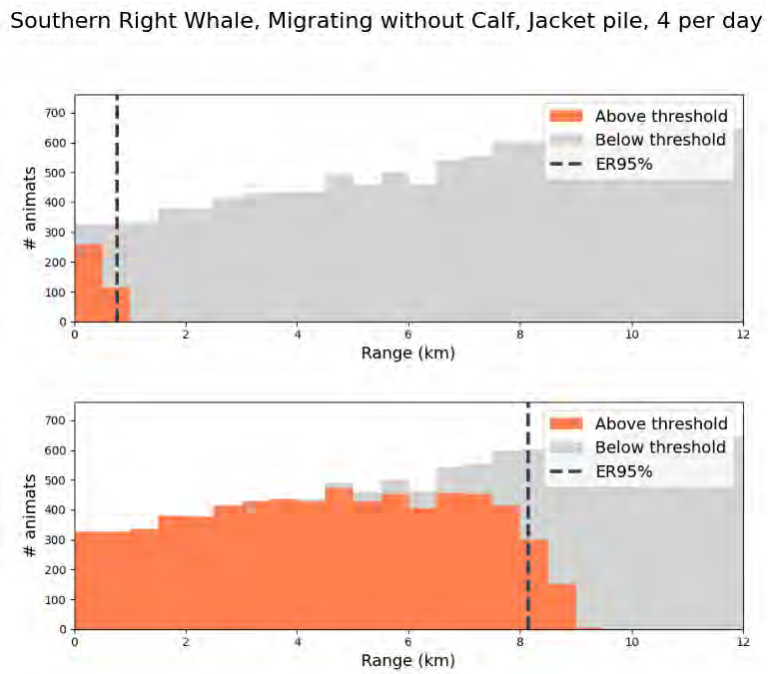


Figure E-163. Jacket pile, 4 per day, PULSE+DBBC, Southern Right Whale, Migrating without Calf, Wood et al. (2012) 50% behavioural threshold for non-migrating mysticetes (>160 dB re 1 µPa weighted SPL) (top), and Wood et al (2012) 50% behavioural threshold for migrating mysticetes (>140 dB re 1 µPa weighted SPL) (bottom) threshold: CPA range histogram for animat to the jacket pile. Bar colours indicate whether the animats exceeded the threshold.

E.2. Vessels

E.2.1. Scenario 1 – WTGIV + PSV + CLV (Third Modelling Round)

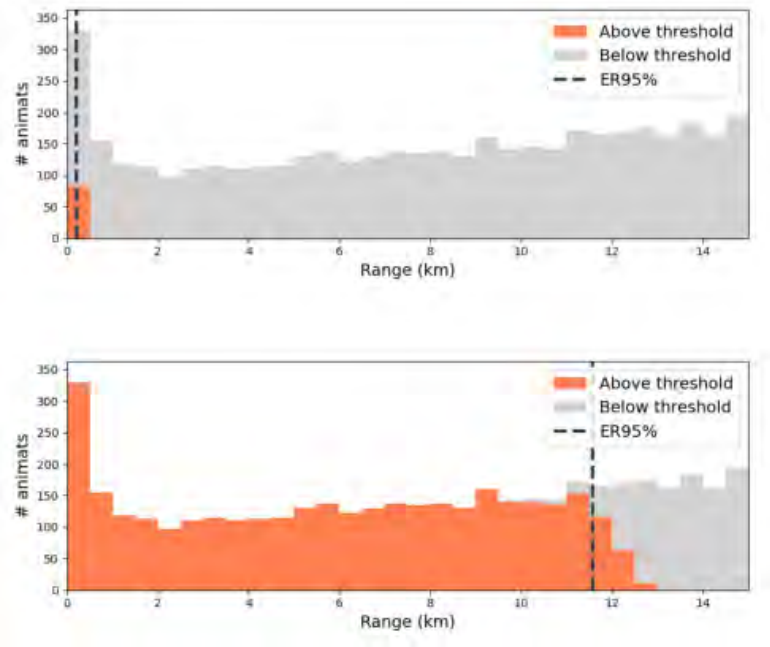


Figure E-164. Intermediate Shallow, pygmy blue whale, feeding, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

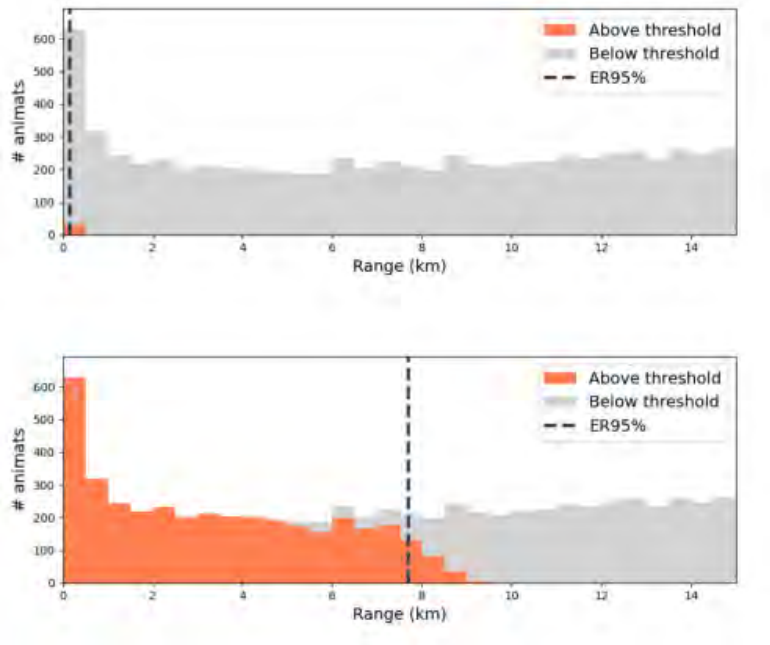


Figure E-165. Deep, pygmy blue whale, feeding, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

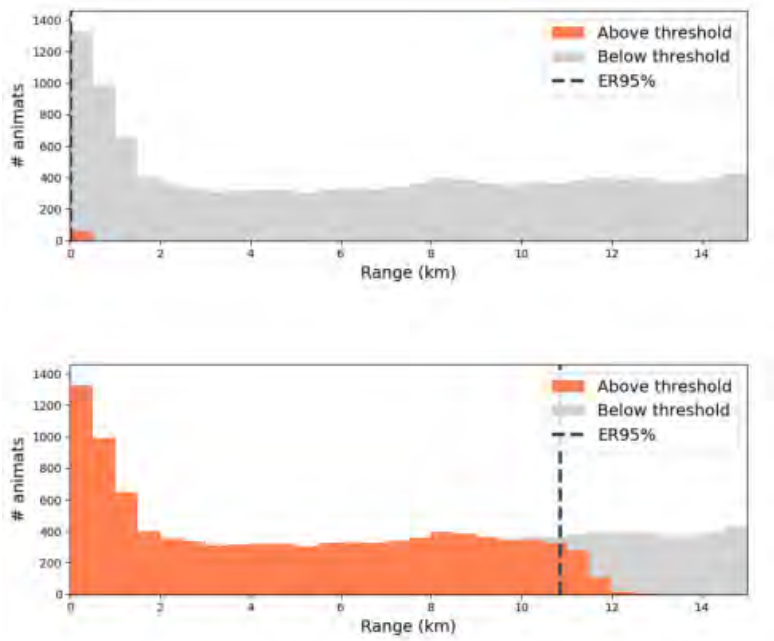


Figure E-166. Intermediate Shallow, pygmy blue whale, northbound migrating, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

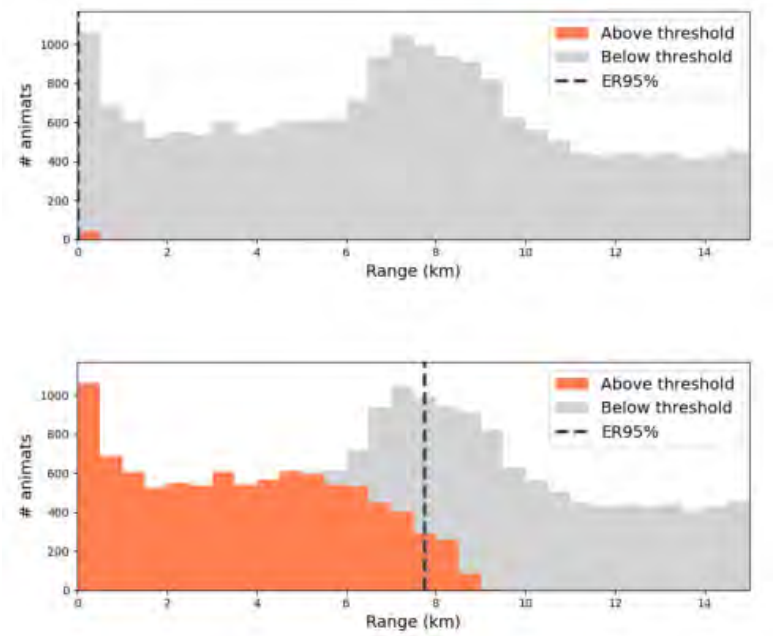


Figure E-167. Deep, pygmy blue whale, northbound migrating, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

