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Appendix R – Noise Supplementary Material

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Appendix R-1. Over-air Noise Supplementary Material

Appendix R-1, Over-air Noise Supplemental Material
Ocean Wind Offshore Wind Farm COP

1. Introduction

The Ocean Wind Offshore Wind Farm Project (Project) is an offshore wind farm near New Jersey. It will have a maximum of 98 wind turbine generators (WTGs). Additional key components include up to three offshore substations, array and interconnector cables between turbines and offshore substations, offshore export cables from substations to landfall, onshore export cables, and onshore substations. The Project will be installed during 2023 through 2024 and commissioned and operational in 2024. The purpose of this appendix is to identify noise regulations that are potentially applicable to the onshore construction and operation components of this Project, and to present results of a desktop analysis and literature review for applicable noise regulations, as well as airborne construction and operational noise.

2. Noise Regulations

2.1 Federal

There are no Federal limits enforced on noise from offshore wind farms or associated construction.

2.2 State

The State of New Jersey Administrative Code (N.J.A.C. 7:29) sets forth limits on continuous noise from industrial, commercial, or community service facilities as shown in Table 1 below. These limits could apply to operational noise from substations, but not to construction noise.

Table 1 - New Jersey limits on continuous noise from industrial, commercial, or community service facilities (N.J.A.C. 7:29).

Octave Band Center Frequency (Hz)	Limit measured at residential property line (dB)		Limit measured at industrial, commercial, or community service facility (dB)
	7:00 a.m. to 10:00 p.m.	10:00 p.m. to 7:00 a.m.	24 hours
31.5	96	86	96
63	82	71	82
125	74	61	74
250	67	53	67
500	63	48	63
1000	60	45	60
2000	57	42	57
4000	55	40	55
8000	53	38	53
dBA	65	50	65

Hz = hertz
dB = decibel
dBA = A-weighted decibel

The ordinance also does not allow for impulsive noise in excess of 80 dBA during the day and 50 dBA at night if the noise repeats more than four times in an hour. Impulsive noise is defined as noise that causes a distinct peak in sound levels with a duration less than one second, such as pile driving.

The ordinance does not set forth specific limits or conditions on construction noise or activities.

2.3 County

Construction would take place in Cape May, Atlantic, and Ocean counties. None of these counties has a noise ordinance.

2.4 Municipal

Construction would take place in the following municipalities: Ocean Township, Lacey Township, Berkeley Township, Upper Township, Ocean City, and Egg Harbor Township.

2.4.1 Ocean Township

The noise policy for the Ocean Township is in Chapter 245 of its Code of Ordinances. It sets forth limits on continuous noise defined in Table 2 below, which is a synthesis of table 1 and table 2 from Section 245-4.

The ordinance also states that construction and demolition activity, excluding emergency work, shall not be performed between the hours of 6:00 p.m. and 7:00 a.m. on weekdays, or between the hours of 6:00 p.m. and 9:00 a.m. on weekends and federal holidays, unless such activities can meet the limits set forth in the table above. All motorized equipment used in construction and demolition activity shall be operated with muffler. At all other times, the limits set forth do not apply to construction and demolition activities.

2.4.2 Lacey Township

Lacey Township's noise code is in Chapter 242 of its Code of Ordinances. The code does not include any quantitative noise limits. It does prohibit construction work or activities relating to construction work to occur between the hours of 10:00 p.m. and 7:00 a.m. of the following day on weekdays and 10:00 p.m. and 9:00 a.m. of the following day when the following day is a Saturday or Sunday, in such a manner as to cause a noise disturbance across a residential real property boundary or within a noise-sensitive zone. Lacey Township defines a noise disturbance as any noise which endangers or injures the safety or health of humans or animals or annoys or disturbs a reasonable person of normal sensitivities or endangers or injures personal or real property.

2.4.3 Berkeley Township

Berkeley Township's noise code is in Section 4-14 of its Municipal Code. The code does not include any quantitative noise limits. Regarding construction activities, the code states that operating or use of any pile driver, steam shovel, pneumatic hammer, derrick, steam or electric hoist or any tools or equipment which shall make any loud or disturbing noise on any weekday between the hours of 9:00 p.m. and 7:00 a.m. or on any weekend day or legal holiday between the hours of 8:00 p.m. and 9:00 a.m. in conducting any excavation, demolition, erection, alteration, repair or other building operation within 1,000 feet of any dwelling or business property, except in the case of urgent necessity in the interest of public safety and then only upon obtaining the consent of the proper authority of the Township or the Police Department of the Township, as the case may be, which permission must be renewed every three days.

Table 2 - Ocean Township limits on continuous noise.

	Residential property, or residential portion of multiuse property				Commercial facility, public service facility, nonresidential portion of multiuse property, or community service facility	Commercial facility*, or nonresidential portion of multiuse property
	OUTDOORS		INDOORS		OUTDOORS	INDOORS
Octave Band Center Frequency, Hz	Octave Band Sound Pressure Level, dB		Octave Band Sound Pressure Level, dB		Octave Band Sound Pressure Level, dB	Octave Band Sound Pressure Level dB
	7:00 a.m. - 10:00 p.m.	10:00 p.m. - 7:00 a.m.	7:00 a.m. - 10:00 p.m.	10:00 p.m. - 7:00 a.m.	24 hours	24 hours
31.5	96	86	86	76	96	86
63	82	71	72	61	82	72
125	74	61	64	51	74	64
250	67	53	57	43	67	57
500	63	48	53	38	63	53
1,000	60	45	50	35	60	50
2,000	57	42	47	32	57	47
4,000	55	40	45	30	55	45
8,000	53	38	43	28	53	43
dBA	65	50	55	40	65	55

*In those instances when commercial facility shares common wall/ceiling/floor with another commercial facility that is producing the sound.
Hz = hertz; dB = decibel, BA = A-weighted decibel

2.4.4 Upper Township

Upper Township does not have a quantitative noise policy.

2.4.5 Ocean City

Ocean City's noise policy is in Section 4-15 and 4-16 of its Code of Ordinances. The noise limits are identical to those set forth in N.J.A.C. 7:29. In addition, the ordinance forbids operating or permitting the operation of any tool or equipment used in exterior construction, drilling, earth moving, excavating, pile driving and demolition between the hours of 6:00 p.m. and 8:00 a.m., Monday through Friday, inclusive, and 5:00 p.m. to 8:00 a.m. on Saturday and any legal holiday.

2.4.6 Egg Harbor Township

Egg Harbor Township's noise ordinance is in Chapter 158 of its Township Code. Its limits on noise are identical to those found in Table 2 above. It also restricts the production of noise such that it would cause a 3 C-weighted decibel (dBC) increase within a residential building on weeknights between 10:00 pm and 7:00 am and weekend nights between 11:00 p.m. and 9:00 a.m., or a 6 dBC increase at any other time. The ordinance also forbids construction activity to between the hours of 6:00 p.m. and 7:00 a.m. on all days unless the activities can meet the noise limits specified in Table 2 above. At other times, the above limits do not apply.

2.5 Construction Noise

Onshore construction activities will include substation construction, as well as open trench excavation and trenchless technologies such as horizontal directional drilling (HDD) or direct pipe for cable installation. Typical noise levels and usage data for common construction equipment are given in Table 3.

Table 3 - Noise levels of typical construction equipment.

Equipment Description	Impact Device?	Acoustical Usage Factor (%)	Spec. 721.560 L_{max} at 50 feet (dBA, slow)	Actual Measured L_{max} at 50 feet (dBA, slow) (Samples Averaged)
All Other Equipment > 5 horsepower (hp)	No	50	85	N/A
Auger Drill Rig	No	20	85	84
Backhoe	No	40	80	78
Bar Bender	No	20	80	N/A
Blasting	Yes	N/A	94	N/A
Boring Jack Power Unit	No	50	80	83
Chain Saw	No	20	85	84
Clam Shovel (dropping)	Yes	20	93	87
Compactor (ground)	No	20	80	83
Compressor (air)	No	40	80	78
Concrete Batch Plant	No	15	83	N/A
Concrete Mixer Truck	No	40	85	79
Concrete Pump Truck	No	20	82	81
Concrete Saw	No	20	90	90
Crane	No	16	85	81
Dozer	No	40	85	82
Drill Rig Truck	No	20	84	79
Drum Mixer	No	50	80	80
Dump Truck	No	40	84	76
Excavator	No	40	85	81
Flat Bed Truck	No	40	84	74
Front End Loader	No	40	80	79
Generator	No	50	82	81
Generator (<25 KVA Variable Message Signs)	No	50	70	73
Gradall	No	40	85	83
Grader	No	40	85	N/A
Grapple (on backhoe)	No	40	85	87
Horizontal Boring Hydraulic Jack	No	25	80	82
Hydra Break Ram	Yes	10	90	N/A
Impact Pile Driver	Yes	20	95	101

Equipment Description	Impact Device?	Acoustical Usage Factor (%)	Spec. 721.560 L_{max} at 50 feet (dBA, slow)	Actual Measured L_{max} at 50 feet (dBA, slow) (Samples Averaged)
Jackhammer	Yes	20	85	89
Man Lift	No	20	85	75
Mounted Impact Hammer (hoe ram)	Yes	20	90	90
Pavement Scarifier	No	20	85	90
Paver	No	50	85	77
Pickup Truck	No	40	55	75
Pneumatic Tools	No	50	85	85
Pumps	No	50	77	81
Refrigerator Unit	No	100	82	73
Rivet Buster/Chipping Gun	Yes	20	85	79
Rock Drill	No	20	85	81
Roller	No	20	85	80
Sand Blasting (single nozzle)	No	20	85	96
Scraper	No	40	85	84
Sheers (on backhoe)	No	40	85	96
Slurry Plant	No	100	78	78
Slurry Trenching Machine	No	50	82	80
Soil Mix Drill Rig	No	50	80	N/A
Tractor	No	40	84	N/A
Vacuum Excavator (Vac-Truck)	No	40	85	85
Vacuum Street Sweeper	No	10	80	82
Ventilation Fan	No	100	85	79
Vibrating Hopper	No	50	85	87
Vibratory Concrete Mixer	No	20	80	80
Vibratory Pile Driver	No	20	95	101
Warning Horn	No	5	85	83
Welder/Torch	No	40	73	74

Source: Federal Highway Administration (FHWA), 2017
Spec. 721.560 gives FHWA-specified noise limits for construction equipment.
L_{max} = maximum sound pressure level
dBA = A-weighted decibel
KVA = kilovolt-amps

In order to minimize impacts, all onshore construction activities will follow the restrictions on noise levels and operating times within each jurisdiction. Other strategies for reducing noise may include limiting idling time, ensuring that all equipment is outfitted with mufflers that meet or exceed original equipment manufacturer specifications, or erecting temporary noise barriers where needed.

Offshore construction activities that would generate airborne noise would include pile driving and increased vessel traffic. Airborne noise monitoring was conducted during active construction periods at the Block Island Wind Farm Project to observe and measure levels of airborne noise produced during installation of the wind turbine foundations (HDR 2018). Noise levels were measured at onshore and offshore locations. Noise during piling was always audible at the closest coastal measurement station (3.1 miles [mi] from piling), intermittently audible at a mid-point coastal location (7 mi from piling), and was never audible at the furthest location (17 mi from piling). At the closest station (3 mi from piling), measured noise levels were more than 10 decibels (dB) above background noise levels. Overwater, the piling noise was barely audible at 7 miles downwind. Of all construction-related sources of noise, pile driving generates the highest level (HDR 2018); therefore; the noise generated by other sources would be expected to emit substantially lower levels. As the proposed Project will be built 15 miles offshore, noise effects to recreation and tourism from offshore construction noise will be temporary and negligible.

2.6 Operational Noise

During operation of the Project, the only source of airborne noise will be the turbines, and to a lesser degree the substations. Turbine noise originates from the gearbox, as well as turbulent noise from the blades. The turbines will be located approximately 15 miles offshore, and are not expected to produce sound in excess of background levels at any onshore locations.

Ocean Wind will coordinate with State and local agencies during Project permitting. Substation noise will be within the limits specified in the permit conditions.

3. Literature Cited

Federal Highway Administration. Construction Noise Handbook. Chapter 9. Updated 8/24/2017. https://www.fhwa.dot.gov/environment/noise/construction_noise/handbook/handbook09.cfm.

HDR. 2018. Field Observations during Wind Turbine Foundation Installation at the Block Island Wind Farm, Rhode Island. Final Report to the U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 2018-029. 175 pp.

Minerals Management Service (MMS). 2008. Cape Wind Energy Project Nantucket Sound Biological Assessment (Appendix G). In MMS January 2009 Cape Wind Energy Project Final EIS. p. 296.

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Appendix R-2. Underwater Noise Supplementary Material

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Underwater Acoustic and Exposure Modeling

Underwater Acoustic and Exposure Modeling

Ocean Wind 1

JASCO Applied Sciences (USA) Inc.

23 February 2022

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This report supports both BOEM and NOAA Fisheries/MMPA permit processes. Results presented here are preliminary and have not been subject to NOAA Fisheries OPR review as part of the MMPA process. NOAA Fisheries OPR may request changes that lead to revised results. A final report will be provided to BOEM upon completion of the NOAA Fisheries review process and in advance of publication of the Draft EIS.

Executive Summary

Ocean Wind, LLC has submitted a Construction and Operations Plan to support the siting and development of the Ocean Wind Offshore Wind Farm (the Project), a project that will generate renewable power off the coast of New Jersey. The Project is being proposed within the Bureau of Ocean Energy Management Renewable Energy Lease Area OCS-A 0498, an area of approximately 75,525 acres located approximately 13 nm southeast of Atlantic City. The Project includes the wind farm, two offshore export cable route corridors in the Atlantic Ocean, and one inshore export cable route corridor in Barnegat Bay, New Jersey. The Ocean Wind Offshore Wind Farm will consist of up to 98 wind turbine generators, up to three offshore substations, array and substation interconnection cables, and up to three export cables. The BL England export Cable is expected to be a single export cable that will make landfall at one of three optional locations along the Atlantic shoreline in Ocean City. The Oyster Creek export cable is expected to be a double export cable that will make landfall at one of three optional locations in either Lacey or Ocean Township from Barnegat Bay.

The wind turbine generators (WTGs) will be supported by tapered monopile foundations and the Offshore Substations (OSS) will be supported by a tapered monopile foundation or piled jacket foundations. The tapered monopiles (monopiles) are up to 8 meter (m) diameter at the expected waterline and 11 m diameter at the mudline. The jacket foundation uses 2.44 m diameter pin piles. Hammering of the 8/11 m monopile and 2.44 m pin pile were selected for quantitative analysis as this installation likely represents the primary underwater noise generated during Project installation considered within the PDE.

Sound generated during pile driving was modeled by characterizing the sound produced at the pile and then calculating how the sound propagates within the surrounding water column. For impact pile driving sounds, time-domain representations of the acoustic pressure waves generated in the water are required to calculate the metrics – sound pressure level (SPL), sound exposure level (SEL), and zero-to-peak pressure (PK) – used to evaluate potential impacts. The goal of the study was to determine the number of individual animals that may be impacted and the associated monitoring distances (exposure and acoustic ranges) for mitigation purposes. JASCO's animal movement modeling software, JASMINE, was used to integrate the computed sound fields with species-typical movement (e.g., dive patterns) to estimate received sound levels for the modeled marine mammals and sea turtles that may occur near the construction area. Using the time history of the received levels, exposure estimates and exposure ranges accounting for 95% of exposures above regulatory-defined injury and behavioral disruption thresholds (NMFS 2018, McCauley et al. 2000a, Finneran et al. 2017) were calculated. Fish were considered static receivers, so the acoustic distance to their regulatory thresholds (FHWG Andersson et al. 2007, Wysocki et al. 2007, 2008, Stadler and Woodbury 2009, Mueller-Blenkle et al. 2010, Purser and Radford 2011) were calculated. Exposure ranges (marine mammals) and acoustic ranges (fish) are reported for various levels (0, 6, 10, 15, and 20 dB) of broadband attenuation that could be expected from the use of mitigation systems such as a bubble curtain.

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Acronyms and Abbreviations

AMAPPS	Atlantic Marine Assessment Program for Protected Species
BOEM	Bureau of Ocean Energy Management
CalTrans	California Department of Transportation
COP	Construction and Operations Plan
dB	decibels
DC	Direct Current
DP	Dynamic Positioning
DPS	Distinct Population Segment
EEZ	Exclusive Economic Zone
$ER_{95\%}$	95% exposure ranges
ESA	Endangered Species Act
ft	feet
FWRAM	Full Wave Range Dependent Acoustic Model
GARFO	Greater Atlantic Regional Fisheries Office
h	hour
HF	high frequency (cetacean hearing group)
HSD	Hydro Sound Damper
Hz	Hertz
IAC	Inter-Array Cables
in	inch
JASMINE	JASCO Animal Simulation Model Including Noise Exposure
kg	kilogram
kHz	kilohertz
kJ	kilojoule
km	kilometer
SEL	sound exposure level
LF	low frequency (cetacean hearing group)
LIPA	Long Island Power Authority
SPL	sound pressure level
PK	peak pressure level
m	meter
MF	mid-frequency (cetacean hearing group)
mi	mile
MMPA	Marine Mammal Protection Act
MONM	Marine Operations Noise Model
μPa	micro-Pascal
m/s	meters per second
NARW	North Atlantic right whale
NAS	noise abatement system
NEFSC	Northeast Fisheries Science Center

NOAA	National Oceanic and Atmospheric Administration
nm	nautical mile
NMFS	National Marine Fisheries Service also known as NOAA Fisheries
NMS	Noise Mitigation System
NY	New York
NYSERDA	New York State Energy Research and Development Authority
OCS	Outer Continental Shelf
OWEC	Ocean Wind Export Cable
OSS–DC	Offshore Substation
OREC	Offshore Renewable Energy Certificate
OPA	offshore planning area
OSP	Optimum Sustainable Population
OCW01	Ocean Wind Offshore WindFarm Project
PAM	passive acoustic monitoring
PDE	Project Design Envelope
PDSM	Pile Driving Source Model
PK	zero-to-peak sound pressure
Project	Ocean Wind Farm Project
PSO	protected species observer
PTS	permanent threshold shift
PPA	phocid (pinniped) in air (hearing group)
PPW	phocid (pinniped) in water (hearing group)
PW	phocid (seal) in water (hearing group)
SEFSC	Southeast Fisheries Science Center
SEL	sound exposure level
SEL_{cum}	cumulative sound exposure level
SPL	sound pressure level
rms	root mean square
TTS	temporary threshold shift
WEA	Wind Energy Area
WTG	wind turbine generator

1. Introduction

1.1. Project Background and Overview of Assessed Activity

Ocean Wind LLC (Ocean Wind), a 75/25 joint venture between Orsted North America Inc. (Orsted NA) and Public Service Enterprise Group (PSE&G), proposes to construct, own, and operate the Ocean Wind Farm Project (the Project). The wind farm portion of the Project will be located on the Outer Continental Shelf (OCS) in the designated Bureau of Ocean Energy Management (BOEM) Renewable Energy Lease Area OCS-A 0498 (Lease Area). The WTGs and offshore substations, array cables, and substation interconnector cables will be located in Federal waters approximately 13 nautical miles (nm, 15 statute miles) southeast of Atlantic City. The location of the wind turbine generators (WTGs), Offshore Substations (OSS), Inter-Array Cables (IAC) and Export Cables (ECs) are collectively referred to as the Ocean Wind Offshore Windfarm Project (OCW01).

Underwater noise may be generated by several activities associated with the project. Impacts of noise on marine fauna for most of these anthropogenic sound sources is expected to be low or very low. Only pile driving for the installation of WTGs and OSS foundations could be expected to have greater impacts. A quantitative assessment of pile driving activities is undertaken here as the primary source of noise associated with the Project. A qualitative assessment of secondary sound sources associated with other construction and operational activities that contribute non-impulsive (aircraft, dredging, drilling, dynamic positioning [DP] thrusters) and continuous (vessel propulsion, turbine operation) sound to the environment can be found in Appendix C.

For the quantitative acoustic analysis, the potential underwater acoustic impacts resulting from the installation of tapered monopile foundations and jacket foundations were modeled. The tapered monopiles are 8 meter (m) (26 foot (ft)) diameter at the expected waterline and 11 m (36 foot (ft)) diameter at the mudline (referred to as an 8/11 m monopile in this report). The jacket foundation uses 2.44 m (8 foot (ft)) diameter pin piles[1]. This underwater noise assessment considers the currently available information; the precise locations, noise sources, and schedule of the construction and operation scenarios is subject to change as the engineering design progresses.

~~[1] The maximum outer diameter of the tapered monopiles, documented in Vol. I, Table 6.1.1-3 of the COP are 10 meter (m) (33 foot (ft)) diameter at the expected waterline and 13m (43 foot (ft)) diameter at the mudline. Since drafting of the COP, project development has continued and for the design development of the monopile foundations, a monopile foundation with maximum outer diameter at seabed of 11 m is being taken forward. This refined envelope is documented in Appendix Z – Design Feasibility Study of the COP.~~

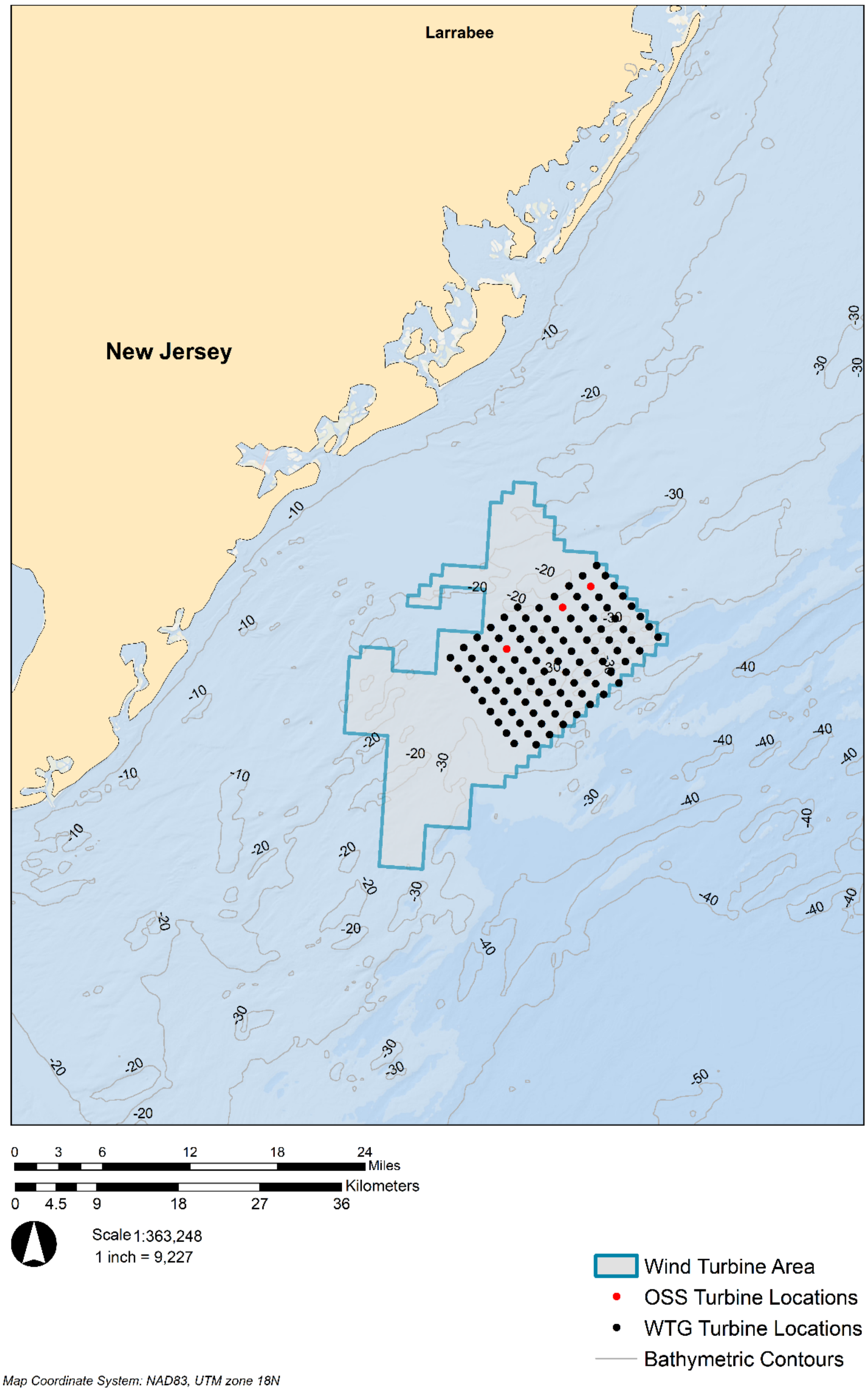

Figure 1. Ocean Wind Offshore WindFarm Project (OCW01).

1.2. Modeling Scope and Assumptions

The objective of this underwater noise assessment was to determine exposure estimates and exposure ranges from impact pile driving for marine mammals and sea turtle species that occur near the OCW01. Exposure ranges and exposure estimates for animals exceeding regulatory acoustic thresholds for injury and behavioral disruption are predicted using animal movement modeling. For fish, acoustic ranges to their regulatory acoustic thresholds predicting injury and behavioral disturbance were calculated.

1.2.1. Foundations

A monopile used as a foundation in a wind farm is a single hollow cylinder fabricated from steel that is installed by driving (hammering) it into the seabed. The 8/11 m monopiles proposed for the OCW01 represent the monopile foundation that will be installed within the PDE as WTG foundations. The 8/11 m monopiles are tapered piles with 8 m top diameter, 11 m bottom diameter, and a tapered section near the water line (nominal dimensions are shown in Table B-2). A jacket foundation, used for OSS consists of a large lattice structure supported/secured by pin piles. Up to three pin piles are expected to be installed per day. The pin piles to secure the jacket structure for the Project are 2.44 m diameter straight piles.

The amount of sound generated during pile driving varies with the energy required to drive piles to a desired depth and depends on the sediment resistance encountered. Sediment types with greater resistance require hammers that deliver higher energy strikes and/or an increased number of strikes relative to installations in softer sediment. Maximum sound levels usually occur during the last stage of impact pile driving where the greatest resistance is encountered (Betke 2008). The make and model of impact hammer (IHC S-4000 and IHC S-2500) and the representative hammering schedule used in the acoustic modeling effort were provided by Ocean Wind in coordination with potential hammer suppliers. The number of strikes at each of the hammer energy levels needed to drive the 8/11 m monopiles are listed in Table 1, and the number of strikes at each of the hammer energy levels needed to drive the 2.44 m jacket foundation pin piles are listed in Table 2.

Sound fields from 8/11 m monopiles were modeled at one representative location in the OCW01 (G10) and one location (Z11) for pin piles as depicted in Figure 2 and Table 3. The modeling locations were selected as they represent the range of water depths in the OCW01. The 8/11 m monopiles were assumed to be vertical and driven to a maximum expected penetration depth of 50 m and the pin piles were assumed to be vertical and driven to a maximum expected depth of 70 m (230ft).

Key modeling assumptions for the 8/11 m monopiles and 2.44 m pin piles are listed in Table 4, with additional modeling details and input parameters shown in Appendix B.

Table 1. Hammer energy schedule and number of strikes for 8/11 m monopile with an IHC S-4000 hammer..

Energy level (kJ)	Strike count	Pile penetration depth (m)
500	763	7
2000	980	6
1000	375	3
3000	385	2
4000	5006	16
3000	1135	6
4000	2202	10
Total	**10846**	**50**
Strike rate (strikes/min)	50	

Table 2. Hammer energy schedule and number of strikes for 2.44 m pin piles for jacket foundations with an IHC S-2500 hammer

Energy level (kJ)	Strike count	Pile penetration distance (m)
500	554	3
200	5373	29
750	1402	8
1000	1604	8
1500	1310	6
2500	1026	6
1500	1922	10
Total	**13191**	**70**
Strike rate (strikes/min)	50	

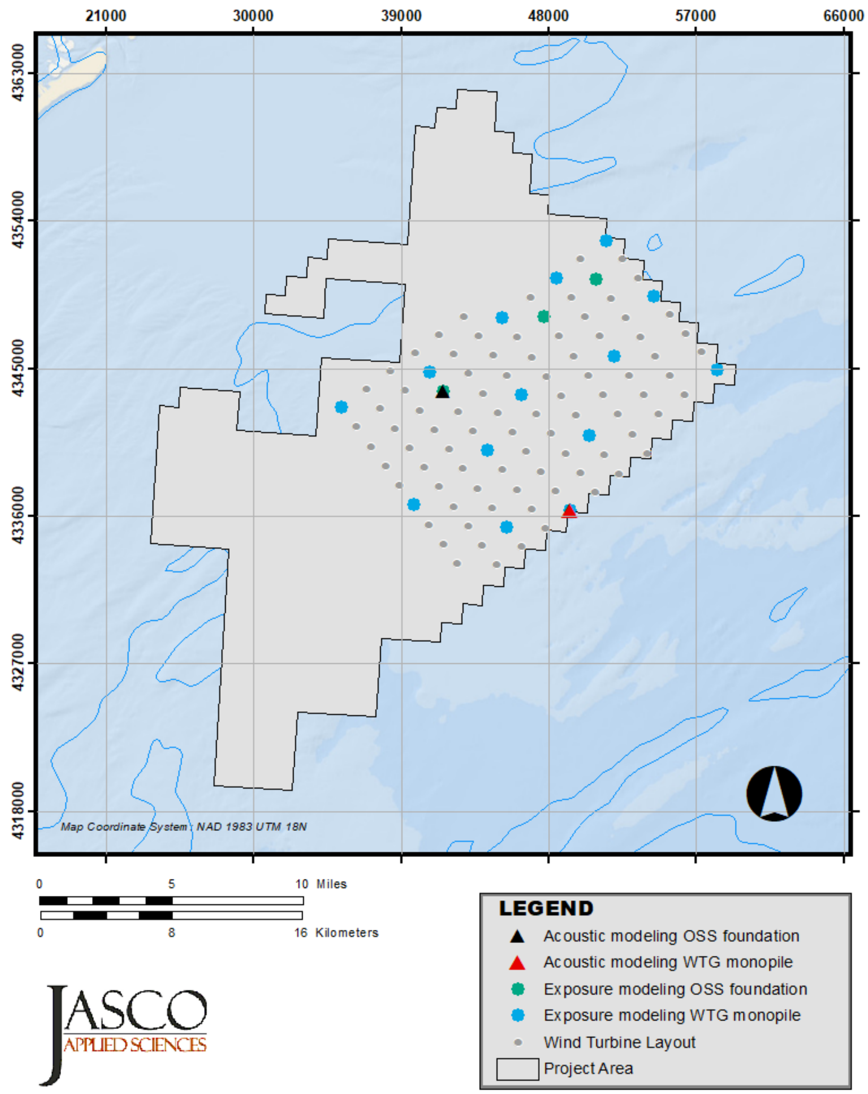

Figure 2. OCW01 monopile and jacket foundation locations with acoustic propagation and animal movement modeling locations.

Table 3. Acoustic modeling locations.

Modeling site	Foundation	Latitude	Longitude
G10	Monopile	39.059526	−74.207596
Z11	Jacket	39.120386	−74.301084

Table 4. Key piling assumptions used in underwater acoustic modeling.

Foundation type	Modeled maximum impact hammer energy (kJ)	Pile length	Pile diameter (m)	Pile wall thickness (mm)	Seabed penetration (m)	Number of piles per day
Monopile	4000	Penetration + water depth	8 to 11	80	50	1-2
Jacket	2500		2.44	75	70	2-3

1.2.2. Modeling Scenario and Pile Construction Schedules

Construction schedules cannot be fully predicted because of environmental factors like weather and because of installation variation such as drivability. To estimate the number of animals likely to be exposed above the regulatory thresholds a conservative construction schedule that maximizes activity during the highest density months for each species was assumed – 60 WTG monopiles (2 per day for 30 days) are assumed installed in the highest density month of each species (see Sections 3.1 and 3.2 for details on animal density estimates) and an additional 38 WTG monopiles (2 per day for 19 days) installed during the month with the second highest density. Two options are being considered for OSS foundations: either 3 monopiles (2 per day for one day and 1 on a third day) or 48 pin piles (3 per day for 16 days) in the highest density month. Construction schedule assumptions are summarized in Table 5.

Table 5. Construction schedule assumptions for WTG and OSS foundations. Dashes indicate no piling days.

<table>
<tr><th rowspan="2">Foundation type</th><th rowspan="2">Configuration</th><th colspan="2">Days of piling</th></tr>
<tr><th>Highest density month</th><th>2nd highest density month</th></tr>
<tr><td>WTG</td><td>Monopile, 2 per day</td><td>30</td><td>19</td></tr>
<tr><td rowspan="2">OSS, option 1</td><td>Monopile, 2 per day</td><td>1</td><td>-</td></tr>
<tr><td>Monopile, 1 per day</td><td>-</td><td>1</td></tr>
<tr><td>OSS, option 2</td><td>Jacket, 3 per day</td><td>16</td><td>-</td></tr>
</table>

2. Methods

The basic modeling approach is to characterize the sound produced by the source, determine how the sounds propagate within the surrounding water column, and then estimate species-specific exposure probability by combing the computed sound fields with animal movement in simulated representative scenarios.

For impact pile driving sounds, time-domain representations of the acoustic pressure waves generated in the water are required for calculating SPL, SEL, and PK. The source signatures associated with installation of each of the modeled 8/11 m monopile and 2.44 m pin pile locations are predicted using a finite-difference model that determines the physical vibration of the pile caused by pile driving equipment. The sound field radiating from the pile is simulated as a vertical array of point sources.

For this study, synthetic pressure waveforms were computed using a Full Waveform Range-dependent Acoustic Model (FWRAM), which is JASCO's acoustic propagation model capable of producing time-domain waveforms. The sound propagation modeling incorporated site-specific environmental data including bathymetry, sound speed in the water column, and seabed geoacoustics in the proposed construction area. Animal movement modeling integrated the estimated sound fields with species-typical behavioral parameters (e.g., dive patterns) in JASMINE to estimate received sound levels for the modeled animals (animats) that may occur in the construction area. Animats that exceed pre-defined acoustic thresholds/criteria (e.g., NMFS 2018) are identified and the distance for the exceedances determined. The analysis to estimate the number of potential injurious and behavioral exposures is ongoing and will be provided in supplemental filings and permit applications.

2.1. Acoustic Environment

OCW01 is located in a continental shelf environment characterized by predominantly sandy seabed sediments, with some thin clay layering. Water depths in the OCW01 vary between approximately 13–34 m. From June to September, the average temperature of the upper (10–15 m) water column is higher, which can lead to a surface layer of increased sound speeds. This creates a downward refracting environment in which propagating sound interacts with the seafloor more than in a well-mixed environment. Increased wind mixing combined with a decrease in solar energy during winter, from December through March, results in a sound speed profile that is more uniform with depth. An average summer and winter sound speed profiles were used in the OCW01 acoustic propagation modeling. See Appendix G for more details on the environmental parameters used in acoustic propagation and exposure modeling.

2.2. Modeling Acoustic Sources

2.2.1. Impact Pile Driving

Piles deform when driven with impact hammers, creating a bulge that travels down the pile and radiates sound into the surrounding air, water, and seabed. This sound may be received as a direct transmission from the sound source to biological receivers (such as marine mammals, sea turtles, and fish) through the water or as the result of reflected paths from the surface or re-radiated into the water from the seabed (Figure 3). Sound transmission depends on many environmental parameters, such as the sound speeds in water and substrates. It also depends on the sound production parameters of the pile and how it is driven, including the pile material, size (length, diameter, and thickness) and the make and energy of the hammer.

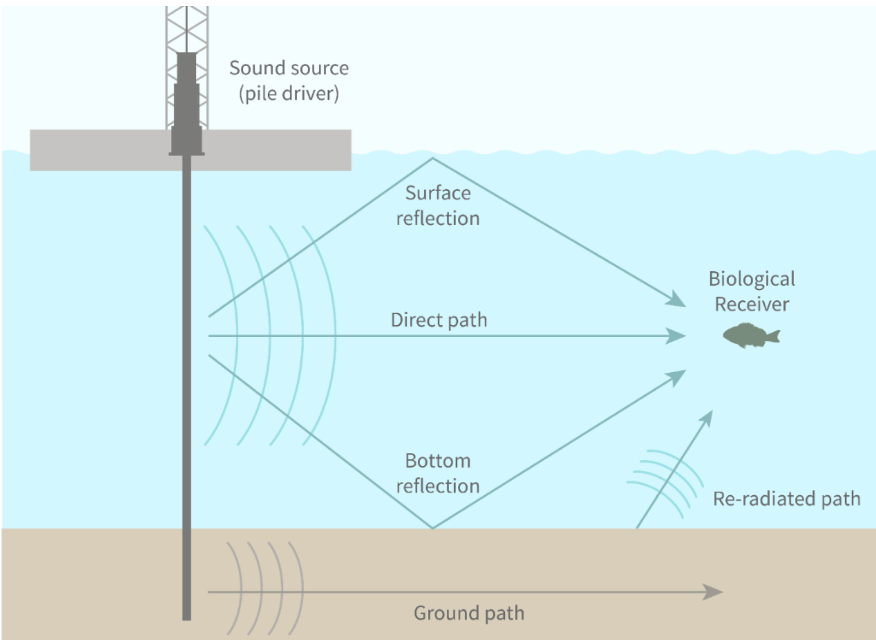

Figure 3. Sound propagation paths associated with pile driving (adapted from Buehler et al. 2015).

JASCO's physical model of pile vibration and near-field sound radiation (MacGillivray 2014) was used in conjunction with the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010) to predict source levels associated with impact pile driving activities. Piles are modeled with a vertical installation using a finite-difference structural model of pile vibration based on thin-shell theory. The sound radiating from the pile itself was simulated using a vertical array of discrete point sources. These models account for several parameters that describe the operation—pile type, material, size, and length—the pile driving equipment, and approximate pile penetration depth. See Appendix F for a more detailed description.

Forcing functions were computed for the 8/11 m monopile and 2.44 jacket foundations, using GRLWEAP 2010 (GRLWEAP, Pile Dynamics 2010). The model assumed direct contact between the representative hammers, helmets, and piles (i.e., no cushion material, which provides a more conservative estimate). The forcing functions serve as the inputs to the pile driving source models (PDSM) used to estimate equivalent acoustic source characteristics detailed in Appendix F.1. Decidecade spectral source levels for each pile type, hammer energy and modeled location, using an average summer sound speed profile are provided in Appendix G.

Acoustic propagation modeling used JASCO's Marine Operations Noise Model (MONM) and FWRAM that combine the outputs of the source model with the spatial and temporal environmental context (e.g., location, oceanographic conditions, and seabed type) to estimate sound fields. The lower frequency bands were modeled using MONM and FWRAM, which are based on the parabolic equation method of acoustic propagation modeling. For higher frequencies, additional losses resulting from absorption were added to the propagation loss model. See Appendix G for a more detailed description.

2.3. Noise Mitigation

Noise abatement systems (NASs) are often used to decrease the sound levels in the water near a source by inserting a local impedance change that acts as a barrier to sound transmission. Attenuation by impedance change can be achieved through a variety of technologies, including bubble curtains, evacuated sleeve systems (e.g., IHC-Noise Mitigation System (NMS)), encapsulated bubble systems (e.g., HydroSound Dampers (HSD)), or Helmholtz resonators (AdBm NMS). The effectiveness of each system is frequency dependent and may be influenced by local environmental conditions such as current and depth. For example, the size of the bubbles determines the effective frequency band of an air bubble curtain, with larger bubbles needed for lower frequencies.

Small bubble curtains (bubble curtains positioned within a small radius around the pile) have been measured to reduce sound levels from ~10 dB to more than 20 dB but are highly dependent on water depth and current and how the curtain is configured and operated (Koschinski and Lüdemann 2013, Bellmann 2014, Austin and Li 2016). Larger bubble curtains tend to perform better and more reliably, particularly when deployed with two rings (Koschinski and Lüdemann 2013, Bellmann 2014, Nehls et al. 2016). A California Department of Transportation (CalTrans) study tested several small, single, bubble-curtain systems and found that the best attenuation systems resulted in 10–15 dB of attenuation. Buehler et al. (2015) concluded that attenuation greater than 10 dB could not be reliably predicted from small, single, bubble curtains because sound transmitted through the seabed and re-radiated into the water column is the dominant source of sound in the water for bubble curtains deployed immediately around (within 32 ft [10 m] of) the pile (Buehler et al. 2015).

A recent analysis by Bellmann et al. (2020) of NASs performance measured during impact driving for wind farm foundation installation provides expected performance for common NASs configurations. Measurements with a single bubble curtain and an air supply of 0.3 m^3/min resulted in 7 to 11 dB of broadband attenuation for optimized systems in up to 131 ft (40 m) water depth. Increased air flow (0.5 m^3/min) may improve the attenuation levels up to 11 to 13 dB (M. Bellmann, personal communication, 2019). Double bubble curtains add another local impedance change and, for optimized systems, can achieve 15 to 16 dB of broadband attenuation (measured in up to 131.25 ft [40 m] water depth). The IHC-NMS can provide 15 to 17 dB of attenuation but is currently limited to piles <8 m diameter. Other NASs such as the AdBm NMS achieved 6 to 8 dB (M. Bellmann, personal communication, 2019), but HSDs were measured at 10 to 12 dB attenuation and are independent of depth (Bellmann et al. 2020). Systems may be deployed in series to achieve higher levels of attenuation.

The NAS must be chosen, tailored, and optimized for site-specific conditions. NAS performance of 10 dB broadband attenuation was chosen for this study as an achievable reduction of sound levels produced during pile driving when one NAS is in use, noting that a 10 dB decrease means the sound energy level is reduced by 90%. For exposure modeling, several levels of attenuation were included for comparison purposes.

2.4. Acoustic Criteria for Marine Fauna

The acoustic criteria used for this study were derived from the current US regulatory acoustic criteria and are summarized below (further details on these criteria are in Sections 2.4.1–2.4.2):

1. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) were from the US National Oceanic and Atmospheric Administration (NOAA) Technical Guidance (NMFS 2018) for marine mammal injury thresholds.
2. Sound pressure level (SPL; L_{p}) for marine mammal behavioral thresholds were based on the unweighted NOAA (2005) and the frequency-weighted Wood et al. (2012) criteria.
3. Injury thresholds (PK and SEL) were derived from the Fisheries Hydroacoustic Working Group (FHWG 2008) and Stadler and Woodbury (2009) for fish that are equal, greater than, or less than 2 g.
4. Injury thresholds (PK and SEL) were obtained from Popper et al. (2014) for fish without swim bladders, fish with swim bladders not involved in hearing, and fish with swim bladders involved in hearing.
5. Behavioral thresholds for fish were developed by the NOAA Fisheries Greater Atlantic Regional Fisheries Office (GARFO) (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011)
6. Peak pressure levels (PK; L_{pk}) and frequency-weighted accumulated sound exposure levels (SEL; $L_{E,24h}$) from Finneran et al. (2017) were used for the onset of permanent threshold shift (PTS) and temporary threshold shift (TTS) in sea turtles.
7. Behavioral response thresholds for sea turtles were obtained from McCauley et al. (2000b).

2.4.1. Acoustic Criteria–Marine Mammals

The Marine Mammal Protection Act (MMPA) prohibits the take of marine mammals. The term “take” is defined as: to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal. MMPA regulations define harassment in two categories relevant to the Project construction and operations. These are:

- **Level A**: Any act of pursuit, torment, or annoyance that has the potential to injure a marine mammal or marine mammal stock in the wild, and
- **Level B**: Any act of pursuit, torment or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing a disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild (16 U.S.C. 1362).

To assess the potential impacts of the underwater sound in the OCW01, it is necessary to first establish the acoustic exposure criteria used by United States regulators to estimate marine mammal takes. In 2016, National Oceanographic and Atmospheric Administration (NOAA) Fisheries issued a Technical Guidance document that provides acoustic thresholds for onset of PTS in marine mammal hearing for most sound sources, which was updated in 2018 (NMFS 2016, 2018). The Technical Guidance document also recognizes two main types of sound sources: impulsive and non-impulsive. Non-impulsive sources are further broken down into continuous or intermittent categories.

NMFS also provided guidance on the use of weighting functions when applying Level A harassment criteria. The Guidance recommends the use of a dual criterion for assessing Level A exposures, including a PK (unweighted/flat) sound level metric and a cumulative SEL metric with frequency weighting. Both acoustic criteria and weighting function application are divided into functional hearing groups (low-, mid-, and high-frequency and phocid pinnipeds) that species are assigned to, based on their respective hearing distances. The acoustic analysis applies the most recent sound exposure criteria utilized by NMFS to estimate acoustic harassment (NMFS 2018).

Based on observations of mysticetes (Malme et al. 1983, 1984, Richardson et al. 1986, 1990b), sound levels thought to elicit disruptive behavioral response are described using the SPL metric (NMFS and NOAA 2005). NOAA Fisheries (NMFS) currently uses a behavioral response threshold of 160 dB re 1 µPa for marine mammals exposed to impulsive sounds with the modification that 120 dB re 1 µPa be used for migrating mysticetes (NOAA 2005). 120 dB re 1 µPa is used for all marine mammals exposed to non-impulsive sounds (NMFS 2018). Alternative thresholds used in acoustic assessments include a graded probability of response approach and take into account the frequency-dependence of animal hearing sensitivity (Wood et al. 2012). The 160 dB threshold is used in this assessment as per NOAA guidance (2019).

The publication of ISO 18405 Underwater Acoustics–Terminology (ISO 2017) provided a dictionary of underwater bioacoustics (the previous standard was [ANSI] American National Standards Institute and [ASA] Acoustical Society of America S1.1-2013). In the remainder of this report, we follow the definitions and conventions of ISO (2017) except where stated otherwise (Table 6).

Table 6. Summary of relevant acoustic terminology used by US regulators and in the modeling report.

Metric	NMFS (2018)	ISO (2017)	
		Main text	Equations/tables
Sound pressure level	n/a	SPL	L_p
Peak pressure level	PK	PK	L_{pk}
Cumulative sound exposure level	SELcum[a]	SEL	L_E

[a] The SEL_{cum} metric used by NOAA Fisheries (NMFS) describes the sound energy received by a receptor over a period of 24 h. Accordingly, following the ISO standard, this will be denoted as SEL in this report, except for in tables and equations where L_E will be used.

2.4.1.1. Marine Mammal Hearing Groups

Current data and predictions show that marine mammal species differ in their hearing capabilities, in absolute hearing sensitivity as well as frequency band of hearing (Richardson et al. 1995, Wartzok and Ketten 1999, Southall et al. 2007, Au and Hastings 2008). While hearing measurements are available for a small number of species based on captive animal studies, there are no direct measurements of many odontocetes or any mysticetes. As a result, hearing distances for many odontocetes are grouped with similar species, and predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001, Parks et al. 2007, Tubelli et al. 2012, Cranford and Krysl 2015); vocalizations (see reviews in Richardson et al. 1995, Wartzok and Ketten 1999, Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990, see review in Reichmuth et al. 2007). In 2007, Southall et al. proposed that marine mammals be divided into hearing groups. This division was updated in 2016 and 2018 by NOAA Fisheries using more recent best available science (Table 7).

Southall et al. (2019) published an updated set of Level A sound exposure criteria (including the onset of temporary threshold shift [TTS] and permanent threshold shift [PTS] in marine mammals). While the authors propose a new nomenclature and classification for the marine mammal functional hearing groups, the proposed thresholds and weighting functions do not differ in effect from those proposed by NOAA

Fisheries (2018). The new hearing groups proposed by Southall et al. (2019) have not yet been adopted by NOAA. The NOAA Fisheries (NMFS 2018) hearing groups presented in Table 7 are used in this analysis.

Table 7. Marine mammal hearing groups (Sills et al. 2014, NMFS 2018).

Faunal group	Generalized hearing distance[a]
Low-frequency (LF) cetaceans (mysticetes or baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (odontocetes: delphinids, beaked whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (other odontocetes)	275 Hz to 160 kHz
Phocid pinnipeds in water (PPW)	50 Hz to 86 kHz
Phocid pinnipeds in air (PPA)[b]	50 Hz to 36 kHz

[a] The generalized hearing distance is for all species within a group. Individual hearing will vary.
[b] Sound from piling will not reach NOAA Fisheries thresholds for behavioral disturbance of seals in air (90 dB [rms] re 20 μPa for harbor seals and 100 dB [rms] re 20 μPa for all other seal species) at the closest land-based sites where seals may spend time out of the water. Thus in-air hearing is not considered further.

2.4.1.2. Marine Mammal Auditory Weighting Functions

The potential for anthropogenic sound to impact marine mammals is largely dependent on whether the sound occurs at frequencies that an animal can hear well unless the sound pressure level is so high that it can cause physical tissue damage regardless of frequency. Auditory (frequency) weighting functions reflect an animal's ability to hear a sound (Nedwell and Turnpenny 1998, Nedwell et al. 2007). Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS thresholds expressed in metrics that consider what is known about marine mammal hearing (e.g., SEL) (Southall et al. 2007, Erbe et al. 2016a, Finneran 2016). Marine mammal auditory weighting functions for all hearing groups (Table 7) published by Finneran (2016) are included in the NMFS (2018) Technical Guidance for use in conjunction with corresponding permanent threshold shift (PTS [Level A]) onset acoustic criteria (Table 8). (See Appendix E for a detailed description of the weighting functions.)

The application of marine mammal auditory weighting functions emphasizes the importance of taking measurements and characterizing sound sources in terms of their overlap with biologically important frequencies (e.g., frequencies used for environmental awareness, communication, and the detection of predators or prey), and not only the frequencies that are relevant to achieving the objectives of the sound producing activity (i.e., context of sound source; NMFS 2018).

2.4.1.3. Marine Mammal Auditory Injury Exposure Criteria

Injury to the hearing apparatus of a marine mammal may result from a fatiguing stimulus measured in terms of SEL, which considers the sound level and duration of the exposure signal. Intense sounds may also damage hearing independent of duration, so an additional metric of peak pressure (PK) is used to assess acoustic exposure injury risk. A PTS in hearing may be considered injurious, but there are no published data on the sound levels that cause PTS in marine mammals. There are data that indicate the received sound levels at which temporary threshold shift, TTS, occurs, and PTS onset may be extrapolated from TTS onset level and an assumed growth function (Southall et al. 2007). The NMFS (2018) criteria incorporate the best available science to estimate PTS onset in marine mammals from sound energy accumulated over 24 h (SEL), or very loud, instantaneous peak sound pressure levels. These dual threshold criteria of SEL and PK are used to calculate marine mammal exposures (Table 8). If a non-impulsive sound has the potential to exceed the peak sound pressure level thresholds associated with impulsive sounds, these thresholds should also be considered.

Table 8. Summary of relevant permanent threshold shift (PTS) onset acoustic thresholds for marine mammal hearing groups (NMFS 2018).

Faunal group	Impulsive signals		Non-impulsive signals
	Unweighted L_{pk} (dB re 1 µPa)	Frequency weighted $L_{E,\,24h}$ (dB re 1 µPa²·s)	Frequency weighted $L_{E,\,24h}$ (dB re 1 µPa²·s)
Low-frequency (LF) cetaceans	219	183	199
Mid-frequency (MF) cetaceans	230	185	198
High-frequency (HF) cetaceans	202	155	173
Phocid seals in water (PW)	218	185	201

2.4.1.4. Marine Mammal Behavioral Response Exposure Criteria

Numerous studies on marine mammal behavioral responses to sound exposure have not resulted in consensus in the scientific community regarding the appropriate metric for assessing behavioral reactions. It is recognized that the context in which the sound is received affects the nature and extent of responses to a stimulus (Southall et al. 2007, Ellison et al. 2012). Due to the complexity and variability of marine mammal behavioral responses to acoustic exposure, NOAA has not yet released technical guidance for determining potential behavioral responses of marine mammals exposed to sounds (NMFS 2018). NOAA's National Marine Fisheries Service (NMFS) currently uses a step function to assess behavioral impact (NOAA 2005). The step function sets an SPL of 160 dB re 1 µPa as the behavioral disruption threshold based on the 50% response rate of collated responses in the HESS (1999) report. An SPL of 120 dB re 1 µPa was set as the behavioral disruption threshold for migrating mysticetes (NOAA 2005), which was based on the responses of migrating mysticete whales to airgun sounds (Malme et al. 1983, 1984). The HESS team recognized that behavioral responses to sound may occur at lower levels, but substantial responses were only likely to occur above an SPL of 140 dB re 1 µPa.

An extensive review of behavioral responses to sound was undertaken by Southall et al. (2007, their Appendix B). Southall et al. (2007) found varying responses for most marine mammals between an SPL of 140 and 180 dB re 1 µPa, consistent with the HESS (1999) report, but lack of convergence in the data prevented them from suggesting explicit step functions. In 2012, Wood et al. proposed a graded probability of response for impulsive sounds using a frequency weighted SPL metric. Wood et al. (2012)

also designated behavioral response categories for sensitive species (including harbor porpoises and beaked whales) and for migrating mysticetes. For this analysis, both the unweighted NOAA (2005) and the frequency-weighted Wood et al. (2012) criteria are used to estimate Level B exposures to impulsive pile-driving sounds (Table 9).

Table 9. Acoustic sound pressure level (SPL) thresholds used to evaluate potential behavioral impacts to marine mammals. NOAA (2005) unweighted SPL for all marine mammals, and Wood et al. (2012) frequency-weighted SPL for different hearing groups. Probabilities are not additive.

<table>
<tr><th rowspan="2">Marine mammal group</th><th rowspan="2">Species</th><th>NOAA (2005)
(L_p; dB re 1 µPa)</th><th colspan="4">Wood et al. (2012)
(L_p; dB re 1 µPa)</th></tr>
<tr><th>>160</th><th>>120</th><th>>140</th><th>>160</th><th>>180</th></tr>
<tr><td>Beaked whales and harbor porpoises</td><td>Harbor porpoise</td><td rowspan="3">100%</td><td>50%</td><td>90%</td><td>-</td><td>-</td></tr>
<tr><td>Migrating mysticete whales</td><td>Minke whale
Humpback whale
North Atlantic right whale
Sei whale</td><td>10%</td><td>50%</td><td>90%</td><td>-</td></tr>
<tr><td colspan="2">All other species</td><td>-</td><td>10%</td><td>50%</td><td>90%</td></tr>
</table>

2.4.2. Acoustic Thresholds for Evaluating Potential Impacts to Sea Turtles and Fish

In a cooperative effort between Federal and State transportation and resource agencies, interim criteria were developed to assess the potential for injury to fish exposed to pile driving sounds (Stadler and Woodbury 2009) and described by the Fisheries Hydroacoustic Working Group (FHWG 2008). Injury and behavioral response levels for fish were based on past literature that was compiled and listed in the NOAA Fisheries Greater Atlantic Regional Fisheries Office acoustics tool (GARFO 2020) for assessing the potential effects to Endangered Species Act (ESA) listed animals exposed to elevated levels of underwater sound from pile driving. Dual acoustic thresholds for physiological injury to fish included in the tool are 206 dB re 1 µPa PK and either 187 dB re 1 µPa^2·s SEL (>2 grams [g] fish weight) or 183 dB SEL (<2 g fish weight) (FHWG 2008, Stadler and Woodbury 2009) (Table 10). The behavioral threshold for fish is ≥150 dB SPL (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011).

A technical report by an American National Standards Institute (ANSI) registered committee (Popper et al. 2014) reviewed available data and suggested metrics and methods for estimating acoustic impacts for fish. Their report includes thresholds for potential injury but does not define sound levels that may result in behavioral response, though does indicate a high likelihood of response near impact pile driving (tens of meters), moderate response at intermediate distances (hundreds of meters), and low response far (thousands of meters) from the pile (Popper et al. 2014).

Injury, impairment, and behavioral thresholds for sea turtles were developed for use by the US Navy (Finneran et al. 2017) based on exposure studies (e.g., McCauley et al. 2000a). Dual criteria (PK and SEL) have been suggested for PTS and TTS, along with auditory weighting functions published by Finneran et al. (2017) used in conjunction with SEL thresholds for PTS and TTS . The behavioral threshold recommended in the GARFO acoustic tool (GARFO 2020) is an SPL of 175 dB re 1 µPa (McCauley et al. 2000a, Finneran et al. 2017) (Table 10).

Table 10. Acoustic metrics and thresholds for fish and sea turtles currently used by NMFS GARFO and Bureau of Ocean Energy Management (BOEM) for impulsive pile driving.

Faunal group	Injury		Impairment		Behavior
	PTS		TTS		
	L_{pk}	$L_{E,\ 24hr}$	L_{pk}	$L_{E,\ 24hr}$	L_p
Fish equal to or greater than 2 g[a,b]	206	187	-	-	150
Fish less than 2 g[a,b]		183	-	-	
Fish without swim bladder[c]	213	216	-	-	-
Fish with swim bladder not involved in hearing[c]	207	203	-	-	-
Fish with swim bladder involved in hearing[c]	207	203	-	-	-
Sea turtles[d,e]	232	204	226	189	175

L_{pk} – peak sound pressure (dB re 1 µPa), L_E – sound exposure level (dB re 1 µPa^2·s), L_p – root mean square sound pressure (dB re 1 µPa).

PTS = permanent threshold shift; TTS = temporary threshold shift, which are recoverable hearing effects.

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014).

[d] Finneran et al. (2017).

[e] McCauley et al. (2000a).

2.5. Animal Movement Modeling and Exposure Estimation

JASMINE was used to estimate the probability of exposure of animals to sound arising from pile driving operations during construction of the OCW01. Sound exposure models such as JASMINE use simulated animals (animats) to sample the predicted 3-D sound fields with movement rules derived from animal observations (Appendix J). The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, and surface times) were determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species (Appendix J). The predicted sound fields were sampled by the model receiver in a way that real animals are expected to by programming animats to behave like marine species that may be present near the OCW01. The output of the simulation is the exposure history for each animat within the simulation. An individual animat's sound exposure levels are summed over a specified duration, i.e., 24 h (Appendix J.1.1), to determine its total received acoustic energy (SEL) and maximum received PK and SPL. These received levels are then compared to the threshold criteria described in Section 2.4 within each analysis period. Appendix J provides fuller description of animal movement modeling and the parameters used in the JASMINE simulations.

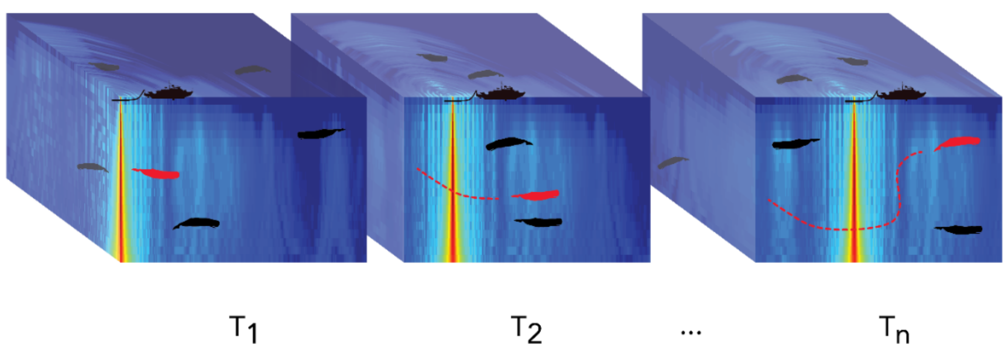

Figure 4. Depiction of animats in an environment with a moving sound field. Example animat (red) shown moving with each time step. The acoustic exposure of each animat is determined by where it is in the sound field, and its exposure history is accumulated as the simulation steps through time.

2.6. Estimating Monitoring Zones for Mitigation

Monitoring zones for mitigation purposes have traditionally been estimated by determining the acoustic distance to injury and behavioral thresholds (see Appendix G.5). The traditional method assumes that all receivers (animals) in the area remain stationary for the duration of the sound event. Because where an animal is in a sound field and the pathway it takes through the sound field as it evolves over time determines the received level for each animal, treating animals as stationary may not produce realistic estimates for the monitoring zones.

Animal movement modeling can account for the movement of animals when estimating distances for monitoring zones. The distance to the closest point of approach (CPA) for each of the species-specific animats (simulated animals) during a simulation is recorded and then the CPA distance that accounts for a specified percentage of the animats that exceed an acoustic impact threshold is determined (Figure 5). For example, the $ER_{95\%}$ (95% exposure range) is the horizontal distance that includes 95% of the CPAs of animats exceeding a given impact threshold, while the $ER_{99\%}$ is the horizontal distance that includes 99% of the CPAs. $ER_{95\%}$ is reported herein for marine mammals and sea turtles. If used as an exclusion zone, keeping animals farther away from the source than the $ER_{95\%}$ will reduce exposure estimates by 95%.

Unlike marine mammals and sea turtles for which animal movement modeling was performed, fish were considered static (not moving) receivers, so exposure ranges were not calculated. Instead, the acoustic ranges to fish impact criteria thresholds were calculated by determining the isopleth at which thresholds could be exceeded (Appendix G.5).

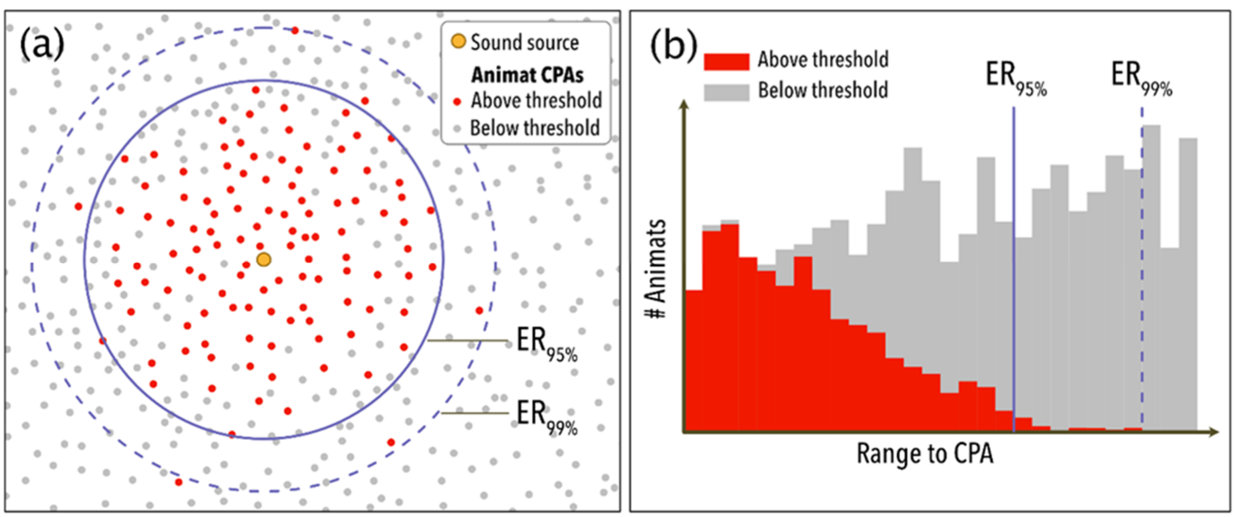

Figure 5. Example distribution of animat closest points of approach (CPAs). Panel (a) shows the horizontal distribution of animat CPAs near a sound source. Panel (b) shows the distribution of distances to animat CPAs. The 95% and maximum exposure ranges ($ER_{95\%}$ and $ER_{99\%}$) are indicated in both panels.

3. Marine Fauna Included in the Acoustic Assessment

Marine mammals (cetaceans and pinnipeds), sea turtles, and fish that may occur near the Project area were considered in this assessment. *Common* and *uncommon* species (Table 11) were selected for quantitative assessment by acoustic impact analysis and exposure modeling. Quantitative assessment of *rare* species was not conducted because impacts to those species approach zero due to their low densities. The modeled species are designated with an asterisk in Table 11 (marine mammals) and Table 12 (sea turtles).

Table 11. Marine mammals potentially occurring within the regional waters of the Western North Atlantic OCS and Project Area (Sources: NOAA Fisheries n.d.[a], 2020b; USFWS 2019).

Species	Scientific name	Stock	Regulatory Status [a]	Relative occurrence in OCW01	Abundance [b]
Baleen whales (Mysteceti)					
Blue whale*	*Balaenoptera musculus*	Western North Atlantic	ESA Endangered MMPA Depleted and Strategic	Rare	402
Fin whale*	*Balaenoptera physalus*	Western North Atlantic	ESA Endangered MMPA Depleted and Strategic	Common	6,802
Humpback whale*	*Megaptera novaeangliae*	Gulf of Maine	MMPA Non-strategic	Common	1,396
Minke whale*	*Balaenoptera acutorostrata*	Canadian Eastern Coastal	MMPA Non-strategic	Common	21,968
North Atlantic right whale*	*Eubalaena glacialis*	Western	ESA Endangered MMPA Depleted and Strategic	Common	412[c]
Sei whale*	*Balaenoptera borealis*	Nova Scotia	ESA Endangered MMPA Depleted and Strategic	Common	6,292
Toothed Whales and Dolphins (Odontoceti)					
Atlantic spotted dolphin	*Stenella frontalis*	Western North Atlantic	MMPA Non-strategic	Rare	39,921
Atlantic white-sided dolphin*	*Lagenorhynchus acutus*	Western North Atlantic	MMPA Non-strategic	Common	93,233
Bottlenose dolphin*	*Tursiops truncatus*	Western North Atlantic, offshore	MMPA Non-strategic	Common	62,851

		Western North Atlantic, Northern Migratory Coastal	MMPA Depleted and Strategic	Common	6,639
Clymene dolphin	*Stenella clymene*	Western North Atlantic	MMPA Non-strategic	Rare	4,237
False killer whale	*Pseudorca crassidens*	Western North Atlantic	MMPA Non-strategic	Rare	1,791
Fraser's dolphin	*Lagenodelphis hosei*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Killer whale	*Orcinus orca*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Melon-headed whale	*Peponocephala electra*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Pan-tropical spotted dolphin	*Stenella attenuata*	Western North Atlantic	MMPA Non-strategic	Rare	6,593
Pilot whale, long-finned*	*Globicephala melas*	Western North Atlantic	MMPA Non-strategic	Uncommon	39,215
Pilot whale, short-finned*	*Globicephala macrorhynchus*	Western North Atlantic	MMPA Non-strategic	Uncommon	28,924
Pygmy killer whale	*Feresa attenuata*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Risso's dolphin*	*Grampus griseus*	Western North Atlantic	MMPA Non-strategic	Uncommon	35,493
Rough-toothed dolphin	*Steno bredanensis*	Western North Atlantic	MMPA Non-strategic	Rare	136
Short-beaked common dolphin*	*Delphinus delphis*	Western North Atlantic	MMPA Non-strategic	Common	172,974
Sperm whale*	*Physeter macrocephalus*	North Atlantic	ESA Endangered MMPA Depleted and Strategic	Uncommon	4,349
Spinner dolphin	*Stenella longirostris*	Western North Atlantic	MMPA Non-strategic	Rare	4,102
Striped dolphin	*Stenella coeruleoalba*	Western North Atlantic	MMPA Non-strategic	Rare	67,036
Beaked whales (Ziphiidae)					
Cuvier's beaked whale	*Ziphius cavirostris*	Western North Atlantic	MMPA Non-strategic	Rare	5,744

Blainville's beaked whale	*Mesoplodon densirostris*	Western North Atlantic	MMPA Non-strategic	Rare	10,107[d]
Gervais' beaked whale	*Mesoplodon europaeus*	Western North Atlantic	MMPA Non-strategic		
Sowerby's beaked whale	*Mesoplodon bidens*	Western North Atlantic	MMPA Non-strategic		
True's beaked whale	*Mesoplodon mirus*	Western North Atlantic	MMPA Non-strategic		
Northern bottlenose whale	*Hyperoodon ampullatus*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
Dwarf and pygmy sperm whales (Kogiidae)					
Dwarf sperm whale	*Kogia sima*	Western North Atlantic	MMPA Non-strategic	Rare	7,750[e]
Pygmy sperm whale	*Kogia breviceps*	Western North Atlantic	MMPA Non-strategic	Rare	7,750[e]
Porpoises (Phocoenidae)					
Harbor porpoise*	*Phocoena phocoena*	Gulf of Maine/ Bay of Fundy	MMPA Non-strategic	Common	95,543
Earless seals (Phocidae)					
Gray seal*	*Halichoerus grypus*	Western North Atlantic	MMPA Non-strategic	Common	27,131[f]
Harbor seal*	*Phoca vitulina*	Western North Atlantic	MMPA Non-strategic	Common	75,834
Harp seal	*Pagophilus groenlandicus*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown[g]
Hooded seal	*Cystophora cristata*	Western North Atlantic	MMPA Non-strategic	Rare	Unknown
	Sirenia				
Florida manatee	*Trichechus manatus latirostris*	Florida	ESA Threatened MMPA Depleted and Strategic	Rare	4,834

* = modeled species

[a] Denotes the highest federal regulatory classification. A strategic stock is defined as any marine mammal stock: 1) for which the level of direct human-caused mortality exceeds the potential biological removal level; 2) that is declining and likely to be listed as threatened under the ESA; or 3) that is listed as threatened or endangered under the ESA or as depleted under the MMPA (NOAA Fisheries 2019b).

[b] Best available abundance estimate is from NOAA Fisheries Stock Assessment Reports (Hayes et al. 2021).

[c] Best available abundance estimate is from NOAA Fisheries Stock Assessment (Hayes et al. 2021). NARW consortium has released the preliminary 2020 report card results predicting a NARW population of 356 (Pettis and et al. 2021). However, the consortium "alters" the methods of Pace et al. (2017) to subtract additional mortality. This method is used in order to estimate

all mortality, not just the observed mortality, therefore the (Hayes et al. 2021) SAR will be used to report an unaltered output of the Pace et al. (2017) model (DoC and NOAA 2020a).

[d] This estimate includes all undifferentiated Mesoplodon spp. beaked whales in the Atlantic. Sources: Kenney and Vigness-Raposa (2009), Rhode Island Ocean Special Area Management Plan (2011), Waring et al. (2011, 2013, 2015), (Hayes et al. 2021).

[e] This estimate includes both dwarf and pygmy sperm whales. Source: Hayes et al. (2021)

[f] Estimate of gray seal population in US waters. Data are derived from pup production estimates; Hayes et al. (2019, 2020, 2021) notes that uncertainty about the relationship between whelping areas along with a lack of reproductive and mortality data make it difficult to reliably assess the population trend.

[g] Hayes et al. (2021) report insufficient data to estimate the population size of harp seals in US waters; the best estimate for the whole population is 7.4 million.

Table 12. Sea turtle species potentially occurring within the regional waters of the Western North Atlantic Outer Continental Shelf (OCS) and Project Area.

Species	Current listing status[a]	Relative occurrence in OCW01
Leatherback sea turtle* (*Dermochelys coriacea*)	ESA Endangered	Common
Loggerhead sea turtle* (*Caretta caretta*)	ESA Threatened	Common
Kemp's ridley sea turtle* (Lepidochelys kempii)	ESA Endangered	Uncommon
Green sea turtle (*Cheloria mydas*)	ESA Threatened	Uncommon

* = modeled species

[a] Listing status as stated in NOAA Fisheries n.d., MA NHESP 2019; RI DEM 2011; NYSDEC 2020a

Atlantic and shortnose sturgeon (*Acipenser oxyrinchus oxyrinchus* and *A. brevirostrum*) are endangered fish species that may occur off the northeast Atlantic coast. Atlantic sturgeon distribution varies by season, but they are primarily found in shallow coastal waters (bottom depth less than 20 m) during the summer months (May to September) and move to deeper waters (20–50 m) in winter and early spring (December to March) (Dunton et al. 2010). It is therefore unlikely that Atlantic sturgeon will be in the Project Area during the pile installation phase of this Project. Shortnose sturgeon occur primarily in fresh and estuarine waters and occasionally enter the coastal ocean. Adults ascend rivers to spawn from February to April, and eggs are deposited over hard bottom, in shallow, fast-moving water (Dadswell et al. 1984). Because of their preference for mainland rivers and fresh and estuarine waters, shortnose sturgeon are unlikely to be found in the vicinity of the Project Area.

3.1. Mean Monthly Marine Mammal Density Estimates

Mean monthly marine mammal density estimates (animals per 100 square kilometers [animals/100 km^2]) for all species are provided in Table 13. These were obtained using the Duke University Marine Geospatial Ecology Laboratory model results (Roberts et al. 2016a, 2016b, 2017, 2018, 2021a, 2021b) and include recently updated model results for North Atlantic right whale (NARW). The updated model includes new estimates for NARW abundance in Cape Cod Bay in December. Additionally, model predictions are summarized over three eras, 2003-2018, 2003-2009 and 2010-2018, to reflect the apparent shift in NARW distribution. The modeling conducted in this report uses the 2010-2018 density predictions.

Densities were calculated within a 50 km buffered polygon around the lease area perimeter. The 50 km limit is derived from studies of mysticetes that demonstrate received levels, distance from the source, and behavioral context are known to influence the probability of behavioral response (Dunlop et al. 2017b).

The mean density for each month was determined by calculating the unweighted mean of all 10 × 10 km (5 × 5 km for NARW) grid cells partially or fully within the analysis polygon (Figure 6). Densities were computed for an entire year to coincide with possible planned activities. In cases where monthly densities were unavailable, annual mean densities were used instead.

