Woodside Browse to NWS Vessel Noise

Acoustic Modelling

JASCO Applied Sciences (Australia) Pty Ltd

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Aaron McDonald
Woodside Energy
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Authors:

Marc C. Green
Craig R. McPherson
Michael A. Wood

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Executive Summary

The Browse Joint Venture (BJV) proposes to develop the Brecknock, Calliance, and Torosa fields (collectively known as the Browse resources) via the development drilling of wells and the installation of a subsea production system that will supply two 1100 million standard cubic feet per day (annual daily export average) Floating Production Storage and Offloading (FPSO) facilities. The Browse Project gas will be transported from the FPSO facilities to the existing NWS Project infrastructure via an approximately 900 km long trunkline. Each FPSO will have a turret mooring system that will be stabilised using mooring lines secured to the seabed by piles. JASCO Applied Sciences previously modelled pile driving operations, vertical seismic profiling (VSP) during drilling operations, Mobile Offshore Drilling Unit (MODU), FPSO operations and Operational Support Vessel (OSV) operations, with the results presented in McPherson et al. (2019).

The BJV provided revised information about the MODU and FPSO operations for the present modelling study, which considers the following scenarios:

- The operations of a Mobile Offshore Drilling Unit (MODU) using only four thrusters at TRA and TRD drill centre locations (as opposed to eight).
- The operations of a MODU in a ‘moored’ configuration using no thrusters.
- The resupply of the MODU during drilling operations at TRA and TRD drill centre locations.
- FPSO operational noise for the Torosa FPSO without heading control, with heading control (thrusters operating), and with optimised heading control.
- Torosa FPSO operational noise during offtake, including the FPSO without heading control, an Offshore Support Vessel (OSV) near the FPSO, and a noiseless condensate tanker.
- Aggregate scenarios that include MODU drilling operations at TRD and the Torosa FPSO during offtake operations.

The objective of this modelling study was to determine ranges to acoustic exposure thresholds representing the best available science for permanent threshold shift (PTS), temporary threshold shift (TTS), and behavioural disturbance of marine fauna including marine mammals, turtles, and fish.

Acoustic fields caused by pressure were modelled and are presented as sound pressure levels (SPL) and accumulated sound exposure levels (SEL) as appropriate for noise effect criteria for continuous (vessel) noise sources. The effects of range-dependent environmental properties on sound propagation in the study area were accounted for by the numerical models.

The modelled sources are as follows:

- *An FPSO facility* that is 370 m long and 67 m wide. This was modelled under:
    - Typical operations, with no heading control and no offtake, only operating processing and associated equipment.
    - Heading control (thrusters operating), representative of typical operational conditions.
    - Heading control (thrusters operating) with optimised thrusters, representative of typical operational conditions.
    - Offtake, during which the FPSO is only operating processing and associated equipment, with an OSV under DP located 700 m behind the FPSO, and a noiseless condensate tanker located between the two.
- *A representative MODU* that is 100 × 80 m, under DP, representative of typical operational loads during 1-year (non-cyclonic) return interval metocean conditions. This was modelled using:
    - Four thruster sources operating at 40% capacity.
    - A central machinery source, representative of a typical drilling operation.

- *A representative OSV*, a DP vessel that is 92.95 m long (vessel design based on the Marin Teknikk MT6016 hull) under DP, representative of typical operational loads during maximum safe operating conditions and resupply operations. This was modelled using five thruster sources operating at a defined capacity, based on the specification of the *Fugro Etive*, as follows:
    - Two Rolls-Royce AZP100 thrusters.
    - Two Rolls Royce TT 2200 DPN thrusters.
    - One Rolls-Royce AZP1001 thruster.

The analysis considered multiple commonly used effect criteria, with the key results of the acoustic modelling summarised below.

Marine Mammals

- The results for the United States (US) National Marine Fisheries Service (NMFS 2018) criteria applied for marine mammal PTS and TTS for vessels are assessed here for a 24 hour period. Vessels are considered to be active continuously across the 24 hour period unless specified otherwise in the table heading. The maximum ranges to PTS are summarised in Tables 1 and 2.
- The maximum ranges to the US National Oceanic and Atmospheric Administration (NOAA 2019) marine mammal behavioural response criterion of 120 dB re 1 µPa (SPL) are summarised in Tables 3 and 4.
- For the aggregate scenario considering both TRD MODU drilling and FPSO offtake operations, it was found that due to the separation between the sites, ranges to PTS and TTS thresholds were unaltered compared to the individual operations. Maximum range to the behavioural response level was increased, and this is shown in Table 5.

Table 1. *Marine mammal SEL$_{24h}$, TRA and TRD Drill Centres*: Maximum (R_{max}) horizontal ranges (km) to modelled maximum-over-depth PTS thresholds from NMFS (2018).

Hearing group	Threshold for PTS, SEL$_{24h}$ (dB re 1 µPa²s)[a]	Range R_{max} (km)					
		MODU (on DP)	MODU (Moored)	OSV (6 h)	OSV (12 h)	MODU Resupply (OSV 6 h)	MODU Resupply (OSV 12 h)
TRA Drill Centre							
LF cetaceans	199	<0.05	—	<0.05	0.06	0.06	0.06
MF cetaceans	198	<0.05	—	<0.05	<0.05	<0.05	<0.05
HF cetaceans	173	0.09	<0.05	0.06	0.10	0.10	0.11
TRD Drill Centre							
LF cetaceans	199	0.06	<0.05	0.06	0.06	0.06	0.06
MF cetaceans	198	0.06	<0.05	<0.05	<0.05	0.06	0.06
HF cetaceans	173	0.09	<0.05	0.06	0.09	0.10	0.11

[a] Frequency weighted.

Table 2. *Marine mammals, SEL$_{24h}$, activities at Torosa FPSO location*: Maximum (R_{max}) horizontal ranges (km) to modelled maximum-over-depth PTS thresholds from NMFS (2018).

Hearing group	Threshold for PTS, SEL$_{24h}$ (dB re 1 µPa²s) [a]	Range R_{max} (km)		
		FPSO, Heading Control	FPSO, Heading Control (Optimised Thrusters)	FPSO Offtake
LF cetaceans	199	<0.05	<0.05	0.07
MF cetaceans	198	<0.05	—	<0.05
HF cetaceans	173	0.06	<0.05	0.11

[a] Frequency weighted.

A dash indicates the level was not reached.

FPSO offtake includes an FPSO, a noiseless condensate tanker and an OSV

Table 3. *Marine mammal behaviour, TRA and TRD Drill Centres*: Summary of maximum behavioural disturbance ranges.

SPL (L_p; dB re 1 µPa)	Range R_{max} (km)			
	MODU (under DP)	MODU (Moored)	OSV	MODU Resupply
TRA Drill Centre				
120[a]	4.49	0.49	2.21	4.95
TRD Drill Centre				
120[a]	4.10	0.49	3.14	5.49

[a] Threshold for marine mammal behavioural response to continuous noise (NOAA 2019).

Table 4. *Marine mammal behaviour, activities at Torosa FPSO location*: Summary of maximum behavioural disturbance ranges.

SPL (L_p; dB re 1 µPa)	Range R_{max} (km)		
	FPSO, Heading Control	FPSO, Heading Control (Optimised Thrusters)	FPSO Offtake
120[a]	2.82	1.67	2.67

[a] Threshold for marine mammal behavioural response to continuous noise (NOAA 2019).

FPSO offtake includes an FPSO under DP, a noiseless condensate tanker and an OSV.

Table 5. *Marine mammal behaviour, Aggregate Scenario*: MODU under DP at TRD and Torosa FPSO Offtake, summary of maximum behavioural disturbance ranges.

SPL (L_p; dB re 1 µPa)	Range R_{max} (km)
120[a]	4.68

[a] Threshold for marine mammal behavioural response to continuous noise (NOAA 2019).

Sea Turtles

The maximum ranges for the Finneran et al. (2017) criteria applied for sea turtles are summarised in Tables 6 and 7. There were no significant differences in ranges for the aggregate scenario compared with the individual operations.

Table 6. *Sea turtle SEL_{24h}, TRA and TRD Drill Centres*: Maximum-over-depth ranges (in km) to PTS threshold.

Threshold for PTS, SEL_{24h} (dB re 1 µPa²s)[a]	Range R_{max} (km)					
	MODU (under DP)	MODU (Moored)	OSV (6 h)	OSV (12 h)	MODU Resupply (OSV 6h)	MODU Resupply (OSV 12 h)
TRA Drill Centre						
220[b]	<0.05	—	<0.05	<0.05	<0.05	<0.05
TRD Drill Centre						
220[b]	0.06	—	—	<0.05	0.06	0.06

[a] Frequency weighted.

[b] Threshold for turtle-weighted SEL_{24h} (Finneran et al. 2017).

A dash indicates the level was not reached.

Table 7. *Sea turtle SEL_{24h}, activities at Torosa FPSO location*: Maximum-over-depth ranges (in km) to PTS threshold.

Threshold for PTS, SEL_{24h} (dB re 1 µPa²s)[a]	Range R_{max} (km)		
	FPSO, Heading Control	FPSO, Heading Control (Optimised Thrusters)	FPSO Offtake
220[b]	—	—	<0.05

[a] Frequency weighted.

[b] Threshold for turtle-weighted SEL_{24h} (Finneran et al. 2017).

A dash indicates the level was not reached.

Fish

- Sound produced by the operations could cause physiological effects and recoverable injury to some fish species, but only if the animals are in close proximity to the sound sources (within a planar range of 60 m) for 48 hours. Temporary impairment due to TTS could occur at similar short ranges if fish remain at the same range for long periods of time (12 hours). The ranges are very similar for all scenarios.
- There is no increased risk to fish from aggregate scenarios.

1. Introduction

JASCO Applied Sciences (JASCO) performed a modelling study of underwater sound levels associated with the Browse to North West shelf (NWS) Project development of the Brecknock, Calliance, and Torosa fields (collectively known as the Browse resources) by the Browse Joint Venture (BJV). This development will involve drilling wells and installing a subsea production system that will supply two 1100 million standard cubic feet per day (annual daily export average) Floating Production Storage and Offloading (FPSO) facilities. Gas will be transported from the FPSO facilities to the existing NWS Project infrastructure via an approximately 900 km long trunkline. Each FPSO will have a turret mooring system that will be stabilised using mooring lines secured to the seabed by piles. JASCO previously modelled pile driving operations, vertical seismic profiling (VSP) during drilling operations, Mobile Offshore Drilling Unit (MODU), and FPSO operations and Operational Support Vessel (OSV) operations. This previous work was presented in McPherson et al. (2019).

The BJV provided revised information about the MODU and FPSO operations for the present modelling study, which considers the following scenarios:

- The operations of a Mobile Offshore Drilling Unit (MODU) using only four thrusters at TRA and TRD drill centre (as opposed to eight).
- The operations of a MODU in a ‘moored’ configuration using no thrusters.
- The resupply of the MODU during drilling operations at TRA and TRD drill centres.
- FPSO operational noise for the Torosa FPSO without heading control, with heading control (thrusters operating), and with optimised heading control.
- Torosa FPSO operational noise during offtake, including the FPSO without heading control, an Offshore Support Vessel (OSV) near the FPSO and a noiseless condensate tanker.
- Aggregate scenarios that include MODU operations at the TRD drill centre and the Torosa FPSO during offtake operations.

The modelling study specifically assessed ranges from operations where underwater sound levels reached thresholds corresponding to various levels of impact on marine fauna. The animals considered here included marine mammals (pygmy blue whales, *Balaenoptera musculus brevicauda*), sea turtles, and fish (including fish eggs and larvae). Due to the variety of species considered, there are several thresholds for evaluating effects, including: mortality, injury, temporary reduction in hearing sensitivity, and behavioural disturbance.

The modelling methodology considered source directivity and range-dependent environmental properties. Estimated underwater acoustic levels are presented as sound pressure levels (SPL, L_p), and or accumulated sound exposure levels (SEL, L_E) as appropriate for different noise effect criteria for non-impulsive (continuous) noise sources.

The geographic coordinates for the modelled sites are provided in Table 8 and an overview of the modelling area is shown in Figure 1.

Table 8. Location details for the modelled sites

Site	Source	Latitude (S)	Longitude (E)	MGA (GDA94), Zone 51		Water depth (m)
				X (m)	Y (m)	
TRA Drill Centre	MODU (centre)	13° 58′ 12.50″	121° 58′ 37.70″	389521	8455338	425
	OSV (centre)	13° 58′ 12.49″	121° 58′ 35.70″	389461	8455338	425
TRD Drill Centre	MODU (centre)	14° 00′ 26.64″	121° 57′ 23.58″	387315	8451207	392
	OSV (centre)	14° 00′ 26.63″	121° 57′ 21.58″	387255	8451207	392
Torosa FPSO	FPSO (centre)	13° 58′ 15.06″	122° 01′ 28.53″	394647	8455281	463
	OSV (centre)	13° 58′ 14.94″	122° 00′ 59.03″	393762	8455281	460

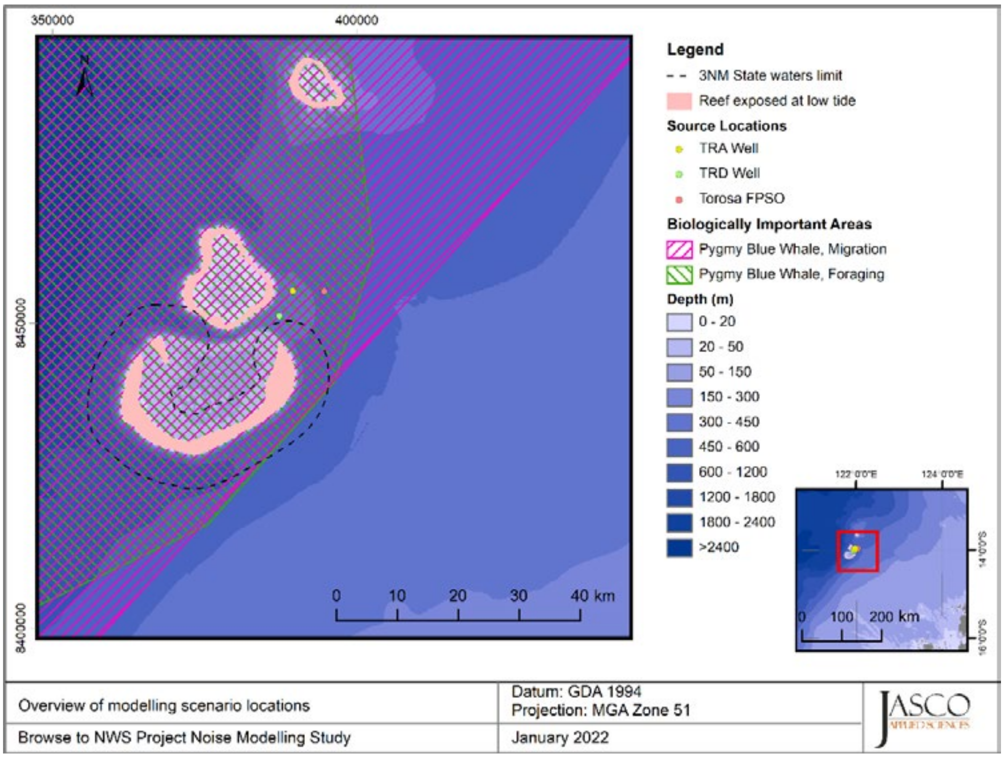

Figure 1. Overview of the modelled area and local features

1.1. Acoustic Modelling Scenario Details

The modelled sources are as follows:

- *An FPSO facility* that is 370 m long and 67 m wide. This was modelled under:
  - Typical operations, with no heading control and no offtake, only operating processing and associated equipment
  - Heading control (thrusters operating), representative of typical operational conditions
  - Heading control (thrusters operating) with optimised thrusters, representative of typical operational conditions
  - Offtake, during which the FPSO is only operating processing and associated equipment

- *A representative MODU* that is 100 × 80 m under DP, representative of typical operational noise during 1-year (non-cyclonic) return interval metocean conditions. This was modelled using:
  - Four thruster sources operating at 40% capacity
  - A central machinery source, representative of a typical drilling operation
- *A representative MODU* that is 100 × 80 m moored (no DP), representative of typical operational noise during drilling. This was modelled using:
  - A central machinery source, representative of a typical drilling operation.
- *A representative OSV*, a DP vessel 92.95 m long (vessel design based on the Marin Teknikk MT6016 hull) under DP, representative of typical operational noise during maximum safe operating conditions and resupply operations. This was modelled using five thruster sources operating a defined capacity, based on the specification of the *Fugro Etive*, as follows:
  - Two Rolls-Royce AZP100 thrusters.
  - Two Rolls Royce TT 2200 DPN thrusters.
  - One Rolls-Royce AZP1001 thruster.

These vessels were modelled in varying configurations at the three different locations shown in Figure 1. Scenarios are summarised in Table 9.

At both TRA and TRD drill centress, the OSV is positioned directly adjacent to the MODU, holding station on the MODU’s west side (Figure 2). Note that this figure shows co-ordinates for the TRA drill centre, but the relative vessel positioning is identical at the TRD drill centre. Resupply was only modelled for the DP MODU, not the moored MODU.

At the Torosa FPSO location, the OSV is positioned 700 m due west of the centre point of the FPSO, representative of an offtake scenario. This scenario also includes a tanker vessel, which has been treated as silent in the modelling. Figure 3 shows the layout for the Torosa location.

Table 9. Modelled scenarios

Scenario	Description	Sources	Length of operation
TRA drill centre			
1(a)	MODU drilling (under DP)	MODU drilling and thrusters (4 × 40%)	24 h
1(b)	MODU drilling (moored)	MODU drilling, no thrusters	24 h
2	Offshore Support Vessel	Support vessel (DP)	6 and 12 h
3	MODU resupply	MODU drilling and thrusters (4 × 40%) Support vessel (DP)	
TRD drill centre			
4(a)	MODU drilling (under DP)	MODU drilling and thrusters (4 × 40%)	24 h
4(b)	MODU drilling (moored)	MODU drilling, no thrusters	24 h
5	Offshore Support Vessel	Support vessel (DP)	6 and 12 h
6	MODU resupply	MODU drilling and thrusters (4 × 40%) Support vessel (DP)	
Torosa FPSO location			
7(a)	FPSO using heading control	FPSO thrusters and topsides machinery	24 h
7(b)	FPSO using optimised heading control	Optimised FPSO thrusters and topsides machinery	
8	FPSO offtake	FPSO with topsides machinery Silent Tanker Support vessel (DP)	
TRD drill centre and Torosa FPSO locations			
9	MODU drilling at TRD, Torosa FPSO Offtake	MODU drilling and thrusters (4 × 40%) Support vessel (DP) FPSO with topsides machinery Silent Tanker	24 h

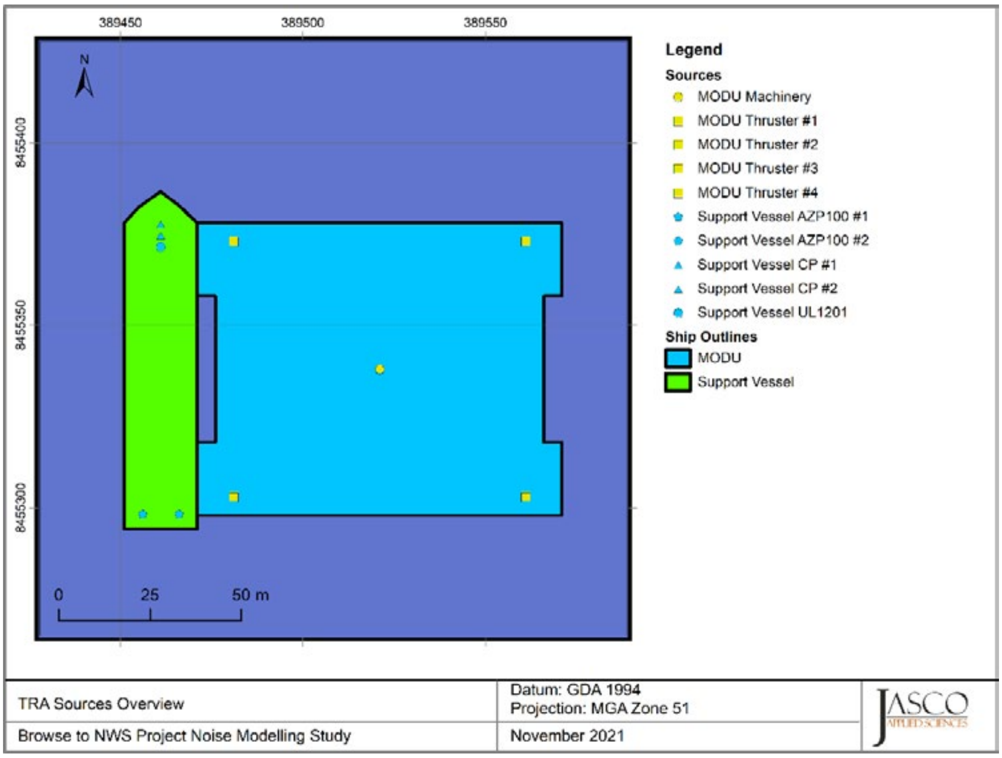

Figure 2. Overview of source layout at the TRA drill centre. Relative positioning of vessels is identical to that at the TRD drill centre. Locations for all sources are shown.