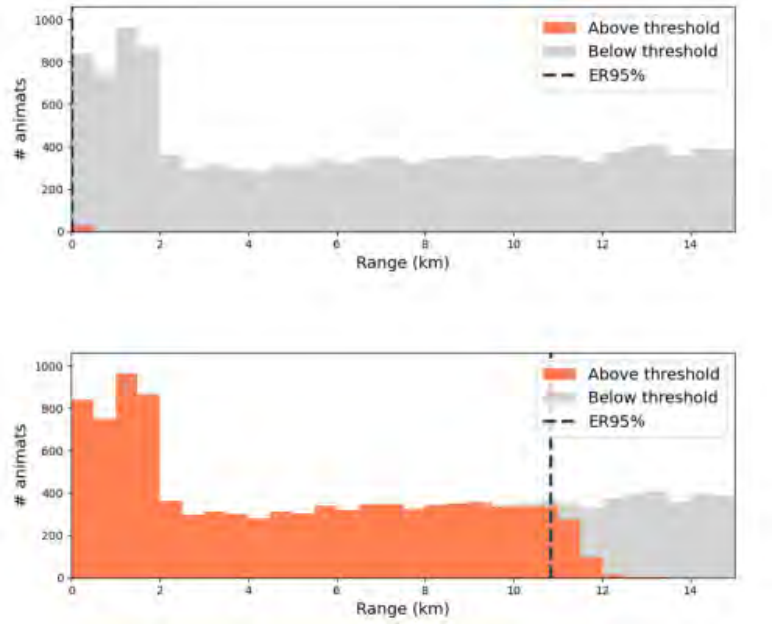


Figure E-168. Intermediate Shallow, pygmy blue whale, southbound migrating, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

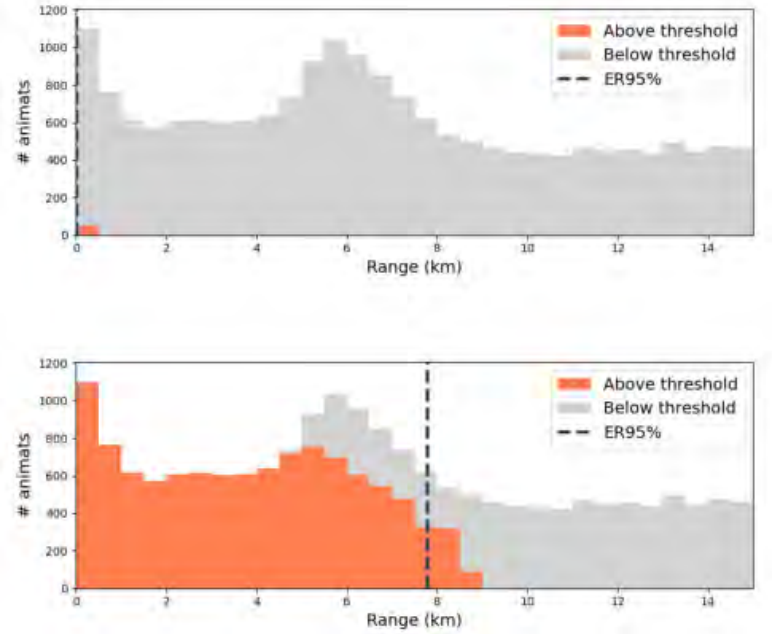


Figure E-169. Deep, pygmy blue whale, southbound migrating, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

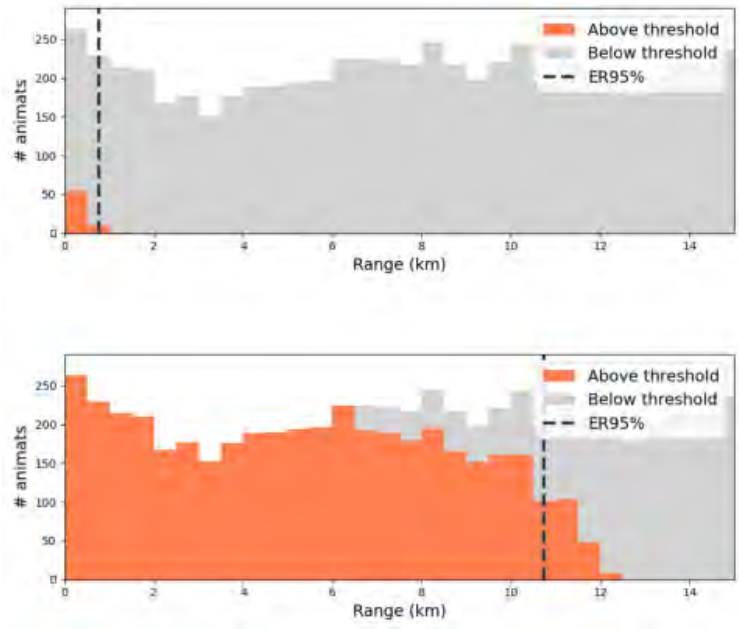


Figure E-170. Intermediate Shallow, humpback whale, migrating with calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

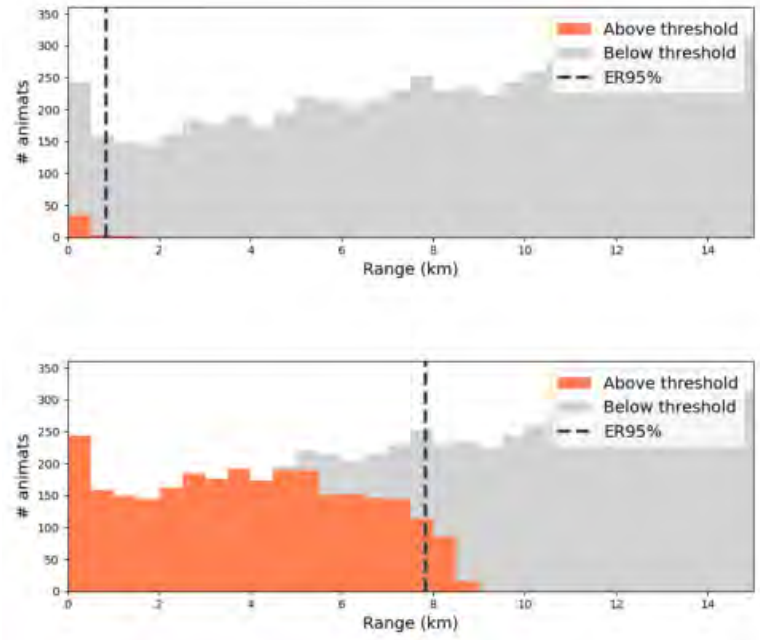


Figure E-171. Deep, humpback whale, migrating with calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

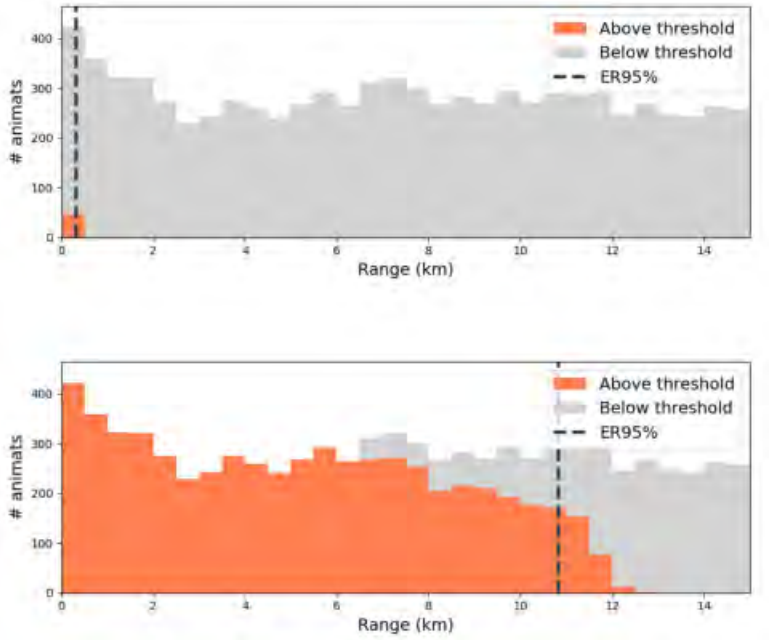


Figure E-172. Intermediate Shallow, humpback whale, migrating without calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

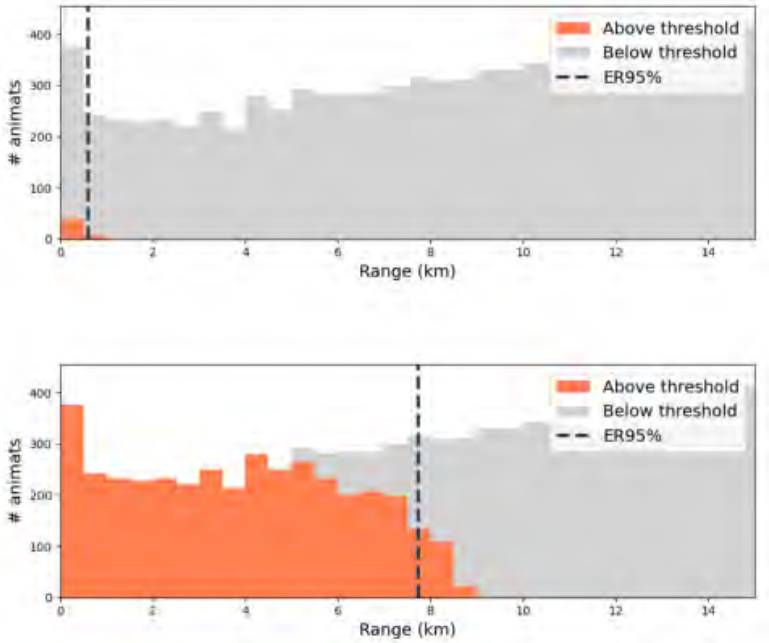


Figure E-173. Deep, humpback whale, migrating without calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