There are two stocks of bottlenose dolphins near the Project Area, coastal and offshore, but only one density model from Roberts et al. (2016a, 2018). Density for both stocks was calculated by estimating the total bottlenose dolphin densities in the buffered area and then scaling by their relative abundances (i.e., the composition ratio of a distinct stock within a defined population). As an example, the equation for calculating the coastal density of bottlenose dolphins begins with estimating their relative abundance:

$$RA_{\text{coastal}} = N_{\text{coastal}} / (N_{\text{coastal}} + N_{\text{offshore}}) \quad (1)$$

$$D_{\text{coastal}} = D_{\text{overall}} \times RA_{\text{coastal}} \quad (2)$$

where *D* is density *RA* is relative abundance and *N* is abundance.

Long-finned and short-finned pilot whales were also modeled separately, although there is only one density model for pilot whales from Roberts et al. (2016a, 2016b, 2017). Densities were adjusted similarly for these species, based on their relative abundances.

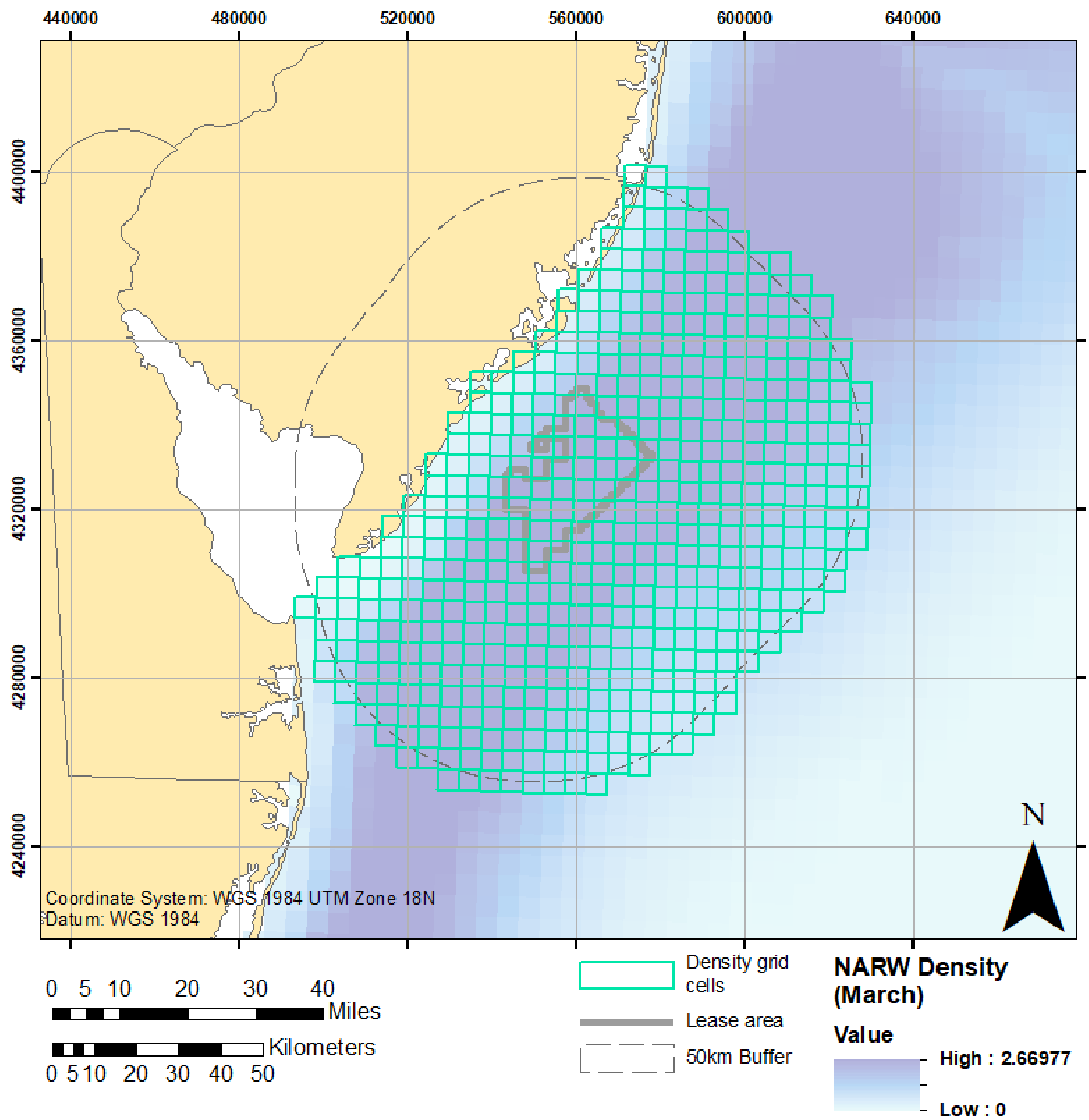

Figure 6. Marine mammal (e.g., NARW) density map showing highlighted grid cells used to calculate mean monthly species estimates within a 50 km buffer around full OCS-A 0498 lease area (Roberts et al. 2016a, 2021a, 2021b).

Table 13. Mean monthly marine mammal density estimates for all modeled species within a 50 km buffer around OCS-A 0498 lease area.

Species of interest	Monthly densities (animals/100 km^2)[a]												Annual mean
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Fin whale[b]	0.116	0.126	0.151	0.185	0.212	0.257	0.137	0.088	0.201	0.197	0.102	0.110	0.157
Minke whale	0.039	0.047	0.046	0.149	0.190	0.100	0.016	0.010	0.018	0.052	0.020	0.029	0.060
Humpback whale	0.068	0.046	0.049	0.048	0.056	0.043	0.007	0.006	0.021	0.061	0.043	0.077	0.044
North Atlantic right whale[b]	0.335	0.396	0.464	0.444	0.054	0.004	0.002	0.001	0.002	0.004	0.021	0.161	0.157
Sei whale[b]	0.001	0.001	0.001	0.012	0.010	0.003	0.001	0.001	0.001	0.003	0.002	0.002	0.003
Atlantic white sided dolphin	1.095	0.675	0.736	2.248	2.228	1.423	0.148	0.045	0.144	0.569	1.121	1.278	0.976
Short-beaked common dolphin	10.999	4.990	3.125	3.657	3.130	3.202	3.266	2.576	2.049	4.582	6.076	10.946	4.883
Bottlenose dolphin, coastal[c]	0.313	0.094	0.105	0.343	1.048	2.157	2.368	3.229	2.094	1.127	0.957	0.470	1.192
Bottlenose dolphin, offshore[c]	2.959	0.893	0.998	3.245	9.919	20.417	22.417	30.568	19.820	10.670	9.062	4.453	11.285
Risso's dolphin	0.024	0.015	0.008	0.007	0.010	0.015	0.103	0.101	0.033	0.010	0.012	0.031	0.031
Long-finned pilot whale[c]	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092	0.092
Short-finned pilot whale[c]	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Sperm whale[b]	0.001	0.001	0.001	0.002	0.003	0.011	0.018	0.012	0.014	0.006	0.003	0.001	0.006
Harbor porpoise	2.403	4.906	6.732	3.196	0.650	0.007	0.016	0.020	0.005	0.072	1.167	2.493	1.805
Seals	4.501	5.589	3.767	3.639	1.089	0.414	0.017	0.007	0.023	0.303	0.438	2.876	1.889

[a] Density estimates are from habitat-based density modeling of the entire Atlantic Exclusive Economic Zone (EEZ) (Roberts et al. 2016a, 2016b, 2017, 2018, 2021a, 2021b).
[b] Listed as Endangered under the ESA.
[c] Density adjusted by relative abundance.

3.2. Sea Turtle Density Estimates

There are limited density estimates for sea turtles in the Project Area. The Project Area is in the Mid-Atlantic North region defined in NEFSC and SEFSC (2011) for sea turtle distribution. Sea turtles are expected to be present in the Project Area during summer and fall due to seasonal habitat use, with sea turtles moving to warmer water habitats in winter (Hawkes et al. 2007, Dodge et al. 2014, DoN, 2017). Sea turtles were most commonly observed in summer and fall, absent in winter, and nearly absent in spring during the Kraus et al. (2016) aerial surveys of the MA WEA and RI/MA WEAs. Kraus et al. (2016) reported that leatherback and loggerhead sea turtles were the most commonly observed turtle species with an additional six Kemp's ridley sea turtles identified over five years.

South of the MA WEA, in the New York Bight, a multi-year series of seasonal aerial surveys were conducted by Normandeau associates for the New York State Energy Research and Development Authority (NYSERDA; Normandeau Associates and APEM 2018b, 2019c, 2019a, 2019, 2020). The purpose of the aerial surveys was to gather high resolution data on marine resources within the offshore planning area (OPA) off Long Island, New York. High-resolution digital aerial photographs were collected along specific line transects each season for three consecutive years.

Four turtle species were reported as being present in the area during the NYSERDA surveys: loggerhead, leatherback, Kemp's ridley, and green. To obtain the densities used in the current study, we extracted the maximum seasonal abundance for each species. The abundance was corrected to represent the abundance in the entire OPA and then scaled by the full OPA area to obtain a density in units of animals per square kilometer. Two categories listed in the reports included more than one species: one combined loggerhead and Kemp's ridley turtles, and the other included turtles that were observed but not identified to the species level. The counts within the two categories that included more than one species were distributed amongst the relevant species with a weighting that reflected the recorded counts for each species. For example, loggerhead turtles were identified far more frequently than any other species; therefore, more of the unidentified counts were assigned to them. The underlying assumption is that a given sample of unidentified turtles would have a distribution of species that was similar to the observed distribution within a given season.

They NYSERDA study (Normandeau Associates and APEM 2018a, 2019c, 2019a, 2019, 2020) reported that in the survey area, most of the sea turtles recorded were loggerhead sea turtles, by an order of magnitude. Seasonal sea turtle densities used in animal movement modeling are listed in Table 14 for loggerhead, leatherback, Kemp's ridley, and green sea turtles.

Table 14. Sea turtle density estimates derived from New York State Energy Research and Development Authority (NYSERDA) annual reports.

Common name	Density (animals/100 km^2)[a]			
	Spring	Summer	Fall	Winter
Kemp's ridley sea turtle[b]	0.050	0.991	0.190	0.000
Leatherback sea turtle[b]	0.000	0.331	0.789	0.000
Loggerhead sea turtle	0.254	26.799	0.190	0.025
Green turtle	0.000	0.038	0.000	0.000

[a] Densities calculated from NYSERDA aerial survey reports (Normandeau Associates and APEM 2018b, 2019c, 2019a, 2019, 2020)

[b] Listed as Endangered under the ESA.

4. Results

Sound fields were modeled at one location for monopiles and one location for pin piles, representing the range of water depths within the OCW01 (Figure 2 and Table 3). This section summarizes the source modeling results (Section 4.1), the acoustic propagation modeling results (Section 4.2), animal movement modeling results for marine mammals and sea turtles (Sections 4.4), and the acoustic range to thresholds for fish (Section 4.4).

4.1. Modeled Source Characteristics

Forcing functions were computed for the 8/11 m monopile and 2.44 m pin pile using GRLWEAP 2010 (GRLWEAP, Pile Dynamics 2010) (Figure 7). The model assumed direct contact between the hammer, helmet, and pile (i.e., no cushion material). The forcing functions serve as the inputs to JASCO's pile driving source models used to estimate equivalent acoustic source characteristics detailed in Appendix B.1. Decidecade spectral levels at 750 m for the modeled piles are shown in Figures 9 and 10.

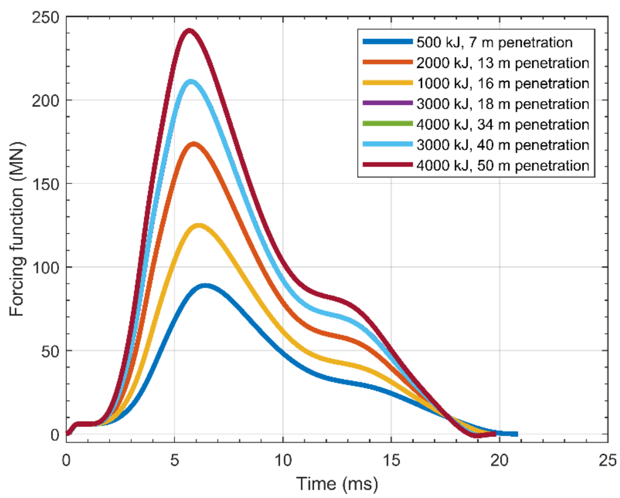

Figure 7. Modeled forcing functions versus time for an 8/11 m diameter monopile as a function of hammer energy.

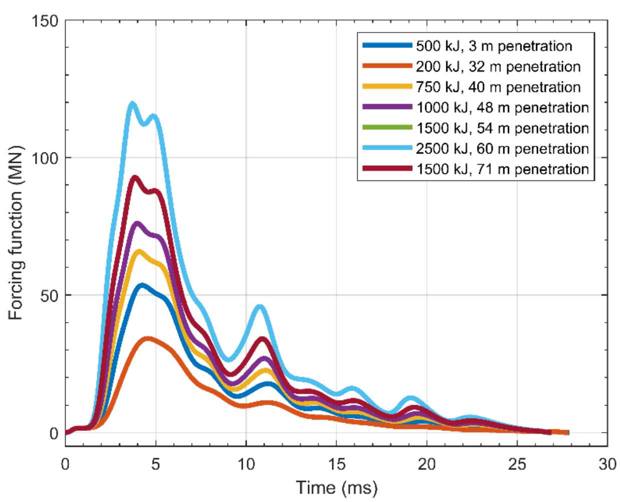

Figure 8. Modeled forcing functions versus time for a 2.44 m diameter monopile as a function of hammer energy.

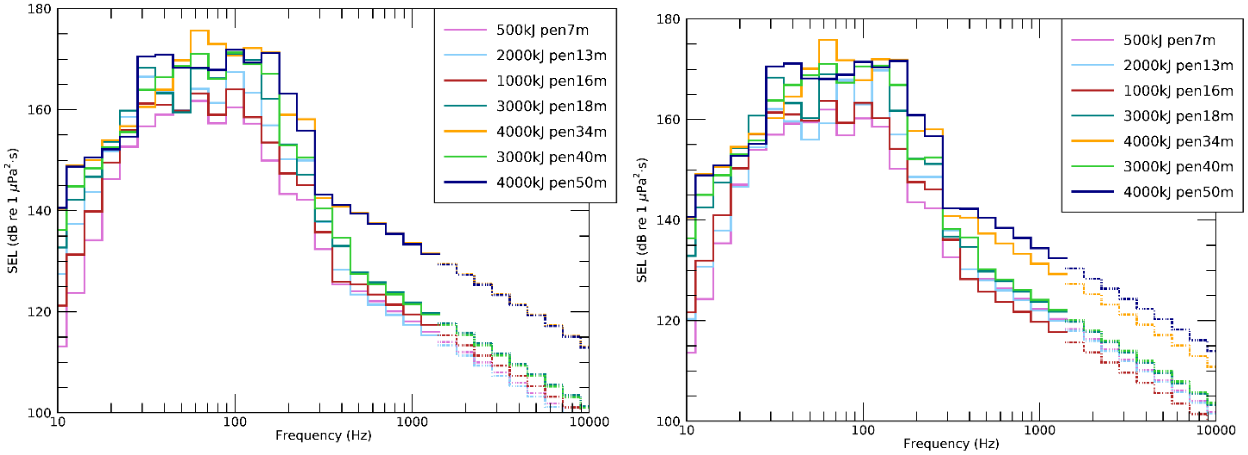

Figure 9. Location G10: Decidecade band spectral levels at 750 m for an 8/11 m diameter monopile assuming an expected installation scenario using an IHC S-4000 kJ hammer with an average summer sound speed profile (left panel) and winter sound speed profile (right panel).

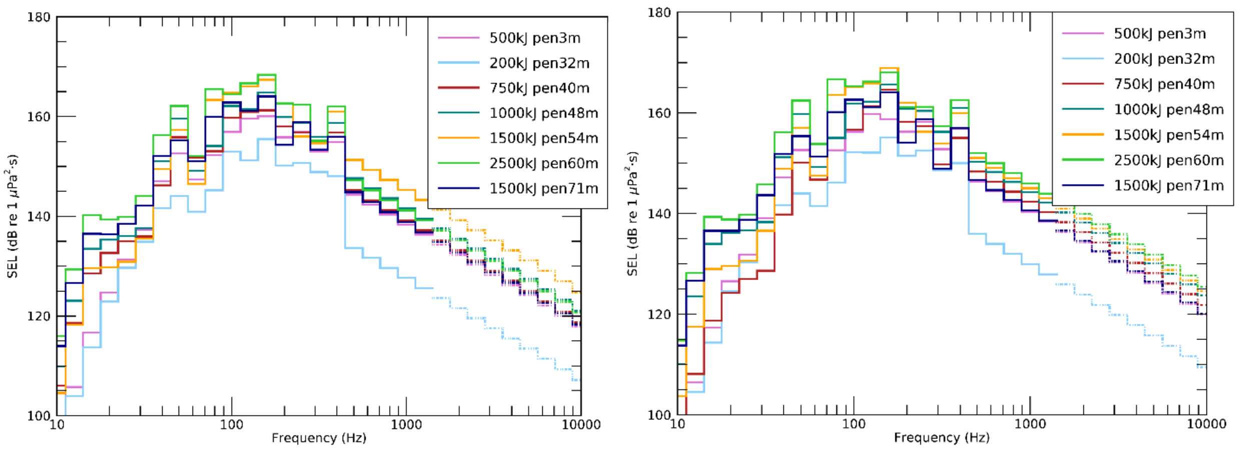

Figure 10. Location Z11: Decidecade band spectral levels at 750 m for a 2.44 m diameter pin pile assuming an expected installation scenario using an IHC S-2500 kJ hammer with an average summer sound speed profile (left panel) and winter sound speed profile (right panel).

4.2. Modeled Sound Fields

Three dimensional (3-D) sound fields for 8/11 m monopiles and 2.44 pin piles were calculated using the source characteristics (Section 4.1 and Appendix F.1) at three representative locations (Table 3). Environmental parameters (bathymetry, geoacoustic information, and sound speed profiles) chosen for the propagation modeling and the modeling procedures are found in Appendix G. Subsequent ranges to various isopleths for single hammer strikes at the different hammer energy levels are shown in Appendix H. A comparison of unweighted, broadband, received levels at 750 m was made between the computed sound fields in this study and forecasted levels for 8/11 m monopiles and 2.44 m pin piles from the ITAP empirical model (Bellmann et al. 2020) (Appendix H.5.1 and Appendix J).

4.3. Exposure Estimates

Maximum exposure estimates were calculated for each marine mammal and sea turtle species for 98 WTG monopiles, 3 OSS monopiles, and 16 pin piles (Tables 15 - 17)in Sections 4.3.1 and 4.3.2). Additional details describing proposed construction schedules for each foundation type can be found in Section 1.2.2. For full results, including all modeled attenuation levels and both summer and winter sound speed profiles, see Appendices J.2.1 and J.2.2.

4.3.1. Marine Mammals

The numbers of individual marine mammals predicted to receive sound levels above threshold criteria were determined using animal movement modeling. Tables 15 - 17 include results assuming broadband attenuation of 10 dB and a summer sound speed profile. Section 4.3.1.1 describes results assuming animal aversion to sound.

Table 15. WTG monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 98 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species		Injury		Behavior	
		$L_{E,24h}$	L_{pk}	L_p [a]	L_p [b]
LF	Fin whale[c]	5.03	0	12.90	10.88
	Minke whale (migrating)	6.06	0.02	17.18	37.46
	Humpback whale (migrating)	2.69	0	8.88	58.20
	North Atlantic right whale[c] (migrating)	3.25	0	11.42	82.64
	Sei whale[c] (migrating)	0.12	0	0.39	1.28
MF	Atlantic white sided dolphin	0	0	227.38	94.62
	Short-beaked common dolphin	0	0	2260.69	1314.80
	Bottlenose dolphin, coastal	0	0	113.39	43.51
	Bottlenose dolphin, offshore	0	0	2212.01	841.76
	Risso's dolphin	0	0	7.92	3.55
	Long-finned pilot whale	0	0	0	0
	Short-finned pilot whale	0	0	0.22	0.11
	Sperm whale[c]	0	0	0	0
HF	Harbor porpoise	53.85	5.33	253.54	4494.28
PW	Gray seal	2.19	0	132.91	163.54
	Harbor seal	3.27	0	133.11	154.16

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table 16. OSS monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 3 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

	Species	Injury		Behavior	
		$L_{E,\,24h}$	L_{pk}	L_p [a]	L_p [b]
LF	Fin whale[c]	0.16	0	0.43	0.37
	Minke whale (migrating)	0.21	<0.01	0.65	1.49
	Humpback whale (migrating)	0.11	0	0.31	2.78
	North Atlantic right whale[c] (migrating)	0.15	0	0.48	4.30
	Sei whale[c] (migrating)	<0.01	0	0.02	0.06
MF	Atlantic white sided dolphin	0	0	8.22	3.36
	Short-beaked common dolphin	0	0	85.98	55.76
	Bottlenose dolphin, coastal	0	0	3.75	1.45
	Bottlenose dolphin, offshore	0	0	78.90	29.91
	Risso's dolphin	0	0	0.24	0.11
	Long-finned pilot whale	0	0	0	0
	Short-finned pilot whale	0	0	<0.01	<0.01
	Sperm whale[c]	0	0	0	0
HF	Harbor porpoise	2.42	0.24	10.20	261.81
PW	Gray seal	0.07	0	5.71	8.23
	Harbor seal	0.11	0	5.78	7.73

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table 17. Pin piles supporting OSS jacket foundation: Number of marine mammals predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 48 pin piles. Construction schedule assumptions are summarized in Section 1.2.2.

Species		Injury		Behavior	
		$L_{E,24h}$	L_{pk}	L_p [a]	L_p [b]
LF	Fin whale[c]	0.71	0	1.83	1.70
	Minke whale (migrating)	0.64	0	4.46	11.50
	Humpback whale (migrating)	0.33	0	2.23	25.00
	North Atlantic right whale[c] (migrating)	0.35	0	2.68	36.51
	Sei whale[c] (migrating)	0.03	0	0.10	0.34
MF	Atlantic white sided dolphin	0	0	56.17	27.93
	Short-beaked common dolphin	0	0	623.78	442.56
	Bottlenose dolphin, coastal	0	0	39.32	20.16
	Bottlenose dolphin, offshore	0	0	454.43	268.53
	Risso's dolphin	0	0	1.71	0.84
	Long-finned pilot whale	0	0	0	0
	Short-finned pilot whale	0	0	0	0
	Sperm whale[c]	0	0	0	0
HF	Harbor porpoise	16.85	1.00	72.04	2169.35
PW	Gray seal	0.26	0	31.56	43.08
	Harbor seal	0.13	0	29.01	40.05

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

4.3.1.1. Effect of Aversion

The mean exposure estimates reported in Tables 15 - 17 do not consider animals avoiding loud sounds (aversion) or implementation of mitigation measures other than sound attenuation using NAS. Some marine mammals are well known for their aversive responses to anthropogenic sound (e.g., harbor porpoise), although it is assumed that most species will avert from noise. The Wood et al. (2012) step function includes a probability of response that is based primarily on observed aversive behavior in field studies. Additional exposure estimates with aversion based on the Wood et al. (2012) response probabilities were calculated for NARW and harbor porpoise in this study. For comparative purposes only, Table 18 shows results with and without aversion for the WTG monopile foundations.

Table 18. WTG monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 98 monopiles and with and without aversion for aversive species. Construction schedule assumptions are summarized in Section 1.2.2.

Species	10 dB attenuation – no aversion				10 dB attenuation – with aversion			
	Injury		Behavior		Injury		Behavior	
	$L_{E,24h}$	L_{pk}	L_p [a]	L_p [b]	$L_{E,24h}$	L_{pk}	L_p [a]	L_p [b]
North Atlantic right whale[c]	3.25	0	11.42	82.64	1.41	0	9.70	80.92
Harbor porpoise	53.85	5.33	253.54	4494.28	0	0	7.99	3034.75

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

4.3.2. Sea Turtles

As was done for marine mammals (see Section 4.3.1), the numbers of individual sea turtles predicted to receive sound levels above threshold criteria were determined using animal movement modeling. Tables 22 - 24 include results assuming broadband attenuation of 10 dB, calculated in the same way as the marine mammal exposures.

Table 19. WTG monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 98 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury		Behavior
	$L_{E,24h}$	L_{pk}	L_p
Kemp's ridley turtle[a]	0.83	0	15.00
Leatherback turtle[a]	0.25	0	6.61
Loggerhead turtle	7.50	0	168.84
Green turtle	0.06	0	0.47

[a] Listed as Endangered under the ESA.

Table 20. OSS monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 3 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury		Behavior
	$L_{E,24h}$	L_{pk}	L_p
Kemp's ridley turtle[a]	0.02	0	0.43
Leatherback turtle[a]	<0.01	0	0.18
Loggerhead turtle	0.23	0	5.97
Green turtle	<0.01	0	0.01

[a] Listed as Endangered under the ESA.

Table 21. Pin piles supporting OSS jacket foundation: Number of sea turtles predicted to receive sound levels above exposure criteria with 10 dB attenuation for a total of 48 pin piles. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury		Behavior
	$L_{E,\,24h}$	L_{pk}	L_p
Kemp's ridley turtle[a]	0	0	0.31
Leatherback turtle[a]	0	0	0.44
Loggerhead turtle	0	0	14.70
Green turtle	0	0	0.02

[a] Listed as Endangered under the ESA.

4.4. Exposure Range Estimates

Exposure ranges ($ER_{95\%}$) were calculated for marine mammals and sea turtles, and these results are summarized in Figure 11 for each of the foundation types and installation schedules. Sections 4.4.1 and 4.4.2 provide additional detail for each species and metric, assuming 10 dB attenuation and a summer sound speed profile. For full results, including all modeled attenuation levels and both summer and winter sound speed profiles, see Appendices J.2.3 and J.2.4.

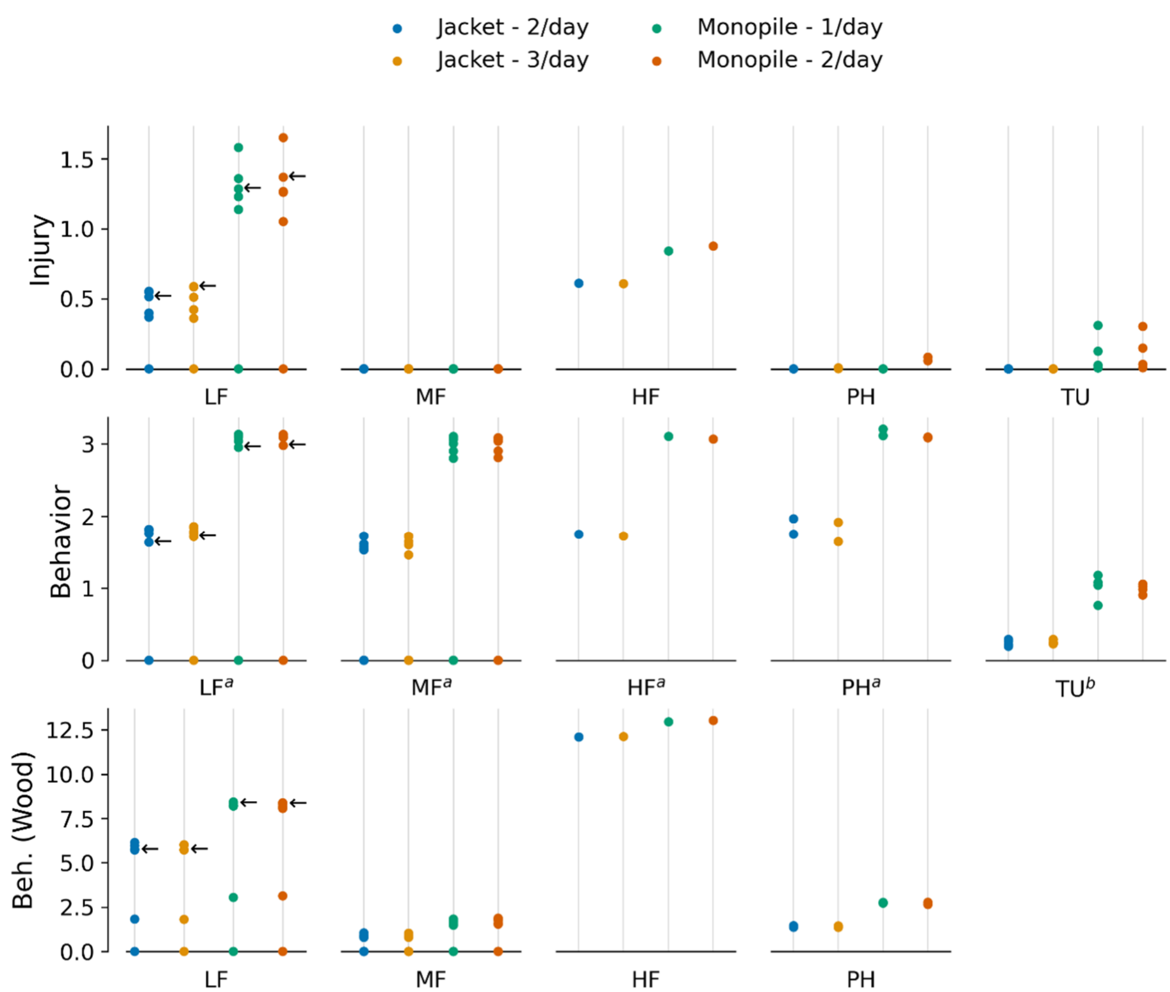

Figure 11. Exposure ranges ($ER_{95\%}$) for injury and behavior thresholds, shown for each hearing group, assuming an attenuation of 10 dB and summer sound speed profile. Each dot represents a species within the indicated hearing group (LF = low frequency, MF = mid frequency, HF = high frequency, PH = pinniped in water, and TU = turtle), and dot color represents a combination of foundation type (Jacket or Monopile) and installation schedule (number of piles installed per day). Black arrows indicate NARW exposure ranges. Note the difference in y-axis scaling between the injury and behavior plots. Subscript *a* indicates that the NOAA (2005) behavioral thresholds for marine mammals were used, and subscript *b* indicates that the Finneran et al. (2017) behavioral threshold for turtles was used.

4.4.1. Marine Mammals

The exposure ranges ($ER_{95\%}$) to injury and behavior thresholds for marine mammals are summarized below for monopile and jacket foundations, assuming 10 dB broadband attenuation and a summer acoustic propagation environment. Exposure ranges are reported for both 1 and 2 piles per day for monopile foundations, and 2 and 3 pin piles per day for jacket foundations. Results for different seasons and at different attenuation levels can be found in Appendix J.2.3. Single strike ranges to various isopleths from acoustic modeling can be found in Appendix H, along with per pile SEL acoustic ranges to isopleths for the hearing groups assuming no movement of animals during pile driving (Appendix H.4).

Table 22. Monopile foundation (8 to 11 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with 10 dB attenuation.

Species		One pile per day				Two piles per day			
		Injury		Behavior		Injury		Behavior	
		$L_{E,\,24h}$	L_{pk}	L_p [a]	L_p [b]	$L_{E,\,24h}$	L_{pk}	L_p [a]	L_p [b]
LF	Fin whale[c]	1.58	0	3.04	3.04	1.65	0	3.13	3.13
	Minke whale (migrating)	1.23	0	3.13	8.21	1.26	<0.01	3.10	8.05
	Humpback whale (migrating)	1.14	0	3.10	8.45	1.05	0	3.09	8.40
	North Atlantic right whale[c] (migrating)	1.28	0	2.95	8.34	1.37	0	2.98	8.30
	Sei whale[c] (migrating)	1.36	0	3.13	8.19	1.27	0	3.09	8.15
MF	Atlantic white sided dolphin	0	0	3.10	1.79	0	0	3.04	1.80
	Short-beaked common dolphin	0	0	3.09	1.82	0	0	3.05	1.85
	Bottlenose dolphin, coastal	0	0	2.80	1.48	0	0	2.81	1.54
	Bottlenose dolphin, offshore	0	0	2.90	1.54	0	0	2.90	1.58
	Risso's dolphin	0	0	3.06	1.66	0	0	3.09	1.87
	Long-finned pilot whale	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	3.01	1.74	0	0	3.08	1.76
	Sperm whale[c]	0	0	0	0	0	0	0	0
HF	Harbor porpoise	0.84	0.07	3.11	12.95	0.88	0.07	3.07	13.03
PW	Gray seal	0	0	3.21	2.76	0.08	0	3.09	2.77
	Harbor seal	0	0	3.11	2.72	0.06	0	3.08	2.64

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table 23. Jacket foundation (2.44 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with 10 dB attenuation.

Species		Two pin piles per day				Three pin piles per day			
		Injury		Behavior		Injury		Behavior	
		$L_{E,24h}$	L_{pk}	L_p [a]	L_p [b]	$L_{E,24h}$	L_{pk}	L_p [a]	L_p [b]
LF	Fin whale[c]	0.55	0	1.82	1.82	0.59	0	1.79	1.81
	Minke whale (migrating)	0.55	0	1.76	5.76	0.51	0	1.76	5.72
	Humpback whale (migrating)	0.40	0	1.81	5.96	0.42	0	1.86	6.01
	North Atlantic right whale[c] (migrating)	0.51	0	1.64	5.71	0.58	0	1.72	5.72
	Sei whale[c] (migrating)	0.37	0	1.81	6.14	0.36	0	1.84	6.01
MF	Atlantic white sided dolphin	0	0	1.55	0.91	0	0	1.72	0.93
	Short-beaked common dolphin	0	0	1.72	1.05	0	0	1.72	1.03
	Bottlenose dolphin, coastal	0	0	1.53	0.84	0	0	1.46	0.80
	Bottlenose dolphin, offshore	0	0	1.58	0.86	0	0	1.60	0.83
	Risso's dolphin	0	0	1.61	0.79	0	0	1.65	0.84
	Long-finned pilot whale	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0
	Sperm whale[c]	0	0	0	0	0	0	0	0
HF	Harbor porpoise	0.61	0.04	1.75	12.12	0.61	0.05	1.73	12.13
PW	Gray seal	0	0	1.75	1.45	<0.01	0	1.65	1.44
	Harbor seal	0	0	1.96	1.36	<0.01	0	1.91	1.35

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

4.4.2. Sea Turtles

Similar to the results presented for marine mammals (Section 4.4), the exposure ranges ($ER_{95\%}$) for sea turtles are summarized below for monopile and jacket foundations, assuming 10 dB broadband attenuation and a summer acoustic propagation environment. Results for different seasons and at different attenuation levels can be found in Appendix J.2. Single strike ranges to various isopleths from acoustic modeling can be found in Appendix H, along with per pile SEL distances to isopleths for the hearing groups assuming no movement of animals during pile driving (Appendix H.4).

Table 24. Monopile foundation (8 to 11 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with 10 dB attenuation.

Species	One pile per day			Two piles per day		
	Injury		Behavior	Injury		Behavior
	$L_{E,\,24h}$	L_{pk}	L_p	$L_{E,\,24h}$	L_{pk}	L_p
Kemp's ridley turtle[a]	0.13	0	1.08	0.15	0	1.06
Leatherback turtle[a]	0.03	0	0.76	0.03	0	0.98
Loggerhead turtle	<0.01	0	1.04	<0.01	0	0.90
Green turtle	0.31	0	1.18	0.30	0	1.02

[a] Listed as Endangered under the ESA.

Table 25. Jacket foundation (2.44 m diameter, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria with 10 dB attenuation.

Species	Two pin piles per day			Three pin piles per day		
	Injury		Behavior	Injury		Behavior
	$L_{E,\,24h}$	L_{pk}	L_p	$L_{E,\,24h}$	L_{pk}	L_p
Kemp's ridley turtle[a]	0	0	0.29	0	0	0.29
Leatherback turtle[a]	0	0	0.22	0	0	0.25
Loggerhead turtle	0	0	0.19	0	0	0.24
Green turtle	0	0	0.26	0	0	0.23

[a] Listed as Endangered under the ESA.

4.5. Fish Acoustic Range Estimates

Although some fish may move during pile driving, they were considered static receivers and acoustic distances where sound levels could exceed fish regulatory thresholds were determined using a maximum-over-depth approach and finding the distance that encompasses at least 95% of the horizontal area that would be exposed to sound at or above the specified level (Appendix G.5). The calculated acoustic distances for fish to the GARFO (2020) and Popper et al. (2014) thresholds (Andersson et al. 2007, Wysocki et al. 2007, FHWG 2008, Stadler and Woodbury 2009, Mueller-Blenkle et al. 2010, Purser and Radford 2011, Popper et al. 2014) with 10 dB of broadband attenuation are shown in Tables 26 - 29 (tables with 0, 6, 15, and 20 dB attenuation can be found in Appendix H.5)

Table 26. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at modeling location G10 for different hammer energy levels with 10 dB attenuation, in summer conditions for one foundation.

Faunal group	Metric	Threshold	Hammer energy in kJ (penetration depth in m)						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	4.93						
	L_{pk} [a]	206	0.01	0.05	0.03	0.06	0.07	0.07	0.07
	L_{p} [b]	150	3.10	3.48	3.20	4.25	5.18	4.40	4.85
Fish less than 2 g	$L_{E,24hr}$ [a]	183	6.06						
	L_{pk} [a]	206	0.05	0.03	0.06	0.07	0.07	0.07	0.05
	L_{p} [b]	150	3.10	3.48	3.20	4.25	5.18	4.40	4.85
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.22						
	L_{pk} [c]	213	0.01	0.00	0.01	0.03	0.01	0.02	0.01
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	1.52						
	L_{pk} [c]	207	0.04	0.02	0.05	0.07	0.06	0.06	0.04
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	1.52						
	L_{pk} [c]	207	0.04	0.02	0.05	0.07	0.06	0.06	0.04

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014).

Table 27. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at modeling location G10 for different hammer energy levels with 10 dB attenuation, in winter conditions for one foundation.

Faunal group	Metric	Threshold	Hammer energy in kJ (penetration depth in m)						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	6.85						
	L_{pk} [a]	206	0.01	0.05	0.03	0.06	0.07	0.07	0.07
	L_{p} [b]	150	3.32	4.52	3.47	5.61	7.18	6.08	7.54
Fish less than 2 g	$L_{E,24hr}$ [a]	183	9.35						
	L_{pk} [a]	206	0.01	0.05	0.03	0.06	0.07	0.07	0.07
	L_{p} [b]	150	3.32	4.52	3.47	5.61	7.18	6.08	7.54
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.24						
	L_{pk} [c]	213	0.00	0.01	0.00	0.01	0.02	0.01	0.02
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	1.75						
	L_{pk} [c]	207	0.01	0.04	0.01	0.05	0.07	0.06	0.07
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	1.75						
	L_{pk} [c]	207	0.01	0.04	0.01	0.05	0.07	0.06	0.07

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E = unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014).

Table 28. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels with 10 dB attenuation, in summer conditions.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	2.14 (one pile) / 2.71 (two piles) / 3.06 (three piles)						
	L_{pk} [a]	206	0.01	0.00	0.04	0.05	0.05	0.06	0.03
	L_p [b]	150	2.53	1.63	2.92	3.21	3.59	3.89	3.05
Fish less than 2 g	$L_{E,24hr}$ [a]	183	2.90 (one pile) / 3.51 (two piles) / 3.89 (three piles)						
	L_{pk} [a]	206	0.01	0.00	0.04	0.05	0.05	0.06	0.03
	L_p [b]	150	2.53	1.63	2.92	3.21	3.59	3.89	3.05
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.04 (one pile) / 0.06 (two piles) / 0.08 (three piles)						
	L_{pk} [c]	213	0.002	0.002	0.003	0.01	0.02	0.01	0.002
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.28 (one pile) / 0.45 (two piles) / 0.61 (three piles)						
	L_{pk} [c]	207	0.01	0.003	0.01	0.04	0.05	0.05	0.02
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.28 (one pile) / 0.45 (two piles) / 0.61 (three piles)						
	L_{pk} [c]	207	0.01	0.003	0.01	0.04	0.05	0.05	0.02

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014).

Table 29. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels with 10 dB attenuation, in winter conditions.

Faunal group	Metric	Threshold	Hammer energy (kJ) Z11 500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	2.63 (one pile) / 3.48 (two piles) / 4.05 (three piles)						
	L_{pk} [a]	206	0.01	0.00	0.04	0.05	0.06	0.06	0.03
	L_p [b]	150	3.38	2.01	3.74	4.09	4.98	5.32	3.51
Fish less than 2 g	$L_{E,24hr}$ [a]	183	3.78 (one pile) / 4.85 (two piles) / 5.69 (three piles)						
	L_{pk} [a]	206	0.01	0.00	0.04	0.05	0.06	0.06	0.03
	L_p [b]	150	3.38	2.01	3.74	4.09	4.98	5.32	3.51
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.03 (one pile) / 0.05 (two piles) / 0.06 (three piles)						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.28 (one pile) / 0.49 (two piles) / 0.64 (three piles)						
	L_{pk} [c]	207	0.01	0.00	0.01	0.04	0.05	0.05	0.02
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.28 (one pile) / 0.49 (two piles) / 0.64 (three piles)						
	L_{pk} [c]	207	0.01	0.00	0.01	0.04	0.05	0.05	0.02

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014).

5. Discussion

Sounds fields produced during impact pile driving for installation of 8/11 m monopile foundations were found by modeling the vibration of the pile when struck with a hammer, determining a far-field representation of the pile as a sound source, and then propagating the sound from the apparent source into the environment. A comparison of the Project's modeled sound fields was made with a forecasting, empirical model (ITAP) that predicts pile driving sound levels at 750 m from the pile (Appendix H.5.1).

Sound fields were sampled by simulating animal movement within the sound fields and determining if simulated marine mammal and sea turtle animats (simulated animals) exceed regulatory thresholds. The mean number of individuals of each species likely to exceed the thresholds was determined by scaling the animat results using the real world density of each species. For those animats that exceeded thresholds, the closest point of approach to the source was found and the distance accounting for 95% of exceedances was reported as the exposure range, $ER_{95\%}$. The species-specific $ER_{95\%}$ (see tables in Section 4) were determined with different broadband attenuation levels (0, 6, 10, 15, and 20 dB) to account for the use of noise reduction systems, such as bubble curtains. Exposure ranges can be used for mitigation purposes, like establishing monitoring or exclusion areas. Fish were considered as static receivers, so exposure ranges were not calculated. Instead, the acoustic distance to their regulatory thresholds were determined and reported, with the different broadband attenuation levels (see tables in Section 4).

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Literature Cited

[ANSI] American National Standards Institute. S1.1-1994 (R2004). *American National Standard: Acoustical Terminology*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIS11994R2004.

[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.

[ANSI] American National Standards Institute and [ASA] Acoustical Society of America. S1.13-2005 (R2010). *American National Standard: Measurement of Sound Pressure Levels in Air*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIASAS1132005R2010.

[ANSI] American National Standards Institute. S12.7-1986 (R2006). *American National Standard: Methods for Measurements of Impulsive Noise*. NY, USA. https://webstore.ansi.org/Standards/ASA/ANSIS121986R2006.

[BOEM] Bureau of Ocean Energy Management. 2014. *Atlantic OCS Proposed Geological and Geophysical Activities: Mid-Atlantic and South Atlantic Planning Area. Final Programmatic Environmental Impact Statement*. Volume I: Chapters 1-8, Figures, Tables, and Keyword Index. OCS EIS/EA BOEM 2014-001. U.S. Department of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region. https://www.boem.gov/sites/default/files/oil-and-gas-energy-program/GOMR/BOEM-2014-001-v1.pdf.

[CBD] Convention on Biological Diversity. 2012. *Scientific synthesis on the impacts of underwater noise on marine and coastal biodiversity and habitats, UNEP/CBD/SBSTTA/16/INF/12*. *Subsidiary Body on Scientific, Technical and Technological Advice Sixteenth Meeting*, 30 Apr to 5 May 2012, Montréal, Canada, p. 93.

[DoC] Department of Commerce (US) and [NOAA] National Oceanic and Atmospheric Administration (US). 2005. Endangered Fish and Wildlife; Notice of Intent to Prepare an Environmental Impact Statement. *Federal Register* 70(7): 1871-1875. https://www.govinfo.gov/content/pkg/FR-2005-01-11/pdf/05-525.pdf.

[DoN] Department of the Navy (US). 2017. *U.S. Navy marine species density database phase III for the Atlantic Fleet training and testing study area. NAVFAC Atlantic Final Technical Report*. Naval Facilities Engineering Command Atlantic, Norfolk, VA.

[FHWG] Fisheries Hydroacoustic Working Group. 2008. *Agreement in Principle for Interim Criteria for Injury to Fish from Pile Driving Activities*. 12 Jun 2008 edition. http://www.dot.ca.gov/hq/env/bio/files/fhwgcriteria_agree.pdf.

[GARFO] Greater Atlantic Regional Fisheries Office. 2020. *GARFO Acoustics Tool: Analyzing the effects of pile driving on ESA-listed species in the Greater Atlantic Region* https://s3.amazonaws.com/media.fisheries.noaa.gov/2020-09/GARFO-Sect7-PileDriving-AcousticsTool-09142020.xlsx?.Egxagq5Dh4dplwJQsmN1gV0nggnk5qX.

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

[NAVO] Naval Oceanography Office (US). 2003. *Database description for the Generalized Digital Environmental Model (GDEM-V) (U)*. Document Number MS 39522-5003. Oceanographic Data Bases Division, Stennis Space Center.

[NMFS] National Marine Fisheries Service (US) and [NOAA] National Oceanic and Atmospheric Administration (US). 2005. Endangered fish and wildlife: Notice of intent to prepare an environmental impact statement. *Federal Register* 70(7): 1871-1875. http://www.nmfs.noaa.gov/pr/pdfs/fr/fr70-1871.pdf.

[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://www.fisheries.noaa.gov/webdam/download/75962998.

[NOAA] National Oceanic and Atmospheric Administration (U.S.). 2019. *Interim Recommendation for Sound Source Level and Propagation Analysis for High Resolution Geophysical Sources*. National Oceanic and Atmospheric Administration, US Department of Commerce. 3 p.

[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.

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 Number 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.

Aguilar Soto, N., M. Johnson, P.T. Madsen, P.L. Tyack, A. Bocconcelli, and J.F. Borsani. 2006. Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziphius cavirostris*)? [note]. *Marine Mammal Science* 22(3): 690-699. https://doi.org/10.1111/j.1748-7692.2006.00044.x.

Andersson, M.H., E. Dock-Åkerman, R. Ubral-Hedenberg, M.C. Öhman, and P. Sigray. 2007. Swimming behavior of roach (*Rutilus rutilus*) and three-spined stickleback (*Gasterosteus aculeatus*) in response to wind power noise and single-tone frequencies. *AMBIO* 36(8): 636-638. https://doi.org/10.1579/0044-7447(2007)36[636:SBORRR]2.0.CO;2.

Anderwald, P., A. Brandecker, M. Coleman, C. Collins, H. Denniston, M.D. Haberlin, M. Donovan, R. Pinfield, F. Visser, et al. 2013. Displacement responses of a mysticete, an odontocete, and a phocid seal to construction-related vessel traffic. *Endangered Species Research* 21(3): 231-240. https://doi.org/10.3354/esr00523.

Aoki, K., M. Amano, M. Yoshioka, K. Mori, D. Tokuda, and N. Miyazaki. 2007. Diel diving behavior of sperm whales off Japan. *Marine Ecology Progress Series* 349: 277-287. https://doi.org/10.3354/meps07068.

Au, W.W.L. and M.C. Hastings. 2008. *Principles of Marine Bioacoustics*. Modern Acoustics and Signal Processing. Springer, New York. 510 p. https://doi.org/10.1007/978-0-387-78365-9.

Austin, M.E. and G.A. Warner. 2012. *Sound Source Acoustic Measurements for Apache's 2012 Cook Inlet Seismic Survey*. Version 2.0. Technical report by JASCO Applied Sciences for Fairweather LLC and Apache Corporation.

Austin, M.E. and L. Bailey. 2013. *Sound Source Verification: TGS Chukchi Sea Seismic Survey Program 2013*. Document Number 00706, Version 1.0. Technical report by JASCO Applied Sciences for TGS-NOPEC Geophysical Company.

Austin, M.E., A. McCrodan, C. O'Neill, Z. Li, and A.O. MacGillivray. 2013. *Marine mammal monitoring and mitigation during exploratory drilling by Shell in the Alaskan Chukchi and Beaufort Seas, July–November 2012: 90-Day Report*. *In*: Funk, D.W., C.M. Reiser, and W.R. Koski (eds.). Underwater Sound Measurements. LGL Rep. P1272D–1. Report from LGL Alaska Research Associates Inc. and JASCO Applied Sciences, for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 266 pp plus appendices.

Austin, M.E. 2014. Underwater noise emissions from drillships in the Arctic. *In*: Papadakis, J.S. and L. Bjørnø (eds.). *UA2014 - 2nd International Conference and Exhibition on Underwater Acoustics*. 22-27 Jun 2014, Rhodes, Greece. pp. 257-263.

Austin, M.E., H. Yurk, and R. Mills. 2015. *Acoustic Measurements and Animal Exclusion Zone Distance Verification for Furie's 2015 Kitchen Light Pile Driving Operations in Cook Inlet*. Version 2.0. Technical report by JASCO Applied Sciences for Jacobs LLC and Furie Alaska.

Austin, M.E. and Z. Li. 2016. *Marine Mammal Monitoring and Mitigation During Exploratory Drilling by Shell in the Alaskan Chukchi Sea, July–October 2015: Draft 90-day report*. *In*: Ireland, D.S. and L.N. Bisson (eds.). Underwater Sound Measurements. LGL Rep. P1363D. Report from LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. For Shell Gulf of Mexico Inc, National Marine Fisheries Service, and US Fish and Wildlife Service. 188 pp + appendices.

Awbrey, F.T. and B.S. Stewart. 1983. Behavioral responses of wild beluga whales (*Delphinapterus leucas*) to noise from oil drilling. *Journal of the Acoustical Society of America* 74(S1): S54-S54. https://doi.org/10.1121/1.2021025.

Baker, C.S. and L.M. Herman. 1989. *Behavioral responses of summering humpback whales to vessel traffic: Experimental and opportunistic observations*. Final report to the National Park Service, Alaska Regional Office. NPS-NR-TRS-89-01, Anchorage, AK.

Balazs, G.H. and E. Ross. 1974. Observations on the Preemergence Behavior of the Green Turtle. *Copeia* 1974(4): 986-988. https://doi.org/10.2307/1442606.

Barber, M.R. 2017. *Effects of Hydraulic Dredging and Vessel Operation on Atlantic Sturgeon Behavior in a Large Coastal River*. MSc Thesis. Virginia Commonwealth University. 46 p. https://doi.org/10.25772/KPFH-Z425.

Barlow, J.P. 1988. Harbor porpoise, *Phocoena phocoena*, abundance estimation for California, Oregon, and Washington. I: Ship surveys. *Fishery Bulletin* 86(3): 417-432. https://spo.nmfs.noaa.gov/sites/default/files/pdf-content/1988/863/barlow.pdf.

Bartol, S.M., J.A. Musick, and M.L. Lenhardt. 1999. Auditory evoked potentials of the loggerhead sea turtle (*Caretta caretta*). *Copeia* 3: 836-840. https://doi.org/10.2307/1447625.

Bel'kovich, V.M. 1960. Some biological observations on the white whale from the aircraft. *Zoologicheskii Zhurnal* 39(9): 1414-1422.

Bellmann, M.A. 2014. Overview of existing noise mitigation systems for reducing pile-driving noise. *Inter-noise2014*. Melbourne, Australia. https://www.acoustics.asn.au/conference_proceedings/INTERNOISE2014/papers/p358.pdf.

Bellmann, M.A., A. May, T. Wendt, S. Gerlach, P. Remmers, and J. Brinkmann. 2020. *Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values*. Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU)), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie (BSH)), Order No. 10036866. Edited by the itap GmbH. https://www.itap.de/media/experience_report_underwater_era-report.pdf.

Bergström, L., F. Sundqvist, and U. Bergström. 2013. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progress Series* 485: 199-210. https://doi.org/10.3354/meps10344.

Bergström, L., L. Kautsky, T. Malm, R. Rosenberg, M. Wahlberg, N.Å. Capetillo, and D. Wilhelmsson. 2014. Effects of offshore wind farms on marine wildlife—A generalized impact assessment. *Environmental Research Letters* 9(3): 12. https://doi.org/10.1088/1748-9326/9/3/034012.

Berthe, C. and D. Lecchini. 2016. Influence of boat noises on escape behaviour of white-spotted eagle ray Aetobatus ocellatus at Moorea Island (French Polynesia). *Comptes Rendus Biologies* 339(2): 99-103. https://doi.org/10.1016/j.crvi.2016.01.001.

Betke, K. 2008. *Measurement of Wind Turbine Construction Noise at Horns Rev II*. Report Number 1256-08-a-KB. Technical report by Institut für technische und angewandte Physik GmbH (ITAP) for BioConsultSH, Husun, Germany. 30 p. https://tethys.pnnl.gov/sites/default/files/publications/Betke-2008.pdf.

Blackwell, S.B., C.R. Greene, Jr., and W.J. Richardson. 2004a. Drilling and operational sounds from an oil production island in the ice-covered Beaufort Sea. *Journal of the Acoustical Society of America* 116(5): 3199-3211. https://doi.org/10.1121/1.1806147.

Blackwell, S.B., J.W. Lawson, and M.T. Williams. 2004b. Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. *Journal of the Acoustical Society of America* 115(5): 2346-2357. https://doi.org/10.1121/1.1701899.

Blackwell, S.B., C.S. Nations, A.M. Thode, M.E. Kauffman, A.S. Conrad, R.G. Norman, and K.H. Kim. 2017. Effects of tones associated with drilling activities on bowhead whale calling rates. *PLOS ONE* 12(11): e0188459. https://doi.org/10.1371/journal.pone.0188459.

Blair, H.B., N.D. Merchant, A.S. Friedlaender, D.N. Wiley, and S.E. Parks. 2016. Evidence for ship noise impacts on humpback whale foraging behaviour. *Biology Letters* 12(8). https://doi.org/10.1098/rsbl.2016.0005.

Brown, M.W., M.K. Marx, and O. Nichols. 2000. *Assessing environmental impacts of offshore wind farms: Lessons learned and recommendations for the future Cape Cod Bay, Massachusetts: January to mid-May*.

Bryant, P.J., C.M. Lafferty, and S.K. Lafferty. 1984. Reoccupation of Laguna Guerrero Negro, Baja California, Mexico, by Gray Whales. (Chapter 15) *In The gray whale: Eschrichtius robustus*. pp. 375-387. https://doi.org/10.1016/B978-0-08-092372-7.50021-2.

Buckingham, M.J. 2005. Compressional and shear wave properties of marine sediments: Comparisons between theory and data. *Journal of the Acoustical Society of America* 117: 137-152. https://doi.org/10.1121/1.1810231.

Buehler, D., R. Oestman, J.A. Reyff, K. Pommerenck, and B. Mitchell. 2015. *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*. Report Number CTHWANP-RT-15-306.01.01. Report by California Department of Transportation (CALTRANS), Division of Environmental Analysis. 532 p. https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/bio-tech-guidance-hydroacoustic-effects-110215-a11y.pdf.

Buerkle, U. 1973. Gill-net catches of cod (*Gadus morhua* L.) in relation to trawling noise. *Marine Behaviour and Physiology* 2(1-4): 277-281. https://doi.org/10.1080/10236247309386930.

Burgess, W.C., P.L. Tyack, B.J. Le Boeuf, and D.P. Costa. 1998. A programmable acoustic recording tag and first results from free-ranging northern elephant seals. *Deep Sea Research Part II* 45(7): 1327-1351. https://doi.org/10.1016/S0967-0645(98)00032-0.

Charifi, M., A. Miserazzi, M. Sow, M. Perrigault, P. Gonzalez, P. Ciret, S. Benomar, and J.-C. Massabuau. 2018. Noise pollution limits metal bioaccumulation and growth rate in a filter feeder, the Pacific oyster *Magallana gigas*. *PLOS ONE* 13(4): e0194174. https://doi.org/10.1371/journal.pone.0194174.

Cheesman, S. 2016. Measurements of operational wind turbine noise in UK waters. *In The effects of noise on aquatic life II*. Springer. pp. 153-160.

Cholewiak, D., A.I. DeAngelis, D.L. Palka, P.J. Corkeron, and S.M. Van Parijs. 2017. Beaked whales demonstrate a marked acoustic response to the use of shipboard echosounders. *Royal Society Open Science* 4(12). https://doi.org/10.1098/rsos.170940.

Clark, C.W., W.T. Ellison, B.L. Southall, L.T. Hatch, S.M. Van Parijs, A.S. Frankel, and D.W. Ponirakis. 2009. Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series* 395: 201-222. https://doi.org/10.3354/meps08402.

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.

Cranford, T.W. and P. Krysl. 2015. Fin whale sound reception mechanisms: Skull vibration enables low-frequency hearing. *PLOS ONE* 10(1). https://doi.org/10.1371/journal.pone.0116222.

Crocker, S.E. and F.D. Fratantonio. 2016. *Characteristics of Sounds Emitted During High-Resolution Marine Geophysical Surveys*. Report by Naval Undersea Warfare Center Division. NUWC-NPT Technical Report 12,203, Newport, RI, USA. 266 p. https://apps.dtic.mil/dtic/tr/fulltext/u2/1007504.pdf.

Dahlheim, E. 1981. Comments on bowhead acoustics. *In San Diego workshop on the interaction between man-made noise and vibration and arctic marine wildlife, Feb. 1980*. Report from Acoustical Society of America, Washington, DC, for Alaska Eskimo Whaling Commission, Barrow, AK. Available from ASA, 2 Huntington Quadrangle, Suite 1N01, Melville, NY 11747-4502. p. 64.

Dahlheim, M.E. and D.K. Ljungblad. 1990. Preliminary hearing study on gray whales (*Eschrichtius robustus*) in the field. *In* Thomas, J.A. and R.A. Kastelein (eds.). *Sensory abilities of cetaceans*. Volume 196. Springer US. pp. 335-346.

De Robertis, A., C.D. Wilson, N.J. Williamson, M.A. Guttormsen, and S. Stienessen. 2010. Silent ships sometimes do encounter more fish. 1. Vessel comparisons during winter pollock surveys. *ICES Journal of Marine Science* 67(5): 985-995. https://doi.org/10.1093/icesjms/fsp299.

DeRuiter, S.L., B.L. Southall, J. Calambokidis, W.M.X. Zimmer, D. Sadykova, E.A. Falcone, A.S. Friedlaender, J.E. Joseph, D. Moretti, et al. 2013. First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology Letters* 9(4): 1-5. https://doi.org/10.1098/rsbl.2013.0223.

Diederichs, A., M. Brandt, and G. Nehls. 2010. Does sand extraction near Sylt affect harbour porpoises? *Wadden Sea Ecosystem* 26: 199-203.

Dow Piniak, W.E., S.A. Eckert, C.A. Harms, and E.M. Stringer. 2012. *Underwater hearing sensitivity of the leatherback sea turtle (Dermochelys coriacea): Assessing the potential effect of anthropogenic noise*. US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2012-00156. 35 p.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, D. Paton, and D.H. Cato. 2015. The behavioural response of humpback whales (*Megaptera novaeangliae*) to a 20 cubic inch air gun. *Aquatic Mammals* 41(4): 412-433. https://doi.org/10.1578/AM.41.4.2015.412.

Dunlop, R.A., M.J. Noad, and D.H. Cato. 2016a. A spatially explicit model of the movement of humpback whales relative to a source. *Meetings on Acoustics (POMA)*. Volume 27(1), 16 Jul 2016. Acoustical Society of America, Dublin, Ireland. https://doi.org/10.1121/2.0000296.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2016b. Response of humpback whales (*Megaptera novaeangliae*) to ramp-up of a small experimental air gun array. *Marine Pollution Bulletin* 103(1–2): 72-83. https://doi.org/10.1016/j.marpolbul.2015.12.044.

Dunlop, R.A., M.J. Noad, R.D. McCauley, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2017a. The behavioural response of migrating humpback whales to a full seismic airgun array. *Proceedings of the Royal Society B* 284(1869): 20171901. https://doi.org/10.1098/rspb.2017.1901.

Dunlop, R.A., M.J. Noad, R.D. McCauley, L. Scott-Hayward, E. Kniest, R. Slade, D. Paton, and D.H. Cato. 2017b. 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.

Dunlop, R.A., R.D. McCauley, and M.J. Noad. 2020. Ships and air guns reduce social interactions in humpback whales at greater ranges than other behavioral impacts. *Marine Pollution Bulletin* 154: 111072. https://doi.org/10.1016/j.marpolbul.2020.111072.

Ellers, O. 1995. Discrimination Among Wave-Generated Sounds by a Swash-Riding Clam. *The Biological Bulletin* 189(2): 128-137. https://doi.org/10.2307/1542463.

Elliott, J., A.A. Khan, Y.-T. Lin, T. Mason, J.H. Miller, A.E. Newhall, G.R. Potty, and K.J. Vigness-Raposa. 2019. *Field Observations during Wind Turbine Operations at the Block Island Wind Farm, Rhode Island*. Final report by HDR for the US Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 2019-028. 281 p. https://espis.boem.gov/final%20reports/BOEM_2019-028.pdf.

Ellison, W.T., K.S. Weixel, and C.W. Clark. 1999. An acoustic integration model (AIM) for assessing the impact of underwater noise on marine wildlife. *Journal of the Acoustical Society of America* 106(4): 2250-2250. https://doi.org/10.1121/1.427674.

Ellison, W.T., B.L. Southall, C.W. Clark, and A.S. Frankel. 2012. A New Context-Based Approach to Assess Marine Mammal Behavioral Responses to Anthropogenic Sounds. *Conservation Biology* 26(1): 21-28. https://doi.org/10.1111/j.1523-1739.2011.01803.x.

Ellison, W.T., R. Racca, C.W. Clark, B. Streever, A.S. Frankel, E. Fleishman, R.P. Angliss, J. Berger, D.R. Ketten, et al. 2016. Modeling the aggregated exposure and responses of bowhead whales *Balaena mysticetus* to multiple sources of anthropogenic underwater sound. *Endangered Species Research* 30: 95-108. https://doi.org/10.3354/esr00727.

Erbe, C. 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. *Marine Mammal Science* 18(2): 394-418. https://doi.org/10.1111/j.1748-7692.2002.tb01045.x.

Erbe, C., R.D. McCauley, and A. Gavrilov. 2016a. Characterizing marine soundscapes. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Volume 875. Springer, New York. pp. 265-271. https://doi.org/10.1007/978-1-4939-2981-8_31.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, and R.J. Dooling. 2016b. Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin* 103(1): 15-38. https://doi.org/10.1016/j.marpolbul.2015.12.007.

Erbe, C. and C.R. McPherson. 2017. Underwater noise from geotechnical drilling and standard penetration testing. *Journal of the Acoustical Society of America* 142(3): EL281-EL285. https://doi.org/10.1121/1.5003328.

Erbe, C., M. Parsons, A. Duncan, S.K. Osterrieder, and K. Allen. 2017. Aerial and underwater sound of unmanned aerial vehicles (UAV). *Journal of Unmanned Vehicle Systems* 5(3): 92-101. https://doi.org/10.1139/juvs-2016-0018.

Erbe, C., R. Williams, M. Parsons, S.K. Parsons, I.G. Hendrawan, and I.M.I. Dewantama. 2018. Underwater noise from airplanes: An overlooked source of ocean noise. *Marine Pollution Bulletin* 137: 656-661. https://doi.org/10.1016/j.marpolbul.2018.10.064.

Filiciotto, F., M. Vazzana, M. Celi, V. Maccarrone, M. Ceraulo, G. Buffa, V. Arizza, G. de Vincenzi, R. Grammauta, et al. 2016. Underwater noise from boats: Measurement of its influence on the behaviour and biochemistry of the common prawn (*Palaemon serratus*, Pennant 1777). *Journal of Experimental Marine Biology and Ecology* 478: 24-33. https://doi.org/10.1016/j.jembe.2016.01.014.

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.

Fletcher, S., B.J. Le Boeuf, D.P. Costa, P.L. Tyack, and S.B. Blackwell. 1996. Onboard acoustic recording from diving northern elephant seals. *Journal of the Acoustical Society of America* 100(4): 2531-2539. https://doi.org/10.1121/1.417361.

Foote, A.D., R.W. Osborne, and A.R. Hoelzel. 2004. Whale-call response to masking boat noise. *Nature* 428(6986): 910. https://doi.org/10.1038/428910a.

Frankel, A.S. and C.W. Clark. 2002. ATOC and other factors affecting the distribution and abundance of humpback whales (*Megaptera novaeangliae*) off the north shore of Kauai. *Marine Mammal Science* 18(3): 644-662. https://doi.org/10.1111/j.1748-7692.2002.tb01064.x.

Frankel, A.S., W.T. Ellison, and J. Buchanan. 2002. Application of the acoustic integration model (AIM) to predict and minimize environmental impacts. *OCEANS 2002*. 29-31 Oct 2002. IEEE, Biloxi, MI, USA. pp. 1438-1443. https://doi.org/10.1109/OCEANS.2002.1191849.

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.

Gales, R.S. 1982. *Effects of noise of offshore oil and gas operations on marine mammals - An introductory assessment*. US Naval Ocean Systems Centre, NOSC TR 844, 2 vol. NTIS AD-A123699 & AD-A123700, San Diego, CA, USA. https://apps.dtic.mil/dtic/tr/fulltext/u2/a123700.pdf.

GEBCO Bathymetric Compilation Group. 2020. The GEBCO_2020 Grid - a continuous terrain model of the global oceans and land. British Oceanographic Data Centre, National Oceanography Centre. https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2020/.

Gedamke, J., J. Harrison, L.T. Hatch, R.P. Angliss, J.P. Barlow, C.L. Berchok, C. Caldow, M. Castellote, D.M. Cholewiak, et al. 2016. *Ocean noise strategy roadmap*. National Oceanic and Atmospheric Administration, Washington, DC. https://cetsound.noaa.gov/Assets/cetsound/documents/Roadmap/ONS_Roadmap_Final_Complete.pdf.

Geo-Marine. 2010. *Ocean/Wind Power Ecological Baseline Studies: January 2008 – December 2009. Final Report*. Volume III: Marine Mammal and Sea Turtle Studies. Report by Geo-Marine, Inc. for the New Jersey Department of Environmental Protection, Office of Science. https://tethys.pnnl.gov/sites/default/files/publications/Ocean-Wind-Power-Baseline-Volume3.pdf.

Goldbogen, J.A., B.L. Southall, S.L. Deruiter, J. Calambokidis, A.S. Friedlaender, E.L. Hazen, E.A. Falcone, G.S. Schorr, A. Douglas, et al. 2013. Blue whales respond to simulated mid-frequency military sonar. *Proceedings of the Royal Society B* 280(1765): 1-8. https://doi.org/10.1098/rspb.2013.0657.

Greene, C.R., Jr. 1987. Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. *Journal of the Acoustical Society of America* 82(4): 1315–1324. https://doi.org/10.1121/1.395265.

Hall, J.D. and J. Francine. 1991. Measurements of underwater sounds from a concrete island drilling structure located in the Alaskan sector of the Beaufort Sea. *Journal of the Acoustical Society of America* 90(3): 1665-1667. https://doi.org/10.1121/1.401907.

Halvorsen, M.B. and K.D. Heaney. 2018. *Propagation characteristics of high-resolution geophysical surveys: open water testing*. Prepared by CSA Ocean Sciences Inc. for U.S. Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2018-052. 806 p.

Handegard, N.O., K. Michalsen, and D. Tjøstheim. 2003. Avoidance behaviour in cod (*Gadus morhua*) to a bottom-trawling vessel. *Aquatic Living Resources* 16(3): 265-270. https://doi.org/10.1016/S0990-7440(03)00020-2.

Hannay, D.E. and R. Racca. 2005. *Acoustic Model Validation*. Document Number 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.

Hastie, G.D., D.J.F. Russell, P. Lepper, J. Elliott, B. Wilson, S. Benjamins, and D. Thompson. 2018. Harbour seals avoid tidal turbine noise: Implications for collision risk. *Journal of Applied Ecology* 55(2): 684-693. https://doi.org/10.1111/1365-2664.12981.

Hatch, L.T., C.W. Clark, S.M. Van Parijs, A.S. Frankel, and D.W. Ponirakis. 2012. Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conservation Biology* 26(6): 983-994. https://doi.org/10.1111/j.1523-1739.2012.01908.x.

Hawkins, A.D., A.E. Pembroke, and A.N. Popper. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. *Reviews in Fish Biology and Fisheries* 25(1): 39-64. https://doi.org/10.1007/s11160-014-9369-3.

Hawkins, A.D. and A.N. Popper. 2017. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. *ICES Journal of Marine Science* 74(3): 635-651. https://doi.org/10.1093/icesjms/fsw205.

Holmes, L.J., J. McWilliam, M.C.O. Ferrari, and M.I. McCormick. 2017. Juvenile damselfish are affected but desensitize to small motor boat noise. *Journal of Experimental Marine Biology and Ecology* 494: 63-68. https://doi.org/10.1016/j.jembe.2017.05.009.

Holt, M.M., D.P. Noren, V. Veirs, C.K. Emmons, and S. Veirs. 2009. Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *Journal of the Acoustical Society of America* 125(1): EL27-EL32. https://doi.org/10.1121/1.3040028.

Houser, D.S. and M.J. Cross. 1999. *Marine Mammal Movement and Behavior (3MB): A Component of the Effects of Sound on the Marine Environment (ESME) Distributed Model*. Version 8.08, by BIOMIMETICA.

Houser, D.S., D.A. Helweg, and P.W.B. Moore. 2001. A bandpass filter-bank model of auditory sensitivity in the humpback whale. *Aquatic Mammals* 27(2): 82-91. https://www.aquaticmammalsjournal.org/share/AquaticMammalsIssueArchives/2001/AquaticMammals_27-02/27-02_Houser.PDF.

Houser, D.S. 2006. A method for modeling marine mammal movement and behavior for environmental impact assessment. *IEEE Journal of Oceanic Engineering* 31(1): 76-81. https://doi.org/10.1109/JOE.2006.872204.

Houser, D.S., S.W. Martin, and J.J. Finneran. 2013. Behavioral responses of California sea lions to mid-frequency (3250–3450 Hz) sonar signals. *Marine Environmental Research* 92: 268-278.

Houser, D.S. and M.J. Cross. 2014. *Marine Mammal Movement and Behavior (3MB) User Manual*. National Marine Mammal Foundation (NMFS), San Diego, CA. 46 p.

Houser, D.S., S.W. Martin, and J.J. Finneran. 2016. Risk functions of dolphins and sea lions exposed to sonar signals. *In The Effects of Noise on Aquatic Life II*. Springer. pp. 473-478.

Hubbard, H.H. 1991. *Aeroacoustics of Flight Vehicles: Theory and Practice*. Volume 2: Noise Control. NASA reference publication 1258, WRDC Technical report 90-3052. https://apps.dtic.mil/sti/pdfs/ADA241142.pdf.

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 Number P1049-1. 277 p.

Jesus, S.M., F.C. Xavier, R.P. Vio, J. Osowsky, M.V.S. Simões, and E.B.F. Netto. 2020. Particle motion measurements near a rocky shore off Cabo Frio Island. *Journal of the Acoustical Society of America* 147(6): 4009-4019. https://doi.org/10.1121/10.0001392.

Jones, I.T., J.A. Stanley, and T.A. Mooney. 2020. Impulsive pile driving noise elicits alarm responses in squid (*Doryteuthis pealeii*). *Marine Pollution Bulletin* 150: 110792. https://doi.org/10.1016/j.marpolbul.2019.110792.

Jones, I.T., J.F. Peyla, H. Clark, Z. Song, J.A. Stanley, and T.A. Mooney. 2021. Changes in feeding behavior of longfin squid (Doryteuthis pealeii) during laboratory exposure to pile driving noise. *Marine Environmental Research* 165: 105250.

Kastelein, R.A. 2008. Effects of vibrations on the behaviour of cockles (bivalve molluscs). *Bioacoustics* 17(1-3): 74-75. https://doi.org/10.1080/09524622.2008.9753770.

Kipple, B. 2002. *Southeast Alaska Cruise Ship Underwater Acoustic Noise*. Document Number NSWCCD-71-TR-2002/574. Prepared by Naval Surface Warfare Center, Detachment Bremerton, for Glacier Bay National Park and Preserve. https://www.nps.gov/glba/learn/nature/upload/CruiseShipSoundSignaturesSEAFAC.pdf.

Kipple, B. and C. Gabriele. 2003. *Glacier Bay Watercraft Noise*. Document Number NSWCCD-71-TR-2003/522. Prepared by Naval Surface Warfare Center – Carderock Division for Glacier Bay National Park and Preserve. https://www.nps.gov/glba/learn/nature/upload/GBWatercraftNoiseRpt.pdf.

Kleĭnenberg, S.E.e., A.V. Yablokov, B.M. Belʹkovich, and M.N. Tarasevich. 1964. *Beluga (Delphinapterus leucas): Investigation of the species [Belukha; opyt monograficheskogo issledovaniya vida)]*. Israel Program for Scientific Translation (1st translated edition 1 Jan 1969), Jerusalem. 376 p. http://hdl.handle.net/2027/uc1.31822014463194.