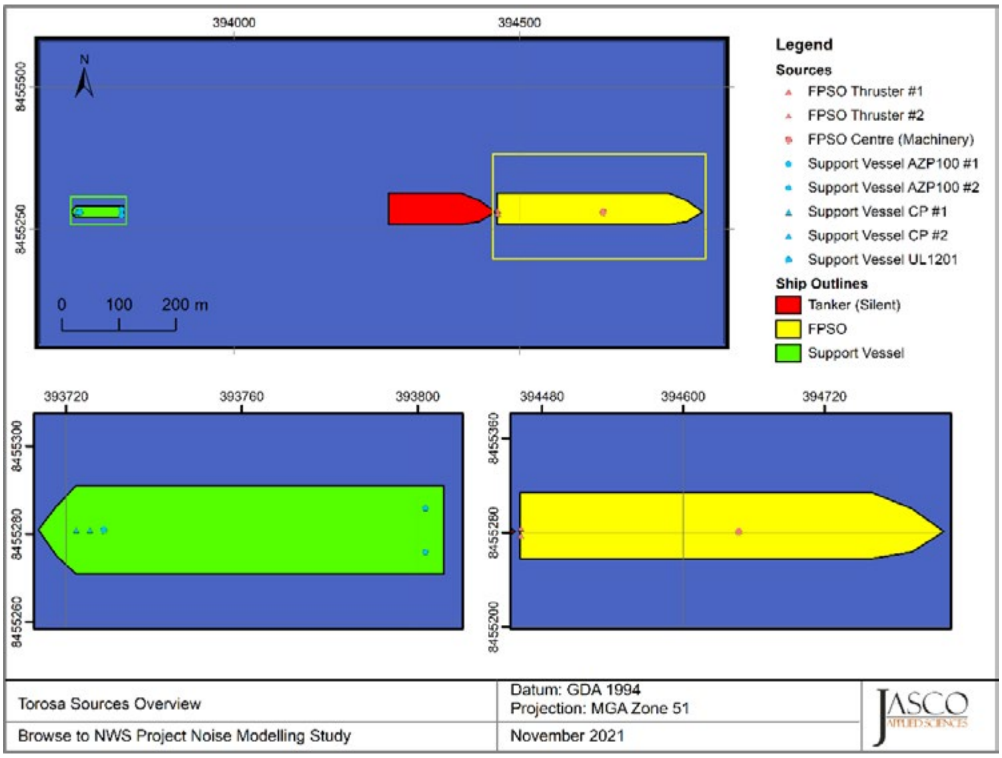

Figure 3. Overview of source layout at Torosa FPSO location, with detail on specific source positioning for FPSO and OSV. Locations for all sources are shown.

2. Noise Effect Criteria

To assess the potential impacts 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 impact 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), and the United States National Marine Fisheries Service (NMFS 2018). The number of studies that investigate the level of behavioural disturbance to marine fauna by anthropogenic sound has also increased substantially.

Several sound level metrics, such as PK, SPL, and SEL, are commonly used to evaluate noise and its effects on marine life (see Appendix A.3). In this report, the duration of the SEL accumulation is integrated over the operational time periods for each vessel, as defined in Table 9.

Appropriate subscripts indicate any applied frequency weighting (Appendix A.3.3). The acoustic metrics in this report reflect the updated ANSI and ISO standards for acoustic terminology, ANSI S1.1 (R2013) and ISO 18405:2017 (2017).

This study applies the following noise criteria (Sections 2.1–2.2 and Appendix A.3.1), chosen for their acceptance by regulatory agencies and because they represent current best available science:

- Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from NMFS (2018) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in marine mammals. This criteria was applied for consistency with previous work (McPherson et al. 2019).
- Marine mammal behavioural threshold based on the current interim U.S. National Oceanic and Atmospheric Administration (NOAA 2019) criterion for marine mammals of 120 dB re 1 µPa SPL (L_p) for non-impulsive sound sources. This is identical to the previously applied behavioural response threshold, however the reference has been updated.
- Sound exposure guidelines for fish, fish eggs, and larvae (Popper et al. 2014).
- Frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in sea turtles.

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 10; Cetaceans (low-, mid-, and high-frequency) were identified as the hearing groups requiring assessment. Details on thresholds related to auditory threshold shifts or hearing loss and behavioural response are provided in A.3, with frequency weighting explained in detail in Appendix A.3.3. Of particular note, whilst the newly published Southall et al. (2021) provides recommendations and discusses the nuances of assessing behavioural response, the authors do not recommend new numerical thresholds for onset of behavioural responses for marine mammals.

Table 10. Criteria for effects of non-impulsive noise exposure, including vessel noise on marine mammals: SPL and Weighted SEL_{24h} thresholds.

Hearing group	NOAA (2019)	NMFS (2018)	
	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 µPa²s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa²s)
LF cetaceans	120	199	179
MF cetaceans		198	178
HF cetaceans		173	153

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 µPa²s.

2.2. Fish, Sea Turtles, Fish Eggs, and Fish Larvae

In 2006, the Working Group on the Effects of Sound on Fish and Turtles was formed to continue developing noise exposure criteria for fish and sea turtles based on work began 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.
- 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 11 for completeness only. Because the presence or absence of a swim bladder has a role in hearing, fish 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.

Table 11 lists the relevant effects thresholds from Popper et al. (2014) for shipping and continuous 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 (Table 12).

Table 11. Criteria for vessel 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 ranges from the source defined in relative terms as near (N), intermediate (I), and far (F).

Table 12. Acoustic effects of continuous noise on sea turtles, weighted SEL_{24h}, Finneran et al. (2017).

PTS onset thresholds (received level)	TTS onset thresholds (received level)
Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^{2}s)	Weighted SEL_{24h} ($L_{E,24h}$; dB re 1 µPa^{2}s)
204	189

L_E denotes cumulative sound exposure over a 24 h period and has a reference value of 1 µPa^{2}s.

3. Methods

The operations considered in this study will occur at the Torosa fields, specifically at the TRA and TRD drill centres and FPSO location, at depths ranging from 390–463 m. Environmental parameters (bathymetry, sound speed profile and geoacoustics) from McPherson et al. (2019) was reused. Details are provided in Appendix C.2.

For the purposes of the environmental impact assessment process, the Browse Joint Venture have proposed acoustic source parameters for certain vessels under specific conditions. Where the BJV have proposed acoustic source parameters, these are provided on the basis of underwater radiated noise source modelling commissioned from DNV's Noise and Vibration division. The underwater radiated noise source modelling considers specific dynamic positioning and heading control system designs of representative vessels under a range of different operating conditions. The BJV have conservatively selected the thruster utilisation for modelling based on marine operational advice regarding specific sea state conditions. Further information regarding the development of the BJV's acoustic source parameters can be found in the BJV's Pygmy Blue Whale Management Plan.

3.1. Acoustic Source Parameters

3.1.1. Mobile Offshore Drilling Unit

Sound source locations and spectrum estimates for the MODU sources were based on the *Seadrill West Sirius*, which is equipped with eight Rolls-Royce UUC 355 thrusters (Figure 4).

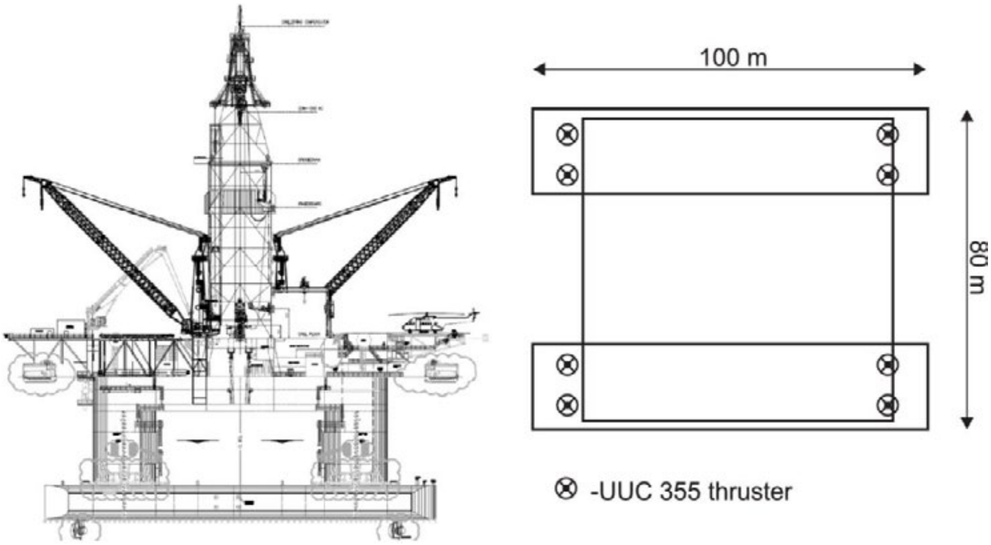

Figure 4. *Seadrill West Sirius* technical drawing showing thruster locations

This study modelled each MODU under dynamic positioning as five sources, representing four active thrusters running at 40% capacity, plus a source for noise incurred by drilling operations. The source levels for the thrusters were theoretically determined, and provided by the Browse Joint Venture (BJV), whilst the spectrum for drilling and machinery noise was taken from a recorded spectrum reported by Austin et al. (2018) for the *Transocean Polar Pioneer*, a similar semi-submersible drilling unit. Broadband source levels are 170.7 dB re 1 µPa and 176.5 dB re 1 µPa for the machinery noise and thrusters, respectively, making the combined broadband source level 182.8 dB re 1 µPa. The moored MODU was represented by the machinery/drilling noise only. The Figure 5 shows the decidecade band monopole source levels.

Machinery noise was modelled as a point source located at the centre of the MODU with a source 12.6 m depth based on 0.7 × ship draft (18 m for *West Sirius*) as specified in ISO 17208-1 (2016). Source depths for the thrusters were set to equal the draft, at 18 m.

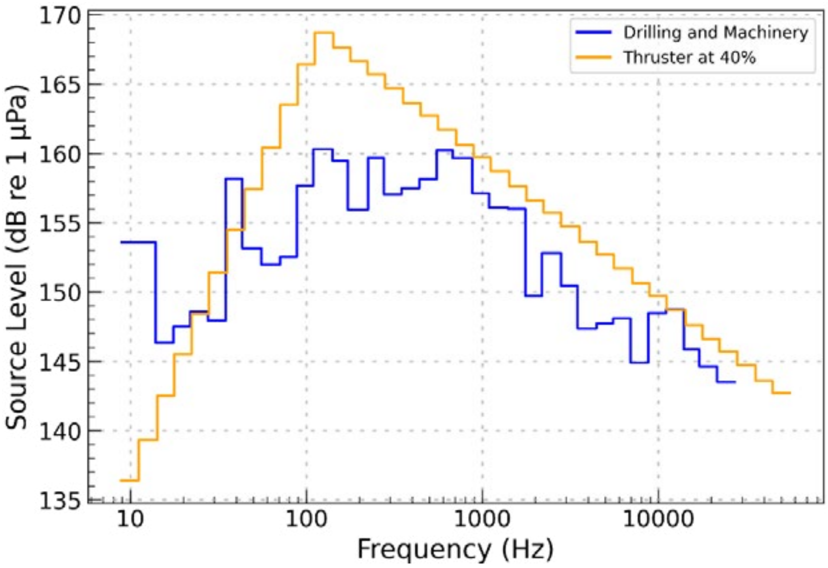

Figure 5. Decidecade band monopole source levels for MODU sources. Drilling and machinery levels from recorded spectrum of *Transocean Polar Pioneer*, 40% thrusters from theoretical data provided by the BJV.

3.1.2. Offshore Support Vessel

Sound source levels for the OSV were based on the *Fugro Etive*, a general purpose vessel 92.95 m in length, and 19.7 m in breadth, featuring two stern azipull thrusters (Rolls-Royce AZP100), two bow controllable pitch thrusters (Rolls-Royce TT 2200 DPN), and a retractable azimuthing thruster (Rolls-Royce UL1201).

For the FPSO offtake, each thruster was modelled as an individual source, operating at 40% capacity, from theoretically developed source levels provided by the BJV. Broadband source levels for these thrusters are 181.2, 174.7, and 174.9 dB re 1 µPa, respectively, giving a total broadband SL of 185.5 dB re 1 µPa. Source level spectra are shown in Figure 6.

For the MODU resupply scenarios, each thruster was modelled as an individual source, with the bow and retractable thrusters operating at 40% capacity, and the stern azipull thrusters operating at 20%, from theoretically developed source levels provided by the BJV. Broadband source levels for these thrusters are 173.3, 174.7, and 174.9 dB re 1 µPa, respectively, giving a total broadband SL of 181.3 dB re 1 µPa. Source level spectra are shown in Figure 7.

The BJV's selection of different levels of thrust for different OSV thrusters in the offtake and OSV resupply scenarios is based on marine operational advice. The azipull thrusters (at the stern) are primarily used for propulsion, as opposed to the bow/retractable thrusters which are primarily used for dynamic positioning. During OSV resupply, the propulsion thrusters are typically used less than the dynamic positioning thrusters during OSV resupply. This is different from OSV use during offtake scenarios where the OSV applies force to maintain tension in the offtake arrangement, and therefore the propulsion thrusters are utilised at higher levels.

Thruster locations, diameters, and depths were derived by referring to a technical drawing and cross-referencing this with the known length and breadth of the ship. Monopole source depths Z_s were calculated using the following equation, derived from Gray and Greeley (1980):

$$Z_s = Z_{prop} - 0.85 \cdot \varphi_{prop} \tag{1}$$

where Z_{prop} is the depth at the bottom of the propeller and φ_{prop} is the diameter of the propeller. Thus, depths were calculated as 3.2 m for the AZP100, 6.4 m for the UL1201, and 3.4 m for the CP thrusters.

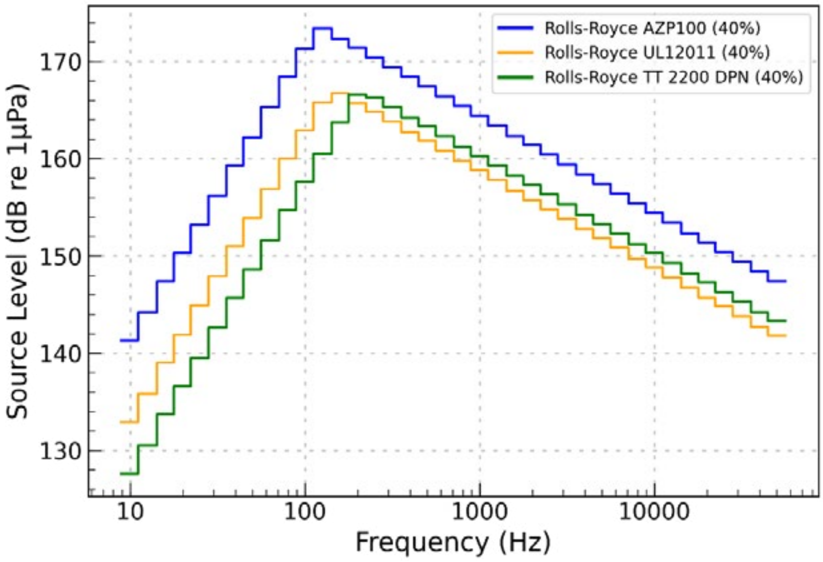

Figure 6. Decidecade band monopole source levels for OSV thruster sources during FPSO offtake. These spectra represent thrusters working at 40% capacity.

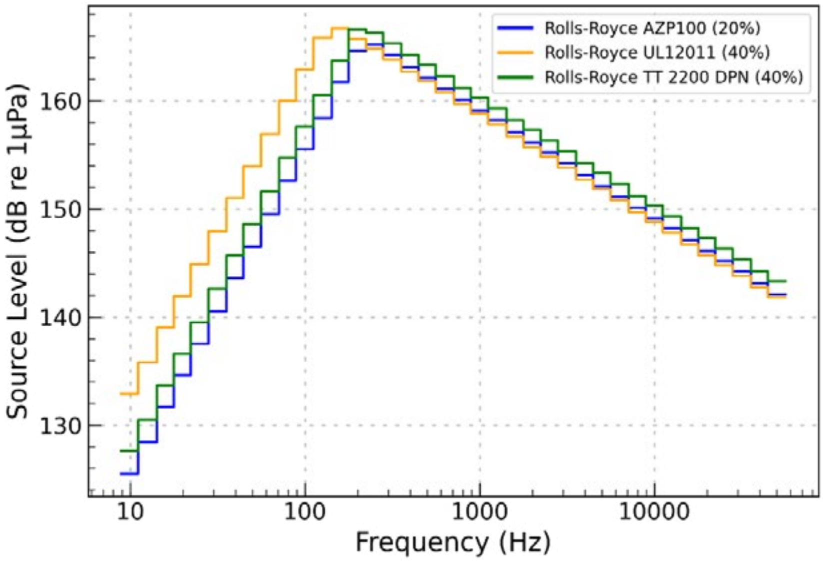

Figure 7. Decidecade band monopole source levels for OSV thruster sources during MODU resupply. These spectra represent thrusters working at 20 and 40% capacity.

3.1.3. Floating Production, Storage, and Offloading (FPSO) Facility

The proposed FPSO facility is a permanently moored, heading controlled production vessel approximately 370 m long and 67 m wide with a draft of 16 m. While in heading control mode, it operates on two stern thrusters positioned laterally on the keel at the stern of the ship 6 m apart.

The major sources of noise from this vessel are the two thrusters and noise associated with pumps, generators, and other machinery within the vessel. As a proxy for the latter noise source, an average of two source levels measured by Erbe et al. (2013) from the FPSO facilities *Nganhurra* and the *Ngujima Yin*, with a broadband source level of 173.9 dB re 1 µPa, was used. The thrusters were modelled as two separate point sources using theoretical source level spectra for 3000 mm nozzled 4 bladed fixed pitch propellers (FPPs), provided by the BJV. These had a broadband source level of 179.5 dB re 1 µPa.

In combination, the machinery noise and two thruster sources reach a broadband source level of 183 dB re 1 µPa. A future design target for the FPSO is a broadband source level of 178 dB re 1 µPa. Given the input spectra, it was calculated that a broadband reduction of 6.6 dB per thruster would be required to reach this target. An offset of −6.6 dB was therefore applied to the thruster spectrum for this additional hypothetical scenario. Figure 8 shows the source spectra for machinery and thrusters with and without the level reduction applied. It can be seen that a broadband reduction of thruster level would have greatest impact in terms of exceeding the machinery noise at frequencies of 80 Hz and above.

Machinery noise was modelled as a point source at the planar centre of the vessel at a depth of 8 m, which is 50% of the draught, consistent with the approach taken in McPherson et al. (2019). The thrusters were modelled as two separate point sources positioned 6 m apart at the stern of the ship (relative to the position of the machinery source) at a depth of 16.5 m, specified by the BJV. Thruster sources were not enabled for the FPSO offtake scenarios.

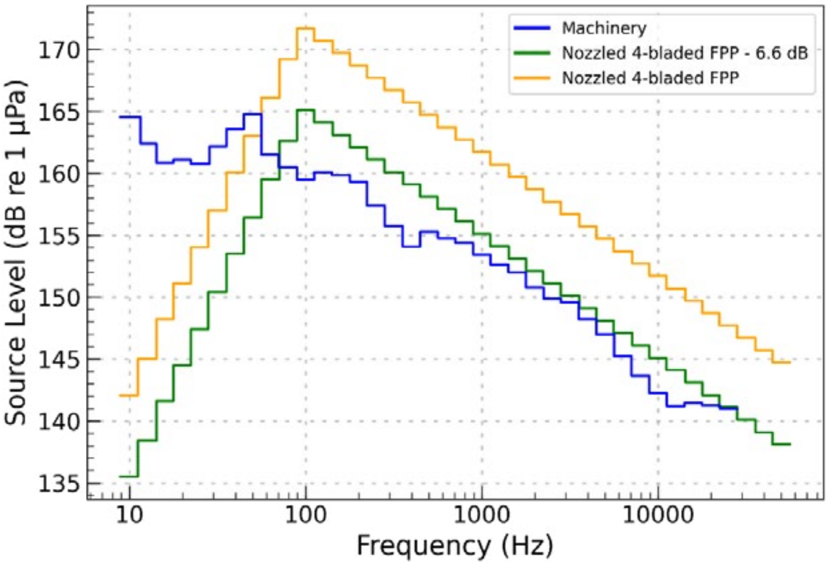

Figure 8. Source levels used for FPSO facility

3.2. Modelling Sound Propagation

JASCO's combined Marine Operations Noise Model (MONM) and gaussian beam acoustic ray-trace model (BELLHOP) were used to predict the acoustic field at frequencies from 10 Hz to 63 kHz. Details on these models are included in Appendix B.1.

Accumulated SEL was calculated using the following equation:

$$L_{E,24h} = L_E + 10\log_{10}(T) \tag{2}$$

where L_E is the per-second energy source level (output by MONM-BELLHOP) and T is the total number of operational seconds in a 24-hour period.

In the modelled scenarios, the FPSO at Torosa, the FPSO offtake activities, and the MODU (either under DP or moored) are considered to be in continuous operation, whilst the OSV during resupply operations at the TRA and TRD drill centres is modelled in operation for both 6 and 12 hours (see Table 9). Using Equation 2, Constant operation over 24 hours yields an offset of 49.3 dB, whilst for 12 hours this is 46.4 dB, and for 6 hours 43.3 dB. These offsets were applied to the relevant calculated received levels.