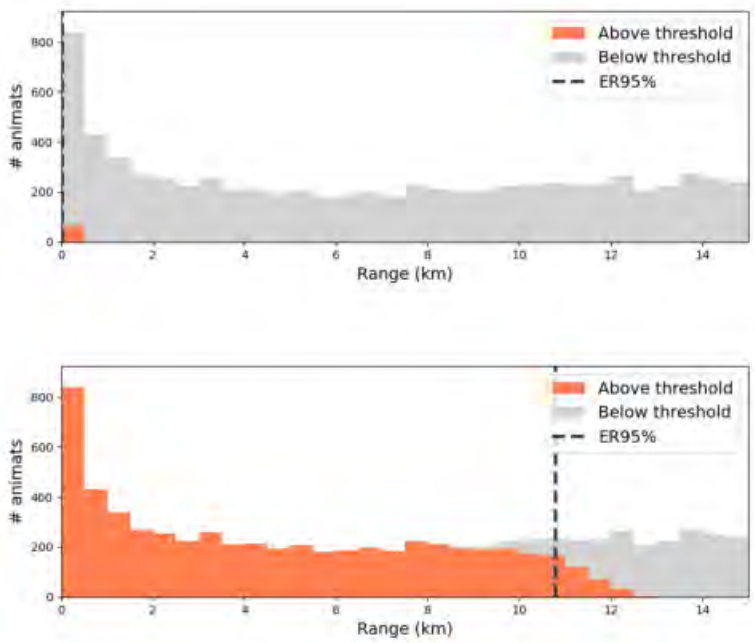


Figure E-174. Intermediate Shallow, minke whale, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

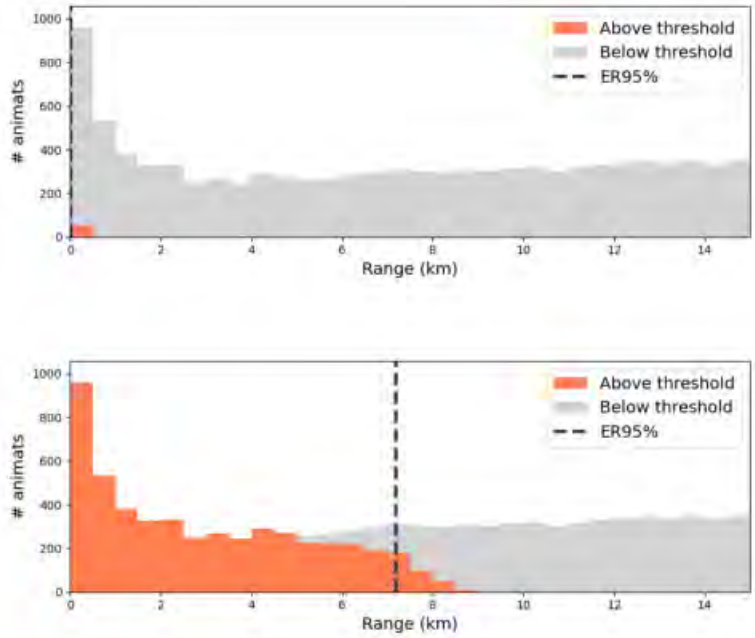


Figure E-175. Deep, minke whale, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

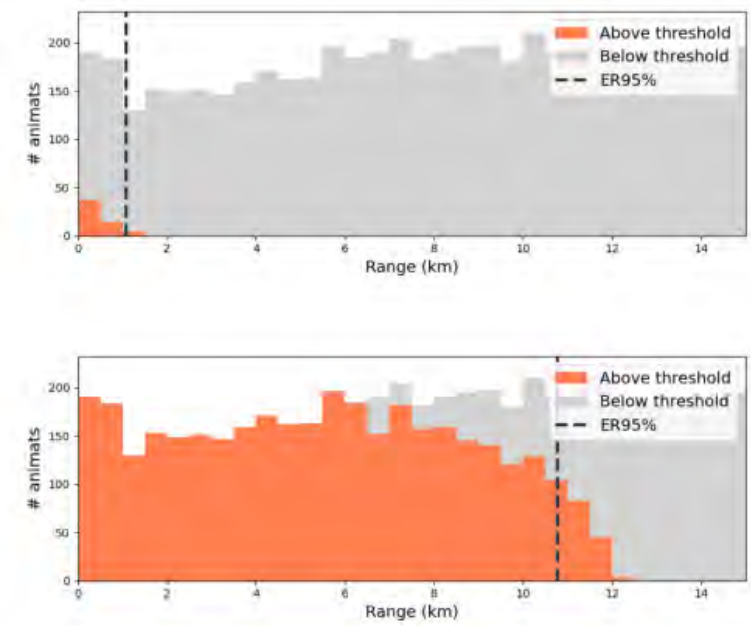


Figure E-176. Intermediate Shallow, Southern Right Whale, migrating with calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

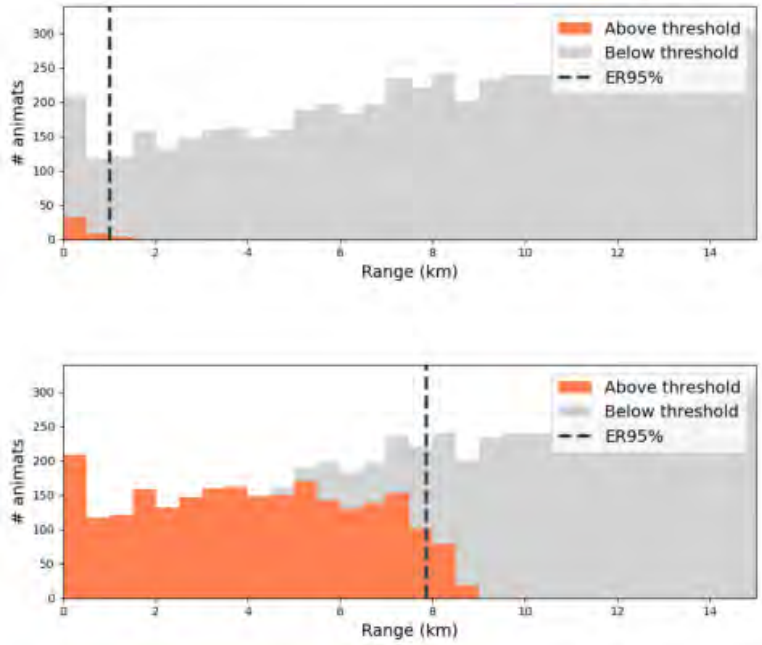


Figure E-177. Deep, Southern Right Whale, migrating with calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

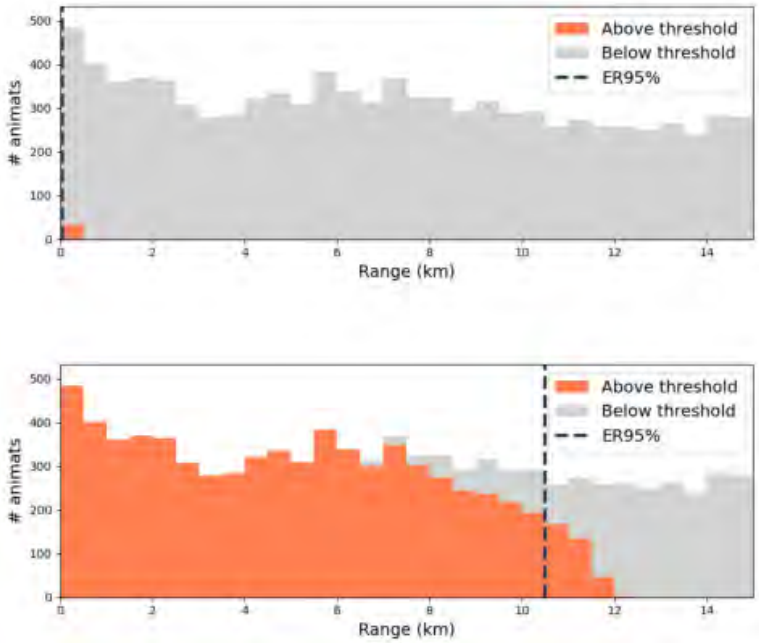


Figure E-178. Intermediate Shallow, Southern Right Whale, migrating without calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

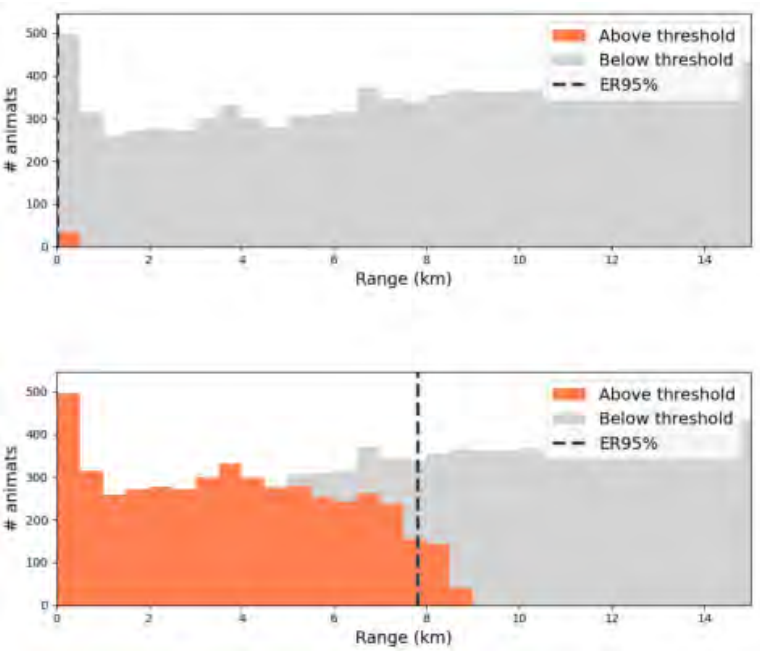


Figure E-179. Deep, Southern Right Whale, migrating without calf, SEL_{24h} TTS (top) and SPL behavioural response (bottom) threshold: CPA range histogram for animats to vessels. Bar colours indicate whether the animats exceeded the threshold.