Koschinski, S., B.M. Culik, O.D. Henriksen, N. Tregenza, G. Ellis, C. Jansen, and G. Kathe. 2003. Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. *Marine Ecology Progress Series* 265: 263-273. https://doi.org/10.3354/meps265263.

Koschinski, S. and K. Lüdemann. 2013. *Development of Noise Mitigation Measures in Offshore Wind Farm Construction*. Commissioned by the Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN). Original report (in German) published Jul 2011, updated Feb 2013, Nehmten and Hamburg, Germany. 97 p. https://www.bfn.de/fileadmin/MDB/documents/themen/meeresundkuestenschutz/downloads/Berichte-und-Positionspapiere/Mitigation-Measures-Underwater-Noise_2013-08-27_final.pdf.

Koski, W.R., G.W. Miller, and R.A. Davis. 1988. *The potential effects of tanker traffic on the bowhead whale in the Beaufort Sea*. Report from LGL Ltd. for Department of Indian Affairs & Northern Development. NTIS MIC-90-04552. 150 p.

Kraus, S.D., M.W. Brown, H. Caswell, C.W. Clark, M. Fujiwara, P.K. Hamilton, R.D. Kenney, A.R. Knowlton, S. Landry, et al. 2005. North Atlantic Right Whales in Crisis. *Science* 309(5734): 561-562. https://doi.org/10.1126/science.1111200.

Kraus, S.D., S. Leiter, K. Stone, B. Wikgren, C.A. Mayo, P. Hughes, R.D. Kenney, C.W. Clark, A.N. Rice, et al. 2016. *Northeast Large Pelagic Survey Collaborative Aerial and Acoustic Surveys for Large Whales and Sea Turtles*. US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2016-054, Sterling, Virginia. 117 + appendices p. https://www.boem.gov/RI-MA-Whales-Turtles/.

Kvadsheim, P.H., E.M. Sevaldsen, L.P. Folkow, and A.S. Blix. 2010. Behavioural and Physiological Responses of Hooded Seals (Cystophora cristata) to 1 to 7 kHz Sonar Signals. *Aquatic Mammals* 36(3).

Kvadsheim, P.H., S. DeRuiter, L.D. Sivle, J. Goldbogen, R. Roland-Hansen, P.J.O. Miller, F.-P.A. Lam, J. Calambokidis, A. Friedlaender, et al. 2017. Avoidance responses of minke whales to 1–4 kHz naval sonar. *Marine Pollution Bulletin* 121(1): 60-68. https://doi.org/10.1016/j.marpolbul.2017.05.037.

Ladich, F. and A.A. Myrberg, Jr. . 2006. Agonistic behavior and acoustic communication. (Chapter 5) *In* Ladich, F., S.P. Collin, P. Moller, and B.G. Kapoor (eds.). *Communication in fishes*. Volume 1. Science Publishers, Enfield, NH. pp. 121-148.

Lesage, V., C. Barrette, M.C.S. Kingsley, and B. Sjare. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science* 15(1): 65-84. https://doi.org/10.1111/j.1748-7692.1999.tb00782.x.

Lindeboom, H.J., H.J. Kouwenhoven, M.J.N. Bergman, S. Bouma, S. Brasseur, R. Daan, R.C. Fijn, D. de Haan, S. Dirksen, et al. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters* 6(3): 1-13. https://doi.org/10.1088/1748-9326/6/3/035101.

Lucke, K., P.A. Lepper, B. Hoeve, E. Everaarts, N. van Elk, and U. Siebert. 2007. Perception of low-frequency acoustic signals by a harbour porpoise (*Phocoena phocoena*) in the presence of simulated offshore wind turbine noise. *Aquatic Mammals* 33(1): 55-68. https://doi.org/10.1578/AM.33.1.2007.55.

Luksenburg, J. and E.C.M. Parsons. 2009. The effects of aircraft on cetaceans: implications for aerial whalewatching. *61st Meeting of the International Whaling Commission*. 8 Jun to 6 Jul 2012, Panama City.

Lusseau, D., D.E. Bain, R. Williams, and J.C. Smith. 2009. Vessel traffic disrupts the foraging behavior of southern resident killer whales *Orcinus orca*. *Endangered Species Research* 6(3): 211-221. https://doi.org/10.3354/esr00154.

MacGillivray, A.O. and N.R. Chapman. 2012. Modeling underwater sound propagation from an airgun array using the parabolic equation method. *Canadian Acoustics* 40(1): 19-25. https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2502/2251.

MacGillivray, A.O. 2014. A model for underwater sound levels generated by marine impact pile driving. *Proceedings of Meetings on Acoustics* 20(1). https://doi.org/10.1121/2.0000030

MacGillivray, A.O. 2018. Underwater noise from pile driving of conductor casing at a deep-water oil platform. *Journal of the Acoustical Society of America* 143(1): 450-459. https://doi.org/10.1121/1.5021554.

Madsen, P.T., M. Wahlberg, J. Tougaard, K. Lucke, and P.L. Tyack. 2006. Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. *Marine Ecology Progress Series* 309: 279-295. https://www.int-res.com/abstracts/meps/v309/p279-295/.

Malme, C.I., P.R. Miles, C.W. Clark, P.L. Tyack, and J.E. Bird. 1983. *Investigations of the Potential Effects of Underwater Noise from Petroleum Industry Activities on Migrating Gray Whale Behavior. Final Report for the Period of 7 June 1982 - 31 July 1983*. Report Number 5366. Report by Bolt Beranek and Newman Inc. for US Department of the Interior, Minerals Management Service, Alaska OCS Office, Cambridge, MA, USA. https://www.boem.gov/sites/default/files/boem-newsroom/Library/Publications/1983/rpt5366.pdf.

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 Number 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.

Marley, S.A., C.P. Salgado Kent, C. Erbe, and I.M. Parnum. 2017. Effects of vessel traffic and underwater noise on the movement, behaviour and vocalisations of bottlenose dolphins in an urbanised estuary. *Scientific Reports* 7: 13437. https://doi.org/10.1038/s41598-017-13252-z.

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.

Martin, B., J.T. MacDonnell, and K. Bröker. 2017a. Cumulative sound exposure levels—Insights from seismic survey measurements. *Journal of the Acoustical Society of America* 141(5): 3603-3603. https://doi.org/10.1121/1.4987709.

Martin, S.B. and A.N. Popper. 2016. Short- and long-term monitoring of underwater sound levels in the Hudson River (New York, USA). *Journal of the Acoustical Society of America* 139(4): 1886-1897. https://doi.org/10.1121/1.4944876.

Martin, S.B., M.-N.R. Matthews, J.T. MacDonnell, and K. Bröker. 2017b. Characteristics of seismic survey pulses and the ambient soundscape in Baffin Bay and Melville Bay, West Greenland. *Journal of the Acoustical Society of America* 142(6): 3331-3346. https://doi.org/10.1121/1.5014049.

Matthews, M.-N.R. and A.O. MacGillivray. 2013. Comparing modeled and measured sound levels from a seismic survey in the Canadian Beaufort Sea. *Proceedings of Meetings on Acoustics* 19(1): 1-8. https://doi.org/10.1121/1.4800553.

McCauley, R.D. 1994. *The Environmental Implications of Offshore Oil and Gas Development in Australia - Seismic Surveys*. *In*: Neff, J.M. and P.C. Young (eds.). Environmental Implications of Offshore Oil and Gas Develpment in Australia - The Findings of an Independent Scientific Review Swan. Australian Petroleum Exploration Association, Sydney. 19-122 p.

McCauley, R.D. 1998. *Radiated underwater noise measured from the drilling rig Ocean General, rig tenders Pacific Ariki and Pacific Frontier, fishing vessel Reef Venture and natural sources in the Timor Sea, northern Australia*. Report Number C98-20. Report by Centre for Marine Science and Technology (CMST) for Shell Australia. https://cmst.curtin.edu.au/wp-content/uploads/sites/4/2016/05/1998-19.pdf.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, et al. 2000a. Marine seismic surveys: A study of environmental implications. *Australian Petroleum Production Exploration Association (APPEA) Journal* 40(1): 692-708. https://doi.org/10.1071/AJ99048.

McCauley, R.D., J. Fewtrell, A.J. Duncan, C. Jenner, M.-N. Jenner, J.D. Penrose, R.I.T. Prince, A. Adhitya, J. Murdoch, et al. 2000b. *Marine seismic surveys: Analysis and propagation of air-gun signals; and effects of air-gun exposure on humpback whales, sea turtles, fishes and squid*. Report Number R99-15. Prepared for Australian Petroleum Production Exploration Association by Centre for Maine Science and Technology, Western Australia. 198 p. https://cmst.curtin.edu.au/wp-content/uploads/sites/4/2016/05/McCauley-et-al-Seismic-effects-2000.pdf.

McCrodan, A., C.R. McPherson, and D.E. Hannay. 2011. *Sound Source Characterization (SSC) Measurements for Apache's 2011 Cook Inlet 2D Technology Test*. Version 3.0. Technical report by JASCO Applied Sciences for Fairweather LLC and Apache Corporation. 51 p.

McKenna, M.F., D. Ross, S.M. Wiggins, and J.A. Hildebrand. 2012. Underwater radiated noise from modern commercial ships. *Journal of the Acoustical Society of America* 131(1): 92-103. https://doi.org/10.1121/1.3664100.

McPherson, C.R. and G.A. Warner. 2012. *Sound Sources Characterization for the 2012 Simpson Lagoon OBC Seismic Survey 90-Day Report*. Document Number 00443, Version 2.0. Technical report by JASCO Applied Sciences for BP Exploration (Alaska) Inc. http://www.nmfs.noaa.gov/pr/pdfs/permits/bp_openwater_90dayreport_appendices.pdf.

McPherson, C.R., K. Lucke, B.J. Gaudet, S.B. Martin, and C.J. Whitt. 2018. *Pelican 3-D Seismic Survey Sound Source Characterisation*. Document Number 001583. Version 1.0. Technical report by JASCO Applied Sciences for RPS Energy Services Pty Ltd.

McPherson, C.R. and B. Martin. 2018. *Characterisation of Polarcus 2380 in^3 Airgun Array*. Document Number 001599, Version 1.0. Technical report by JASCO Applied Sciences for Polarcus Asia Pacific Pte Ltd.

McQueen, A.D., B.C. Suedel, C.A.F. de Jong, and F. Thomsen. 2020. Ecological risk assessment of underwater sounds from dredging operations. *Integrated Environmental Assessment and Management* 16(4): 481-493. https://doi.org/10.1002/ieam.4261.

McQueen, A.D.S., Burton C; Wilkens, Justin L. 2019. Review of the adverse biological effects of dredging-induced underwater sounds. *WEDA Journal of Dredging* 17(1): 1-22.

Mikkelsen, L., M.P. Johnson, D.M. Wisniewska, A. van Neer, U. Siebert, P.T. Madsen, and J. Teilmann. 2019. Long-term sound and movement recording tags to study natural behavior and reaction to ship noise of seals. *Ecology and Evolution* 9(5): 2588-2601. https://doi.org/10.1002/ece3.4923.

Miller, G.W., V.D. Moulton, R.A. Davis, M. Holst, P. Millman, A.O. MacGillivray, and D.E. Hannay. 2005. Monitoring seismic effects on marine mammals—southeastern Beaufort Sea, 2001-2002. *In* Armsworthy, S.L., P.J. Cranford, and K. Lee (eds.). *Offshore oil and gas environmental effects monitoring/Approaches and technologies*. Battelle Press, Columbus, OH, USA. pp. 511-542.

Miller, J.H. and G.R. Potty. 2017. Overview of underwater acoustic and seismic measurements of the construction and operation of the Block Island Wind Farm. *Journal of the Acoustical Society of America* 141(5): 3993-3993. https://doi.org/10.1121/1.4989144.

Miller, P.J.O., P.H. Kvadsheim, F.-P.A. Lam, P.L. Tyack, C. Curé, S.L. DeRuiter, L. Kleivane, L.D. Sivle, S.P. van IJsselmuide, et al. 2015. First indications that northern bottlenose whales are sensitive to behavioural disturbance from anthropogenic noise. *Royal Society Open Science* 2(6): 140484. https://doi.org/10.1098/rsos.140484.

Mitson, R.B. and H.P. Knudsen. 2003. Causes and effects of underwater noise on fish abundance estimation. *Aquatic Living Resources* 16(3): 255-263. https://doi.org/10.1016/S0990-7440(03)00021-4.

Mooney, T.A., J.E. Samson, A.D. Schlunk, and S. Zacarias. 2016. Loudness-dependent behavioral responses and habituation to sound by the longfin squid (*Doryteuthis pealeii*). *Journal of Comparative Physiology A* 202(7): 489-501. https://doi.org/10.1007/s00359-016-1092-1.

Mosher, J.I. 1972. The responses of *Macoma balthica* (bivalvia) to vibrations. *Journal of Molluscan Studies* 40(2): 125-131. https://doi.org/10.1093/oxfordjournals.mollus.a065209.

Moulton, V.D., W.J. Richardson, M.T. Williams, and S.B. Blackwell. 2003. Ringed seal densities and noise near an icebound artificial island with construction and drilling. *Acoustics Research Letters Online* 4: 112-117. https://doi.org/10.1121/1.1605091.

Mueller-Blenkle, C., P.K. McGregor, A.B. Gill, M.H. Andersson, J. Metcalfe, V. Bendall, P. Sigray, D.T. Wood, and F. Thomsen. 2010. *Effects of Pile-driving Noise on the Behaviour of Marine Fish*. COWRIE Ref: Fish 06-08; Cefas Ref: C3371. 62 p. https://dspace.lib.cranfield.ac.uk/handle/1826/8235.

Myrberg, A.A., Jr. and M. Lugli. 2006. Reproductive behavior and acoustical interactions *In* Ladich, F., S.P. Collin, P. Moller, and B.G. Kapoor (eds.). *Communication in fishes*. Volume 1. Science Publishers, Enfield, NH. pp. 149-176.

Nedelec, S.L., A.N. Radford, S.D. Simpson, B. Nedelec, D. Lecchini, and S.C. Mills. 2014. Anthropogenic noise playback impairs embryonic development and increases mortality in a marine invertebrate. *Scientific Reports* 4(5891): 1-4. https://doi.org/10.1038/srep05891.

Nedelec, S.L., S.C. Mills, D. Lecchini, B. Nedelec, S.D. Simpson, and A.N. Radford. 2016. Repeated exposure to noise increases tolerance in a coral reef fish. *Environmental Pollution* 216: 428-436. https://doi.org/10.1016/j.envpol.2016.05.058.

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. and B. Edwards. 2004. *A review of measurements of underwater man-made noise carried out by Subacoustech Ltd, 1993 – 2003*. Document Number 534R0109. Report by Subacoustech Ltd. for ChevronTexaco Ltd., TotalFinaElf Exploration UK PLC, DSTL, Department of Trade and Industry, and Shell U.K. Exploration and Production Ltd. 131 p. http://www.subacoustech.com/information/downloads/reports/534R0109.pdf.

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 Number 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.

Nehls, G., A. Rose, A. Diederichs, M.A. Bellmann, and H. Pehlke. 2016. Noise Mitigation During Pile Driving Efficiently Reduces Disturbance of Marine Mammals. (Chapter 92) *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Volume 875. Springer, NY, USA. pp. 755-762. https://doi.org/10.1007/978-1-4939-2981-8_92.

Nguyen, J.-P. 1996. *Drilling: Oil and gas field development techniques*. Balvet, B.B. (trans.). Editions TECHNIP. Institut Français du Pétrole, Paris. 384 p.

Noren, D.P., A.H. Johnson, D. Rehder, and A. Larson. 2009. Close approaches by vessels elicit surface active behaviors by southern resident killer whales. *Endangered Species Research* 8: 179-192. https://doi.org/10.3354/esr00205

Normandeau Associates, Inc. 2012. *Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities*. A Workshop Report for the US Department of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 361 p. https://www.cbd.int/doc/meetings/mar/mcbem-2014-01/other/mcbem-2014-01-submission-boem-04-en.pdf.

Normandeau Associates, Inc. and APEM Inc. 2018a. *Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy: Summer 2018 Taxonomic Analysis Summary Report*. Report by Normandeau Associates, Inc. and APEM Inc. for New York State Energy Research and Development Authority. https://remote.normandeau.com/docs/NYSERDA_Summer_2018_Taxonomic_Analysis_Summary_Report.pdf.

Normandeau Associates, Inc. and APEM Inc. 2018b. *Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy: Spring 2018 Taxonomic Analysis Summary Report*. Report by Normandeau Associates, Inc. and APEM Inc. for New York State Energy Research and Development Authority. https://remote.normandeau.com/docs/NYSERDA_Spring_2018_Taxonomic_Analysis_Summary_Report.pdf.

Normandeau Associates, Inc. and APEM Inc. 2019a. *Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy: Spring 2019 Taxonomic Analysis Summary Report*. Report by Normandeau Associates, Inc. and APEM Inc. for New York State Energy Research and Development Authority. https://remote.normandeau.com/docs/NYSERDA_Spring_2019_Taxonomic_Analysis_Summary_Report.pdf.

Normandeau Associates, Inc. and APEM Inc. 2019b. *Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy: Fall 2018 Taxonomic Analysis Summary Report*. Report by Normandeau Associates, Inc. and APEM Inc. for New York State Energy Research and Development Authority. https://remote.normandeau.com/docs/NYSERDA_Fall_2018_Taxonomic_Analysis_Summary_Report.pdf.

Normandeau Associates, Inc. and APEM Inc. 2020. *Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy: Winter 2018-2019 Taxonomic Analysis Summary Report*. Report by Normandeau Associates, Inc. and APEM Inc. for New York State Energy Research and Development Authority. https://remote.normandeau.com/docs/NYSERDA_Winter_2018_19_Taxonomic_Analysis_Summary_Report.pdf.

Nowacek, D.P., M.P. Johnson, and P.L. Tyack. 2004. North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. *Proceedings of the Royal Society B* 271(1536): 227-231. https://doi.org/10.1098/rspb.2003.2570.

Nowacek, D.P., L.H. Thorne, D.W. Johnston, and P.L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. *Mammal Review* 37(2): 81-115. https://doi.org/10.1111/j.1365-2907.2007.00104.x.

O'Hara, J. and J.R. Wilcox. 1990. Avoidance responses of loggerhead turtles, *Caretta caretta*, to low frequency sound. *Copeia* 2: 564-567. https://doi.org/10.2307/1446362.

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.

Olsen, K., J. Agnell, F. Pettersen, and A. Løvik. 1983. Observed fish reactions to a surveying vessel with special reference to herring, cod, capelin and polar cod. *Symposium of Fisheries Acoutics*. FAO Fisheries Reports No. 300, Bergen, Norway. pp. 131-138.

Ona, E., O.R. Godø, N.O. Handegard, V. Hjellvik, R. Patel, and G. Pedersen. 2007. Silent research vessels are not quiet. *Journal of the Acoustical Society of America* 121(4): EL145-EL150. https://doi.org/10.1121/1.2710741.

Pangerc, T., P.D. Theobald, L.S. Wang, S.P. Robinson, and P.A. Lepper. 2016. Measurement and characterisation of radiated underwater sound from a 3.6 MW monopile wind turbine. *Journal of the Acoustical Society of America* 140(4): 2913-2922. https://doi.org/10.1121/1.4964824.

Parks, S.E., C.W. Clark, and P.L. Tyack. 2007. Short-and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication. *Journal of the Acoustical Society of America* 122(6): 3725-3731. https://doi.org/10.1121/1.2799904.

Patenaude, N.J., W.J. Richardson, M.A. Smultea, W.R. Koski, G.W. Miller, B. Würsig, and C.R. Greene, Jr. 2002. Aircraft sound and disturbance to bowhead and beluga whales during spring migration in the alaskan Beaufort sea. *Marine Mammal Science* 18(2): 309-335. https://doi.org/10.1111/j.1748-7692.2002.tb01040.x.

Pile Dynamics, Inc. 2010. GRLWEAP. https://www.pile.com/.

Pine, M.K., A.G. Jeffs, and C.A. Radford. 2012. Turbine sound may influence the metamorphosis behaviour of estuarine crab Megalopae. *PLOS ONE* 7(12). https://doi.org/10.1371/journal.pone.0051790.

Pirotta, E., R. Milor, N. Quick, D. Moretti, N. Di Marzio, P.L. Tyack, I. Boyd, and G. Hastie. 2012. Vessel noise affects beaked whale behavior: Results of a dedicated acoustic response study. *PLOS ONE* 7(8). https://doi.org/10.1371/journal.pone.0042535.

Pirotta, E., B.E. Laesser, A. Hardaker, N. Riddoch, M. Marcoux, and D. Lusseau. 2013. Dredging displaces bottlenose dolphins from an urbanised foraging patch. *Marine Pollution Bulletin* 74(1): 396-402. https://doi.org/10.1016/j.marpolbul.2013.06.020.

Polacheck, T. and L. Thorpe. 1990. The swimming direction of harbor porpoise in relationship to a survey vessel. *Report for the International Whaling Commission* 40: 463-470.

Popper, A.N. and R.R. Fay. 1993. Sound detection and processing by Fish: Critical review and major research questions. *Brain, Behavior and Evolution* 41(1): 14-25. https://doi.org/10.1159/000113821.

Popper, A.N. and M.C. Hastings. 2009. The effects of human-generated sound on fish. *Integrative Zoology* 4(1): 43-52. https://doi.org/10.1111/j.1749-4877.2008.00134.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.

Popper, A.N. and A.D. Hawkins. 2018. The importance of particle motion to fishes and invertebrates. *Journal of the Acoustical Society of America* 143(1): 470-488. https://doi.org/10.1121/1.5021594.

Popper, A.N. and A.D. Hawkins. 2019. An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes (Review Paper). *Journal of Fish Biology* 94(5): 692-713. https://doi.org/10.1111/jfb.13948.

Purser, J. and A.N. Radford. 2011. Acoustic noise induces attention shifts and reduces foraging performance in three-spined sticklebacks (*Gasterosteus aculeatus*). *PLOS ONE* 6(2): e17478. https://doi.org/10.1371/journal.pone.0017478.

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.

Racca, R., M.E. Austin, A.N. Rutenko, and K. Bröker. 2015. Monitoring the gray whale sound exposure mitigation zone and estimating acoustic transmission during a 4-D seismic survey, Sakhalin Island, Russia. *Endangered Species Research* 29(2): 131-146. https://doi.org/10.3354/esr00703.

Reichmuth, C., J. Mulsow, J.J. Finneran, D.S. Houser, and A.Y. Supin. 2007. Measurement and Response Characteristics of Auditory Brainstem Responses in Pinnipeds. *Aquatic Mammals* 33(1): 132-150. https://doi.org/10.1578/AM.33.1.2007.132.

Richardson, W.J., M.A. Fraker, B. Würsig, and R.S. Wells. 1985a. Behaviour of Bowhead Whales Balaena mysticetus summering in the Beaufort Sea: Reactions to industrial activities. *Biological Conservation* 32(3): 195-230. https://doi.org/10.1016/0006-3207(85)90111-9.

Richardson, W.J., R.S. Wells, and B. Würsig. 1985b. Disturbance responses of bowheads, 1980-84. *In* Richardson, W.J. (ed.). *Behavior, disturbance responses and distribution of bowhead whales Balaena mysticetus in the eastern Beaufort Sea, 1980-84*. Report by LGL Ecological Research Associates, Inc. and US Minerals Managment Service. OCS Study MMS 85-0034. pp. 89-196.

Richardson, W.J., B. Würsig, and C.R. Greene, Jr. 1986. Reactions of bowhead whales, *Balaena mysticetus*, to seismic exploration in the Canadian Beaufort Sea. *Journal of the Acoustical Society of America* 79(4): 1117-1128. https://doi.org/10.1121/1.393384.

Richardson, W.J., C.R. Greene, W.R. Koski, C. Malme, and G. Miller. 1990a. Acoustic effects of oil-production activities on bowhead and white whales visible during spring migration near Pt. Barrow, Alaska-1989 phase: Sound propagation and whale responses to playbacks of continuous drilling noise from an ice platform, as studied in pack ice conditions. Final report.

Richardson, W.J., B. Würsig, and C.R. Greene, Jr. 1990b. Reactions of bowhead whales, *Balaena mysticetus*, to drilling and dredging noise in the Canadian Beaufort Sea. *Marine Environmental Research* 29(2): 135-160. https://doi.org/10.1016/0141-1136(90)90032-J.

Richardson, W.J. and C.I. Malme. 1993. Man-made noise and behavioral responses *In* Burnes, J.J., J.J. Montague, and C.J. Cowles (eds.). *The Bowhead Whale*. 1st edition. Society for Marine Mammalogy. pp. 631-700.

Richardson, W.J., C.R. Greene, Jr., C.I. Malme, and D.H. Thomson. 1995. *Marine Mammals and Noise*. Academic Press, San Diego, CA, USA. 576 p. https://doi.org/10.1016/C2009-0-02253-3.

Richardson, W.J. and B. Würsig. 1997. Influences of man-made noise and other human actions on cetacean behaviour. *Marine and Freshwater Behaviour and Physiology* 29(1-4): 183-209. https://doi.org/10.1080/10236249709379006.

Richardson, W.J., G.W. Miller, and C.R. Greene, Jr. 1999. Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea. *Journal of the Acoustical Society of America* 106(4): 2281-2281. https://doi.org/10.1121/1.427801.

Richter, C., S. Dawson, and E. Slooten. 2006. Impacts of commercial whale watching on male sperm whales at Kaikoura, New Zealand. *Marine Mammal Science* 22(1): 46-63. https://doi.org/10.1111/j.1748-7692.2006.00005.x.

Richter, C.F., S. Dawson, and E. Slooten. 2003. *Sperm whale watching off Kaikoura, New Zealand: Effects of current activities on surfacing and vocalisation patterns*, Volume 219. Department of Conservation, Wellington, NZ. https://www.doc.govt.nz/documents/science-and-technical/SFC219.pdf.

Ridgway, S.H., E.G. Wever, J.G. McCormick, J. Palin, and J.H. Anderson. 1969. Hearing in the giant sea turtle, *Chelonia mydas*. *Proceedings of the National Academy of Sciences of the United States of America* 64(3): 884-890. https://doi.org/10.1073/pnas.64.3.884.

Roberts, J.J., B.D. Best, L. Mannocci, P.N. Halpin, D.L. Palka, L.P. Garrison, K.D. Mullin, T.V.N. Cole, and W.M. McLellan. 2015a. *Density Model for Seals (Phocidae) Along the U.S. East Coast, Preliminary Results*. Version 3.2. Marine Geospatial Ecology Lab, Duke University, Durham, NC.

Roberts, J.J., B.D. Best, L. Mannocci, E. Fujioka, P.N. Halpin, D.L. Palka, L.P. Garrison, K.D. Mullin, T.V.N. Cole, et al. 2016a. Habitat-based cetacean density models for the U.S. Atlantic and Gulf of Mexico. *Scientific Reports* 6. https://doi.org/10.1038/srep22615.

Roberts, J.J., L. Mannocci, and P.N. Halpin. 2016b. *Final Project Report: Marine Species Density Data Gap Assessments and Update for the AFTT Study Area, 2015-2016 (Base Year)*. Version 1.0. Report by the Duke University Marine Geospatial Ecology Lab for Naval Facilities Engineering Command, Atlantic Durham, NC, USA.

Roberts, J.J., L. Mannocci, and P.N. Halpin. 2017. *Final Project Report: Marine Species Density Data Gap Assessments and Update for the AFTT Study Area, 2016-2017 (Opt. Year 1)*. Version 1.4. Report by Duke University Marine Geospatial Ecology Lab for Naval Facilities Engineering Command, Atlantic, Durham, NC, USA.

Roberts, J.J., L. Mannocci, R.S. Schick, and P.N. Halpin. 2018. *Final Project Report: Marine Species Density Data Gap Assessments and Update for the AFTT Study Area, 2017-2018 (Opt. Year 2)*. Version 1.2. Report by the Duke University Marine Geospatial Ecology Lab for Naval Facilities Engineering Command, Atlantic Durham, NC, USA.

Roberts, J.J., R.S. Schick, and P.N. Halpin. 2020. *Final Project Report: Marine Species Density Data Gap Assessments and Update for the AFTT Study Area, 2018-2020 (Opt. Year 3)*. Version 1.4. Report by the Duke University Marine Geospatial Ecology Lab for Naval Facilities Engineering Command, Atlantic Durham, NC, USA.

Roberts, L., S. Cheesman, T. Breithaupt, and M. Elliott. 2015b. Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically generated noise. *Marine Ecology Progress Series* 538: 185-195. https://doi.org/10.3354/meps11468.

Roberts, L. and T. Breithaupt. 2016. Sensitivity of crustaceans to substrate-borne vibration. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Volume 875. Springer, New York. pp. 925-931. https://doi.org/10.1007/978-1-4939-2981-8_114.

Roberts, L. and M. Elliott. 2017. Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos. *Science of The Total Environment* 595: 255-268. https://doi.org/10.1016/j.scitotenv.2017.03.117.

Robinson, S.P., P.D. Theobald, G. Hayman, L.-S. Wang, P.A. Lepper, V.F. Humphrey, and S. Mumford. 2011. *Measurement of Underwater Noise Arising from Marine Aggregate Dredging Operations: Final Report*. Document Number 09/P108. Marine Environment Protection Fund (MEPF). https://webarchive.nationalarchives.gov.uk/20140305134555/http://cefas.defra.gov.uk/alsf/projects/direct-and-indirect-effects/09p108.aspx.

Rogers, P.H., A.D. Hawkins, A.N. Popper, R.R. Fay, and M.D. Gray. 2016. Parvulescu Revisited: Small Tank Acoustics for Bioacousticians. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life II*. Springer, New York. pp. 933-941. https://doi.org/10.1007/978-1-4939-2981-8_115.

Sand, O. 2008. Detection of sound by fish: A minireview. *Bioacoustics* 17: 92-95. https://doi.org/10.1080/09524622.2008.9753778.

Sarà, G., J.M. Dean, D. D'Amato, G. Buscaino, A. Oliveri, S. Genovese, S. Ferro, G. Buffa, M. Lo Martire, et al. 2007. Effect of boat noise on the behaviour of bluefin tuna *Thunnus thynnus* in the Mediterranean Sea. *Marine Ecology Progress Series* 331: 243-253. https://www.int-res.com/abstracts/meps/v331/p243-253/.

Schlesinger, A., M.-N.R. Matthews, Z. Li, J.E. Quijano, and D.E. Hannay. 2016. *Aurora LNG Acoustic Study: Modelling of Underwater Sounds from Pile Driving, Rock Socket Drilling, and LNG Carrier Berthing and Transiting*. Document Number 01134, Version 3.0. Technical report by JASCO Applied Sciences for Stantec Consulting Ltd. https://projects.eao.gov.bc.ca/api/document/58923174b637cc02bea163f1/fetch/Appendix_P_Acoustic_Modelling_Final_screening.pdf.

Schwarz, A.L. and G.L. Greer. 1984. Responses of Pacific Herring, *Clupea harengus pallasi*, to Some Underwater Sounds. *Canadian Journal of Fisheries and Aquatic Sciences* 41(8): 1183-1192. https://doi.org/10.1139/f84-140.

Shell Gulf of Mexico Inc. 2015. *Marine Mammal Monitoring and Mitigation Plan: Exploration Drilling of Selected Lease Areas in The Alaskan Chukchi Sea*. 30 p. http://www.nmfs.noaa.gov/pr/permits/incidental/oilgas/shell_2015_revised4mp.pdf.

Sigray, P. and M.H. Andersson. 2012. Underwater Particle Acceleration Induced by a Wind Turbine in the Baltic Sea. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 489-492. https://doi.org/10.1007/978-1-4419-7311-5_111.

Sills, J.M., B.L. Southall, and C. Reichmuth. 2014. Amphibious hearing in spotted seals (*Phoca largha*): Underwater audiograms, aerial audiograms and critical ratio measurements. *Journal of Experimental Biology* 217(5): 726-734. https://doi.org/10.1242/jeb.097469.

Sivle, L.D., P.H. Kvadsheim, C. Curé, S. Isojunno, P.J. Wensveen, F.-P.A. Lam, F. Visser, L. Kleivanec, P.L. Tyack, et al. 2015. Severity of Expert-Identified Behavioural Responses of Humpback Whale, Minke Whale, and Northern Bottlenose Whale to Naval Sonar. *Aquatic Mammals* 41(4). https://doi.org/10.1578/AM.41.4.2015.469.

Sivle, L.D., P.J. Wensveen, P.H. Kvadsheim, F.-P.A. Lam, F. Visser, C. Curé, C.M. Harris, P.L. Tyack, and P.J.O. Miller. 2016. Naval sonar disrupts foraging in humpback whales. *Marine Ecology Progress Series* 562: 211-220. https://doi.org/10.3354/meps11969.

Smultea, M.A., J.R. Mobley, Jr., D. Fertl, and G.L. Fulling. 2008. An unusual reaction and other observations of sperm whales near fixed-wing aircraft. *Gulf and Caribbean Research* 20(1): 75-80. https://doi.org/10.18785/gcr.2001.10.

Solan, M., C. Hauton, J.A. Godbold, C.L. Wood, T.G. Leighton, and P. White. 2016. Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. *Scientific Reports* 6: 20540. https://doi.org/10.1038/srep20540.

Solé, M., P. Sigray, M. Lenoir, M. Van Der Schaar, E. Lalander, and M. André. 2017. Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma. *Scientific Reports* 7: 45899. https://doi.org/10.1038/srep45899.

Soria, M., P. Fréon, and F. Gerlotto. 1996. Analysis of vessel influence on spatial behaviour of fish schools using a multi-beam sonar and consequences for biomass estimates by echo-sounder. *ICES Journal of Marine Science* 53(2): 453-458. https://doi.org/10.1006/jmsc.1996.0064.

Southall, B.L. 2005. *Shipping noise and marine mammals: A forum for science, management, and technology*. *Final Report of the 2004 International Symposium*, 18-19 May. NOAA Fisheries Acoustics Program, Office of Protected Resources (OPR), National Marine Fisheries Service (NMFS), and National Oceanic and Atmospheric Administration (NOAA), Alrington, VA, USA, p. 40. http://www.beamreach.org/wiki/images/4/47/2004NoiseReport.pdf.

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., 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.

Stadler, J.H. and D.P. Woodbury. 2009. Assessing the effects to fishes from pile driving: Application of new hydroacoustic criteria. *Inter-Noise 2009: Innovations in Practical Noise Control*. 23-29 Aug 2009, Ottawa, Canada.

Stenberg, C., J.G. Støttrup, M. van Deurs, C.W. Berg, G.E. Dinesen, H. Mosegaard, T.M. Grome, and S.B. Leonhard. 2015. Long-term effects of an offshore wind farm in the North Sea on fish communities. *Marine Ecology Progress Series* 528: 257-265. https://doi.org/10.3354/meps11261.

Stimpert, A.K., S.L. DeRuiter, B.L. Southall, D.J. Moretti, E.A. Falcone, J.A. Goldbogen, A.S. Friedlaender, G.S. Schorr, and J. Calambokidis. 2014. Acoustic and foraging behavior of a Baird's beaked whale, *Berardius bairdii*, exposed to simulated sonar. *Scientific Reports* 4. https://doi.org/10.1038/srep07031.

Stöber, U. and F. Thomsen. 2021. How could operational underwater sound from future offshore wind turbines impact marine life? *The Journal of the Acoustical Society of America* 149(3): 1791-1795.

Teilmann, J. and J. Carstensen. 2012. Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic - evidence of slow recovery. *Environmental Research Letters* 7(4). https://doi.org/10.1088/1748-9326/7/4/045101.

Thomsen, F., A.B. Gill, M. Kosecka, M. Andersson, M. André, S. Degraer, T. Folegot, J. Gabriel, A. Judd, et al. 2016. *MaRVEN – Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy. Final study report*. Document Number RTD-KI-NA-27-738-EN-N. Report for European Commission, Directorate General for Research and Innovation.

Todd, V.L.G., W.D. Pearse, N.C. Tregenza, P.A. Lepper, and I.B. Todd. 2009. Diel echolocation activity of harbour porpoises (*Phocoena phocoena*) around North Sea offshore gas installations. *ICES Journal of Marine Science* 66(4): 734-745. https://doi.org/10.1093/icesjms/fsp035.

Todd, V.L.G., I.B. Todd, J.C. Gardiner, E.C.N. Morrin, N.A. MacPherson, N.A. DiMarzio, and F. Thomsen. 2015. A review of direct and indirect impacts of marine dredging activities on marine mammals. *ICES Journal of Marine Science* 72(2): 328-340. https://doi.org/10.1093/icesjms/fsu187.

Tougaard, J., O.D. Henriksen, and L.A. Miller. 2009. Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals. *Journal of the Acoustical Society of America* 125(6): 3766-3773. https://doi.org/10.1121/1.3117444.

Tougaard, J., L. Hermannsen, and P.T. Madsen. 2020. How loud is the underwater noise from operating offshore wind turbines? *The Journal of the Acoustical Society of America* 148(5): 2885-2893.

Tsujii, K., T. Akamatsu, R. Okamoto, K. Mori, Y. Mitani, and N. Umeda. 2018. Change in singing behavior of humpback whales caused by shipping noise. *PLOS ONE* 13(10): e0204112. https://doi.org/10.1371/journal.pone.0204112.

Tubelli, A.A., A. Zosuls, D.R. Ketten, and D.C. Mountain. 2012. Prediction of a mysticete audiogram via finite element analysis of the middle ear. *In* Popper, A.N. and A.D. Hawkins (eds.). *The Effects of Noise on Aquatic Life*. Volume 730. Springer, New York. pp. 57-59. https://doi.org/10.1007/978-1-4419-7311-5_12.

Tyack, P.L., W.M.X. Zimmer, D. Moretti, B.L. Southall, D.E. Claridge, J.W. Durban, C.W. Clark, A. D'Amico, N. DiMarzio, et al. 2011. Beaked whales respond to simulated and actual navy sonar. *PLOS ONE* 6(3): e17009. https://doi.org/10.1371/journal.pone.0017009.

Urick, R.J. 1972. Noise signature of aircraft in level flight over and hydrophone in the sea. *Journal of the Acoustical Society of America* 52: 993. https://doi.org/10.1121/1.1913206.

Vabø, R., K. Olsen, and I. Huse. 2002. The effect of vessel avoidance of wintering Norwegian spring spawning herring. *Fisheries Research* 58(1): 59-77. https://doi.org/10.1016/S0165-7836(01)00360-5.

Van Parijs, S.M. and P.J. Corkeron. 2001. Vocalizations and behaviour of Pacific humpback dolphins *Sousa chinensis*. *Ethology* 107(8): 701-716. https://doi.org/10.1046/j.1439-0310.2001.00714.x.

Wahlberg, M. and H. Westerberg. 2005. Hearing in fish and their reactions to sounds from offshore wind farms. *Marine Ecology Progress Series* 288: 295-309. https://www.int-res.com/abstracts/meps/v288/p295-309/.

Wale, M.A., S.D. Simpson, and A.N. Radford. 2013a. Size-dependent physiological responses of shore crabs to single and repeated playback of ship noise. *Biology Letters* 9(2). https://doi.org/10.1098/rsbl.2012.1194.

Wale, M.A., S.D. Simpson, and A.N. Radford. 2013b. Noise negatively affects foraging and antipredator behaviour in shore crabs. *Animal Behaviour* 86(1): 111-118. https://doi.org/10.1016/j.anbehav.2013.05.001.

Wale, M.A., R.A. Briers, D. Bryson, M.G.J. Hartl, and K. Diele. 2016. The effects of anthropogenic noise playbacks on the blue mussel *Mytilus edulis*. *Annual Science Meeting of Marine Alliance for Science and Technology for Scotland (MASTS)*. 19-21 Oct 2016. https://www.masts.ac.uk/media/36069/2016-abstracts-gen-sci-session-3.pdf.

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.

Warner, G.A., M.E. Austin, and A.O. MacGillivray. 2017. Hydroacoustic measurements and modeling of pile driving operations in Ketchikan, Alaska [Abstract]. *Journal of the Acoustical Society of America* 141(5): 3992. https://doi.org/10.1121/1.4989141.

Wartzok, D. and D.R. Ketten. 1999. Marine Mammal Sensory Systems. (Chapter 4) *In* Reynolds, J. and S. Rommel (eds.). *Biology of Marine Mammals*. Smithsonian Institution Press, Washington, DC. pp. 117-175.

Weilgart, L.S. 2007. A Brief Review of Known Effects of Noise on Marine Mammals. *International Journal of Comparative Psychology* 20(2): 159-168. https://escholarship.org/uc/item/11m5g19h.

Wensveen, P.J., P.H. Kvadsheim, F.-P.A. Lam, A.M. von Benda-Beckmann, L.D. Sivle, F. Visser, C. Curé, P.L. Tyack, and P.J.O. Miller. 2017. Lack of behavioural responses of humpback whales (*Megaptera novaeangliae*) indicate limited effectiveness of sonar mitigation. *Journal of Experimental Biology* 220(22): 4150-4161. https://doi.org/10.1242/jeb.161232.

Wensveen, P.J., S. Isojunno, R.R. Hansen, A.M. von Benda-Beckmann, L. Kleivane, S. van IJsselmuide, F.-P.A. Lam, P.H. Kvadsheim, S.L. DeRuiter, et al. 2019. Northern bottlenose whales in a pristine environment respond strongly to close and distant navy sonar signals. *Proceedings of the Royal Society B* 286(1899). https://doi.org/10.1098/rspb.2018.2592.

Whittock, P.A., K.L. Pendoley, R. Larsen, and M. Hamann. 2017. Effects of a dredging operation on the movement and dive behaviour of marine turtles during breeding. *Biological Conservation* 206: 190-200. https://doi.org/10.1016/j.biocon.2016.12.015.

Williams, R., A.W. Trites, and D.E. Bain. 2002. Behavioural reponses of killer whales (*Orcinus orca*) to whale-watching boats: Opportunistics observations and experimental approaches. *Journal of Zoology* 256(2): 255-270. https://doi.org/10.1017/S0952836902000298.

Williams, R., C. Erbe, E. Ashe, A. Beerman, and J. Smith. 2014. Severity of killer whale behavioral responses to ship noise: A dose–response study. *Marine Pollution Bulletin* 79(1-2): 254-260. https://doi.org/10.1016/j.marpolbul.2013.12.004.

Willis, M.R., M. Broudic, M. Bhurosah, and I. Masters. 2010. Noise associated with small scale drilling operations. *3rd International Conference on Ocean Energy*. 6 Oct 2010, Bilbao. pp. 1-5.

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.

Würsig, B., S.K. Lynn, T.A. Jefferson, and K.D. Mullin. 1998. Behaviour of cetaceans in the northern Gulf of Mexico relative to survey ships and aircraft. *Aquatic Mammals* 24(1): 41-50.

Wysocki, L.E., J.P. Dittami, and F. Ladich. 2006. Ship noise and cortisol secretion in European freshwater fishes. *Biological Conservation* 128(4): 501-508. https://doi.org/10.1016/j.biocon.2005.10.020.

Wysocki, L.E., S. Amoser, and F. Ladich. 2007. Diversity in ambient noise in European freshwater habitats: Noise levels, spectral profiles, and impact on fishes. *Journal of the Acoustical Society of America* 121(5): 2559-2566. https://doi.org/10.1121/1.2713661.

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.

Zykov, M.M. and J.T. MacDonnell. 2013. *Sound Source Characterizations for the Collaborative Baseline Survey Offshore Massachusetts Final Report: Side Scan Sonar, Sub-Bottom Profiler, and the R/V Small Research Vessel experimental*. Document Number 00413, Version 2.0. Technical report by JASCO Applied Sciences for Fugro GeoServices, Inc. and the (US) Bureau of Ocean Energy Management.

Appendix A. Glossary

1/3-octave

One third of an octave. Note: A one-third octave is approximately equal to one decidecade (1/3 oct ≈ 1.003 ddec; ISO 2017).

1/3-octave-band

Frequency band whose bandwidth is one one-third octave. Note: The bandwidth of a one-third octave-band increases with increasing centre frequency.

absorption

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

attenuation

The gradual loss of acoustic energy from absorption and scattering as sound propagates through a medium.

audiogram weighting

The process of applying an animal's audiogram to sound pressure levels to determine the sound level relative to the animal's hearing threshold (HT). Unit: dB re HT.

Auditory frequency weighting (auditory weighting function, frequency-weighting function)

The process of band-pass filtering sounds to reduce the importance of inaudible or less-audible frequencies for individual species or groups of species of aquatic mammals (ISO 2017). One example is M-weighting introduced by Southall et al. (2007) to describe "Generalized frequency weightings for various functional hearing groups of marine mammals, allowing for their functional bandwidths and appropriate in characterizing auditory effects of strong sounds".

azimuth

A horizontal angle relative to a reference direction, which is often magnetic north or the direction of travel. In navigation, it is also called bearing.

bandwidth

The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI and ASA S1.13-2005 (R2010)).

bathymetry

The submarine topography of a region, usually expressed in terms of water depth

broadband sound level

The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

continuous sound

A sound whose sound pressure level remains above ambient sound during the observation period (ANSI and ASA S1.13-2005 (R2010)). A sound that gradually varies in intensity with time, for example, sound from a marine vessel.

compressional wave

A mechanical vibration wave in which the direction of particle motion is parallel to the direction of propagation. Also called primary wave or P-wave.

decade

Logarithmic frequency interval whose upper bound is ten times larger than its lower bound (ISO 2006).

decidecade

One tenth of a decade (ISO 2017). 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)

One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 (R2004)).

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.

geoacoustic

Relating to the acoustic properties of the seabed.

hearing threshold

The sound pressure level for any frequency of the hearing group that is barely audible for a given individual in the absence of significant background noise during a specific percentage of experimental trials.

hertz (Hz)

A unit of frequency defined as one cycle per second.

impulsive sound

Sound that is typically brief and intermittent with rapid (within a few seconds) rise time and decay back to ambient levels (NOAA and US Dept of Commerce 2013, ANSI S12.7-1986 (R2006)). For example, seismic airguns and impact pile driving.

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 transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

peak sound pressure (L_{pk})

The maximum instantaneous sound pressure, in a stated frequency band, within a stated period. Also called zero-to-peak sound pressure. Unit: decibel (dB).

permanent threshold shift (PTS)

A permanent 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 (ANSI S1.1-1994 (R2004)).

pressure, acoustic

The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

pressure, hydrostatic

The pressure at any given depth in a static liquid that is the result of the weight of the liquid acting on a unit area at that depth, plus any pressure acting on the surface of the liquid. Unit: pascal (Pa).

propagation loss

The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called transmission loss.

received level

The sound level measured at a receiver.

rms

root-mean-square.

rms sound pressure level (L_p)

The root-mean-square average of the instantaneous sound pressure as measured over some specified time interval. For continuous sound, the time interval is one second. See also sound pressure level (L_p) and 90% rms SPL.

shear wave

A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or S-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

signature

Pressure signal generated by a source.

sound

A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound exposure

Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second (Pa^2·s) (ANSI S1.1-1994 (R2004)).

sound exposure level (SEL)

A cumulative measure related to the sound energy in one or more pulses. Unit: dB re 1 μPa^2·s. SEL is expressed over the summation period (e.g., per-pulse SEL [for airguns], single-strike SEL [for pile drivers], 24-hour SEL).

sound field

Region containing sound waves (ANSI S1.1-1994 (R2004)).

sound pressure level (SPL)

The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 (R2004)).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 μPa) and the unit for SPL is dB re 1 μPa^2:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square (rms) pressure level. See also 90% sound pressure level and fast-average sound pressure level. Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile

The speed of sound in the water column as a function of depth below the water surface.

source level (SL)

The sound level measured in the far-field and scaled back to a standard reference distance of 1 meter from the acoustic centre of the source. Unit: dB re 1 μPa·m (pressure level) or dB re 1 μPa^2·s·m (exposure level).

temporary threshold shift (TTS)

Temporary loss of hearing sensitivity caused by excessive noise exposure.

Appendix B. Summary of Acoustic Assessment Assumptions

B.1. Impact Pile Driving

The amount of sound generated during pile installation varies with the energy required to drive the piles to the desired depth, which depends on the sediment resistance encountered. Sediment types with greater resistance require pile drivers that deliver higher energy strikes. Maximum sound levels from pile installation usually occur during the last stage of driving (Betke 2008). The representative make and model of impact hammers, and the hammering energy schedule, were provided by Ocean Wind.

Ocean Wind is expected to construct WTG monopile foundations consisting of single, tapered piles (dimensions shown in Table B-2.). For monopile foundation models, piles are assumed to be vertical and driven to a penetration depth of 148 ft (45 m). While pile penetrations across the OCW01 will vary, this value was chosen as the maximum penetration depth. The estimated number of strikes required to install piles to completion were obtained from Ocean Wind in consultation with potential hammer suppliers. All acoustic evaluation was performed assuming that only one pile is driven at a time. Modeling input, assumptions, and methods are listed in Table B-1. Sound from the piling barge was not included in the model.

Table B-1. Details of model inputs, assumptions, and methods for the expected installation scenarios.

Parameter	Description
Monopile pile driving source model	
8 to 11 m monopile foundation	
Modeling method	Finite-difference structural model of pile vibration based on thin-shell theory; Hammer forcing functions computed using GRLWEAP
Impact hammer energy	4000 kJ
Ram weight	1,977.151 kN
Helmet weight	3,776.9 kN
Strike rate (min^{-1})	50
Estimated number of strikes to drive pile	10,846
Expected maximum penetration	50 m
Modeled seabed penetration per energy level	7, 6, 3, 2, 16, 6, 10 m
Pile length	107 m
Pile diameter	8 m (top) to 11 m (bottom)
Pile wall thickness	8 cm (top – tapered)
Shaft resistance	38%, 53%, 91%, 50%, 78%, 98%, 99% (for each energy level in increasing order of soil penetration)
2.44 m Jacket Foundation	
Modeling method	Finite-difference structural model of pile vibration based on thin-shell theory; Hammer forcing functions computed using GRLWEAP

Impact hammer energy	2500 kJ
Ram weight	1,227.32 kN
Helmet weight	279 kN
Strike rate (min-1)	50
Estimated number of strikes to drive pile	13,191
Expected maximum penetration	70 m
Modeled seabed penetration per energy level	3, 29, 8, 8, 6, 6, 11 m
Pile length	75.05 m
Pile diameter	2.44 m
Pile wall thickness	7.5 cm
Shaft resistance	16%, 69%, 73%, 77%, 79%, 80%, 83% (for each energy level in increasing order of soil penetration)
Environmental parameters for all pile types	
Sound speed profile	GDEM data averaged over region
Bathymetry	GEBCO 2020 data
Geoacoustics	Elastic seabed properties based on client-supplied description of seabed layering
Quake (shaft and toe)	2.54 mm
Shaft damping	0.164 s/m; 0.323, 0.275, 0.194, 0.269 s/m for monopile at 1000 kJ-16 m, 3000 kJ-18 m, 4000 kJ-34 m, and 4000 kJ-50 m, respectively
Toe damping	0.49 s/m
Propagation model for all pile types	
Modeling method	Parabolic-equation propagation model with 2.5° azimuthal resolution; FWRAM full-waveform parabolic equation propagation model for 4 radials
Source representation	Vertical line array
Frequency range	10–25,000 Hz
Synthetic trace length	500 ms
Maximum modeled range	100 km

Table B-2. Nominal dimensions of an 8/11 m, tapered monopile foundation.

Section length (m)	Outside diameter top (m)	Outside diameter bottom (m)
0.297	8	8
2.518	8	8
3.365	8	8
4.125	8	8
4.2	8	8
4.2	8	8
4.2	8	8
4.2	8	8
4.2	8	8
4	8	8.6
4	8.6	9.2
4	9.2	9.8
4	9.8	10.4
4	10.4	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
4.2	11	11
1.835	11	11
3.65	11	11

Appendix C. Secondary Sound Sources in the Project Area

The primary sources of underwater sound generated during the project are associated with installation of monopile and jacket pile foundations. These primary sound sources are the focus of the quantitative analysis presented in the main text. The objective of this Appendix is to provide a qualitative description and evaluation of other underwater sound sources associated with project construction and operation, collectively referred to as secondary sound sources. Secondary sound sources are anthropogenic sound sources that are only likely to cause behavioral responses and short-term stress in marine fauna. Secondary sound sources are expected to be of very low or low risk (Table C-1), and, because of their limited risk, a qualitative (instead of quantitative) evaluation of these sound sources was undertaken and is detailed for each source type below.

C.1. Vessels

All vessels emit sound from propulsion systems while in transit, and engines and machinery emit noise through the hull while in use. The emitted sounds are typically broadband, non-impulsive, continuous, low-frequency noise. A vessel’s acoustic signature depends on the vessel type (e.g., tanker, bulk carrier, tug, container ship, recreational vessel) and vessel characteristics (e.g., engine specifications, propeller dimensions and number, length, draft, hull shape, gross tonnage, speed). Large shipping vessels and tankers produce lower frequency sounds with primary acoustic energy ~40 Hz and apparent underwater source levels (SLs) of SPL 177 to 188 dB re 1 µPa (McKenna et al. 2012). Dynamically positioned (DP) vessels use thrusters to maneuver and maintain station, and generate substantial underwater noise with apparent SLs ranging from SPL 150 to 180 dB re 1 µPa depending on operations and thruster use (BOEM 2014). Smaller, high-speed vessels may produce higher-frequency sound (1,000 to 5,000 Hz) with apparent SLs between SPL 150 and 180 dB re 1 µPa (Kipple 2002, Kipple and Gabriele 2003).

Marine mammals, sea turtles, fish and invertebrates in many locations are regularly subjected to vessel activity and may be habituated to vessel noise as a result of frequent or prolonged exposure (BOEM 2014). Non-Project vessel traffic in the vicinity of the Project may include recreational vessels, fishing vessels, cargo vessels, tankers, passenger vessels, and others. Vessels associated with the project during construction and operation will not contribute considerably more vessel traffic above baseline conditions and therefore the potential risk of impact from Project vessel noise is low to very low.

C.1.1. Potential Impacts to Marine Fauna

C.1.2. Marine Mammals

The vessel sounds emitted by ship engines, propellers, thrusters, and hulls are within the (assumed) best hearing frequency ranges of low-frequency cetaceans and are audible by all marine mammals (NMFS 2018). Vessel activities in the Project Area will add to the existing ambient vessel sound level of regular vessel traffic in the area, which could cause behavioral impacts to marine mammals (Kraus et al. 2005, Southall 2005, Clark et al. 2009, Geo-Marine 2010). As with other anthropogenic sound, the potential effects from vessel noise depends on factors such as the marine mammal species, the marine mammal’s location and activity, the novelty of the sound, habitat, and oceanographic conditions.

Marine mammals exposed to vessel sounds have reported variable behavioral responses. Analyses of observations made during the Behavioral Response of Australian Humpback whales (*Megaptera novaeangliae*) to Seismic Surveys (BRAHSS) study, Dunlop et al. (2015, 2016a, 2016b, 2017a, 2017b, 2018) found only minor and temporary changes in the migratory behavior of humpback whales in response to exposure to vessel and seismic airgun sounds. Increased proximity of vessels, however, led to aversive reactions (Dunlop et al. 2017b) and to reduced social interactions between migrating humpback whales (Dunlop et al. 2020). In other studies of humpback whales, most individuals did not respond to sonar vessels with the sonar turned off (Sivle et al. 2016, Wensveen et al. 2017), and Tsujii et al. (2018) found that humpback whales moved away from large vessels, while others noted temporary changes in respiratory behavior (Baker and Herman 1989, Frankel and Clark 2002)) or temporary cessation of foraging activities (Blair et al. 2016). Researchers have also reported a temporary change in the distribution and behavior of marine mammals in areas experiencing increased vessel traffic, particularly associated with whale watching, likely due to increases in ambient noise from concentrated vessel activity (Erbe 2002, Nowacek et al. 2004). The large number of studies on humpback whales and the resulting variety of documented responses clearly demonstrate how context affects behavior.

Marine mammals in the Project Area are regularly subjected to commercial shipping traffic and other vessel noise and could potentially be habituated to vessel noise (BOEM 2014). Hatch et al. (2012) estimated that calling North Atlantic right whales (*Eubalaena glacialis*) (NARWs) may have lost 63 to 67% of their communication "space" due to shipping noise. Although received levels of sound may, at times, be above the non-impulsive sound threshold for Level B harassment (120 dB SPL), NARWs have been known to continue to feed in Cape Cod Bay, Massachusetts despite disturbance from passing vessels (Brown et al. 2000). In another study, NARWs showed no behavioral response to ship sounds at all, or at least not to received levels of 132 to 142 dB re 1 µPa from large ships passing within 1 nm (1.9 km) distance, nor to received levels of 129 to 139 dB re 1 µPa (main energy between 50 and 500 Hz) to artificial playback of ship noise (Nowacek et al. 2004).

Studies of responses by mid-frequency cetaceans to vessel sounds, conducted in various parts of the world and with a variety of species, have also shown mixed results. Groups of Pacific humpback dolphins (*Sousa chinensis*) in eastern Australia that included mother-calf pairs, increased their rate of whistling after a vessel transited the area (Van Parijs and Corkeron 2001). The authors postulated that vessel sounds disrupted group cohesion, especially between mother-calf pairs, requiring re-establishment of vocal contact after vessel noise temporarily masked their communication. Lesage et al. (1999) revealed that beluga whales (*Delphinapterus leucas*) reduced their overall call rate in the presence of vessels but increased the emission and repetition of specific calls and shifted to higher frequency bands. In response to high levels of vessel traffic, killer whales increased the duration (Foote et al. 2004) or the amplitude (Holt et al. 2009) of their calls. Other studies of killer whales (*Orcinus orca)* showed temporary changes in behavior in response to vessel noise including less foraging and increased surface-active behavior), respiration, swim speed, and direction occurred at received levels above 130 dB re 1 µPa (0.01 to 50 kHz) (Williams et al. 2002, Lusseau et al. 2009, Noren et al. 2009, Williams et al. 2014). Marley et al. (2017) found that Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in Fremantle Inner Harbor, Australia significantly increased their average movement speed in the presence of high vessel densities during resting behavior. Behavioral budgets also changed in the presence of vessels, with animals spending more time traveling and less time resting or socializing.

Mid-frequency Cuvier's beaked whales (*Ziphius cavirostris*) responded to ship sounds by decreasing their vocalizations when they attempted to catch prey (Aguilar Soto et al. 2006), and foraging changes were observed in Blainville's beaked whales (*Mesoplodon densirostris*) when they were exposed to vessel noise (Pirotta et al. 2012). Harbor porpoises (*Phocoena phocoena*) tend to swim away from approaching vessels emitting high frequency noise in the Bay of Fundy, Canada (Polacheck and Thorpe 1990) and have been observed to move rapidly out of the path of a survey vessel within 1 km on the western coast of North America (Barlow 1988). Both harbor porpoises and beaked whale species are known to avoid relatively low levels of anthropogenic sound, and are generally recognized as behaviorally sensitive species (Wood et al. 2012 criteria).

In response to vessel noise, a tagged seal changed its diving behavior, switching quickly from a dive ascent to descent (Mikkelsen et al. 2019). This observation agrees with descriptions of changes in diving reported from juvenile northern elephant seals (*Mirounga angustirostris*) (Fletcher et al. 1996, Burgess et al. 1998). The tagging study also found that harbor seals (*Phoca vitulina*) and grey seals (Halichoerus grypus) are routinely exposed to vessel noise 2.2 to 20.5% of their time at sea (Mikkelsen et al. 2019).

Sound levels and the presence of vessels associated with the Project may result in behavioral responses by marine mammals, but within the context of an already highly trafficked region, the intermittent nature of vessel activity suggests that the impacts due to Project vessels are likely to be low.

C.1.3. Sea Turtles

Most of the underwater sound produced by ships is low frequency (~20–500 Hz) and overlaps with the known or assumed best hearing frequency range of all sea turtles. The broadband (20–1,000 Hz) apparent source level of a modern commercial ship (54,000 gross ton container ship traveling at 21.7 knots) is up to 188 dB re 1µPa (McKenna et al. 2012). This source level is below the non-impulsive acoustic injury threshold of 200 dB re 1 µPa for sea turtles (Finneran et al. (2017), meaning that only behavioral responses could be expected from sea turtles exposed to Project related vessel noise. Underwater noise that is detectable by sea turtles can mask signal detection, and influence behavior, but the consequences of masking and attendant behavioral changes on the survival of sea turtles are not known (Popper et al. 2014).

Many of the proposed Project-related vessels are significantly smaller than cargo ships and most will transit at slower speeds than cargo ships. The apparent source levels of smaller, slower vessels may be below the behavioral response thresholds of sea turtles or limited to the area immediately adjacent to the vessel. As with marine mammals, sea turtles are regularly subjected to commercial shipping traffic and other vessel noise and may be habituated to vessel noise as a result of this exposure (BOEM 2014). Given the lower sound levels associated with vessel transit and operation and the limited ensonified area produced by this source, the risk of impact to sea turtles is expected to be very low to low.

C.1.4. Fish

Vessel noise may interfere with feeding and breeding, alter schooling behaviors and migration patterns (Buerkle 1973, Olsen et al. 1983, Schwarz and Greer 1984, Soria et al. 1996, Vabø et al. 2002, Mitson and Knudsen 2003, Ona et al. 2007, Sarà et al. 2007), mask important environmental auditory cues (CBD 2012, Barber 2017), and induce endocrine stress response (Wysocki et al. 2006). Fish communication is mainly in the low-frequency (<1000 Hz) range (Ladich and Myrberg 2006, Myrberg and Lugli 2006) so masking is a particular concern because many fish species have unique vocalizations that allow for inter- and intra-species identification, and because fish vocalizations are generally not loud, usually ~120 dB SPL with the loudest sounds reaching 160 dB SPL (Normandeau Associates 2012). Behavioral responses in fishes differ depending on species and life stage, with younger, less mobile age classes being the most vulnerable to vessel noise impacts (Popper and Hastings 2009, Gedamke et al. 2016).

Underwater sound from vessels can cause avoidance behavior, which has been observed for Atlantic herring (*Clupea harengus*) and Atlantic cod (*Gadus morhua*), and is a likely behavior of other species as well (Vabø et al. 2002, Handegard et al. 2003). Fish may respond to approaching vessels by diving towards the seafloor or by moving horizontally out of the vessel's path, with reactions often initiated well before the vessel reaches the fish (Ona et al. 2007, Berthe and Lecchini 2016). The avoidance of vessels by fish has been linked to high levels of infrasonic and low-frequency sound (~10 to 1,000 Hz) emitted by vessels. Accordingly, it was thought that quieter vessels would result in less avoidance (and consequently quieter vessels would have a higher chance of encountering fish) (De Robertis et al. 2010). By comparing the effects of a quieted and conventional research vessel on schooling herring, it was found that the avoidance reaction initiated by the quieter vessel was stronger and more prolonged than the one initiated by the conventional vessel (Ona et al. 2007). In a comment to this publication, Sand et al. (2008) pointed out that fish are sensitive to particle acceleration and that the cue in this case may have been low-frequency particle acceleration caused by displacement of water by the moving hull. This could explain the stronger response to the larger, noise-reduced vessel in the study by Ona et al. (2007), which would have displaced more water as it approached.

Nedelec et al. (2016) investigated the response of reef-associated fish by exposing them in their natural environment to playback of vessel engine sounds. They found that juvenile fish increased hiding and ventilation rate after a short-term vessel sound playback, but responses diminished after long-term playback, indicating habituation to sound exposure over longer durations. These results were corroborated by Holmes et al. (2017) who also observed short-term behavioral changes in juvenile reef fish after exposure to vessel noise as well as desensitization over longer exposure periods.

While sounds emitted by vessel activity are unlikely to injure fish, vessel sound has been documented to cause temporary behavioral responses (Holmes et al. 2017). Fish in the area are already exosed to vessels sounds in this high-traffic area. Project-related vessel noise will be intermittent and of short duration, so the overall impacts to fish are expected to be low.

C.1.5. Invertebrates

Although the study of effects of sound on invertebrates (e.g., crustaceans, cephalopods, and bivalves) is in its nascency, it is evident that invertebrates are sensitive to particle motion (as opposed to pressure) (Popper and Hawkins 2018) and that they can detect vibrations in the sea bed (Roberts et al. 2015b, Roberts and Breithaupt 2016, Roberts and Elliott 2017). While there are currently no agreed upon metrics or clearly defined levels (in terms of sound pressure or particle motion) for assessing the effects or impacts of sound on invertebrates (Hawkins and Popper 2017), recent experiments have measured sound pressure levels and particle motion associated with trauma in cuttlefish (*Sepia officinalis*) (Solé et al. 2017) and longfin squid (*Doryteuthis pealeii*) (Mooney et al. 2016, Jones et al. 2020, Jones et al. 2021). And, some studies have found potential behavioral effects (e.g., flight or retraction) or physiological (e.g., stress) responses in invertebrates. For example, shore crabs (*Carcinus maenas*) in the presence of vessel noise ceased feeding and were slower to retreat to shelter (Wale et al. 2013b). The common prawn (*Palaemon serratus*) had fewer intra-specific interactions and spent more time outside of their shelters where the sound pressure levels were lower (Filiciotto et al. 2016). Lobsters (*Nephrops norvegicus*) reduced locomotor activity and clams (*Ruditapes philippinarum*) exhibited behaviors that ultimately prevented feeding (Solan et al. 2016).

Shore crabs exposed to playbacks of vessel noise demonstrated an increase in oxygen consumption that was presumed to indicate a higher metabolic rate and/or stress (Wale et al. 2013a). A similar response was observed in the blue mussel (*Mytilus edulis*), which not only increased oxygen consumption but also had more fragmentation of cellular DNA (Wale et al. 2016). In Pacific oysters (*Magallana gigas*), chronic exposure to vessel noise was shown to depress activity and food uptake, ultimately limiting growth (Charifi et al. 2018). Evidence from a field experiment with sea hares (*Stylocheilus striatus*) demonstrated a significant increase in the likelihood of developmental failure at the embryonic stage and mortality at the free-swimming stage, when exposed to play-backs of vessel noise (Nedelec et al. 2014).

Overall, while there are preliminary indications of potential impacts of vessel noise on some invertebrates, most research has been conducted in a laboratory setting, where tank boundaries may affect the acoustic field and observed behavioral response (Rogers et al. 2016, Popper and Hawkins 2018). Further, nearly all studies measured sound pressure rather than particle motion (Jesus et al. (2020). Although high-intensity noise may produce high sound pressure levels and high levels of particle motion concurrently, it is impossible to determine this relationship without proper measurements (Popper and Hawkins 2018). It is unlikely, however, that these stimuli have more than short-term consequences. For example, the shore crabs that showed an increase in oxygen consumption did not respond after repeated exposures to vessel noise (Wale et al. 2013a). Thus, overall risks of impacts to invertebrates associated with vessel noise are expected to be low.

C.1.6. Monitoring and Mitigation

Sound levels associated with vessels vary with vessel class, speed, and activity. High speeds and the use of thrusters increase noise levels significantly (Richardson et al. 1995) though marine fauna are regularly subjected to commercial shipping traffic and other vessel noise and are likely habituated to vessel noise as a result of this regular exposure (BOEM 2014). Many of the proposed Project-related vessels are much smaller than cargo ships that frequently transit the area and, for mitigation purposes, will typically transit at slower speeds.

C.2. Aircraft

Aircraft, both fixed wing and helicopter, may be used during Project construction and operation for crew transfers and biological monitoring activities. The evaluation of aircraft sound on marine fauna differs from other underwater sound sources in that sound generated by aircraft is produced within the air, transmitted through the water surface, and propagated underwater. Most sound energy from aircraft reflects off the air-water interface; only sound radiated downward within a 26-degree cone penetrates below the water surface (Urick 1972).

In general, underwater sound levels produced by fixed wing aircraft and helicopters are typically low frequency (16-500 Hz) and range between 84-159 dB re 1 µPa (Richardson et al. 1995, Patenaude et al. 2002, Erbe et al. 2018). (Patenaude et al. 2002) recorded the transmission of sound into water from two types of aircraft: a Twin Otter fixed-wing airplane and a Bell 212 helicopter. Sound levels were measured at 3 m and 18 m below the water surface while the aircraft flew at various airspeeds and four altitudes overhead. Maximum received levels in the 10 to 500 Hz frequency band at 18 m water depth were approximately 120 dB re 1 µPa for both the Twin Otter and Bell 212 (Patenaude et al. 2002). Received PK sound levels were generally higher at 3 m depth than 18 m depth by an average of 2.5 dB but varied considerably with both the altitude and speed of the aircraft (Patenaude et al. 2002). Because underwater sound from aircraft depends on height, angle, speed, and sound propagation in different environmental conditions (temperature, humidity in air, and salinity in water) (Hubbard 1991, Erbe et al. 2018), underwater sound levels from aircraft are highly variable.

There is limited research on the impacts of aircraft sounds to marine fauna, however, sound emitted by aircraft that propagations underwater has the potential to cause behavioral responses in marine mammal, sea turtle, and fish (McCauley et al. 2000b, Popper et al. 2014, Todd et al. 2015, Finneran et al. 2017, [NMFS] National Marine Fisheries Service (US) 2018). Further information is required to determine the potential underwater effects of aircraft in invertebrates (Hawkins et al. 2015). Given that the majority of sound emitted by aircraft is reflected off the surface of the water, impacts to marine fauna are expected to be very low to low.

C.2.1. Potential Impacts to Marine Fauna

C.2.2. Marine mammals

Aircraft noise is typically low- to mid-frequency, overlapping with cetacean calls and with the potential to cause temporary changes in behavior and localized displacement of marine mammals when transmitted from air through the water surface (Richardson et al. 1985a, Richardson and Würsig 1997, Nowacek et al. 2007). Marine mammals react to aircraft noise more often when the aircraft is lower in altitude, closer in lateral distance, and flying over shallow water (Richardson et al. 1985b, Patenaude et al. 2002). Temporary reactions displayed by marine mammals include short surfacing, hasty dives, aversion from the aircraft, or dispersal from the incoming aircraft (Bel'kovich 1960, Kleĭnenberg et al. 1964, Richardson et al. 1985a, Richardson et al. 1985b, Luksenburg and Parsons 2009). The response of cetaceans to aircraft noise largely depends on the species as well as the animals' behavioral state at the time of exposure (e.g., migrating, resting, foraging, socializing) (Würsig et al. 1998).

Cetaceans within the low frequency hearing group showed varied behavioral response when exposed to aircraft noise. Bowhead whales (*Balaena mysticetus*) displayed frequent behavioral reactions to fixed-wing aircraft and helicopter sounds at altitudes <305 m (Dahlheim 1981, Richardson et al. 1985b, Koski et al. 1988, Richardson and Malme 1993). However, Patenaude et al. (2002) noted that only 17% of observed bowhead whales showed behavioral response to passing helicopters, even at the lower altitudes (150 m) and lateral distances of 250 m. Behavioral changes were also seen in gray whales (*Eschrichtius robustus*) in response to the sound from a Bell 212 helicopter (Malme et al. 1984).

Variable behavioral reactions to aircraft sound were also observed in mid-frequency cetaceans. In the Gulf of Mexico, beaked whales, pygmy and dwarf sperm whales (*Kogia spp*.), and various delphinids (pantropical spotted [*Stenella attenuate*], Clymene [*Stenella clymene*], striped [*Stenella coeruleoalba*] and spinner [*Stenella longirostris*] dolphins) showed a strong behavioral response to an approaching fixed-winged aircraft by quickly diving (Würsig et al. 1998). Several studies reported defensive behavioral responses to approaching aircraft in sperm whales (Würsig et al. 1998, Richter et al. 2003, Richter et al. 2006, Smultea et al. 2008). In contrast, only 3.2% (or 24 of 760) of beluga whales responded to fixed wing aircraft at heights above the water ranging from 182 m to 427 m (Patenaude et al. 2002). Given that recorded SPL at 18 m was approximately equivalent (~120 dB SPL) to the regulatory defined acoustic behavioral response threshold level for marine mammals, the lack of response is unsurprising in this study (Patenaude et al. 2002).

The sound emitted by aircraft has the potential to elicit temporary behavioral responses in marine mammals and Project-related aircraft can be at low altitude, but due to the intermittent nature and the small ensonified area of this sound source, the risks of aircraft impact to marine mammals are expected to be low.

Sea turtles

Although aircraft sounds can be within the hearing frequency range of turtles, very few studies have analyzed the impacts of aircraft noise on sea turtles. The only documented behavioral responses were from nesting sea turtles near (1.7 km) a military jet airfield in which the turtles exhibited postnatal behavioral reactions to in-air aircraft noise (Balazs and Ross 1974).

Given the frequency range and sound levels produced by aircraft, sea turtles may have adverse behavioral responses to this source. However, the intermittent nature and the small area of ensonification produced by aircraft is unlikely to impact sea turtles. Risk of impact are therefore expected to be very low.

C.2.3. Fish

Because documented sound levels in water from aircraft can be higher than the regulatory-defined non-impulsive behavioral acoustic thresholds for fish (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011), it can be inferred that aircraft may cause behavioral responses in fish. It is unlikely, however, that the underwater sound from aircraft associated with the Project will have much impact on fish because the sound produced by these aircraft is intermittent and has a small ensonified area. The risks of impacts to fish from aircraft sound are expected to be very low.

C.2.4. Invertebrates

Aircraft may produce low-frequency sounds within the hearing range of marine invertebrates but there are currently no data available on the potential impacts of this underwater sound on marine invertebrates. As with fish, the risks of impacts to invertebrates from aircraft sound propagated underwater are expected to be very low due to the small ensonified area and intermittent nature of the source.