4. Results

Sound field results for all scenarios are presented in this section as tables and maps showing propagation ranges and isopleths with relevant effect thresholds. These are organised to show SPL results (Tables 13–16, Figures 9–19), followed by SEL results (Tables 17–19, Figures 20–34). The results for the aggregate scenario (Scenario 9, Table 9) are provided in Tables 20–22 and Figures 35–36.

A table entry showing <0.05 indicates a case where a particular noise level has been exceeded in the modelling, but at a range shorter than the minimum grid interpolation distance of 50 m. Figures are presented for each vessel in isolation, as well as offtake and resupply scenarios involving aggregation of noise from multiple vessels.

4.1. Tables

Table 13. *TRA/TRD drill centres, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (in km) to various SPL levels from the centroids of the vessels involved.

SPL (L_p; dB re 1 µPa)	MODU (under DP)		MODU (Moored)		OSV		MODU Resupply	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
TRA Drill centre								
180	—	—	—	—	—	—	—	—
170	<0.05	<0.05	—	—	<0.05	<0.05	<0.05	<0.05
160	<0.05	<0.05	—	—	<0.05	<0.05	<0.05	<0.05
150	0.08	0.08	—	—	0.06	0.06	0.07	0.07
140	0.22	0.22	<0.05	<0.05	0.17	0.16	0.27	0.26
130	0.69	0.67	0.15	0.15	0.53	0.51	0.96	0.91
120[a]	4.49	2.87	0.49	0.47	2.21	2.10	4.95	3.79
110	13.82	12.39	2.28	2.18	10.89	6.78	17.06	12.96
TRD Drill centre								
180	—	—	—	—	—	—	—	—
170	<0.05	<0.05	—	—	<0.05	<0.05	<0.05	<0.05
160	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
150	0.09	0.09	<0.05	<0.05	0.06	0.06	0.09	0.07
140	0.22	0.22	<0.05	<0.05	0.17	0.16	0.26	0.25
130	0.69	0.67	0.15	0.15	0.54	0.51	1.11	0.99
120[a]	4.10	2.73	0.49	0.47	3.14	2.04	5.49	3.66
110	12.97	11.24	2.25	2.13	10.36	6.12	16.49	11.65

[a] Threshold for marine mammal behavioural response to continuous noise (NOAA 2019).

A dash indicates the level was not reached.

Table 14. *Torosa FPSO location, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (in km) to various SPL levels from the centroids of the vessels involved.

SPL (L_p; dB re 1 µPa)	FPSO, Heading Control		FPSO, Heading Control (Optimised Thrusters)		FPSO Offtake	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
180	—	—	—	—	—	—
170	<0.05	<0.05	—	—	<0.05	<0.05
160	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
150	0.06	0.06	<0.05	<0.05	0.07	0.07
140	0.21	0.19	0.09	0.08	0.25	0.24
130	0.66	0.63	0.34	0.32	0.99	0.94
120[a]	2.82	2.66	1.67	1.55	2.67	2.49
110	13.05	9.78	5.65	5.19	9.45	8.14

[a] Threshold for marine mammal behavioural response to continuous noise (NOAA 2019).

FPSO offtake includes an FPSO, a noiseless condensate tanker and an OSV.

A dash indicates the level was not reached.

Table 15. *TRA/TRD drill centres, SPL, fish effect thresholds*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth SPL thresholds based on the quantifiable thresholds for fish with a swim bladder involved in hearing (Popper et al. 2014).

SPL (L_p; dB re 1 µPa)	MODU (under DP)		MODU (Moored)		OSV		MODU Resupply	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
TRA Drill centre								
170[a]	<0.05	<0.05	—	—	<0.05	<0.05	<0.05	<0.05
158[b]	<0.05	<0.05	—	—	<0.05	<0.05	<0.05	<0.05
TRD Drill centre								
170[a]	0.06	0.06	—	—	<0.05	<0.05	<0.05	<0.05
158[b]	0.06	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

[a] Recoverable injury (Popper et al. 2014)

[b] TTS

Table 16. *Torosa FPSO location, SPL, fish effect thresholds*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth SPL thresholds based on the quantifiable thresholds for fish with a swim bladder involved in hearing (Popper et al. 2014).

SPL (L_p; dB re 1 µPa)	FPSO, Heading Control		FPSO, Heading Control (Optimised Thrusters)		FPSO Offtake	
	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
170[a]	<0.05	<0.05	—	—	<0.05	<0.05
158[b]	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

[a] Recoverable injury (Popper et al. 2014)

[b] TTS

FPSO offtake includes an FPSO, a noiseless condensate tanker and an OSV.

A dash indicates the level was not reached.

Table 17. *TRA drill centre, SEL$_{24h}$*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth PTS and TTS thresholds for marine mammals (NMFS 2018) and sea turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL$_{24h}$ ($L_{E,24h}$; dB re 1 µPa²s)[a]	MODU (under DP)		MODU (Moored)		OSV (6 h)		OSV (12 h)		MODU Resupply (OSV 6 h)		MODU Resupply (OSV 12 h)	
		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)
PTS													
LF cetaceans	199	<0.05	<0.05	—	—	<0.05	<0.05	0.06	0.06	0.06	0.06	0.06	0.06
MF cetaceans	198	<0.05	<0.05	—	—	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
HF cetaceans	173	0.09	0.09	<0.05	<0.05	0.06	0.06	0.07	0.07	0.09	0.09	0.10	0.09
Sea turtles	220	<0.05	<0.05	—	—	—	—	—	—	<0.05	<0.05	<0.05	<0.05
TTS													
LF cetaceans	179	0.51	0.50	0.12	0.12	0.24	0.23	0.35	0.33	0.55	0.52	0.58	0.55
MF cetaceans	178	0.08	0.08	—	—	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07
HF cetaceans	153	0.77	0.75	0.30	0.29	0.43	0.42	0.66	0.64	0.89	0.86	1.02	0.98
Sea turtles	200	<0.05	<0.05	—	—	<0.05	<0.05	0.06	0.06	0.06	0.06	0.06	0.06

[a] Frequency weighted.

A dash indicates the level was not reached.

Table 18. *TRD drill centre, SEL$_{24h}$*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth PTS and TTS thresholds for marine mammals (NMFS 2018) and sea turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL$_{24h}$ ($L_{E,24h}$; dB re 1 µPa²s)[a]	MODU (under DP)		MODU (Moored)		OSV (6 h)		OSV (12 h)		MODU Resupply (OSV 6 h)		MODU Resupply (OSV 12 h)	
		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)
PTS													
LF cetaceans	199	0.06	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
MF cetaceans	198	0.06	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
HF cetaceans	173	0.09	0.09	<0.05	<0.05	<0.05	<0.05	0.06	0.06	0.10	0.09	0.10	0.09
Sea turtles	220	0.06	0.06	—	—	—	—	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
TTS													
LF cetaceans	179	0.51	0.50	0.13	0.13	0.25	0.24	0.35	0.33	0.54	0.51	0.58	0.55
MF cetaceans	178	0.07	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	0.07	0.07	0.07
HF cetaceans	153	0.77	0.75	0.30	0.29	0.43	0.42	0.66	0.63	0.90	0.86	1.02	0.98
Sea turtles	200	0.07	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

[a] Frequency weighted.

A dash indicates the level was not reached.

Table 19. *Torosa FPSO location, SEL$_{24h}$*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth PTS and TTS thresholds for marine mammals (NMFS 2018) and sea turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL$_{24h}$ ($L_{E,24h}$; dB re 1 µPa²s)[a]	FPSO, Heading Control		FPSO, Heading Control (Optimised Thrusters)		FPSO Offtake	
		R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)	R_{max} (km)	$R_{95\%}$ (km)
PTS							
LF cetaceans	199	<0.05	<0.05	<0.05	<0.05	0.07	0.07
MF cetaceans	198	<0.05	<0.05	—	—	<0.05	<0.05
HF cetaceans	173	0.06	0.06	<0.05	<0.05	0.11	0.10
Sea turtles	220	—	—	—	—	<0.05	<0.05
TTS							
LF cetaceans	179	0.46	0.43	0.22	0.21	0.63	0.60
MF cetaceans	178	<0.05	<0.05	<0.05	<0.05	0.07	0.07
HF cetaceans	153	0.66	0.63	0.34	0.32	1.24	1.18
Sea turtles	200	<0.05	<0.05	<0.05	<0.05	0.06	0.06

[a] Frequency weighted.

A dash indicates the level was not reached.

4.1.1. Aggregate Scenario

Table 20. *Torosa FPSO location and TRD drill centre, Aggregate FPSO offtake and MODU under DP, SPL*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (in km) to various SPL levels from the centroids of the vessels involved.

SPL (L_p; dB re 1 µPa)	R_{max} (km)	$R_{95\%}$ (km)
180	—	—
170	<0.05	<0.05
160	<0.05	<0.05
150	0.09	0.07
140	0.24	0.22
130	1.00	0.85
120[a]	4.68	2.54
110	15.45	9.78

[a] Threshold for marine mammal behavioural response to continuous noise (NOAA 2019).

A dash indicates the level was not reached.

Table 21. *Torosa FPSO location and TRD drill centre, Aggregate FPSO offtake and MODU under DP, SPL, fish effect thresholds*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth SPL thresholds based on the quantifiable thresholds for fish with a swim bladder involved in hearing (Popper et al. 2014).

SPL (L_p; dB re 1 µPa)	R_{max} (km)	$R_{95\%}$ (km)
170[a]	<0.05	<0.05
158[b]	<0.05	<0.05

[a] Recoverable injury (Popper et al. 2014)

[b] TTS

FPSO offtake includes an FPSO, a noiseless condensate tanker and an OSV.

Table 22. *Torosa FPSO location and TRD drill centre, Aggregate FPSO offtake and MODU under DP, SEL$_{24h}$*: Maximum (R_{max}) and 95% ($R_{95\%}$) planar ranges (km) from the vessels to modelled maximum-over-depth PTS and TTS thresholds for marine mammals (NMFS 2018) and sea turtles (Finneran et al. 2017).

Hearing group	Threshold for SEL$_{24h}$ ($L_{E,24h}$; dB re 1 µPa²s)[a]	R_{max} (km)	$R_{95\%}$ (km)
PTS			
LF cetaceans	199	<0.05	<0.05
MF cetaceans	198	<0.05	<0.05
HF cetaceans	173	0.09	0.09
Sea turtles	220	<0.05	<0.05
TTS			
LF cetaceans	179	0.63	0.53
MF cetaceans	178	0.07	0.07
HF cetaceans	153	1.24	1.06
Sea turtles	200	0.07	<0.05

[a] Frequency weighted.

4.2. Maps

4.2.1. Maximum-over-depth SPL Sound Fields

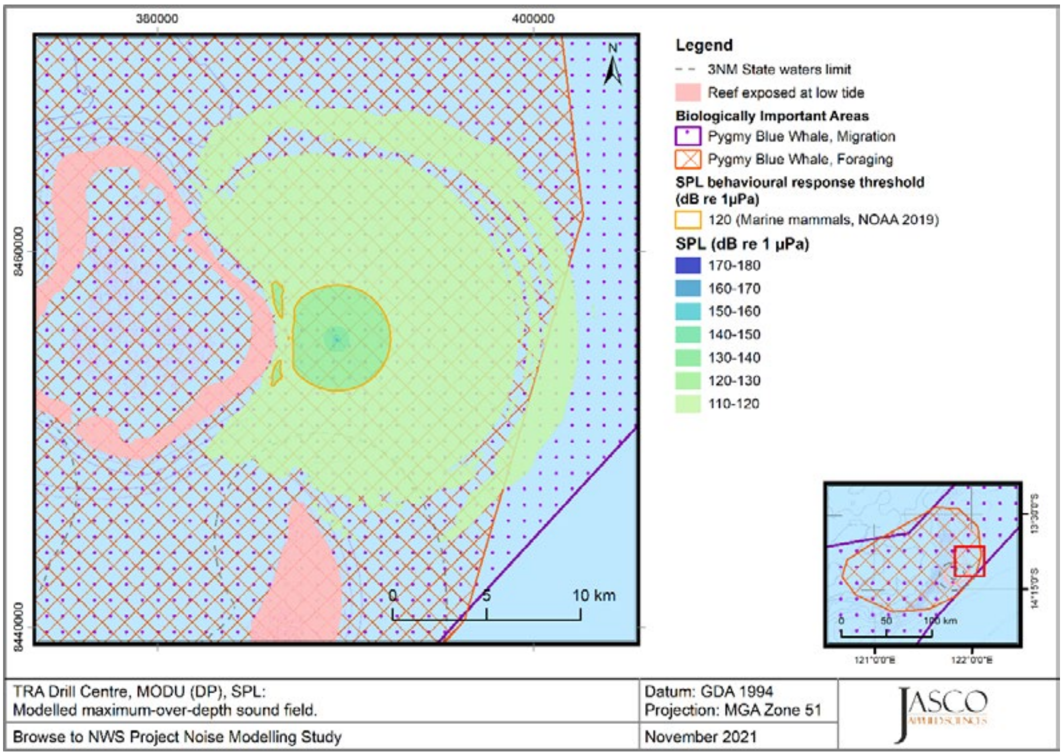

Figure 9. *TRA Drill centre, MODU, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

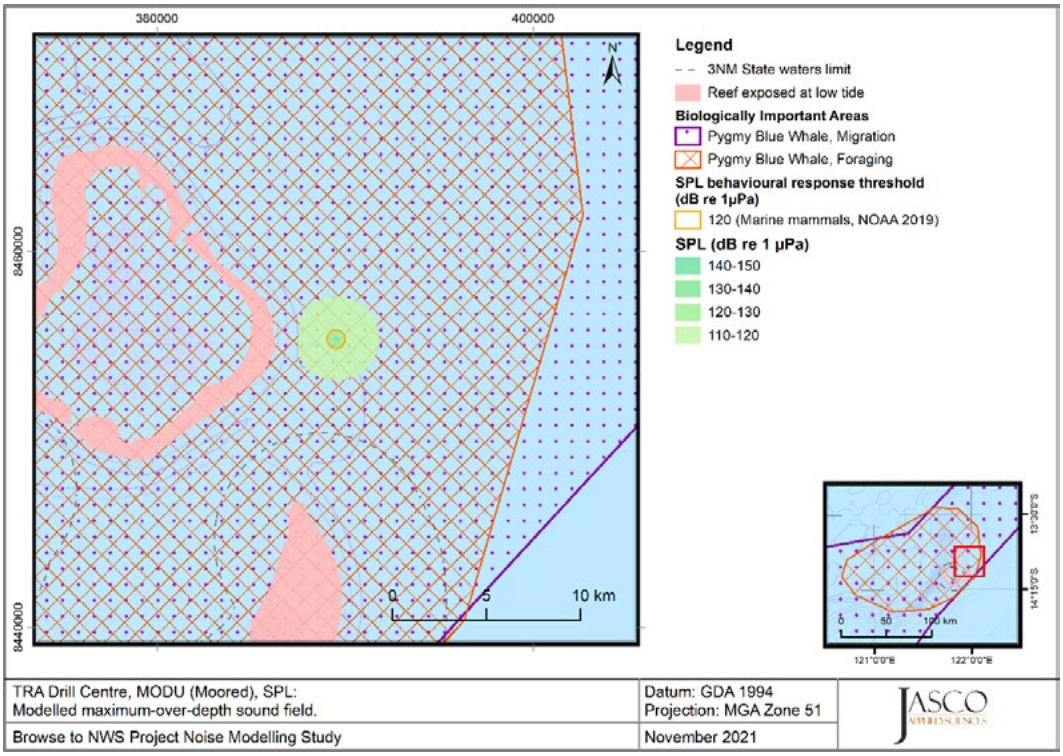

Figure 10. *TRA Drill centre, MODU (Moored), SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

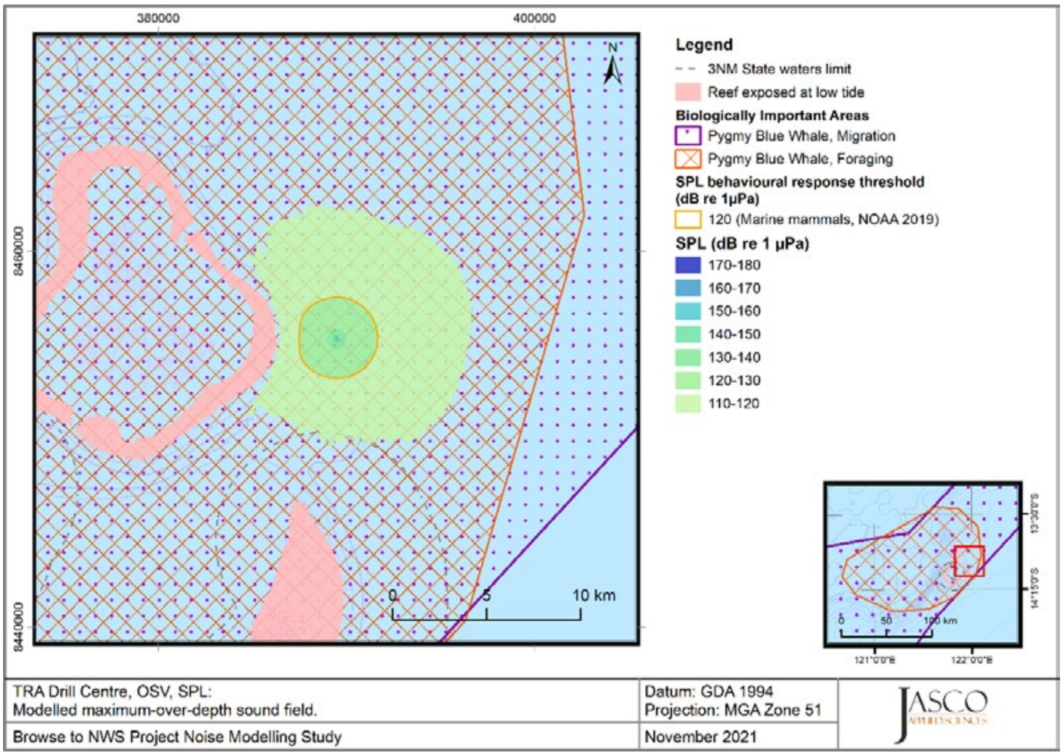

Figure 11. *TRA Drill centre, OSV, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

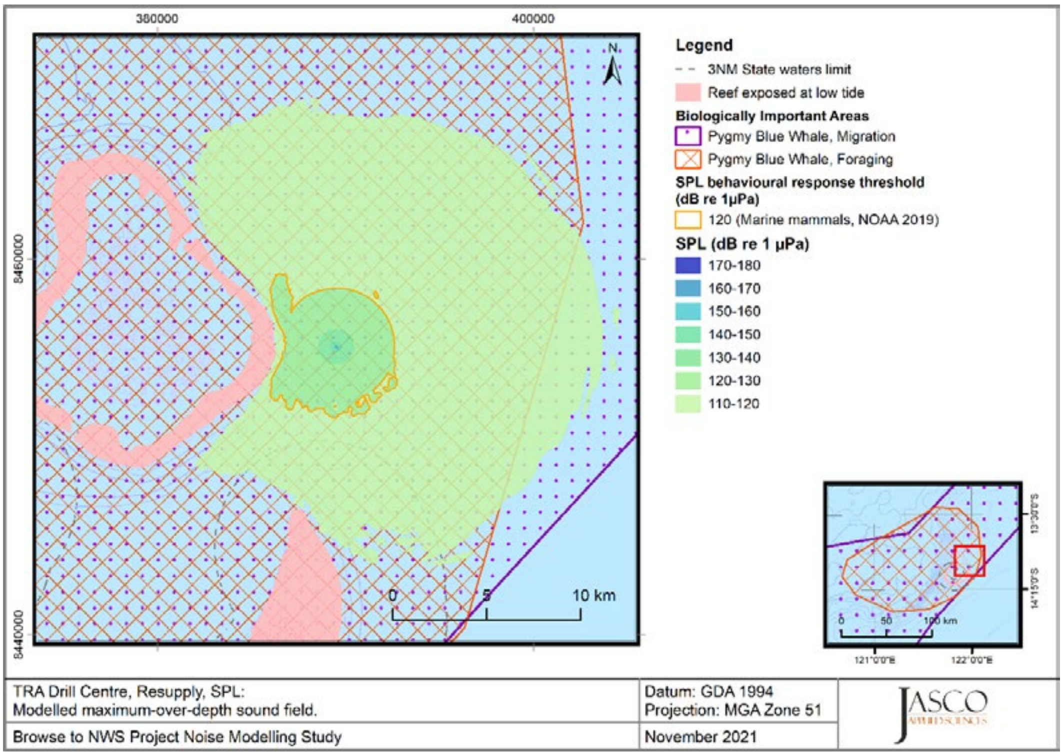

Figure 12. *TRA Drill centre, MODU under DP resupply, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