Appendix F. Additional Results: Per-Strike Vertical Slice Plots

F.1. Impact Pile Driving

F.1.1. Monopile

F.1.1.1. Scenario 1 – Unmitigated (First Modelling Round)

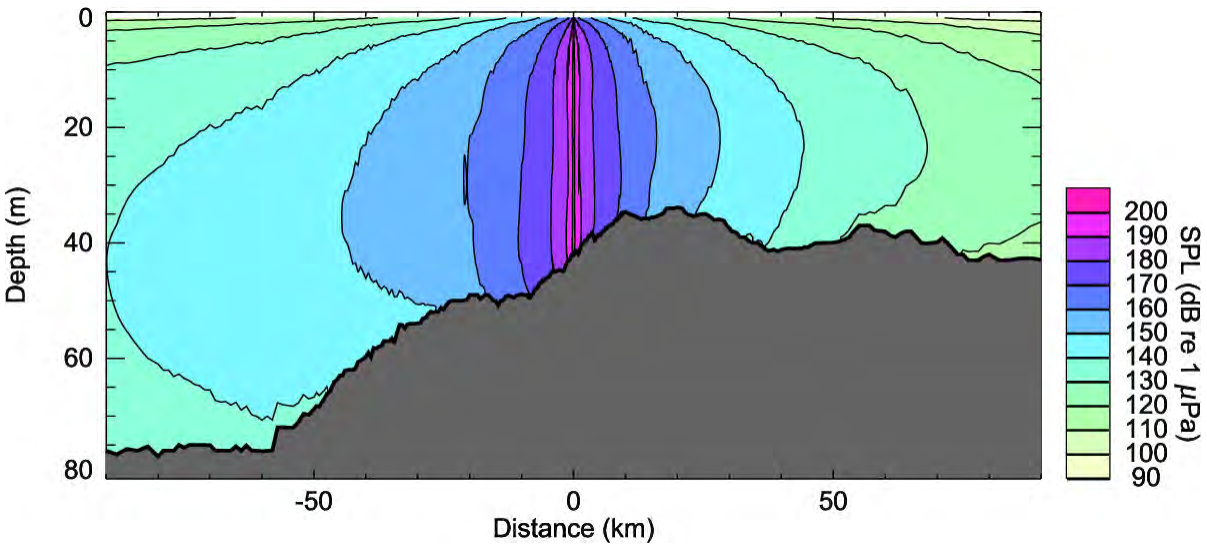


Figure F-1. *Monopile 1, summer, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 45°/225° from North (positive distance/negative distance).

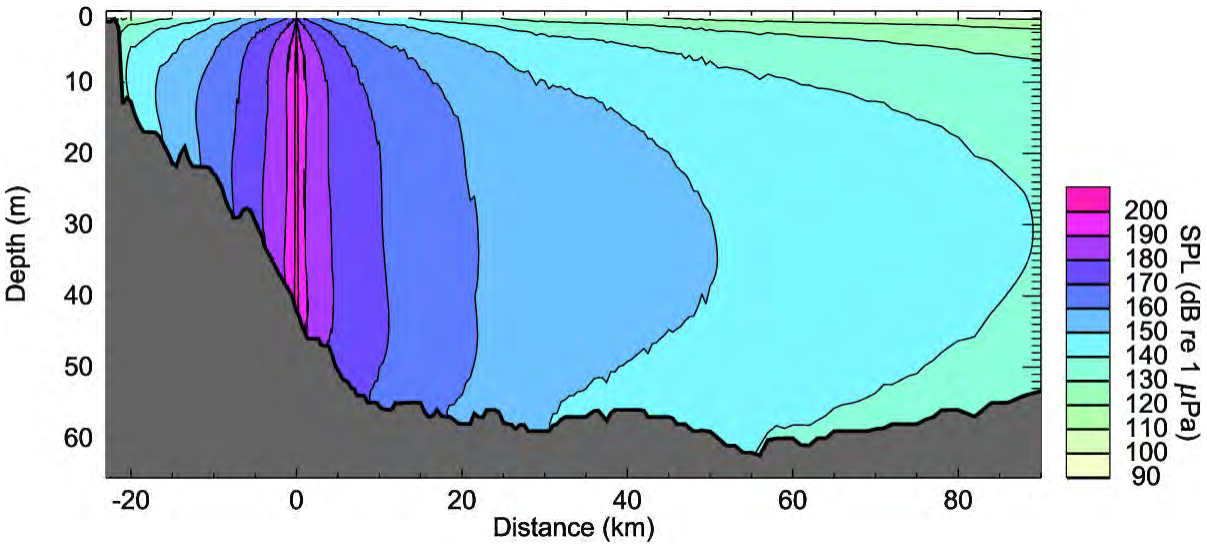


Figure F-2. *Monopile 1, summer, SPL: Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

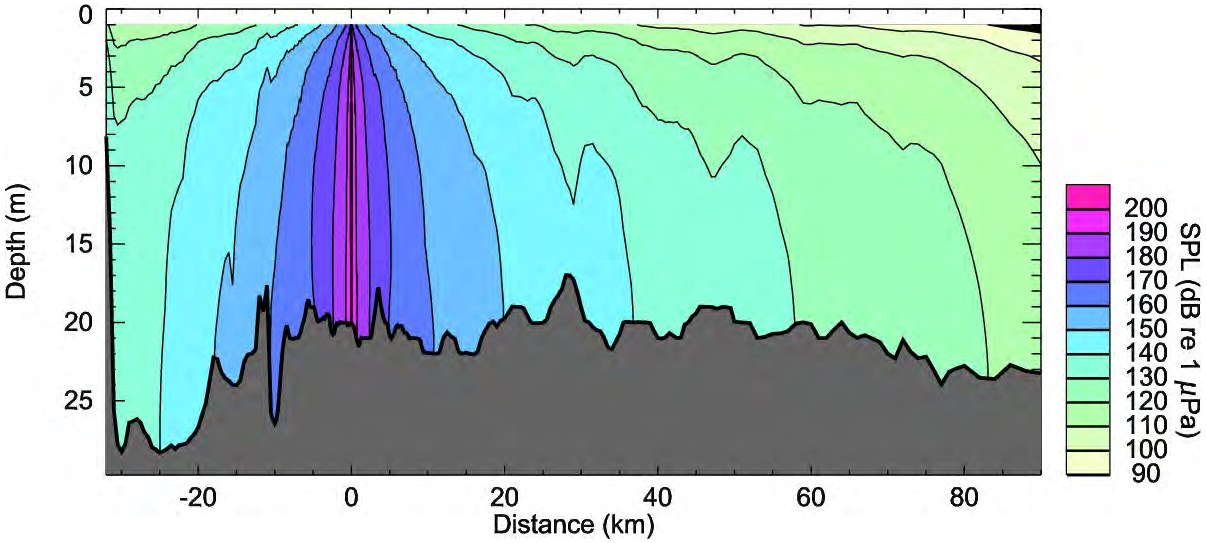


Figure F-3. *Monopile 2, summer, SPL: Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

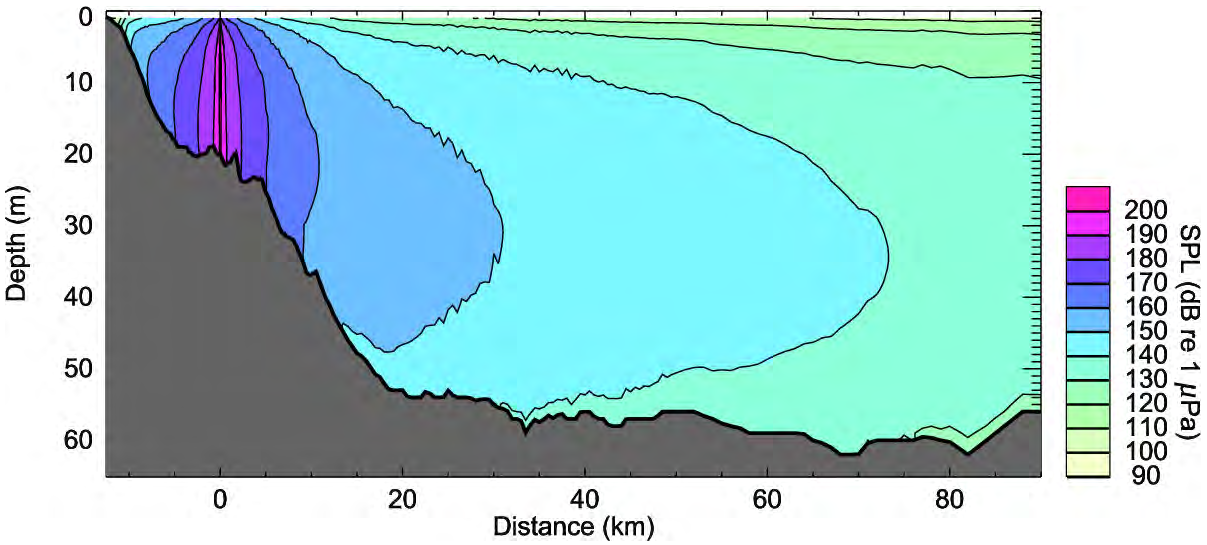


Figure F-4. *Monopile 2, summer, SPL: Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

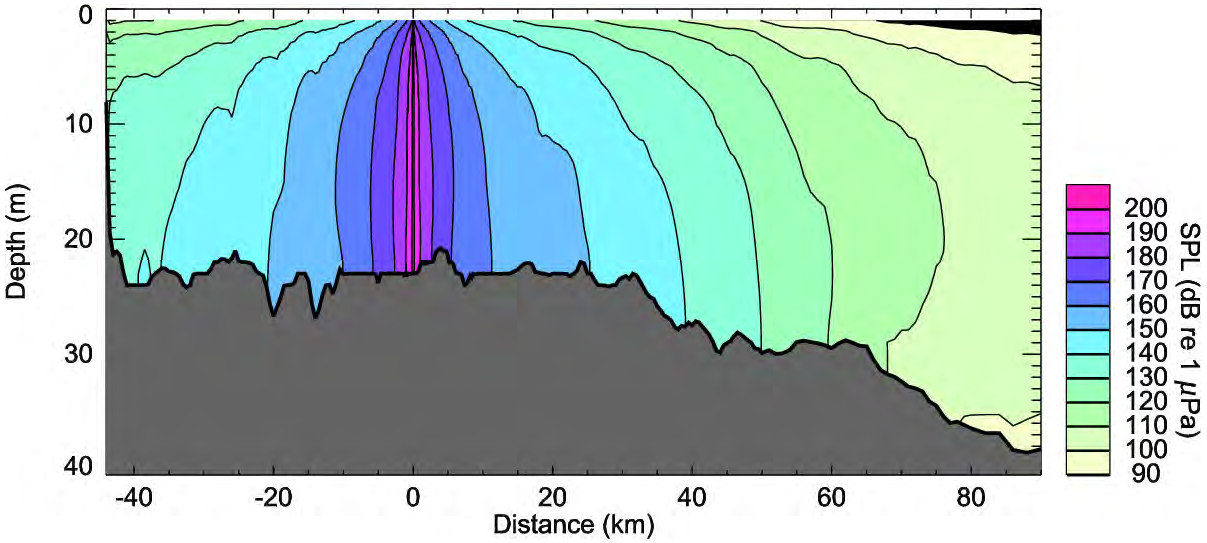


Figure F-5. *Monopile 3, summer, SPL: Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