C.2.5. Monitoring and Mitigation

To mitigate potential impacts to marine fauna from aircraft noise during aerial surveys, uncrewed aerial systems (drones) equipped with a camera system may be used instead for real time monitoring of marine mammals. With uncrewed aerial systems, Protected Species Observers (PSOs) monitor high-definition drone camera footage in real time from shore or a vessel. This monitoring approach minimizes traditional, more intrusive methods to detect marine mammals and limits sound from fixed-wing aircraft that is typically used in marine mammal and sea turtle aerial surveys. The underwater sound levels recorded from drones (<100 dB re 1 µPa) is well below underwater noise regulatory thresholds (Erbe et al. 2017). Helicopter and fixed-wing aircraft used during the Project construction and operation phase will be in operation intermittently and primarily maintain safe altitudes (150 to 300 m) above sea level. At these heights, overall aircraft noise may elicit only short-term behavioral response in marine mammals such that the impact risk is very low. No drone-use is planned to support Project construction.

C.3. High Resolution Geophysical (HRG) Surveys

High resolution geophysical (HRG) surveys are required to characterize the seafloor and inform the Project design. Seafloor mapping and bottom-penetrating imaging systems differ primarily in the frequency range that the various sources produce. Higher frequencies resolve smaller features so seafloor mapping is conducted using high-frequency sources while lower frequencies are used to characterize conditions below the seabed.

Acoustic signals produced by HRG sources are impulsive, tonal, or frequency-modulated (FM) chirp pulses (short duration signals that sweep through a band of frequencies) (Halvorsen and Heaney 2018). Impulsive signals are produced by a variety of sources such as airguns, boomers, and sparkers using a variety of mechanisms (e.g., release of compressed air and electrostatic discharge) (Crocker and Fratantonio 2016). Tonal and FM chirp signals are produced by electromechanical sonars. Sub-bottom profilers are electromechanical sources that (typically) produce FM chirp signals at low frequencies able to penetrate the seafloor. Other electromechanical HRG sources such as side-scan and multibeam sonars, and echosounders produce tonal or FM chirp signals at higher frequencies for seafloor mapping. The source level, beamwidth, pulse duration, and pulse repetition rate of such sources are typically adjustable and selected for the needs of each survey. For regulatory purposes, sound signals are classified as either impulsive or non-impulsive with accompanying thresholds for assessing potential impacts on animals (see Section 2.4. Airguns, boomers, sub-bottom profilers, and sparkers are classified by NMFS as impulsive sound sources, while all electromechanical HRG sources are classified as non-impulsive.

Penetrating HRG systems produce low frequency sounds with high source levels. Mini-airguns emit sounds <5 kHz with source levels of 217-228 re 1 μPa (Crocker and Fratantonio 2016). Sub-bottom profilers produce sounds with primary acoustic energy in frequency bands 2-115 kHz at levels from 178 to 241 dB re 1 μPa and penetrating seismic profilers produce sound at lower frequencies (0.25-15 kHz) with source levels 205-206 dB re 1 μPa range (Crocker and Fratantonio 2016). Many seafloor mapping systems are operated at frequencies >200 kHz, which is above the hearing range of all marine animals and not expected to have any impacts. Some electromechanical systems, however, operate at lower frequencies and are audible to marine mammals. These systems produce sounds within the 0.4-170 kHz frequency range and sound levels from 177-247 dB re 1 μPa (Crocker and Fratantonio 2016). For example, multibeam echosounders (MBES) produced sounds ~30 to 70 kHz at source levels up to ~230 dB re 1 μPa. And, though not used for imaging, underwater positioning equipment (e.g., ultra-short baseline, USBL, systems) used during HRG surveys emit sound in the 20-50 kHz band with source levels up to 188-191 dB re 1 μPa.

There is an overall paucity of information on the effects of HRG sounds on marine fauna. Impulsive sources used for imaging below the seabed such as sub-bottom profilers and airguns are likely audible to all marine fauna and their use may result in injury and behavioral disruption. If such sources are used, a quantitative impact analysis following established guidelines should be conducted. Electromechanical HRG sources operating within the established hearing range of marine fauna are classified as non-impulsive by NMFS, eliminating the potential for injury, but do have the potential to cause behavioral disturbance. These sources tend to be highly directive with narrow beams and small ensonified areas so animals are likely to receive only short-duration exposures. Impacts to marine fauna from HRG sounds are expected to be low.

C.3.1. Potential Impacts to Marine Fauna

C.3.2. Marine Mammals

Many HRG sources operate at frequencies (>200 kHz) above the hearing range of marine mammals so are not expected to result in impacts. Research suggests that sound levels produced by HRG sources operating within the hearing range of marine mammals are unlikely to cause injury but could result in temporary behavioral responses.

While Varghese et al. (2020) found no consistent changes in Cuvier's beaked whale foraging behavior during multibeam echosounder surveys, analogous studies assessing mid-frequency active sonar on beaked whale foraging found that individuals would stop echolocating and leave the area. Other studies have focused on the responses of marine mammals exposed to sonar. For example, minke whales (*Balaenoptera acutorostrata*) demonstrated strong avoidance to mid-frequency sonar at 146 dB re 1 µPa (Sivle et al. 2015, Kvadsheim et al. 2017) and Wensveen et al. (2019) showed northern bottlenose whales (*Hyperoodon ampullatus*) had a greater response to (military) sonar signals. Surface-feeding blue whales showed no changes in behavior to mid-frequency sonar, but blue whales (*Balaenoptera musculus*) feeding at deeper depths and non-feeding whales displayed temporary reactions to the source; including cessation of feeding, reduced initiation of deep foraging dives, generalized avoidance responses, and changes to dive behavior (DeRuiter et al. 2013, Goldbogen et al. 2013, Sivle et al. 2015). Several behavioral reactions were seen in beaked whale species in response to mid-frequency sonar sounds (12-400 kHz and 230 dB re 1 µPa) including cessation of clicking, termination of foraging dives, changes in direction to avoid the sound source, slower ascent rates to the surface, longer deep and shallow dive durations, and other atypical dive behavior (Tyack et al. 2011, DeRuiter et al. 2013, Stimpert et al. 2014, Miller et al. 2015, Cholewiak et al. 2017). Exposure to mid-frequency sonar at various sound levels (125–185 dB re 1 µPa) caused behavioral responses in California sea lions (*Zalophus californianus*), including a refusal to participate in trials, hauling out, an increase in respiration rate, and an increase in the time spent submerged (Houser et al. 2013, Houser et al. 2016). Hooded seals (*Cystophora cristata*) showed initial avoidance behavior to 1–7 kHz sonar signals at levels between 160 and 170 dB re 1 µPa, but these animals did adapt to the sound and stopped avoiding the source (Kvadsheim et al. 2010).

Non-impulsive, sonar-type HRG sources operating within the hearing range of marine mammals are unlikely to produce injury but could cause behavioral responses. These sources typically have narrow beams that would expose marine mammals for short time periods and only negligible effects on marine mammal species could be expected. A previous analysis by BOEM (2014) on the potential effects of sound associated with HRG surveys on marine mammals in the Mid- and South-Atlantic wind planning areas concluded that impacts are expected to be minimal with the implementation of mitigation measures for sources operating at or below 200 kHz. With mitigation and monitoring practices, impacts to marine mammals from HRG sound sources are expected to be low.

C.3.3. Sea Turtles

HRG surveys that use non-impulsive sources are not expected to impact sea turtles because they operate at frequencies above the sea turtle hearing range (<1 kHz). Low-frequency impulsive HRG equipment may produce sounds within the hearing ranges of sea turtles and impacts should be evaluated using a quantitative approach.

C.3.4. Fish

Non-impulsive sounds produced by HRG survey operations are outside of fish hearing range and are not expected to produce injury or behavioral responses in fish (BOEM 2014, Popper et al. 2014, Popper and Hawkins 2019). Potential impacts of low frequency impulsive HRG sources on fish may include behavioral responses, masking of biologically important sounds, temporary hearing loss, and physiological effects (BOEM 2014, Popper et al. 2014, Popper and Hawkins 2019). Given the mobile and therefore intermittent nature of HRG surveys, the short-duration and infrequent surveying of small areas of the seafloor relative to the overall area, and the likelihood that fish will move away from the sound source, the impacts of underwater noise from impulsive HRG source surveys are expected to be low.

C.3.5. Invertebrates

As with sea turtles and fish, non-impulsive HRG sound sources are above the hearing range of invertebrates and are not expected to cause impacts, but impulsive sources may be within the hearing range of some invertebrates. For most marine invertebrate species sensitivity to underwater sound and susceptibility to noise-induced effects has not been investigated. Anatomical and experimental evidence suggests that particle motion (not sound pressure) is the primary mode for marine invertebrates perceiving acoustic stimuli. Nearly all studies on noise-induced effects on marine invertebrates, however, have measured sound pressure rather than particle motion reducing the relevance of their findings. There are currently no appropriate metrics or clearly defined levels (sound pressure or particle motion) for assessing the effect of underwater sound on marine invertebrates (Hawkins and Popper 2017). Even though criteria and thresholds are not available for invertebrates, the short-term and infrequent nature of impulsive HRG surveys are expected to be of low risk of impact to invertebrates.

C.3.6. Monitoring and Mitigation

Monitoring and mitigation during HRG surveys can decrease the potential impacts to marine mammals from HRG sound exposure by reducing the zone of influence (ZOI) and therefore the likelihood of sound exposures exceeding regulatory thresholds. The National Oceanic and Atmospheric Administration (NOAA) and BOEM have advised that HRG sources that operate at and below 200 kilohertz (kHz) have the potential to cause acoustic harassment to marine species, including marine mammals, and therefore require the establishment and monitoring of exclusion zones (BOEM 2014). Standard mitigation employed during HRG surveys includes the use of PSOs, time of year restrictions, protective zones, ramp-up of active sound sources and shut down of sources should marine mammals or sea turtles enter the established exclusion zones.

C.4. Drilling

Project construction activities will likely include drilling for geotechnical surveys and horizontal directional drilling (HDD). Geotechnical studies are conducted using drill rigs or other excavating tools to characterize the subsurface conditions in locations where foundational structures are expected to be installed (Shell Gulf of Mexico Inc. 2015). In some areas, such as the export cable landfall location, an HDD rig may be needed to create a conduit for the cable to be pulled through.

For both activities, a drill head produces vibrations that propagate as sound through the sediment and water column (Hall and Francine 1991, Nguyen 1996, Willis et al. 2010). Geotechnical drilling operations can emit sound both from the drill at the seabed and from the machinery on the barge (Gales 1982). HDD emits sound at the mouth of the borehole and the drill head. Unlike offshore drill rigs used for geotechnical drilling that are acoustically connected to the water column via drillships (floating rigs) or drill rigs (bottomed rigs), HDD rigs are installed on shore and the sound they produce that enters the water is often negligible (Hall and Francine 1991, Nguyen 1996, Willis et al. 2010).

Most measurements of offshore drilling sounds have been made for oil exploration and production drilling. The sound levels associated with those drilling operations have been documented to be within the hearing range of many marine species and above the recommended marine mammal, sea turtle, and fish injury and behavioral thresholds (Greene 1987, NOAA 2005, Popper et al. 2014, Finneran et al. 2017, NMFS 2018). The underwater sounds from those drilling activities are non-impulsive, low frequency (20 - 1000 Hz), and of varying levels ranging from an SPL of 117 to 184 dB re 1 µPa (Greene 1987, Blackwell et al. 2004a, Dow Piniak et al. 2012). However, the types of drilling likely to be used during project construction are of a smaller scale and are unlikely to produce the maximum sounds reported for oil drilling. Schlesinger et al. (2016) estimated a broadband source level of 170.7 dB re 1 µPa for offshore rock socket drilling in British Columbia. The modeled maximum distance to an SPL of 120 dB re 1 µPa was 5.8 km for that drilling activity. Only two papers have measured sounds from geotechnical drilling. Erbe and McPherson (2017) measured broadband (30 Hz to 2 kHz) sound source levels of 142 and 145 dB re 1 µPa for small-core drilling from a jack-up rig at two locations off western Australia. The sound levels were up to 35 dB above ambient sound levels at some frequencies, and thus audible to marine fauna, but much less than oil production drilling sounds and below levels used in marine noise regulations. Willis et al. (2010) recorded a peak sound level of 107 dB re 1 $\mu Pa_{0\text{-}pk}$ at 7.5 m from hard-rock drilling.

Underwater sound emitted by project construction drilling activities is not expected to produce injury to marine fauna but is likely to be audible and could elicit temporary behavioral responses. Impacts associated with this activity are expected to be low.

C.4.1. Potential Impacts to Marine Fauna

C.4.2. Marine Mammals

Impacts to marine mammals from underwater sound from drilling depend on the species, distance from the source, and type of drilling activity (Awbrey and Stewart 1983, Richardson et al. 1990a, Richardson et al. 1990b, Miller et al. 2005, Blackwell et al. 2017). Observed responses can include changes in migratory pathways, avoidance, changes in calling behavior, and altered diving and feeding patterns . For prolonged, large, drilling activities, acoustic masking may be a concern for marine mammals if the sounds interfere with their ability to detect or recognize important biological acoustic signals (Richardson et al. 1999, Houser and Cross 2014).

While underwater drilling sounds can have a negative effect on some marine mammals (bowhead and beluga whales), others (ringed seals and harbor porpoises) have been documented to be far more tolerant to drilling activities (Moulton et al. 2003, Todd et al. 2009). Received sound levels of drilling from construction operations were within the hearing range of phocid seals (<100 Hz); however, no aversion to sound was observed for ringed seals (Blackwell et al. 2004b). In the North Sea, high frequency odontocete species, such as harbor porpoises, have been found feeding around offshore drilling rigs and platforms during routine drilling and production operations at relatively low sound pressure levels (120 dB re 1 µPa) (Todd et al. 2009). The lack of behavioral response from harbor porpoises to drilling sounds could cause acoustic masking; however, this impact was not discussed within this study (Todd et al. 2009).

The potential impacts on marine mammals from underwater sound exposure produced by drilling operations may be behavioral disruption, acoustic masking, and physiological responses (i.e. stress) (Richardson et al. 1999, Miller et al. 2005, Blackwell et al. 2017). These responses are expected when underwater sounds associated with drilling activities are above marine mammal behavioral thresholds (NOAA 2005). However, past research suggests not all marine mammals respond negatively to drilling operations and any reactions to this source are short-term (Blackwell et al. 2004b, Todd et al. 2009). In addition, most behavioral reactions have been reported in response to oil production drilling, whereas drilling operations associated with wind farm construction activities would be of a much smaller magnitude. Sounds emitted by offshore drilling activities for wind farm development are non-impulsive and intermittent, which makes this activity unlikely to cause prolonged behavioral responses or acoustic masking. Given the short-duration and non-impulsive nature of this source, behavioral responses to underwater marine drilling sounds during the construction phase are expected to be minor.

C.4.3. Sea Turtles

There is insufficient information on the impacts of underwater drilling sounds to sea turtles. However, sea turtle hearing sensitivity is within the frequency range (100-1000 Hz) of sound produced by low-frequency sources such as marine drilling (for a summary, see Popper et al. 2014). Sound levels emitted by construction drilling operations are likely to be audible to sea turtles. However, it is unlikely that the sound from construction drilling operations will reach behavioral thresholds, and even more unlikely that the sound will reach injury thresholds, unless the sea turtle is within close proximity to the drilling activity (McCauley et al. 2000a, Dow Piniak et al. 2012, Finneran et al. 2017). Risks of impact are expected to be low, but further research is required to understand the potential effects of marine drilling noise during wind turbine installation to sea turtles.

C.4.4. Fish

It is unclear whether or not the sound emitted by marine drilling activities impact fish. The available literature suggests that noise effects on fish produced by continuous drilling operations may mask acoustic signals conveying important environmental information (McCauley 1994, Popper et al. 2014). Masking may arise when sounds exceed the hearing thresholds of fish and it is probable that, within close proximity to drilling operations, sounds would reach above the recommend thresholds. McCauley (1998) determined that any noise effects to fish from marine drilling activity would likely be temporary behavioral changes within a few hundred meters of the source. For instance, measured source levels during drilling operations reached 120 dB at 3-5 km, which may have caused fish avoidance (McCauley 1998). Recordings of planktivorous fish choruses were still active during drilling operations off the coast of the Timor Sea; however, it is likely that partial masking of their calls would have occurred (McCauley 1998). The sounds emitted by marine drilling operations for wind farm construction are expected to be short-term and intermittent. It is therefore unlikely that the acoustic characteristics of this source will cause prolonged acoustic masking to fish and the risk of impact from this activity is expected to be low.

C.4.5. Invertebrates

There are no data on the effect of sound from drilling on marine invertebrates. However, evidence from research on the levels of particle motion associated with behavioral responses in blue mussels indicates that the threshold of sensitivity in this species falls within vibration levels measured near blasting, pile driving, and impact drilling (Roberts et al. 2015b). Only a small number of studies have indicated reception of vibration in bivalves and an associated behavioral response, which included closing syphons and, in more active mollusks, moving away from the substrate (Mosher 1972, Ellers 1995, Kastelein 2008). Anticipated drilling for the Project is typically short duration and intermittent, so it is unlikely that drilling has more than short-term consequences. Risk of impact to invertebrates from sounds emitted by marine drilling are expected to be low.

C.4.6. Monitoring and Mitigation

Recorded drilling operation source levels were highly variable, ranging from 123 dB to 184 dB SPL for oil production drilling (Greene 1987, Blackwell et al. 2004a, Dow Piniak et al. 2012). While received sound levels could exceed behavioral response thresholds for some marine fauna, the limited area of ensonification and intermittent nature of drilling operations mean the noise impacts from this activity are expected to be very low to low. Currently, no monitoring or mitigation practices are used for sound produced by underwater drilling.

C.5. Dredging

Dredging is most often used to create or maintain depth in channels or harbors by removing materials from the seafloor, but other uses for dredging include contaminated sediment removal, flood/storm protection, extraction of mineral resources, and fishing benthic species. As it pertains to offshore wind, dredging may be used to remove materials from the seafloor in preparation of offshore foundation and export cable locations.

There are two fundamental types of dredge that could be used by the Project – mechanical and hydraulic. Mechanical dredging refers to crane-operated buckets, grabs (clamshell), or backhoes used to remove seafloor material. Hydraulic (suction) dredging and controlled flow excavation (CFE) dredging involve the use of a suction to either remove sediment from the seabed or relocate sediment from a particular location on the seafloor. There are a variety of hydraulic and CFE dredge types including trailing suction, cutter-suction, auger suction, jet-lift, and air-lift. The sound produced by hydraulic dredging results from the combination of sounds generated by the impact and abrasion of the sediment passing through the draghead, suction pipe, and pump. The frequency of the sounds produced range from ~1 to 2 kHz, with reported sound levels from 172 to 190 dB re 1 µPa for suction dredges (Robinson et al. 2011, Todd et al. 2015, McQueen 2019).

There is limited research on the impacts of underwater noise related to dredging activity on marine fauna. It is unlikely that dredging operations will exceed the marine mammal, sea turtle, and fish injury thresholds unless animals are within the immediate vicinity of the operating equipment (McCauley et al. 2000b, Popper et al. 2014, Todd et al. 2015, Finneran et al. 2017, NMFS 2018). Further information is required to determine the effects of dredging activity to underwater invertebrates (Hawkins et al. 2015). Overall, the impacts of dredging are expected to be expected to be very low to low.

C.5.1. Potential Impacts to Marine Fauna

C.5.1.1. Marine Mammals

Few studies have investigated the direct effects of sound of dredging on marine mammals. The topic is further confounded by the difficulty of separating the effects of dredging from other anthropogenic activity (such as vessel noise). Most marine mammals would not be expected to exceed PTS (injury) thresholds, but as dredging occurs in one area for relatively long periods, they may experience TTS and behavioral responses (Todd et al. 2015, NMFS 2018). A case study by McQueen et al. (2020) on the expected effects of underwater dredging noise concluded that although harbor porpoises may experience TTS within 74 m from the sound source there was no evidence of significant behavioral avoidance. However, the modeling scenario was based on relatively simple sound exposure estimates, there was uncertainty about sound propagation in the environment, and uncertainty in the exposure-response relationship in the behavior of the animals, leading the authors to conclude that the impacts may be underestimated (McQueen et al. 2020).

Although most research cannot isolate the acoustic impacts of dredging from other anthropogenic activity, there is evidence to suggest that it at least contributes to the negative effects observed on some marine mammals, including displacement in bowhead whales(Richardson et al. (1990b), grey whales Bryant et al. (1984), minke whales, Anderwald et al. (2013), and grey seals (*Halichoerus grypus*, Anderwald et al. (2013)). Diederichs et al. (2010) found short-term avoidance in harbor porpoises at ranges of 600 m from a dredger operating in the North Sea. However, the most compelling evidence for potential impacts of dredging is from research that used models to differentiate the observed impacts of dredging from the vessel traffic in a busy Scotland harbor (Pirotta et al. 2013). Despite a documented tolerance of high vessel presence, bottlenose dolphins spent less time in the area during periods of high-intensity dredging (Pirotta et al. 2013).

The few existing studies suggest that acoustic exposure from dredging operations may elicit behavioral responses or cause TTS to marine mammals close to the source. With the short-duration and intermittent sounds produced by dredging activities, risks to marine mammals are expected to be low.

C.5.1.2. Sea Turtles

While the acoustic impacts of dredging to sea turtles are expected to be similar to other secondary sound sources, the response thresholds for sea turtles are not well researched and are poorly understood relative to marine mammals. There are no thresholds suggested for sea turtles exposed to non-impulsive noise but suction dredging may produce sounds up to 190 dB re 1 µPa (Robinson et al. 2011, Todd et al. 2015), which exceeds the impulsive threshold of 175 dB re 1 µPa for behavioral disruption suggested by Finneran et al. (2017) (based on impulsive sounds studied by (McCauley et al. 2000a). Accumulated sound energy will not exceed the recommended sea turtle cumulative sound exposure threshold for TTS or PTS (SEL: 189 and 204 dB re 1 µPa, respectively) (Popper et al. 2014, Finneran et al. 2017).

There is currently no information on the direct effects of dredging noise on sea turtles (Popper et al. 2014). There is evidence, however, of potentially positive impacts of dredging to breeding flatback turtles (*Natator depressus*), which increased their use of a dredging area and made longer and deeper resting dives during dredging operations (Whittock et al. 2017). The most likely driver for the observed behavioral response was speculated to be the absence of predators which were displaced by the noise from dredging operations. In general, sound emitted by dredging operations is intermittent and typically short-term. The impacts of noise from dredging operations are likely to be very low to low.

C.5.1.3. Fish

Sound generated by dredging operations is assumed to be primarily relevant to fish that are sensitive to sound pressure (i.e., have swim bladders) (McQueen et al. 2020). However, underwater sound from activities such as dredging can cause avoidance behavior, which has been observed in Atlantic herring and Atlantic cod (Vabø et al. 2002, Handegard et al. 2003). It is unlikely that fish would be exposed to noise levels from dredging that would result in impairment or injury, but behavioral effects, such as auditory masking, could result from exposure to dredging noise (Popper et al. 2014, McQueen et al. 2020). Given that dredging operations are short-term and localized, the impacts from underwater noise to fish from are expected to be low.

C.5.1.4. Invertebrates

There is no available research on the effect of sound from dredging on invertebrates. Contact of the draghead with the seabed may result in substrate-borne vibration, which is likely to be of greater concern to benthic invertebrates than sound pressure (Roberts et al. 2015b, Roberts and Breithaupt 2016, Roberts and Elliott 2017). Only a small number of studies have indicated reception of vibration in bivalves and an associated behavioral response, which included closing syphons and, in more active mollusks, moving away from the substrate (Mosher 1972, Ellers 1995, Kastelein 2008). Nevertheless, to date, there is no convincing evidence for any significant effects induced by non-impulsive noise in benthic invertebrates. It is unlikely that these stimuli have more than short-term consequences so the potential impacts of dredging sounds to invertebrates are expected to be very low.

C.6. Wind Turbine Generator Operations

Sound is generated by operating wind turbine generators (WTGs) due to pressure differentials across the airfoils of moving turbine blades and from mechanical noise of bearings and the generator converting kinetic energy to electricity. Sound generated by the airfoils, like aircraft, is produced in air and enters the water through the air water interface. Mechanical noise associated with the operating WTG is transmitted into the water as vibration through the foundation and subsea cable. There is also a known particle motion component to noise from wind turbines (Sigray and Andersson 2012). Both airfoil sound and mechanical vibration may result in continuous underwater noise.

Underwater sound radiated from operating WTGs is low-frequency and low level (Nedwell and Edwards 2004). At distances of 14 to 20 m from operational WTGs in Europe, underwater sound pressure levels ranged from 109 dB to 127 dB re 1µPa (Tougaard et al. 2009). Pangerc et al. (2016) recorded sound levels at ~50 m from two individual 3.6 megawatt (MW) WTGs monopile foundations over a 21-day operating period. The sound pressure level increased with wind speed up to an average value of 128 dB re 1 µPa at a wind speed of ~10 m/s, and then showed a general decrease in sound levels with increasing wind speed as the turbine blades were feathered. Miller and Potty (2017) measured an SPL of 100 dB re 1 µPa within 50 m of five General Electric Haliade 150-6 MW wind turbines with a peak signal frequency of 72 Hz. At the Block Island Wind Farm off of Rhode Island, sound levels were found to be 112 -120 dB re 1 µPa near the WTG when wind speeds were 2 to 12 m/s and the WTG sound levels declined to ambient within 1 km from the WTG (Elliott et al. 2019). Tougaard et al. (2009) found that sound level from three different WTG types in European waters was only measurable above ambient sound levels at frequencies below 500 Hz, and Thomsen et al. (2016) suggest that at approximately 500 m from operating WTGs, sound levels are expected to approach ambient levels.
WTG foundation design was found to influence sound levels in the water as a function of distance. Sound levels measured at 150 m from a steel monopile WTG foundation were 133 dB re 1µPa with peak frequencies between 50-140 Hz, while measurements at 150 m from a jacket WTG foundation were 122 dB re 1µPa with a peak frequency of 50 Hz and secondary peaks at 150, 400, 500, and 1,200 Hz. However, at 40 m the sound pressure levels were comparable between the steel monopile (135 dB) and jacket foundation types (137 dB) (Thomsen et al. 2016).

Two recent meta-papers (Tougaard et al. 2020, Stöber and Thomsen 2021) assessed WTG operational sounds by extracting sound levels measured at various distances from operating WTGs from currently available reports. Tougaard et al. (2020) used a linear model to fit sound levels as a function of turbine size, wind speed, and distance. Their model suggested that sound from multiple WTGs would be detectable out to a few km in areas with very low ambient noise levels but would be below ambient unless "very close" to individual WTGs in areas with high ambient noise from shipping or wind. Notably, the available data were from lower-power WTGs than are currently being planned for the U.S. east coast, and primarily from geared, rather than direct drive, WTGs. Stöber and Thomsen (2021) attempted to fill this knowledge gap by extracting a strictly defined subset of the data used by Tougaard et al. (2020) to extrapolate sound levels to larger turbine sizes and to direct drive turbines. However, the small size of their data subset greatly increases the already considerable uncertainty of the modeling results. Additionally, their model assumed that SPL increases linearly with WTG capacity, which contrasts with what is known of typical mechanical systems. Both studies found sounds to generally be higher for higher powered WTGs, and thus distances to a given sound threshold are likely to be greater for higher powered WTGs. However, as Stöber and Thomsen (2021) point out, direct drive technology could reduce these distances substantially. Importantly, no measurements exist for these larger turbine sizes and few measurements have been made for direct drive turbines so the uncertainty in these estimates is large. The frequency and sound level generated from operating WTGs depend on WTG size, wind speed and rotation, foundation type, water depth, seafloor characteristics, and wave conditions (Cheesman 2016, Elliott et al. 2019). Operational noise from WTGs is low frequency (60 to 300 Hz) and at relatively low sound pressure levels near the foundation (100 to 151 dB re 1 µPa) and decreases to ambient within 1 km (Tougaard et al. 2009, Lindeboom et al. 2011, Dow Piniak et al. 2012). Underwater sounds emitted by WTGs are audible to marine mammals, sea turtles, fish, and invertebrates but are lower than the regulatory injury and typically lower than the behavioral thresholds for marine fauna, and often are lower than the ambient sound levels that these animals typically experience. It is unlikely that WTG operations will cause injury or behavioral responses to marine fauna, so the risk is of impact is expected to be low.

C.6.1. Potential Impacts to Marine Fauna

C.6.1.1. Marine Mammals

While underwater noise from WTGs has been measured within the hearing frequency range of marine mammals, impacts at the anticipated noise levels are limited to behavioral response and auditory masking (Bergström et al. 2014) (MMS 2007). Behavioral responses may include changes in foraging, socialization, or movement, including avoidance of the area. For example, there is evidence that harbor porpoises avoided WTGs during construction and initial operation (Teilmann and Carstensen 2012). However, they appeared to slowly increase their use of the WTG area during continued operation, demonstrating potential long-term habituation. This result also suggests that noise impacts are greater during construction than operation (Madsen et al. 2006). Harbor seals also show avoidance behavior when exposed to simulated sound from WTGs, however this response was limited to distances of less than 500m to the source (Hastie et al. 2018). Finally, research into both harbor porpoises and harbor seals demonstrated fewer surfacings when exposed to playbacks of noise from WTGs, but this response was limited to 200m from the source (Koschinski et al. 2003)

Auditory masking could also impact marine mammals, potentially affecting foraging, social interactions, and predator avoidance (Weilgart 2007, Erbe et al. 2016b). The potential for masking is highly dependent on the species in question, and those with low-frequency hearing will be more susceptible due to the overlap with the frequency range of WTG underwater noise.

Research with captive harbor porpoises indicated the potential for auditory masking from simulated WTG underwater noise. As with behavioral responses, the area of impact was predicted to be relatively close to the source (10-20m) (Lucke et al. 2007).Therefore, the potential for auditory masking is likely limited to short ranges from the WTG.

Tougaard et al. (2020) estimated that WTG sounds would drop below the 120-dB re 1 µPa U.S. regulatory threshold for marine mammal behavioral impacts from continuous sounds (NMFS 2005) within approximately 50-100 m of the WTG, using currently available sound measurements taken at various distances from operational WTGs. These WTGs all had a lower capacity than those planned for installation off the US east coast and most were from geared-drive WTGs. Thus, Stöber and Thomsen (2021) extrapolated sound levels to larger WTG sizes, and found the distance to the behavioral threshold could extend out to several kilometers. However, the small size of their dataset and choice of modeling methods make these predicted distances unreliable. Additionally, those authors suggest that this distance could be reduced substantially (almost fivefold) for newer direct drive WTGs. The authors also noted that larger sized wind farms, for which data are nonexistent, might only have limited impacts related to behavioral response in marine mammals.

Overall, noise generated from WTG operation is minor and does not cause injury or lead to permanent avoidance at distances greater than 0.5 nm (1 km) for the species studied (e.g., harbor porpoise, seals, and fish) (Wahlberg and Westerberg 2005, Stenberg et al. 2015), with potential to have minimal effects at much closer distances up to within a few meters of the WTG (Bergström et al. 2013). Underwater noise impact to marine mammals associated with WTG operation is expected to be very low to low.

C.6.1.2. Sea Turtles

Low-frequency sound emitted by WTG is of concern for sea turtles. Their most sensitive hearing range is confined to low frequencies (Ridgway et al. 1969, Bartol et al. 1999), and sea turtles have shown behavioral avoidance to low frequency sound (O'Hara and Wilcox 1990, Dow Piniak et al. 2012). Operational WTG underwater noise may be slightly higher than ambient sound however, WTG sound levels decline to ambient levels within 1 km from the turbine (Kraus et al. 2016, Elliott et al. 2019). Because of these lower sound levels, sea turtles are unlikely to detect sounds generated by WTGs at large distances away from the Project in the presences of ambient sound. Therefore, sea turtles are at very low risk from exposure due to WTG noise. Any behavioral changes caused by exposure to WTG underwater sounds are expected to be short-term and localized to areas near the WTGs.

C.6.1.3. Fish

Underwater sound generated by operating WTGs is in the best hearing frequency range of fish but is of low intensity (Madsen et al. 2006). The measured sound levels are well below existing non-impulsive acoustic thresholds for injury or behavioral response in fish (McCauley et al. 2000b, Popper et al. 2014, Finneran et al. 2017). While the underwater sound levels are related to WTG power and wind speed, with increased wind speeds creating increased underwater sound levels, even at high wind speeds Wahlberg and Westerberg (2005) estimated permanent avoidance by fish would only occur within four meters of a WTG foundation. Stöber and Thomsen (2021) extrapolated measured sound levels to larger WTG sizes and found larger distances to a given sound threshold but noted that impacts might be limited to behavioral responses in fishes that could be offset by benefits from lower fishing effort and the creation of artificial reefs at wind farm sites.

In a study on fish near the Svante wind farm in Sweden, Atlantic cod, and roach (*Rutilus rutilus*) catch rates were significantly higher near turbines when the rotors were stopped, which could indicate fish attraction to turbine structure and avoidance to noise when operational (Westerberg 2000 as cited in Thomsen et al. 2006). In another study, no avoidance behavior was observed as fish densities increased around turbine foundations of the Lillgrund offshore wind farm in Sweden (Bergström et al. 2014). It is important to note that ambient sound levels can influence how fish detect other sounds and a change in background noise could alter how fish perceive and react to biological stimuli (Popper and Fay 1993). Current understanding is that underwater noise generated by WTG operation is of minor significance for fish (Wahlberg and Westerberg 2005, Stenberg et al. 2015). Underwater noise risks to fish associated with WTG operation is expected to be low.

C.6.1.4. Invertebrates

There is limited data on the effects of underwater sound from operating WTGs on invertebrates. Pine et al. (2012) found potential impacts on the median time to metamorphosis of estuarine crabs (*Austrohelice crassa* and *Hemigrapsus crenulatus*), although this experiment only measured the sound pressure level, not particle motion. Invertebrates may be susceptible to detecting particle motion produced by operational WTGs at the seabed, which could cause a behavioral response (Roberts et al. 2015b, Roberts and Breithaupt 2016, Roberts and Elliott 2017). However, there is a paucity of data regarding responses of invertebrates to acoustic exposure, and no studies of noise-induced hearing effects. Overall, risks are expected to be very low.

C.6.1.5. Monitoring and Mitigation

Noise generated by operating WTGs is typically below regulatory thresholds for injury and behavioral disruption, and does not lead to permanent avoidance at distances >1 km for the species studied (e.g., harbor porpoise, seals, and fish) (Wahlberg and Westerberg 2005, Stenberg et al. 2015). Although there are potential behavioral impacts within a few meters of an operational WTG (Bergström et al. 2013), the risks are very low to low and no mitigation or monitoring is used for underwater sound produced by WTG operations.

C.7. Impact Risk Definitions

Risk rankings of secondary sound sources are very low, low, moderate, or high based on the probability of marine fauna exposure and the vulnerability of the marine species to a particular development stressor (Table C-1). Marine species occurrence and their relationships to the established criteria were evaluated using: existing literature on marine mammal, sea turtle, fish distribution and presence/use of Lease Area OCS-A 0487, information on the potential impacts of offshore wind farm construction and operations in both the U.S and globally, and studies that provide a general understanding of hearing, response to anthropogenic sound, and other factors that influence the potential underwater noise impacts of offshore wind construction, operations, and decommissioning activities on marine fauna.

Table C-1. Definitions of Impact Risk, Exposure, and Vulnerability used in Impact Assessment

Risk level	Exposure	Individual vulnerability
Very low	• No or limited observations of the species in or near the proposed Project infrastructure and acoustic exposure zones (low expected occurrence), and/or • Species tends to occur mainly in other habitat (e.g., deeper water or at lower/higher latitudes), and/or • No indication that the Lease Area has regional importance as it pertains to a particular species life history characteristics.	• Literature and/or research suggest the affected species and timing of the stressor are not likely to overlap, and/or • Literature suggests limited sensitivity to the stressor, and/or • Little or no evidence of impacts from the stressor in the literature.
Low	• Few observations of the species in or near the proposed Project infrastructure and noise exposure zones (occasional occurrence), and/or • Seasonal pattern of occurrence in or near the proposed Project infrastructure and acoustic exposure zones.	• Literature and/or research suggest the affected species and timing of the stressor may overlap and/or • Literature suggests some low sensitivity to the stressor and/or • Literature suggests impacts are typically short-term (end within days or weeks of exposure) and/or • Literature describes mitigation/best management practices (BMPs) that reduce risk
Moderate	• Moderate year-round use of the areas associated with proposed Project infrastructure and acoustic exposure zones	• Literature and/or research suggest the affected species and timing of the stressor are likely to overlap, and/or • Literature and/or research suggest a moderate susceptibility to the stressor exists in the region and/or from similar activities elsewhere, and • Literature does not describe mitigation/BMPs that reduce risk.
High	• Significant year-round use of the areas associated with proposed Project infrastructure and acoustic exposure zones	• Literature and/or research suggest the affected species and timing of the stressor will overlap, and • Literature suggests significant use of WTA and ECC and acoustic exposure zones for feeding, breeding, or migration, and • Literature does not describe mitigation/BMPs that reduce risk.

Appendix D. Underwater Acoustics

This section provides a detailed description of the acoustic metrics relevant to the modeling study and the modeling methodology.

D.1. Acoustic Metrics

Underwater sound pressure amplitude is measured in decibels (dB) relative to a fixed reference pressure of p_0 = 1 μPa in water and p_0 = 20 μPa in air. Because the perceived loudness of sound, especially impulsive noise 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 noise and its effects on marine life. Here we provide specific definitions of relevant metrics used in the accompanying report. Where possible, we follow ISO standard definitions and symbols for sound metrics (e.g., ISO 2017).

The zero-to-peak sound pressure, or peak sound pressure (PK or L_{pk}; dB re 1 μPa), is the decibel level of the maximum instantaneous acoustic pressure in a stated frequency band attained by an acoustic pressure signal, $p(t)$:

$$L_{p,\mathrm{pk}} = 10\log_{10}\frac{\max|p^2(t)|}{p_0^2} = 20\log_{10}\frac{\max|p(t)|}{p_0} \tag{D-1}$$

PK is often included as a criterion for assessing whether a sound is potentially injurious; however, because it does not account for the duration of a noise event, it is generally a poor indicator of perceived loudness.

The peak-to-peak sound pressure (PK-PK or $L_{pk\text{-}\mathrm{pk}}$; dB re 1 μPa) is the difference between the maximum and minimum instantaneous sound pressure, possibly filtered in a stated frequency band, attained by an impulsive sound, $p(t)$:

$$L_{p,\mathrm{pk\text{-}pk}} = 10\log_{10}\frac{[\max(p(t)) - \min(p(t))]^2}{p_0^2} \tag{D-2}$$

The sound pressure level (SPL or L_p; dB re 1 μPa) is the root-mean-square (rms) pressure level in a stated frequency band over a specified time window (T; s). It is important to note that SPL always refers to an rms pressure level and therefore not instantaneous pressure:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T g(t)\,p^2(t)\,dt \Big/ p_0^2\right)\,\mathrm{dB} \tag{D-3}$$

where $g(t)$ is an optional time weighting function. In many cases, the start time of the integration is marched forward in small time steps to produce a time-varying L_p 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 L_p ($L_{p,\mathrm{fast}}$) 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

$L_{p,\text{boxcar 125ms}}$. Another approach, historically used to evaluate L_p 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):

$$L_E = 10\log_{10}\left(\int_T p^2(t)\,dt \Big/ T_0 p_0^2\right)\text{ dB} \tag{D-4}$$

where T_0 is a reference time interval of 1 s. L_E 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 in terms of relevance for 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 impulsive 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:

$$L_{E,N} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{E,i}}{10}}\right)\text{ dB} \tag{D-5}$$

D.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, analyzing 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 center frequency of the ith band, $f_c(i)$, is defined as:

$$f_c(i) = 10^{\frac{i}{10}}\text{ kHz} \tag{D-6}$$

and the low (f_{lo}) and high (f_{hi}) frequency limits of the ith decade band are defined as:

$$f_c(i) = 10^{\frac{i}{10}}\text{ kHz} \tag{D-7}$$

The decidecade bands become wider with increasing frequency, and on a logarithmic scale the bands appear equally spaced (Figure D-1). The acoustic modeling spans from band −24 (f_c (−24) = 0.004 kHz) to band 14 (f_c (14) = 25 kHz).

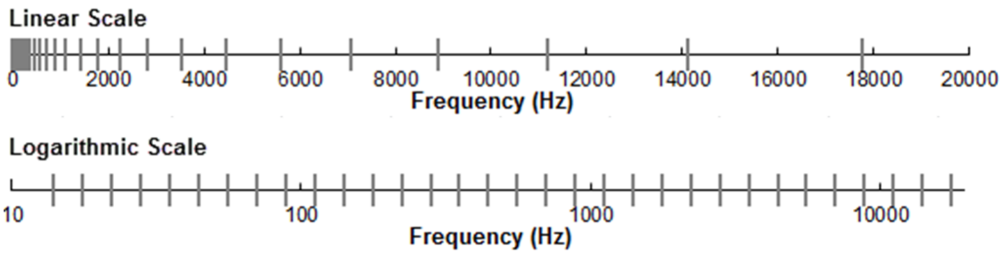

Figure D-1. Decidecade frequency bands (vertical lines) shown on a linear frequency scale and a logarithmic scale.

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

$$L_{p,i} = 10\log_{10}\int_{f_{\text{lo},i}}^{f_{\text{hi},i}} S(f)\,df \tag{D-8}$$

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

$$\text{Broadband SPL} = 10\log_{10}\sum_i 10^{\frac{L_{p,i}}{10}} \tag{D-9}$$

Figure D-2 shows an example of how the decidecade band sound pressure levels compare to the sound pressure spectral density levels of an ambient noise signal. Because the decidecade bands are wider than 1 Hz, the decidecade band SPL is higher than the spectral levels at higher frequencies. Acoustic modeling 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.

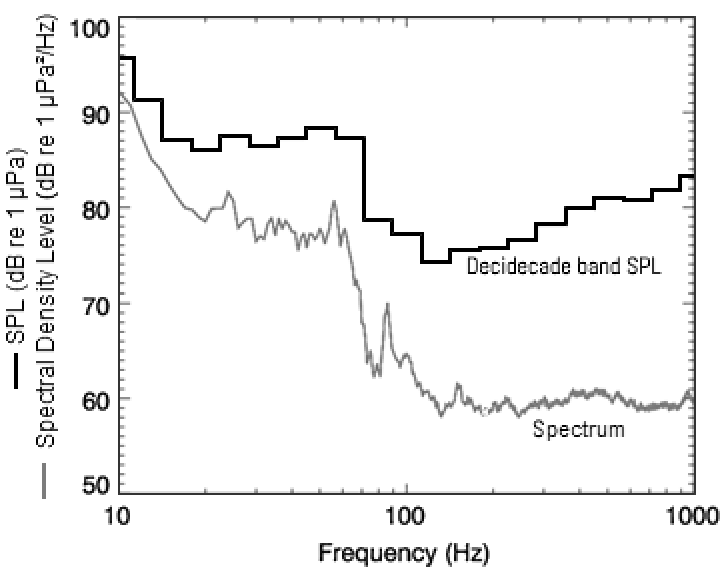

Figure D-2. Sound pressure spectral density levels and the corresponding decidecade band sound pressure levels of example ambient noise shown on a logarithmic frequency scale. Because the decidecade bands are wider with increasing frequency, the decidecade band SPL is higher than the power spectrum.

Appendix E. Auditory (Frequency) Weighting Functions

The potential for noise to affect animals of a certain species 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).

E.1. Frequency Weighting Functions-Technical Guidance (NMFS 2018)

In 2015, a U.S. 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. This frequency-weighting function is expressed as:

$$G(f) = K + 10\log_{10}\left[\left(\frac{(f/f_{lo})^{2a}}{\left[1+(f/f_{lo})^2\right]^a\left[1+(f/f_{hi})^2\right]^b}\right)\right]. \quad \text{(E-1)}$$

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, 2018). Table E-1 lists the frequency-weighting parameters for each hearing group; Figure E-1 shows the resulting frequency-weighting curves.

In 2017, the Criteria and Thresholds for US Navy Acoustic and Explosive Effects Analysis (Finneran et al. 2017) updated the auditory weighting functions to include sea turtles. The sea turtle weighting curve uses the same equation used for marine mammal auditory weighting functions (Equation E-1). Parameters are provided in Table E-1.

Table E-1. Parameters for the auditory weighting functions recommended by NMFS (2018).

Hearing group	a	b	f_{lo} (Hz)	f_{hi} (kHz)	K (dB)
Low-frequency cetaceans	1.0	2	200	19,000	0.13
Mid-frequency cetaceans	1.6	2	8,800	110,000	1.20
High-frequency cetaceans	1.8	2	12,000	140,000	1.36
Phocid pinnipeds in water	1.0	2	1,900	30,000	0.75
Otariid pinnipeds in water	2.0	2	940	25,000	0.64
Sea turtles	1.4	2	77	440	2.35

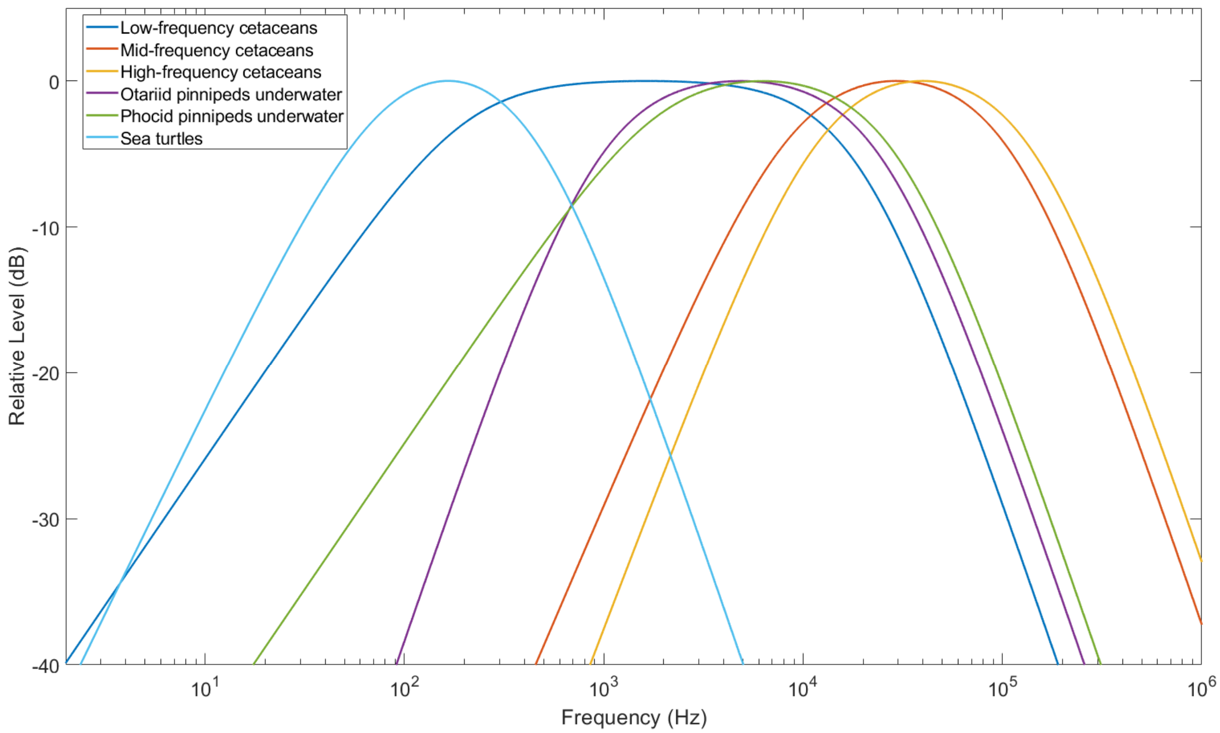

Figure E-1. Auditory weighting functions for the functional marine mammal hearing groups as recommended by NMFS (2018).

E.2. Southall et al. (2019) Frequency Weighting Functions

Auditory weighting functions for marine mammals—called M-weighting functions—were proposed by Southall et al. (2007). These M-weighting functions are applied in a similar way as A-weighting for noise level assessments for humans. Functions were defined for five hearing groups of marine mammals:

- Low-frequency (LF) cetaceans—mysticetes (baleen whales)
- Mid-frequency (MF) cetaceans—some odontocetes (toothed whales)
- High-frequency (HF) cetaceans—odontocetes specialized for using high-frequencies
- Pinnipeds in water (Pw)—seals, sea lions, and walrus
- Pinnipeds in air (not addressed here)

The M-weighting functions have unity gain (0 dB) through the passband and their high- and low-frequency roll-offs are approximately –12 dB per octave. The amplitude response in the frequency domain of each M-weighting function is defined by:

$$G(f) = -20\log_{10}\left[\left(1+\frac{a^2}{f^2}\right)\left(1+\frac{f^2}{b^2}\right)\right] \quad \text{(E-2)}$$

where $G(f)$ is the weighting function amplitude (in dB) at the frequency f (in Hz), and a and b are the estimated lower and upper hearing limits, respectively, which control the roll-off and passband of the weighting function. The parameters a and b are defined uniquely for each hearing group (Table E-2). Figure E-2 shows the auditory weighting functions.

Table E-2. Parameters for the auditory weighting functions recommended by Southall et al. (2007).

Functional hearing group	*a* (Hz)	*b* (Hz)
Low-frequency cetaceans	7	22,000
Mid-frequency cetaceans	150	160,000
High-frequency cetaceans	200	180,000
Pinnipeds in water	75	75,000

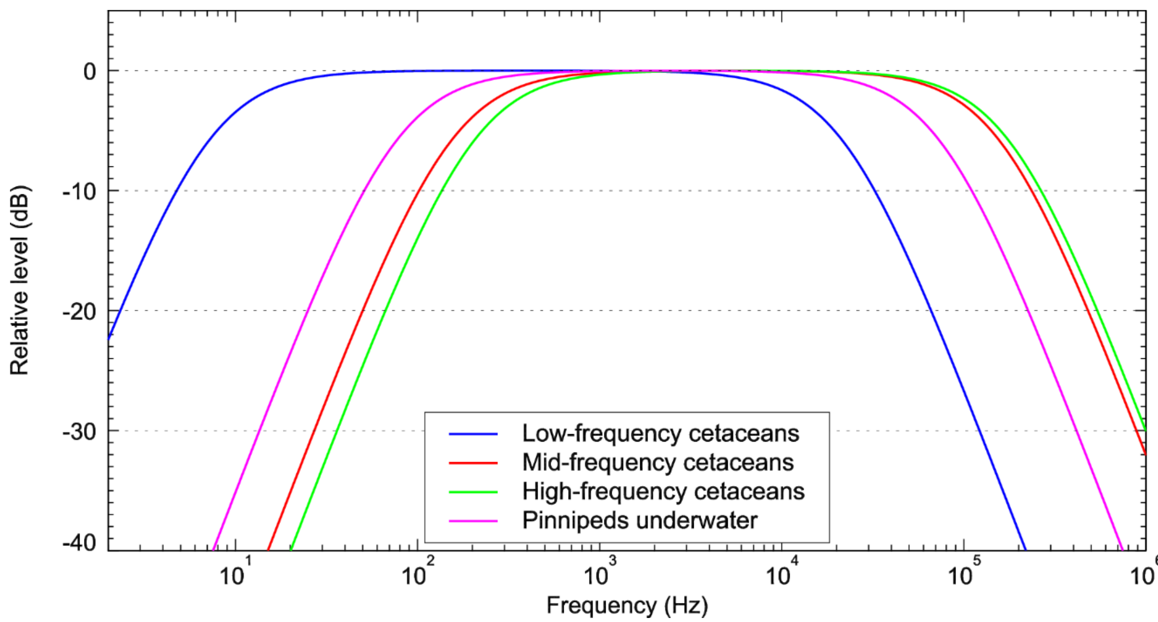

Figure E-2. Auditory weighting functions for the functional marine mammal hearing groups as recommended by Southall et al. (2007).

Appendix F. Source Models

F.1. Pile Driving Source Model (PDSM)

A physical model of pile vibration and near-field sound radiation is used to calculate source levels of piles. The physical model employed in this study computes the underwater vibration and sound radiation of a pile by solving the theoretical equations of motion for axial and radial vibrations of a cylindrical shell. These equations of motion are solved subject to boundary conditions, which describe the forcing function of the hammer at the top of the pile and the soil resistance at the base of the pile (Figure F-1). Damping of the pile vibration due to radiation loading is computed for Mach waves emanating from the pile wall. The equations of motion are discretised using the finite difference (FD) method and are solved on a discrete time and depth mesh.

To model the sound emissions from the piles, the force of the pile driving hammers also had to be modeled. The force at the top of each pile was computed using the GRLWEAP 2010 wave equation model (GRLWEAP, Pile Dynamics 2010), which includes a large database of simulated hammers—both impact and vibratory—based on the manufacturer's specifications. The forcing functions from GRLWEAP were used as inputs to the FD model to compute the resulting pile vibrations.

The sound radiating from the pile itself is simulated using a vertical array of discrete point sources. The point sources are centered on the pile axis. Their amplitudes are derived using an inverse technique, such that their collective particle velocity, calculated using a near-field wave-number integration model, matches the particle velocity in the water at the pile wall. The sound field propagating away from the vertical source array is then calculated using a time-domain acoustic propagation model (see Appendix G.3). MacGillivray (2014) describes the theory behind the physical model in more detail.

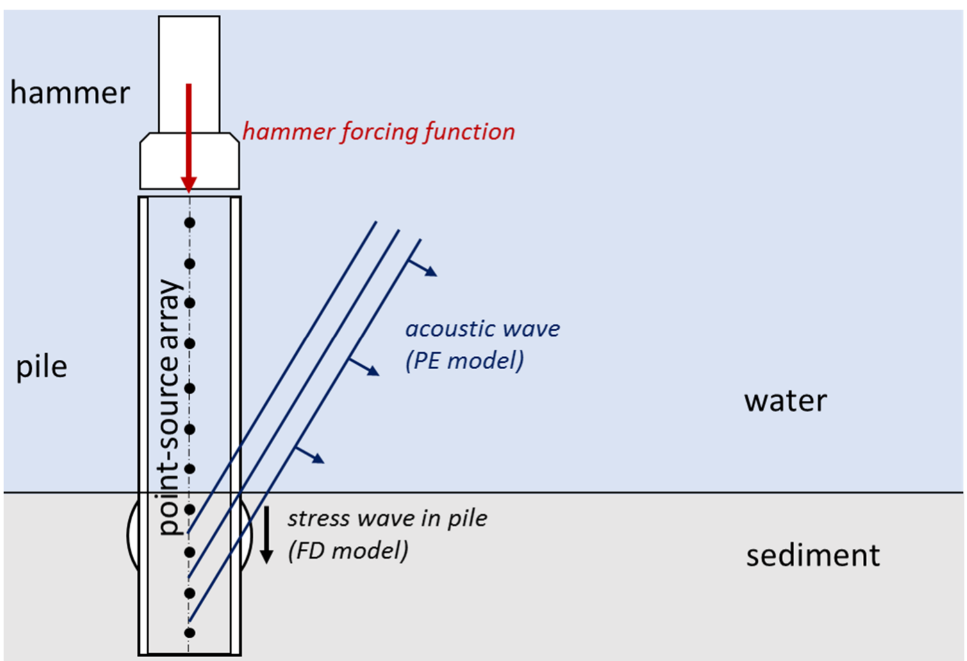

Figure F-1. Physical model geometry for impact driving of a cylindrical pile (vertical cross-section). The hammer forcing function is used with the finite difference (FD) model to compute the stress wave vibration in the pile. A vertical array of point sources is used with the parabolic equation (PE) model to compute the acoustic waves that the pile wall radiates.

Appendix G. Sound Propagation Modeling

G.1. Environmental Parameters

G.1.1. Bathymetry

A bathymetry grid for the acoustic propagation model was compiled based on the General Bathymetric Chart of the Oceans (GEBCO Bathymetric Compilation Group 2020). These data were chosen due to their finer resolution and for being available in a gridded format, which is easily input into JASCO's propagation models. This data set has a spatial resolution of 15 arc seconds, the elevation data is referred to Mean Sea Level, and the grid is assumed to be relative to the WGS84 datum.

G.1.2. Geoacoustics

In shallow water environments where there is increased interaction with the seafloor, the properties of the substrate have a large influence over the sound propagation. A simplified geoacoustic profile was developed from site specific seabed layering information provided by OCW01. This profile consisted of a top layer of sand, a second layer of slightly denser sand, a stiff clay layer, and sand below. Table G-1 shows the sediment layer geoacoustic property profile based on the sediment type and generic porosity-depth profile using a sediment grain-shearing model (Buckingham 2005).

Table G-1. Estimated geoacoustic properties for summer conditions used for modeling, as a function of depth. Within an indicated depth range, the parameters vary linearly.

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)
0–8.5	Sand	2.014–2.025	1,742–1,753	0.88–0.878	300	3.65
8.5–17		2.025–2.037	1,753–1,764	0.878–0.876		
17	Denser Sand	2.185	1,835	0.864		
17–26		2.185–2.197	1,835–1,847	0.864–0.861		
26–35		2.197–2.209	1,847–1,858	0.861–0.858		
35	Stiff Clay	1.954	1,636	0.47		
35–41		1.954	1,636–1,642	0.47–0.494		
41–45		1.954	1,642–1,646	0.494–0.509		
45–57		1.954	1,646–1,656	0.509–0.549		
57	Sand	2.161	1,849	0.863		
57–204.67		2.161–2.342	1,849–2,015	0.863–0.804		
204.67–352.33		2.342–2.5	2,015–2,155	0.804–0.734		
352.33–500		2.5–2.634	2,155–2,275	0.734–0.663		
>500		2.634	2,275	0.663		

Table G-2. Estimated geoacoustic properties for winter conditions used for modeling, as a function of depth. Within an indicated depth range, the parameters vary linearly.

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)
0–8.5	Sand	2.01–2.025	1,729–1,740	0.88–0.878	300	3.65
8.5–17		2.025–2.037	1,740–1,751	0.878–0.876		
17	Denser Sand	2.185	1,822	0.865		
17–26		2.185–2.197	1,822–1,833	0.865–0.862		
26–35		2.197–2.209	1,833–1,845	0.862–0.858		
35	Stiff Clay	1.949	1,625	0.475		
35–41		1.949	1,625–1,632	0.475–0.5		
41–45		1.949	1,632–1,636	0.5–0.515		
45–57		1.949	1,636–1,646	0.515–0.555		
57	Sand	2.161	1,835	0.863		
57–204.67		2.161–2.342	1,835–2,001	0.863–0.805		
204.67–352.33		2.342–2.5	2,001–2,142	0.805–0.736		
352.33–500		2.5–2.634	2,142–2,262	0.736–0.665		
>500		2.634	2,262	0.665		

G.1.3. Sound Speed Profile

The speed of sound in sea water is a function of temperature, salinity, and pressure (depth) (Coppens 1981). Sound speed profiles were obtained from the US Navy's Generalized Digital Environmental Model (GDEM; NAVO 2003). Considering the greater area around the proposed construction area and deep waters, the shape of the sound speed profiles do not change much in summer (Figure G-1). The mean sound speed profile for spring also did not differ much from the summer mean profile; therefore, the summer average was used for the acoustic modeling. Water depths in the OCW01 are less than 60 m mean lower low water (MLLW). An average profile, obtained by calculating the mean of all summer profiles shown in Figure G-1, was assumed to be representative of the entire area for modeling purposes.

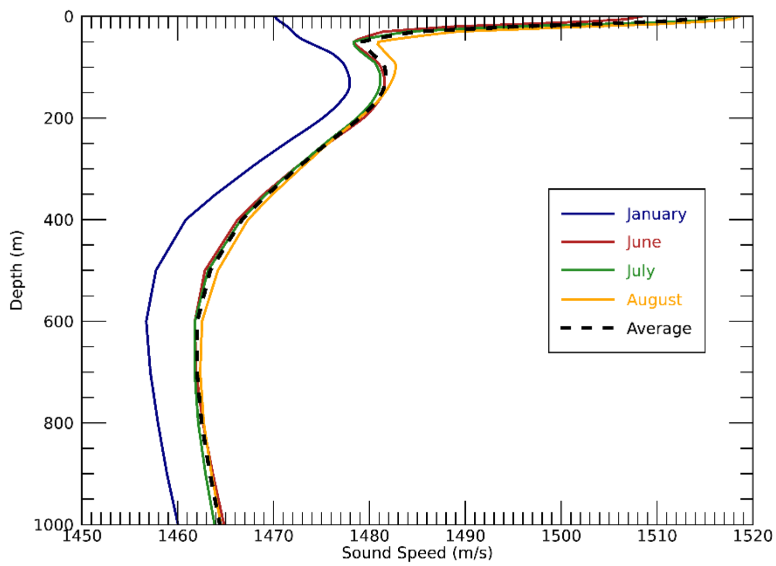

Figure G-1. Sound speed profiles up to 1000 m for the month of January (winter), the months of June through August and the average of these months (summer) used in the modeling for Ocean Wind Farm (OCW01).

G.2. Propagation Loss

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

If the acoustic energy source level ($L_{S,E}$), expressed in dB re 1 µPa²m²s, and energy propagation loss ($N_{\mathrm{PL},E}$), in units of dB, at a given frequency are known, then the received level ($L_{E,p}$) at a receiver location can be calculated in dB re 1 µPa²s by:

$$L_{E,p}(\theta,r) = L_{S,E}(\theta) - N_{\mathrm{PL},E}(\theta,r), \tag{G-1}$$

where θ defines the specific direction, and r is the distance of the receiver from the source.

G.3. Sound Propagation with MONM

Transmission loss (i.e., sound propagation) can be predicted with JASCO's Marine Operations Noise Model (MONM). MONM computes received sound energy, the sound exposure level (L_E), for directional sources. MONM uses a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). 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). MONM accounts for the additional reflection loss at the seabed due to 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 site-specific environmental properties, such as bathymetry, underwater sound speed as a function of depth, and a geoacoustic profile the seafloor.

MONM treats frequency dependence by computing acoustic transmission loss at the center frequencies of decidecade bands. At each center frequency, the transmission loss is modeled as a function of depth and range from the source. Composite broadband received SEL are then computed by summing the received decidecade band levels across the modeled frequency range.

For computational efficiency, MONM and similar models such as PE-RAM, do not track temporal aspects of the propagating signal (as opposed to models that can output time-domain pressure signals, see Appendix G.4). It is the total sound energy transmission loss that is calculated. For our purposes, that is equivalent to propagating the L_E acoustic metric. For continuous, steady-state signals SPL is readily obtained from the SEL.

Acoustic fields in three dimensions are generated by modeling propagation loss within two-dimensional (2-D) vertical planes aligned along radials covering a 360° swath from the source, an approach commonly referred to as N×2-D (Figure G-2). These vertical radial planes are separated by an angular step size of $\Delta\theta$, yielding N = 360°/$\Delta\theta$ planes.

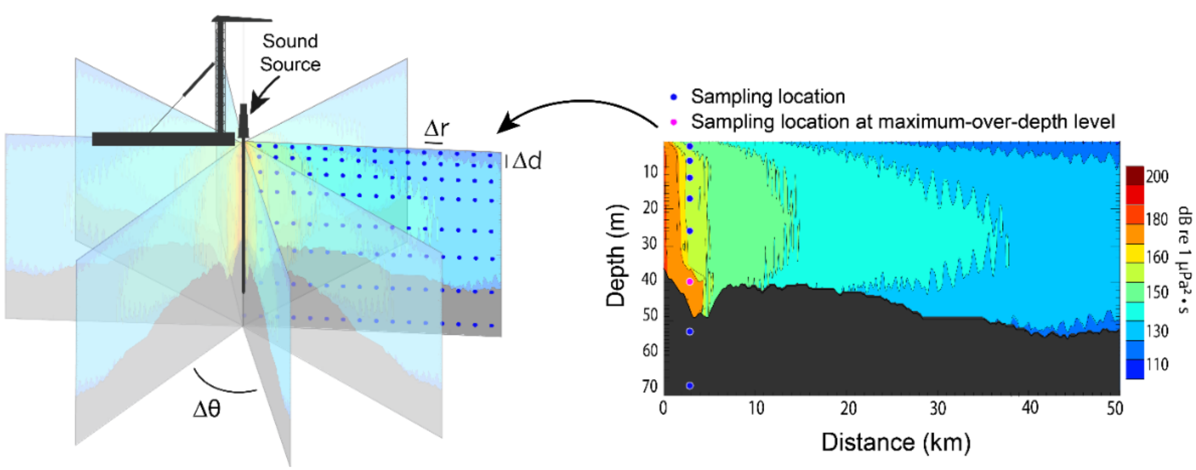

Figure G-2. Modeled three-dimensional sound field (N×2-D method) and maximum-over-depth modeling approach. Sampling locations are shown as blue dots on both figures. On the right panel, the pink dot represents the sampling location where the sound level is maximum over the water column. This maximum-over-depth level is used in calculating distances to sound level thresholds for some marine animals.

G.4. Sound Propagation with FWRAM

For impulsive sounds from impact pile driving, time-domain representations of the pressure waves generated in the water are required for calculating SPL and peak pressure level. Furthermore, the pile must be represented as a distributed source to accurately characterize vertical directivity effects in the near-field zone. For this study, synthetic pressure waveforms were computed using FWRAM, which is a time-domain acoustic model based on the same wide-angle parabolic equation (PE) algorithm as MONM. FWRAM computes synthetic pressure waveforms versus range and depth for range-varying marine acoustic environments, and it takes the same environmental inputs as MONM (bathymetry, water sound speed profile, and seabed geoacoustic profile). Unlike MONM, FWRAM computes pressure waveforms via Fourier synthesis of the modeled acoustic transfer function in closely spaced frequency bands. FWRAM employs the array starter method to accurately model sound propagation from a spatially distributed source (MacGillivray and Chapman 2012).

Synthetic pressure waveforms were modeled over the frequency range 10–2048 Hz, inside a 1 s window (e.g., Figure G-3). The synthetic pressure waveforms were post-processed, after applying a travel time correction, to calculate standard SPL and SEL metrics versus range and depth from the source.

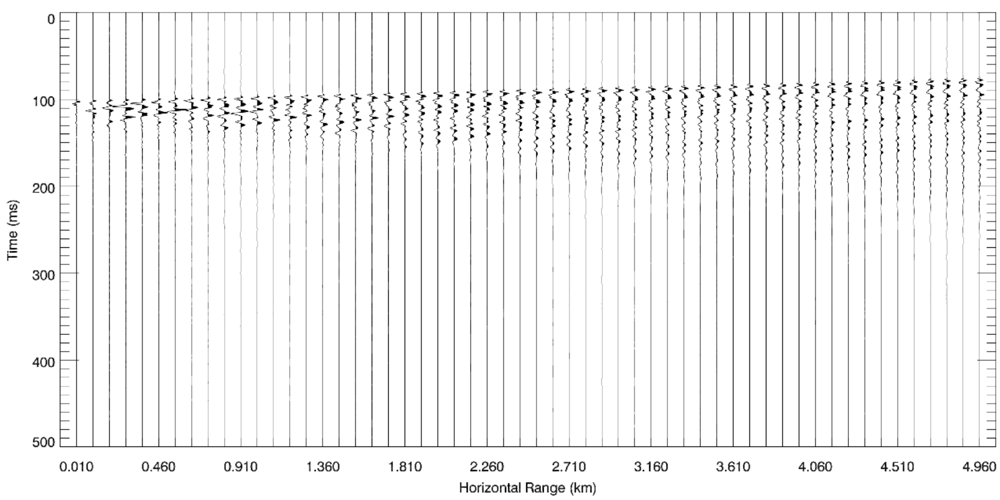

Figure G-3. Example of synthetic pressure waveforms computed by FWRAM at multiple range offsets. Receiver depth is 35 m and the amplitudes of the pressure traces have been normalised for display purposes.

G.5. Estimating Acoustic Distance to Threshold Levels

A maximum-over depth approach is used to determine acoustic distances to the defined thresholds (distances to isopleths). That is, at each horizontal sampling distance, the maximum received level that occurs within the water column is used as the value at that distance. The distances to a threshold typically differ along different radii and may not be continuous because sound levels may drop below threshold at some distances and then exceed threshold at farther distances. Figure G-4 shows an example of an area with sound levels above threshold and two methods of reporting the injury or behavioral disruption distance: (1) R_{max}, the maximum distance at which the sound level was encountered in the modeled maximum-over-depth sound field, and (2) $R_{95\%}$, the maximum distance at which the sound level was encountered after the 5% farthest such points were excluded. $R_{95\%}$ is used because, regardless of the shape of the maximum-over-depth footprint, the predicted distance encompasses at least 95% of the horizontal area that would be exposed to sound at or above the specified level. The difference between R_{max} and $R_{95\%}$ depends on the source directivity and the heterogeneity of the acoustic environment. $R_{95\%}$ excludes ends of protruding areas or small isolated acoustic foci not representative of the nominal ensonification zone.

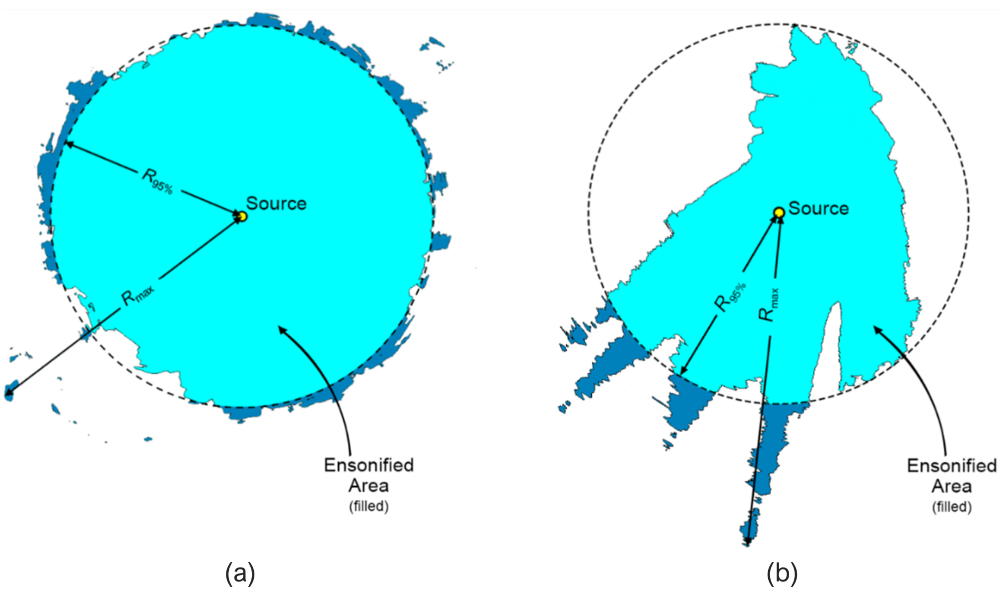

Figure G-4. Sample areas ensonified to an arbitrary sound level with R_{max} and $R_{95\%}$ distances shown for two different scenarios. (a) Largely symmetric sound level contour with small protrusions. (b) Strongly asymmetric sound level contour with long protrusions. Light blue indicates the ensonified areas bounded by $R_{95\%}$; darker blue indicates the areas outside this boundary which determine R_{max}.

G.6. Model Validation Information

Predictions from JASCO's propagation models (MONM and FWRAM) have been validated against experimental data from a number of underwater acoustic measurement programs conducted by JASCO globally, including the United States and Canadian Arctic, Canadian and southern United States waters, Greenland, Russia and Australia (Hannay and Racca 2005, Aerts et al. 2008, Funk et al. 2008, Ireland et al. 2009, O'Neill et al. 2010, Warner et al. 2010, Racca et al. 2012a, Racca et al. 2012b, Matthews and MacGillivray 2013, Martin et al. 2015, Racca et al. 2015, Martin et al. 2017a, Martin et al. 2017b, Warner et al. 2017, MacGillivray 2018, McPherson et al. 2018, McPherson and Martin 2018).

In addition, JASCO has conducted measurement programs associated with a significant number of anthropogenic activities which have included internal validation of the modeling (including McCrodan et al. 2011, Austin and Warner 2012, McPherson and Warner 2012, Austin and Bailey 2013, Austin et al. 2013, Zykov and MacDonnell 2013, Austin 2014, Austin et al. 2015, Austin and Li 2016, Martin and Popper 2016).

Appendix H. Acoustic Ranges

The following subsections contain tables of acoustic ranges (R_{max} and $R_{95\%}$ in km) to marine mammal (NMFS 2018), sea turtle (Finneran et al. 2017) and fish (FHWG 2008, Stadler and Woodbury 2009, Popper et al. 2014) injury and impairment thresholds. The acoustic ranges to behavioral thresholds for marine mammal (NOAA 2005, Wood et al. 2012), sea turtle (McCauley et al. 2000b), and fish (Andersson et al. 2007, Wysocki et al. 2007, Mueller-Blenkle et al. 2010, Purser and Radford 2011) are also included. The acoustic ranges are shown for the following categories: Flat is unweighted, LF is low-frequency cetaceans, MF is mid-frequency cetaceans, HF is high-frequency cetaceans, PPW is pinnipeds in water, and TUW is turtles in water. TUW weighting functions are from the US Navy (Finneran et al. 2017), the rest are from the Technical Guidance (NMFS 2018). R_{max} is the maximum distance at which the sound level was encountered in the modeled maximum-over-depth sound field and $R_{95\%}$ is the maximum distance at which the sound level was encountered after the 5% farthest such points were excluded.