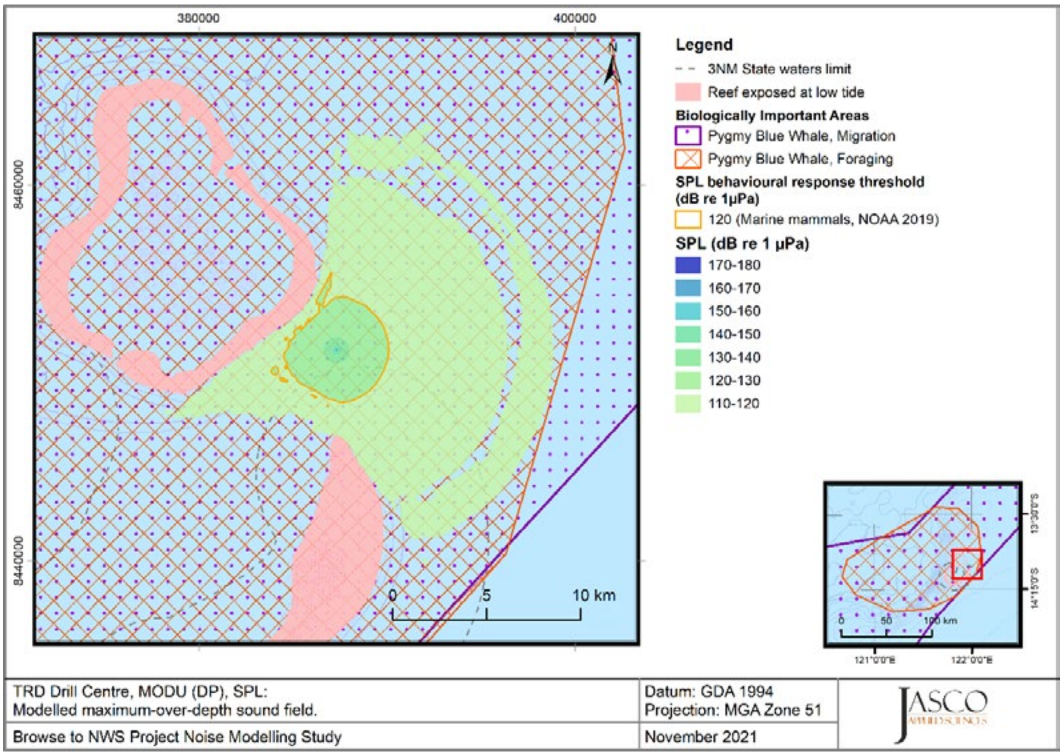

Figure 13. *TRD Drill centre, MODU, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

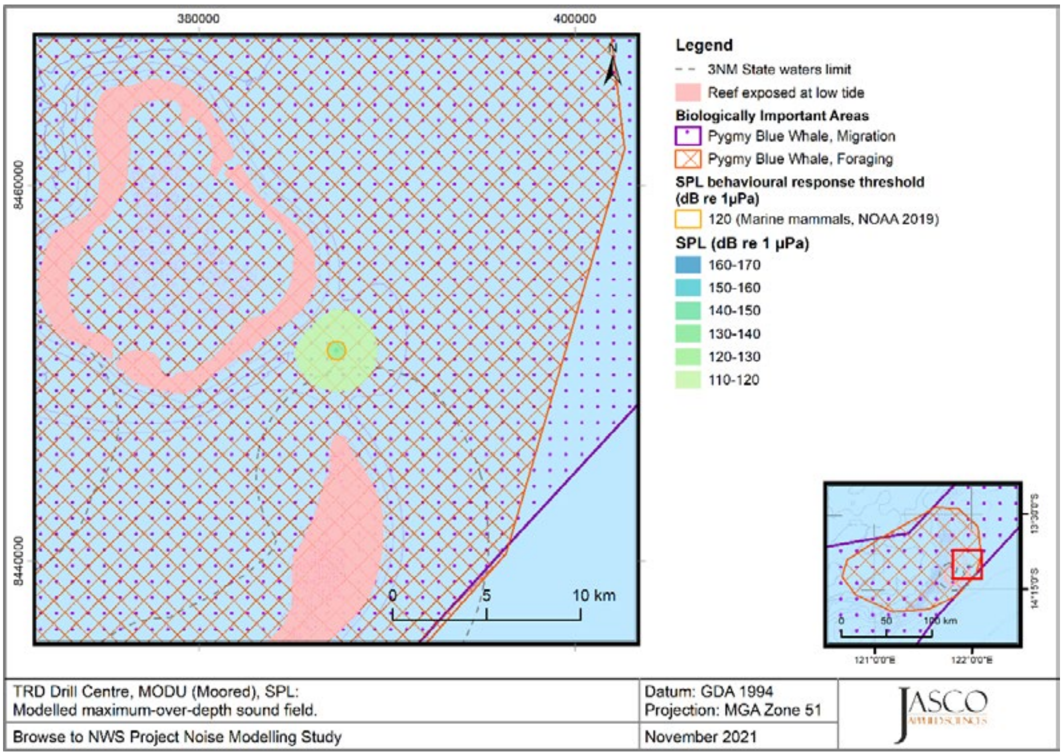

Figure 14. *TRD Drill centre, MODU (Moored), SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

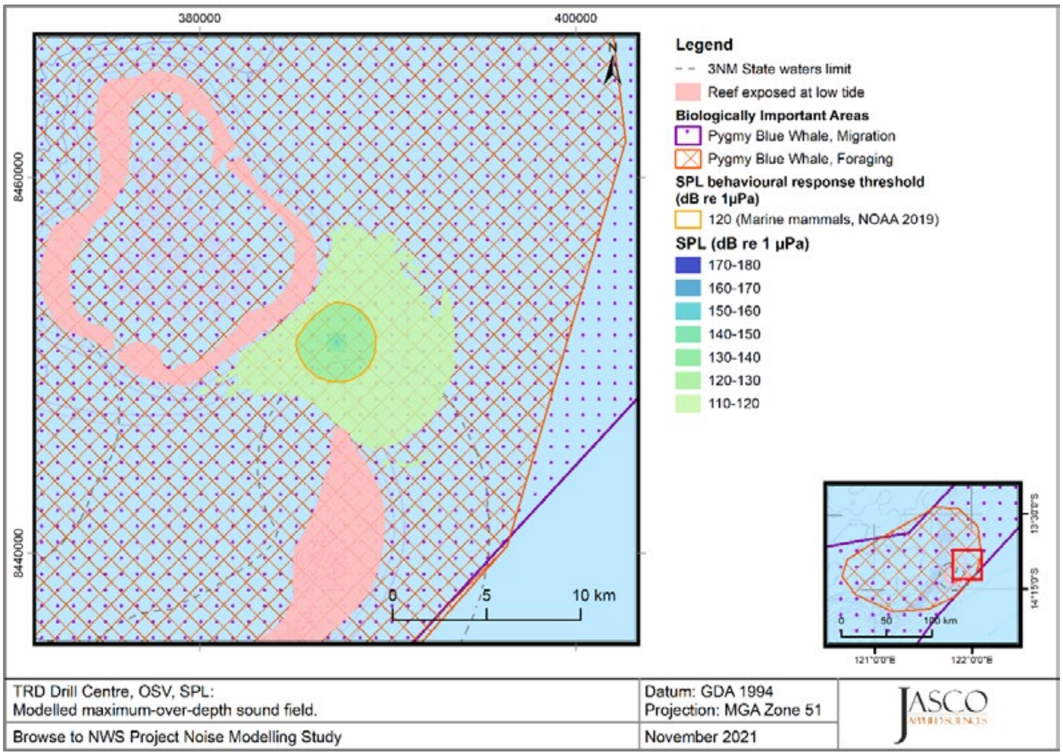

Figure 15. *TRD Drill centre, OSV, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

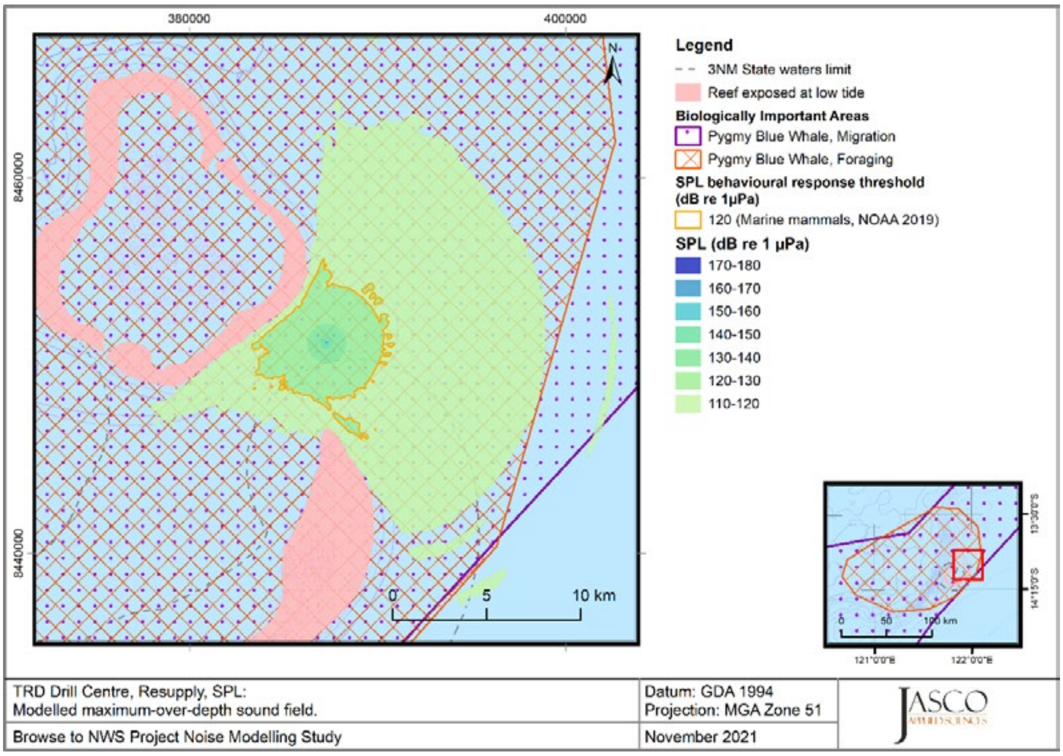

Figure 16. *TRD Drill centre, MODU under DP resupply, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

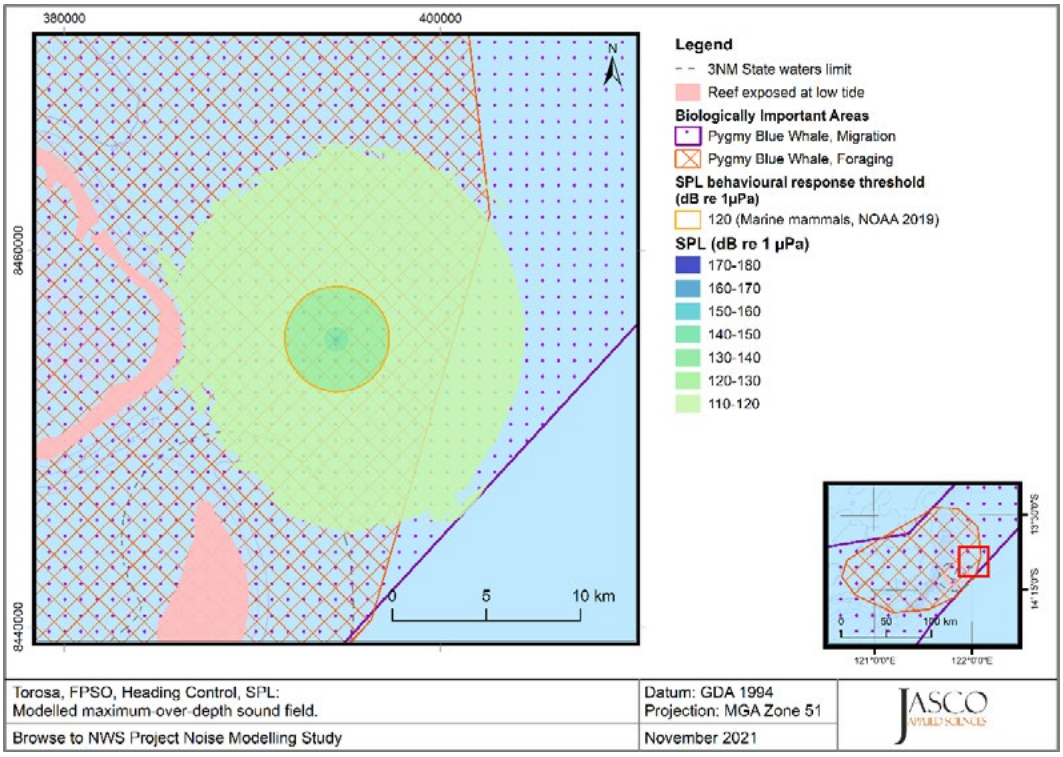

Figure 17. *Torosa location, FPSO, Heading Control, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

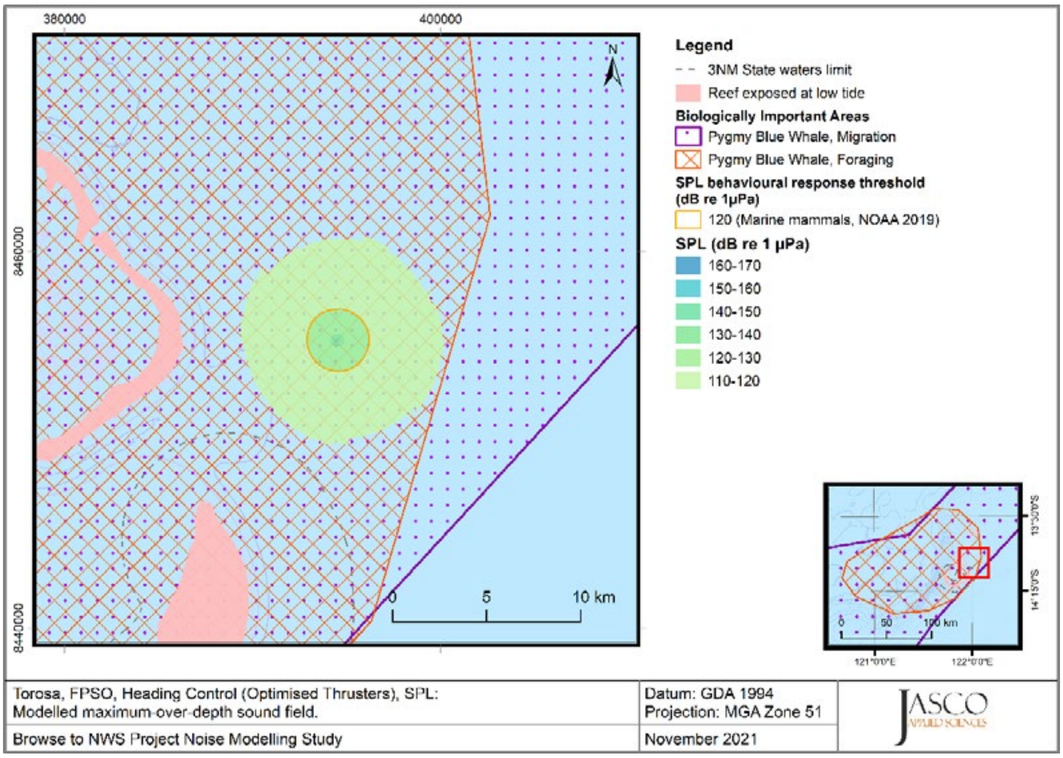

Figure 18. *Torosa, FPSO, Heading Control (Optimised Thrusters), SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

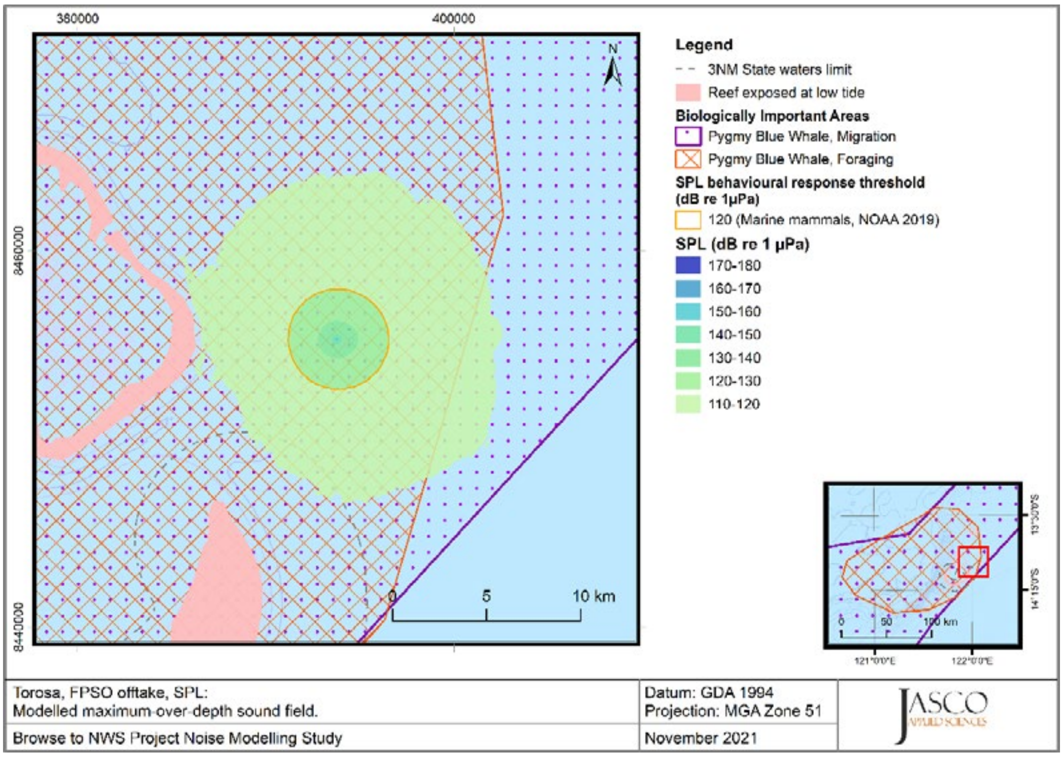

Figure 19. *Torosa location, FPSO Offtake, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

4.2.2. Accumulated SEL Sound Fields

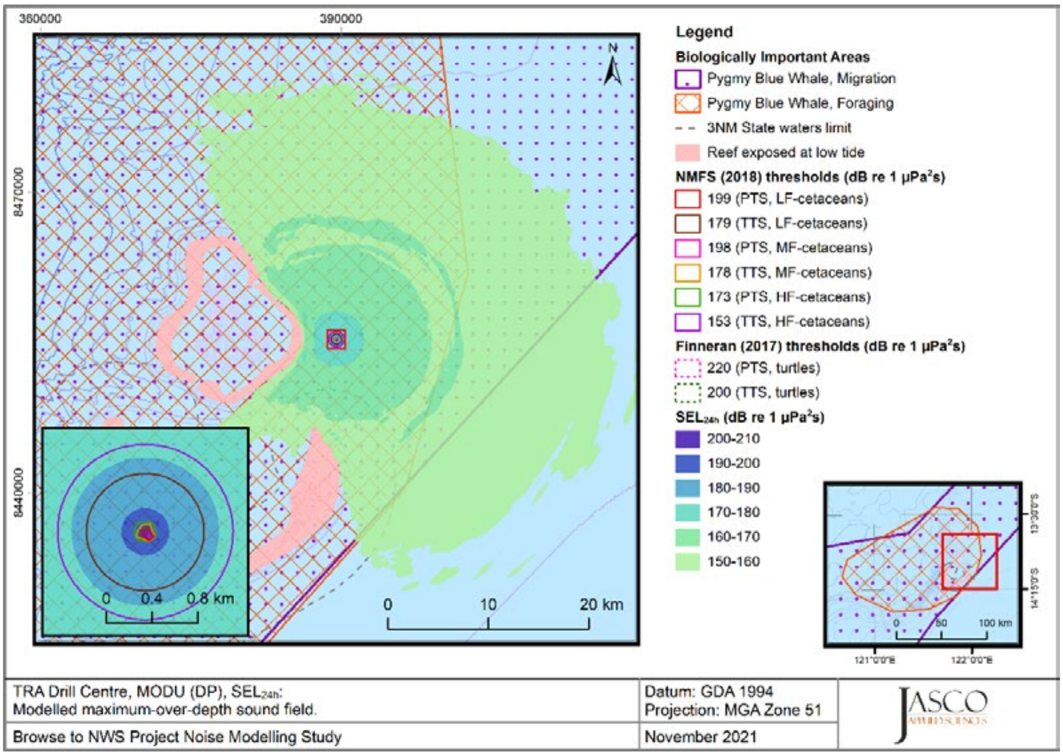

Figure 20. *TRA Drill centre, MODU, SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