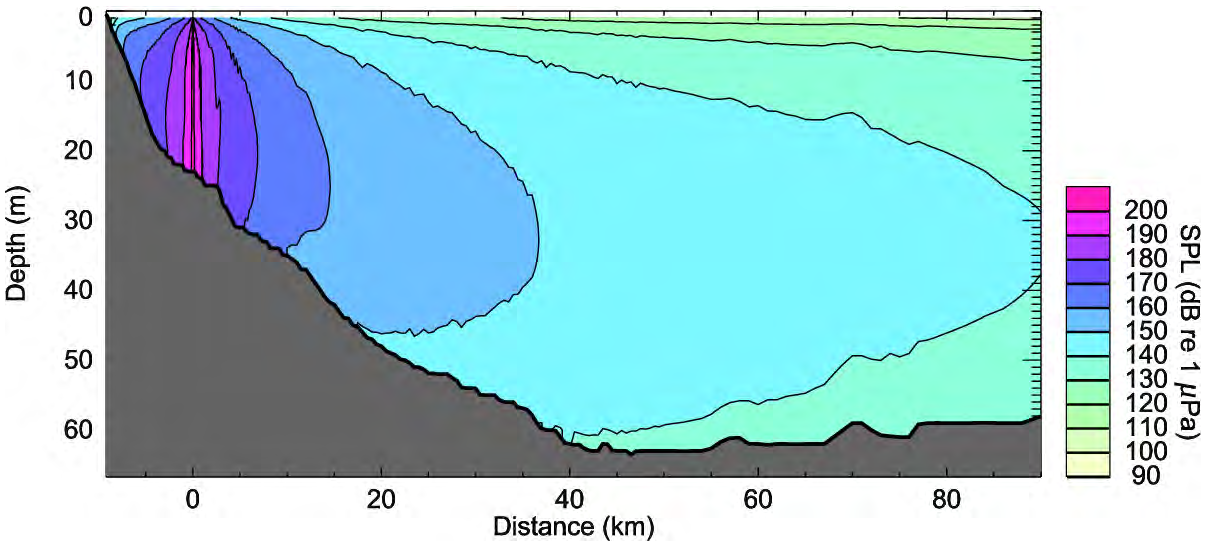


Figure F-6. *Monopile 3, summer, SPL: Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

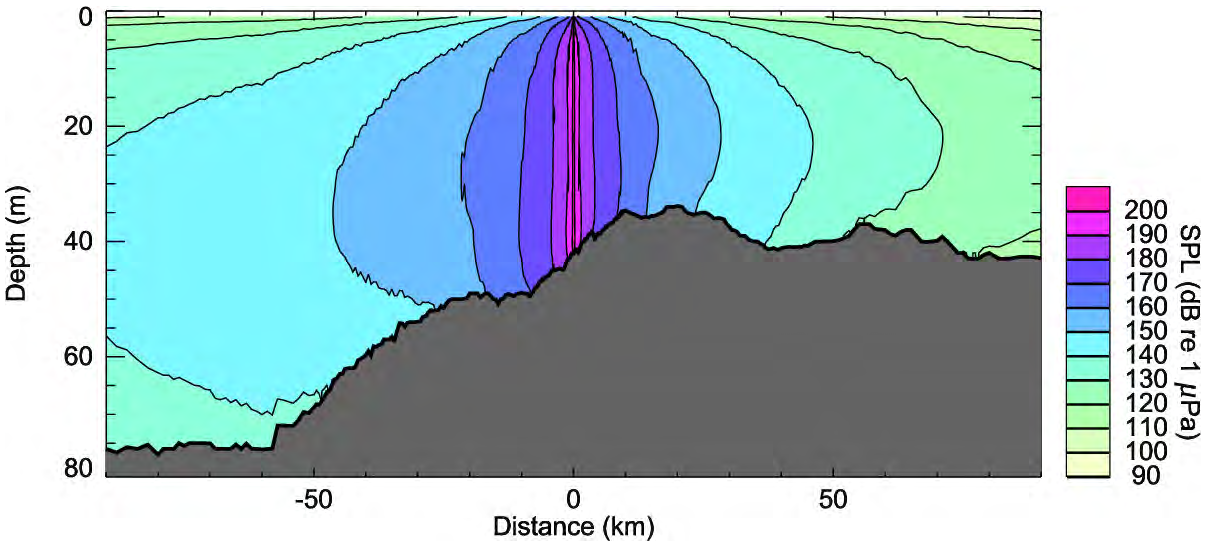


Figure F-7. *Monopile 1, winter, SPL*: Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 45°/225° from North (positive distance/negative distance).

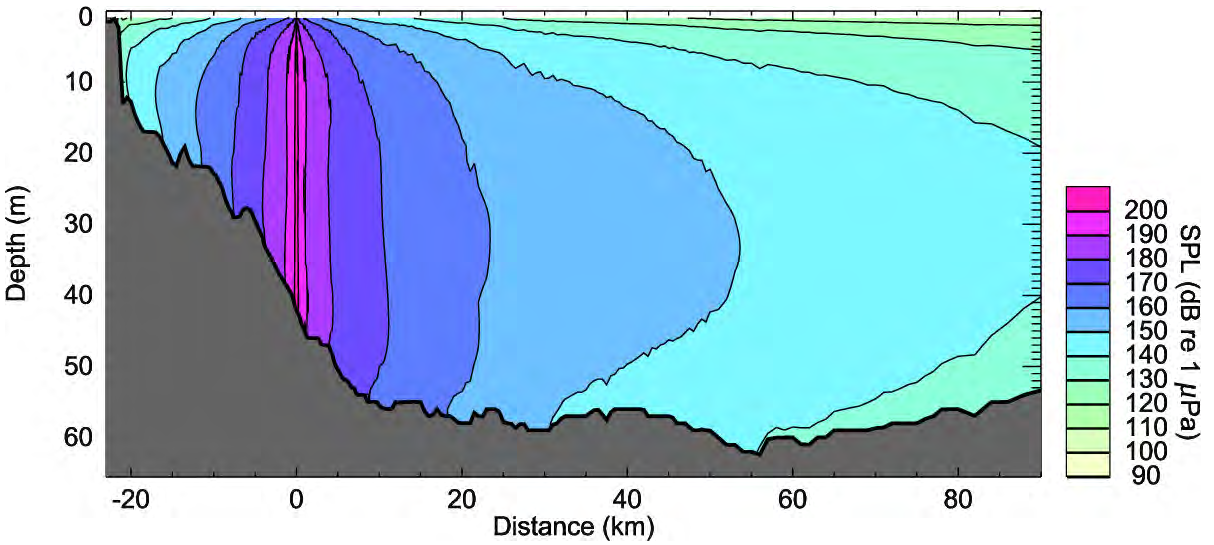


Figure F-8. *Monopile 1, winter, SPL*: Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

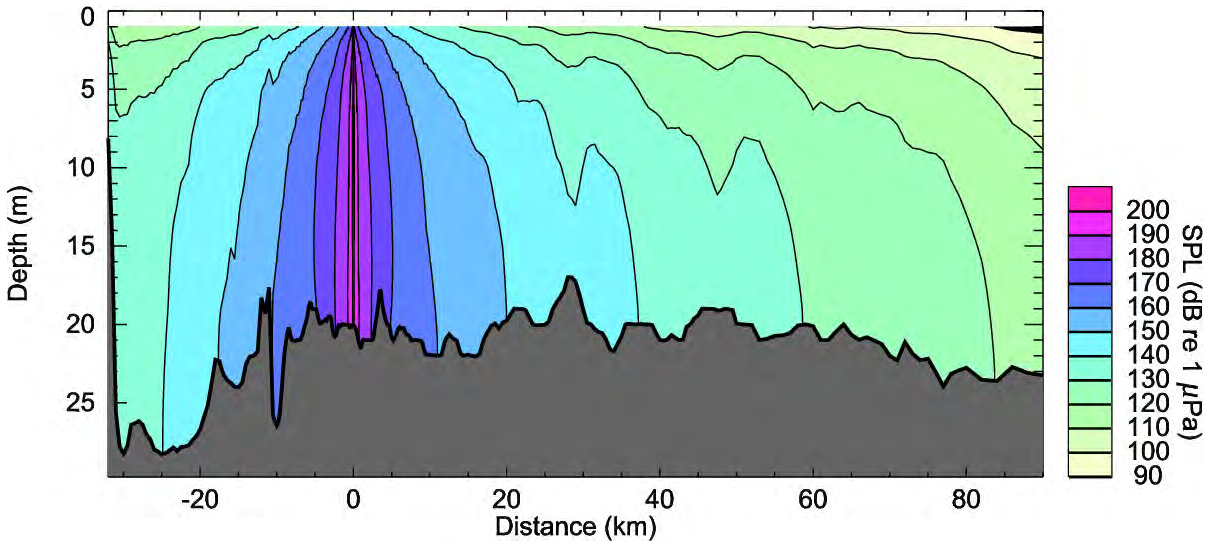


Figure F-9. *Monopile 2, winter, SPL*: Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 45°/225° from North (positive distance/negative distance).