H.1. Impact Pile Driving Single-Strike PK Acoustic Ranges

H.1.1. Location G10: Monopile Foundation Hammer Energy level and Pile Penetration Depth

Table H-1. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels.

Level (L_{pk})	Hammer energy in kJ (at pile penetration depth in m)													
	Summer							Winter						
	500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)	500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
232	-	0.000	0.000	0.000	0.003	0.002	0.002	-	0.000	0.000	0.000	0.003	0.002	0.002
230	-	0.000	0.000	0.002	0.004	0.003	0.003	-	0.000	0.000	0.002	0.004	0.003	0.003
219	0.005	0.020	0.008	0.037	0.053	0.045	0.051	0.005	0.013	0.008	0.037	0.053	0.044	0.052
218	0.006	0.032	0.010	0.044	0.059	0.051	0.057	0.006	0.031	0.010	0.044	0.059	0.051	0.058
202	0.101	0.290	0.180	4.000	4.000	4.000	4.000	0.105	4.000	4.000	4.000	4.000	4.000	4.000

Values within the parentheses indicate penetration depth.

H.1.2. Location Z11: Jacket Foundation Hammer Energy level and Pile Penetration Depth

Table H-2. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels.

Level (L_{pk})	Hammer energy in kJ (at pile penetration depth in m)													
	Summer							Winter						
	500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)	500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
232	-	-	-	-	0	0	-	-	-	-	-	0	0	-
230	-	-	-	-	0	0.003	0	-	-	-	-	0	0.003	0
219	0.005	0.002	0.006	0.009	0.032	0.038	0.017	0.005	0.002	0.006	0.009	0.031	0.039	0.016
218	0.006	0.002	0.008	0.011	0.043	0.045	0.02	0.006	0.002	0.007	0.01	0.04	0.047	0.019
202	0.184	0.077	0.22	0.25	0.34	0.36	0.22	0.178	0.082	0.22	0.25	0.33	0.34	0.24

Values within the parentheses indicate penetration depth.

H.2. Impact Pile Driving Single-Strike SEL Distances

H.2.1. Location G10: Monopile Foundation

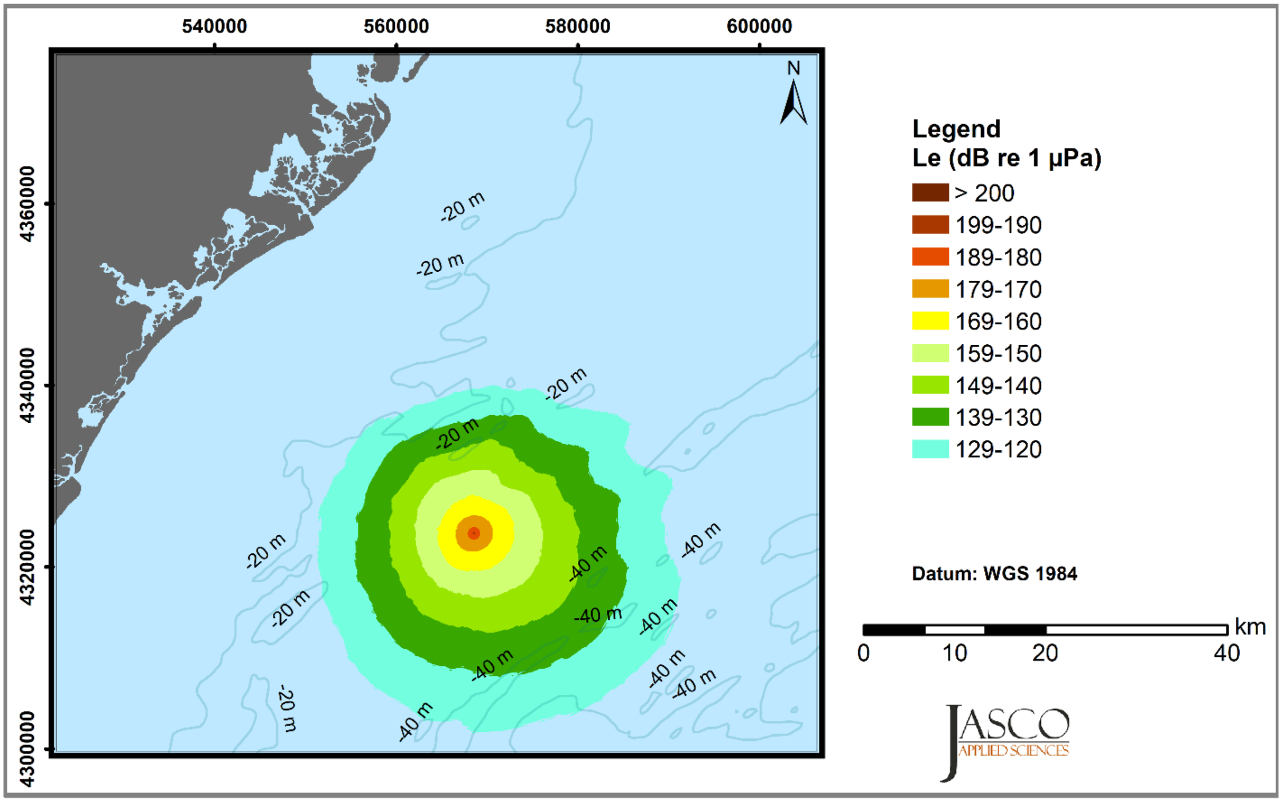

Figure H-1. Unweighted single-strike sound exposure level (SEL) at 4000 kJ at 50 m penetration depth. This sound field was produced by the highest energy for the monopile installation in summer conditions.

Table H-3. Monopile foundation (8 to 11 m diameter, IHC S-4000, 500 kJ energy level, 7 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
180	0.117	0.116	0.021	0.021	0	0	0	0	0.001	0.001	0.057	0.057	0.114	0.108	0.021	0.021	0	0	0	0	0.001	0.001	0.057	0.057
170	0.533	0.51	0.128	0.127	0	0	0	0	0.001	0.001	0.324	0.31	0.577	0.554	0.127	0.122	0.001	0.001	0	0	0.001	0.001	0.358	0.342
160	1.849	1.723	0.656	0.618	0.001	0.001	0.001	0.001	0.029	0.029	1.49	1.381	2.126	1.964	0.734	0.699	0.001	0.001	0.001	0.001	0.045	0.045	1.617	1.528
150	3.953	3.616	2.197	2.003	0.001	0.001	0.001	0.001	0.181	0.172	3.489	3.197	4.84	4.434	2.776	2.541	0.001	0.001	0.001	0.001	0.244	0.233	4.408	4.036
140	6.8	6.129	4.681	4.26	0.06	0.045	0.001	0.001	0.997	0.94	6.369	5.764	10.10	8.82	6.87	6.18	0.10	0.09	0.04	0.04	1.39	1.27	9.60	8.31
130	10.89	9.42	8.16	7.22	0.41	0.39	0.16	0.14	3.00	2.69	10.42	9.10	20.99	17.85	16.81	14.02	0.48	0.45	0.28	0.24	5.16	4.38	18.69	16.13
120	15.75	13.38	12.97	11.10	1.58	1.25	0.90	0.82	6.09	5.44	15.58	13.10	55.51	48.76	53.20	44.55	2.49	2.21	1.54	1.20	17.35	13.74	38.00	33.53

Table H-4. Monopile foundation (8 to 11 m diameter, IHC S-4000, 2000 kJ energy level, 13 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.045	0.045	0.001	0.001	0	0	0	0	0.001	0.001	0.029	0.029	0.045	0.045	0.001	0.001	0	0	0	0	0.001	0.001	0.029	0.029
180	0.255	0.243	0.06	0.057	0	0	0	0	0.001	0.001	0.172	0.165	0.27	0.261	0.073	0.072	0	0	0	0	0.001	0.001	0.172	0.169
170	1.272	1.19	0.383	0.364	0.001	0.001	0.001	0.001	0.021	0.021	0.906	0.796	1.341	1.271	0.413	0.388	0.001	0.001	0.001	0.001	0.021	0.021	1.041	0.977
160	3.102	2.823	1.599	1.456	0.001	0.001	0.001	0.001	0.114	0.108	2.81	2.493	3.815	3.466	1.941	1.799	0.001	0.001	0.001	0.001	0.128	0.127	3.47	3.161
150	5.78	5.242	3.935	3.555	0.001	0.001	0.001	0.001	0.605	0.53	5.52	4.991	8.2	7.25	5.449	4.946	0.041	0.04	0.001	0.001	0.766	0.722	7.856	6.946
140	9.66	8.48	7.19	6.46	0.11	0.11	0.10	0.10	2.19	1.99	9.36	8.22	16.80	14.12	13.11	11.02	0.25	0.22	0.13	0.11	3.35	2.99	16.10	13.41
130	14.68	12.41	11.70	10.17	0.87	0.79	0.47	0.44	4.94	4.48	14.36	12.17	36.59	31.44	33.45	27.63	1.36	1.17	0.80	0.64	11.13	9.07	29.84	25.54
120	19.80	17.17	16.91	14.56	3.07	2.54	1.98	1.61	9.05	7.90	19.52	16.93	70.68	57.60	70.68	57.29	5.53	4.53	3.41	2.62	36.71	30.30	70.68	54.95

Table H-5. Monopile foundation (8 to 11 m diameter, IHC S-4000, 1000 kJ energy level, 16 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.029	0.029	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.029	0.029	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
180	0.162	0.161	0.029	0.029	0	0	0	0	0.001	0.001	0.1	0.1	0.165	0.162	0.041	0.04	0	0	0	0	0.001	0.001	0.09	0.09
170	0.772	0.74	0.181	0.173	0.001	0.001	0	0	0.001	0.001	0.484	0.464	0.861	0.811	0.204	0.199	0.001	0.001	0.001	0.001	0.001	0.001	0.566	0.541
160	2.359	2.171	1.01	0.948	0.001	0.001	0.001	0.001	0.045	0.045	1.953	1.757	2.748	2.534	1.191	1.13	0.001	0.001	0.001	0.001	0.063	0.063	2.337	2.151
150	4.68	4.258	2.853	2.665	0.001	0.001	0.001	0.001	0.311	0.291	4.34	3.927	6.206	5.596	3.898	3.512	0.001	0.001	0.001	0.001	0.405	0.385	5.76	5.247
140	7.95	7.06	5.73	5.20	0.10	0.10	0.06	0.06	1.53	1.41	7.64	6.79	13.16	11.18	9.61	8.19	0.15	0.13	0.10	0.09	2.11	1.90	12.18	10.60
130	12.45	10.73	9.87	8.57	0.48	0.46	0.41	0.39	3.82	3.51	12.08	10.48	27.55	23.27	24.48	19.95	1.01	0.78	0.48	0.44	7.43	6.36	24.13	20.32
120	17.36	15.10	15.14	12.69	2.19	1.90	1.57	1.23	7.39	6.64	17.19	14.81	70.68	55.39	70.68	54.95	4.43	3.18	2.30	1.93	25.63	20.84	54.39	47.02

Table H-6. Monopile foundation (8 to 11 m diameter, IHC S-4000, 3000 kJ energy level, 18 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.09	0.09	0.021	0.021	0	0	0	0	0.001	0.001	0.045	0.045	0.09	0.09	0.021	0.021	0	0	0	0	0.001	0.001	0.045	0.045
180	0.451	0.431	0.129	0.128	0	0	0	0	0.001	0.001	0.314	0.3	0.468	0.452	0.127	0.122	0.001	0.001	0	0	0.001	0.001	0.341	0.3
170	1.733	1.598	0.656	0.621	0.001	0.001	0.001	0.001	0.029	0.029	1.495	1.38	1.96	1.824	0.727	0.69	0.001	0.001	0.001	0.001	0.041	0.04	1.631	1.531
160	3.907	3.564	2.32	2.036	0.001	0.001	0.001	0.001	0.184	0.179	3.599	3.277	4.939	4.509	2.874	2.62	0.001	0.001	0.001	0.001	0.241	0.224	4.592	4.203
150	6.934	6.24	4.861	4.432	0.06	0.045	0.001	0.001	1.013	0.948	6.621	5.977	10.36	9.11	7.06	6.34	0.09	0.09	0.03	0.03	1.36	1.23	9.94	8.69
140	11.23	9.71	8.50	7.50	0.40	0.36	0.15	0.14	3.07	2.76	10.93	9.44	20.67	17.51	16.66	13.65	0.42	0.35	0.22	0.19	4.77	4.17	18.86	16.26
130	16.07	13.75	13.39	11.43	1.58	1.24	0.89	0.81	6.13	5.57	15.93	13.49	50.62	43.44	45.48	38.73	2.26	1.75	1.26	1.01	16.06	12.20	35.32	31.33
120	21.48	18.68	18.68	16.12	4.09	3.45	3.07	2.52	10.71	9.30	21.15	18.41	70.68	58.72	70.68	58.70	8.05	6.23	5.11	3.77	52.74	44.00	70.68	55.57

Table H-7. Monopile foundation (8 to 11 m diameter, IHC S-4000, 4000 kJ energy level, 34 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.029	0.029	0.001	0.001	0	0	0	0	0.001	0.001	0.021	0.021	0.029	0.029	0.001	0.001	0	0	0	0	0.001	0.001	0.021	0.021
190	0.146	0.145	0.041	0.04	0	0	0	0	0.001	0.001	0.108	0.107	0.153	0.145	0.041	0.04	0	0	0	0	0.001	0.001	0.103	0.102
180	0.781	0.746	0.19	0.188	0.001	0.001	0	0	0.001	0.001	0.542	0.515	0.866	0.82	0.229	0.221	0.001	0.001	0	0	0.001	0.001	0.632	0.581
170	2.414	2.242	1.11	0.98	0.001	0.001	0.001	0.001	0.061	0.06	2.098	1.921	2.89	2.631	1.293	1.215	0.001	0.001	0.001	0.001	0.064	0.063	2.467	2.282
160	4.85	4.452	3.106	2.84	0.001	0.001	0.001	0.001	0.345	0.325	4.54	4.106	6.462	5.833	4.05	3.709	0.001	0.001	0.001	0.001	0.413	0.397	6.096	5.515
150	8.258	7.313	6.002	5.453	0.101	0.09	0.041	0.04	1.571	1.458	7.952	7.047	13.82	11.66	9.92	8.63	0.10	0.10	0.09	0.08	2.11	1.92	13.27	11.26
140	12.87	11.08	10.27	8.95	0.47	0.44	0.23	0.20	3.93	3.57	12.59	10.86	26.94	23.15	23.26	19.48	0.76	0.60	0.41	0.34	7.11	6.10	24.93	21.25
130	18.02	15.66	15.62	13.19	1.98	1.60	1.27	1.15	7.50	6.66	17.71	15.44	70.68	54.44	67.83	53.51	3.42	2.65	1.88	1.63	24.04	18.45	50.20	44.26
120	23.81	20.85	21.10	18.34	4.90	4.16	3.66	3.02	12.60	10.67	23.70	20.65	70.68	59.13	70.68	59.12	11.44	8.49	6.45	5.08	70.68	55.26	70.68	57.10

Table H-8. Monopile foundation (8 to 11 m diameter, IHC S-4000, 3000 kJ energy level, 40 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.103	0.102	0.021	0.021	0	0	0	0	0.001	0.001	0.057	0.057	0.102	0.1	0.021	0.021	0	0	0	0	0.001	0.001	0.06	0.059
180	0.485	0.469	0.142	0.141	0.001	0.001	0	0	0.001	0.001	0.342	0.306	0.562	0.539	0.145	0.141	0.001	0.001	0	0	0.001	0.001	0.383	0.367
170	1.837	1.701	0.683	0.645	0.001	0.001	0.001	0.001	0.045	0.045	1.528	1.425	2.186	2.013	0.856	0.797	0.001	0.001	0.001	0.001	0.045	0.045	1.826	1.684
160	4.03	3.712	2.39	2.21	0.001	0.001	0.001	0.001	0.213	0.204	3.701	3.383	5.33	4.857	3.265	2.97	0.001	0.001	0.001	0.001	0.291	0.278	4.981	4.564
150	7.159	6.429	5.113	4.676	0.101	0.09	0.041	0.04	1.218	1.101	6.849	6.171	11.66	10.20	8.22	7.27	0.10	0.10	0.06	0.06	1.71	1.57	11.26	9.79
140	11.48	10.01	8.90	7.93	0.46	0.43	0.21	0.19	3.43	3.07	11.18	9.78	24.65	20.89	20.85	17.25	0.60	0.51	0.32	0.29	6.35	5.10	22.14	19.12
130	16.63	14.30	14.22	12.09	1.96	1.57	1.27	1.12	6.84	6.14	16.57	14.09	62.92	52.63	58.54	50.15	3.07	2.43	1.68	1.48	20.82	16.03	45.94	39.65
120	22.33	19.48	19.62	17.13	4.89	4.12	3.66	3.00	11.82	10.16	22.10	19.29	70.68	59.04	70.68	59.03	9.74	7.74	5.56	4.70	66.97	53.16	70.68	56.65

Table H-9. Monopile foundation (8 to 11 m diameter, IHC S-4000, 4000 kJ energy level, 50 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.021	0.021	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001	0.021	0.021	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
190	0.142	0.141	0.029	0.029	0	0	0	0	0.001	0.001	0.085	0.083	0.14	0.134	0.029	0.029	0	0	0	0	0.001	0.001	0.089	0.085
180	0.701	0.673	0.185	0.181	0.001	0.001	0.001	0.001	0.001	0.001	0.469	0.447	0.762	0.732	0.229	0.221	0.001	0.001	0.001	0.001	0.001	0.001	0.524	0.495
170	2.15	1.991	0.934	0.883	0.001	0.001	0.001	0.001	0.1	0.085	1.826	1.676	2.662	2.455	1.312	1.199	0.001	0.001	0.001	0.001	0.113	0.108	2.303	2.089
160	4.536	4.125	3.064	2.676	0.041	0.04	0.001	0.001	0.515	0.477	4.144	3.795	6.642	5.995	4.51	4.116	0.09	0.08	0.029	0.029	0.707	0.656	6.171	5.545
150	7.84	7.014	5.852	5.384	0.393	0.221	0.108	0.102	2.157	1.911	7.594	6.739	16.76	13.98	13.68	11.54	0.41	0.34	0.20	0.18	3.54	3.17	15.43	12.53
140	12.53	10.87	10.33	9.07	1.31	1.19	0.85	0.77	5.17	4.56	12.17	10.59	47.91	41.48	43.82	36.99	2.19	1.68	1.15	0.96	16.00	11.27	34.01	29.34
130	17.80	15.61	15.95	13.60	4.07	3.32	2.84	2.31	9.68	8.47	17.48	15.26	70.68	58.68	70.68	58.65	7.75	6.05	4.82	3.57	52.63	42.02	70.68	55.43
120	24.34	21.13	21.99	19.17	7.60	6.50	5.98	5.00	15.31	13.12	23.80	20.73	70.68	59.04	70.68	59.04	21.61	16.40	12.78	9.74	70.68	59.13	70.68	58.80

H.2.2. Location Z11: Jacket Foundation

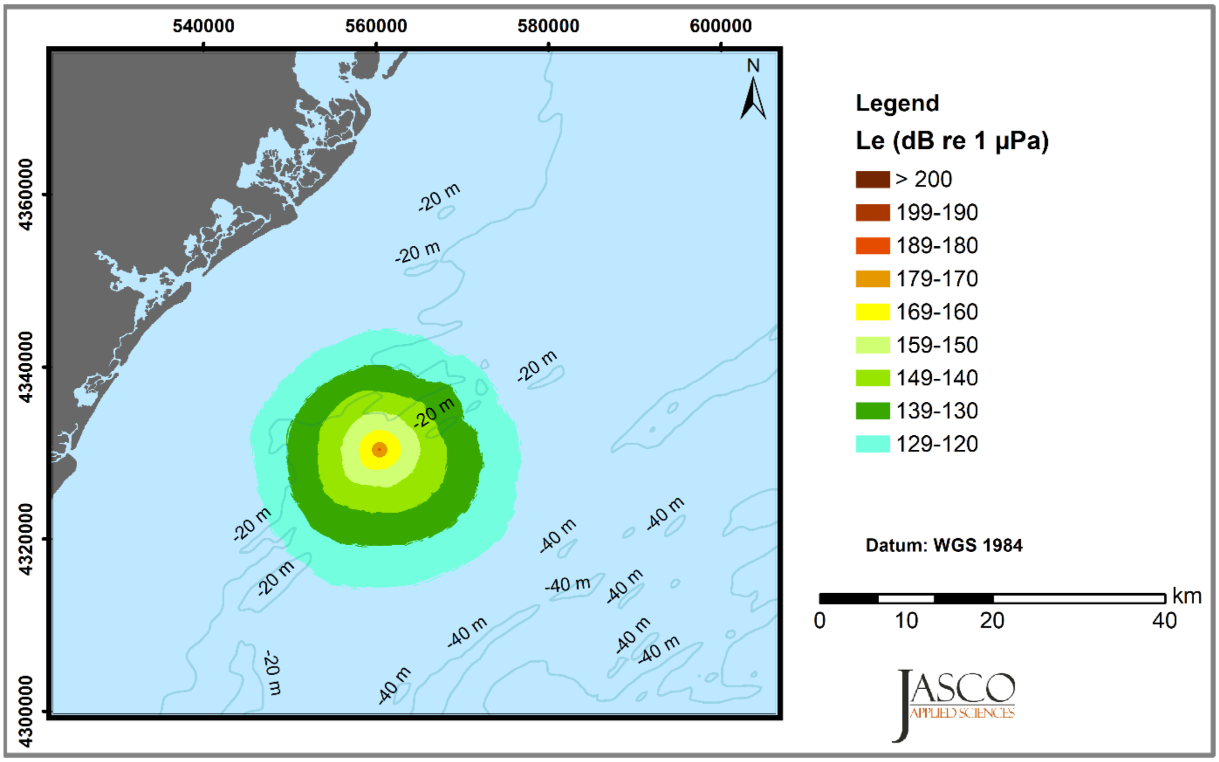

Figure H-2. Unweighted single-strike sound exposure level (SEL) at 2500 kJ at 60 m penetration depth. This sound field was produced by the highest energy for the jacket foundation installation in summer conditions.

Table H-10. Jacket foundation (2.44 m diameter, IHC S-2500, 500 kJ energy level, 3 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
180	0.045	0.045	0.021	0.021	0	0	0	0	0.001	0.001	0.029	0.029	0.045	0.045	0.001	0.001	0	0	0	0	0.001	0.001	0.029	0.029
170	0.228	0.219	0.119	0.116	0.001	0.001	0.001	0.001	0.001	0.001	0.182	0.179	0.253	0.243	0.113	0.108	0.001	0.001	0.001	0.001	0.001	0.001	0.206	0.198
160	1.15	1.072	0.605	0.581	0.001	0.001	0.001	0.001	0.085	0.083	1.028	0.905	1.313	1.241	0.718	0.68	0.001	0.001	0.001	0.001	0.09	0.089	1.174	1.075
150	3.04	2.745	2.196	2.006	0.059	0.045	0.021	0.021	0.514	0.484	2.888	2.58	4.277	3.747	3.199	2.878	0.061	0.06	0.001	0.001	0.522	0.468	3.875	3.417
140	5.667	5.075	4.787	4.309	0.354	0.319	0.135	0.127	2.238	1.892	5.452	4.828	11.27	9.55	9.69	8.28	0.36	0.31	0.17	0.16	3.00	2.58	8.99	7.86
130	9.389	8.4	8.57	7.647	1.567	1.437	1.042	0.758	5.308	4.663	9.026	7.945	34.96	28.28	32.72	26.09	1.82	1.54	1.04	0.86	12.39	9.47	21.34	18.06
120	13.82	12.38	12.95	11.74	4.37	3.68	3.07	2.62	9.70	8.54	13.20	11.64	70.68	57.09	70.68	56.84	6.42	5.29	3.59	3.05	44.04	33.44	62.96	52.61

Table H-11. Jacket foundation (2.44 m diameter, IHC S-2500, 200 kJ energy level, 32 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0	0	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0	0	0.001	0.001
190	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
180	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
170	0.108	0.107	0.045	0.045	0.001	0.001	0.001	0.001	0.001	0.001	0.083	0.083	0.1	0.09	0.045	0.045	0.001	0.001	0.001	0.001	0.001	0.001	0.083	0.083
160	0.528	0.5	0.25	0.241	0.001	0.001	0.001	0.001	0.041	0.04	0.432	0.416	0.605	0.566	0.301	0.291	0.001	0.001	0.001	0.001	0.041	0.04	0.51	0.474
150	1.934	1.77	1.323	1.2	0.001	0.001	0.001	0.001	0.205	0.197	1.791	1.632	2.447	2.252	1.641	1.509	0.001	0.001	0.001	0.001	0.209	0.201	2.154	2.011
140	4.274	3.769	3.55	3.069	0.108	0.102	0.101	0.099	1.207	1.135	4.075	3.57	6.579	5.849	5.53	4.88	0.108	0.103	0.1	0.09	1.557	1.404	5.789	5.039
130	7.401	6.618	6.492	5.872	0.776	0.726	0.481	0.402	3.759	3.204	6.925	6.225	18.88	16.07	17.50	14.71	0.91	0.72	0.46	0.43	6.15	5.30	13.74	11.92
120	11.45	10.33	10.84	9.7	2.925	2.383	1.976	1.589	7.467	6.613	10.95	9.67	66.12	54.31	63.20	52.46	3.47	2.99	2.07	1.82	24.22	18.21	37.68	30.73

Table H-12. Jacket foundation (2.44 m diameter, IHC S-2500, 750 kJ energy level, 40 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
180	0.057	0.057	0.021	0.021	0.001	0.001	0	0	0.001	0.001	0.045	0.045	0.057	0.057	0.021	0.021	0.001	0.001	0	0	0.001	0.001	0.045	0.045
170	0.335	0.323	0.162	0.161	0.001	0.001	0.001	0.001	0.001	0.001	0.26	0.245	0.361	0.344	0.17	0.162	0.001	0.001	0.001	0.001	0.001	0.001	0.291	0.272
160	1.443	1.323	0.82	0.77	0.001	0.001	0.001	0.001	0.113	0.108	1.371	1.252	1.728	1.612	1.052	0.985	0.001	0.001	0.001	0.001	0.121	0.116	1.531	1.423
150	3.585	3.156	2.71	2.407	0.101	0.099	0.041	0.04	0.758	0.718	3.357	2.99	5.099	4.432	4.103	3.542	0.1	0.09	0.061	0.06	0.914	0.723	4.582	3.999
140	6.335	5.672	5.48	4.875	0.5	0.411	0.255	0.241	2.682	2.317	5.993	5.376	13.56	11.59	12.33	10.28	0.46	0.44	0.23	0.21	4.58	3.28	10.96	9.22
130	10.23	9.13	9.38	8.39	2.21	1.75	1.41	1.14	6.10	5.34	9.76	8.62	44.65	36.79	41.39	33.85	2.27	1.88	1.52	1.15	15.96	12.31	26.82	21.63
120	14.78	13.22	13.84	12.59	5.04	4.25	3.57	3.09	10.57	9.38	14.05	12.41	70.68	58.17	70.68	58.17	8.33	6.48	4.61	4.04	52.83	43.62	70.68	55.91

Table H-13. Jacket foundation (2.44 m diameter, IHC S-2500, 1000 kJ energy level, 48 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
180	0.099	0.09	0.041	0.04	0.001	0.001	0	0	0.001	0.001	0.057	0.057	0.085	0.084	0.041	0.04	0.001	0.001	0	0	0.001	0.001	0.057	0.057
170	0.462	0.443	0.19	0.188	0.001	0.001	0.001	0.001	0.029	0.029	0.373	0.355	0.514	0.487	0.228	0.22	0.001	0.001	0.001	0.001	0.021	0.021	0.405	0.376
160	1.766	1.623	1.052	0.981	0.001	0.001	0.001	0.001	0.152	0.145	1.584	1.452	2.1	1.926	1.289	1.199	0.001	0.001	0.001	0.001	0.152	0.142	1.849	1.712
150	3.909	3.481	3.005	2.741	0.102	0.102	0.081	0.073	1.02	0.789	3.734	3.3	5.567	4.906	4.615	4.005	0.102	0.1	0.061	0.06	1.007	0.913	5.061	4.414
140	6.82	6.129	6.034	5.334	0.727	0.663	0.356	0.323	3.15	2.746	6.433	5.812	14.97	12.99	13.60	11.60	0.60	0.54	0.35	0.30	4.63	3.95	11.52	10.04
130	10.86	9.71	10.08	9.01	2.52	2.03	1.57	1.42	6.75	5.92	10.39	9.14	50.91	42.12	47.81	39.38	2.85	2.21	1.58	1.39	17.59	13.97	30.33	24.06
120	15.63	13.87	14.66	13.27	5.67	4.73	4.33	3.51	11.50	10.04	14.82	13.02	70.68	58.20	70.68	58.20	9.18	7.26	5.73	4.34	59.86	49.47	70.68	55.62

Table H-14. Jacket foundation (2.44 m diameter, IHC S-2500, 1500 kJ energy level, 54 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.029	0.029	0.001	0.001	0	0	0	0	0.001	0.001	0.021	0.021	0.021	0.021	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
180	0.146	0.145	0.045	0.045	0.001	0.001	0.001	0.001	0.001	0.001	0.122	0.121	0.146	0.145	0.057	0.057	0.001	0.001	0.001	0.001	0.001	0.001	0.114	0.108
170	0.735	0.693	0.325	0.314	0.001	0.001	0.001	0.001	0.045	0.045	0.621	0.584	0.832	0.797	0.373	0.36	0.001	0.001	0.001	0.001	0.045	0.045	0.695	0.654
160	2.27	2.103	1.463	1.373	0.001	0.001	0.001	0.001	0.229	0.216	2.175	1.96	2.945	2.653	1.916	1.761	0.001	0.001	0.001	0.001	0.248	0.229	2.648	2.407
150	4.653	4.104	3.721	3.309	0.117	0.108	0.101	0.099	1.222	1.161	4.449	3.931	7.369	6.407	6.233	5.27	0.122	0.119	0.1	0.09	1.765	1.461	6.377	5.575
140	7.917	6.995	6.861	6.14	0.809	0.732	0.5	0.425	3.804	3.314	7.535	6.677	20.63	16.92	18.31	15.54	0.92	0.84	0.56	0.45	6.94	5.61	14.71	12.64
130	11.86	10.65	10.99	9.94	2.99	2.47	2.21	1.73	7.69	6.76	11.48	10.11	69.58	54.96	66.23	54.21	3.65	3.05	2.16	1.86	24.25	19.25	40.11	32.37
120	17.00	14.92	16.05	14.25	6.34	5.37	4.83	4.07	12.32	10.96	16.10	14.08	70.68	58.24	70.68	58.23	12.86	9.65	7.73	5.74	70.68	54.92	70.68	54.81

Table H-15. Jacket foundation (2.44 m diameter, IHC S-2500, 2500 kJ energy level, 60 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.041	0.04	0.001	0.001	0	0	0	0	0.001	0.001	0.021	0.021	0.029	0.029	0.001	0.001	0	0	0	0	0.001	0.001	0.021	0.021
180	0.173	0.171	0.073	0.072	0.001	0.001	0.001	0.001	0.001	0.001	0.146	0.145	0.173	0.171	0.061	0.06	0.001	0.001	0.001	0.001	0.001	0.001	0.129	0.128
170	0.925	0.879	0.405	0.386	0.001	0.001	0.001	0.001	0.045	0.045	0.728	0.684	0.948	0.874	0.428	0.411	0.001	0.001	0.001	0.001	0.045	0.045	0.759	0.709
160	2.619	2.344	1.723	1.588	0.029	0.029	0.001	0.001	0.339	0.297	2.406	2.174	3.182	2.804	2.004	1.869	0.001	0.001	0.001	0.001	0.282	0.256	2.818	2.547
150	5.001	4.404	4.062	3.606	0.146	0.135	0.103	0.102	1.547	1.42	4.779	4.195	7.741	6.693	6.264	5.443	0.139	0.128	0.102	0.1	1.81	1.581	6.554	5.762
140	8.303	7.403	7.365	6.578	1.172	1.006	0.73	0.665	4.35	3.721	7.978	7.053	21.50	17.67	20.18	16.11	0.95	0.85	0.57	0.47	7.71	5.74	15.13	12.97
130	12.48	11.16	11.56	10.47	3.51	2.86	2.37	1.95	8.24	7.33	11.88	10.53	70.68	55.04	67.98	54.63	4.24	3.23	2.36	1.91	25.96	20.02	41.47	33.84
120	17.52	15.53	16.57	14.89	6.94	5.87	5.40	4.49	13.02	11.62	16.78	14.60	70.68	58.25	70.68	58.24	12.91	10.05	7.75	5.97	70.68	55.53	70.68	55.10

Table H-16. Jacket foundation (2.44 m diameter, IHC S-2500, 1500 kJ energy level, 70 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for each of the flat and frequency weighted categories (Finneran et al. 2017, NMFS 2018).

Level (L_E)	Summer												Winter											
	Flat		LF		MF		HF		PPW		TUW		Flat		LF		MF		HF		PPW		TUW	
	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
200	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0	0	0.001	0.001
190	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0	0	0	0	0.001	0.001	0.001	0.001
180	0.09	0.09	0.029	0.029	0	0	0	0	0.001	0.001	0.045	0.045	0.073	0.072	0.021	0.021	0	0	0	0	0.001	0.001	0.045	0.045
170	0.408	0.389	0.166	0.162	0.001	0.001	0.001	0.001	0.001	0.001	0.323	0.301	0.386	0.362	0.157	0.153	0.001	0.001	0.001	0.001	0.001	0.001	0.313	0.288
160	1.615	1.493	0.903	0.855	0.001	0.001	0.001	0.001	0.108	0.107	1.443	1.315	1.727	1.613	0.975	0.881	0.001	0.001	0.001	0.001	0.102	0.09	1.534	1.434
150	3.706	3.258	2.719	2.441	0.101	0.1	0.029	0.029	0.735	0.7	3.58	3.125	4.83	4.17	3.706	3.221	0.089	0.089	0.029	0.029	0.632	0.569	4.42	3.852
140	6.357	5.712	5.452	4.809	0.424	0.36	0.241	0.206	2.542	2.244	6.121	5.459	11.97	10.24	11.06	8.94	0.42	0.34	0.18	0.17	3.27	2.90	10.17	8.50
130	10.16	9.07	9.24	8.25	1.88	1.54	1.20	1.09	5.88	5.16	9.82	8.64	37.60	30.38	34.95	28.30	1.90	1.69	1.07	0.93	13.61	10.37	22.80	19.24
120	14.67	13.06	13.70	12.37	4.83	4.03	3.52	2.93	10.31	9.11	14.03	12.36	70.68	57.48	70.68	57.39	7.72	5.56	4.24	3.41	45.91	36.24	65.56	55.01

H.3. Impact Pile Driving Single-Strike SPL Acoustic Ranges

H.3.1. Location G10: Monopile Foundation

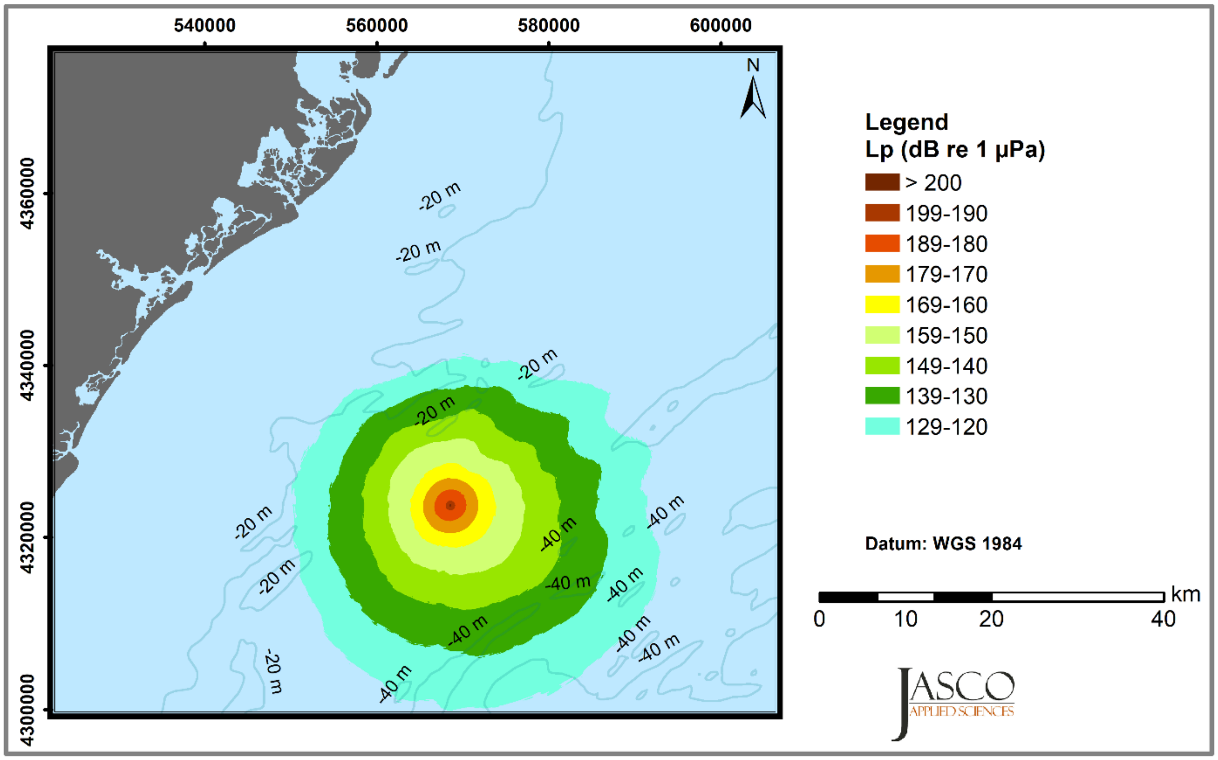

Figure H-3. Unweighted single-strike sound pressure level (SPL) at 4000 kJ at 50 m penetration depth. This sound field was produced by the highest energy for the monopile installation in summer conditions.

Table H-17. Monopile foundation (8 to 11 m diameter, IHC S-4000, 500 kJ energy level, 7 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.1	0.1
180	0.471	0.456
175	0.993	0.948
170	1.709	1.577
160	3.273	3.097
150	4.64	4.25
140	7.792	6.926
130	12.08	10.453
120	16.931	14.641

Table H-18. Monopile foundation (8 to 11 m diameter, IHC S-4000, 500 kJ energy level, 7 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.100	0.100
180	0.487	0.470
175	1.071	1.016
170	1.884	1.759
160	3.490	3.320
150	6.250	5.646
140	13.121	11.107
130	27.660	23.398
120	70.682	55.532

Table H-19. Monopile foundation (8 to 11 m diameter, IHC S-4000, 2000 kJ energy level, 13 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.045	0.045
190	0.217	0.212
180	1.05	0.993
175	1.814	1.678
170	2.771	2.532
160	3.711	3.483
150	6.76	6.074
140	10.978	9.534
130	15.989	13.612
120	21.384	18.57

Table H-20. Monopile foundation (8 to 11 m diameter, IHC S-4000, 2000 kJ energy level, 13 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.045	0.045
190	0.235	0.228
180	1.206	1.107
175	2.126	1.950
170	3.158	2.979
160	4.948	4.517
150	10.591	9.275
140	21.282	18.104
130	54.182	45.980
120	70.682	58.784

Table H-21. Monopile foundation (8 to 11 m diameter, IHC S-4000, 1000 kJ energy level, 16 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.021	0.021
190	0.145	0.144
180	0.685	0.658
175	1.293	1.214
170	2.122	1.95
160	3.355	3.201
150	5.458	4.973
140	9.184	8.008
130	13.838	11.844
120	18.888	16.497

Table H-22. Monopile foundation (8 to 11 m diameter, IHC S-4000, 1000 kJ energy level, 16 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.021	0.021
190	0.144	0.141
180	0.744	0.710
175	1.437	1.360
170	2.459	2.282
160	3.661	3.473
150	7.761	6.891
140	16.301	13.640
130	36.628	31.760
120	70.682	57.899

Table H-23. Monopile foundation (8 to 11 m diameter, IHC S-4000, 3000 kJ energy level, 18 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.085	0.083
190	0.372	0.36
180	1.522	1.425
175	2.43	2.248
170	3.141	2.98
160	4.66	4.249
150	7.972	7.088
140	12.464	10.771
130	17.377	15.09
120	22.927	20.076

Table H-24. Monopile foundation (8 to 11 m diameter, IHC S-4000, 3000 kJ energy level, 18 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.080	0.073
190	0.385	0.372
180	1.697	1.593
175	2.861	2.642
170	3.401	3.252
160	6.220	5.613
150	12.868	10.979
140	25.186	21.480
130	70.427	54.334
120	70.683	59.117

Table H-25. Monopile foundation (8 to 11 m diameter, IHC S-4000, 4000 kJ energy level, 34 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.129	0.128
190	0.647	0.621
180	2.138	1.987
175	3.015	2.809
170	3.400	3.253
160	5.730	5.178
150	9.415	8.294
140	14.367	12.216
130	19.559	17.057
120	25.483	22.440

Table H-26. Monopile foundation (8 to 11 m diameter, IHC S-4000, 4000 kJ energy level, 34 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.128	0.126
190	0.719	0.683
180	2.472	2.300
175	3.275	3.119
170	3.777	3.534
160	8.095	7.175
150	16.835	14.183
140	35.070	30.128
130	70.682	56.853
120	70.683	59.121

Table H-27. Monopile foundation (8 to 11 m diameter, IHC S-4000, 3000 kJ energy level, 40 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.090	0.085
190	0.439	0.422
180	1.716	1.548
175	2.581	2.397
170	3.157	3.015
160	4.815	4.400
150	8.249	7.307
140	12.979	11.132
130	18.085	15.778
120	24.144	21.036

Table H-28. Monopile foundation (8 to 11 m diameter, IHC S-4000, 3000 kJ energy level, 40 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.085	0.083
190	0.464	0.444
180	1.931	1.791
175	3.009	2.820
170	3.439	3.296
160	6.734	6.076
150	15.287	12.446
140	31.132	26.624
130	70.682	55.889
120	70.683	59.154

Table H-29. Monopile foundation (8 to 11 m diameter, IHC S-4000, 4000 kJ energy level, 50 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for summer conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.122	0.121
190	0.564	0.539
180	1.980	1.801
175	2.811	2.644
170	3.278	3.119
160	5.366	4.846
150	8.957	7.988
140	14.205	12.068
130	19.632	17.064
120	26.074	22.861

Table H-30. Monopile foundation (8 to 11 m diameter, IHC S-4000, 4000 kJ energy level, 50 m penetration depth) acoustic ranges (R_{max} and $R_{95\%}$ in km) for winter conditions.

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.120	0.117
190	0.646	0.610
180	2.328	2.156
175	3.183	3.036
170	3.619	3.432
160	8.539	7.543
150	22.372	18.907
140	67.953	53.776
130	70.683	59.084
120	70.683	59.001

H.3.2. Location Z11: Jacket Foundation

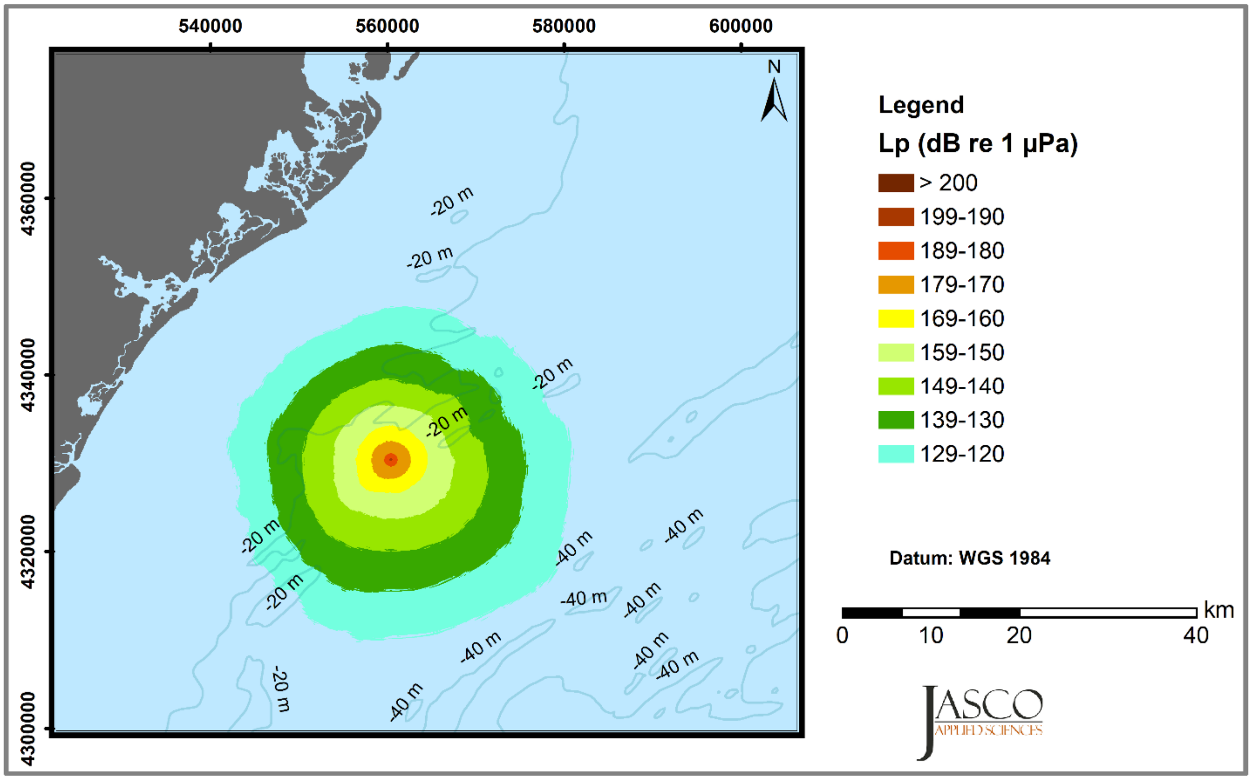

Figure H-4. Unweighted single-strike sound pressure level (SPL) at 2500 kJ at 60 m penetration depth. This sound field was produced by the highest energy for the jacket foundation installation in summer conditions.

Table H-31. Jacket foundation (2.44 m diameter, IHC S-2500, 500 kJ energy level, 3 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.041	0.040
180	0.185	0.184
175	0.451	0.432
170	0.961	0.909
160	2.858	2.526
150	5.309	4.721
140	8.975	7.928
130	13.272	11.829
120	18.671	16.308

Table H-32. Jacket foundation (2.44 m diameter, IHC S-2500, 500 kJ energy level, 3 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.029	0.029
180	0.216	0.208
175	0.522	0.500
170	1.189	1.079
160	3.809	3.382
150	10.151	8.436
140	28.622	23.750
130	70.683	55.406
120	70.683	58.387

Table H-33. Jacket foundation (2.44 m diameter, IHC S-2500, 200 kJ energy level, 32 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.001	0.001
180	0.090	0.090
175	0.184	0.179
170	0.445	0.426
160	1.766	1.625
150	3.899	3.491
140	6.848	6.175
130	10.958	9.804
120	15.649	13.993

Table H-34. Jacket foundation (2.44 m diameter, IHC S-2500, 200 kJ energy level, 32 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.001	0.001
180	0.083	0.083
175	0.209	0.201
170	0.514	0.483
160	2.180	2.008
150	5.934	5.047
140	16.257	13.719
130	55.197	46.383
120	70.683	58.208

Table H-35. Jacket foundation (2.44 m diameter, IHC S-2500, 750 kJ energy level, 40 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.045	0.045
180	0.278	0.268
175	0.648	0.620
170	1.369	1.252
160	3.310	2.921
150	5.721	5.117
140	9.404	8.447
130	13.844	12.438
120	19.575	17.016

Table H-36. Jacket foundation (2.44 m diameter, IHC S-2500, 750 kJ energy level, 40 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.045	0.045
180	0.310	0.291
175	0.713	0.681
170	1.534	1.427
160	4.276	3.740
150	11.269	9.566
140	34.971	28.402
130	70.683	57.121
120	70.683	58.644

Table H-37. Jacket foundation (2.44 m diameter, IHC S-2500, 1000 kJ energy level, 48 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.073	0.072
180	0.405	0.384
175	0.889	0.840
170	1.598	1.467
160	3.594	3.209
150	6.264	5.514
140	10.064	8.959
130	14.632	13.022
120	20.607	17.721

Table H-38. Jacket foundation (2.44 m diameter, IHC S-2500, 1000 kJ energy level, 48 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.064	0.063
180	0.428	0.409
175	0.969	0.886
170	1.821	1.703
160	4.656	4.085
150	12.311	10.345
140	39.710	31.148
130	70.683	57.580
120	70.683	58.857

Table H-39. Jacket foundation (2.44 m diameter, IHC S-2500, 1500 kJ energy level, 54 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.021	0.021
190	0.129	0.128
180	0.652	0.620
175	1.333	1.208
170	2.155	1.938
160	4.046	3.588
150	6.841	6.152
140	10.825	9.656
130	15.602	13.764
120	21.717	18.555

Table H-40. Jacket foundation (2.44 m diameter, IHC S-2500, 1500 kJ energy level, 54 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.021	0.021
190	0.122	0.121
180	0.709	0.671
175	1.467	1.365
170	2.600	2.354
160	5.649	4.978
150	14.975	13.021
140	50.907	42.107
130	70.683	58.202
120	70.683	59.219

Table H-41. Jacket foundation (2.44 m diameter, IHC S-2500, 2500 kJ energy level, 60 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.029	0.029
190	0.157	0.153
180	0.787	0.736
175	1.457	1.354
170	2.400	2.155
160	4.431	3.892
150	7.485	6.685
140	11.477	10.304
130	16.529	14.521
120	22.654	19.466

Table H-42. Jacket foundation (2.44 m diameter, IHC S-2500, 2500 kJ energy level, 60 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.021	0.021
190	0.142	0.141
180	0.810	0.761
175	1.586	1.485
170	2.787	2.522
160	6.236	5.319
150	16.755	13.832
140	55.197	46.423
130	70.683	58.209
120	70.683	59.319

Table H-43. Jacket foundation (2.44 m diameter, IHC S-2500, 1500 kJ energy level, 70 m penetration depth, summer) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.073	0.072
180	0.342	0.325
175	0.735	0.691
170	1.424	1.318
160	3.381	3.051
150	5.657	5.031
140	9.250	8.206
130	13.421	12.067
120	19.070	16.547

Table H-44. Jacket foundation (2.44 m diameter, IHC S-2500, 1500 kJ energy level, 70 m penetration depth, winter) acoustic ranges (R_{max} and $R_{95\%}$ in km).

Level (L_p)	Flat R_{max}	Flat $R_{95\%}$
200	0.001	0.001
190	0.061	0.060
180	0.331	0.312
175	0.747	0.698
170	1.534	1.437
160	3.851	3.511
150	9.288	8.039
140	26.849	21.870
130	70.683	54.338
120	70.683	58.321

H.4. Impact Pile Driving Per-Pile SEL Acoustic Ranges with Attenuation

Table H-45. Monopile (Location G10, summer, 8 to 11 m diameter, IHC S-4000) and jacket (Location Z11, 2.44 m diameter, IHC S-2500) foundation acoustic ranges ($R_{95\%}$ in km) with attenuation (Finneran et al. 2017, NMFS 2018).

Hearing group	Threshold (dB)	G10					Z11				
		Attenuation level (dB)					Attenuation level (dB)				
		0	6	10	15	20	0	6	10	15	20
LF	183	7.45	5.49	4.31	3.04	1.96	4.40	2.93	2.10	1.28	0.62
MF	185	0.36	0.10	0.04	0.00	0.00	0.23	0.10	0.03	0.00	0.00
HF	155	5.19	3.42	2.48	1.48	0.81	4.84	3.16	2.23	1.29	0.72
PPW	185	2.40	1.27	0.74	0.32	0.15	1.53	0.73	0.36	0.14	0.06
TUW	204	2.90	1.69	1.10	0.50	0.21	0.91	0.37	0.17	0.09	0.03

Table H-46. Monopile (Location G10, winter, 8 to 11 m diameter, IHC S-4000) and jacket (Location Z11, 2.44 m diameter, IHC S-2500) foundation acoustic ranges ($R_{95\%}$ in km) with attenuation (Finneran et al. 2017, NMFS 2018).

Hearing group	Threshold (dB)	G10					Z11				
		Attenuation level (dB)					Attenuation level (dB)				
		0	6	10	15	20	0	6	10	15	20
LF	183	16.56	9.59	6.69	4.28	2.58	8.15	4.34	2.88	1.56	0.70
MF	185	0.36	0.13	0.09	0.03	0.00	0.18	0.09	0.04	0.00	0.00
HF	155	10.34	5.92	3.85	2.24	1.09	7.15	3.87	2.40	1.36	0.62
PPW	185	3.76	1.79	0.98	0.41	0.17	1.80	0.71	0.34	0.14	0.06
TUW	204	3.71	2.04	1.26	0.57	0.24	1.03	0.38	0.18	0.08	0.03

H.5. Fish Acoustic Distances to threshold

H.5.1. Location G10: Monopile Foundations

Table H-47. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 0 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	7.98						
	L_{pk} [a]	206	0.07	0.14	0.10	0.25	0.30	0.27	0.31
	L_{p} [b]	150	4.25	6.07	4.97	7.09	8.29	7.31	7.99
Fish less than 2 g	$L_{E,24hr}$ [a]	183	9.50						
	L_{pk} [a]	206	0.07	0.14	0.10	0.25	0.30	0.27	0.31
	L_{p} [b]	150	4.25	6.07	4.97	7.09	8.29	7.31	7.99
Fish without swim bladder	$L_{E,24hr}$ [c]	216	1.12						
	L_{pk} [c]	213	0.03	0.07	0.05	0.08	0.10	0.09	0.10
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	3.44						
	L_{pk} [c]	207	0.06	0.11	0.09	0.18	0.27	0.24	0.29
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	3.44						
	L_{pk} [c]	207	0.06	0.11	0.09	0.18	0.27	0.24	0.29

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa²·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-48. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 0 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	14.30						
	L_{pk} [a]	206	0.07	0.12	0.10	0.24	0.30	0.25	0.31
	L_p [b]	150	5.65	9.28	6.89	10.98	14.18	12.45	18.91
Fish less than 2 g	$L_{E,24hr}$ [a]	183	20.01						
	L_{pk} [a]	206	0.07	0.12	0.10	0.24	0.30	0.25	0.31
	L_p [b]	150	5.65	9.28	6.89	10.98	14.18	12.45	18.91
Fish without swim bladder	$L_{E,24hr}$ [c]	216	1.24						
	L_{pk} [c]	213	0.03	0.07	0.05	0.08	0.10	0.09	0.10
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	4.37						
	L_{pk} [c]	207	0.07	0.11	0.09	0.18	0.25	0.23	0.27
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	4.37						
	L_{pk} [c]	207	0.07	0.11	0.09	0.18	0.25	0.23	0.27

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-49. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 6 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	6.06						
	L_{pk} [a]	206	0.04	0.07	0.05	0.09	0.10	0.10	0.11
	L_{p} [b]	150	3.35	4.38	3.52	5.32	6.32	5.47	6.01
Fish less than 2 g	$L_{E,24hr}$ [a]	183	7.29						
	L_{pk} [a]	206	0.04	0.07	0.05	0.09	0.10	0.10	0.11
	L_{p} [b]	150	3.35	4.38	3.52	5.32	6.32	5.47	6.01
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.46						
	L_{pk} [c]	213	0.01	0.02	0.01	0.04	0.05	0.05	0.05
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	2.22						
	L_{pk} [c]	207	0.03	0.07	0.05	0.08	0.10	0.09	0.10
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	2.22						
	L_{pk} [c]	207	0.03	0.07	0.05	0.08	0.10	0.09	0.10

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-50. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 6 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	9.35						
	L_{pk} [a]	206	0.03	0.07	0.05	0.09	0.11	0.10	0.12
	L_{p} [b]	150	3.69	6.08	4.51	7.31	9.65	8.09	10.78
Fish less than 2 g	$L_{E,24hr}$ [a]	183	12.44						
	L_{pk} [a]	206	0.03	0.07	0.05	0.09	0.11	0.10	0.12
	L_{p} [b]	150	3.69	6.08	4.51	7.31	9.65	8.09	10.78
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.52						
	L_{pk} [c]	213	0.01	0.01	0.01	0.04	0.05	0.04	0.05
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	2.62						
	L_{pk} [c]	207	0.03	0.07	0.05	0.08	0.10	0.09	0.10
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	2.62						
	L_{pk} [c]	207	0.03	0.07	0.05	0.08	0.10	0.09	0.10

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-51. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 15 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ) G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	3.66						
	L_{pk} [a]	206	0.00	0.01	0.01	0.02	0.04	0.03	0.04
	L_p [b]	150	2.42	3.15	2.74	3.33	3.89	3.35	3.59
Fish less than 2 g	$L_{E,24hr}$ [a]	183	4.66						
	L_{pk} [a]	206	0.00	0.01	0.01	0.02	0.04	0.03	0.04
	L_p [b]	150	2.42	3.15	2.74	3.33	3.89	3.35	3.59
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.12						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.85						
	L_{pk} [c]	207	0.00	0.01	0.00	0.01	0.03	0.02	0.03
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.85						
	L_{pk} [c]	207	0.00	0.01	0.00	0.01	0.03	0.02	0.03

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-52. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 15 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	4.73						
	L_{pk} [a]	206	0.00	0.01	0.01	0.02	0.04	0.03	0.04
	L_{p} [b]	150	2.76	3.42	3.10	3.85	5.07	4.14	5.01
Fish less than 2 g	$L_{E,24hr}$ [a]	183	6.40						
	L_{pk} [a]	206	0.00	0.01	0.01	0.02	0.04	0.03	0.04
	L_{p} [b]	150	2.76	3.42	3.10	3.85	5.07	4.14	5.01
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.11						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.94						
	L_{pk} [c]	207	0.00	0.01	0.00	0.01	0.03	0.02	0.03
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.94						
	L_{pk} [c]	207	0.00	0.01	0.00	0.01	0.03	0.02	0.03

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-53. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 20 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	2.62						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.01	0.01	0.01
	L_p [b]	150	1.58	2.53	1.95	2.98	3.25	3.02	3.12
Fish less than 2 g	$L_{E,24hr}$ [a]	183	3.44						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.01	0.01	0.01
	L_p [b]	150	1.58	2.53	1.95	2.98	3.25	3.02	3.12
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.05						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.42						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.42						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.01	0.01

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-54. Monopile foundation (8 to 11 m diameter, IHC S-4000 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 20 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			G10						
			500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	3.15						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.01	0.01	0.01
	L_p [b]	150	1.76	2.98	2.28	3.25	3.53	3.30	3.43
Fish less than 2 g	$L_{E,24hr}$ [a]	183	4.37						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.01	0.01	0.01
	L_p [b]	150	1.76	2.98	2.28	3.25	3.53	3.30	3.43
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.05						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.43						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.01	0.01
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.43						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.01	0.01

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

H.5.2. Location Z11: Jacket Foundation

Table H-55. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 0 dB attenuation. SEL accumulated for one foundation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	4.15 (one pile) / 4.93 (two piles) / 5.43 (three piles)						
	L_{pk} [a]	206	0.08	0.06	0.12	0.20	0.23	0.26	0.11
	L_{p} [b]	150	4.72	3.49	5.12	5.51	6.15	6.69	5.03
Fish less than 2 g	$L_{E,24hr}$ [a]	183	5.20 (one pile) / 6.12 (two piles) / 6.70 (three piles)						
	L_{pk} [a]	206	0.08	0.06	0.12	0.20	0.23	0.26	0.11
	L_{p} [b]	150	4.72	3.49	5.12	5.51	6.15	6.69	5.03
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.17 (one pile) / 0.28 (two piles) / 0.38 (three piles)						
	L_{pk} [c]	213	0.04	0.01	0.06	0.06	0.07	0.08	0.04
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	1.25 (one pile) / 1.65 (two piles) / 1.95 (three piles)						
	L_{pk} [c]	207	0.07	0.05	0.09	0.13	0.22	0.23	0.09
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	1.25 (one pile) / 1.65 (two piles) / 1.95 (three piles)						
	L_{pk} [c]	207	0.07	0.05	0.09	0.13	0.22	0.23	0.09

L_{pk}= unweighted peak sound pressure (dB re 1 μPa); L_E= unweighted sound exposure level (dB re 1 μPa^2·s); L_p= unweighted sound pressure (dB re 1 μPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-56. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 0 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	6.40 (one pile) / 8.58 (two piles) / 10.14 (three piles)						
	L_{pk} [a]	206	0.08	0.06	0.10	0.18	0.23	0.24	0.18
	L_{p} [b]	150	8.44	5.05	9.57	10.35	13.02	13.83	8.04
Fish less than 2 g	$L_{E,24hr}$ [a]	183	9.45 (one pile) / 12.76 (two piles) / 15.05 (three piles)						
	L_{pk} [a]	206	0.08	0.06	0.10	0.18	0.23	0.24	0.18
	L_{p} [b]	150	8.44	5.05	9.57	10.35	13.02	13.83	8.04
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.17 (one pile) / 0.28 (two piles) / 0.386 (three piles)						
	L_{pk} [c]	213	0.04	0.01	0.06	0.06	0.08	0.08	0.04
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	1.36 (one pile) / 1.93 (two piles) / 2.33 (three piles)						
	L_{pk} [c]	207	0.08	0.06	0.09	0.14	0.22	0.23	0.10
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	1.36 (one pile) / 1.93 (two piles) / 2.33 (three piles)						
	L_{pk} [c]	207	0.08	0.06	0.09	0.14	0.22	0.23	0.10

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-57. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 6 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	2.90 (one pile) / 3.51 (two piles) / 3.88 (three piles)						
	L_{pk} [a]	206	0.05	0.01	0.06	0.06	0.07	0.08	0.04
	L_{p} [b]	150	3.32	2.32	3.64	3.94	4.45	4.86	3.63
Fish less than 2 g	$L_{E,24hr}$ [a]	183	3.73 (one pile) / 4.42 (two piles) / 4.86 (three piles)						
	L_{pk} [a]	206	0.05	0.01	0.06	0.06	0.07	0.08	0.04
	L_{p} [b]	150	3.32	2.32	3.64	3.94	4.45	4.86	3.63
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.06 (one pile) / 0.12 (two piles) / 0.15 (three piles)						
	L_{pk} [c]	213	0.01	0.00	0.01	0.01	0.03	0.04	0.02
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.55 (one pile) / 0.86 (two piles) / 1.07 (three piles)						
	L_{pk} [c]	207	0.04	0.01	0.06	0.06	0.07	0.08	0.04
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.55 (one pile) / 0.86 (two piles) / 1.07 (three piles)						
	L_{pk} [c]	207	0.04	0.01	0.06	0.06	0.07	0.08	0.04

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-58. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 6 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	3.78 (one pile) / 4.85 (two piles) / 5.69 (three piles)						
	L_{pk} [a]	206	0.05	0.01	0.07	0.07	0.08	0.09	0.05
	L_p [b]	150	4.73	3.07	5.29	5.78	7.27	7.77	4.66
Fish less than 2 g	$L_{E,24hr}$ [a]	183	5.29 (one pile) / 7.13 (two piles) / 8.39 (three piles)						
	L_{pk} [a]	206	0.05	0.01	0.07	0.07	0.08	0.09	0.05
	L_p [b]	150	4.73	3.07	5.29	5.78	7.27	7.77	4.66
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.06 (one pile) / 0.10 (two piles) / 0.13 (three piles)						
	L_{pk} [c]	213	0.01	0.00	0.01	0.01	0.03	0.04	0.02
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.57 (one pile) / 0.90 (two piles) / 1.17 (three piles)						
	L_{pk} [c]	207	0.04	0.01	0.06	0.06	0.08	0.08	0.04
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.57 (one pile) / 0.90 (two piles) / 1.17 (three piles)						
	L_{pk} [c]	207	0.04	0.01	0.06	0.06	0.08	0.08	0.04

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-59. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 15 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	1.33 (one pile) / 1.78 (two piles) / 2.09 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.01	0.01	0.03	0.01
	L_{p} [b]	150	1.64	0.90	1.99	2.28	2.81	3.09	2.12
Fish less than 2 g	$L_{E,24hr}$ [a]	183	1.98 (one pile) / 2.52 (two piles) / 2.86 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.01	0.01	0.03	0.01
	L_{p} [b]	150	1.64	0.90	1.99	2.28	2.81	3.09	2.12
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.01 (one pile) / 0.02 (two piles) / 0.03 (three piles)						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.13 (one pile) / 0.19 (two piles) / 0.27 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.02	0.01
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.13 (one pile) / 0.19 (two piles) / 0.27 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.02	0.01

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-60. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 15 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	1.53 (one pile) / 2.15 (two piles) / 2.58 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.01	0.01	0.03	0.01
	L_{p} [b]	150	2.02	1.05	2.52	2.89	3.46	3.60	2.47
Fish less than 2 g	$L_{E,24hr}$ [a]	183	2.38 (one pile) / 3.19 (two piles) / 3.72 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.01	0.01	0.03	0.01
	L_{p} [b]	150	2.02	1.05	2.52	2.89	3.46	3.60	2.47
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.01 (one pile) / 0.02 (two piles) / 0.03 (three piles)						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.12 (one pile) / 0.20 (two piles) / 0.27 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.02	0.01
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.12 (one pile) / 0.20 (two piles) / 0.27 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.01	0.02	0.01

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa²·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-61. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for summer conditions with 20 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	0.70 (one pile) / 1.08 (two piles) / 1.30 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	L_p [b]	150	0.91	0.43	1.25	1.47	1.94	2.16	1.32
Fish less than 2 g	$L_{E,24hr}$ [a]	183	1.25 (one pile) / 1.65 (two piles) / 1.95 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	L_p [b]	150	0.91	0.43	1.25	1.47	1.94	2.16	1.32
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.01 (one pile) / 0.01 (two piles) / 0.01 (three piles)						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.06 (one pile) / 0.10 (two piles) / 0.13 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.06 (one pile) / 0.10 (two piles) / 0.13 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.00	0.01	0.00

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Table H-62. Jacket foundation (2.44 m diameter, IHC S-2500 hammer) acoustic ranges (R_{max} in km) at different energy levels for winter conditions with 20 dB attenuation.

Faunal group	Metric	Threshold	Hammer energy (kJ)						
			Z11						
			500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
Fish equal to or greater than 2 g	$L_{E,24hr}$ [a]	187	0.78 (one pile) / 1.20 (two piles) / 1.49 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	L_{p} [b]	150	1.08	0.48	1.43	1.70	2.35	2.52	1.44
Fish less than 2 g	$L_{E,24hr}$ [a]	183	1.36 (one pile) / 1.93 (two piles) / 2.33 (three piles)						
	L_{pk} [a]	206	0.00	0.00	0.00	0.00	0.00	0.01	0.00
	L_{p} [b]	150	1.08	0.48	1.43	1.70	2.35	2.52	1.44
Fish without swim bladder	$L_{E,24hr}$ [c]	216	0.01 (one pile) / 0.01 (two piles) / 0.01 (three piles)						
	L_{pk} [c]	213	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fish with swim bladder not involved in hearing	$L_{E,24hr}$ [c]	203	0.05 (one pile) / 0.08 (two piles) / 0.12 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.00	0.01	0.00
Fish with swim bladder involved in hearing	$L_{E,24hr}$ [c]	203	0.05 (one pile) / 0.08 (two piles) / 0.12 (three piles)						
	L_{pk} [c]	207	0.00	0.00	0.00	0.00	0.00	0.01	0.00

L_{pk}= unweighted peak sound pressure (dB re 1 µPa); L_E= unweighted sound exposure level (dB re 1 µPa^2·s); L_p= unweighted sound pressure (dB re 1 µPa).

[a] NMFS recommended criteria adopted from the Fisheries Hydroacoustic Working Group (FHWG 2008).

[b] Andersson et al. (2007), Mueller-Blenkle et al. (2010), Purser and Radford (2011), Wysocki et al. (2007).

[c] Popper et al. (2014)

Appendix I. ITAP Comparison

ITAP GmbH is a German agency accredited for measuring and forecasting sound levels produced during impact pile driving for installations such as wind farms (see Appendix I.1). Sound level predictions were made using ITAP's empirical model to forecast single-strike SEL at 750 m from the pile (results provided by ITAP and included for this analysis at Ørsted's request). ITAP's empirical forecasting model was created by compiling and fitting numerous measurements at 750 m for a variety of pile dimensions, hammer types and hammer energy levels, and at several locations (though primarily in the North Sea). The ITAP model is based on the 95th percentile of the single-strike SEL measurement. That is, the SEL value used to generate the model was the level inclusive of 95% of the single-strike measurements at a given hammer energy level (the highest 5% of single-strike SEL measurements were discarded). Because the ITAP model forecasts mean values from aggregated measurements, application to specific pile driving scenarios may be expected to differ to some degree from the forecast.

As a way of validating the acoustic modeling for this study, single-strike SEL received levels at 750 m from the driven pile were determined from the calculated 3-D sound fields (see Appendices F, G, and H) and compared to the ITAP forecast (Table I-1 and I-2). ITAP's model forecasts the 95th percentile of SEL values while the acoustic modeling in this study results in an estimate of a median value (50th percentile), so the levels calculated for this study at 750 m are expected to be lower than the forecasted levels.

Table I-1 shows that the single- strike SEL levels at 750 m predicted in this study for monopile foundations, and Table I-2 shows the same for jacket foundation pin piles (with 2.5 dB added to the original modeling to account for the jacket structure and an additional 1.5 dB safety factor). Both the monopile and jacket pin pile predictions are in reasonable agreement with the ITAP forecast. At lower hammer energy levels this study's predicted received levels are lower than the ITAP forecast and at higher hammer energy levels the predicted received levels in this study are generally similar to the forecast levels. It is likely that the pile penetration depth accounts for this trend. When more of the pile has penetrated into the seabed, the pile as a sound source has a larger radiating area in the water and substrate and produces more sound energy. In this study, lower hammer energy levels occur at the start of pile driving when little of the pile has penetrated into the substrate. Within the ITAP model, measurements from all hammer energy levels represent a range of pile penetration depths such that measurements of lower hammer energy strikes include piles near full penetration and driven with smaller hammers, which may produce louder sounds. Differences may also occur at the deeper penetrations for jacket foundation pin piles. When the pile is driven to the point where the top of the pile and hammer are underwater, there is little of the pile radiating sound directly into the water and this situation is not directly comparable to ITAP.

Table I-1. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of modeled monopile sound fields with ITAP (Bellmann et al. 2020) at 750 m.

Source location	Hammer energy in kJ (at pile penetration depth in m)													
	Summer							Winter						
	500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)	500 (7)	2000 (13)	1000 (16)	3000 (18)	4000 (34)	3000 (40)	4000 (50)
ITAP	175.8	180.9	178.4	182.4	183.5	182.4	183.5	175.8	180.9	178.4	182.4	183.5	182.4	183.5
G10	169.0	175.1	171.6	178.3	181.8	178.9	181.0	169.9	176.1	172.5	179.2	182.5	179.9	182.0

Table I-2. Broadband single-strike SEL (dB re 1 µPa^2·s) comparison of modeled pin piles for jacket foundation sound fields with ITAP (Bellmann et al. 2020) at 750 m.

Source location	Hammer energy in kJ (at pile penetration depth in m)													
	Summer							Winter						
	500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)	500 (3)	200 (32)	750 (40)	1000 (48)	1500 (54)	2500 (60)	1500 (70)
ITAP	169.5			172	173.5	174.6	173.5	169.5			172	173.5	174.6	173.5
Z11	165.7	160.5	167.8	169.5	172.6	173.8	168.6	163.9	160.6	167.9	169.5	172.5	173.2	167.9

I.1. ITAP Description and Qualifications

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Ørsted Wind Power

INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

Messstelle nach §29b BImSchG für Geräusche

Oldenburg, August 10th 2020

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Qualification and References of the *itap GmbH*

Dear Mr. Matej Simurda,

as requested, please find below a short description / biography of the *itap GmbH*. In case you need more detailed information, please feel free to contact me.

Short description of the *itap GmbH*

Graduates from the Carl von Ossietzky University of Oldenburg founded the Institute of Technical and Applied Physics (itap) in 1992 (https://www.itap.de/en/). As the demand for technical-scientific services rose, the institute was transferred into an independent limited liability company in 1995.

Meanwhile, the company can look on 25 years business experience, during which new areas of activity opened up constantly. Over time, different physical problems were dealt with; the focus however always was in the field of technical acoustics. To be named hereby in particular: our sustainable activities in the field of immission (pollution) control onshore as well as our pioneering role in the investigation of underwater noise with the aim to protect marine life.

Qualification and certification

The *itap GmbH* is a notified measuring agency in Germany according to §29b BImSchG (Federal Control of Pollution Act) and has an accredited quality management system (QMS) according to the ISO/IEC 17025 for emission and immission (pollution) measurements of sounds and vibrations (accreditation in accordance with the DAkkS – German accreditation body – for measurements and forecasts of underwater noise (impulse and continuous noise), the immission (pollution) protection module sounds and vibrations, as well as noise in the workplace).