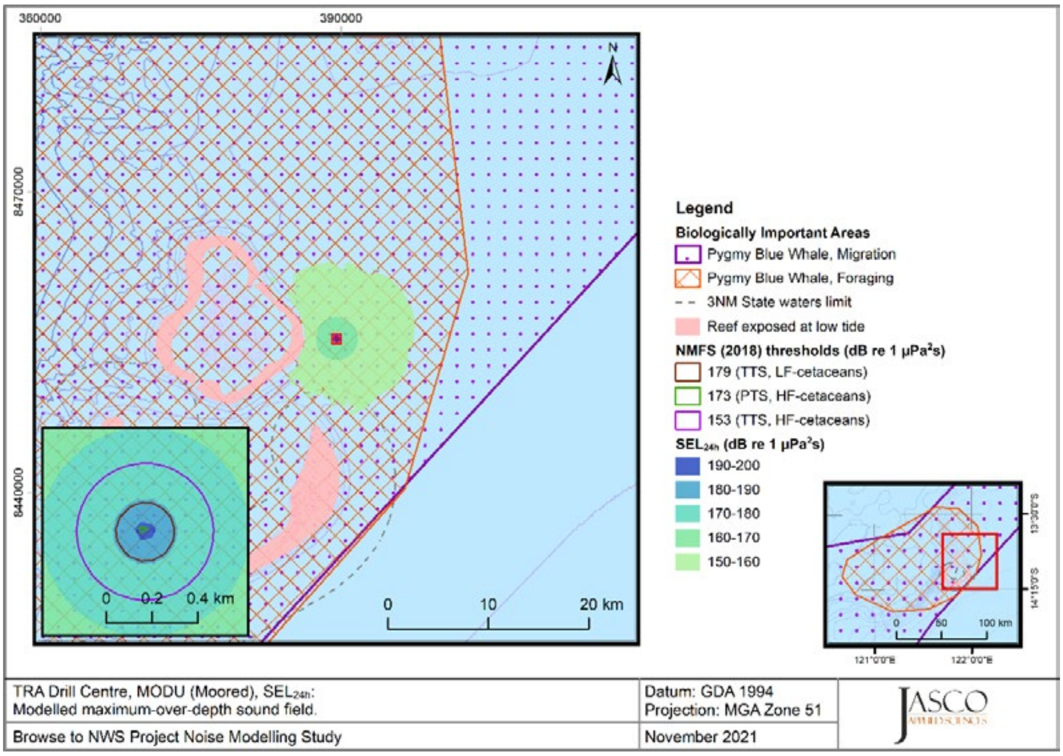

Figure 21. *TRA Drill centre, MODU (Moored), SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{6h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

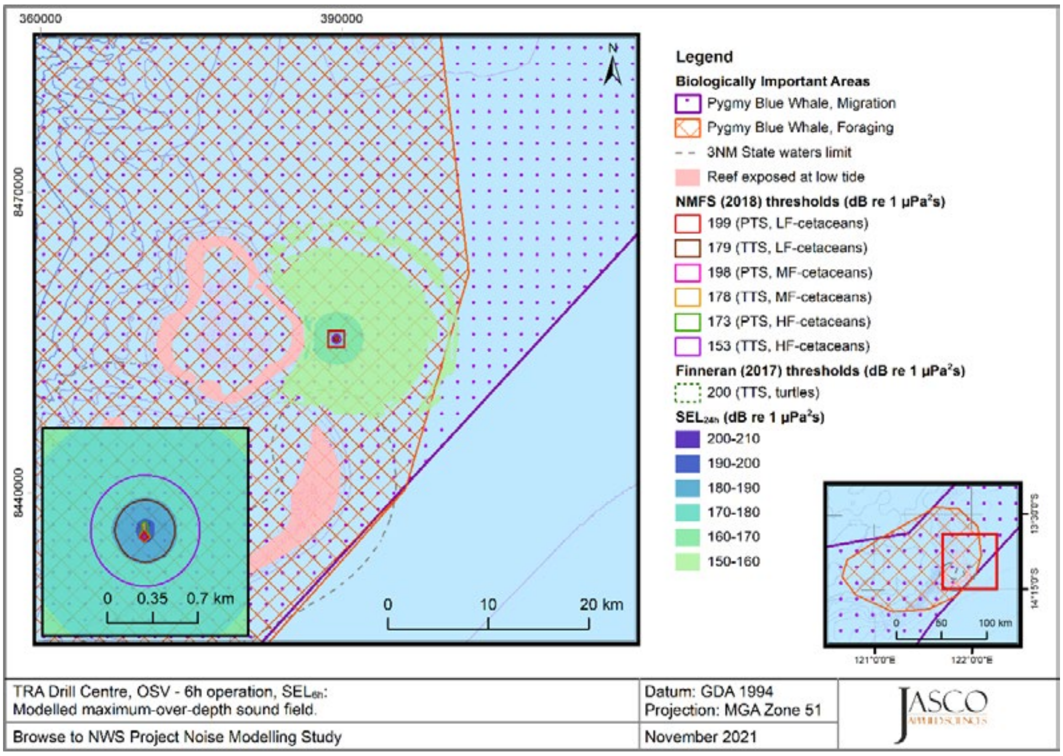

Figure 22. *TRA Drill centre, OSV-6 h operation, SEL$_{6h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{6h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

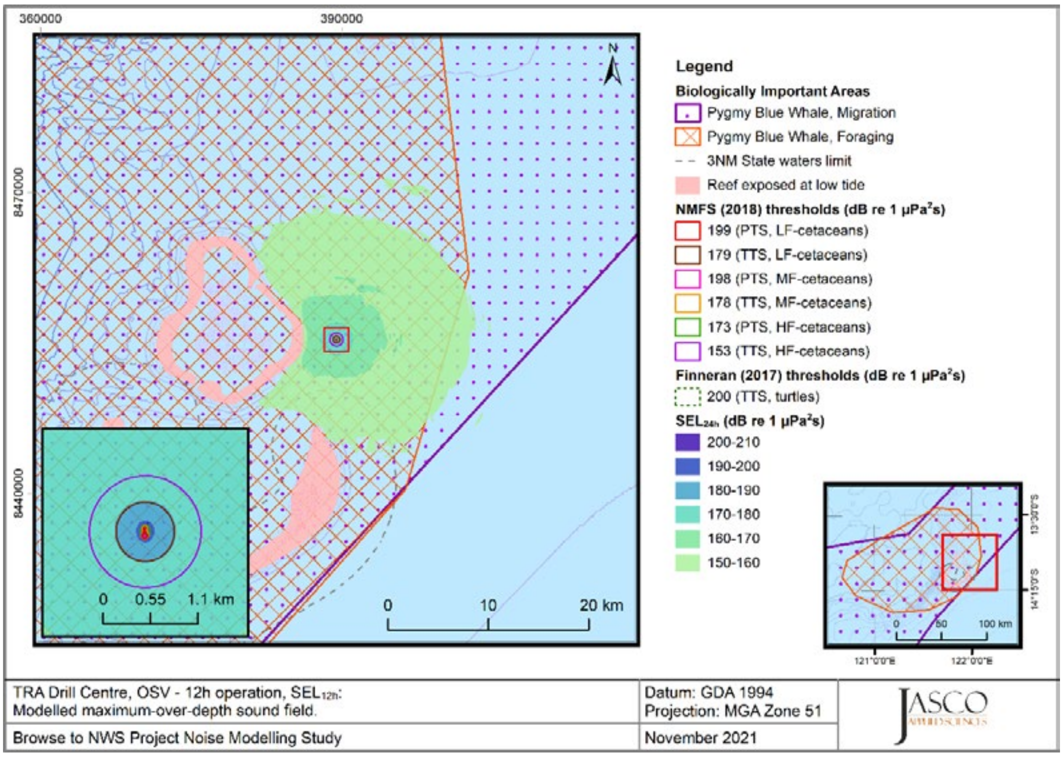

Figure 23. *TRA Drill centre, OSV-12 h operation, SEL$_{12h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{12h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

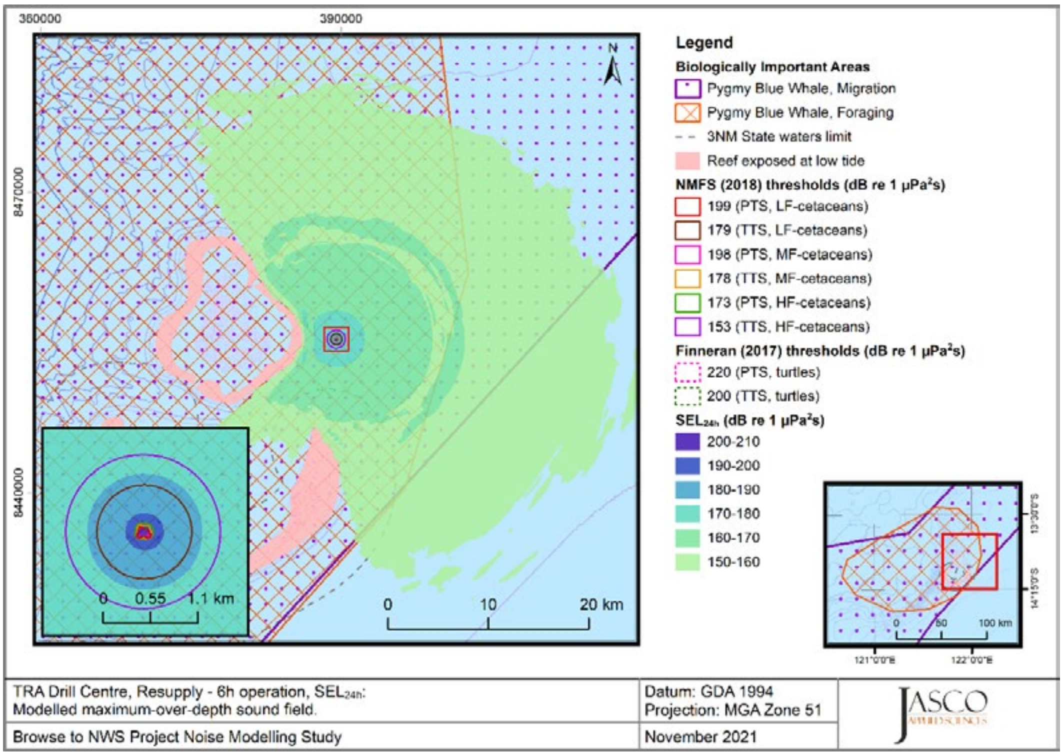

Figure 24. *TRA Drill centre, MODU under DP resupply-6 h operation, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL24h results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

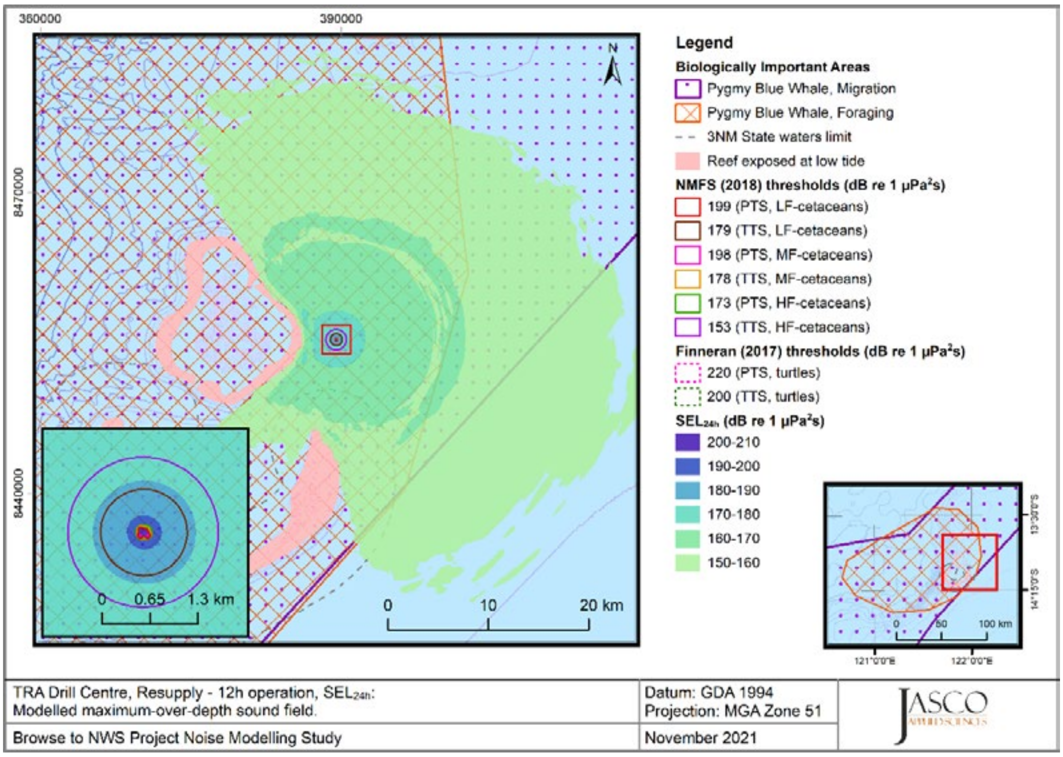

Figure 25. *TRA Drill centre, MODU under DP resupply-12 h operation, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

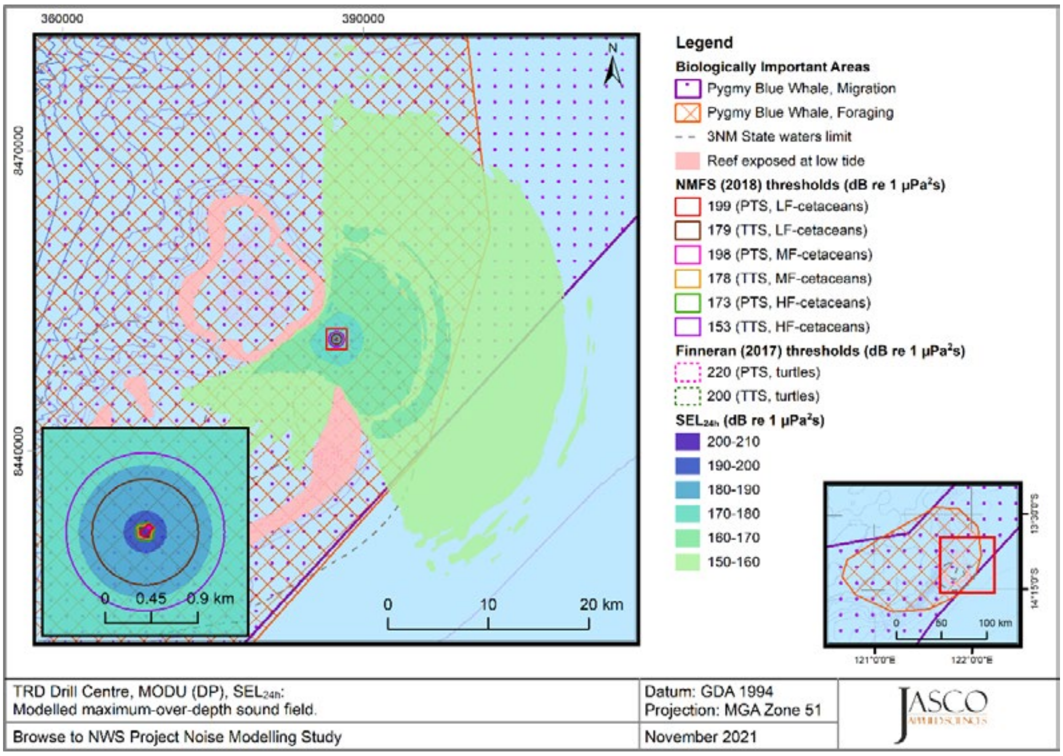

Figure 26. *TRD Drill centre, MODU, SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{24h} results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

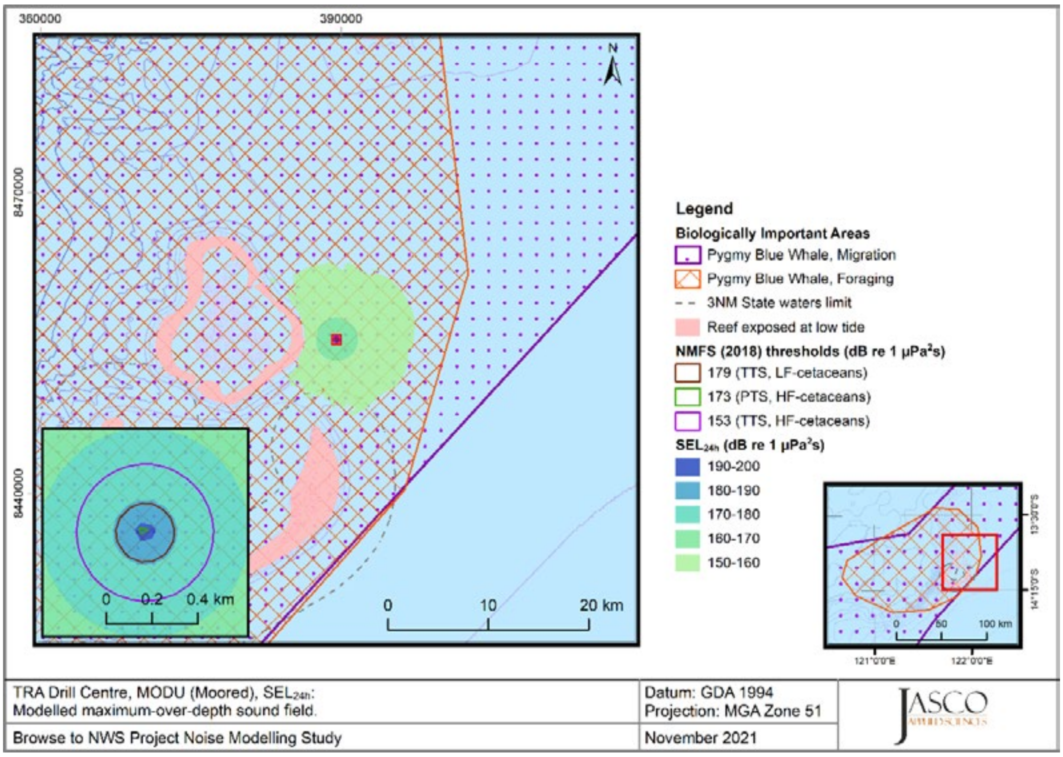

Figure 27. *TRD Drill centre, MODU (Moored), SEL_{24h}*: Sound level contour map showing unweighted maximum-over-depth SEL_{6h} results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

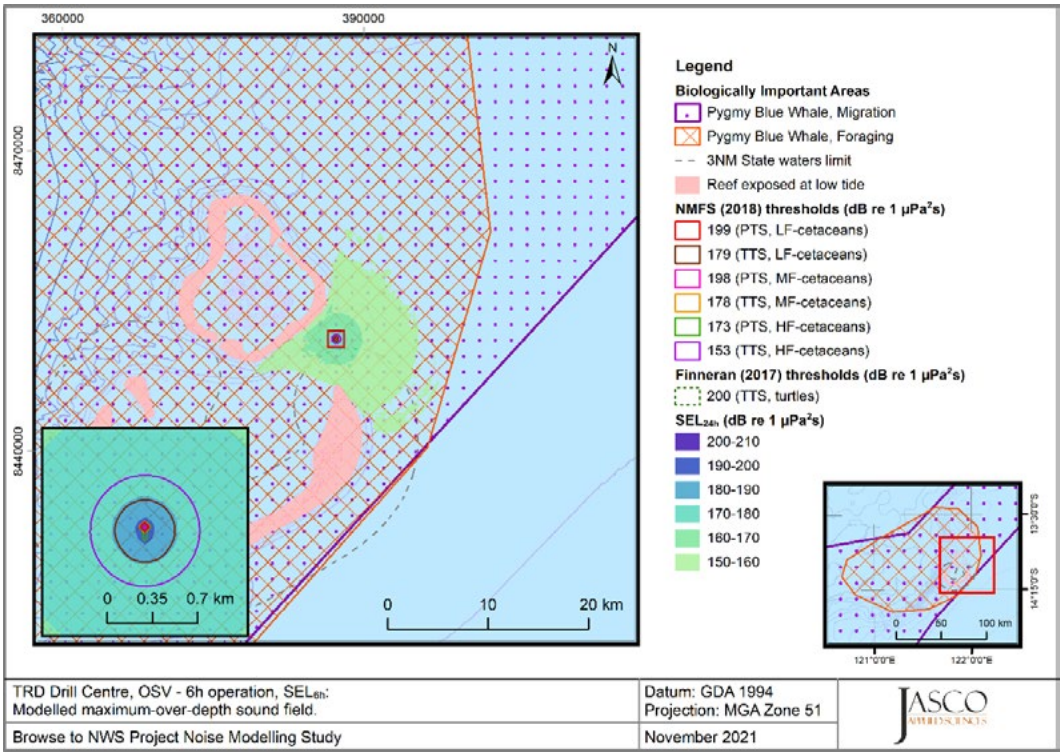

Figure 28. *TRD Drill centre, OSV-6 h operation, SEL$_{6h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{6h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