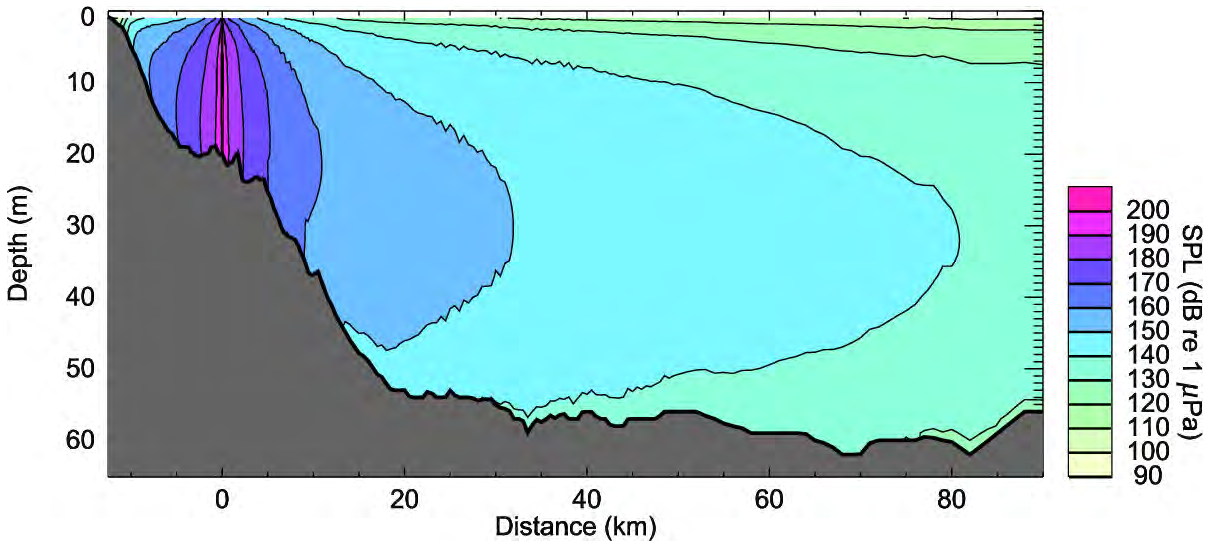


Figure F-10. *Monopile 2, winter, SPL*: Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

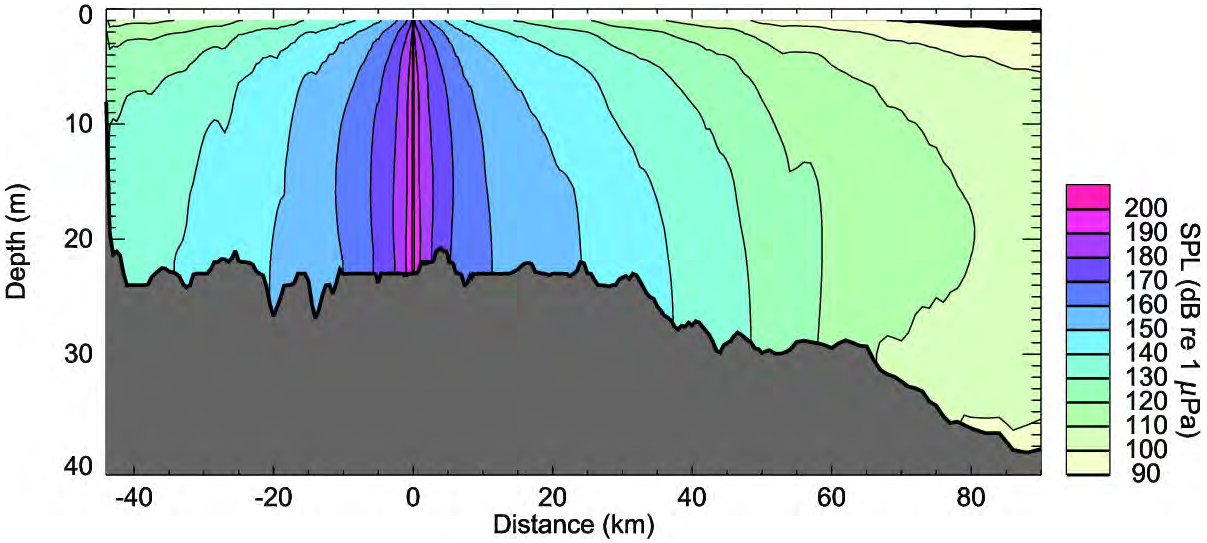


Figure F-11. *Monopile 3, winter, SPL*: Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 45°/225° from North (positive distance/negative distance).

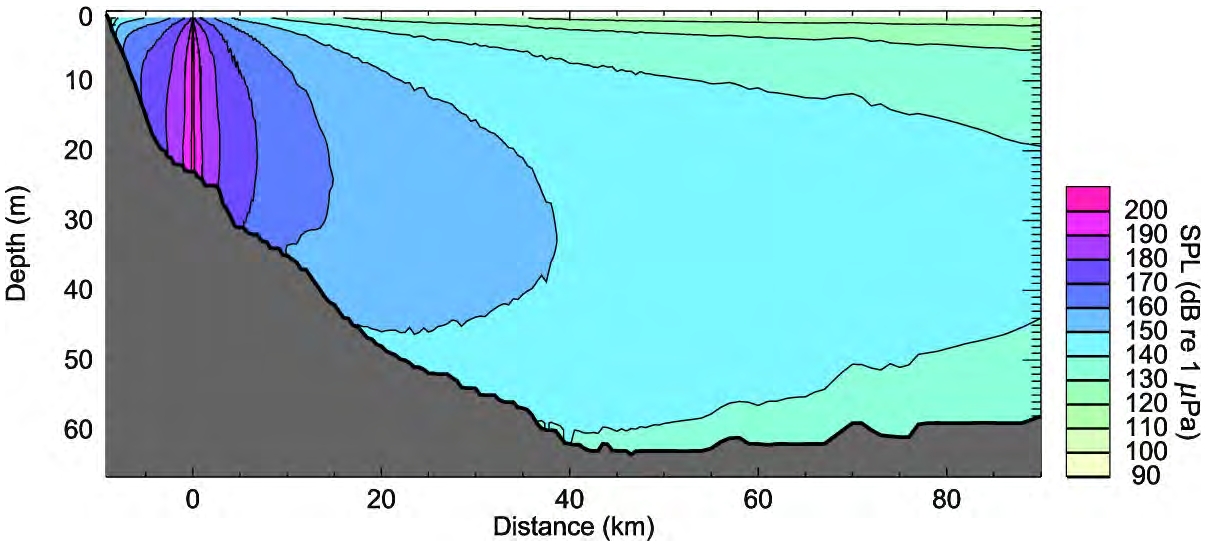


Figure F-12. *Monopile 3, winter, SPL*: Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

F.1.1.2. Scenario 2 – DBBC (First Modelling Round)

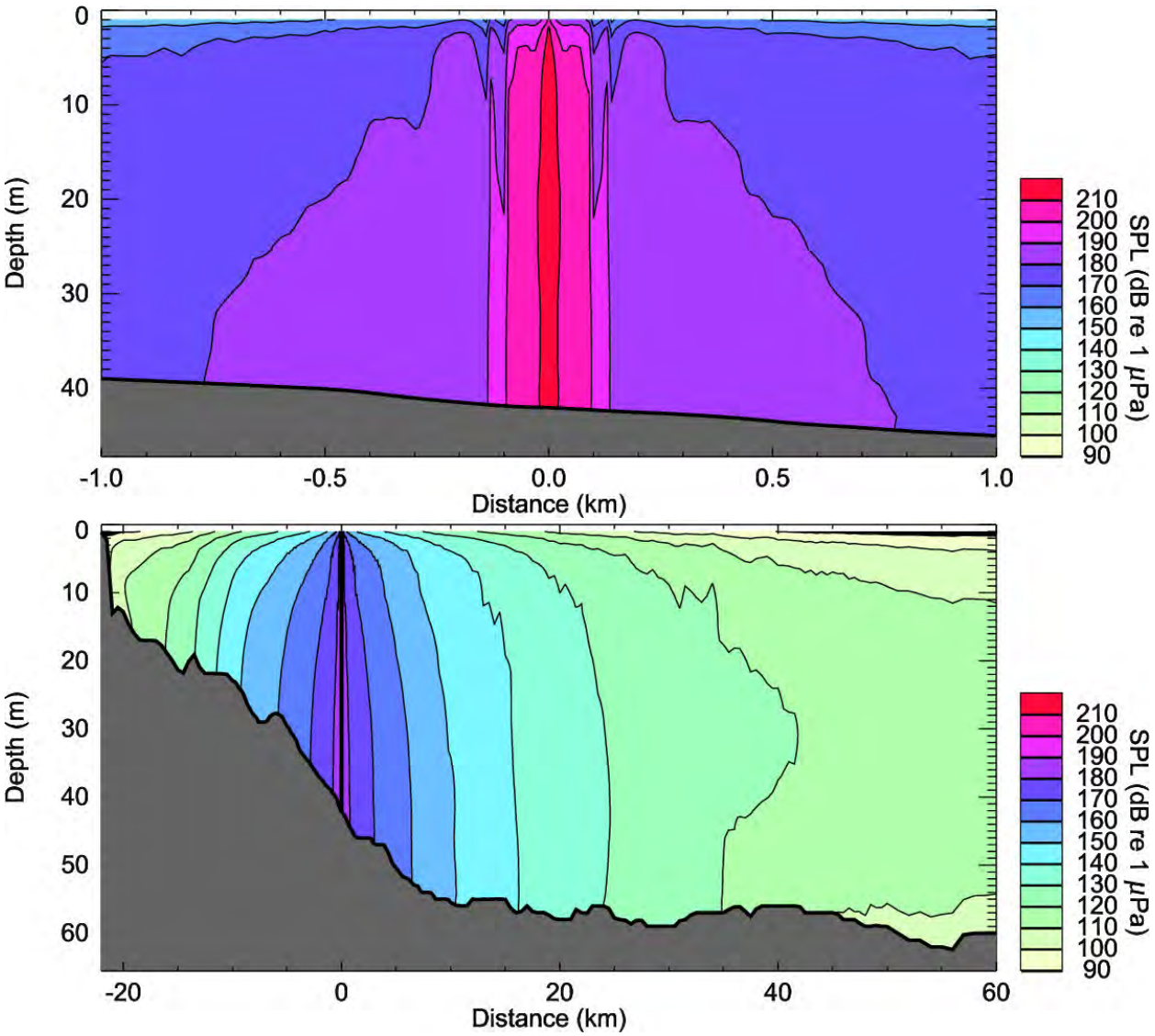


Figure F-13. *Monopile 1, - DBBC, Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