Technical references: underwater noise

The itap GmbH was involved in all German Offshore Windfarm (OWF) construction projects since 2008, by predicting the estimated pile-driving noise during construction, consultancy services regarding noise measurements and noise mitigation strategies, as well as measuring ambient and pile-driving noise during the construction phase and operational noise of Offshore Wind Turbine Generators after completion of construction works.

Within a Research and Development (R&D) project the technical information system for underwater noise MarinEARS (Marine Explorer and Registry of Sound https://marinears.bsh.de) was designed in cooperation with the German regulatory authority BSH (Bundesamt für Seeschifffahrt und Hydrographie). All quality checked and post-processed underwater noise measurement data from 2012 till 2020 for German OWF projects within MarinEARS were provided by the *itap GmbH*. The technical field report regarding the experiences with impact pile-driving noise as well as the application of noise mitigation measures of this R&D project is available in German and English version at our homepage: https://www.itap.de/en/news/field-report-pile-driving-noise-published/.

Furthermore, the *itap GmbH* was also involved in OWF construction projects in Belgium, The Netherlands, Denmark, Sweden, United Kingdom and Taiwan, providing underwater noise predictions and consultancy services as well as performing underwater noise measurements.

The *Itap GmbH* has measured underwater noise during use of all available noise mitigation measures (noise mitigation systems as well as noise abatement systems) for offshore constructions worldwide under offshore conditions (offshore reliable and state-of-the-art noise mitigation measures as well as prototypes in accordance to DIN SPEK 45653 (2017)).

Besides the main task domain of underwater noise in connection with OWF construction projects (pile-driving noise), the *itap GmbH* predicts and measures underwater noise of all kinds of maritime activities. Such as for offshore projects like cable or pipe laying activities, cable fault detection, any acoustical surveys (e. g. sonar operations), clearance of unexploded ordnances (UXO), detonations or decommissioning of any offshore constructions, vessel based noise as well as for costal projects (e. g. within harbor facilities).

Services: underwater noise

Consultancy: The *itap GmbH* provides consultancy services related to the full scope of underwater noise predictions and measurements (especially related to Offshore Wind Farms). In recent years, our experience in Europe has expanded and extended beyond Europe to the United States of America, Taiwan and Australia. Due to our pioneering role in this field and the associated 20 years of experience in Europe, we can offer a wide range of consulting services. Such as preparation of noise mitigation concepts, selection of suitable noise mitigation measures, support within approval procedures and contact to local authorities.

Underwater noise prognosis: In recent years, our portfolio of underwater noise prediction services regarding pile driving noise has grown to meet a variety of different local regulatory requirements for various noise mitigation values throughout Europe and Taiwan and to assist the environmental impact assessment by species specific underwater noise modelling like in UK, Australia and the USA. The *itap GmbH* is able to perform underwater noise prognosis for various noise sources regarding impulsiveness and continuous noise according to national guidelines and project-specific requirements of the local approval authorities and respective local environmental conditions.

For underwater noise prognosis we are using our extensive experiences within this domain. Based on this, we have developed two models for underwater noise prediction:

1) Impulsiveness underwater noise model: Our validated pile-driving noise model based on measured values over the last 20 years within more than 35 pcs OWF and more than 30 pcs single foundation projects (empirical approach). With this pile-driving model, mitigated as well as unmitigated pile-driving noise can be predicted (broadband as well as frequency depending).
   This model also contains the empirical approach of Soloway and Dahl (2014) as well as own measured data during UXO clearance activities and detonations.
2) Continuous noise model: *Itap GmbH* also developed a model for continuous noise activities like vessel based construction projects (pipe and cable laying projects as well as operational noise from Offshore Wind Turbine Generator). However, this model will currently be extended to vibro-piling activities based on measured data as well.

Underwater noise measurements: At the beginning of the underwater noise measurements with regard to OWFs in 2000, there was no measurement device commercially available on the market, so the decision was made to develop an own system. The benefit of our own developed and constructed devices is that we can adapt our measurement devices to a variety of special requirements regarding amplitude and frequency range (from ambient noise till noise during UXO clearance from 20 Hz up to 200 kHz). Furthermore, the mooring systems for our measurement devices are self-constructed and can be adapted to the local environmental conditions easily. During the last 20 years we have been able to gain a lot of experience with different measurements under different environmental conditions.

All measurement devices of *itap GmbH* are fulfilling the requirements of national and international standards (e. g. BSH, 2011; ISO 18406) and the calibration is performed in accordance to ISO/IEC 17025 (2018).

Research and Development: Due the special expertise in the field of technical acoustics the *itap GmbH* has participated in various research projects dealing with underwater noise (https://www.itap.de/en/research-projects/). E. g. in the field of underwater sound propagation, further development of noise mitigation measures and the evaluation of the impact of underwater noise on marine mammals.

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Appendix J. Animal Movement and Exposure Modeling

To assess the risk of impacts from anthropogenic sound exposure, an estimate of the received sound levels for individuals of each species known to occur in the Project Area during the assessed activities is required. Both sound sources and animals move. The sound fields may be complex, and the sound received by an animal is a function of where the animal is at any given time. To a reasonable approximation, the locations of the project sound sources are known, and acoustic modeling can be used to predict the individual and aggregate 3-D sound fields of the sources. The location and movement of animals within the sound field, however, is unknown. Realistic animal movement within the sound field can be simulated. Repeated random sampling (Monte Carlo method simulating many animals within the operations area) is used to estimate the sound exposure history of the population of simulated animals (animats) during the operation.

Monte Carlo methods provide a heuristic approach for determining the probability distribution function (PDF) of complex situations, such as animals moving in a sound field. The probability of an event's occurrence is determined by the frequency with which it occurs in the simulation. The greater the number of random samples, in this case the more animats, the better the approximation of the PDF. Animats are randomly placed, or seeded, within the simulation boundary at a specified density (animats/km^2). Higher densities provide a finer PDF estimate resolution but require more computational resources. To ensure good representation of the PDF, the animat density is set as high as practical allowing for computation time. The animat density is much higher than the real-world density to ensure good representation of the PDF. The resulting PDF is scaled using the real-world density.

Several models for marine mammal movement have been developed (Ellison et al. 1999, Frankel et al. 2002, Houser 2006). These models use an underlying Markov chain to transition from one state to another based on probabilities determined from measured swimming behavior. The parameters may represent simple states, such as the speed or heading of the animal, or complex states, such as likelihood of participating in foraging, play, rest, or travel. Attractions and aversions to variables like anthropogenic sounds and different depth distances can be included in the models.

The JASCO Animal Simulation Model Including Noise Exposure (JASMINE) was based on the open-source marine mammal movement and behavior model (3MB; Houser 2006) and used to predict the exposure of animats (virtual marine mammals and sea turtles) to sound arising from sound sources in simulated representative surveys. Inside JASMINE, the sound source location mimics the movement of the source vessel through the proposed survey pattern. Animats are programmed to behave like the marine animals likely to be present in the survey area. The parameters used for forecasting realistic behaviors (e.g., diving, foraging, aversion, surface times, etc.) are determined and interpreted from marine species studies (e.g., tagging studies) where available, or reasonably extrapolated from related species. An individual animat's modeled sound exposure levels are summed over the total simulation duration, such as 24 hours or the entire simulation, to determine its total received energy, and then compared to the assumed threshold criteria.

JASMINE uses the same animal movement algorithms as the 3MB model (Houser 2006) but has been extended to be directly compatible with MONM and FWRAM acoustic field predictions, for inclusion of source tracks, and importantly for animats to change behavioral states based on time and space dependent modeled variables such as received levels for aversion behavior (Ellison et al. 2016).

J.1. Animal Movement Parameters

JASMINE uses previously measured behavior to forecast behavior in new situations and locations. The parameters used for forecasting realistic behavior are determined (and interpreted) from marine species studies (e.g., tagging studies). Each parameter in the model is described as a probability distribution. When limited or no information is available for a species parameter, a Gaussian or uniform distribution may be chosen for that parameter. For the Gaussian distribution, the user determines the mean and standard deviation of the distribution from which parameter values are drawn. For the uniform distribution, the user determines the maximum and minimum distribution from which parameter values are drawn. When detailed information about the movement and behavior of a species are available, a user-created distribution vector, including cumulative transition probabilities, may be used (referred to here as a vector model; Houser 2006). Different sets of parameters can be defined for different behavior states. The probability of an animat starting out in or transitioning into a given behavior state can in turn be defined in terms of the animat's current behavioral state, depth, and the time of day. In addition, each travel parameter and behavioral state has a termination function that governs how long the parameter value or overall behavioral state persists in simulation.

The parameters used in JASMINE describe animal movement in both the vertical and horizontal planes. A description of parameters relating to travel in these two planes are briefly described below. JASCO maintains species-specific choices of values for the behavioral parameters used in this study. The parameter values are available for limited distribution upon request.

Travel sub-models

Direction–determines an animat's choice of direction in the horizontal plane. Sub-models are available for determining the heading of animats, allowing for movement to distance from strongly biased to undirected. A random walk model can be used for behaviors with no directional preference, such as feeding and playing. In a random walk, all bearings are equally likely at each parameter transition time step. A correlated random walk can be used to smooth the changes in bearing by using the current heading as the mean of the distribution from which to draw the next heading. An additional variant of the correlated random walk is available that includes a directional bias for use in situations where animals have a preferred absolute direction, such as migration. A user-defined vector of directional probabilities can also be input to control animat heading. For more detailed discussion of these parameters, see Houser (2006) and Houser and Cross (1999).

- **Travel rate**–defines an animat's rate of travel in the horizontal plane. When combined with vertical speed and dive depth, the dive profile of the animat is produced.

Dive sub-models

- **Ascent rate**–defines an animat's rate of travel in the vertical plane during the ascent portion of a dive.
- **Descent rate**–defines an animat's rate of travel in the vertical plane during the descent portion of a dive.
- **Depth**–defines an animat's maximum dive depth.
- **Bottom following**–determines whether an animat returns to the surface once reaching the ocean floor, or whether it follows the contours of the bathymetry.
- **Reversals**–determines whether multiple vertical excursions occur once an animat reaches the maximum dive depth. This behavior is used to emulate the foraging behavior of some marine mammal species at depth. Reversal-specific ascent and descent rates may be specified.
- **Surface interval**–determines the duration an animat spends at, or near, the surface before diving again.

J.1.1. Exposure Integration Time

The interval over which acoustic exposure (L_E) should be integrated and maximal exposure (*SPL*) determined is not well defined. Both Southall et al. (2007) and the NMFS (2018) recommend a 24 h baseline accumulation period, but state that there may be situations where this is not appropriate (e.g., a high-level source and confined population). Resetting the integration after 24 h can lead to overestimating the number of individual animals exposed because individuals can be counted multiple times during an operation. The type of animal movement engine used in this study simulates realistic movement using swimming behavior collected over relatively short periods (hours to days) and does not include large-scale movement such as migratory circulation patterns. Therefore, the simulation time should be limited to a few weeks, the approximate scale of the collected data (e.g., marine mammal tag data) (Houser 2006). For this study, one-week simulations (i.e., 7 days) were modeled.

Ideally, a simulation area is large enough to encompass the entire range of a population so that any animal that might be present in the Project Area during sound-producing activities is included. However, there are limits to the simulation area, and computational overhead increases with area. For practical reasons, the simulation area is limited in this analysis to a maximum distance of 38 miles (70 km) from the OCW01 (see figures in Section J.2). In the simulation, every animat that reaches and leaves a border of the simulation area is replaced by another animat entering at an opposite border—e.g., an animat departing at the northern border of the simulation area is replaced by an animat entering the simulation area at the southern border at the same longitude. When this action places the animat in an inappropriate water depth, the animat is randomly placed on the map at a depth suited to its species definition (Appendix Section J.2). The exposures of all animats (including those leaving the simulation and those entering) are kept for analysis. This approach maintains a consistent animat density and allows for longer integration periods with finite simulation areas.

J.1.2. Aversion

Aversion is a common response of animals to sound, particularly at relatively high sound exposure levels (Ellison et al. 2012). As received sound level generally decreases with distance from a source, this aspect of natural behavior can strongly influence the estimated maximum sound levels an animal is predicted to receive and significantly affects the probability of more pronounced direct or subsequent behavioral effects. Additionally, animals are less likely to respond to sound levels distant from a source, even when those same levels elicit response at closer distances; both proximity and received levels are important factors in aversive responses (Dunlop et al. 2017b). As a supplement to this modeling study for comparison purposes only, parameters determining aversion at specified sound levels were implemented for the North Atlantic right whale, in recognition of its endangered status, and harbor porpoise, a species known to have a strong aversive response to loud sounds.

Aversion is implemented in JASMINE by defining a new behavioral state that an animat may transition in to when a received level is exceeded. There are very few data on which aversive behavior can be based. Because of the dearth of information and to be consistent within this report, aversion probability is based on the Wood et al. (2012) step function that was used to estimate potential behavioral disruption. Animats will be assumed to avert by changing their headings by a fixed amount away from the source, with greater deflections associated with higher received levels (Tables J-1 and J-2). Aversion thresholds for marine mammals are based on the Wood et al. (2012) step function. Animats remain in the aversive state for a specified amount of time, depending on the level of exposure that triggered aversion (Tables J-1 and J-2). During this time, travel parameters are recalculated periodically as with normal behaviors. At the end of the aversion interval, the animat model parameters are changed (see Tables J-1 and J-2), depending on the current level of exposure and the animat either begins another aversion interval or transitions to a non-aversive behavior; while if aversion begins immediately, transition to a regular behavior occurs at the end of the next surface interval, consistent with regular behavior transitions.

Table J-1. North Atlantic right whales: Aversion parameters for the animal movement simulation based on Wood et al. (2012) behavioral response criteria.

Probability of aversion (%)	Received sound level (L_p, dB re 1 µPa)	Change in course (°)	Duration of aversion (s)
10	140	10	300
50	160	20	60
90	180	30	30

Table J-2. Harbor porpoises: Aversion parameters for the animal movement simulation based on Wood et al. (2012) behavioral response criteria.

Probability of aversion (%)	Received sound level (L_p, dB re 1 µPa)	Change in course (°)	Duration of aversion (s)
50	120	20	60
90	140	30	30

J.1.3. Simulation Area: Animat Seeding

The exposure criteria for impulsive sounds were used to determine the number of animats exceeding exposure thresholds. To generate statistically reliable probability density functions, all simulations were seeded with an animat density of 0.5 animats/km^2 over the entire simulation area. Some species have depth preference restrictions, e.g., sperm whales prefer deeper water (Aoki et al. 2007), and the simulation location contained a relatively high portion of shallow water areas.

J.2. Animal Movement Modeling Supplemental Results

J.2.1. Marine Mammal Exposure Estimates

This section contains marine mammal exposure estimates for the proposed construction schedule described in Section 1.2.2, assuming 0, 6, 10, 15, and 20 dB of broadband attenuation.

Table J-3. WTG monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with sound attenuation for a total of 98 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{pk}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	17.85	8.70	5.03	2.22	0.68	0.12	0.03	0	0	0	25.16	15.27	12.90	10.12	6.33	21.27	13.86	10.88	7.98	5.14
	Minke whale (migrating)	17.78	9.36	6.06	2.32	0.29	0.08	0.03	0.02	0	0	28.41	19.80	17.18	13.81	9.46	57.45	44.51	37.46	29.75	22.66
	Humpback whale (migrating)	14.12	5.54	2.69	0.97	0.22	0.04	<0.01	0	0	0	21.52	11.83	8.88	7.14	4.43	133.65	75.24	58.20	45.25	33.71
	North Atlantic right whale[c] (migrating)	17.60	6.76	3.25	0.90	0.27	0.03	0	0	0	0	26.50	14.99	11.42	9.05	6.01	206.81	108.54	82.64	65.38	49.99
	Sei whale[c] (migrating)	0.46	0.23	0.12	0.06	0.02	<0.01	<0.01	0	0	0	0.80	0.46	0.39	0.32	0.21	2.20	1.59	1.28	0.96	0.69
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	377.41	263.19	227.38	185.21	125.66	183.17	130.47	94.62	59.04	34.86
	Short-beaked common dolphin	0	0	0	0	0	0	0	0	0	0	4215.79	2812.56	2260.69	1913.20	1349.41	4399.56	2005.61	1314.80	744.63	413.50
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	174.42	130.07	113.39	85.20	52.23	93.58	62.72	43.51	24.90	16.52
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	3686.68	2589.02	2212.01	1574.76	964.21	1851.01	1225.11	841.76	497.78	311.95
	Risso's dolphin	0.01	0	0	0	0	0.03	0	0	0	0	13.82	9.22	7.92	6.36	4.38	6.98	4.83	3.55	2.21	1.43
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0.55	0.29	0.22	0.16	0.09	0.44	0.20	0.11	0.05	0.03
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	270.62	113.03	53.85	13.45	2.95	32.20	12.72	5.33	1.62	0.81	553.90	334.43	253.54	209.64	146.80	6790.29	5010.07	4494.28	4047.28	3079.71
PW	Gray seal	33.71	7.67	2.19	0.24	0	1.21	0	0	0	0	367.54	188.36	132.91	108.46	65.78	756.89	278.51	163.54	87.56	42.90
	Harbor seal	44.01	9.79	3.27	0.47	0	0.58	0.29	0	0	0	351.27	185.29	133.11	104.37	65.70	759.89	268.73	154.16	83.85	43.41

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-4. OSS monopile foundations: Number of marine mammals predicted to receive sound levels above exposure criteria with sound attenuation for a total of 3 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{pk}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	0.59	0.29	0.16	0.07	0.02	<0.01	<0.01	0	0	0	0.86	0.51	0.43	0.34	0.21	0.75	0.47	0.37	0.27	0.17
	Minke whale (migrating)	0.67	0.35	0.21	0.08	<0.01	<0.01	<0.01	<0.01	0	0	1.09	0.76	0.65	0.52	0.35	2.34	1.78	1.49	1.17	0.88
	Humpback whale (migrating)	0.58	0.22	0.11	0.04	<0.01	<0.01	<0.01	0	0	0	0.83	0.44	0.31	0.26	0.16	6.88	3.63	2.78	2.19	1.62
	North Atlantic right whale[c] (migrating)	0.80	0.30	0.15	0.04	0.01	<0.01	0	0	0	0	1.18	0.65	0.48	0.39	0.26	11.27	5.67	4.30	3.42	2.61
	Sei whale[c] (migrating)	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0	0	0	0.03	0.02	0.02	0.01	<0.01	0.10	0.07	0.06	0.04	0.03
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	13.89	9.50	8.22	6.62	4.38	6.72	4.70	3.36	2.08	1.24
	Short-beaked common dolphin	0.06	0	0	0	0	0.06	0	0	0	0	172.34	110.13	85.98	72.78	51.34	220.81	88.67	55.76	30.63	16.26
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	5.84	4.33	3.75	2.80	1.73	3.22	2.11	1.45	0.83	0.54
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	130.69	92.65	78.90	56.12	33.79	66.52	43.77	29.91	17.94	11.19
	Risso's dolphin	<0.01	0	0	0	0	<0.01	0	0	0	0	0.43	0.28	0.24	0.19	0.13	0.22	0.15	0.11	0.07	0.04
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0.02	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	11.75	4.87	2.42	0.64	0.12	1.34	0.55	0.24	0.08	0.03	23.94	13.94	10.20	8.48	5.91	395.76	290.03	261.81	235.63	176.54
PW	Gray seal	1.46	0.27	0.07	<0.01	0	0.04	0	0	0	0	17.51	8.51	5.71	4.61	2.77	44.03	14.93	8.23	4.13	1.96
	Harbor seal	1.86	0.38	0.11	0.02	0	0.02	<0.01	0	0	0	16.57	8.45	5.78	4.52	2.75	44.16	14.37	7.73	3.93	1.94

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-5. Pin piles supporting OSS jacket foundation: Number of marine mammals predicted to receive sound levels above exposure criteria with sound attenuation for a total of 48 pin piles. Construction schedule assumptions are summarized in Section 1.2.2.

	Species	Injury										Behavior									
		$L_{E,24h}$					L_{pk}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	2.50	1.29	0.71	0.22	0.03	0	0	0	0	0	4.15	2.62	1.83	1.11	0.63	3.75	2.39	1.70	1.08	0.66
	Minke whale (migrating)	4.84	1.83	0.64	0.10	0.02	<0.01	0	0	0	0	9.46	6.47	4.46	2.59	1.20	18.29	14.01	11.50	8.80	6.65
	Humpback whale (migrating)	3.07	0.94	0.33	0.05	0.02	<0.01	0	0	0	0	7.05	3.70	2.23	1.07	0.46	59.55	31.85	25.00	19.07	13.29
	North Atlantic right whale[c] (migrating)	3.17	0.89	0.35	0.06	0	0	0	0	0	0	7.58	4.30	2.68	1.28	0.56	95.77	46.48	36.51	28.60	20.09
	Sei whale[c] (migrating)	0.10	0.05	0.03	<0.01	<0.01	<0.01	0	0	0	0	0.19	0.13	0.10	0.06	0.03	0.61	0.43	0.34	0.24	0.17
MF	Atlantic white sided dolphin	0.08	0	0	0	0	0	0	0	0	0	126.83	82.17	56.17	29.37	11.51	66.65	41.20	27.93	16.92	10.08
	Short-beaked common dolphin	0.45	0	0	0	0	0	0	0	0	0	1553.58	943.80	623.78	319.11	140.82	1619.08	726.83	442.56	236.65	133.29
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	94.27	61.40	39.32	18.13	6.12	49.61	29.93	20.16	12.36	7.60
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	1171.32	707.16	454.43	222.36	78.98	662.45	392.95	268.53	155.65	92.71
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	3.16	2.23	1.71	0.99	0.59	1.92	1.21	0.84	0.54	0.33
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	<0.01	0	0	0	0
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	105.73	41.12	16.85	1.99	0.11	9.09	2.66	1.00	0.33	0	177.32	110.38	72.04	39.23	18.18	2965.40	2435.55	2169.35	1886.73	997.28
PW	Gray seal	9.52	2.35	0.26	0	0	0.26	0.13	0	0	0	82.03	48.38	31.56	16.95	6.78	265.78	82.84	43.08	20.04	9.31
	Harbor seal	10.13	1.50	0.13	0	0	0.13	0	0	0	0	80.64	43.64	29.01	14.13	5.50	256.74	78.37	40.05	18.33	8.86

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

J.2.2. Sea Turtle Exposure Estimates

This section contains sea turtle exposure estimates for the construction schedules described in Section 1.2.2, assuming 0, 6, 10, 15, and 20 dB of broadband attenuation.

Table J-6. WTG monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria with sound attenuation for a total of 98 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	16.38	5.09	0.83	0	0	0	0	0	0	0	44.17	26.56	15.00	6.74	3.03
Leatherback turtle[a]	5.53	0.92	0.25	0.08	0	0	0	0	0	0	25.70	13.06	6.61	3.26	0.59
Loggerhead turtle	78.79	18.76	7.50	3.75	0	0	0	0	0	0	686.61	326.42	168.84	82.54	30.02
Green turtle	0.64	0.23	0.06	0.02	0	0	0	0	0	0	1.49	0.75	0.47	0.24	0.06

[a] Listed as Endangered under the ESA.

Table J-7. OSS monopile foundations: Number of sea turtles predicted to receive sound levels above exposure criteria (Finneran et al. 2017) with sound attenuation for a total of 3 monopiles. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	0.44	0.13	0.02	0	0	0	0	0	0	0	1.31	0.75	0.43	0.19	0.07
Leatherback turtle[a]	0.15	0.03	<0.01	<0.01	0	0	0	0	0	0	0.80	0.40	0.18	0.10	0.03
Loggerhead turtle	2.60	0.54	0.23	0.08	0	0	0	0	0	0	22.67	10.41	5.97	2.53	1.00
Green turtle	0.02	<0.01	<0.01	<0.01	0	0	0	0	0	0	0.05	0.02	0.01	<0.01	<0.01

[a] Listed as Endangered under the ESA.

Table J-8. Pin piles supporting OSS jacket foundation: Number of sea turtles predicted to receive sound levels above exposure criteria (Finneran et al. 2017) with sound attenuation for a total of 48 pin piles. Construction schedule assumptions are summarized in Section 1.2.2.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	0.27	0	0	0	0	0	0	0	0	0	4.31	1.17	0.31	0.09	0.04
Leatherback turtle[a]	0.19	0	0	0	0	0	0	0	0	0	3.69	1.34	0.44	0.14	0.08
Loggerhead turtle	3.68	0	0	0	0	0	0	0	0	0	77.18	36.75	14.70	6.13	2.45
Green turtle	0.03	0	0	0	0	0	0	0	0	0	0.15	0.05	0.02	<0.01	<0.01

[a] Listed as Endangered under the ESA.

J.2.3. Marine Mammal Exposure Ranges

This section contains marine mammal exposure ranges for each of the modeled foundation types and seasons assuming 0, 6, 10, 15, and 20 dB broadband attenuation.

Table J-9. Monopile foundation (8 to 11 m diameter, one pile per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

	Species	Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	3.98	2.50	1.58	0.99	0.36	0	0	0	0	0	5.00	3.50	3.04	2.68	1.84	5.09	3.50	3.04	2.68	1.84
LF	Minke whale (migrating)	3.38	1.99	1.23	0.51	0.06	0.02	0	0	0	0	4.77	3.45	3.13	2.66	1.81	12.03	9.68	8.21	6.35	4.85
LF	Humpback whale (migrating)	3.15	1.81	1.14	0.40	0.07	0.02	<0.01	0	0	0	4.82	3.32	3.10	2.53	1.82	12.55	9.81	8.45	6.46	4.94
LF	North Atlantic right whale[c] (migrating)	3.20	2.01	1.28	0.85	0.21	0	0	0	0	0	4.82	3.40	2.95	2.47	1.68	12.41	9.92	8.34	6.55	4.97
LF	Sei whale[c] (migrating)	3.49	2.01	1.36	0.59	0.10	<0.01	<0.01	0	0	0	4.97	3.49	3.13	2.63	1.80	12.23	9.61	8.19	6.49	5.03
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	4.75	3.42	3.10	2.63	1.84	3.14	2.52	1.79	1.05	0.50
MF	Short-beaked common dolphin	<0.01	0	0	0	0	<0.01	0	0	0	0	4.89	3.44	3.09	2.57	1.85	3.16	2.55	1.82	1.08	0.48
MF	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	4.19	3.08	2.80	2.18	1.47	2.96	2.24	1.48	0.77	0.35
MF	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	4.42	3.20	2.90	2.35	1.49	3.03	2.25	1.54	0.86	0.40
MF	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	4.96	3.51	3.06	2.69	1.64	3.16	2.59	1.66	1.11	0.52
MF	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MF	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.09	3.37	3.01	2.67	1.55	3.01	2.50	1.74	1.00	0.32
MF	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	2.56	1.05	0.84	0.21	0.04	0.48	0.18	0.07	0.03	0.01	4.82	3.37	3.11	2.66	1.78	18.69	15.06	12.95	10.57	8.51
PW	Gray seal	1.10	0.05	0	0	0	0.05	0	0	0	0	4.99	3.45	3.21	2.74	1.95	3.95	3.20	2.76	1.96	1.31
PW	Harbor seal	0.94	0.09	0	0	0	0	0	0	0	0	4.66	3.48	3.11	2.44	1.81	3.88	3.13	2.72	1.82	1.15

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-10. Monopile foundation (8 to 11 m diameter, two piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	4.07	2.48	1.65	0.90	0.26	0.04	<0.01	0	0	0	4.96	3.50	3.13	2.62	1.81	5.03	3.51	3.13	2.62	1.79
LF	Minke whale (migrating)	3.45	1.92	1.26	0.54	0.16	0.03	<0.01	<0.01	0	0	4.75	3.44	3.10	2.63	1.79	12.18	9.53	8.05	6.34	4.89
LF	Humpback whale (migrating)	3.25	1.78	1.05	0.41	0.13	0.03	<0.01	0	0	0	4.77	3.38	3.09	2.57	1.82	12.72	9.90	8.40	6.49	4.86
LF	North Atlantic right whale[c] (migrating)	3.45	1.99	1.37	0.65	0.12	0.02	0	0	0	0	4.89	3.35	2.98	2.48	1.75	12.52	9.81	8.30	6.39	5.03
LF	Sei whale[c] (migrating)	3.67	2.19	1.27	0.62	0.18	<0.01	<0.01	0	0	0	4.91	3.49	3.09	2.57	1.86	12.31	9.65	8.15	6.40	5.00
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	4.73	3.39	3.04	2.55	1.81	3.10	2.55	1.80	1.05	0.50
MF	Short-beaked common dolphin	0	0	0	0	0	0	0	0	0	0	4.77	3.41	3.05	2.59	1.86	3.15	2.56	1.85	1.09	0.51
MF	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	4.19	3.10	2.81	2.25	1.43	2.91	2.21	1.54	0.83	0.36
MF	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	4.39	3.15	2.90	2.36	1.52	2.96	2.29	1.58	0.83	0.33
MF	Risso's dolphin	<0.01	0	0	0	0	<0.01	0	0	0	0	4.85	3.44	3.09	2.62	1.82	3.20	2.56	1.87	1.07	0.48
MF	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MF	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	5.18	3.54	3.08	2.72	1.77	3.17	2.64	1.76	0.82	0.50
MF	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	2.45	1.44	0.88	0.32	0.06	0.52	0.22	0.07	0.03	0.01	4.86	3.40	3.07	2.63	1.82	18.55	15.18	13.03	10.52	8.46
PW	Gray seal	1.15	0.24	0.08	0	0	0.05	0	0	0	0	4.89	3.45	3.09	2.71	1.90	3.97	3.13	2.77	1.97	1.22
PW	Harbor seal	1.07	0.28	0.06	0	0	<0.01	<0.01	0	0	0	4.82	3.33	3.08	2.53	1.77	3.91	3.12	2.64	1.85	1.15

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-11. Monopile foundation (8 to 11 m diameter, one pile per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	6.79	3.64	2.33	1.14	0.52	0	0	0	0	0	7.36	4.63	3.48	3.01	2.20	7.43	4.66	3.49	3.01	2.19
	Minke whale (migrating)	6.59	3.38	1.98	0.90	0.16	0.02	0	0	0	0	7.07	4.52	3.39	3.02	2.06	54.26	27.28	17.77	10.98	7.17
	Humpback whale (migrating)	6.19	3.11	1.75	0.66	0.11	0.02	<0.01	0	0	0	7.33	4.58	3.32	3.02	2.13	55.76	28.18	18.98	11.34	7.44
	North Atlantic right whale[c] (migrating)	6.59	3.46	1.85	0.98	0.24	0	0	0	0	0	7.14	4.42	3.28	2.91	2.12	56.81	28.23	19.24	11.35	7.23
	Sei whale[c] (migrating)	6.33	3.20	1.86	0.92	0.28	<0.01	<0.01	0	0	0	7.26	4.66	3.42	3.00	2.04	54.88	27.71	18.41	11.12	7.29
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	7.15	4.40	3.37	2.87	2.13	4.50	3.06	2.54	1.39	0.61
	Short-beaked common dolphin	<0.01	0	0	0	0	<0.01	0	0	0	0	7.07	4.37	3.40	2.96	2.15	4.36	3.05	2.56	1.42	0.62
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	6.58	4.01	3.12	2.71	1.58	4.20	2.91	2.29	1.24	0.50
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	6.59	4.09	3.22	2.78	1.95	4.27	2.95	2.44	1.26	0.44
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	7.15	4.54	3.49	2.95	2.13	4.74	3.06	2.52	1.46	0.54
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	7.64	4.76	3.31	2.86	1.95	4.88	2.96	2.11	1.07	0.59
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	4.45	2.19	1.06	0.57	0.15	0.49	0.18	0.08	0.03	0.01	7.16	4.46	3.34	2.96	2.09	64.05	61.00	59.56	57.83	53.64
PW	Gray seal	1.46	0.37	0	0	0	0.05	0	0	0	0	7.28	4.56	3.44	3.09	2.18	6.33	3.50	3.23	2.49	1.44
	Harbor seal	1.89	0.63	0.07	0	0	0	0	0	0	0	6.98	4.49	3.47	3.01	2.16	6.19	3.53	3.18	2.36	1.38

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-12. Monopile foundation (8 to 11 m diameter, two piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

	Species	Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	7.48	4.07	2.49	1.23	0.49	0.04	<0.01	0	0	0	7.20	4.53	3.44	2.97	2.09	7.26	4.54	3.47	2.97	2.09
	Minke whale (migrating)	7.31	3.54	1.98	0.82	0.48	0.03	<0.01	<0.01	0	0	7.06	4.43	3.42	3.03	2.10	54.49	27.05	17.90	11.09	7.19
	Humpback whale (migrating)	6.39	3.12	1.77	0.64	0.26	0.03	<0.01	0	0	0	7.23	4.53	3.37	2.95	2.18	57.02	28.28	18.69	11.40	7.36
	North Atlantic right whale[c] (migrating)	6.69	3.44	2.03	0.99	0.38	0.02	0	0	0	0	7.18	4.42	3.35	2.86	2.08	57.68	28.28	19.03	11.44	7.35
	Sei whale[c] (migrating)	7.01	3.68	2.19	0.92	0.22	<0.01	<0.01	0	0	0	7.28	4.54	3.45	3.00	2.12	55.34	27.40	18.10	11.05	7.37
MF	Atlantic white sided dolphin	0	0	0	0	0	0	0	0	0	0	7.03	4.37	3.33	2.97	2.10	4.48	3.05	2.51	1.38	0.64
	Short-beaked common dolphin	0	0	0	0	0	0	0	0	0	0	6.98	4.39	3.36	2.95	2.17	4.43	3.09	2.53	1.40	0.67
	Bottlenose dolphin, coastal	0.05	0	0	0	0	0	0	0	0	0	6.42	3.91	3.15	2.68	1.81	4.00	2.90	2.27	1.22	0.55
	Bottlenose dolphin, offshore	0.03	0	0	0	0	0	0	0	0	0	6.65	4.00	3.18	2.76	1.81	4.22	2.94	2.44	1.15	0.53
	Risso's dolphin	<0.01	<0.01	0	0	0	<0.01	0	0	0	0	7.06	4.52	3.36	2.98	2.13	4.55	3.09	2.58	1.43	0.68
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	7.65	4.64	3.41	3.00	1.88	4.61	3.10	2.57	1.21	0.58
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	4.68	2.22	1.43	0.64	0.22	0.53	0.21	0.07	0.03	0.01	7.05	4.47	3.37	2.95	2.14	65.02	61.25	59.60	57.90	53.07
PW	Gray seal	1.77	0.60	0.14	0.01	0	0.05	0	0	0	0	7.24	4.51	3.42	3.02	2.17	6.29	3.56	3.16	2.53	1.38
	Harbor seal	1.88	0.70	0.24	<0.01	0	<0.01	<0.01	0	0	0	6.96	4.52	3.31	2.99	2.12	6.07	3.48	3.12	2.35	1.38

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-13. Jacket foundation (2.44 m diameter, two pin piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

	Species	Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	2.28	1.21	0.55	0.16	0.06	0	0	0	0	0	3.40	2.51	1.82	1.08	0.51	3.45	2.51	1.82	1.09	0.52
	Minke whale (migrating)	1.88	0.99	0.55	0.09	<0.01	<0.01	0	0	0	0	3.09	2.33	1.76	1.17	0.64	9.19	7.07	5.76	4.22	3.15
	Humpback whale (migrating)	1.90	0.98	0.40	0.05	0.03	<0.01	0	0	0	0	3.30	2.52	1.81	1.19	0.56	9.52	7.25	5.96	4.44	3.31
	North Atlantic right whale[c] (migrating)	1.70	0.94	0.51	0.09	0	0	0	0	0	0	3.20	2.39	1.64	1.15	0.54	9.44	7.35	5.71	4.23	3.21
	Sei whale[c] (migrating)	1.85	0.97	0.37	0.13	0.01	0.03	0	0	0	0	3.39	2.40	1.81	1.07	0.52	9.48	7.33	6.14	4.69	3.52
MF	Atlantic white sided dolphin	<0.01	0	0	0	0	0	0	0	0	0	3.19	2.35	1.55	1.05	0.57	2.43	1.41	0.91	0.55	0.28
	Short-beaked common dolphin	0	0	0	0	0	0	0	0	0	0	3.06	2.34	1.72	1.19	0.61	2.49	1.57	1.05	0.49	0.24
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	2.91	2.13	1.53	0.99	0.50	2.34	1.29	0.84	0.47	0.11
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	3.15	2.12	1.58	0.88	0.44	2.43	1.30	0.86	0.37	0.16
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	3.34	2.27	1.61	1.08	0.52	2.46	1.41	0.79	0.40	0.17
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	2.09	1.02	0.61	0.19	<0.01	0.20	0.19	0.04	0.04	0	3.19	2.44	1.75	1.02	0.61	16.75	13.90	12.12	10.01	8.02
PW	Gray seal	0.62	0.10	0	0	0	0	0	0	0	0	3.49	2.45	1.75	1.21	0.51	3.32	2.25	1.45	0.85	0.26
	Harbor seal	0.59	0.10	0	0	0	0	0	0	0	0	3.43	2.37	1.96	1.01	0.63	3.17	2.08	1.36	0.72	0.30

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-14. Jacket foundation (2.44 m diameter, three pin piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

Species		Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	2.35	1.22	0.59	0.24	0.06	0	0	0	0	0	3.45	2.43	1.79	1.02	0.53	3.51	2.45	1.81	1.03	0.53
	Minke whale (migrating)	1.88	0.98	0.51	0.09	<0.01	<0.01	0	0	0	0	3.09	2.25	1.76	1.13	0.58	9.26	7.04	5.72	4.21	3.14
	Humpback whale (migrating)	1.92	0.97	0.42	0.08	0.03	0.02	0	0	0	0	3.32	2.53	1.86	1.17	0.64	9.64	7.40	6.01	4.46	3.37
	North Atlantic right whale[c] (migrating)	1.70	1.03	0.58	0.12	0	0	0	0	0	0	3.24	2.38	1.72	1.11	0.62	9.50	7.23	5.72	4.28	3.27
	Sei whale[c] (migrating)	1.98	0.87	0.36	0.11	0.06	0.03	0	0	0	0	3.30	2.28	1.84	1.07	0.53	9.56	7.33	6.01	4.69	3.35
MF	Atlantic white sided dolphin	<0.01	0	0	0	0	0	0	0	0	0	3.12	2.32	1.72	1.13	0.60	2.43	1.54	0.93	0.56	0.22
	Short-beaked common dolphin	<0.01	0	0	0	0	0	0	0	0	0	3.08	2.33	1.72	1.16	0.60	2.49	1.53	1.03	0.48	0.24
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	2.87	2.05	1.46	0.97	0.50	2.32	1.29	0.80	0.46	0.12
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	3.16	2.12	1.60	0.86	0.45	2.43	1.29	0.83	0.41	0.14
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	3.35	2.15	1.65	1.05	0.51	2.42	1.38	0.84	0.42	0.18
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	2.07	1.10	0.61	0.23	<0.01	0.24	0.20	0.05	0.04	0	3.17	2.36	1.73	1.01	0.59	16.76	13.97	12.13	10.04	7.89
PW	Gray seal	0.65	0.16	<0.01	0	0	<0.01	<0.01	0	0	0	3.49	2.42	1.65	1.17	0.54	3.15	2.10	1.44	0.78	0.28
	Harbor seal	0.58	0.15	<0.01	0	0	<0.01	0	0	0	0	3.37	2.47	1.91	0.97	0.62	3.17	2.05	1.35	0.73	0.34

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-15. Jacket foundation (2.44 m diameter, two pin piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

	Species	Injury										Behavior									
		$L_{E,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	3.27	1.52	0.84	0.19	0.06	0	0	0	0	0	4.98	3.10	2.11	1.25	0.51	5.05	3.12	2.11	1.21	0.51
	Minke whale (migrating)	3.06	1.29	0.58	0.11	<0.01	<0.01	0	0	0	0	4.37	2.85	2.09	1.24	0.65	54.06	19.79	12.31	7.30	4.41
	Humpback whale (migrating)	2.76	1.20	0.52	0.13	0.03	<0.01	0	0	0	0	4.53	2.94	2.18	1.22	0.63	58.00	20.28	12.49	7.61	4.56
	North Atlantic right whale[c] (migrating)	2.64	1.27	0.69	0.09	0	0	0	0	0	0	4.38	2.82	2.06	1.22	0.64	57.47	20.67	12.80	7.84	4.39
	Sei whale[c] (migrating)	2.74	1.14	0.59	0.13	0.01	0.03	0	0	0	0	4.84	3.03	2.13	1.13	0.52	55.08	20.54	12.96	7.67	4.89
MF	Atlantic white sided dolphin	<0.01	0	0	0	0	0	0	0	0	0	4.31	2.80	2.12	1.15	0.61	3.39	1.90	1.13	0.57	0.28
	Short-beaked common dolphin	0	0	0	0	0	0	0	0	0	0	4.30	2.72	2.09	1.34	0.63	3.22	1.98	1.22	0.54	0.25
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	4.15	2.62	1.97	1.10	0.53	3.14	1.79	1.08	0.47	0.05
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	4.25	2.72	1.91	1.13	0.46	3.27	1.81	0.99	0.37	0.16
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	4.57	2.90	1.93	1.24	0.52	3.41	1.82	1.20	0.43	0.22
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	2.79	1.32	0.63	0.18	<0.01	0.20	0.15	0.05	0.04	0	4.31	2.87	2.16	1.14	0.62	63.30	60.69	58.96	56.87	36.09
PW	Gray seal	0.78	0.14	0	0	0	0	0	0	0	0	4.71	3.08	2.33	1.36	0.55	4.20	2.73	1.72	0.91	0.34
	Harbor seal	0.66	0.12	0	0	0	0	0	0	0	0	4.64	2.88	2.24	1.04	0.63	4.20	2.66	1.86	0.77	0.43

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

Table J-16. Jacket foundation (2.44 m diameter, three pin piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to marine mammal threshold criteria with sound attenuation.

	Species	Injury										Behavior									
		$L_{E,\,24h}$					L_{PK}					L_p [a]					L_p [b]				
		Attenuation (dB)										Attenuation (dB)									
		0	6	10	15	20	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
LF	Fin whale[c]	3.75	1.66	0.74	0.32	0.06	0	0	0	0	0	4.87	3.09	2.04	1.14	0.53	4.91	3.10	2.09	1.15	0.53
	Minke whale (migrating)	3.27	1.30	0.59	0.12	<0.01	<0.01	0	0	0	0	4.29	2.80	2.06	1.21	0.59	53.75	19.64	12.16	7.37	4.36
	Humpback whale (migrating)	2.79	1.20	0.51	0.13	0.03	0.02	0	0	0	0	4.57	2.93	2.11	1.22	0.64	58.92	20.47	12.62	7.68	4.59
	North Atlantic right whale[c] (migrating)	2.73	1.26	0.70	0.12	0	0	0	0	0	0	4.38	2.85	2.11	1.19	0.63	58.00	20.69	12.81	7.66	4.40
	Sei whale[c] (migrating)	3.16	1.23	0.53	0.10	0.06	0.03	0	0	0	0	4.89	3.01	2.03	1.14	0.54	55.25	20.36	12.86	7.61	4.92
MF	Atlantic white sided dolphin	<0.01	0	0	0	0	0	0	0	0	0	4.25	2.74	2.08	1.21	0.64	3.34	1.90	1.15	0.57	0.27
	Short-beaked common dolphin	<0.01	0	0	0	0	0	0	0	0	0	4.24	2.72	2.06	1.28	0.63	3.24	1.95	1.20	0.54	0.25
	Bottlenose dolphin, coastal	0	0	0	0	0	0	0	0	0	0	3.97	2.55	1.88	1.10	0.57	3.02	1.67	1.07	0.46	0.07
	Bottlenose dolphin, offshore	0	0	0	0	0	0	0	0	0	0	4.25	2.81	1.85	1.04	0.48	3.31	1.73	1.00	0.42	0.14
	Risso's dolphin	0	0	0	0	0	0	0	0	0	0	4.62	2.85	1.87	1.25	0.51	3.46	1.74	1.23	0.45	0.22
	Long-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Short-finned pilot whale	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sperm whale[c]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF	Harbor porpoise	2.87	1.23	0.70	0.21	<0.01	0.23	0.19	0.06	0.04	0	4.41	2.86	2.06	1.13	0.61	63.60	60.96	59.17	57.00	35.96
PW	Gray seal	0.84	0.19	<0.01	0	0	<0.01	<0.01	0	0	0	4.77	3.00	2.14	1.23	0.62	4.29	2.70	1.62	0.88	0.47
	Harbor seal	0.86	0.17	<0.01	0	0	<0.01	0	0	0	0	4.67	2.95	2.19	1.13	0.63	4.20	2.62	1.78	0.83	0.42

[a] NOAA (2005), [b] Wood et al. (2012), [c] Listed as Endangered under the ESA.

J.2.4. Sea Turtle Exposure Range Estimates

This section contains sea turtle exposure ranges for each of the modeled foundation types and seasons assuming 0, 6, 10, 15, and 20 dB broadband attenuation.

Table J-17. Monopile foundation (8 to 11 m diameter, one pile per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	1.04	0.45	0.13	0	0	0	0	0	0	0	2.61	1.61	1.08	0.46	0.12
Leatherback turtle[a]	0.67	0.07	0.03	0	0	0	0	0	0	0	2.35	1.56	0.76	0.48	0.13
Loggerhead turtle	0.64	0.02	<0.01	0	0	0	0	0	0	0	2.26	1.37	1.04	0.44	0.06
Green turtle	1.42	0.58	0.31	0	0	0	0	0	0	0	2.69	1.61	1.18	0.49	0.15

[a] Listed as Endangered under the ESA.

Table J-18. Monopile foundation (8 to 11 m diameter, two piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	1.21	0.46	0.15	0	0	0	0	0	0	0	2.48	1.63	1.06	0.50	0.22
Leatherback turtle[a]	1.20	0.34	0.03	0.01	0	0	0	0	0	0	2.44	1.52	0.98	0.46	0.18
Loggerhead turtle	0.50	0.13	<0.01	<0.01	0	0	0	0	0	0	2.23	1.51	0.90	0.35	0.12
Green turtle	1.48	0.58	0.30	0.02	0	0	0	0	0	0	2.68	1.58	1.02	0.57	0.15

[a] Listed as Endangered under the ESA.

Table J-19. Monopile foundation (8 to 11 m diameter, one pile per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	1.56	0.51	0.12	<0.01	0	0	0	0	0	0	2.95	1.89	1.12	0.55	0.12
Leatherback turtle[a]	1.41	0.34	0.07	<0.01	0	0	0	0	0	0	2.92	1.93	1.21	0.57	0.14
Loggerhead turtle	0.80	0.04	<0.01	0	0	0	0	0	0	0	2.78	1.68	1.21	0.44	0.07
Green turtle	2.03	0.66	0.34	0	0	0	0	0	0	0	2.95	1.99	1.22	0.66	0.28

[a] Listed as Endangered under the ESA.

Table J-20. Monopile foundation (8 to 11 m diameter, two piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	1.69	0.57	0.22	0.03	0	0	0	0	0	0	2.98	1.84	1.26	0.65	0.24
Leatherback turtle[a]	1.49	0.60	0.27	0.01	0	0	0	0	0	0	2.88	1.81	1.21	0.47	0.26
Loggerhead turtle	0.86	0.13	<0.01	<0.01	0	0	0	0	0	0	2.76	1.69	1.03	0.48	0.12
Green turtle	2.01	0.78	0.44	0.06	0	0	0	0	0	0	3.05	1.91	1.13	0.62	0.23

[a] Listed as Endangered under the ESA.

Table J-21. Jacket foundation (2.44 m diameter, two pin piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	0.29	0	0	0	0	0	0	0	0	0	0.94	0.48	0.29	0.07	0.02
Leatherback turtle[a]	0.20	0	0	0	0	0	0	0	0	0	0.91	0.50	0.22	0.04	0.02
Loggerhead turtle	0.02	0	0	0	0	0	0	0	0	0	0.93	0.32	0.19	0.04	0.02
Green turtle	0.33	0	0	0	0	0	0	0	0	0	1.20	0.39	0.26	0.02	0

[a] Listed as Endangered under the ESA.

Table J-22. Jacket foundation (2.44 m diameter, three pin piles per day, summer): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	0.30	0	0	0	0	0	0	0	0	0	0.96	0.56	0.29	0.07	0.02
Leatherback turtle[a]	0.34	0	0	0	0	0	0	0	0	0	0.98	0.47	0.25	0.04	0.02
Loggerhead turtle	0.06	0	0	0	0	0	0	0	0	0	0.95	0.34	0.24	0.06	0.02
Green turtle	0.29	0	0	0	0	0	0	0	0	0	1.14	0.41	0.23	0.06	<0.01

[a] Listed as Endangered under the ESA.

Table J-23. Jacket foundation (2.44 m diameter, two pin piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	0.29	0	0	0	0	0	0	0	0	0	1.05	0.54	0.29	0.07	0.02
Leatherback turtle[a]	0.20	0	0	0	0	0	0	0	0	0	0.92	0.49	0.22	0.04	0.02
Loggerhead turtle	0.02	0	0	0	0	0	0	0	0	0	1.12	0.36	0.19	0.04	0.02
Green turtle	0.33	0	0	0	0	0	0	0	0	0	1.25	0.39	0.28	0.02	0

[a] Listed as Endangered under the ESA.

Table J-24. Jacket foundation (2.44 m diameter, three pin piles per day, winter): Exposure ranges ($ER_{95\%}$) in km to sea turtle threshold criteria (Finneran et al. 2017) with sound attenuation.

Species	Injury										Behavior				
	$L_{E,\,24h}$					L_{pk}					L_p				
	Attenuation (dB)										Attenuation (dB)				
	0	6	10	15	20	0	6	10	15	20	0	6	10	15	20
Kemp's ridley turtle[a]	0.30	0	0	0	0	0	0	0	0	0	1.08	0.56	0.29	0.07	0.02
Leatherback turtle[a]	0.31	0	0	0	0	0	0	0	0	0	1.04	0.47	0.25	0.04	0.02
Loggerhead turtle	0.06	0	0	0	0	0	0	0	0	0	1.16	0.34	0.24	0.06	0.02
Green turtle	0.34	0	0	0	0	0	0	0	0	0	1.25	0.41	0.26	0.06	<0.01

[a] Listed as Endangered under the ESA.

J.3. Animat Seeding Area

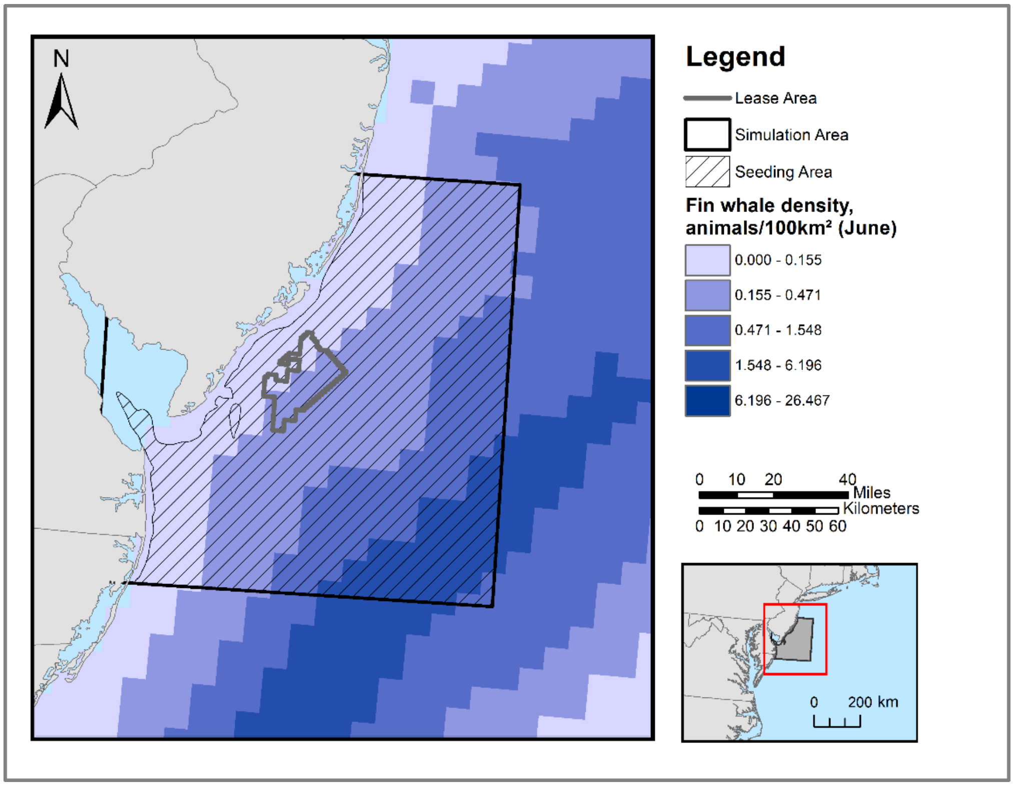

Figure J-1. Map of fin whale animat seeding range for June, the month with the highest density.

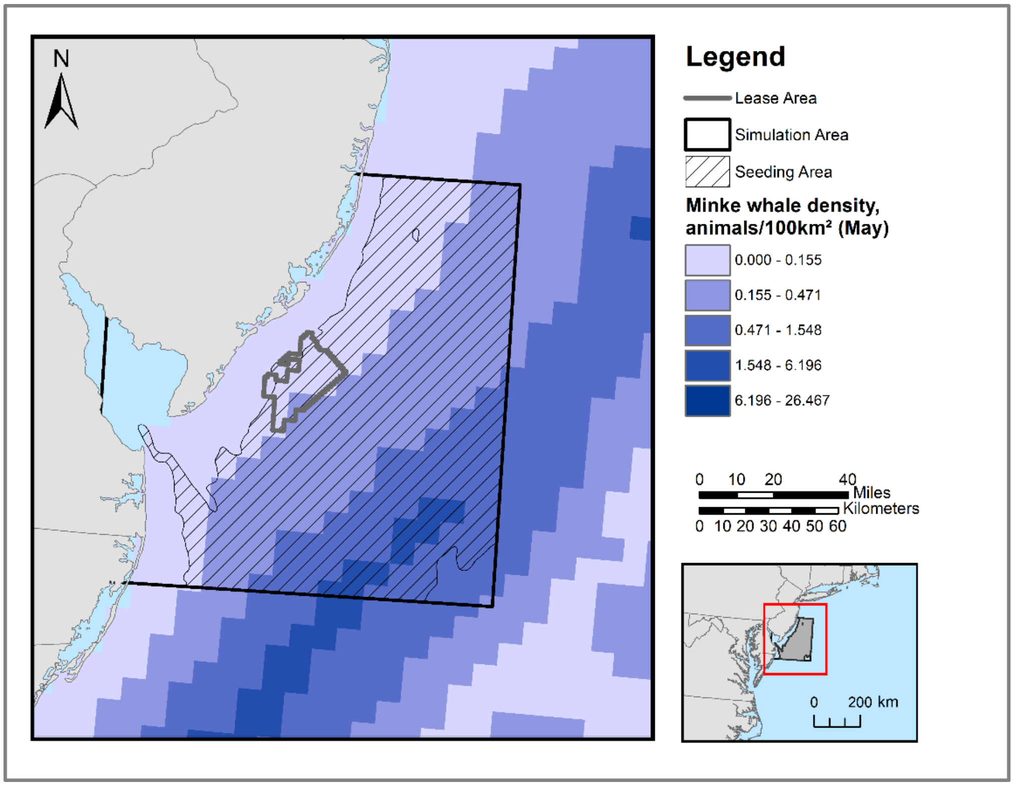

Figure J-2. Map of minke whale animat seeding range for May, the month with the highest density.

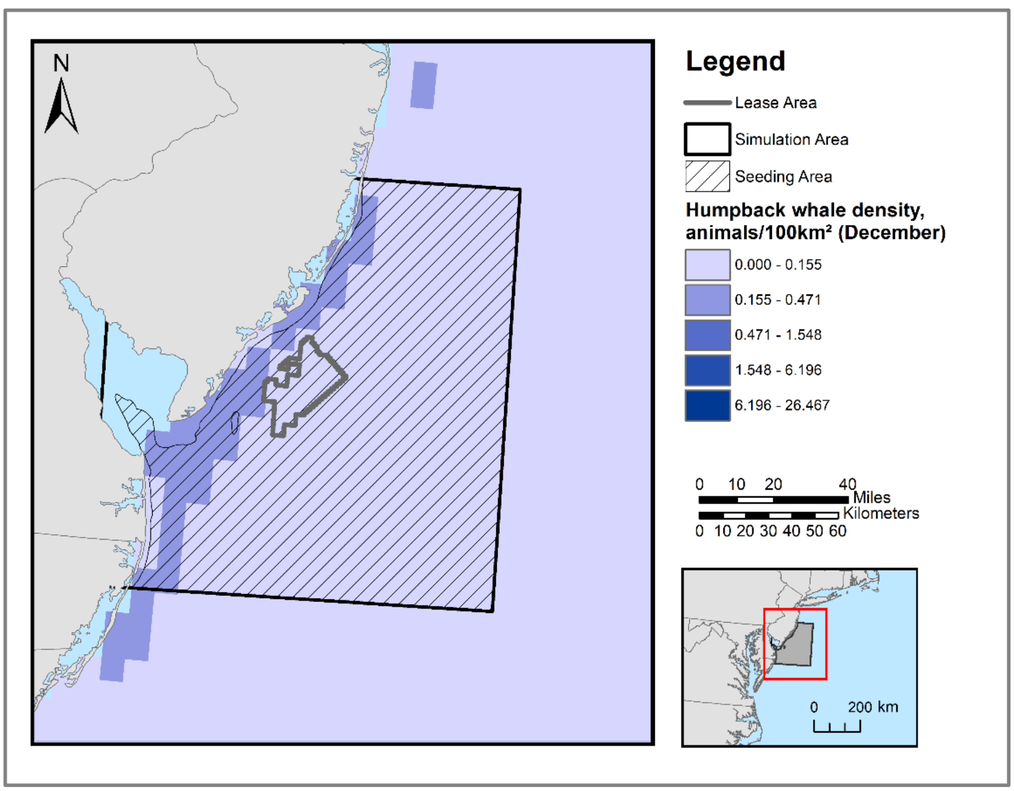

Figure J-3. Map of humpback whale animat seeding range for December, the month with the highest density.

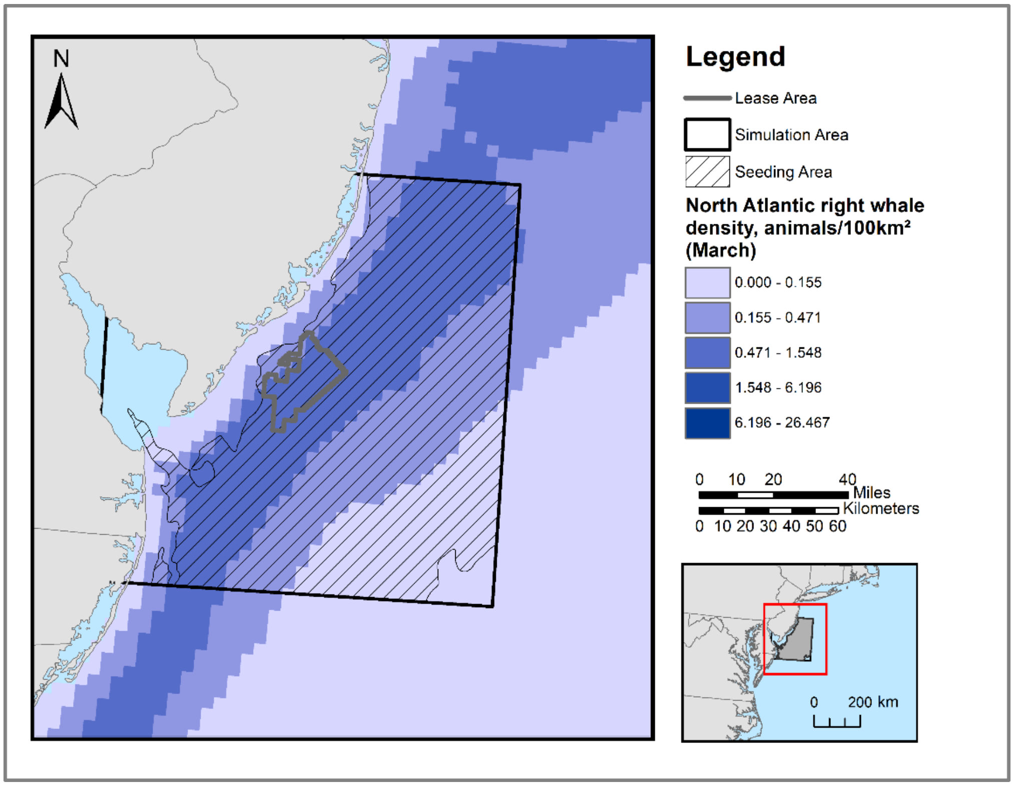

Figure J-4. Map of North Atlantic right whale animat seeding range for March, the month with the highest density.

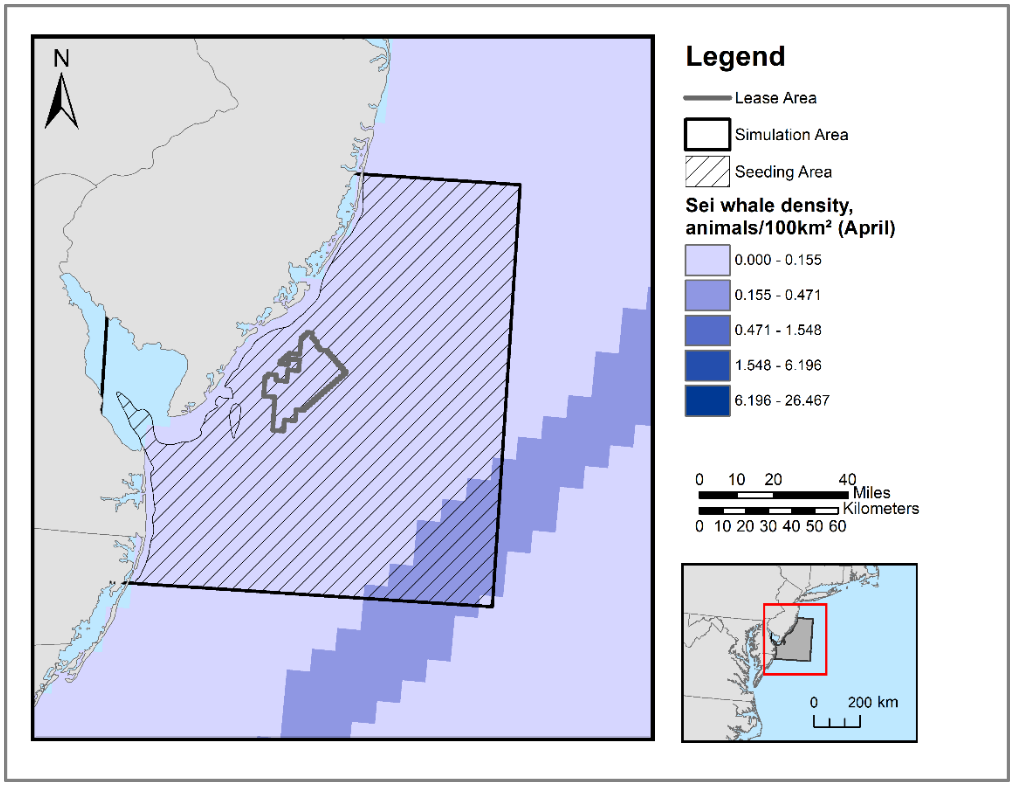

Figure J-5. Map of sei whale animat seeding range for April, the month with the highest density.

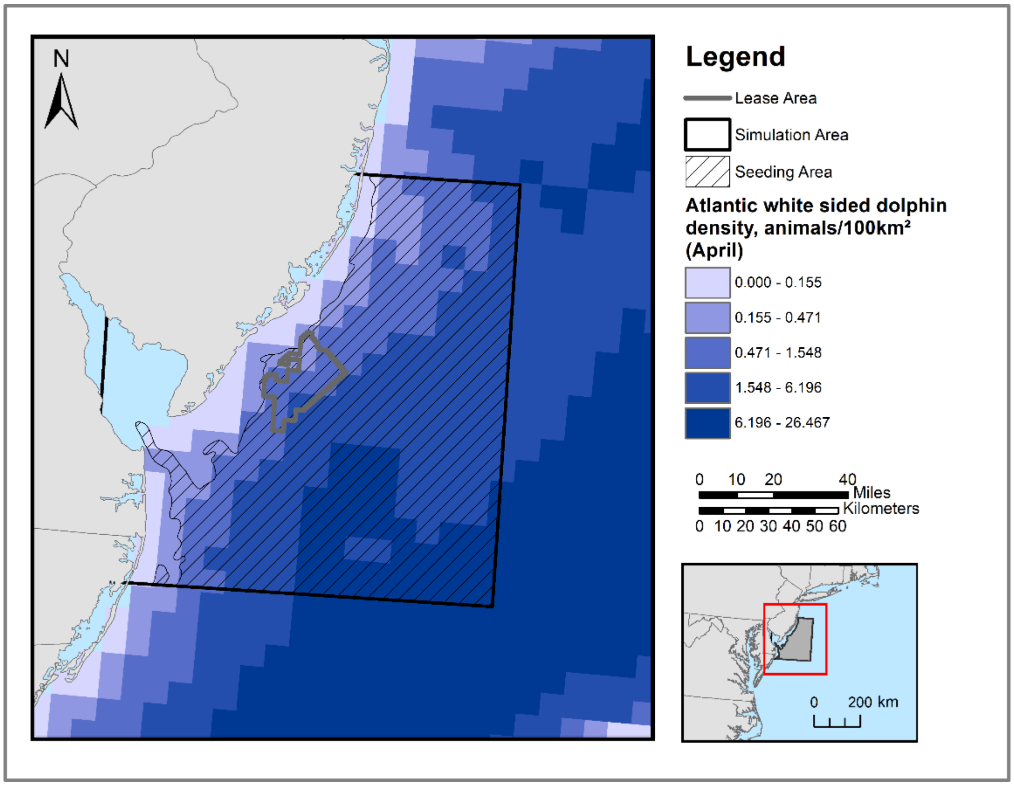

Figure J-6. Map of Atlantic white sided dolphin (AWSD) animat seeding range for April, the month with the highest density.

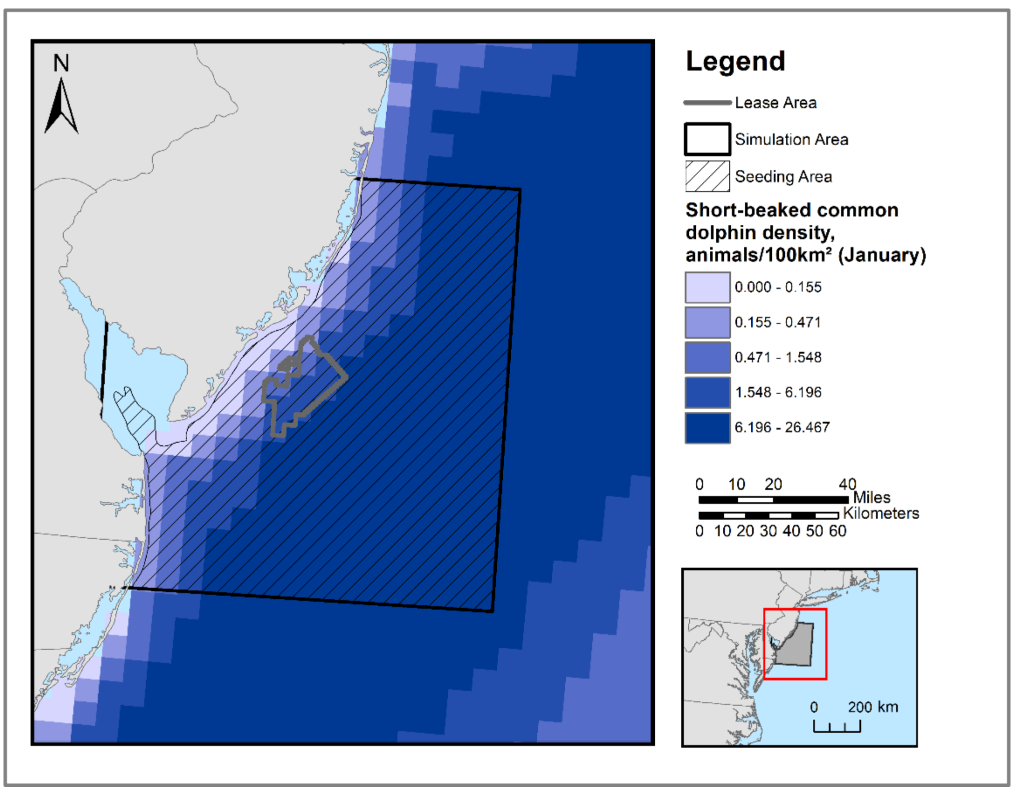

Figure J-7. Map of short-beaked common dolphin (SBCD) animat seeding range for January, the month with the highest density.

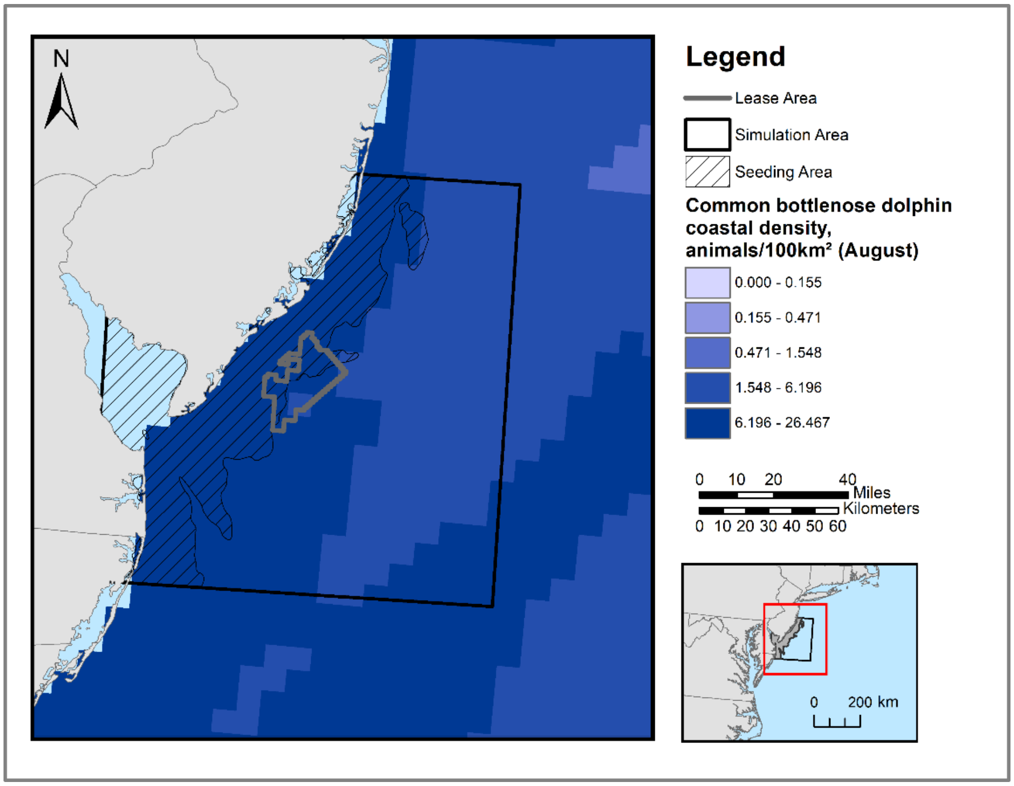

Figure J-8. Map of bottlenose dolphin, coastal animat seeding range for August, the month with the highest density.

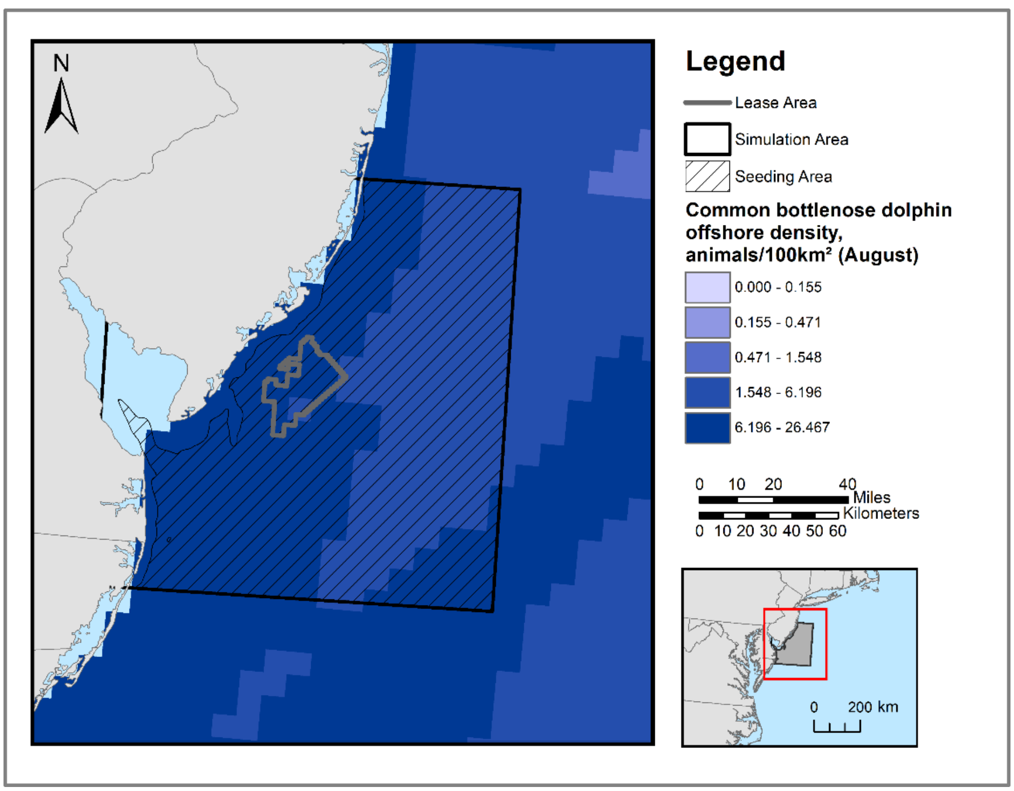

Figure J-9. Map of bottlenose dolphin, offshore animat seeding range for August, the month with the highest density.