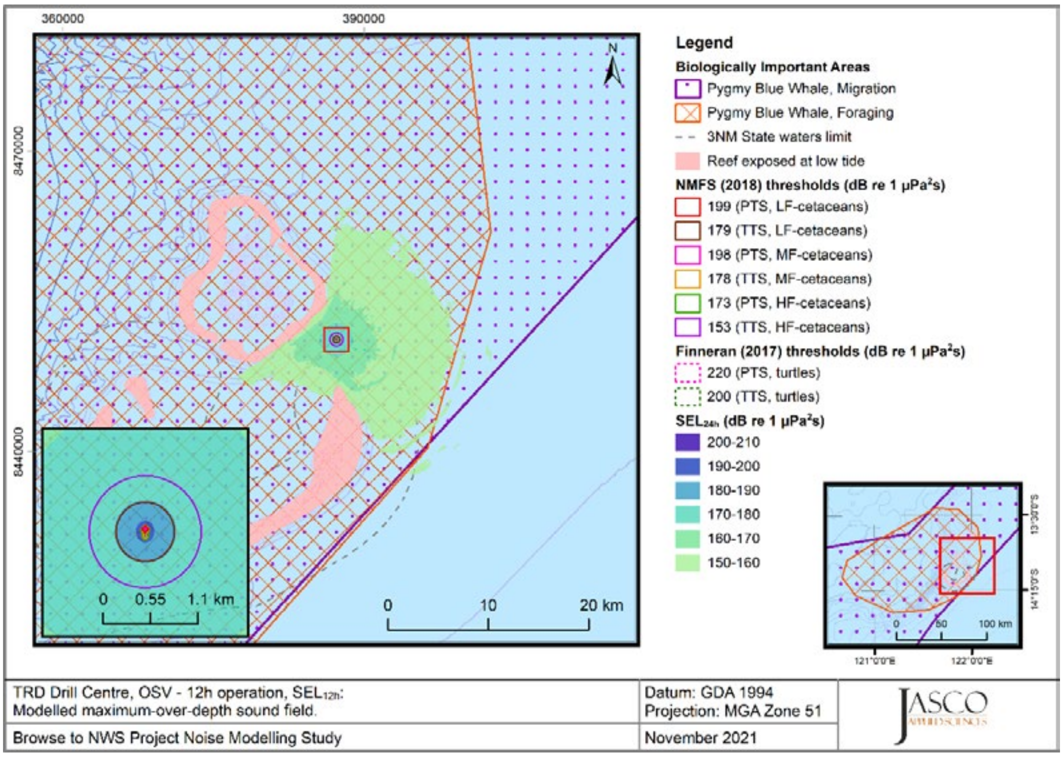

Figure 29. *TRD Drill centre, OSV-12 h operation, SEL$_{12h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{12h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

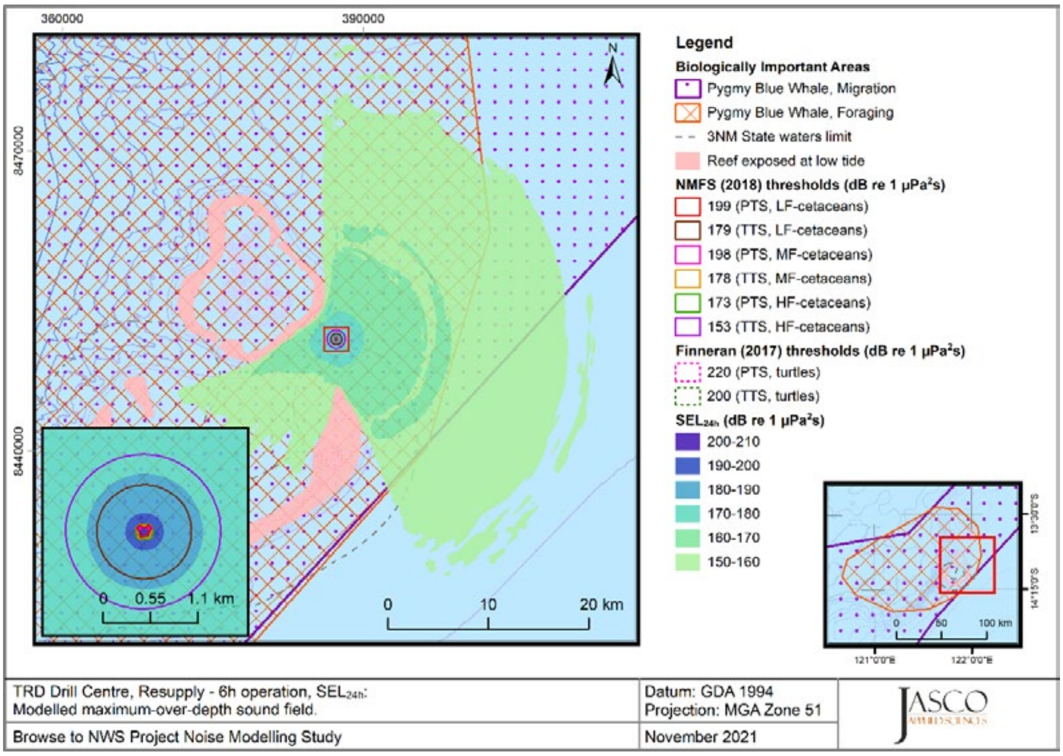

Figure 30. *TRD Drill centre, MODU under DP resupply-6 h operation, SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

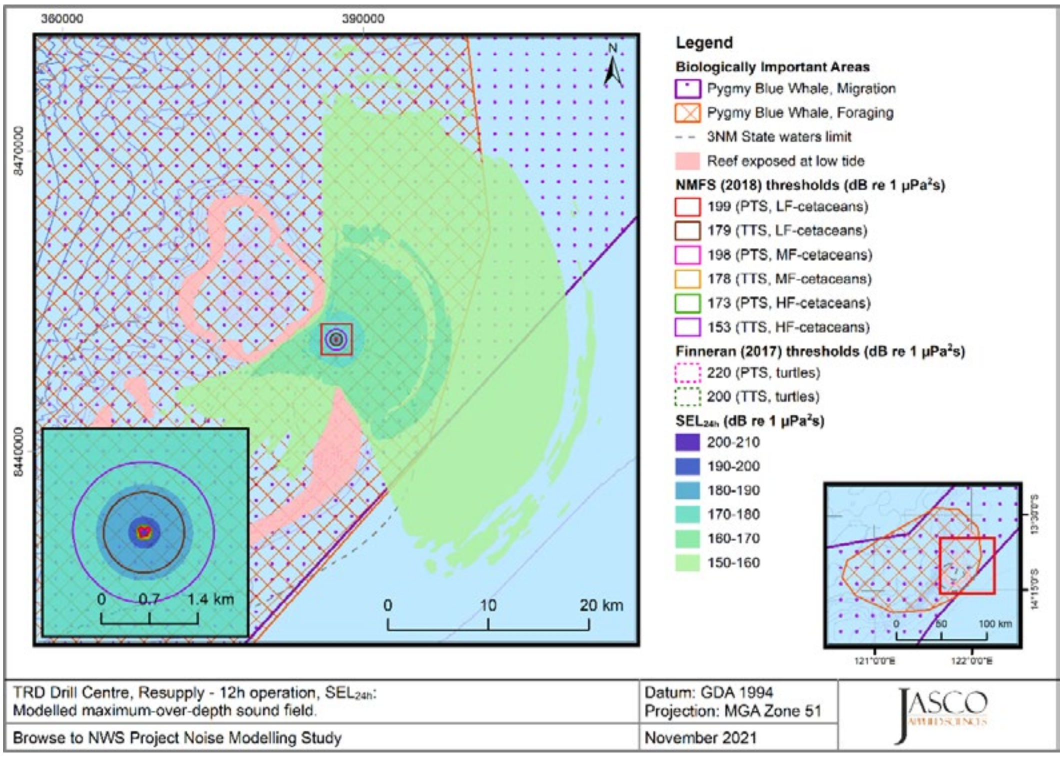

Figure 31. *TRD Drill centre, MODU under DP resupply-12 h operation, SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

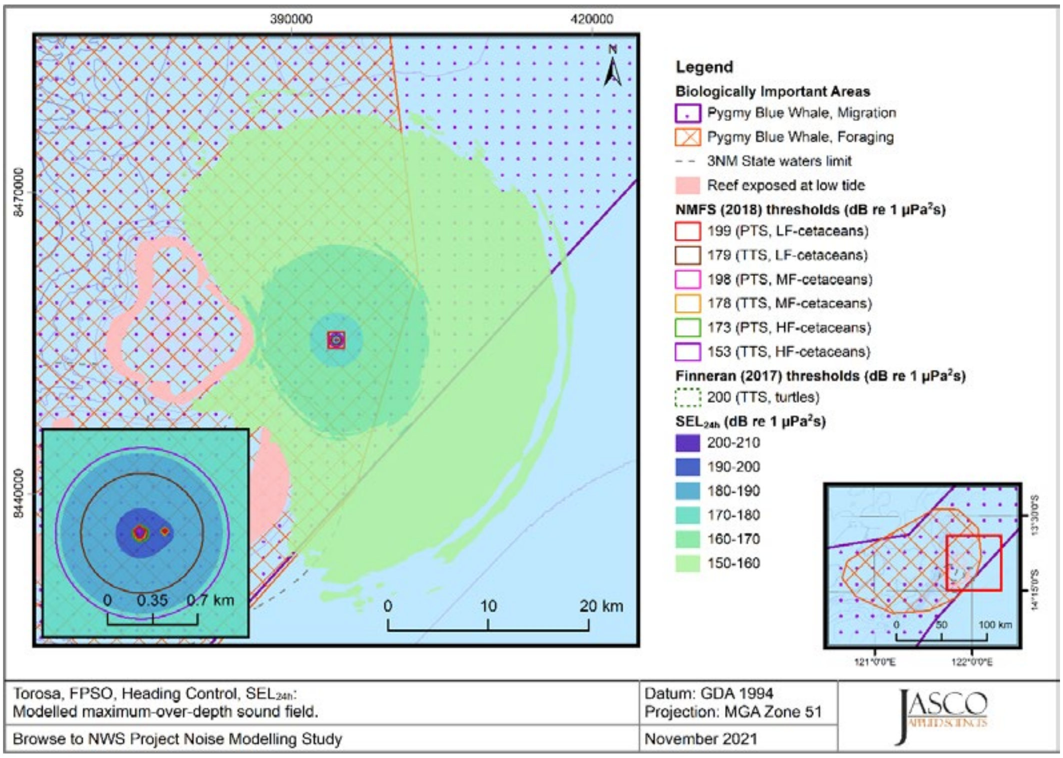

Figure 32. *Torosa location, FPSO, Heading Control. SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

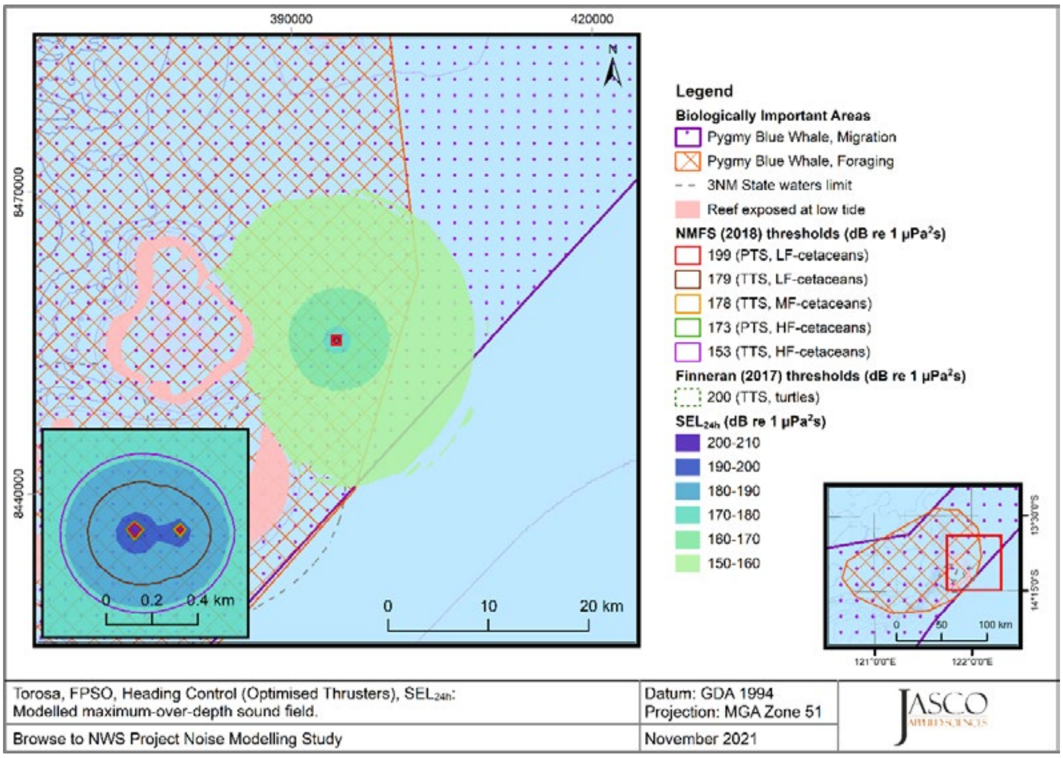

Figure 33. *Torosa FPSO, Heading Control (Optimised Thrusters), SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

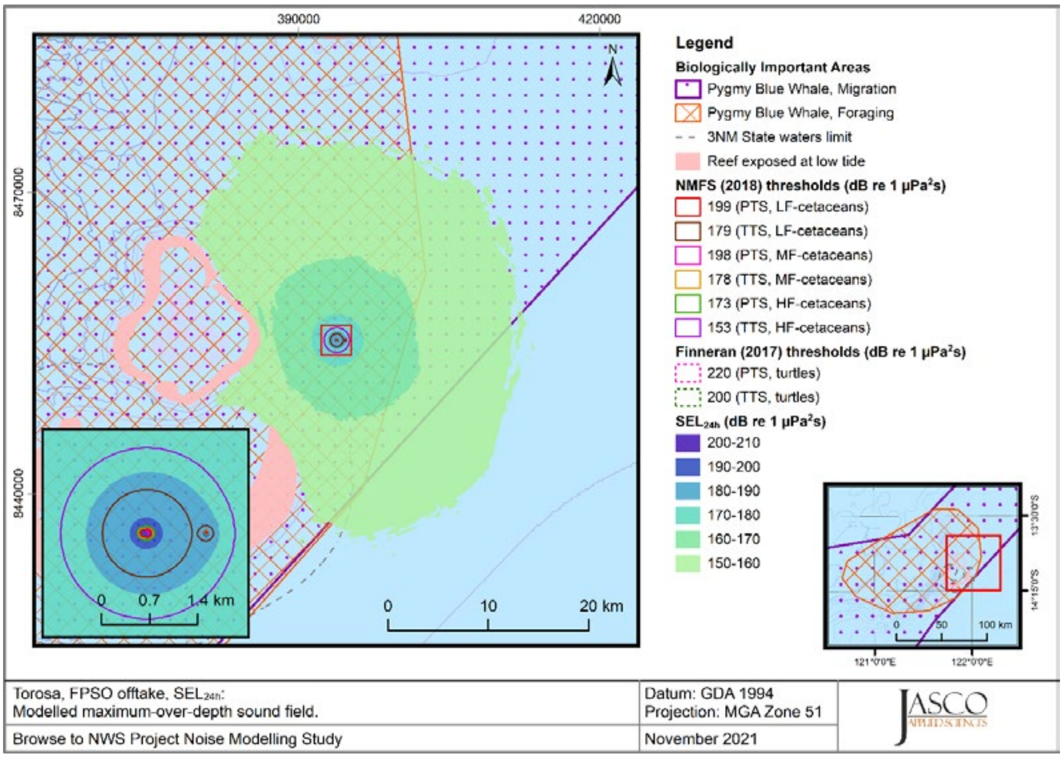

Figure 34. *Torosa location, FPSO Offtake, SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

4.2.3. Aggregate Scenario

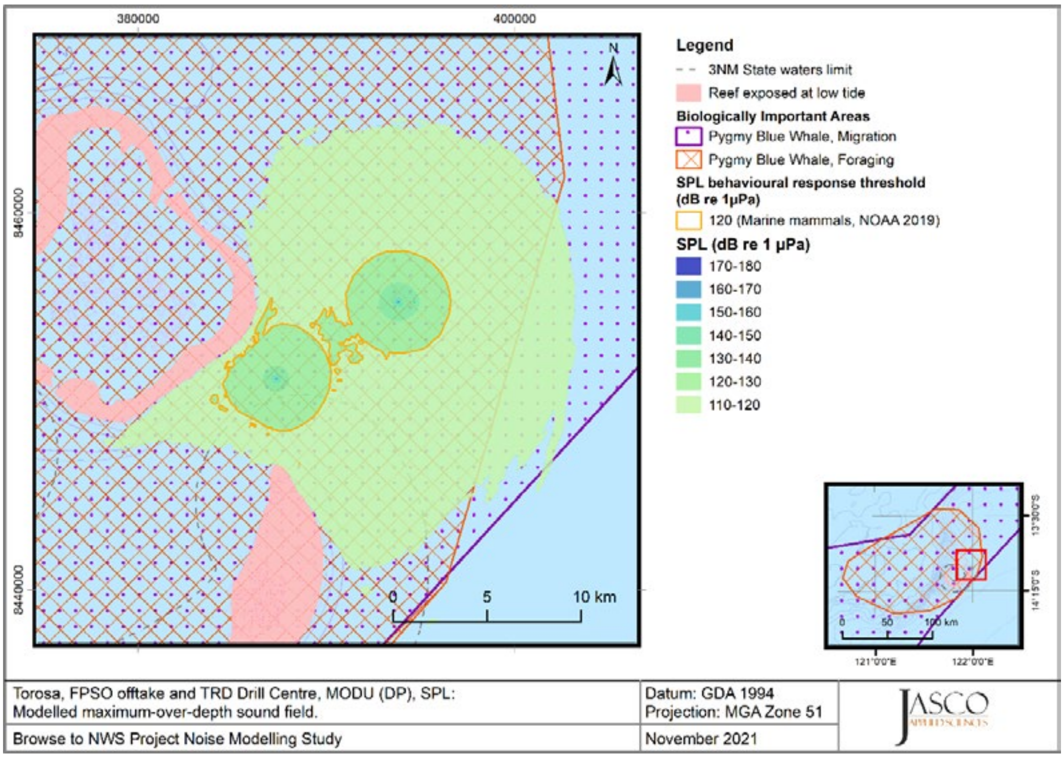

Figure 35. *Torosa FPSO location and TRD Drill centre, Aggregate FPSO offtake and MODU under DP, SPL*: Sound level contour map, showing maximum-over-depth results. Isopleth shows marine mammal behavioural criteria (120 dB re 1 µPa).

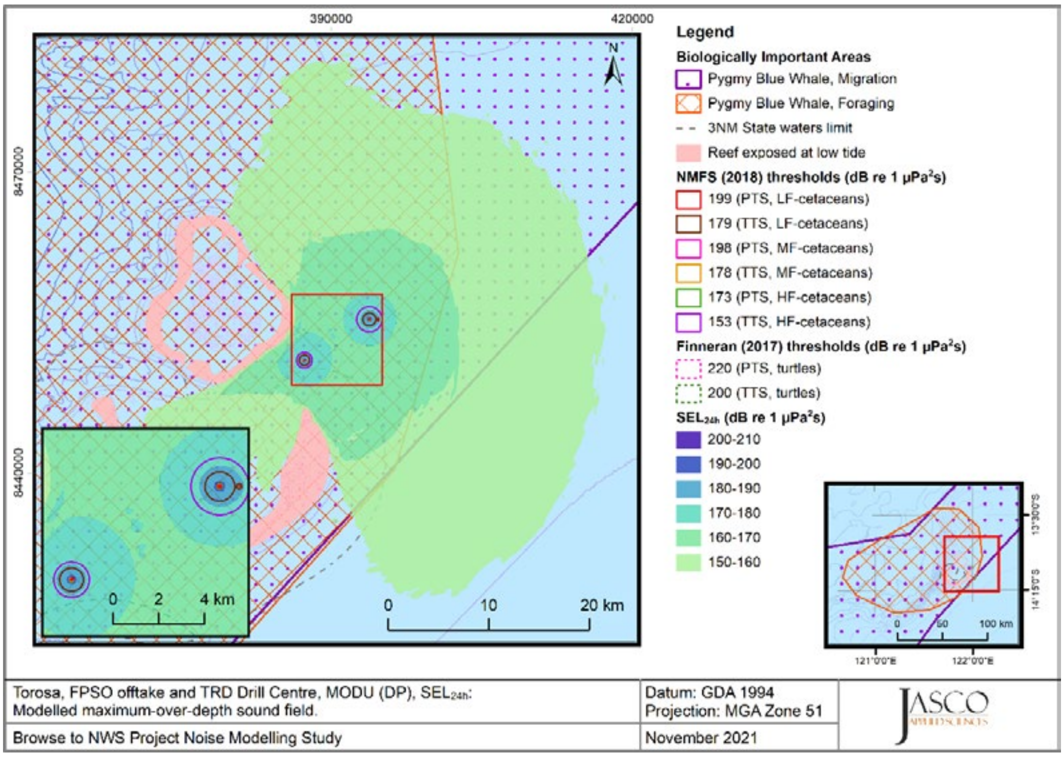

Figure 36. *TRD Drill Centre, Aggregate FPSO offtake and MODU under DP, SEL$_{24h}$*: Sound level contour map showing unweighted maximum-over-depth SEL$_{24h}$ results, along with isopleths for PTS and TTS thresholds in low, mid, and high-frequency cetaceans and sea turtles.

5. Discussion

5.1.1. Acoustic Propagation

Results have been presented showing the propagation of sound from a dynamically positioned and moored MODU during drilling operations at both TRA and TRD drill centres, and an FPSO using heading control at Torosa, with associated offshore support vessels (OSVs). Single-vessel and combination scenarios were modelled at each location, as well as an aggregate scenario involving the MODU at the TRD drill centre and the FPSO offtake scenario at the Torosa field.