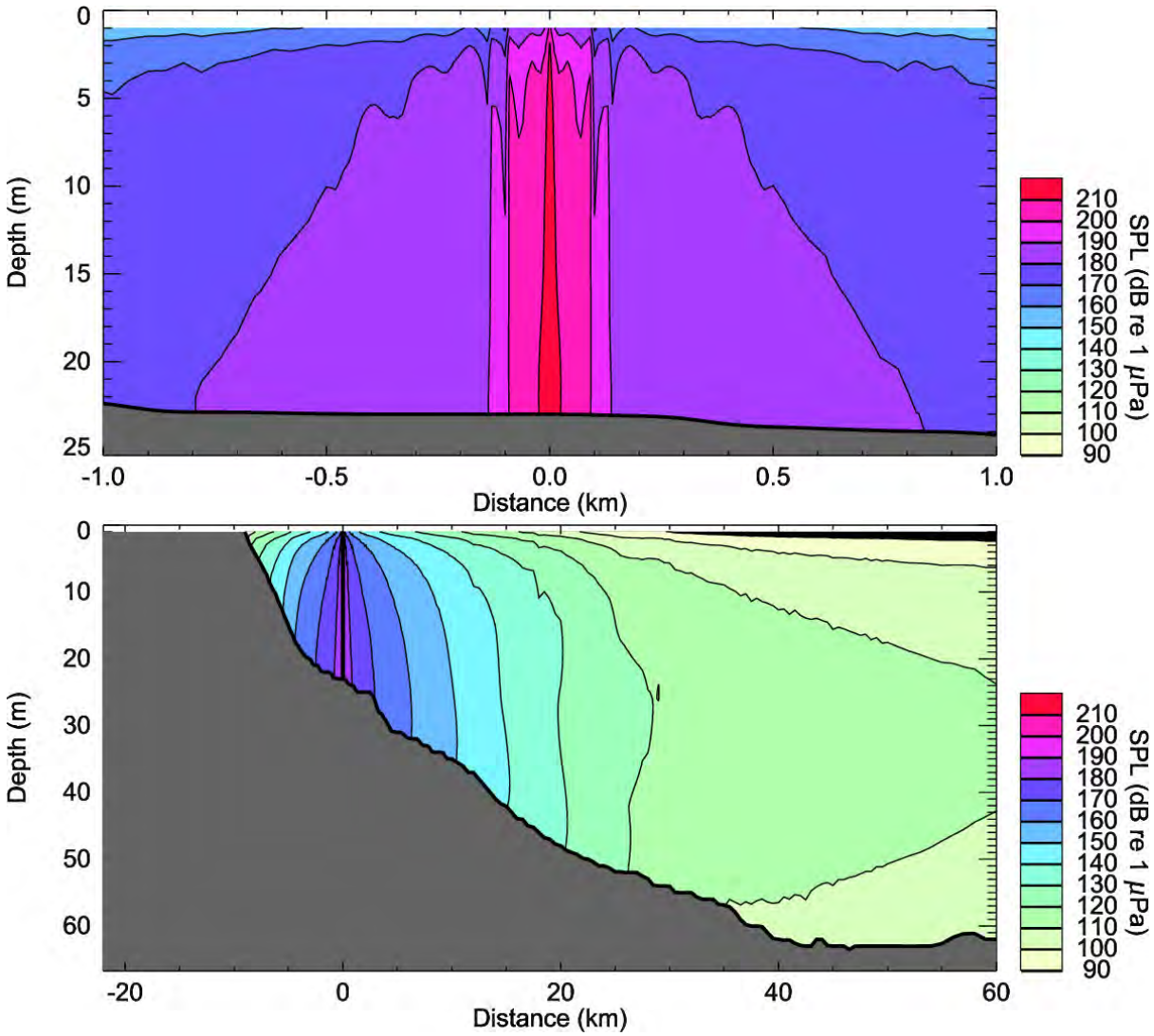


Figure F-14. *Monopile 3, – DBBC, Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

F.1.1.3. Scenario 3 – DBBC + HSD (First Modelling Round)

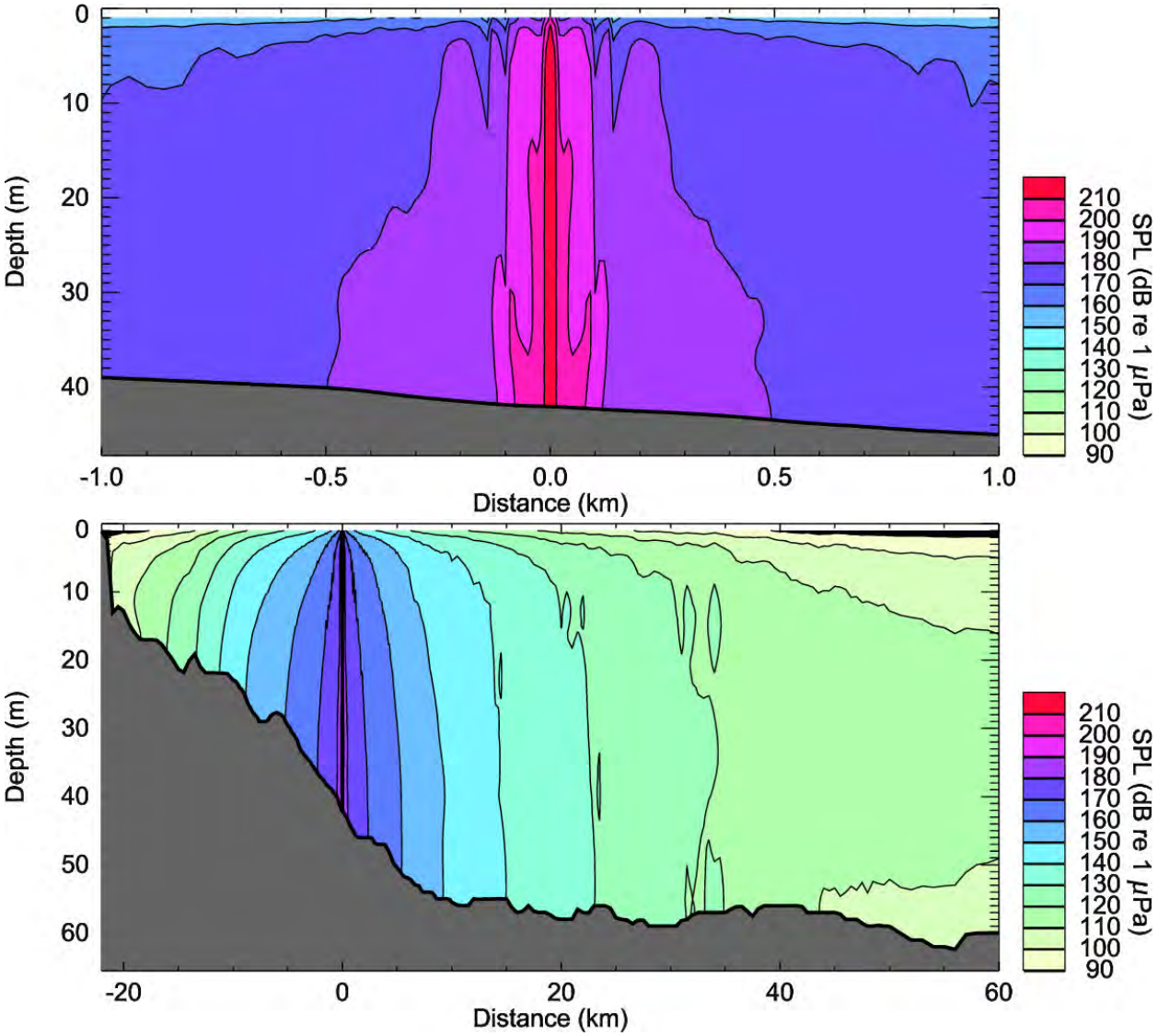


Figure F-15. *Monopile 1, – HSD + DBBC, Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