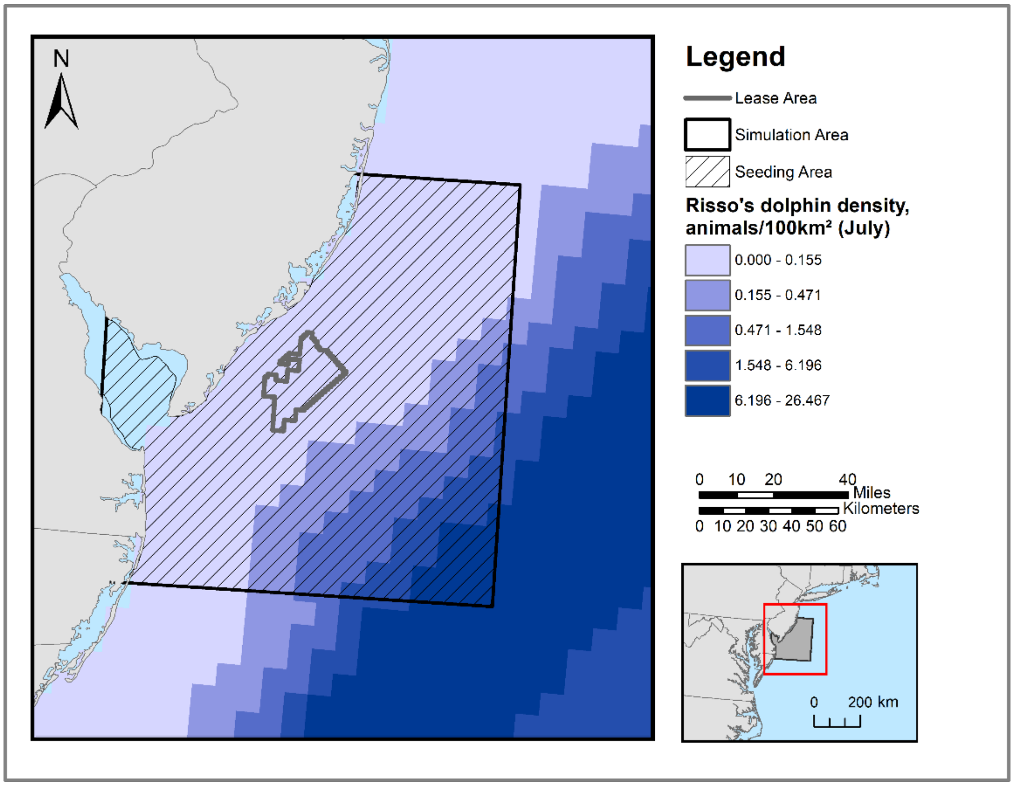

Figure J-10. Map of Risso's dolphin animat seeding range for July, the month with the highest density.

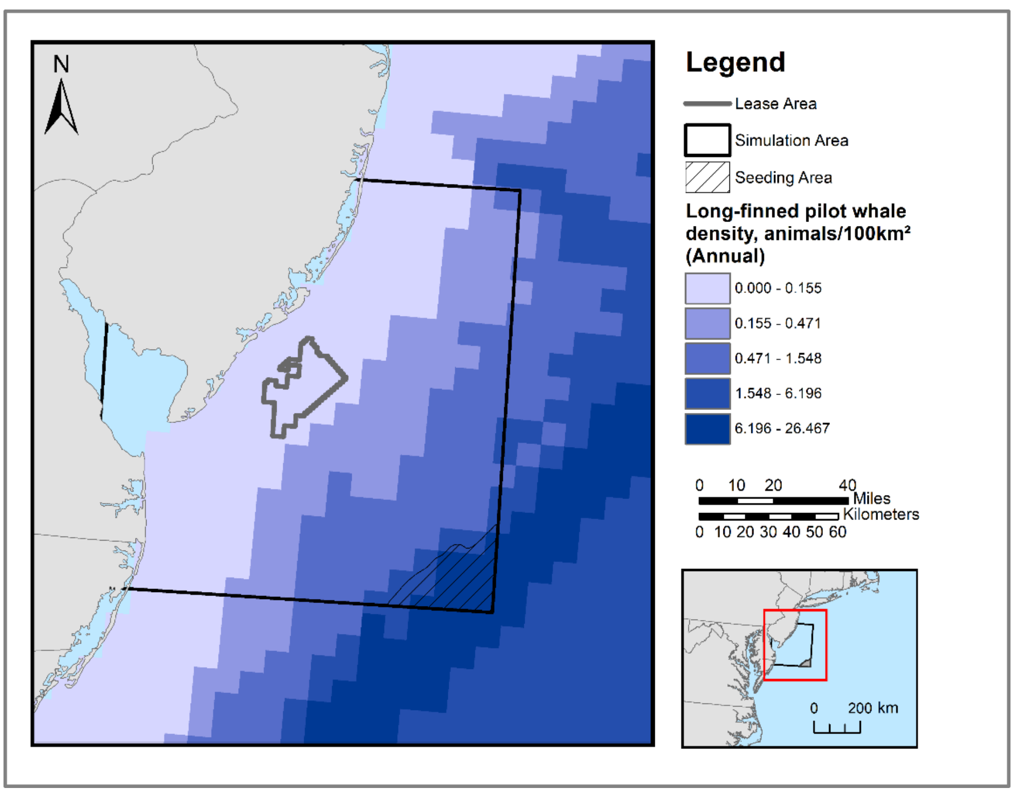

Figure J-11. Map of long-finned pilot whale animat seeding range. Displayed density data is for the pilot whale guild.

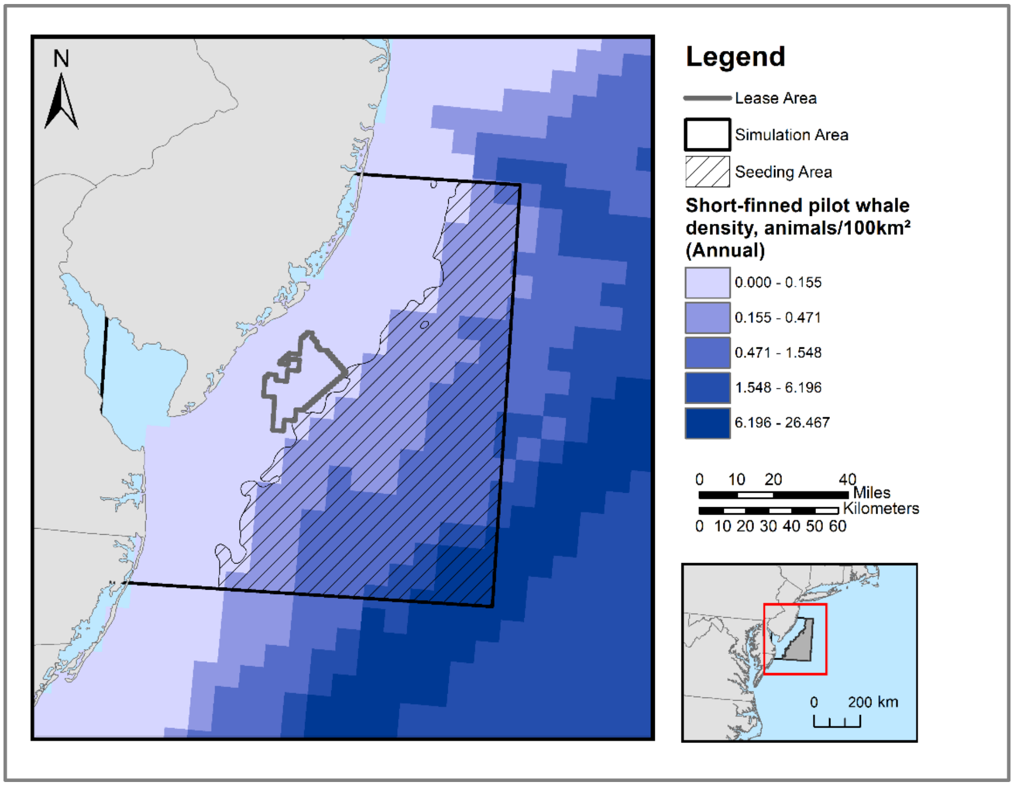

Figure J-12. Map of short-finned pilot whale animat seeding range. Displayed density data is for the pilot whale guild.

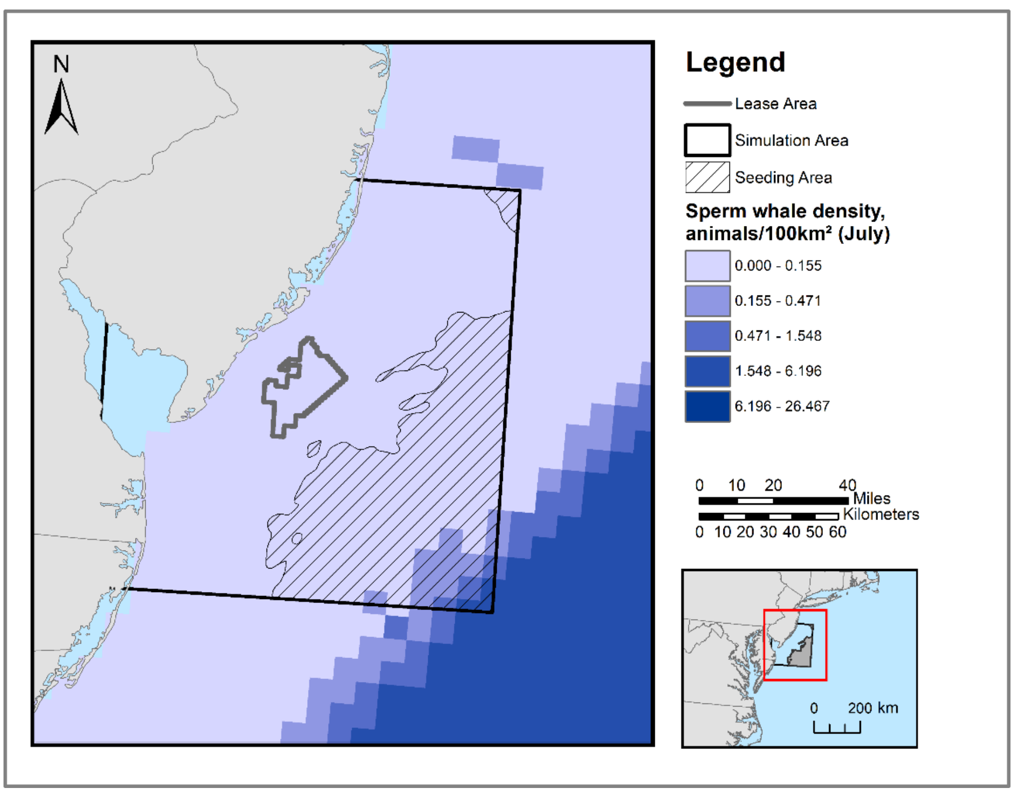

Figure J-13. Map of sperm whale animat seeding range for July, the month with the highest density.

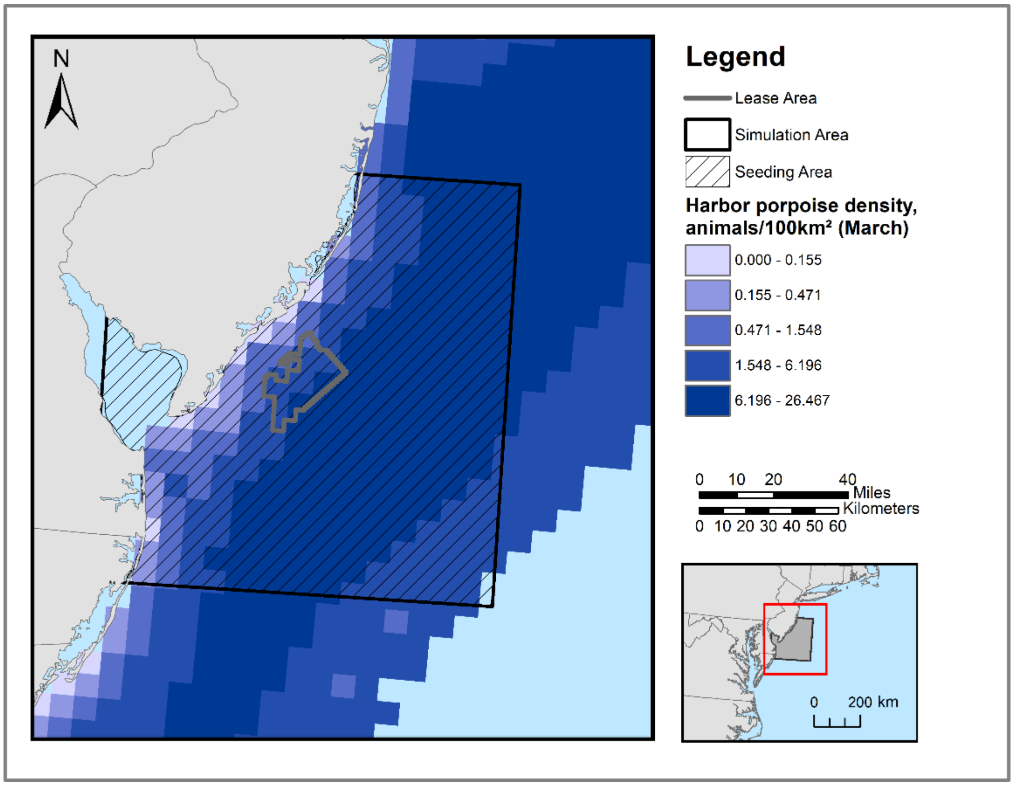

Figure J-14. Map of harbor porpoise animat seeding range for March, the month with the highest density.

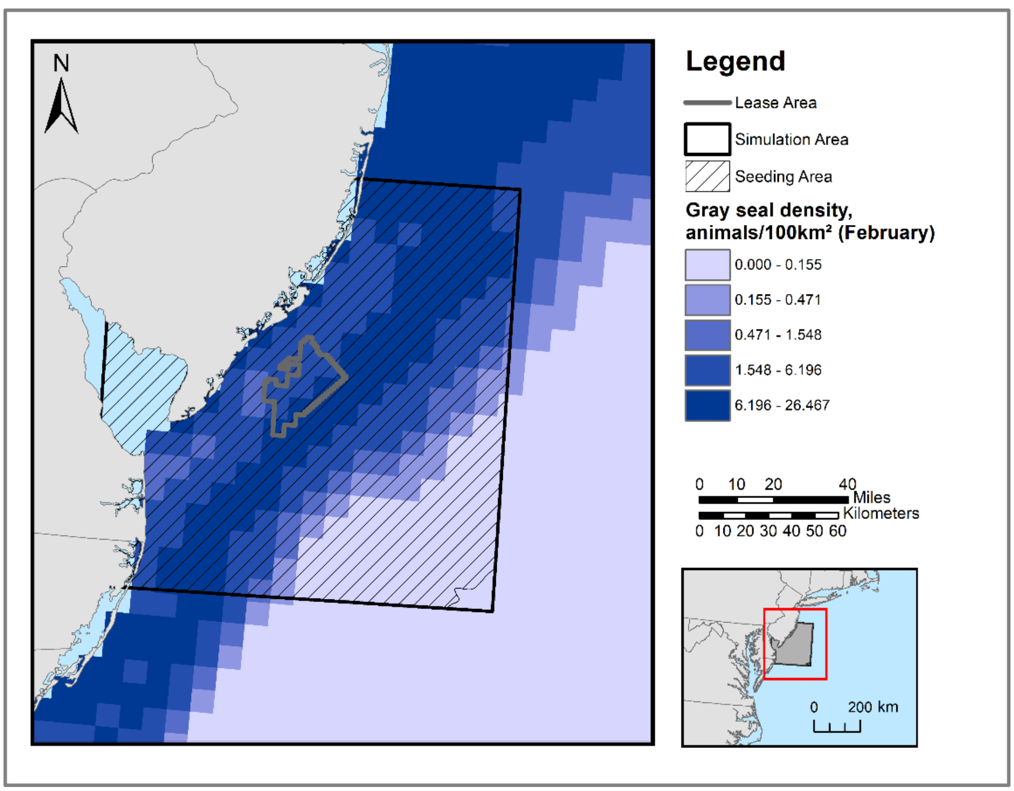

Figure J-15. Map of gray seal animat seeding range for February, the month with the highest density.

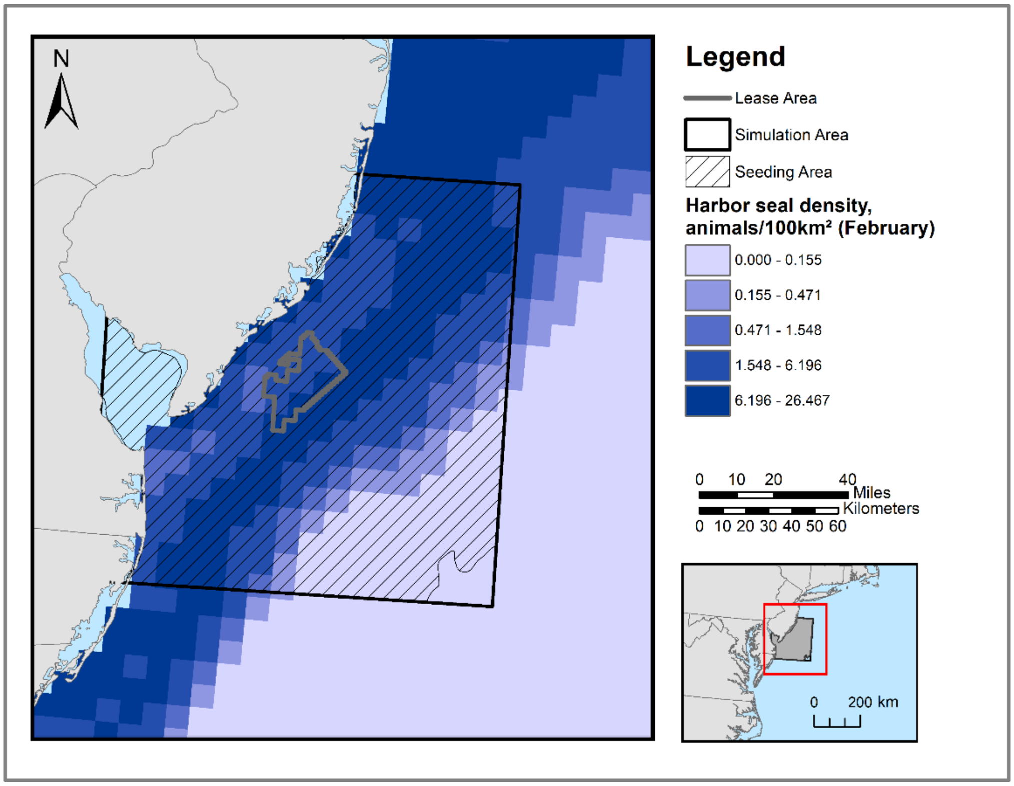

Figure J-16. Map of harbor seal animat seeding range for February, the month with the highest density.

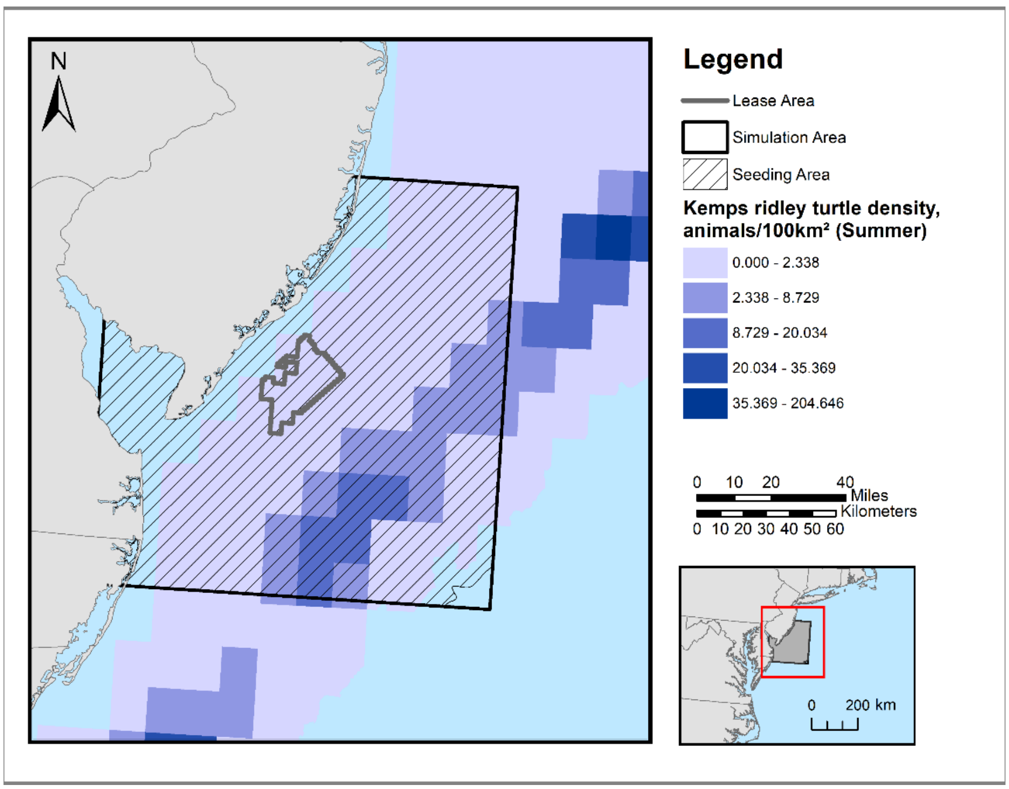

Figure J-17. Map of Kemp's ridley sea turtle animat seeding range with density (DoN 2017) for summer, the season with the highest density. Densities used in exposure modeling were calculated from NYSERDA aerial survey reports (Normandeau Associates and APEM Inc. 2018b, 2018a, 2019a, 2019b, 2020).

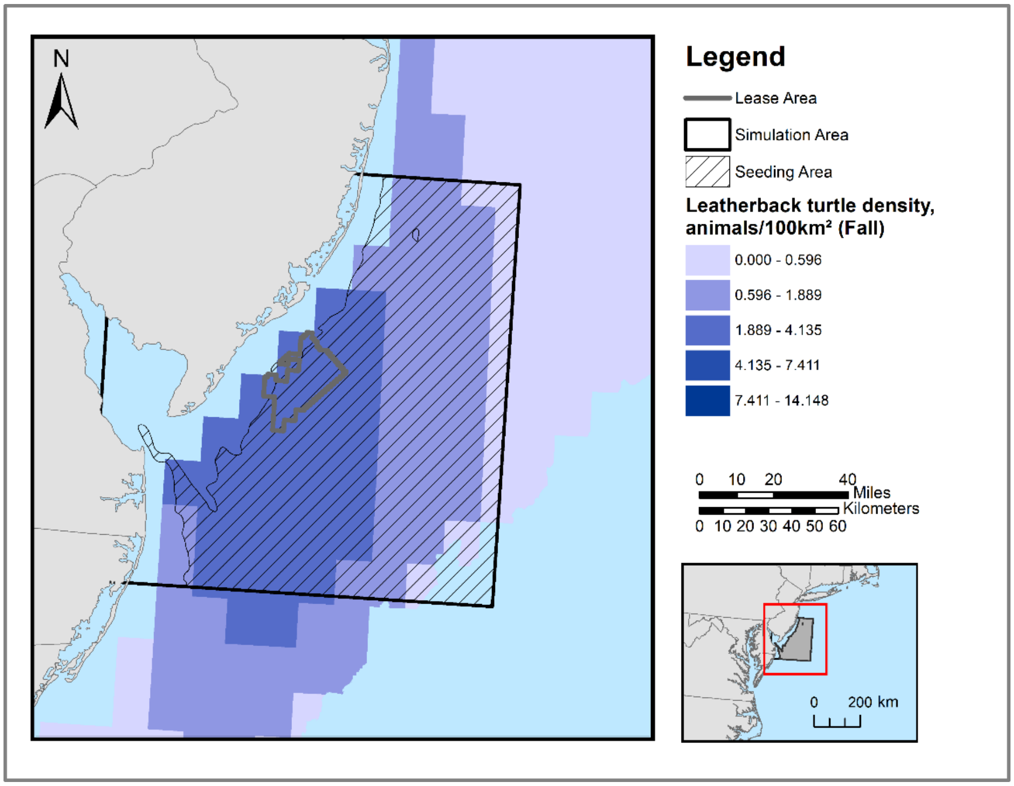

Figure J-18. Map of leatherback sea turtle animat seeding range with density from (DoN 2017) for fall, the season with the highest density. Densities used in exposure modeling were calculated from NYSERDA aerial survey reports (Normandeau Associates and APEM Inc. 2018b, 2018a, 2019a, 2019b, 2020).

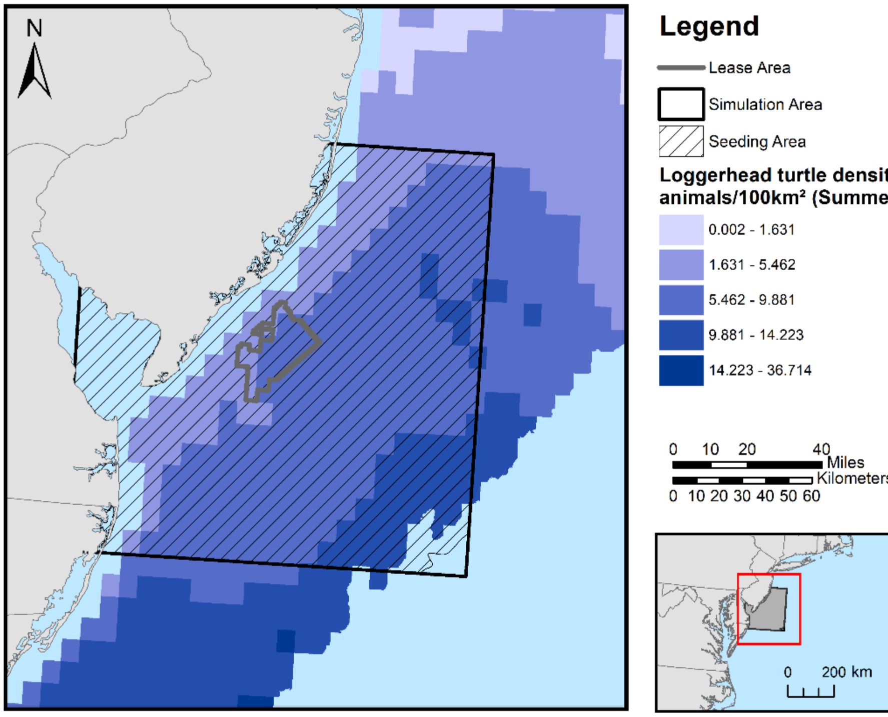

Figure J-19. Map of loggerhead sea turtle animat seeding range with density from (DoN 2017) for summer, the season with the highest density. Densities used in exposure modeling were calculated from NYSERDA aerial survey reports (Normandeau Associates and APEM Inc. 2018b, 2018a, 2019a, 2019b, 2020).

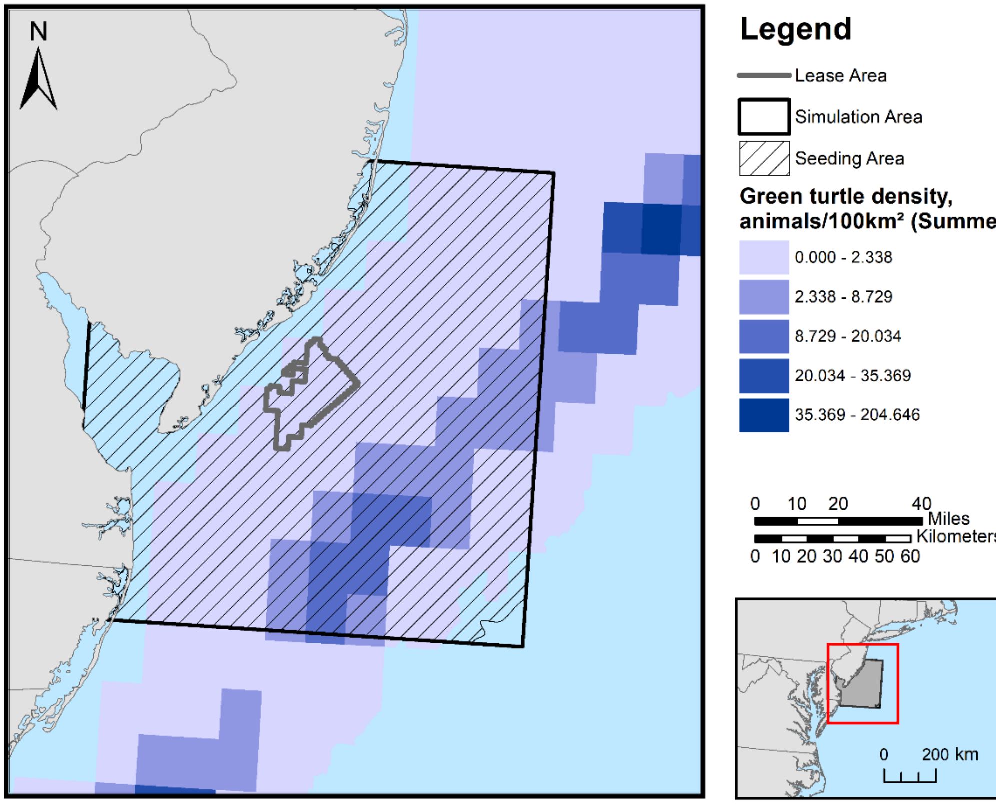

Figure J-20. Map of green turtle animat seeding range with density from (DoN 2017) for summer, the season with the highest density, showing Kemp's Ridley sea turtle density as an example. Densities used in exposure modeling were calculated from NYSERDA aerial survey reports (Normandeau Associates and APEM Inc. 2018b, 2018a, 2019a, 2019b, 2020).

Ocean Wind
An Ørsted & PSEG project

Underwater Acoustic Modeling of Detonations of Unexploded Ordnance (UXO) for Ørsted Wind Farm Construction, US East Coast

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Contents

1. Introduction

Orsted's offshore wind projects along the eastern US seaboard may encounter unexploded ordinances (UXO) on the seabed in the wind farm lease areas and along export cable routes. While non-explosive methods may be employed to lift and move these objects, some may need to be removed by explosive detonation. Underwater detonation explosions generate sound waves with high pressure levels that could cause disturbance and/or injury to marine fauna. Mitigation measures will likely be required to avoid Level-A (injurious) takes of animals, and Level-B (behavior) takes will need to be accounted for in the project letter of authorization (LOA) or incidental harassment authorization (IHA). The study described in this report has modeled acoustic source and sound propagation to estimate the sizes of Level-A and Level-B take zones for several species and for a selection of charge weights spanning the expected UXO types that may be encountered. The results provided here do not directly predict numbers of takes but they are intended for that purpose. Takes can be computed using approaches such as multiplication of zone areas by the corresponding animal densities (number of animals per unit area).

Most UXO assessment work in the US has been performed by or for the US Navy, who have worked closely with National Marine Fisheries Service (NMFS) to choose and define appropriate criteria for effects based on best available science. We have evaluated effects thresholds based on three key sound pressure metrics considered by the Navy and NMFS as indicators of injury and behavioral disturbance: unweighted peak compressional pressure level ($L_{pk,c}$ and abbreviated here L_{pk}), frequency-weighted sound exposure level (SEL or $L_{E,w}$), and acoustic impulse (J_p). A fourth metric, sound pressure level (SPL or L_p), which is often used for other impulsive sound assessments, has not been evaluated here because it is not presently used by NMFS as an assessment criterion for sounds from explosive detonations. The names and symbols used for the above metrics follow the terminology of International Organization of Standards (ISO) 18405 (ISO 2017), except where tables and equations have been copied from previous regulatory documents.

The thresholds applied here for each of the acoustic metrics have been obtained from three primary sources:

1.) *Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III), June 2017* (Navy, 2017). This report provides thresholds for gastrointestinal and lung injury, and mortality to marine mammals, sea turtles and fish due to explosive pressure based on impulse and peak pressure.

2.) *Marine Mammal Acoustic Technical Guidance (2018 Revision to Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing*), Office of Protected Resources, NOAA Technical Memorandum NMFS-OPR-59, April 2018 (NMFS, 2018). This technical memorandum incorporates the report by J.J. Finneran (2016) that provides auditory weighting functions for SEL calculations and provides thresholds for hearing-related effects.

3.) *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 (Popper et al., 2014). This report provides peak pressure thresholds for injury and mortality to fish.

The acoustic metrics and thresholds for effects depend on species and in some cases animal size and submersion depth. Specialized acoustic models and semiempirical formulae are applied to evaluate the threshold exceedance distances from explosive charges detonated on the seabed and exposed directly to seawater. The theory underlying these models is provided in the technical discussion sections of this report.

This assessment considers acoustic effects to marine mammals, sea turtles and fish from five possible charge sizes at sites with four water depths near Orsted's Revolution Wind project areas. The results are also relevant for sites with similar water depths at Orsted's Ocean Wind 1 project, Orsted's Sunrise Wind project, and possibly other wind farm sites with similar depths and seabed sediment properties. An unmitigated and mitigated scenario are considered at each site, with mitigation considering a 10 decibel (dB) reduction to L_{pk}, J_{p}, and L_E, that might be obtained using an air bubble curtain or similar system. The results for unmitigated and mitigated UXO detonations are provided in Sections 8 and 9 respectively.

Because of the large number of result tables, the Summary (Section 10) provides cross-references for effects assessment criteria to the relevant tables for both unmitigated and mitigated scenarios.

A key assumption of the model predictions presented in this report is that the full weights of UXO explosive charges are detonated together with their donor charges. A recent review of UXO explosive removals in the North Sea indicates that in most cases the UXO charge weights either did not detonate or only partly detonated, with the result being that the pressure waves generated were produced by the donor charge and only a small fraction of the UXO charge (Bellman, 2021). As such, it is likely that the full UXO charge will not detonate in all cases and the results presented herein assume full UXO charge detonation and therefore should be considered the worst case.

2. UXO Charge Sizes

The UXO charges considered here are characterized by their equivalent trinitrotoluene (TNT) weight. Five charge weight “bins” were defined, with each bin representing a group of similar weapons using a categorization defined by the US Navy. The modeling performed here considered the largest charge weight for the corresponding bin. The final set of bins are listed in Table 1. We note that the effect of the donor charges used to detonate the UXO are assumed to be included in the TNT equivalent weight for the respective bin.

Table 1. Navy "bins" and corresponding maximum UXO charge weights (Maximum equivalent weight TNT) to be modeled.

Navy bin	Maximum equivalent weight TNT	
	(kg)	(lbs)
E4	2.3	5
E6	9.1	20
E8	45.5	100
E10	227	500
E12	454	1000

3. Modeling Locations and Depths

Sound propagation away from UXO detonations is affected by acoustic reflections from the sea surface and seabed. Water depth and seabed properties, which are site-dependent, will influence the sound exposure levels and sound pressure levels at distance from detonations. However, when water depths and seabed conditions are similar, the predictions from one site can be used to approximate the acoustic levels at other sites. The influence of the seabed and water depth on sound propagation away from the detonation site is complex but it can be predicted accurately by acoustic models.

Orsted’s recent projects under development in the US include the Revolution Wind project off Massachusetts, the Sunrise Wind project located just south of Revolution Wind, and the Ocean Wind 1 project on the Avalon Shoal off New Jersey. Each project is located in relative shallow waters of 20-54 meter (m) depth, and have sandy seabeds. The results of the present study are relevant for all three projects even though the specific locations modeled here were chosen inside the Revolution Wind project area. The key influencing parameter for these results is water depth; however, small variances of water depth (<10 m) are not expected to generate significant differences to the sound fields, so the propagation results will be relevant for each project area at sites with similar water depth as the sites modeled. The only possible exception is the shallowest site, located in a constrained channel of Narragansett Bay with nearby islands blocking sounds propagating in some directions. Maximum distances to specific sound level thresholds will be similar when islands are not nearby, but the area ensonified above the thresholds could be larger.

Four specific sites (S1 to S4) were chosen for this modeling assessment; two are along the export cable route and two are inside the wind lease area of the Revolution Wind project. The sites are shown on the map of Figure 1 and include:

In shallow waters along export cable route:

- Site S1: In the channel within Narragansett Bay in 12 m depth.
- Site S2: Intermediate waters outside of the Bay in 20 m depth.

Inside the lease area:

- Site S3: Shallower waters in southern portion of Hazard Zone 2 area, in 30 m depth.
- Site S4: Deeper waters in northern portion of Hazard Zone 2 area, in 45 m depth.

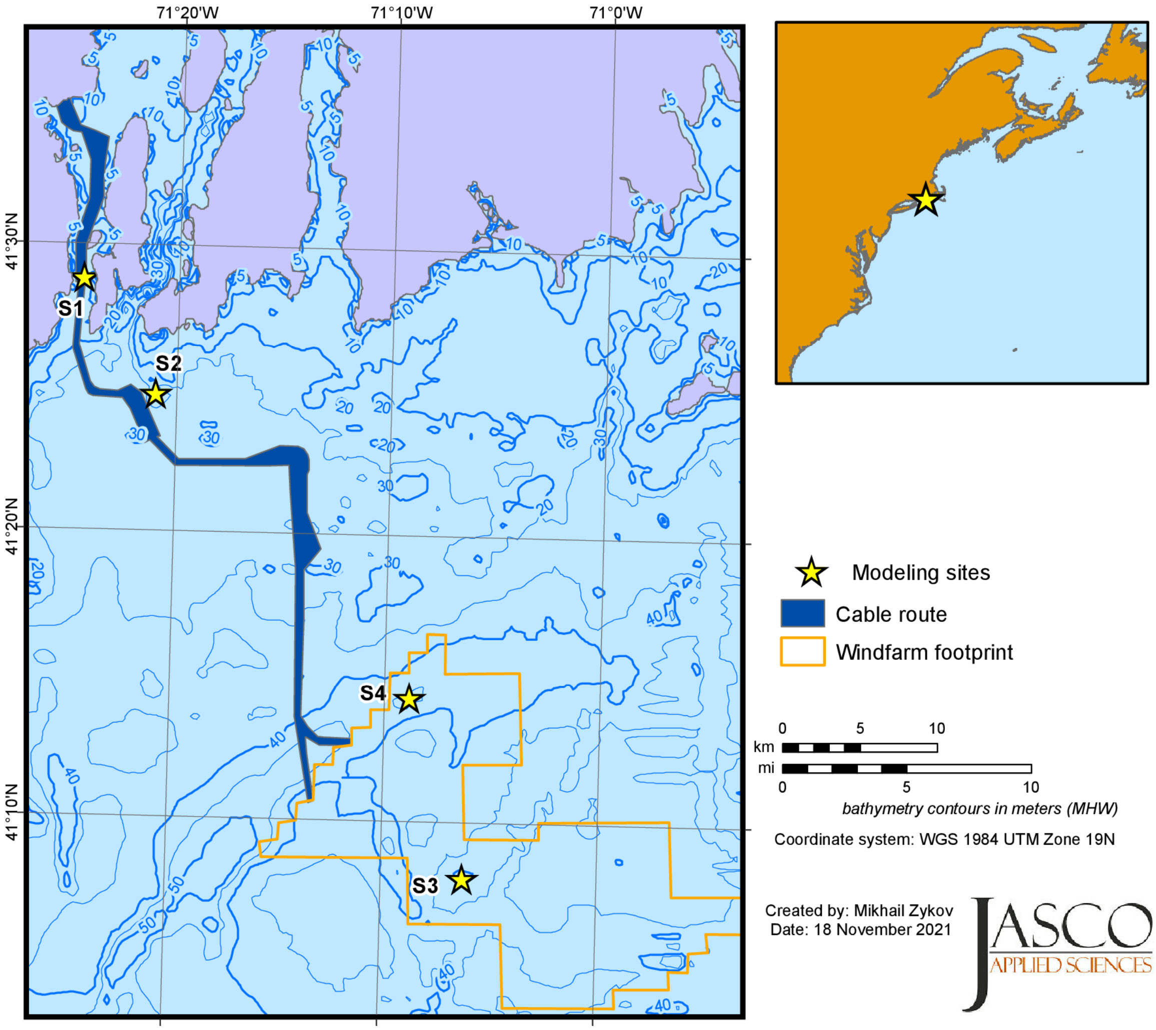

Figure 1. Map showing locations of the four modeling sites.

4. Blast Mitigation

Predictions of exceedance distances for effects to marine mammals were performed for unmitigated and mitigated scenarios, where the mitigated results were obtained by reducing the detonation source levels by 10 dB at all sound frequencies. The 10 dB reduction was applied to L_{pk} and decidecade band L_E and $L_{E,w}$. The corresponding reduction to J_p was applied using a multiplicative factor of $10^{-1/2}$. This amount of acoustic reduction is expected to be achievable by deploying an air bubble curtain or similar system around the detonation site. A review of the expected attenuation for modern bubble curtain systems is provided below.

There is a little published information available on direct measurements of bubble curtain effectiveness for reducing peak pressure, SEL and impulse produced by underwater explosives detonations. One measurement of a small bubble curtain showed good performance for 1 kilogram (kg) charges, providing approximately 16 dB attenuation at all frequencies greater than 1 kilohertz (kHz) using small curtains of less than 11.5 m diameter (Schmidke et al., 2009). The same study evaluated another relatively small bubble curtain (diameter 22 m in 20 m water depth) surrounding 300 kg mines. That bubble curtain configuration produced smaller attenuations of approximately 2 dB at 100 hertz (Hz) to 6 dB at 10 kHz. These values are substantially smaller than observed attenuations at corresponding frequencies for modern bubble curtains applied to mitigate sounds from large pile installations. The smaller attenuation values observed by Schmidke et al are likely due to use of a small bubble curtain for a relatively large detonation charge size, even though the air flow rate per unit curtain length was similar. Modern curtains also apply bubble size optimization to maximize the frequency-dependent attenuation characteristics, but it is not clear if that was performed for the bubble curtains used in the Schmidke et al study.

A recent review of bubble curtain effectiveness for pile driving noise mitigation by Bellman et al (2020) found the attenuation performance of modern bubble curtains increases with sound frequency from about 20 Hz to 1.5 kHz, and then decreases slowly with further increase in frequency. They tabulated attenuation results for a Big Bubble Curtain (BBC) that indicated attenuations of at least 10 dB at 32 Hz, increasing to approximately 35 dB near 1 kHz. A follow-up report indicates first results for attenuation of UXO acoustic levels by BBC of 11 dB for broadband L_E and up to 18 dB for L_{pk}, although particulars of the charge sizes and water depths in the study were not provided (Bellman, 2021).

The spectral energy distribution of the pressure waveforms of explosives detonated in water will differ from the spectral distribution of pile driving sounds. Nevertheless, the frequency-dependent attenuations are expected to be similar if the bubble curtain radius is large enough to avoid nearfield effects of the explosive detonations. The spectra of smaller charges contain relatively more high-frequency energy than the spectra of larger charges after accounting for the higher overall energy of the larger charges. This spectral shape dependence on charge size is discussed in detail in Section 7.2.1. The maximum spectral levels of all charge sizes considered in this report occur at less than 10 Hz, but their spectral roll-off is small so their maximum decidecade L_E band levels occur above a few hundred Hz. Pile driving spectra have maximum band levels at lower frequencies, which suggests bubble curtain performance for explosive charges should in general produce greater broadband attenuation than for pile driving. The minimum modern bubble curtain attenuation effectiveness for the frequency bands dominating explosive detonation L_E in shallow waters is well above 10 dB. Therefore, the choice of 10 dB as a broadband L_E attenuation is expected to be conservative.

The very rapid onset of the shock pulse, within a few microseconds (μs), and its rapid decay constant of less than 2 ms for the largest charge size considered (454 kg), suggests the shock pulse peak pressure is dominated by high frequencies that are likely much higher than 500 Hz. The results compiled by Bellman et al (2020) indicate the peak pressure attenuation at those frequencies by modern bubble curtains should be greater than 10 dB. As mentioned above, the first results that applied the use of BBC for UXO produced attenuations slightly larger than 10 dB.

As a final note regarding UXO removal detonation pressures: Bellman (2021) noted that many UXO charges are situated slightly below the seafloor elevation after removal of overlying sedimentation. These charges then lie slightly below the seafloor grade and are then partly shielded by surrounding sediments. The generated pressure waves propagating away in the horizontal direction must pass through the sediments, which have higher absorption characteristics than seawater. Bellman found that propagation loss coefficients were higher for these partially buried charges than for charges detonated in seawater. In this study we assumed no such shielding by sediments.

5. Environmental Parameters

5.1. Seafloor Geoacoustic Parameters

Sound propagation in the shallow water environments of Orsted's wind projects is influenced by the properties of the seafloor substrate. A general profile for the area has been used for all four modeling sites. The surficial sediments are primarily sand as described for the seabed at the adjacent South Fork Wind site (Denes et al. 2018). Table 2 shows the sediment layer geoacoustic property profile used for acoustic modeling of SEL in this study. The geoacoustic parameters are not considered by the peak and impulse models, as those metrics are dominated by direct path and surface reflected signals only. The geoacoustic properties are based on the sediment type and generic porosity-depth profile using a sediment grain-shearing model (Buckingham 2005). This general profile should be relevant for sites throughout the Sunrise Wind, Ocean Wind, and Revolution Wind lease areas.

Table 2. Estimated geoacoustic properties used for modeling at all sites, as a function of depth. Within each depth range, the parameter varies linearly within the stated range.

<table>
<tr><th>Depth below seafloor (m)</th><th>Material</th><th>Density (g/cm³)</th><th>P-wave speed (m/s)</th><th>P-wave attenuation (dB/λ)</th><th>S-wave speed (m/s)</th><th>S-wave attenuation (dB/λ)</th></tr>
<tr><td>0–5</td><td rowspan="4">Sand</td><td>1.87</td><td>1,650–1,690</td><td>0.74–1.0</td><td rowspan="4">300</td><td rowspan="4">3.65</td></tr>
<tr><td>5–10</td><td>1.87–2.04</td><td>1,690–1,830</td><td>1.0</td></tr>
<tr><td>10–100</td><td rowspan="2">2.04</td><td>1,830–2,140</td><td>1.0–1.67</td></tr>
<tr><td>>100</td><td>2,140</td><td>1.67</td></tr>
</table>

5.2. Ocean Sound Speed Profile

The gradients of the speed of sound in seawater affect acoustic refraction during sound propagation. The sound speed is a function of water temperature, salinity, and pressure (i.e., depth) (Coppens 1981). Monthly average sound speed profiles near the proposed construction areas, for the months of April to November, were obtained from the US Navy's Generalized Digital Environmental Model (GDEM; NAVO 2003) and are plotted in Figure 2. The sound speed profiles change little with depth, so these environments do not have strong seasonal dependence. The propagation modeling was performed using a sound speed profile representative of September, which is slightly downward refracting and represents the most likely time of year for UXO removal activities.

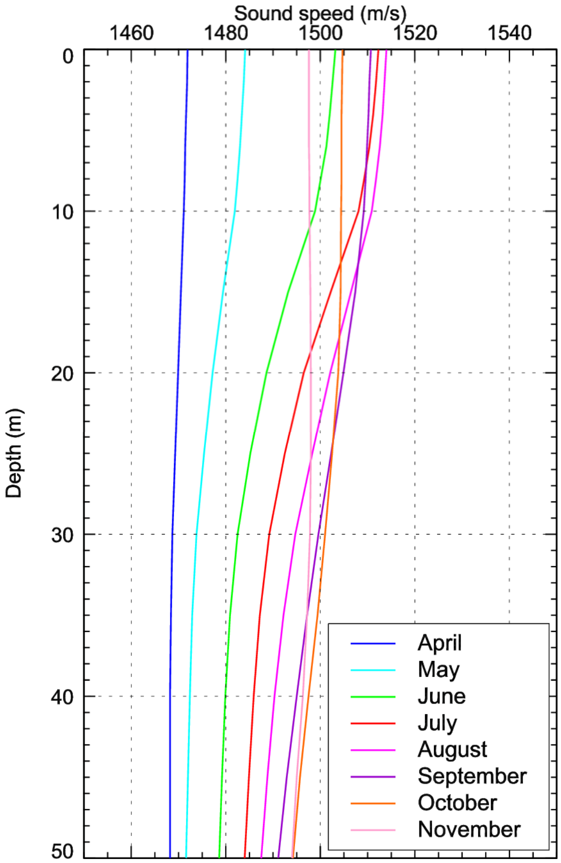

Figure 2. Monthly average sound speed profiles in proposed construction area (excluding winter season) (source: GDEM (NAVO 2003)).

6. Acoustic Thresholds for Mitigation Zones and Take Estimates

6.1. Marine Mammals and Sea Turtles: Auditory Injury (PTS)

The injury zones surrounding explosives detonations are of key importance for developing mitigation designed to minimize takes. Two injury mechanisms are assessed for marine mammals: auditory injury and non-auditory injury. We follow the US Navy approach for assessing both types of effects (Navy, 2017). Auditory injury (onset of permanent threshold shift [PTS]) is assessed using a dual criteria of L_{pk} and frequency-weighted SEL ($L_{E,w}$), where the frequency weighting functions are dependent on the species group (NMFS, 2018). The Navy follows NMFS's guidelines for assessing PTS and temporary threshold shift (TTS) using metrics L_{pk} and $L_{E,w}$ for marine mammals. These thresholds and additional thresholds for sea turtles are provided (Table 3). Note the TTS thresholds also listed in that table are used for Level-B take assessments (see Section 6.3). The Group column in Table 3 represents species groups from top to bottom: low-frequency cetaceans (LF), mid-frequency cetaceans (MF), high-frequency cetaceans (HF), sirenians (SI), otariids in water (OW), pinnipeds in water (PW), and sea turtles (TU).

Table 3. US Navy peak (2017) pressure and frequency-weighted sound exposure thresholds for onset of PTS and TTS. See text for a description of the Group abbreviations.

Group	Hearing threshold at f_0	TTS threshold		PTS threshold	
	L_p	$L_{E,w}$	L_{pk}	$L_{E,w}$	L_{pk}
LF	54	168	213	183	219
MF	54	170	224	185	230
HF	48	140	196	155	202
SI	61	175	220	190	226
OW	67	188	226	203	232
PW	53	170	212	185	218
TU	95	189	226	204	232

f_0 = frequency of blast hearing; L_p = sound pressure level, or SPL; $L_{E,w}$ = frequency-weighted sound exposure level, or SEL; L_{pk} = peak pressure level, or PK

6.2. Marine Mammals and Sea Turtles: Non-Auditory Injury and Mortality

Non-auditory injury and mortality mitigation zones are calculated using metrics representing onset of injury to animal's lungs and gastrointestinal tracts from compression of enclosed air volumes or bubbles. The relevant metrics are L_{pk} and J_p of the blast shock pulse. The peak pressure threshold for injury to gastrointestinal tract is provided in Table 6 as L_{pk} = 237 dB re µPa and this is independent of animal mass. However, that criterion originated from studies on mid-sized terrestrial animals and adult human divers, and it may not be conservative for smaller animals that could be more suspectable to blast injury than larger animals. Our recommendation is to avoid its use for animals with mass less than 100 kg until its validity for smaller animals can be confirmed. The impulse calculation for lung injury and mortality integrates pressure through the time of the shock pulse, with the integration period limited by the arrival of the surface-reflected path or 20% of the animal's lung oscillation period – whichever is smaller. These integration time limits are applied because the arrival of the phase-inverted surface reflection signal reduces or truncates the positive phase of the shock pulse, and because the excitation of lung compression is reduced if the impulse duration is greater than 20% of the lung's oscillation period. The lung oscillation limiting times are straightforward to calculate using the Goertner formulas (Goertner 1982) but they depend on animal mass and submersion depth. The surface reflection arrival time is determined by the geometry of the source and receiving animal relative to each other and the sea surface.

The Navy's impulse criteria for onset of lung injury and mortality are based on measurements of blast effects on a variety of mammals experimentally exposed to detonation pressures (Yelverton 1973). The Navy has published two sets of equations for effects thresholds for impulse that depend on animal mass and submersion depth. The first set of equations (Table 5) produces thresholds based on effects observed in 50% of exposed animals. The second set of equations (Table 6) represent thresholds for onset of effects, based on observed effects in 1% of the exposed animals. NMFS has asked that the more conservative (onset of effects) values also be used for take assessments for Orsted's projects if the distances exceed those of other take criteria.

The impulse thresholds for lung injury and mortality to marine mammals and sea turtles depend on the animal lung volume, which is dependent on animal mass and submersion depth. To be conservative, maximum horizontal distances for threshold exceedances were calculated in 1 m submersion depth increments from the surface to seabed at the respective assessment location. The maximum distance over these depths was listed as the representative exceedance distance.

The animal masses used for exceedance calculations were obtained from a tabulation of animal masses (Table C.9, Navy, 2017). The Navy table provides conservative calf/pup and adult masses for all marine mammal species. The adult mass is the smallest mass from the range of adult masses for the respective species. Five animal groups are defined in Table 4 that represent and comprise similar-mass species to those that may be encountered at the project sites, including rare species for those areas. For each group, a representative species with the smallest calf and adult masses are used as conservative values for the entire animal group. Sperm whales were grouped with larger baleen whales due to their similar adult masses, but the sei whale calf mass was used for this group due to their smaller mass. The smallest animals of dolphin, kogia, pinniped, and sea turtle families had very similar mass to harbor seals. Harbor seal calf and adult masses were therefore used as the representative species for that animal group for conservatism. Table 4 lists the defined animal groups and the corresponding calf/pup and adult masses of representative species used for impulse threshold calculations. Table 7 and Table 8 provide the corresponding thresholds for onset of lung injury and onset of mortality, respectively, for all relevant animal masses at a selection of submersion depths.

Table 4. Representative calf/pup and adult mass estimates for the animal groups defined for this assessment. These mass values are based on the smallest expected animals for the species that might be present within project areas. Masses listed here are used for assessing impulse-based onset of lung injury and mortality threshold exceedance distances.

Impulse Animal Group	Representative Species	Calf/Pup Mass (kg)	Adult Mass (kg)
Baleen whales and Sperm whale	Sei whale calf (*Balaenoptera borealis*) Sperm whale adult (*Physeter macrocephalus*)	650	16,000
Pilot and Minke whales	Minke whale (*Balaenoptera acutorostrata*)	200	4,000
Beaked whales	Gervais' beaked whale (*Mesoplodon europaeus*)	49	366
Dolphins, Kogia, Pinnipeds, and Sea Turtles	Harbor Seal (*Phoca vitulina*)	8	60
Porpoises	Harbor Porpoise (*Phocoena phocoena*)	5	40

Table 5. US Navy impulse and peak pressure threshold equations for onset lung injury in marine mammals and sea turtles due to explosive detonations (Department of the Navy 2017). These thresholds are based on observed effects to 50% of exposed animals. Note that this table is provided for information purposes only. The threshold formula in Table 6 are used as the non-auditory injury and mortality criteria this assessment.

Impact Assessment Criterion	*Threshold*
Mortality - Impulse	$144M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Injury - Impulse	$65.8M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Injury - Peak Pressure	243 dB re 1 μPa peak

Where M is animal mass (kg) and D is animal depth (m).

Table 6. US Navy impulse and peak pressure threshold equations for onset of lung injury in marine mammals and sea turtles due to explosive detonations (Department of the Navy 2017). These thresholds are based on observed effects to 1% of exposed animals and are used in this study for onset of non-auditory injury and mortality. The peak pressure criterion (third row) may not be suitable for application to small animals. We recommend avoiding its use for animals with mass less than 100 kg until its validity for smaller animals can be confirmed.

Onset effect for mitigation consideration	Threshold
Onset Mortality - Impulse	$103M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Onset Injury - Impulse (Non-auditory)	$47.5M^{1/3}\left(1+\frac{D}{10.1}\right)^{1/6}$ Pa-s
Onset Injury - Peak Pressure (Non-auditory)	237 dB re 1 µPa peak

Where M is animal mass (kg) and D is animal depth (m).

Table 7. Impulse thresholds (units of Pa·s) for Onset Injury from equation in Table 6 for all animal masses in Table 4, for selected animal submersion depths between 1 and 60 m. This assessment evaluated impulse exposures against thresholds at 1 m submersion depth intervals.

Submersion Depth (m)	Animal mass (kg) / Impulse Thresholds for Onset Lung Injury (Pa s)									
	5 kg	8 kg	40 kg	49 kg	60 kg	200 kg	366 kg	680 kg	4,000 kg	16,000 kg
1	82.5	96.5	165.0	176.6	188.9	282.2	345.2	424.3	766.0	1215.9
10	91.1	106.5	182.2	194.9	208.6	311.5	381.1	468.5	845.7	1342.4
20	97.4	114	194.9	208.5	223.1	333.2	407.6	501.1	904.5	1435.8
30	102.2	119.5	204.4	218.7	234	349.5	427.6	525.6	948.8	1506.2
40	106.1	124.1	212.1	227.0	242.8	362.8	443.7	545.5	984.7	1563.1
50	109.3	127.9	218.7	234.0	250.3	373.9	457.4	562.3	1015.0	1611.2
60	112.2	131.2	224.4	240.1	256.8	383.7	469.3	576.9	1041.4	1653.1

Table 8. Impulse thresholds (units of Pa·s) for Onset Mortality from equation in Table 6 for all animal masses in Table 4, for selected animal submersion depths between 1 and 60 m. This assessment evaluated impulse exposures against thresholds at 1 m submersion depth intervals.

Submersion Depth (m)	Animal mass (kg) / Impulse Thresholds for Onset Mortality (Pa s)									
	5 kg	8 kg	40 kg	49 kg	60 kg	200 kg	366 kg	680 kg	4,000 kg	16,000 kg
1	178.9	209.3	357.8	382.9	409.6	611.9	748.5	920.1	1661.0	2636.6
10	197.5	231	395.1	422.7	452.2	675.6	826.3	1015.8	1833.7	2910.9
20	211.3	247.1	422.6	452.1	483.7	722.6	883.8	1086.5	1961.4	3113.5
30	221.6	259.2	443.3	474.3	507.4	758.0	927.1	1139.8	2057.4	3266.0
40	230.0	269.0	460.0	492.2	526.6	786.6	962.2	1182.8	2135.2	3389.5
50	237.1	277.3	474.2	507.4	542.8	810.8	991.8	1219.3	2201	3493.8
60	243.3	284.5	486.5	520.6	556.9	831.9	1017.6	1250.9	2258.2	3584.6

6.3. Marine Mammals and Sea Turtles: Level-B takes and Disturbance

The acoustic criteria relevant for Level-B takes include L_{pk} and $L_{E,w}$ thresholds. All SEL modeling in this study assumes a single detonation per day as the assessment criteria and thresholds are different when more than one detonation occurs in a 24-hour period, as discussed below.

Single blast events within a 24-hour period are not presently considered by NMFS to produce behavior effects if received levels are below the onset of TTS thresholds for $L_{E,w}$ and L_{pk} (Table 3). When multiple blast events occur within a 24-hour period, the US Navy approach applies a disturbance threshold of TTS $L_{E,w}$ minus 5 dB. Thus, the effective Level-B take threshold for single events in each 24-hour period is the $L_{E,w}$ for TTS onset, and for multiple events it is the $L_{E,w}$ for TTS – 5 dB.

The calculation of TTS onset and behavioural effects (TTS – 5 dB) is more difficult when multiple blasts occur within a 24-hour period. In this case marine mammals and sea turtles could receive partial doses of SEL from multiple detonations. The individual event doses depend on the charge sizes, relative detonation timing, animal locations, and geoacoustic environment parameters along paths between the detonation and the exposed animals, most of which are not known in advance of the UXO detonations. If the parameters other than animal locations were known, then animal movement models could be used to provide exposure and take estimates. However, since Orsted plans on only one charge detonation per day, a single event SEL model scenario is sufficient to calculate an $L_{E,w}$ map around each charge, and the TTS zones can be evaluated using the TTS criteria from Table 3.

Note: For multiple blast events an SPL-based disturbance threshold of L_p = 175 dB re 1 µPa^2 would be relevant. Here we are considering only a single blast event per day, so we have not considered that threshold. The approach for calculating L_p is defined in ISO 18405, but that metric is not currently applied by the Bureau of Ocean Energy Management (BOEM) or NMFS for explosives effects assessment of single blast events. Modeling of SPL requires using full wave source and propagation models that are not required for SEL-based assessments. That has not been done here, but it could be added later if required.

6.4. Fish Injury

Injury to fish from exposures to blast pressure waves is attributed to compressive damage to tissue surrounding the swim bladder and gastrointestinal tract, which may contain small gas bubbles. Effects of detonation pressure exposures to fish have been assessed according to the L_{pk} limits for onset of mortality or injury leading to mortality due to explosives, as recommended by the American National Standards Institute (ANSI) expert working group (Popper et al. 2014) and provided in Table 9. The injurious effects thresholds for all fish species groups are the same: L_{pk} = 229–234 dB re 1 µPa. The present assessment has applied the lower range value of L_{pk} = 229 dB re 1 µPa for potential mortal injury and mortality.

Table 9. Recommended Fish Injury thresholds for explosives from Popper et al. (2014).

Type of Animal	Mortality and potential mortal injury	Impairment			Behavior
		Recoverable injury	TTS	Masking	
Fish: no swim bladder (particle motion detection)	229 - 234 dB peak	(N) High (I) Low (F) Low	(N) High (I) Moderate (L) Low	NA	(N) High (I) Moderate (F) Low
Fish where swim bladder is not involved in hearing (particle motion detection)	229 - 234 dB peak	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	NA	(N) High (I) High (F) Low
Fish where swim bladder is involved in hearing (primarily pressure detection)	229 - 234 dB peak	(N) High (I) High (F) Low	(N) High (I) High (F) Low	NA	(N) High (I) High (F) Low

6.5. Fish Disturbance

This assessment has not quantitatively assessed zones of non-injurious effects to fish from explosive detonations because the Popper et al. (2014) guidelines (see Table 9) are qualitative and vague on that subject. For fish species that use swim bladders for hearing, Popper et al suggest a high likelihood of TTS and recoverable injury at near and intermediate distances, where near refers to within a few tens of meters and intermediate refers to a few hundreds of meters. For fish species with swim bladders not used for hearing, the guidelines indicate high likelihood of recoverable impairment at near and intermediate distances but low levels of TTS at intermediate distances. For fish without swim bladders the guidelines indicate low likelihood of recoverable injury at intermediate distances and moderate likelihood of TTS at intermediate distances and low levels of both effects at far distances of a few kilometers.

7. Acoustic Modeling

7.1. Peak Pressure and Impulse

7.1.1. Shock Pulse Source Function

Modeling of acoustic fields generated by UXO detonations is performed using a combination of semi-empirical and physics-based computational models. The source pressure function used for estimating L_{pk} and J_p metrics is calculated using a semiempirical model that approximates the rapid conversion (within approximately 1 µs for high explosive) of solid explosive to gaseous form in a small gas bubble under high pressure, followed by an exponential pressure decay as that bubble expands outwards from the charge detonation location. This behavior imparts an initial pressure “shock pulse” into the water that is represented well by an instantaneous rise to peak pressure P_0 followed by an exponentially decaying pressure function of the form:

$$P(t) = P_0 e^{-t/\tau} \quad (1)$$

The shape and amplitude of the pressure versus time signature of the shock pulse changes with distance from the detonation location due to non-linear propagation effects caused by its high L_{pk}. Arons and Yennie (1949) made measurements of the detonations of a range of charge sizes in Vineyard Sound, coincidentally just a few miles from Orsted's wind leases, and derived empirical formulae for P_0 in Pascals, and exponential time constant τ in seconds as functions of equivalent TNT charge weight W in kilograms, and distance from the detonation r in meters (note the original equations used different weight and distance units and are converted to metric system units in the formulae presented here.

$$P_0 = 5.24 \times 10^7 \left(\frac{W^{\frac{1}{3}}}{r}\right)^{1.13} \text{ Pa} \qquad 2$$

$$\tau = 9.25 \times 10^{-5} W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{r}\right)^{-0.22} \text{ s} \qquad 3$$

7.1.2. Shock Pulse Pressure Range Dependence

The shock pulse source function variation with distance described above is valid only close to the source. Beyond a certain distance R_0, the functional dependence of P_0 and τ on W and r are better-described by weak shock theory (Rogers 1977). The transition distance was defined by Gaspin (1983) as $R_0 = 4.76\,W^{1/3}$ meters. For example, R_0 is 47.6 m for a 1000 kg charge. At distances greater than R_0, the L_{pk} and time constant are obtained by modified formulae (Rogers 1977):

$$P_0(r > R_0) = \frac{P_0(R_0)\left\{\left[1 + \frac{2R_0}{L_0}\ln\frac{r}{R_0}\right]^{\frac{1}{2}} - 1\right\}}{\left(\frac{r}{L_0}\right)\ln\frac{r}{R_0}} \text{ Pa} \qquad 4$$

$$\tau(r > R_0) = \tau(R_0)\left[1 + 2\left(\frac{R_0}{L_0}\right)\ln\frac{r}{R_0}\right]^{\frac{1}{2}} \text{ s} \qquad 5$$

where $L_0 = (\rho_0 {c_0}^3 \tau(R_0))/(\beta P_0(R_0)$.

In Eq. 5, water density ρ_0=1026 kg/m^3, water sound speed c_0 = 1500 m/s, and β=3.5. The values for ρ_0 and c_0 were chosen specifically for this report. These equations lead to a pressure decay with range r that transitions to spherical spreading at long distances. The time constant also increases as the higher frequencies of the shock pulse, responsible for its sharp peak, are preferentially attenuated by absorptive loss. The pressure calculations were performed for the charge sizes of Table 1 and these results are graphed as a function of distance from the charges in Figure 3. The corresponding shock pulse time constant versus distance from Eqs. 3 and 5 is plotted in Figure 4.

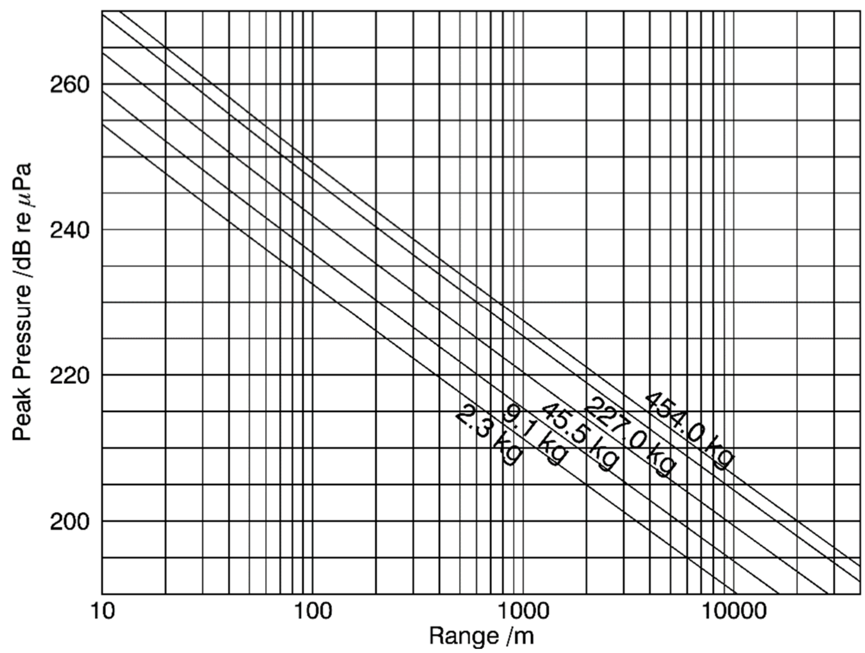

Figure 3. Peak pressures versus distance from detonations of the charge weights listed in Table 1, calculated with Eqs. 2 and 4.

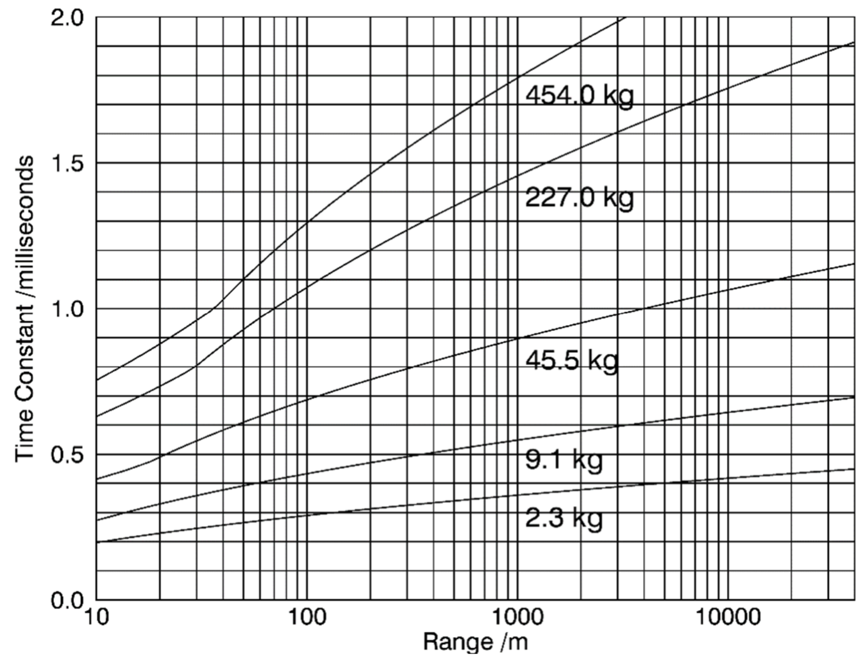

Figure 4. Time constants calculated with Eqs. 3 and 5 and converted to milliseconds for the exponential decay approximation of the shock pulse, for each of the charge weights listed in Table 1.

7.1.3. Impulse

Acoustic impulse is defined as the integral of pressure through time. Assuming the onset of the pressure signal of the direct acoustic path starts at $t = 0$ and ends at $t = T$, the impulse is given by:

$$J_p = \int_0^T P(t)\,dt \quad (6)$$

If the integration end time T is within the part of the shock pulse pressure waveform approximated well by the exponential function (Eq. 1) then Eq. 6 can be expressed:

$$J_p(r) = P_0(r)\tau(r)\left(1 - e^{-T/\tau(r)}\right) \quad (7)$$

In practice, this approximation is accurate for integration times much larger than the time constant because most of the contribution to impulse occurs near the shock pulse onset and the right bracketed term in Eq. 7 approaches 1.0 as the integration time exceeds a few time constants (e.g., see Figure 4).

The US Navy applies an integration time window starting at the onset of the shock pulse and ending at the lesser of the arrival time of the surface reflection and 20% of the oscillation period of an exposed animal's lung, i.e., T = *minimum*(T_{surf}, 0.2 T_{lung}). The arrival time of the surface-reflected path relative to the direct path can be calculated from the depths of the source charge z_s and the exposed animal z_r, their horizontal separation x and the water sound speed c_0:

$$T_{surf} = \left(\sqrt{x^2 + (z_s + z_r)^2} - \sqrt{x^2 + (z_s - z_r)^2}\right)/c_0 \quad (8)$$

The lung oscillation period can be approximated by the oscillation period of a gas sphere of the same volume. The lung volume of animals at atmospheric pressure is approximately proportional to the animal's mass M in kilograms, and this volume decreases with animal submersion depth z_r due to compression by hydrostatic pressure. Goertner (1982) provides the following approximation for lung volume V and equivalent volume fundamental oscillation period t_{osc} for a submerged animal:

$$V = 3.5 \times 10^{-5}\, M \frac{p_{atm}}{(\rho_0 g z_r + p_{atm})} \quad \mathrm{m}^3 \quad (9)$$

$$t_{osc} = 97.1\,(V 4\pi/3)^{\frac{1}{3}}/\sqrt{\rho_0 g z_r + p_{atm}} \quad \mathrm{s} \quad (10)$$

where $g = 9.81\ m/s^2$ is the gravitational acceleration and p_{atm} is the atmospheric pressure in pascals at the sea surface. Figure 5 shows lung fundamental oscillation periods calculated from Eq. 10 for four animal masses, versus submersion depth.