The main influence on sound propagation is the bathymetry in the local area. In particular, the nearby presence of Scott Reef blocks most propagation in westerly and south-westerly directions. This is especially true of sources at the TRA and TRD drill centres, as both of these are closer to the reef than the facility at Torosa. Looking at the maps in Figures 17–19, it can be seen that the presence of Scott Reef does not significantly affect propagation from Torosa at the levels of interest for SPL, whereas Figures 9–16 clearly show the effect of the reef on the propagation from the TRA and TRD drill centres. The SEL_{24h} levels are visibly affected by the reef from all sites, though not at ranges that affect any relevant thresholds (see Figures 20–34).

5.1.2. Exposure Thresholds

At the TRA and TRD drill centres, there are several significant effects of combining the MODU (under DP) and OSV sources in the resupply scenarios. At the TRA drill centre, the SPL behavioural threshold range for marine mammals is almost 5 km for the resupply scenario, and at the TRD drill centre it exceeds 5 km, whereas it is between 2–4.5 km for scenarios with single vessels including thruster sources. This is mirrored in SEL_{24h} TTS threshold ranges for high-frequency cetaceans, which are above 0.9 km for multi-vessel scenarios, but generally less than 0.8 km for single-vessel scenarios (see Tables 17 and 18). The omission of the thrusters in the 'moored' MODU scenarios significantly reduce threshold ranges, from 4.49 km to 0.5 km for marine mammal behavioural disturbance, and from 0.77 km to 0.3 km for the high-frequency cetacean TTS threshold.

One phenomenon of note is that the FPSO offtake scenario has a shorter range to the 120 dB marine mammal SPL disturbance threshold (2.67 km) than the standalone FPSO on heading control scenario (2.82 km; see Table 14). This is despite the fact that the broadband source level of the OSV, the dominant source in the offtake scenario, is 185.5 dB re 1 µPa, whereas the broadband source level of the FPSO with heading control is lower, at 183 dB re 1 µPa. The machinery source on the FPSO has much more energy at low frequencies than any of the thruster sources on the OSV. These low frequencies are less readily absorbed, and it is possible this is causing the observed effect. This is also reflected in the fact that at levels above 130 dB, ranges are shorter for the offtake scenario than for the FPSO on heading control scenario.

For the aggregate scenario including both FPSO offtake and the MODU under DP at the TRD drill centre, it was found that due to the separation between the sites, ranges to PTS and TTS thresholds (Table 22) were not significantly different than the individual operations (Tables 18 and 19). Maximum behavioural threshold ranges (Table 20), on the other hand, increased by 580 m relative to the MODU operating in isolation under DP (Tables 13 and 14). The $R_{95\%}$, however, is not significantly altered from either scenario in isolation, indicating that this increase in $R_{\max}$ is probably due to a specific propagation path between the two sites (see Figure 35).

Glossary

Unless otherwise stated in an entry, these definitions are consistent with ISO 80000-3 (2017).

absorption

The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

animal movement modelling

Simulation of animal movement based on behavioural rules for the purpose of predicting an animal's experience of an environment.

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.

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.

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 80000-3:2006).

decidecade

One tenth of a decade. *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.

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) (NMFS 2018, Southall et al. 2019). See **auditory frequency weighting functions**, which are often applied to these groups. 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).

hertz (Hz)

A unit of frequency defined as one cycle per second.

high-frequency (HF) cetacean

See **hearing group**.

isopleth

A line drawn on a map through all points having the same value of some quantity.

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**.

mid-frequency (MF) cetacean

See **hearing group**.

monopole source level (MSL)

A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point-like (monopole) sound source. Also see **radiated noise level**.

M-weighting

See **auditory frequency weighting function** (as proposed by Southall et al. 2007).

***N* percent exceedance level**

The sound level exceeded N% of the time during a specified time interval. Also see **percentile level**.

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.

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.

percentile level

The sound level not exceeded N% of the time during a specified time interval. The Nth percentile level is equal to the $(100-N)$% exceedance level. Also see ***N* percent exceedance level**.

permanent threshold shift (PTS)

An irreversible loss of hearing sensitivity caused by excessive noise exposure. PTS is considered auditory injury.

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**.

radiated noise level (RNL)

A source level that has been calculated assuming sound pressure decays geometrically with distance from the source, with no influence of the sea-surface and seabed. Also see **monopole source level**.

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 µm/s^2

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.

$$L_E := 10\log_{10}(E/E_0)\ \mathrm{dB}\ = 20\log_{10}\left(E^{1/2}/E_0^{1/2}\right)\ \mathrm{dB}$$

The frequency band and integration time should be specified. Abbreviation: SEL.

sound field

Region containing sound waves.

sound pressure

The contribution to total pressure caused by the action of sound.

sound pressure level (rms sound pressure level)

The level ($L_{p,\mathrm{rms}}$) of the time-mean-square sound pressure (p^2_{rms}). Unit: decibel (dB). Reference value (p^2_0) for sound in water: 1 µPa^2.

$$L_{p,\mathrm{rms}} := 10\log_{10}(p^2_{\mathrm{rms}}/p^2_0)\ \mathrm{dB}\ = 20\log_{10}(p_{\mathrm{rms}}/p_0)\ \mathrm{dB}$$

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).

unweighted

Term indicating that no frequency weighting function is applied. Synonymous with flat weighting.

Literature Cited

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.1-2013. *American National Standard: Acoustical Terminology*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS12013.

[HESS] High Energy Seismic Survey. 1999. *High Energy Seismic Survey Review Process and Interim Operational Guidelines for Marine Surveys Offshore Southern California*. Prepared for the California State Lands Commission and the United States Minerals Management Service Pacific Outer Continental Shelf Region by the High Energy Seismic Survey Team, Camarillo, CA, USA. 98 p. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2001100103.xhtml.

[ISO] International Organization for Standardization. 2006. *ISO 80000-3:2006 Quantities and units – Part 3: Space and time*. https://www.iso.org/standard/31888.html.

[ISO] International Organization for Standardization. 2016. *ISO 17208-1:2016. Underwater acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: Requirements for precision measurements in deep water used for comparison purposes*. https://www.iso.org/standard/62408.html.

[ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. https://www.iso.org/standard/62406.html.

[NMFS] National Marine Fisheries Service (US). 1998. *Acoustic Criteria Workshop*. Dr. Roger Gentry and Dr. Jeanette Thomas Co-Chairs.

[NMFS] National Marine Fisheries Service (US). 2016. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55. 178 p.

[NMFS] National Marine Fisheries Service (US). 2018. *2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts*. US Department of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-59. 167 p. https://media.fisheries.noaa.gov/dam-migration/tech_memo_acoustic_guidance_(20)_(pdf)_508.pdf.

[NOAA] National Oceanic and Atmospheric Administration (US). 2013. *Draft guidance for assessing the effects of anthropogenic sound on marine mammals: Acoustic threshold levels for onset of permanent and temporary threshold shifts*. National Oceanic and Atmospheric Administration, US Department of Commerce, and NMFS Office of Protected Resources, Silver Spring, MD, USA. 76 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2015. *Draft guidance for assessing the effects of anthropogenic sound on marine mammal hearing: Underwater acoustic threshold levels for onset of permanent and temporary threshold shifts*. NMFS Office of Protected Resources, Silver Spring, MD, USA. 180 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2016. *Document Containing Proposed Changes to the NOAA Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts*. National Oceanic and Atmospheric Administration and US Department of Commerce. 24 p.

[NOAA] National Oceanic and Atmospheric Administration (US). 2019. *ESA Section 7 Consultation Tools for Marine Mammals on the West Coast* (web page), 27 Sep 2019. https://www.fisheries.noaa.gov/west-coast/endangered-species-conservation/esa-section-7-consultation-tools-marine-mammals-west.

[ONR] Office of Naval Research. 1998. *ONR Workshop on the Effect of Anthropogenic Noise in the Marine Environment*. Dr. R. Gisiner, Chair.

Aerts, L.A.M., M. Blees, S.B. Blackwell, C.R. Greene, Jr., K.H. Kim, D.E. Hannay, and M.E. Austin. 2008. *Marine mammal monitoring and mitigation during BP Liberty OBC seismic survey in Foggy Island Bay, Beaufort*

Sea, July-August 2008: 90-day report. Document P1011-1. Report by LGL Alaska Research Associates Inc., LGL Ltd., Greeneridge Sciences Inc., and JASCO Applied Sciences for BP Exploration Alaska. 199 p. ftp://ftp.library.noaa.gov/noaa_documents.lib/NMFS/Auke%20Bay/AukeBayScans/Removable%20Disk/P1011-1.pdf.

Amoser, S. and F. Ladich. 2003. Diversity in noise-induced temporary hearing loss in otophysine fishes. *Journal of the Acoustical Society of America* 113(4): 2170-2179. https://doi.org/10.1121/1.1557212.

ANSI S1.1-2013. R2013. *American National Standard Acoustical Terminology*. American National Standards Institute, NY, USA.

Austin, M.E., D.E. Hannay, and K.C. Bröker. 2018. Acoustic characterization of exploration drilling in the Chukchi and Beaufort seas. *Journal of the Acoustical Society of America* 144: 115-123. https://doi.org/10.1121/1.5044417

Bureau of Meterology (Australian Government). 2019. Tide Predictions for Australia, South Pacific and Antarctica: Scott Reef (WA), WA – July 2019. http://www.bom.gov.au/australia/tides/#!/wa-scott-reef-wa (Accessed 10 Dec 2021).

Carnes, M.R. 2009. *Description and Evaluation of GDEM-V 3.0*. US Naval Research Laboratory, Stennis Space Center, MS. NRL Memorandum Report 7330-09-9165. 21 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/a494306.pdf.

Collins, M.D. 1993. A split-step Padé solution for the parabolic equation method. *Journal of the Acoustical Society of America* 93(4): 1736-1742. https://doi.org/10.1121/1.406739.

Collins, M.D., R.J. Cederberg, D.B. King, and S. Chin-Bing. 1996. Comparison of algorithms for solving parabolic wave equations. *Journal of the Acoustical Society of America* 100(1): 178-182. https://doi.org/10.1121/1.415921.

Coppens, A.B. 1981. Simple equations for the speed of sound in Neptunian waters. *Journal of the Acoustical Society of America* 69(3): 862-863. https://doi.org/10.1121/1.382038.

Duncan, A. 2014. *Prediction of underwater noise levels associated with the operation of FLNG facilities in the Browse Basin*. Report prepared by the Centre for Marine Science and Technology, Curtin University, for Browse FLNG Development. 55 p. https://tinyurl.com/yyoo7nhp.

Dunlop, R.A., M.J. Noad, R.D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2017. Determining the behavioural dose–response relationship of marine mammals to air gun noise and source proximity. *Journal of Experimental Biology* 220(16): 2878-2886. https://doi.org/10.1242/jeb.160192.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2018. A behavioural dose-response model for migrating humpback whales and seismic air gun noise. *Marine Pollution Bulletin* 133: 506-516. https://doi.org/10.1016/j.marpolbul.2018.06.009.

Ellison, W.T. and P.J. Stein. 1999. *SURTASS LFA High Frequency Marine Mammal Monitoring (HF/M3) Sonar: Sustem Description and Test & Evaluation*. Under US Navy Contract N66604-98-D-5725. http://www.surtass-lfa-eis.com/wp-content/uploads/2018/02/HF-M3-Ellison-Report-2-4a.pdf.

Ellison, W.T. and A.S. Frankel. 2012. A common sense approach to source metrics. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 433-438. https://doi.org/10.1007/978-1-4419-7311-5_98.

Erbe, C., R.D. McCauley, C.R. McPherson, and A. Gavrilov. 2013. Underwater noise from offshore oil production vessels. *Journal of the Acoustical Society of America* 133(6): EL465-EL470. https://doi.org/10.1121/1.4802183.

Finneran, J.J. and C.E. Schlundt. 2010. Frequency-dependent and longitudinal changes in noise-induced hearing loss in a bottlenose dolphin (*Tursiops truncatus*). *Journal of the Acoustical Society of America* 128(2): 567-570. https://doi.org/10.1121/1.3458814.

Finneran, J.J. and A.K. Jenkins. 2012. *Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis*. SPAWAR Systems Center Pacific, San Diego, CA, USA. 64 p.

Finneran, J.J. 2015. *Auditory weighting functions and TTS/PTS exposure functions for cetaceans and marine carnivores*. Technical report by SSC Pacific, San Diego, CA, USA.

Finneran, J.J. 2016. *Auditory weighting functions and TTS/PTS exposure functions for marine mammals exposed to underwater noise*. Technical Report for Space and Naval Warfare Systems Center Pacific, San Diego, CA, USA. 49 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf.

Finneran, J.J., E.E. Henderson, D.S. Houser, K. Jenkins, S. Kotecki, and J. Mulsow. 2017. *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III)*. Technical report by Space and Naval Warfare Systems Center Pacific (SSC Pacific). 183 p. https://nwtteis.com/portals/nwtteis/files/technical_reports/Criteria_and_Thresholds_for_U.S._Navy_Acoustic_and_Explosive_Effects_Analysis_June2017.pdf.

Fisher, F.H. and V.P. Simmons. 1977. Absorption of sound in sea water. *Journal of the Acoustical Society of America* 62(S13): 558-564. https://doi.org/10.1121/1.2015423.

Funk, D.W., D.E. Hannay, D.S. Ireland, R. Rodrigues, and W.R. Koski. 2008. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–November 2007: 90-day report*. LGL Report P969-1. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Research Ltd. for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 218 p. http://www-static.shell.com/static/usa/downloads/alaska/shell2007_90-d_final.pdf.

Gray, L.M. and D.S. Greeley. 1980. Source level model for propeller blade rate radiation for the world's merchant fleet. *Journal of the Acoustical Society of America* 67(2): 516-522. https://doi.org/10.1121/1.383916.

Hannay, D.E. and R. Racca. 2005. *Acoustic Model Validation*. Document 0000-S-90-04-T-7006-00-E, Revision 02, Version 1.3. Technical report by JASCO Research Ltd. for Sakhalin Energy Investment Company Ltd. 34 p.

Ireland, D.S., R. Rodrigues, D.W. Funk, W.R. Koski, and D.E. Hannay. 2009. *Marine mammal monitoring and mitigation during open water seismic exploration by Shell Offshore Inc. in the Chukchi and Beaufort Seas, July–October 2008: 90-Day Report*. Document P1049-1. 277 p.

Lucke, K., U. Siebert, P.A. Lepper, and M.-A. Blanchet. 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. *Journal of the Acoustical Society of America* 125(6): 4060-4070. https://doi.org/10.1121/1.3117443.

Malme, C.I., P.R. Miles, C.W. Clark, P. Tyak, and J.E. Bird. 1983. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior*. Report 5366. http://www.boem.gov/BOEM-Newsroom/Library/Publications/1983/rpt5366.aspx.

Malme, C.I., P.R. Miles, C.W. Clark, P.L. Tyack, and J.E. Bird. 1984. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Phase II: January 1984 Migration*. Report 5586. Report by Bolt Beranek and Newman Inc. for the US Department of the Interior, Minerals Management Service, Cambridge, MA, USA. https://www.boem.gov/sites/default/files/boem-newsroom/Library/Publications/1983/rpt5586.pdf.

Malme, C.I., B. Würsig, J.E. Bird, and P.L. Tyack. 1986. *Behavioral responses of gray whales to industrial noise: Feeding observations and predictive modeling*. Document 56. NOAA Outer Continental Shelf Environmental Assessment Program. Final Reports of Principal Investigators. 393-600 p.

Martin, B., K. Bröker, M.-N.R. Matthews, J.T. MacDonnell, and L. Bailey. 2015. Comparison of measured and modeled air-gun array sound levels in Baffin Bay, West Greenland. *OceanNoise 2015*. 11-15 May 2015, Barcelona, Spain.

McPherson, C.R., J.E. Quijano, M.J. Weirathmueller, K.R. Hiltz, and K. Lucke. 2019. *Browse to North-West-Shelf Noise Modelling Study: Assessing Marine Fauna Sound Exposures*. Document 01824, Version 2.2.

Technical report by JASCO Applied Sciences for Jacobs. https://www.epa.wa.gov.au/sites/default/files/PER_documentation2/Appendix%20D%203.pdf.

Nedwell, J.R. and A.W. Turnpenny. 1998. The use of a generic frequency weighting scale in estimating environmental effect. *Workshop on Seismics and Marine Mammals*. 23–25 Jun 1998, London, UK.

Nedwell, J.R., A.W. Turnpenny, J. Lovell, S.J. Parvin, R. Workman, J.A.L. Spinks, and D. Howell. 2007. *A validation of the dB$_{ht}$ as a measure of the behavioural and auditory effects of underwater noise*. Document 534R1231 Report prepared by Subacoustech Ltd. for Chevron Ltd, TotalFinaElf Exploration UK PLC, Department of Business, Enterprise and Regulatory Reform, Shell UK Exploration and Production Ltd, The Industry Technology Facilitator, Joint Nature Conservation Committee, and The UK Ministry of Defence. 74 p. https://tethys.pnnl.gov/sites/default/files/publications/Nedwell-et-al-2007.pdf.

O'Neill, C., D. Leary, and A. McCrodan. 2010. Sound Source Verification. (Chapter 3) *In* Blees, M.K., K.G. Hartin, D.S. Ireland, and D.E. Hannay (eds.). *Marine mammal monitoring and mitigation during open water seismic exploration by Statoil USA E&P Inc. in the Chukchi Sea, August-October 2010: 90-day report*. LGL Report P1119. Prepared by LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. for Statoil USA E&P Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. pp. 1-34.

Payne, R. and D. Webb. 1971. Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences* 188: 110-141. https://doi.org/10.1111/j.1749-6632.1971.tb13093.x.

Popper, A.N., A.D. Hawkins, R.R. Fay, D.A. Mann, S. Bartol, T.J. Carlson, S. Coombs, W.T. Ellison, R.L. Gentry, et al. 2014. *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI*. ASA S3/SC1.4 TR-2014. SpringerBriefs in Oceanography. ASA Press and Springer. https://doi.org/10.1007/978-3-319-06659-2.

Porter, M.B. and Y.C. Liu. 1994. Finite-element ray tracing. *In*: Lee, D. and M.H. Schultz (eds.). *International Conference on Theoretical and Computational Acoustics*. Volume 2. World Scientific Publishing Co. pp. 947-956.

Racca, R., A.N. Rutenko, K. Bröker, and M.E. Austin. 2012a. A line in the water - design and enactment of a closed loop, model based sound level boundary estimation strategy for mitigation of behavioural impacts from a seismic survey. *11th European Conference on Underwater Acoustics*. Volume 34(3), Edinburgh, UK.

Racca, R., A.N. Rutenko, K. Bröker, and G. Gailey. 2012b. Model based sound level estimation and in-field adjustment for real-time mitigation of behavioural impacts from a seismic survey and post-event evaluation of sound exposure for individual whales. *In*: McMinn, T. (ed.). *Acoustics 2012*. Fremantle, Australia. http://www.acoustics.asn.au/conference_proceedings/AAS2012/papers/p92.pdf.

Scholik, A.R. and H.Y. Yan. 2002. Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*. *Environmental Biology of Fishes* 63(2): 203-209. https://doi.org/10.1023/A:1014266531390.

Smith, M.E., A.B. Coffin, D.L. Miller, and A.N. Popper. 2006. Anatomical and functional recovery of the goldfish (*Carassius auratus*) ear following noise exposure. *Journal of Experimental Biology* 209(21): 4193-4202. https://doi.org/10.1242/jeb.02490.

Southall, B.L., A.E. Bowles, W.T. Ellison, J.J. Finneran, R.L. Gentry, C.R. Greene, Jr., D. Kastak, D.R. Ketten, J.H. Miller, et al. 2007. Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. *Aquatic Mammals* 33(4): 411-521. https://doi.org/10.1578/AM.33.4.2007.411.

Southall, B.L., D.P. Nowaceck, P.J.O. Miller, and P.L. Tyack. 2016. Experimental field studies to measure behavioral responses of cetaceans to sonar. *Endangered Species Research* 31: 293-315. https://doi.org/10.3354/esr00764.

Southall, B.L., J.J. Finneran, C.J. Reichmuth, P.E. Nachtigall, D.R. Ketten, A.E. Bowles, W.T. Ellison, D.P. Nowacek, and P.L. Tyack. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals* 45(2): 125-232. https://doi.org/10.1578/AM.45.2.2019.125.

Southall, B.L., D.P. Nowacek, A.E. Bowles, V. Senigaglia, L. Bejder, and P.L. Tyack. 2021. Marine Mammal Noise Exposure Criteria: Assessing the Severity of Marine Mammal Behavioral Responses to Human Noise. *Aquatic Mammals* 47(5): 421-464. https://doi.org/10.1578/AM.47.5.2021.421.

Teague, W.J., M.J. Carron, and P.J. Hogan. 1990. A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *Journal of Geophysical Research* 95(C5): 7167-7183. https://doi.org/10.1029/JC095iC05p07167.

Warner, G.A., C. Erbe, and D.E. Hannay. 2010. Underwater Sound Measurements. (Chapter 3) *In* Reiser, C.M., D. Funk, R. Rodrigues, and D.E. Hannay (eds.). *Marine Mammal Monitoring and Mitigation during Open Water Shallow Hazards and Site Clearance Surveys by Shell Offshore Inc. in the Alaskan Chukchi Sea, July-October 2009: 90-Day Report*. LGL Report P1112-1. Report by LGL Alaska Research Associates Inc. and JASCO Applied Sciences for Shell Offshore Inc., National Marine Fisheries Service (US), and Fish and Wildlife Service (US). pp. 1-54.