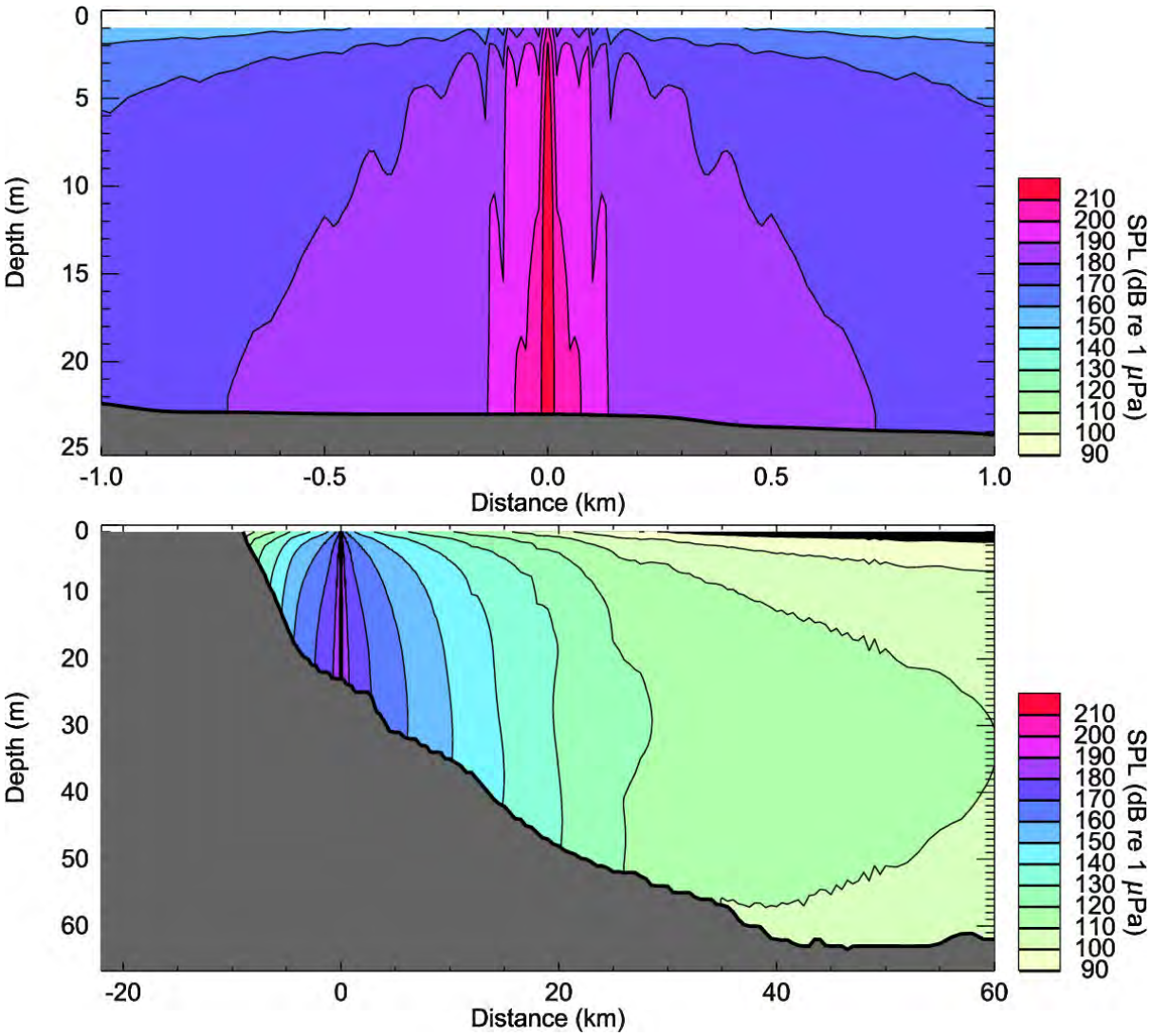


Figure F-16. *Monopile 3, – HSD + DBBC, Winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

F.1.1. Jacket Pile

F.1.1.1. Scenario 1 – Unmitigated (First Modelling Round)

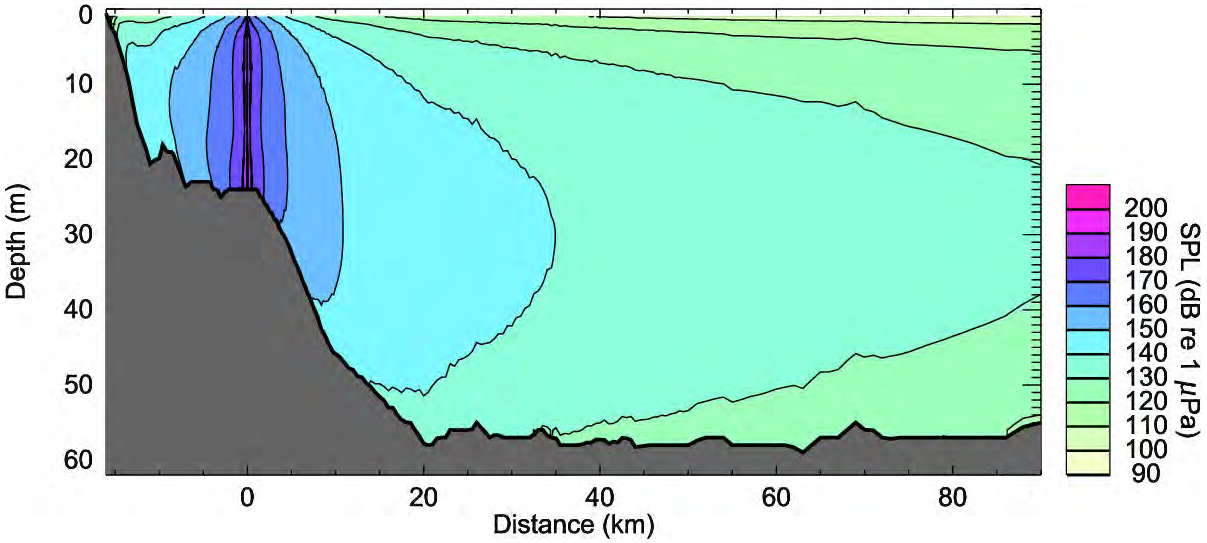


Figure F-17. *Sub–station jacket pile, winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the first penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

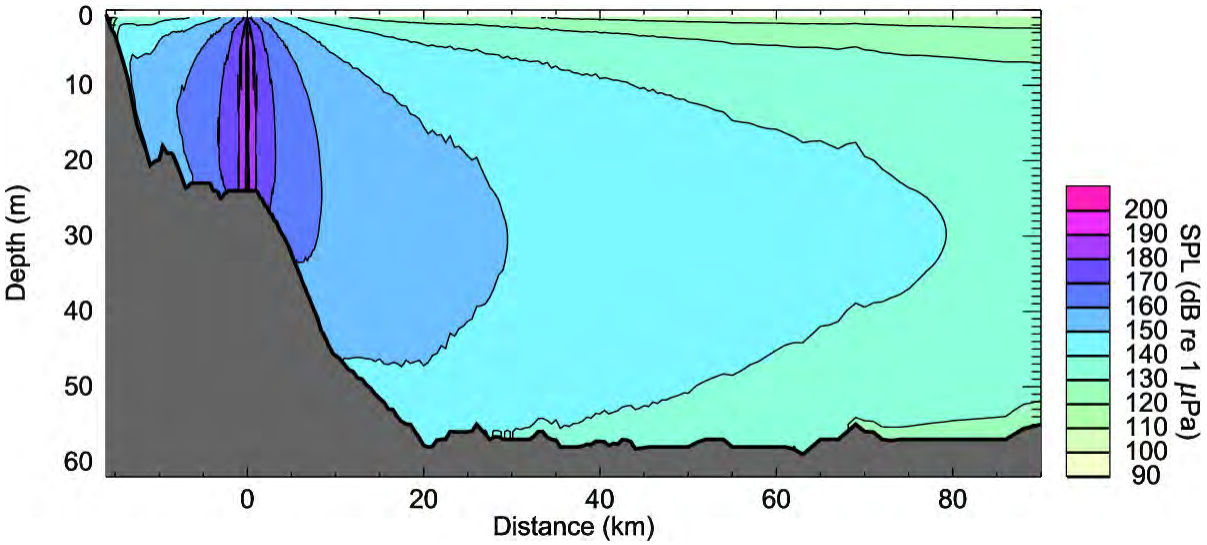


Figure F-18. *Sub–station jacket pile, winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the second penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).

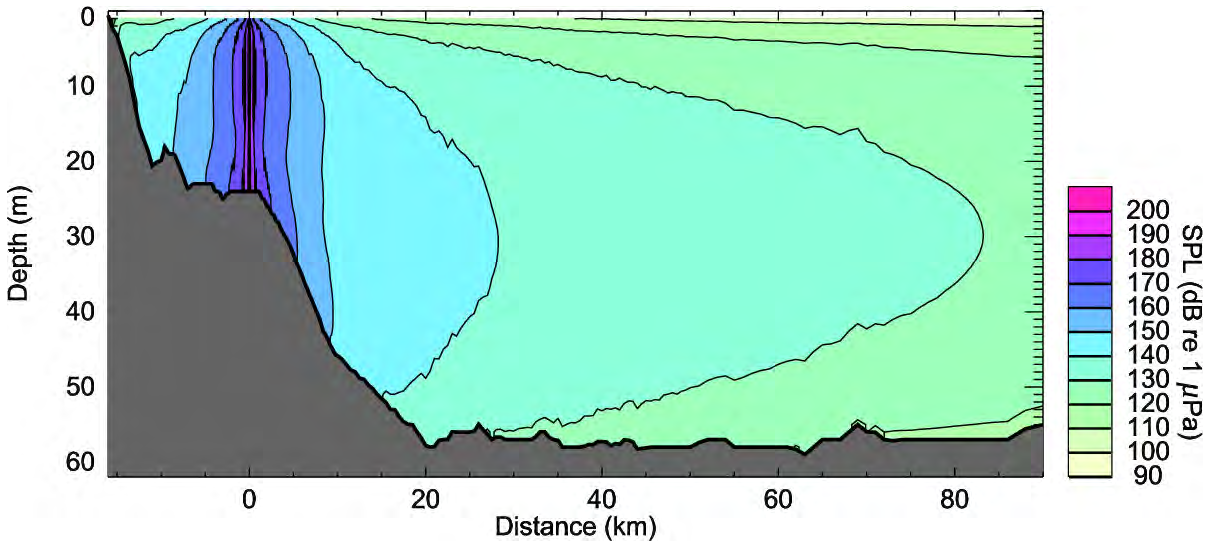


Figure F-19. *Sub–station jacket pile, winter, SPL:* Vertical slice plot showing variations with depth and distance from the pile for the third penetration depth. The seabed is shown as dark grey. The transects are along direction of 125°/305° from North (positive distance/negative distance).