Whiteway, T. 2009. *Australian Bathymetry and Topography Grid, June 2009*. GeoScience Australia, Canberra. http://pid.geoscience.gov.au/dataset/ga/67703.

Wood, J.D., B.L. Southall, and D.J. Tollit. 2012. *PG&E offshore 3-D Seismic Survey Project Environmental Impact Report–Marine Mammal Technical Draft Report*. Report by SMRU Ltd. 121 p. https://www.coastal.ca.gov/energy/seismic/mm-technical-report-EIR.pdf.

Zhang, Z.Y. and C.T. Tindle. 1995. Improved equivalent fluid approximations for a low shear speed ocean bottom. *Journal of the Acoustical Society of America* 98(6): 3391-3396. https://doi.org/10.1121/1.413789.

Appendix A. Underwater 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 2017, ANSI S1.1-2013).

A.1. Acoustic Metrics

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:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt\Big/p_0^2\right)\,\mathrm{dB} \qquad \text{(A-1)}$$

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 $g(t)$ 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 $g(t)$ 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 $g(t)$ 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 have been 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):

$$L_E = 10\log_{10}\left(\int_T p^2(t)\,dt\Big/T_0p_0^2\right)\,\mathrm{dB} \qquad \text{(A-2)}$$

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:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right) \text{dB} \tag{A-3}$$

Because the SPL(T_{90}) and SEL are both computed from the integral of square pressure, these metrics are related numerically by the following expression, which depends only on the duration of the time window T:

$$L_p = L_E - 10\log_{10}(T) \tag{A-4}$$

$$L_{p90} = L_\mathrm{E} - 10\log_{10}(T_{90}) - 0.458 \tag{A-5}$$

where the 0.458 dB factor accounts for the 10% of pulse SEL missing from the SPL(T_{90}) integration time window.

Energy equivalent SPL (L_{eq}; dB re 1 µPa) denotes the SPL of a stationary (constant amplitude) sound that generates the same SEL as the signal being examined, $p(t)$, over the same time period, T:

$$L_\mathrm{eq} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)\,dt \Big/ p_0^2\right) \tag{A-6}$$

The equations for SPL and the energy-equivalent SPL are numerically identical. Conceptually, the difference between the two metrics is that the SPL is typically computed over short periods (typically of 1 s or less) and tracks the fluctuations of a non-steady acoustic signal, whereas the L_{eq} reflects the average SPL of an acoustic signal over time periods typically of 1 min to several hours.

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, $f_\mathrm{c}(i)$, is defined as:

$$f_\mathrm{c}(i) = 10^{\frac{i}{10}}\,\mathrm{kHz} \tag{A-7}$$

and the low (f_lo) and high (f_hi) frequency limits of the ith decade band are defined as:

$$f_{\mathrm{lo},i} = 10^{\frac{-1}{20}} f_\mathrm{c}(i) \quad \text{and} \quad f_{\mathrm{hi},i} = 10^{\frac{1}{20}} f_\mathrm{c}(i) \tag{A-8}$$

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 $f_c(1) = 10\ Hz$ to $f_c(37) = 63\ kHz$.

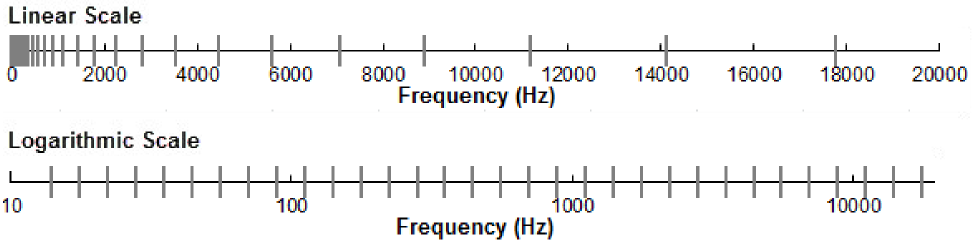

Figure A-1. Decidecade frequency bands (vertical lines) shown on both linear and logarithmic frequency scales

The sound pressure level in the ith band ($L_{p,i}$) is computed from the spectrum $S(f)$ between $f_{\mathrm{lo},i}$ and $f_{\mathrm{hi},i}$:

$$L_{p,i} = 10\log_{10} \int_{f_{\mathrm{lo},i}}^{f_{\mathrm{hi},i}} S(f)\,\mathrm{d}f \ \ \mathrm{dB} \tag{A-9}$$

Summing the sound pressure level of all the bands yields the broadband sound pressure level:

$$\mathrm{Broadband\ SPL} = 10\log_{10} \sum_i 10^{\frac{L_{p,i}}{10}}\,\mathrm{dB} \tag{A-10}$$

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.

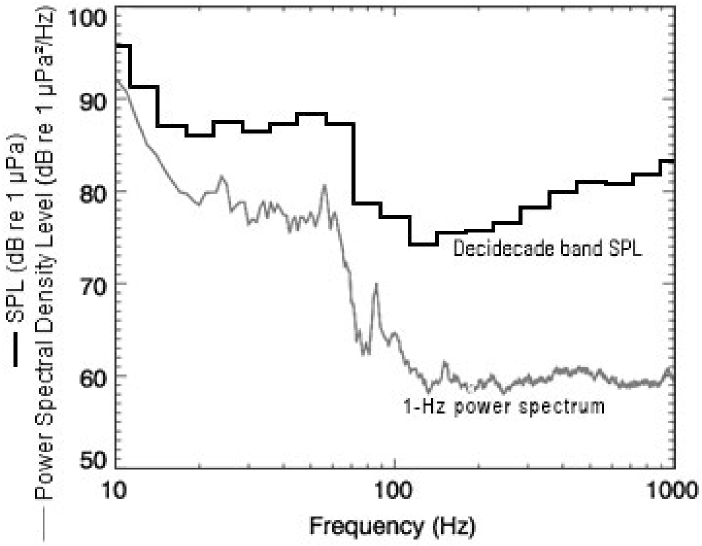

Figure A-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient sound shown on a logarithmic frequency scale. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum.

A.3. Marine Mammal Impact Criteria

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.3.1. Injury and Hearing Sensitivity Changes

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 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 human; Appendix A.3.3). 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. (2012) refined Southall et al.'s (2007) 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 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$. Because there were no data available for baleen whales, Wood et al. (2012) 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. (2012) thus recommended a more conservative TTS-onset level for LF cetaceans of 192 dB re 1 $\mu\mathrm{Pa}^2\cdot\mathrm{s}$.

As of 2017, 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). The latest revision to this work was published 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-frequency cetaceans from NMFS (2018) are classified as high-frequency cetaceans in Southall et al. (2019), and high-frequency cetaceans from NMFS (2018) are classified as very-high-frequency cetaceans in Southall et al. (2019).

A.3.2. 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 (Southall et al. 2007, Ellison and Frankel 2012, Southall et al. 2016).

NMFS currently uses step function (all-or-none) threshold of 120 dB re 1 µPa SPL (unweighted) for non-impulsive sounds to assess and regulate noise-induced behavioural effects to marine mammals (NOAA 2019). The 120 dB re 1 µPa threshold is associated with continuous sources and was derived based on studies examining behavioural responses to drilling and dredging, referring to Malme et al. (1983), Malme et al. (1984), and Malme et al. (1986), which were considered in Southall et al. (2007). Malme et al. (1986) found that playback of drillship noise did not produce clear evidence of disturbance or avoidance for levels below 110 dB re 1 µPa (SPL), possible avoidance occurred for exposure levels approaching 119 dB re 1 µPa. Malme et al. (1984) determined that measurable reactions usually consisted of rather subtle short-term changes in speed and/or heading of the whale(s) under observation. It has been shown that both received level and proximity of the sound source is a contributing factor in eliciting behavioural reactions in humpback whales (Dunlop et al. 2017, Dunlop et al. 2018).

A.3.3. 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).

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:

$$G(f) = K + 10\log_{10}\left(\frac{\left(\frac{f}{f_{lo}}\right)^{2a}}{\left(1+\left(\frac{f}{f_{lo}}\right)^{2}\right)^{a}\left(1+\left(\frac{f}{f_{hi}}\right)^{2}\right)^{b}}\right) \qquad \text{(A-11)}$$

Finneran (2015) proposed five functional hearing groups for marine mammals in water: low-, mid-, and high-frequency cetaceans, 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 noise impacts on marine mammals (NMFS 2016, NMFS 2018). A further update to these weighting functions is presented in Southall (2019), whereby mid- and high- frequency cetaceans are now known as high- and very-high-frequency cetaceans. Table A-1 lists the frequency-weighting parameters for each hearing group; Figure A-3 shows the resulting frequency-weighting curves.

Table A-1. Parameters for the auditory weighting functions used in this project as recommended by NMFS (2018) and Finneran et al. (2017).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (Hz)	K (dB)
LF cetaceans (baleen whales)	1.0	2	200	19,000	0.13
MF cetaceans (dolphins, plus toothed, beaked, and bottlenose whales)	1.6	2	8,800	110,000	1.20
HF cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* and *L. australis*)	1.8	2	12,000	140,000	1.36
Sea turtles	1.4	2	77	440	2.35

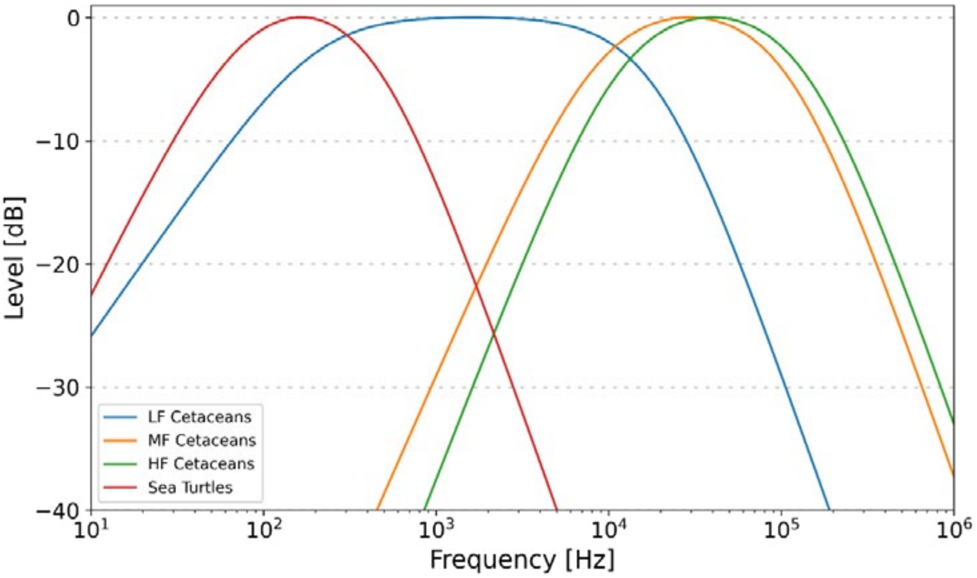

Figure A-3. Auditory weighting functions for functional marine mammal hearing groups as recommended by NMFS (2018) and Finneran et al. (2017)

Appendix B. Sound Source Propagation

B.1. Marine Operations Noise Model

Underwater sound propagation (i.e., transmission loss) at frequencies of 10 Hz to 1.6 kHz was predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes SEL over 1 s for non-impulsive sources, at a specified source depth. Sound propagation at frequencies of 2 kHz and greater was computed via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

MONM computes acoustic propagation via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the US Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). 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. Additionally, BELLHOP accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water (Fisher and Simmons 1977). This type of sound attenuation is important for frequencies higher than 5 kHz and cannot be neglected without noticeably affecting the model results.

MONM computes acoustic fields in three dimensions by modelling transmission 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 $N = 360^\circ/\Delta\theta$ number of planes (Figure B-1).

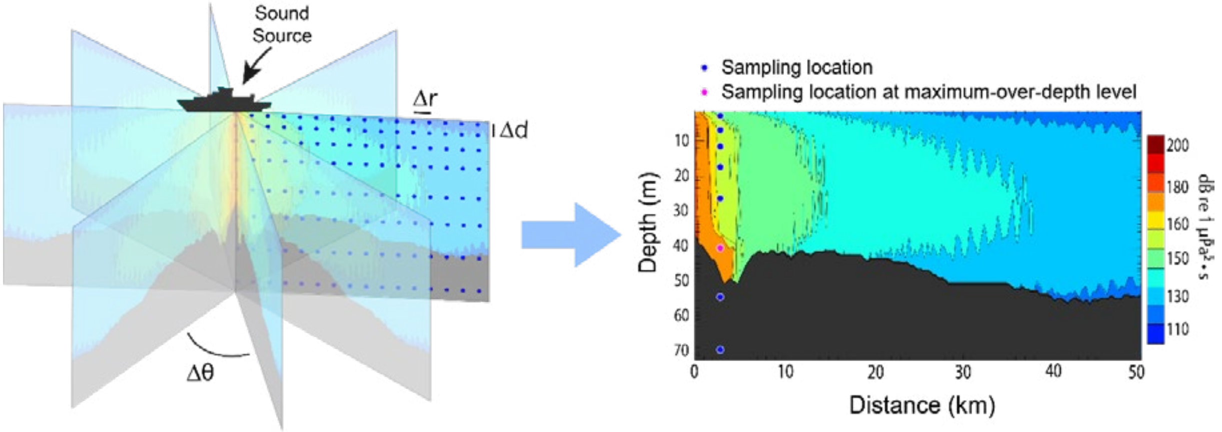

Figure B-1. The N×2-D and maximum-over-depth modelling approach used by MONM

MONM treats frequency dependence by computing acoustic transmission 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 transmission loss is modelled within each of the N vertical planes as a function of depth and range from the source. The decidecade received per-pulse SEL are computed by subtracting the band propagation loss values from the directional source level in that frequency band. Composite broadband received per-pulse SEL are then computed by summing the received decidecade levels.

The received per-pulse SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size (Δr in Figure B-1). At each sampling range along the surface, the sound field is sampled at various depths (Δd in Figure B-1), 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 for the sound speed profile. For areas with deep water, sampling is not performed at depths beyond those reachable by marine mammals. The received per-pulse 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-pulse SEL. These maximum-over-depth per-pulse SEL are presented as colour contours around the source.

MONM's predictions have been validated against experimental data from several underwater acoustic measurement programs conducted by JASCO (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, Martin et al. 2015).

Appendix C. Additional Methods and Parameters

C.1. Estimating Ranges to Threshold 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 seafloor for each location in the modelled region. The predicted ranges to specific levels were computed from these contours. Two ranges relative to the source are reported for each sound level: R_{max}, the maximum range to the given sound level over all azimuths, and $R_{95\%}$, the range to the given sound level after the 5% farthest points were excluded (see examples in Figure C.1).

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 Figure C.1a. 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 contrast, in strongly radially asymmetric cases such as shown in Figure C.1b, $R_{95\%}$ neglects to account for substantial 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 that affect propagation. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the non-uniformity of the acoustic environment.

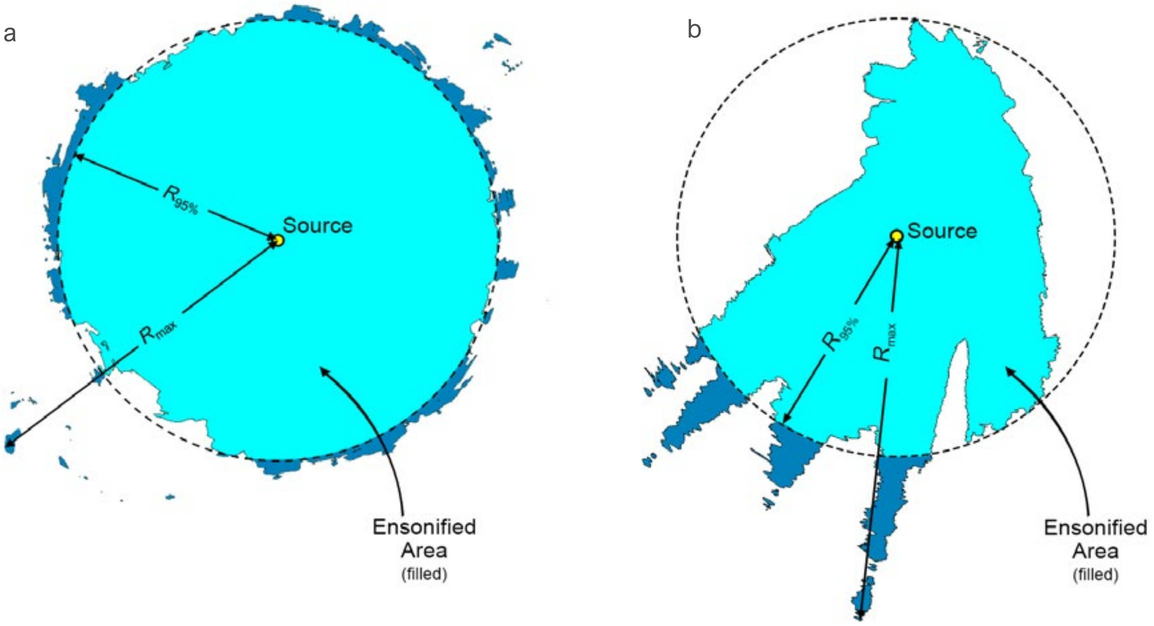

Figure C.1. R_{max} and $R_{95\%}$ ranges shown for two contrasting scenarios. Cyan indicates the ensonified areas bounded by $R_{95\%}$, whilst dark blue indicates the ensonified areas beyond $R_{95\%}$ that determine R_{max}.

C.2. Environmental Parameters

The parameters used are the same as applied in McPherson et al. (2019).

C.2.1. Bathymetry

Water depths (Mean Sea Level) at close- and mid-range from the pile were provided by Woodside. Within ~5–7 km from the pile, the data has a grid resolution of 2 × 2 m, while data at the passage between Scott Reef South and Scott Reef Central has a grid resolution of 1 × 1 m. Bathymetry data with grid resolution of 10 × 10 m was provided as far as 33 km northeast of the pile, and as far as 85 km southwest of the pile. Modelling was conducted along 80 km long radials emanating from the pile in all directions. For this reason, the high-resolution data was complemented using the Australian Bathymetry and Topography Grid, a 9 arc-second grid rendered for Australian waters (Whiteway 2009). The data were adjusted for an increase of 1.7 m in depth (Bureau of Meterology 2019), so the modelling results correspond to the most conservative propagation conditions at maximum tide at Scott Reef. Bathymetry data were re-gridded onto a Map Grid of Australia (MGA) coordinate projection (Zone 51) with a regular grid spacing of 50 × 50 m.

C.2.2. Sound speed profile

The sound speed profile in the area was derived from temperature and salinity profiles from the U.S. 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 U.S. 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 at distances less than 76 km around the modelled site. The June sound speed profile is expected to be most favourable to longer-range sound propagation across the entire year. As such, June was selected for sound propagation modelling to ensure precautionary estimates of ranges to received sound level thresholds. Figure C-2 shows the resulting profile, which was used as input to the sound propagation modelling.

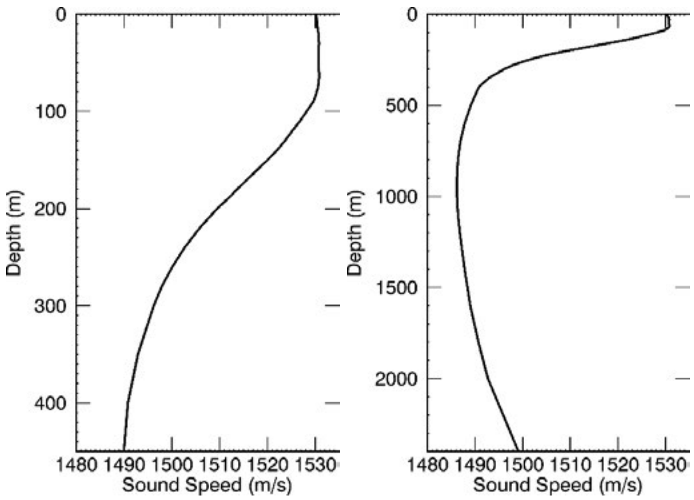

Figure C-2. The modelling sound speed profile corresponding to June: (left) top 450 m and (right) full profile. Profiles are calculated from temperature and salinity profiles from *Generalized Digital Environmental Model* V 3.0 (GDEM; Teague et al. 1990, Carnes 2009).

C.2.3. Geoacoustics

In previous acoustic studies in the area (Duncan 2014, McPherson et al. 2019), the modelling area was divided into three seabed types, with a silt seabed typical of the continental slope considered for most of the modelling area, and coarser gravel and limestone in the areas in and around the reefs. Due to the type of propagation modelling used in this study, however, the silt seabed was used for the entire modelling area. This is detailed in Table C-1.

Table C-1. Continental slope geoacoustic profile. Within each depth range, each parameter varies linearly within the stated range. The compressional wave is the primary wave, and the shear wave is the secondary wave.

Depth below seafloor (m)	Material	Density (g/cm^3)	Compressional wave		Shear wave	
			Speed (m/s)	Attenuation (dB/λ)	Speed (m/s)	Attenuation (dB/λ)
0–50	Silt	1.70–1.75	1566–1627	1.0	210	1.5
50–100		1.75–1.80	1627–1686			
100–150		1.80–1.85	1686–1742			
150–200		1.85–1.90	1742–1795			
>200		1.90	1795			