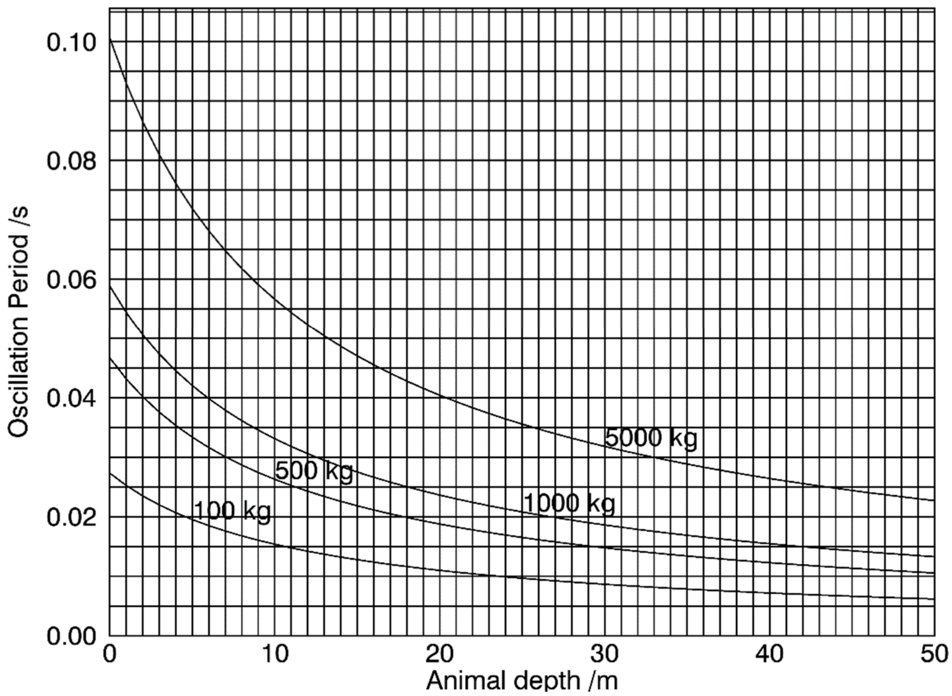

Figure 5. Lung oscillation periods for animal masses of 100 kg, 500 kg, 1000 kg, and 5000 kg versus submersion depth, calculated using Eq. 10.

7.2. Sound Exposure Level Model

SEL and SPL calculations for blast pressure waveforms depend on the characteristics of the initial shock pulse, as described above, and the subsequent oscillation of the detonation gas bubble. The oscillations lead to a series of alternating negative and positive pressure phases trailing the initial positive pressure shock pulse (Figure 6). The positive pressures (relative to hydrostatic pressure) occur when the bubble volume is small, and the negative pressures occur when the bubble volume is large. The shape of the resulting pressure waveform can be calculated using an explosive waveform model (e.g., Wakeley 1977) that includes the shock pulse model of Eq. 1 and extends the pressure prediction in time through several oscillations of the bubble. The negative phase pressure troughs and bubble pulse peaks following the shock pulse are responsible for most of the low frequency energy of the overall blast waveform.

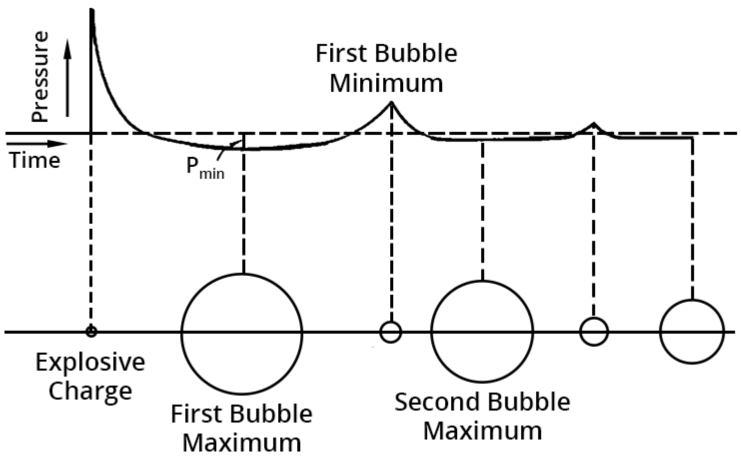

Figure 6. Pictorial representation of the relationship between the radiated pressure signal and the volume of the gas bubble as it oscillates in size after the detonation. This figure is reproduced from Discovery of Sound in the Sea (DOSITS) website https://dosits.org/galleries/technology-gallery/basic-technology/explosive-sound-sources.

The SEL thresholds for PTS and TTS occur at distances of several water depths in the relatively shallow waters of Orsted's Sunrise Wind, Ocean Wind, and Revolution Wind's wind farm environments. The sound field at becomes increasingly influenced by the contributions of sound energy reflected from the sea surface and sea bottom multiple times. In many instances the reflected paths become dominant over the direct acoustic path at horizontal distances greater than a few water depths. Some acoustic energy is also transmitted into the seafloor on each reflection and that energy can propagate partly through the seafloor before re-emerging into the water column and interacting in a complex way with waterborne energy. We apply acoustic propagation models to account for the effects of multiple reflections and sound propagation partly in the seabed. The modeling of SEL does not require use of a full waveform signature model. Nevertheless, the rate of decay of L_E with distance from the detonation varies in a complex way with sound frequency, so a source model that accounts for frequency dependence is necessary. The modeling of $L_{E,w}$ performed here was carried out by first modeling L_E in decidecade frequency bands using the marine operations noise model (MONM, JASCO Applied Sciences). This model uses an energy source level model, described in the next section, and then calculates acoustic propagation loss using parabolic equation (PE) approach for frequencies below 4 kHz, and a Gaussian beam ray trace model at higher frequencies. The PE model applied here also accounts for shear wave conversion losses from reflections at layer interfaces.

7.2.1. Energy Source Levels in Decidecade Frequency Bands

A key input for the MONM model is the energy source level (ESL), which quantifies the acoustic energy (SEL) and its distribution across different frequency bands for each of the charges considered. The distribution depends on the charge weight and detonation depth. The ESL is calculated using an approach described by Urick (1971 and 1983). A series of energy source level spectral density curves for normalized underwater explosion events at various depths (Figure 7) are defined in terms of frequency relative to the frequency of the first bubble pulse. The first bubble pulse frequency is calculated using an equation provided by Chapman (1985):

$$f_{b1} = (2.11 W^{\frac{1}{3}} z_0^{-5/6})^{-1}, \qquad 11$$

where W is the weight of the charge in kg of equivalent TNT and z_0 is the hydrostatic depth of the charge ($z_0 = z_s + 10.1 \text{ meters}$).

The energy source level scaling factor for charge weight is calculated as:

$$\Delta \mathrm{ESL} = 13.3 \log W. \tag{12}$$

The ESL in decidecade bands is calculated as follows:

1. The appropriate energy source level spectral density (ESLSD) curve is selected from the chart (Figure 7) based on the charge depth;
2. The first bubble pulse frequency f_{b1} is calculated using Equation 11 and absolute frequencies for the ESLSD curve are obtained by scaling their normalized frequency by multiplying by f_{b1};
3. The spectral levels are adjusted for the charge weight using Equation 12;
4. The ESLs are calculated by integrating the corrected ESLSD spectral function through the bandwidth of each decidecade band.

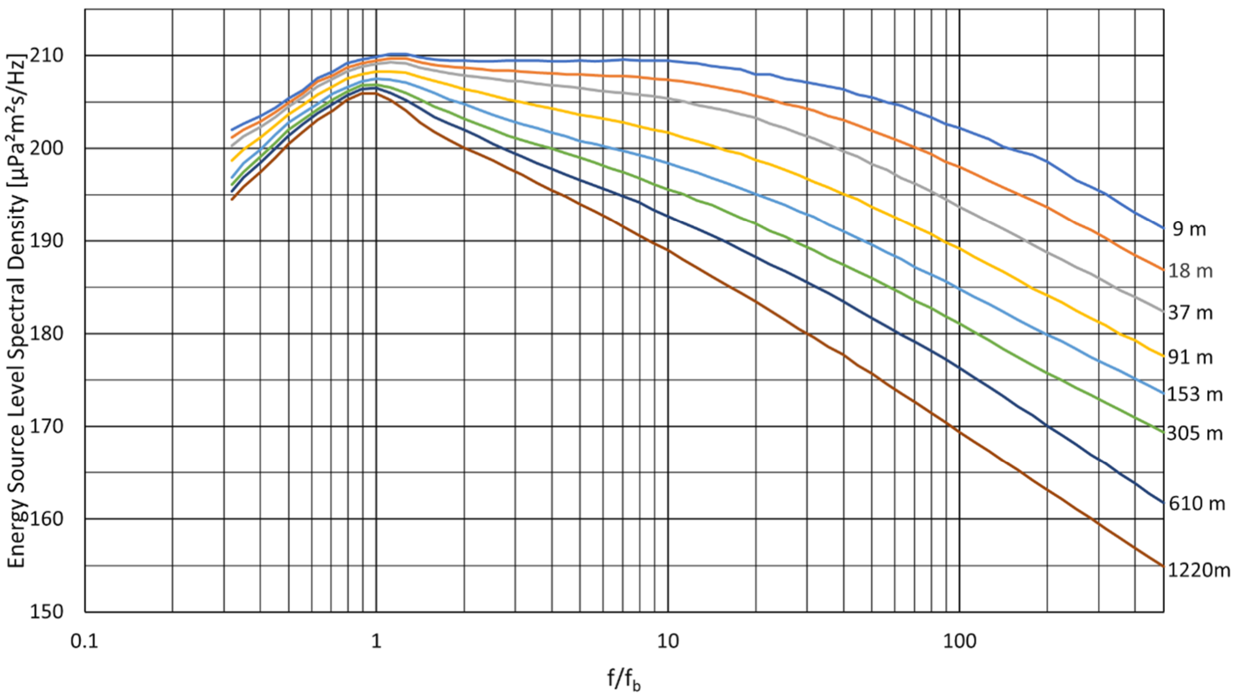

Figure 7. Energy source level spectral density curves for underwater explosion events at various depths expressed in normalized frequency, relative to the frequency f_{b1} of the first bubble pulse (after Urick 1983).

8. Exceedance Distance Results (Unmitigated)

8.1. Marine Mammals and Sea Turtles TTS and PTS by Peak Pressure Distances

Peak pressure exceedance distances are not dependent on water depth or seabed properties, so the results of Table 10 are relevant for all sites.

Table 10. Marine mammals and sea turtles PTS and TTS maximum exceedance distances for peak pressure for various UXO charge sizes for all sites.

Marine mammal group	TTS / PTS L_{pk} threshold (dB re 1 µPa)	Maximum distances (meters) to TTS and PTS thresholds for peak pressure									
		E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
Low-frequency cetaceans	213 / 219	826	426	1306	678	2233	1162	3817	1982	4813	2497
Mid-frequency cetaceans	224 / 230	246	130	394	206	674	350	1150	602	1450	758
High-frequency cetaceans	196 / 202	5357	2761	8476	4373	14490	7476	24764	12775	31202	16098
Phocid pinnipeds	212 / 218	922	478	1458	754	2493	1294	4261	2213	5369	2785
Otariid pinnipeds and sea turtles	226 / 232	198	102	314	166	542	282	926	486	1170	610

8.2. Marine Mammals and Sea Turtles Gastrointestinal Injury by Peak Pressure Distances

The threshold exceedances in Table 11 are for Onset Gastrointestinal Injury (effects observed in 1% of exposed animals). The peak pressure threshold listed here is based on studies on humans and mid-sized terrestrial animals and may not be conservative for smaller marine animals, less than approximately 100 kg. Further examination of that threshold is recommended before it is applied for smaller animals.

Table 11. Maximum exceedance distances for Gastrointestinal Injury (1% of exposed animals) due to peak pressure exposures for five UXO charge sizes. The peak pressure threshold formula applied here is from Table 6, Onset Injury – Peak Pressure (Non-auditory). We do not recommend applying these criteria for animals with mass less than 100 kg.

Effect	L_{pk} Threshold (dB re 1 µPa)	All sites: Maximum distance to L_{pk} threshold for gastrointestinal injury (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
Onset Gastrointestinal Injury (1% of exposed animals)	237	61 m	97 m	167 m	285 m	359 m

8.3. Marine Mammals and Sea Turtles Onset Lung Injury by Impulse Distances

The exceedance distances in this section represent the onset of lung injury based on the threshold formula in Table 6. These thresholds represent effects observed in 1% of exposed animals.

Impulse levels and thresholds are depth-dependent, so maximum exceedance distances vary between sites with different depths. The results for the four sites evaluated are presented in Table 12 through Table 15.

Table 12. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S1 (12 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 1: 12 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	24	7	62	19	150	59	247	129	291	160
Minke whales	38	12	93	33	199	93	310	174	361	210
Beaked whales	63	30	144	76	268	174	399	277	461	325
Dolphins, Kogia, Pinnipeds and Sea Turtles	114	58	234	136	383	257	548	385	628	446
Porpoises	132	67	261	153	418	280	594	413	680	478

Table 13. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S2 (20 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion-depth and based on the threshold formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 2: 20 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	22	6	62	18	172	60	352	161	431	219
Minke whales	36	11	96	31	249	97	455	234	546	300
Beaked whales	62	28	152	78	362	208	599	402	707	487
Dolphins, Kogia, Pinnipeds and Sea Turtles	117	58	263	142	541	344	839	576	975	681
Porpoises	137	67	297	162	591	380	913	623	1059	733

Table 14. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S3 (30 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 3: 30 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	21	6	60	17	177	58	432	168	563	251
Minke whales	33	10	96	29	261	98	583	260	730	369
Beaked whales	59	26	155	77	392	216	775	505	966	644
Dolphins, Kogia, Pinnipeds and Sea Turtles	118	54	274	145	589	371	1044	747	1289	929
Porpoises	138	65	312	166	644	412	1110	804	1364	1004

Table 15. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury to Lung – Impulse at Site S4 (45 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 4: 45 m depth – Impulse threshold exceedance distances for onset lung injury (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	19	6	52	16	181	51	463	172	648	262
Minke whales	31	10	92	27	270	95	631	270	843	402
Beaked whales	51	25	156	71	412	222	846	546	1084	746
Dolphins, Kogia, Pinnipeds and Sea Turtles	115	47	283	145	630	389	1148	815	1421	1052
Porpoises	137	57	324	167	695	435	1228	878	1518	1127

8.4. Marine Mammals and Sea Turtles Onset of Mortality by Impulse Distances

The exceedance distances in this section represent the onset of mortality based on the threshold formula in Table 6. These thresholds represent effects observed in 1% of exposed animals.

Impulse exposure levels and impulse effects thresholds are depth-dependent, so maximum exceedance distances vary between sites with different depths. Interestingly, the trends of maximum horizontal exposure effects distance with water depth at each site are not always consistent. That occurs due to three reasons:

1.) Impulse exposure, for a given animal submersion depth, depends on water depth because the seabed (and charge location) is further from the animal in deeper environments.

2.) The impulse exposure is site and submersion depth-dependent because the impulse integration time depends on the minimum of arrival time of surface reflection and 20% of the lung oscillation period (which also depends on submersion depth)

3.) The impulse criteria decrease with increased animal submersion depth.

The trends would be consistent had we calculated each table at a fixed animal submersion depth, but instead we search for the maximum criterion exceedance distance over all possible animal submersion depths, in 1 m depth increments from the surface to seafloor. The maximum horizontal effects criteria exceedance distances over all submersion depths are presented in Table 16 through Table 19.

Table 16. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S1 (12 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 1: 12 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	9	5	27	7	78	26	155	72	189	97
Pilot and Minke whales	15	5	43	13	113	43	199	104	238	132
Beaked whales	27	12	69	34	161	95	261	177	307	213
Dolphins, Kogia, Pinnipeds and Sea Turtles	52	25	123	64	242	154	364	252	422	296
Porpoises	62	29	140	74	266	169	396	271	458	319

Table 17. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S2 (20 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion-depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 2: 20 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	9	5	25	7	81	24	203	76	266	116
Pilot and Minke whales	14	5	41	12	121	42	275	120	346	173
Beaked whales	25	11	70	32	186	99	376	238	458	305
Dolphins, Kogia, Pinnipeds and Sea Turtles	52	23	128	65	293	176	534	360	644	441
Porpoises	61	27	147	75	319	197	573	393	702	477

Table 18. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S3 (30 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 3: 30 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	8	5	23	7	80	22	219	77	316	120
Pilot and Minke whales	14	5	37	12	123	38	308	124	421	188
Beaked whales	23	11	68	30	194	100	425	262	552	367
Dolphins, Kogia, Pinnipeds and Sea Turtles	47	22	130	63	310	183	586	406	736	536
Porpoises	58	25	150	73	343	206	633	440	786	575

Table 19. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S4 (45 m water depth) for five UXO charge sizes. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 4: 45 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	8	5	22	6	76	21	227	72	334	121
Pilot and Minke whales	13	5	34	11	123	36	325	125	453	194
Beaked whales	22	10	61	28	199	98	455	275	602	392
Dolphins, Kogia, Pinnipeds and Sea Turtles	39	20	129	55	328	186	637	434	814	580
Porpoises	49	23	152	67	361	212	690	477	868	628

8.5. Fish Injury by Peak Pressure Distances

Table 20. Maximum exceedance distances for Onset of Injury for fish without and with a swim bladder due to peak pressure exposures for various UXO charge sizes. The threshold of 229 dB re 1 µPa is the minimum of the threshold range from Popper et al. (2014).

Fish Hearing Group	Onset Injury L_{pk} (dB re 1 µPa)	All sites: Maximum distance to L_{pk} onset injury threshold exceedance (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
All fish hearing groups	229	145	230	393	671	847

8.6. Marine Mammals and Sea Turtles: PTS by SEL Distances

The methods discussed in Section 7.2 were applied to calculate SEL, at receiver depths from the surface to the seabed, versus distance and direction from each charge detonation. The maxima of these results over depth were extracted over depth to create noise maps of the type shown in Figure 8. This map and similar maps for the other sites modeled for the 2.3 kg and 454 kg charge sizes are provided in Appendix A.

Exceedance distances to each of the marine mammal, sea turtle, and fish SEL PTS thresholds listed in Table 3, were obtained from these maps in two ways:

- R_{max}: represents the maximum distance in any direction that the threshold was exceeded. This metric is often overly conservative for take estimates because it reflects the influence of coherent constructive interference effects, produced by most propagation loss models, due to model approximations of highly uniform environments. In practice, these coherent effects are almost always disrupted by rough interfaces and ocean inhomogeneities.
- $R_{95\%}$: represents the radius of a circle that encompasses 95% of the area predicted by the model to exceed the threshold. The circle radius is typically larger than the maximum distances in most directions, but it cuts off “fingers” of ensonification that protrude in a small number of directions. This metric is typically also conservative, but less so than the R_{max} distance.

The SEL effects thresholds are not dependent on animal depth, but SEL exposure levels generally do depend on depth. The PTS threshold exceedance distances provided in Tables 21 to 24 are maxima over depth. The site-to-site variations in final exceedance distances are typically less then 20% between sites and attributed to dependence of propagation loss on water depth and bathymetry variations. The spectral shape of larger charges has greater relative low frequency sound energy than small charges, so propagation loss frequency dependence also affects the exceedance distance trends by charge size between sites. These features of location and charge size effects combine to produce non-uniform trends in exceedance distances with site depth and charge size, although the trend variations are relatively small.

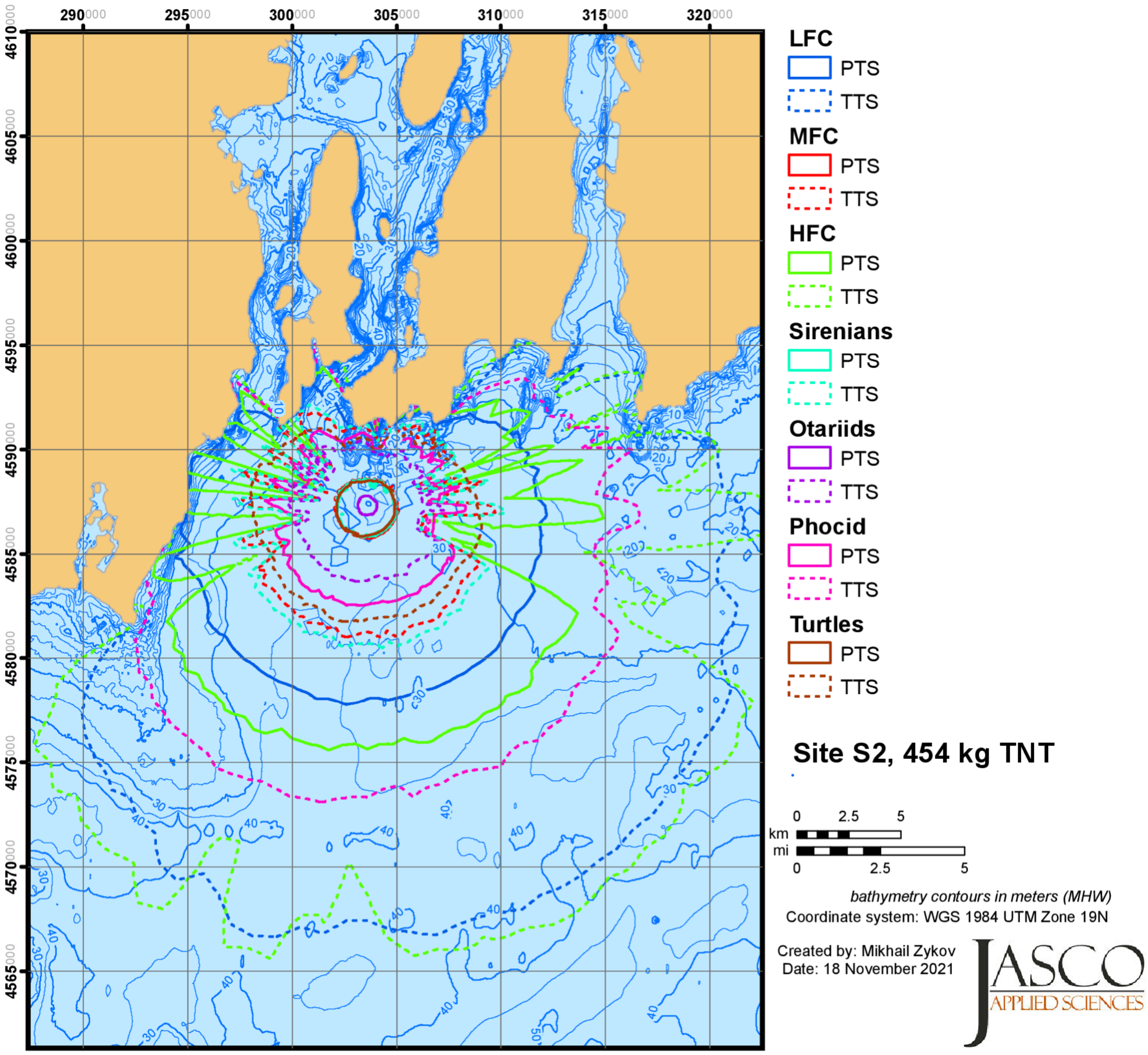

Figure 8. Frequency-weighted SEL PTS and TTS exceedance zone maps for the 454 kg charge size at Site S2, for each species group.

Table 21. SEL-based criteria ranges to PTS-onset at Site S1 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	2010	1710	3060	2640	4710	4140	7280	6460	8490	7640
Mid-frequency cetaceans	185	252	214	455	385	822	714	1500	1220	1840	1540
High-frequency cetaceans	155	4930	4250	6500	5700	8590	7610	11100	10200	12200	11300
Phocid pinnipeds	185	970	804	1520	1310	2530	2190	4040	3580	4990	4340
Otariid pinnipeds	203	59	56	119	106	240	221	539	466	720	615
Sea turtles	204	110	104	259	241	637	545	1180	946	1370	1150

Table 22. SEL-based criteria ranges to PTS-onset at Site S2 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	1820	1590	3110	2810	5460	4880	8170	7520	9580	8800
Mid-frequency cetaceans	185	148	139	372	332	761	633	1300	1130	1590	1450
High-frequency cetaceans	155	4760	4290	6280	5750	8510	7810	10900	10000	12000	11000
Phocid pinnipeds	185	741	644	1380	1210	2500	2190	4190	3660	4900	4500
Otariid pinnipeds	203	<50	<50	66	62	165	155	377	346	508	456
Sea turtles	204	76	76	190	182	535	473	1160	1030	1580	1390

Table 23. SEL-based criteria ranges to PTS-onset at Site S3 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	1630	1540	2890	2720	5080	4750	7810	7270	9130	8440
Mid-frequency cetaceans	185	181	161	388	358	734	636	1290	1140	1630	1480
High-frequency cetaceans	155	4790	4300	6390	5750	8510	7710	10700	9760	12100	10700
Phocid pinnipeds	185	653	592	1230	1120	2370	2170	3930	3620	4900	4450
Otariid pinnipeds	203	<50	<50	60	57	134	128	333	313	501	462
Sea turtles	204	<50	<50	184	181	444	416	980	931	1400	1220

Table 24. SEL-based criteria ranges to PTS-onset at Site S4 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 μPa^{2}s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	1620	1470	2870	2610	5090	4640	8060	7280	9510	8540
Mid-frequency cetaceans	185	108	89	362	272	749	684	1260	1120	1640	1410
High-frequency cetaceans	155	4650	4170	6400	5660	8520	7670	11100	9890	12300	10900
Phocid pinnipeds	185	666	607	1140	1010	2360	2140	4100	3740	4970	4520
Otariid pinnipeds	203	<50	<50	<50	<50	89	89	233	221	400	372
Sea turtles	204	<50	<50	144	141	350	340	884	852	1330	1260

8.7. Marine Mammals and Sea Turtles: TTS by SEL Distances

The SEL distances thresholds are not dependent on animal depth, but the SEL exposure levels are. The TTS threshold exceedance distances provided in Tables 25 to 28 are maxima over depth.

Table 25. SEL-based criteria ranges to TTS-onset at Site S1 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 μPa^{2}s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	7600	6830	10700	9780	14300	13100	18000	16700	19900	18300
Mid-frequency cetaceans	170	1820	1520	2660	2290	3760	3340	5650	4970	6660	5860
High-frequency cetaceans	140	12100	11200	14600	13400	17400	16000	20600	19100	21900	20200
Phocid pinnipeds	170	4780	4120	6840	6080	9630	8750	13000	11900	14500	13300
Otariid pinnipeds	188	681	569	1230	965	1930	1670	3210	2760	3830	3400
Sea turtles	189	822	708	1380	1160	2290	1920	3180	2750	3810	3220

Table 26. SEL-based criteria ranges to TTS-onset at Site S2 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 μPa^{2}s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	8000	7340	11200	10300	15200	13900	19500	17500	21300	19200
Mid-frequency cetaceans	170	1590	1430	2520	2160	4030	3460	5510	5020	6380	5850
High-frequency cetaceans	140	12000	11000	14200	13100	17500	15900	20800	18800	22200	20200
Phocid pinnipeds	170	4630	4200	6730	6200	9760	9060	13000	11800	14500	13200
Otariid pinnipeds	188	444	406	926	788	1790	1560	3120	2720	3950	3440
Sea turtles	189	706	639	1540	1350	2780	2520	4660	4340	5670	5260

Table 27. SEL-based criteria ranges to TTS-onset at Site S3 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	7610	7000	10600	9790	14700	13400	19100	17400	21100	19300
Mid-frequency cetaceans	170	1600	1450	2510	2210	3890	3490	5590	5020	6500	5840
High-frequency cetaceans	140	12000	10700	14200	12700	17500	15600	20800	18700	22400	20200
Phocid pinnipeds	170	4420	4070	6690	6070	9700	8780	12800	11500	14400	12800
Otariid pinnipeds	188	412	394	796	756	1720	1600	3000	2730	3750	3400
Sea turtles	189	605	581	1340	1200	2550	2340	4440	4150	5500	5070

Table 28. SEL-based criteria ranges to TTS-onset at Site S4 for various UXO charge sizes: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	7650	6950	11100	9850	15600	13600	20600	17400	22500	19000
Mid-frequency cetaceans	170	1580	1350	2400	2160	3760	3420	5710	5040	6540	5810
High-frequency cetaceans	140	12100	10700	14900	13000	18400	15800	22300	18700	23700	20000
Phocid pinnipeds	170	4260	3940	6680	6010	10000	8850	13800	12000	15300	13300
Otariid pinnipeds	188	283	261	782	725	1640	1470	3100	2810	3820	3460
Sea turtles	189	495	480	1290	1190	2480	2340	4320	4030	5220	4870

9. Exceedance Distance Results with 10 dB Mitigation

This section provides exceedance distances assuming 10 dB reduction to the exposure pressures and SEL achieved via mitigation measures (e.g., bubble curtain or similar system).

9.1. Marine Mammals and Sea Turtles TTS and PTS by Peak Pressure Distances with 10 dB mitigation

L_{pk} exceedance distances are not dependent on water depth or seabed properties, so Table 29 is relevant for all sites.

Table 29. Marine mammals and sea turtles PTS and TTS maximum exceedance distances for peak pressure for maximum charge weights for various UXO charge sizes with 10 dB mitigation, relevant for all sites.

Marine mammal group	TTS / PTS threshold (dB re 1 µPa)	Maximum distances (meters) to TTS and PTS thresholds for peak pressure									
		E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
Low-frequency cetaceans	213 / 219	278	142	438	230	750	390	1282	670	1618	846
Mid-frequency cetaceans	224 / 230	82	42	134	70	226	118	390	206	494	258
High-frequency cetaceans	196 / 202	1778	922	2813	1458	4813	2493	8228	4261	10367	5369
Phocid pinnipeds	212 / 218	310	158	490	254	838	438	1430	746	1802	942
Otariid pinnipeds and sea turtles	226 / 232	66	34	106	54	182	98	314	166	398	210

9.2. Marine Mammals and Sea Turtles Gastrointestinal Injury by Peak Pressure Distances with 10 dB mitigation

The threshold exceedances in Table 30 are for Onset Gastrointestinal Injury (effects observed in 1% of exposed animals) and Gastrointestinal Injury (effects observed in 50% of exposed animals).

Table 30. Maximum exceedance distances for Gastrointestinal Injury (1% exposed animals) due to peak pressure exposures for five UXO charge sizes with 10 dB mitigation. The peak pressure threshold formula applied here are from Table 6, Onset Injury – Peak Pressure (Non-auditory). We do not recommend applying these criteria for animals with mass less than 100 kg.

Effect	L_{pk} Threshold (dB re 1 µPa)	All sites: Maximum distance to L_{pk} threshold exceedance (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
Onset Gastrointestinal Injury (1% of exposed animals)	237	21 m	34 m	58 m	99 m	125 m

9.3. Marine Mammals and Sea Turtles Onset of Lung Injury Distances for Impulse with 10 dB mitigation

Impulse thresholds are depth-dependent, so maximum exceedance distances could vary between sites with different depths with 10 dB mitigation. The results for each of the sites evaluated are presented in Table 31 through Table 34.

Table 31. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S1 (12 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 1: 12 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	6	5	17	5	54	16	121	50	151	73
Pilot and Minke whales	10	5	28	8	80	28	158	77	192	103
Beaked whales	17	8	47	22	121	66	210	139	250	171
Dolphins, Kogia, Pinnipeds and Sea Turtles	35	16	86	44	189	115	297	202	347	241
Porpoises	42	19	99	50	210	128	323	219	377	260

Table 32. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S2 (20 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 2: 20 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	6	5	16	5	54	15	147	51	204	80
Pilot and Minke whales	9	5	26	8	83	26	208	83	272	126
Beaked whales	16	7	46	20	131	68	290	176	366	237
Dolphins, Kogia, Pinnipeds and Sea Turtles	32	15	88	42	211	123	404	277	508	351
Porpoises	39	17	102	50	235	139	433	303	541	381

Table 33. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S3 (30 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 3: 30 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	15	5	51	14	153	49	226	81
Pilot and Minke whales	9	5	24	7	83	25	221	84	310	131
Beaked whales	15	7	41	19	135	66	310	186	413	267
Dolphins, Kogia, Pinnipeds and Sea Turtles	29	14	88	38	223	126	441	298	557	400
Porpoises	34	16	103	46	248	144	471	325	594	429

Table 34. Mitigated Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset Injury – Impulse at Site S4 (45 m water depth) for various UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the formula in Table 6, Onset Injury – Impulse (Non-auditory).

Marine mammal group	Site 4: 45 m depth - Maximum distances to Impulse threshold exceedance (meters)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	14	5	45	13	156	44	237	78
Pilot and Minke whales	8	5	22	7	79	23	230	81	330	132
Beaked whales	14	6	37	18	135	59	331	192	448	282
Dolphins, Kogia, Pinnipeds and Sea Turtles	26	13	83	34	231	126	471	315	606	429
Porpoises	29	15	100	39	261	145	512	347	648	465

9.4. Marine Mammals and Sea Turtles Onset of Mortality Distances by Impulse with 10 dB mitigation

The exceedance distances in this section represent the onset of mortality based on the threshold formula in Table 6 and assuming 10 dB of sound level reduction is obtained through a noise mitigation device. These thresholds represent effects observed in 1% of exposed animals.

Impulse levels and thresholds are depth-dependent, so maximum exceedance distances vary between sites with different depths. The results for the four sites evaluated are presented in Table 35 through Table 38.

Table 35. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S1 (12 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 1: 12 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	7	5	23	6	66	21	90	34
Pilot and Minke whales	5	5	11	5	37	11	93	36	120	56
Beaked whales	7	5	19	9	60	29	130	79	161	105
Dolphins, Kogia, Pinnipeds and Sea Turtles	14	6	39	18	101	56	190	124	228	154
Porpoises	17	7	46	21	112	64	209	136	248	167

Table 36. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S2 (20 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion-depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 2: 20 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	6	5	21	6	69	20	105	34
Pilot and Minke whales	5	5	10	5	35	10	103	35	150	58
Beaked whales	6	5	18	8	60	27	151	85	206	127
Dolphins, Kogia, Pinnipeds and Sea Turtles	13	6	37	17	105	56	220	144	285	198
Porpoises	15	7	45	19	119	65	239	158	307	215

Table 37. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S3 (30 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 3: 30 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	6	5	20	6	68	19	109	31
Pilot and Minke whales	5	5	10	5	32	10	106	32	157	57
Beaked whales	6	5	17	8	58	25	160	86	220	132
Dolphins, Kogia, Pinnipeds and Sea Turtles	12	5	31	16	108	54	233	152	308	211
Porpoises	14	6	40	18	122	63	258	168	330	231

Table 38. Impulse exceedance distances (meters) for marine mammals and sea turtles, for Onset of Mortality at Site S4 (45 m water depth) for five UXO charge sizes with 10 dB mitigation. The Impulse thresholds are dependent on animal mass and submersion depth and based on the threshold formula in Table 6, Onset Mortality - Impulse.

Marine mammal group	Site 4: 45 m depth – Impulse threshold exceedance distances for onset mortality (m)									
	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult	Calf/Pup	Adult
Baleen whales and Sperm whale	5	5	6	5	18	5	63	18	108	29
Pilot and Minke whales	5	5	9	5	29	9	105	30	162	50
Beaked whales	6	5	15	7	50	23	164	83	234	135
Dolphins, Kogia, Pinnipeds and Sea Turtles	11	5	26	14	106	44	247	155	332	224
Porpoises	12	6	29	16	122	56	270	173	353	243

9.5. Fish Injury Distances for Peak Pressure with 10 dB mitigation

Table 39. Mitigated exceedance distances for Onset of Injury for fish without and with a swim bladder due to peak pressure exposures, for various UXO charge sizes with 10 dB mitigation. Water depth 50 m. The threshold of 229 dB re 1 µPa is from Popper et al. (2014).

Species	Onset injury L_{pk} (dB re 1 µPa)	All sites: Maximum distance to L_{pk} threshold exceedance (m)				
		E4 (2.3 kg)	E6 (9.1 kg)	E8 (45.5 kg)	E10 (227 kg)	E12 (454 kg)
All fish hearing groups	229	49	80	135	230	290

9.6. Marine Mammals and Sea Turtles: PTS distances by SEL with 10 dB mitigation

The SEL effects thresholds are not dependent on animal depth, but the exposure levels are. The PTS threshold exceedance distances provided in Tables 40 to 43 are maxima over depth.

Table 40. Mitigated SEL-based criteria ranges to PTS-onset at Site S1 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	632	552	1230	982	2010	1720	3080	2660	3640	3220
Mid-frequency cetaceans	185	<50	<50	79	75	175	156	419	337	535	461
High-frequency cetaceans	155	2100	1820	2940	2590	4220	3710	6090	5340	6960	6200
Phocid pinnipeds	185	192	182	413	357	822	690	1410	1220	1830	1600
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	100	98	147	136
Sea turtles	204	<50	<50	<50	<50	166	159	366	348	518	472

Table 41. Mitigated SEL-based criteria ranges to PTS-onset at Site S2 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	450	421	954	850	1990	1730	3370	2970	4270	3780
Mid-frequency cetaceans	185	<50	<50	52	51	120	113	332	280	444	386
High-frequency cetaceans	155	1960	1680	3020	2550	4400	3860	5880	5390	6750	6190
Phocid pinnipeds	185	124	113	294	248	656	590	1340	1140	1630	1430
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	62	61	93	89
Sea turtles	204	<50	<50	<50	<50	140	137	309	293	451	422

Table 42. Mitigated SEL-based criteria ranges to PTS-onset at Site S3 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	405	385	789	753	1660	1580	3040	2870	3900	3610
Mid-frequency cetaceans	185	<50	<50	<50	<50	100	85	349	323	484	412
High-frequency cetaceans	155	1960	1750	2940	2590	4330	3900	6000	5400	6840	6190
Phocid pinnipeds	185	89	89	221	204	566	538	1140	1020	1600	1480
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	57	57	72	72
Sea turtles	204	<50	<50	<50	<50	89	89	242	228	385	369

Table 43. Mitigated SEL-based criteria ranges to PTS-onset at Site S4 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	183	288	269	800	757	1770	1580	3190	2930	3940	3610
Mid-frequency cetaceans	185	<50	<50	<50	<50	85	80	279	261	449	412
High-frequency cetaceans	155	1890	1700	2800	2550	4200	3790	6130	5400	6860	6160
Phocid pinnipeds	185	72	72	152	144	577	468	1100	988	1520	1350
Otariid pinnipeds	203	<50	<50	<50	<50	<50	<50	<50	<50	63	63
Sea turtles	204	<50	<50	<50	<50	63	63	190	189	297	288

9.7. Marine Mammals and Sea Turtles: TTS distances by SEL with 10 dB mitigation

The SEL effects thresholds are not dependent on animal depth, but the exposure levels are. The TTS threshold exceedance distances provided in Tables 44 to 47 are maxima over depth.

Table 44. Mitigated SEL-based criteria ranges to TTS-onset at Site S1 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	3140	2710	4820	4160	7320	6500	10500	9610	12000	11000
Mid-frequency cetaceans	170	535	453	910	773	1520	1240	2400	2120	2820	2550
High-frequency cetaceans	140	6920	6160	8970	8000	11100	10200	14000	12900	15400	14100
Phocid pinnipeds	170	1730	1470	2710	2350	4080	3620	6460	5700	7480	6750
Otariid pinnipeds	188	131	125	254	238	539	472	1070	898	1310	1130
Sea turtles	189	214	203	498	448	1040	865	1720	1440	2020	1710

Table 45. Mitigated SEL-based criteria ranges to TTS-onset at Site S2 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	3110	2820	5230	4680	8160	7490	11500	10500	13200	11900
Mid-frequency cetaceans	170	444	379	781	658	1450	1200	2310	1980	2930	2430
High-frequency cetaceans	140	6700	6140	8630	7960	11200	10300	13700	12600	15000	13800
Phocid pinnipeds	170	1450	1300	2510	2200	4340	3820	6490	5980	7610	6990
Otariid pinnipeds	188	70	68	165	155	392	364	803	721	1110	974
Sea turtles	189	169	165	441	383	985	870	2020	1780	2510	2250

Table 46. Mitigated SEL-based criteria ranges to TTS-onset at Site S3 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	2910	2740	4860	4450	7760	7210	10900	10100	12500	11500
Mid-frequency cetaceans	170	484	410	777	653	1430	1230	2350	2030	2820	2480
High-frequency cetaceans	140	6770	6140	8620	7840	11200	10000	13700	12200	15000	13300
Phocid pinnipeds	170	1300	1210	2430	2180	4150	3810	6410	5840	7580	6900
Otariid pinnipeds	188	63	63	134	128	374	341	777	728	1010	922
Sea turtles	189	171	134	372	358	810	773	1780	1610	2270	2130

Table 47. Mitigated SEL-based criteria ranges to TTS-onset at Site S4 for various UXO charge sizes with 10 dB mitigation: Maximum (R_{max}, m) and 95% ($R_{95\%}$, m) horizontal distances to specific thresholds.

Marine mammal group	Threshold (dB re 1 µPa²s)	E4 (2.3 kg)		E6 (9.1 kg)		E8 (45.5 kg)		E10 (227 kg)		E12 (454 kg)	
		R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$	R_{max}	$R_{95\%}$
Low-frequency cetaceans	168	2890	2630	4860	4400	7820	7130	11700	10300	13500	11800
Mid-frequency cetaceans	170	437	400	800	707	1330	1180	2270	2000	2730	2480
High-frequency cetaceans	140	6720	6030	8650	7790	11300	10100	14600	12600	15600	13700
Phocid pinnipeds	170	1290	1130	2340	2130	4150	3800	6640	5970	7820	7020
Otariid pinnipeds	188	<50	<50	89	89	247	234	768	716	982	888
Sea turtles	189	120	108	286	283	833	796	1680	1590	2130	2000

10. Summary and Guide for Use of Results

This study has produced a large number of result tables containing effects threshold exceedance distances for multiple species or species groups, five charge sizes, and four locations. While the specific sites were chosen inside Orsted's Revolution Wind project area, the model results are expected to be valid for sites inside the Sunrise Wind and Ocean Wind 1 project areas and other sites having the same water depths and seabed properties. The results presented here also assume the full explosive weight of the combined UXO and donor charge are detonated, with a total equivalent-TNT weight matching the values in Table 1. A recent review of UXO detonations in the North Sea has found UXO detonations of charges that have remained underwater for more than 75 years yielded very little explosive energy. More research is needed to determine if older underwater UXO degrade over time to become partly benign, in which case methods such as deflagration may be preferred over explosive removal. Until that question is answered, for conservancy and for personnel safety reasons we recommend assuming their full explosive weights will detonate.

All threshold distances presented here are relevant to address NMFS's assessment requirements for species-dependent effects criteria for assessing injurious or lethal (Level-A) and disturbance or behavioural (Level-B) takes of marine mammals and sea turtles, and for assessing injurious effects on fish. The take criteria are based on three specific acoustic metrics: L_{pk}, J_p, and $L_{E,w}$. The frequency-weighted SEL levels, $L_{E,w}$, are dependent on species group while the impulse levels are dependent on animal mass and submersion depth. All three metrics also have species or animal size dependent thresholds. The SEL and impulse levels vary with water depth or location. Five charge sizes are considered at four separate modeling sites with different depths. The consideration of these many results for estimating marine mammal and sea turtle takes, and fish effects zones is clearly not straightforward. To assist in that assessment, a summary of the Level-A and Level-B take context for each assessment metric is provided here, together with cross-references to the tables that contain the relevant exceedance distance information for each type of take. Examples of the maximum exceedance distance, resulting from the largest UXO charge weight, on the most-sensitive species group are provided here but the user will need to review the referenced exceedance distance tables to look up the relevant distances for other species groups and charge sizes. We expect the peak pressure based gastrointestinal tract injury distances and impulse based onset of lung injury and onset of mortality distances will be used primarily for setting mitigation zone requirements, but these distances could be used for Level A take estimates if animals could not be excluded from the respective zones.

10.1. Unmitigated Take Distances

10.1.1. Unmitigated Level-A Takes

The tables of threshold exceedance distances from UXO detonations relevant for Level-A (injurious) effects to marine mammals and sea turtles are:

- L_{pk}: Table 10 contains PTS (auditory injury) exceedance distances valid for all sites. The greatest PTS distance is 16,098 m from the 454 kg charge, for high-frequency cetaceans.
- L_{pk}: Table 11 contains mitigated onset of gastrointestinal injury (1% of exposed animals) exceedance distances valid for all sites and species. The greatest onset of effects distance is 359 m from the 454 kg charge. We note that the gastrointestinal injury distances for small animals using the L_{pk} criterion can be smaller than those for onset of mortality using the J_p criterion (next bullet). That occurs because the L_{pk} criterion originates from studies on mid-sized terrestrial animals and adult humans. We recommend against using this criterion for animals smaller than approximately 100 kg.
- J_p: Tables 12 to 15 contain onset of lung injury (1% of animals) distances for Sites S1 to S4, respectively. Note for each species group there are separate distances for small (calves/pups) and adult animals representative of the group. Smaller animals in each group have lower

thresholds, leading to larger exceedance distances. The deeper sites often, but not always, have larger exceedance distances than shallower sites. The unusual dependence of exceedance distances on site depth and charge size is discussed in Section 8.6. The greatest distance for onset of lung injury is 1518 m from the unmitigated 454 kg charge at site S4 for porpoise calves.

- SEL (species-group frequency-weighted): Tables 21 to 24 contain PTS threshold exceedance distances at Sites S1 to S4, respectively. These tables contain R_{max} and $R_{95\%}$ distances, and we recommend using the $R_{95\%}$ distances because R_{max} is often influenced by an artefact of the type of models used, as discussed in Section 8.6. The greatest distance is 11,300 m for high-frequency cetaceans at Site S1.
- SEL and peak pressure auditory injury distances are always larger than the impulse non-auditory injury exceedance distances, so the impulse threshold exceedance distances will not dictate Level-A takes. Nevertheless, they are important and relevant for assessments of non-auditory injuries.

10.1.2. Unmitigated Level-B Takes

The tables relevant for Level-B (disturbance or behavioral effects) takes are:

- L_{pk}: Table 10 contains TTS (temporary effect not considered injurious) exceedance distances valid for all sites. The greatest TTS distance is 31,202 m from the 454 kg charge, for high-frequency cetaceans.
- SEL (species-group weighted): Tables 25 to 28 contain TTS threshold exceedance distances at Sites S1 to S4, respectively. We recommend using the $R_{95\%}$ distances as discussed in this report. The greatest distance is 20,200 m for high-frequency cetaceans at Sites S1, S2 and S3.
- Note: NMFS uses TTS onset as the threshold for Level-B takes by SEL for single detonations in a 24-hour period. NMFS applies a different threshold (TTS minus 5 dB) for multiple detonations in day, but its application is more difficult because it requires considering if animals receive SEL doses from more than one of the detonations. TTS zones for multiple blasts in a single day were not assessed.

10.1.3. Unmitigated Effects on Fish

- L_{pk}: Table 20 provides onset of injury distances relevant for all fish groups. The unmitigated distances for mortality or injury likely to lead to mortality range from 145 m from the 2.3 kg charge to 847 m from the 454 kg charge. These distances are relevant for all sites.
- A quantitative assessment of non-mortal effects to fish has not been included, but the guidelines of Popper et al. (2014) provide qualitative assessment information. This is discussed in Sections 6.4 and 6.5.

10.2. Mitigated Take Distances (10 dB Reduction)

Reduced effects threshold distances were calculated with a flat 10 dB reduction of pressure to all metrics, as an approximation of noise abatement that could be achieved, for example, using a bubble curtain. The mitigated results tables are provided in Section 9 and discussed here.

10.2.1. Mitigated Level-A Takes

The tables of threshold exceedance distances relevant for Level A (injurious) effects to marine mammals and sea turtles are:

- L_{pk}: Table 29 contains mitigated PTS (auditory injury) exceedance distances valid for all sites. The greatest PTS distance is 5,369 m from the 454 kg charge, for high-frequency cetaceans. The mitigated PTS distances from peak pressure for all other species groups are less than 1,000 m.
- L_{pk}: Table 30 contains mitigated onset of gastrointestinal injury (1% of exposed animals) exceedance distances valid for all sites and species. The greatest onset of effects distance is 125 m from the 454 kg charge. We note that the gastrointestinal injury distances for small animals using the L_{pk} criterion can be smaller than those for onset of mortality using the J_p criterion (next bullet). That occurs because the L_{pk} criterion originates from studies on mid-sized terrestrial animals and adult humans. We recommend against using this criterion for animals smaller than approximately 100 kg.
- J_p: Tables 31 to 34 contain onset of lung injury (1% of animals) exceedance distances for Sites S1 to S4, respectively. The greatest distance for onset of lung injury is 648 m from the 454 kg charge at Site S4, for porpoise calves.
- SEL (species-group weighted): Tables 40 to 43 contain PTS threshold exceedance distances at Sites S1 to S4, respectively. The greatest $R_{95\%}$ distance is 6,200 m for high-frequency cetaceans at Site 1.

10.2.2. Mitigated Level-B Takes

The tables relevant for mitigated Level-B (disturbance or behavioral effects) takes of marine mammals and sea turtles are:

- Peak pressure: Table 29 contains TTS (temporary effect not considered injurious) exceedance distances valid for all sites. The greatest TTS distance is 10,367 m from the 454 kg charge, for high-frequency cetaceans.
- SEL (species-group weighted): Tables 44 to 47 contain TTS threshold exceedance distances at Sites S1 to S4, respectively. The greatest $R_{95\%}$ distance is 14,100 m for high-frequency cetaceans at Site S1.

10.2.3. Mitigated Effects on Fish

- Peak pressure: Table 39 provides mitigated onset of injury for all fish groups. The unmitigated distances range from 49 m from the 2.3 kg charge to 290 m from the 454 kg charge. These values are relevant for all sites.
- A quantitative assessment of non-mortal effects to fish has not been included, as discussed in Section 6.4 and 6.5. Those sections provide a qualitative assessment approach.

Literature Cited

Arons, A.B. and D.R. Yennie. 1948. Energy Partition in Underwater Explosion Phenomena. *Reviews of Modern Physics* 20(3): 519-536.

Bellmann M. A., Brinkmann J., May A., Wendt T., Gerlach S. & Remmers P. (2020) Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Supported by the *Federal Ministry for the Environment, Nature Conservation and Nuclear Safety* (*Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit* (BMU)), FKZ UM16 881500. Commissioned and managed by the *Federal Maritime and Hydrographic Agency* (*Bundesamt für Seeschifffahrt und Hydrographie* (BSH)), Order No. 10036866. Edited by the *itap GmbH*.

Bellman M. A., Expert opinion report regarding underwater noise emissions during UXO-clearance activity and possible options for noise mitigation. Report by Institut für Technische und angewandte Physik (ITAP) GmbH, for Orsted Wind Power A/S. Report number 3960, June 2021.

Buckingham, M.J. 2005. Compressional and shear wave properties of marine sediments: Comparisons between theory and data. *Journal of the Acoustical Society of America* 117: 137-152. https://doi.org/10.1121/1.1810231.

Chapman, N.R. 1985. Measurements of the waveform parameters of shallow explosive charges. *Journal of the Acoustical Society of America* 78: 672-681.

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

Denes, S.L., D.G. Zeddies, and M.J. Weirathmueller. 2018. *Turbine Foundation and Cable Installation at South Fork Wind Farm: Underwater Acoustic Modeling of Construction Noise*. Document Number 01584, Version 3.0. Technical report by JASCO Applied Sciences for Jacobs Engineering Group Inc.

Department of the Navy (Navy). 2017. *Request for Regulations and Letters of Authorization for the Incidental Taking of Marine Mammals Resulting from U.S. Navy Training and Testing Activities in the Atlantic Fleet Training and Testing Study Area.* Prepared for U.S. Department of Commerce, National Marine Fisheries Service, Office of Protected Resources by U.S Department of the Navy, Commander U.S. Fleet Forces Command. 15 June 2017, Updated 4 August 2017. 560 p.

Finneran J.J., Auditory Weighting Functions and TTS/PTS Exposure Functions for marine Mammals Exposed to Underwater Noise, Technical Report 3026 for SSC Pacific, December 2016.

Gaspin, J.B. 1983. *Safe swimmer ranges from bottom explosions*. Document Number NSWC/WOL TR-83-84. Naval Surface Weapons Center, White Oak Lab, and Defence Technical Information Center, Silver Spring, MD, USA. 51 p.

Goertner, J.F. 1982. *Prediction of Underwater Explosion Safe Ranges for Sea Mammals*. Dahlgren, VA: Naval Surface Weapons Center.

[ISO] International Organization for Standardization. 2017. ISO/DIS 18405:2017. *Underwater acoustics – Terminology*. Prepared by Technical Committee ISO/TC 43, Acoustics, Subcommittee SC 3, Underwater Acoustics.

[NAVO] Naval Oceanography Office (US). 2003. *Database description for the Generalized Digital Environmental Model (GDEM-V) (U).* Document Number MS 39522-5003. Oceanographic Data Bases Division, Stennis Space Center.

NMFS. 2018. Marine Mammal Acoustic Technical Guidance (2018 Revision to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing, Office of Protected Resources, NOAA Technical Memorandum NMFS-OPR-59, April 2018.

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.

Rogers, P.H. 1977. Weak-shock solution for underwater explosive shock waves. *Journal of the Acoustical Society of America* 62(6): 1412-1419.

Schmidtke, E., B. Nutzel, and S. Ludwig. 2009. Risk Mitigation for sea mammals – The use of air bubbles against shock waves. Proceedings of the International Conference on Acoustics NAG/DAGA, Rotterdam, March 2009.

Urick, R.J. 1971. Handy curves for finding the source level of an explosive charge fired at a depth in the sea. *Journal of the Acoustical Society of America* 49: 935-936.

Urick, R.J. 1983. *Principles of Underwater Sound*, 3rd ed. McGraw-Hill, New York.

Wakeley Jr., J. 1977. Pressure-signature model for an underwater explosive charge. *US Navy Journal of Underwater Acozxustics* 27(2): 445-449.

US Navy, Criteria and Thresholds for U.S. Navy Acoustic and Explosive Effects Analysis (Phase III), June 2017

Yelverton, J.T., D.A. Richmond, E.R. Fletcher, and R.K. Jones. 1973. *Safe distances from underwater explosions for mammals and birds.* Document Number AD-766 952. Report by Lovelace Foundation for Medical Education and Research for Defense Nuclear Agency. Distributed by National Technical Information Service, US Department of Commerce. 64 p.

Appendix A. PTS and TTS Exceedance Zone Maps (Unmitigated)

This appendix presents PTS and TTS exceedance zone maps for various marine mammal hearing groups and sea turtles for 2.3 and 454 kg charges (minimum and maximum charge weights modeled) at each of the four sites.

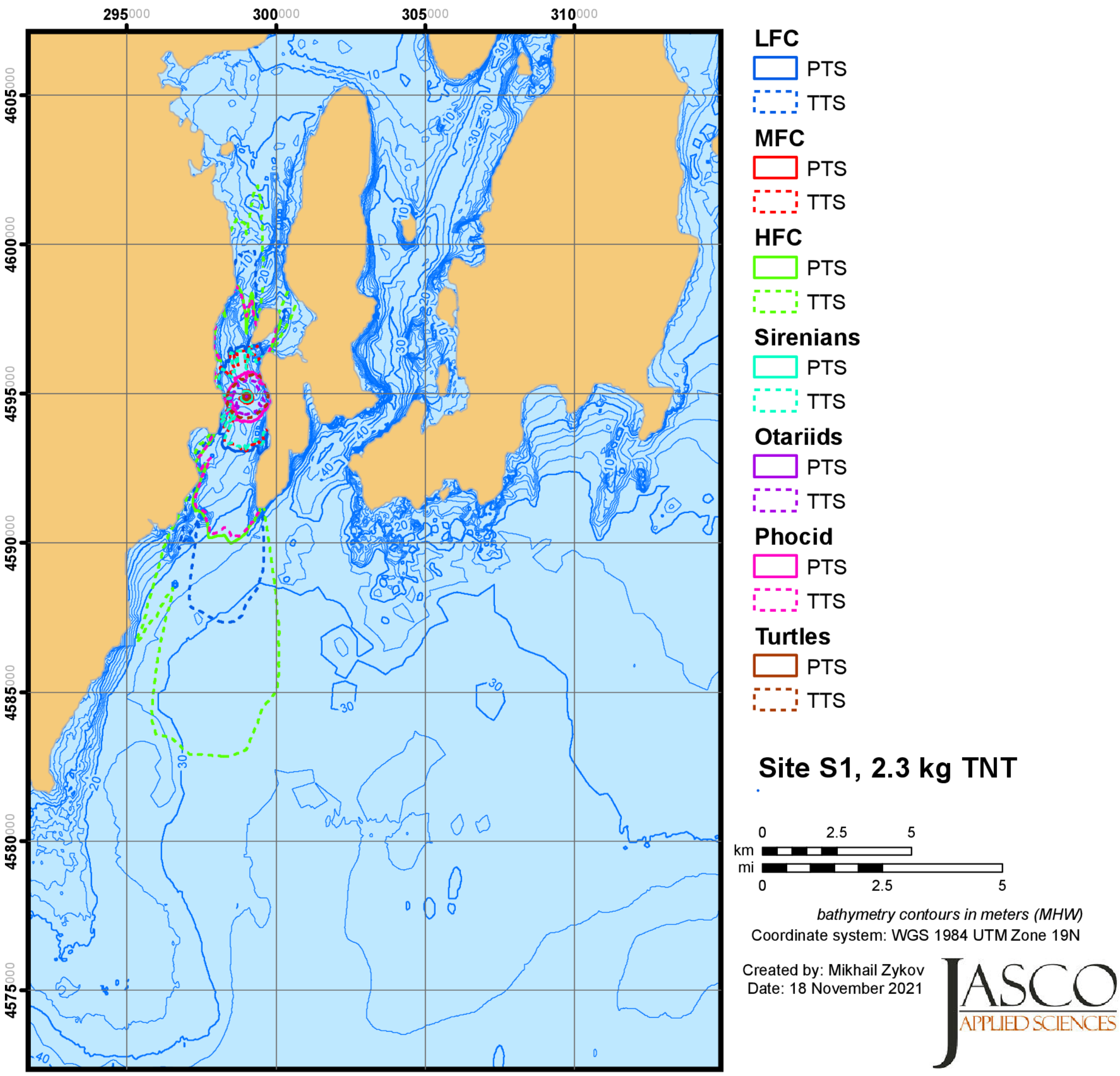

Figure A-1. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S1.

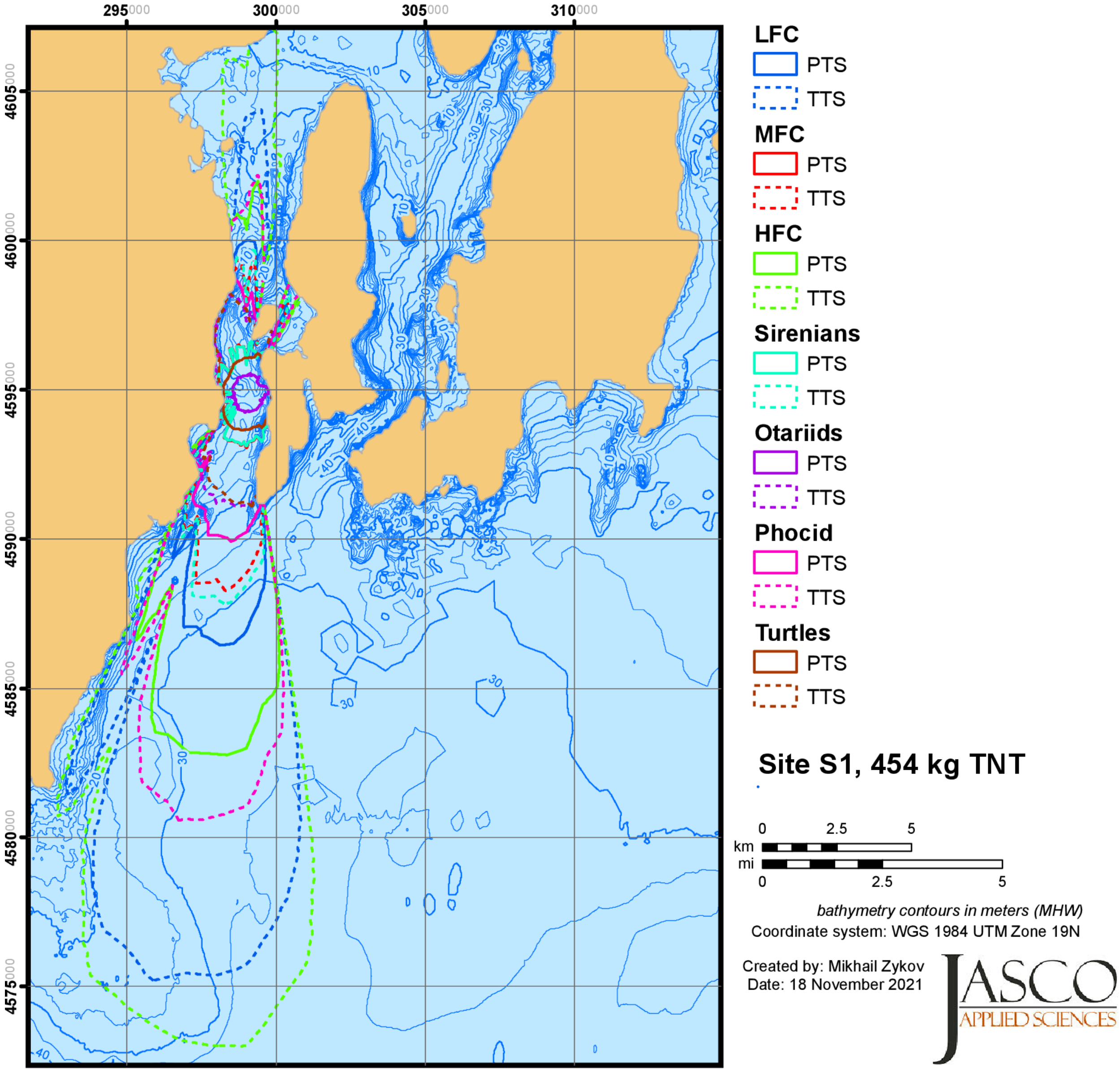

Figure A-2. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S1.

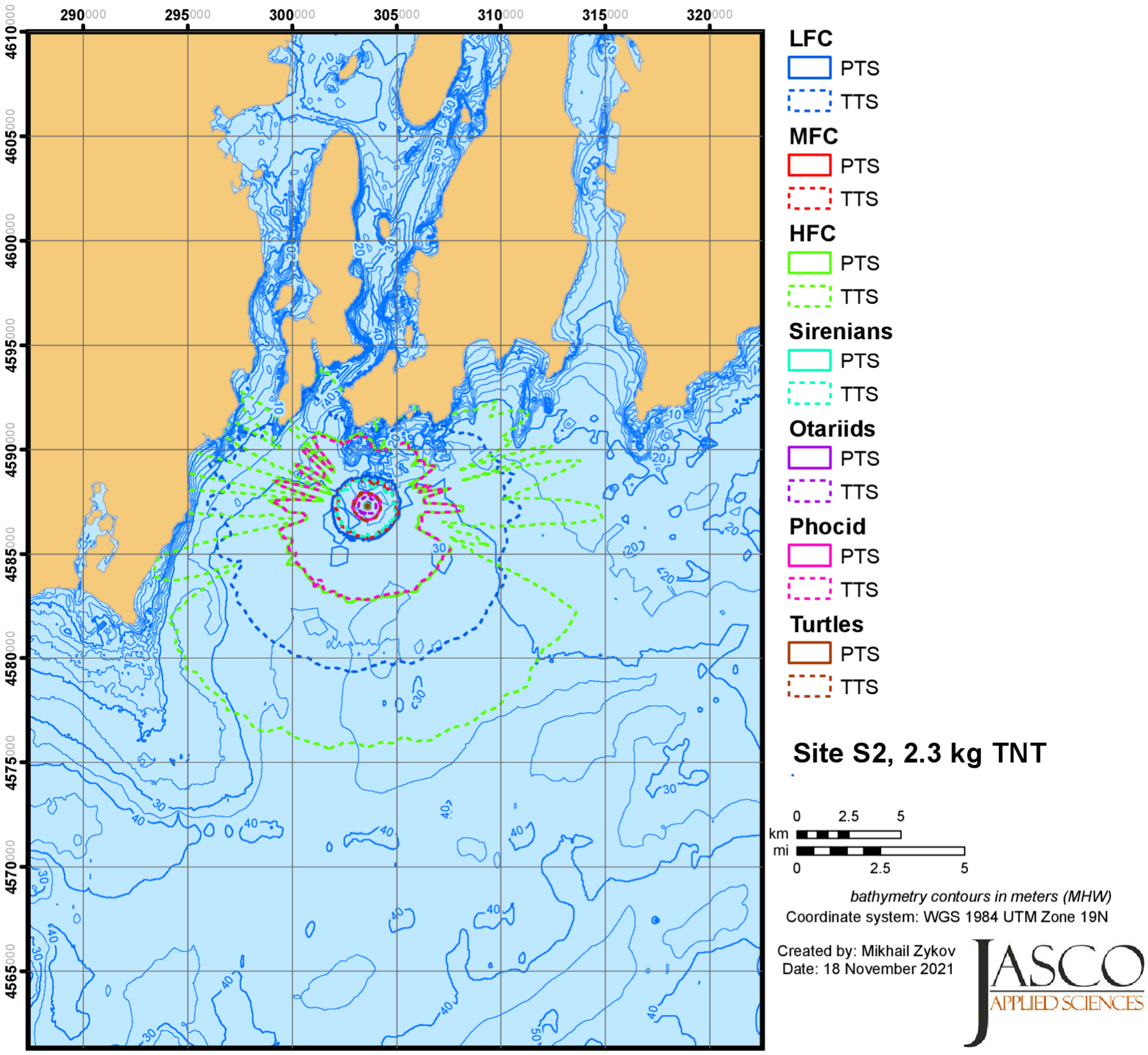

Figure A-3. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S2.

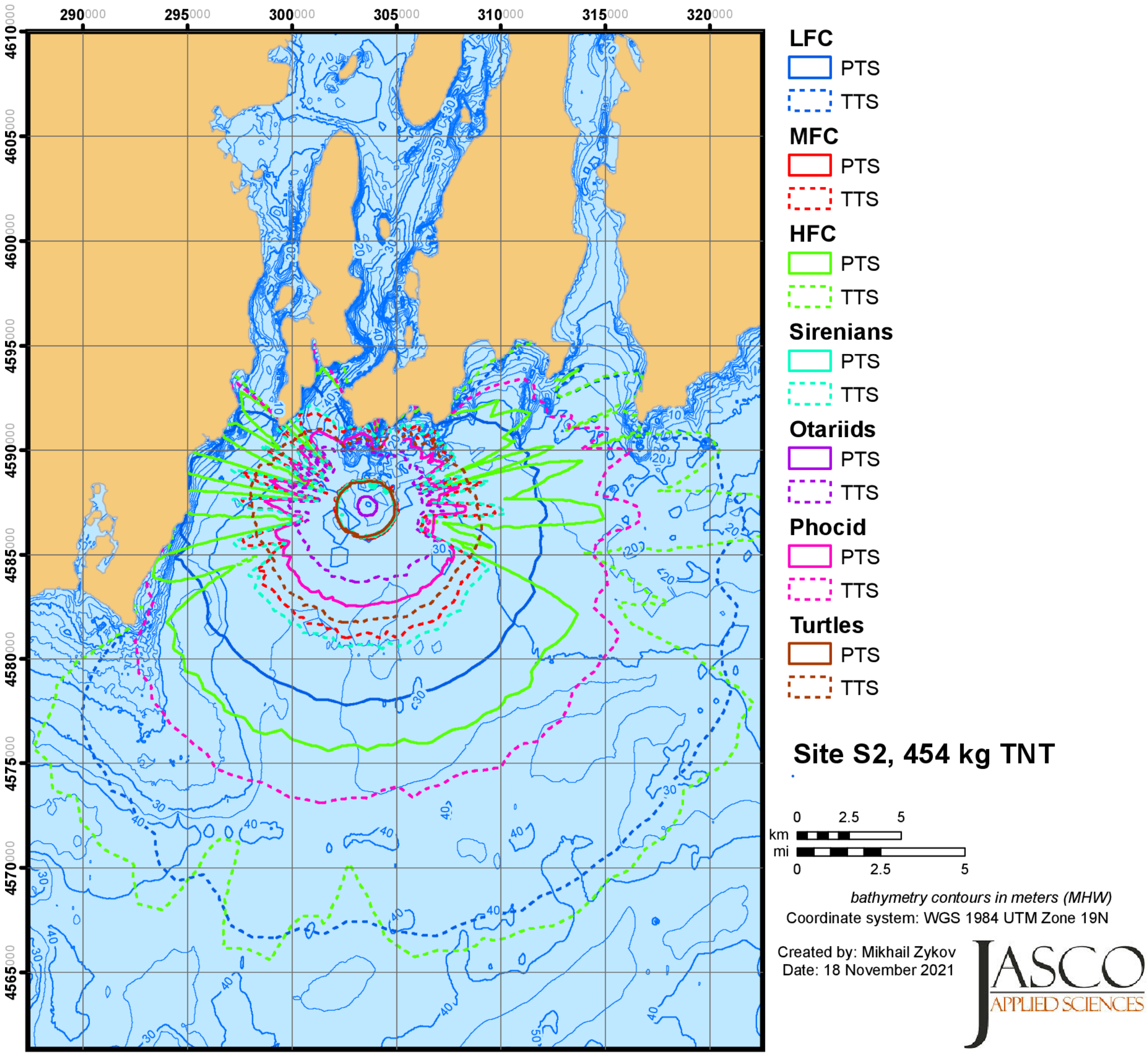

Figure A-4. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S2.

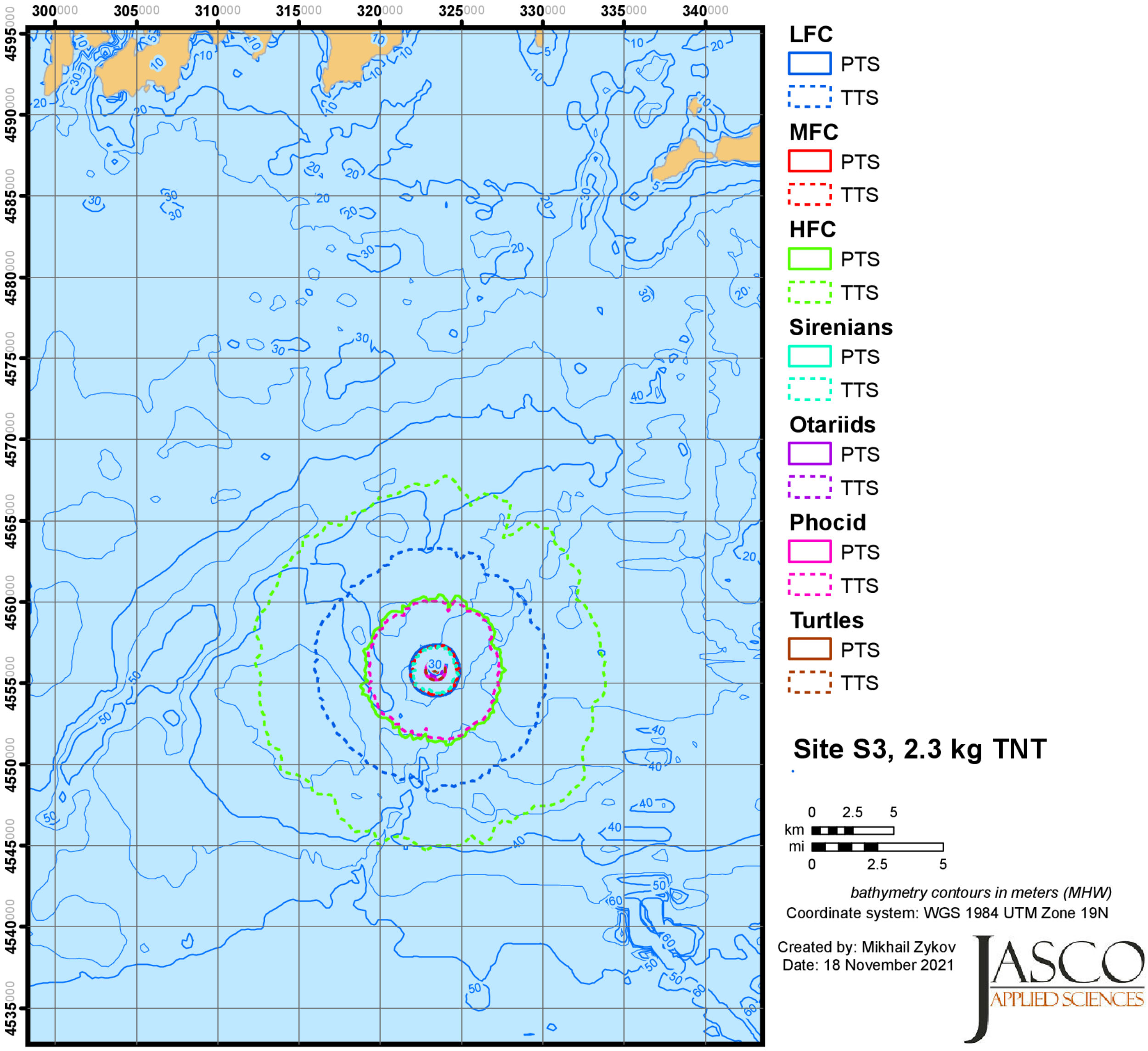

Figure A-5. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S3.

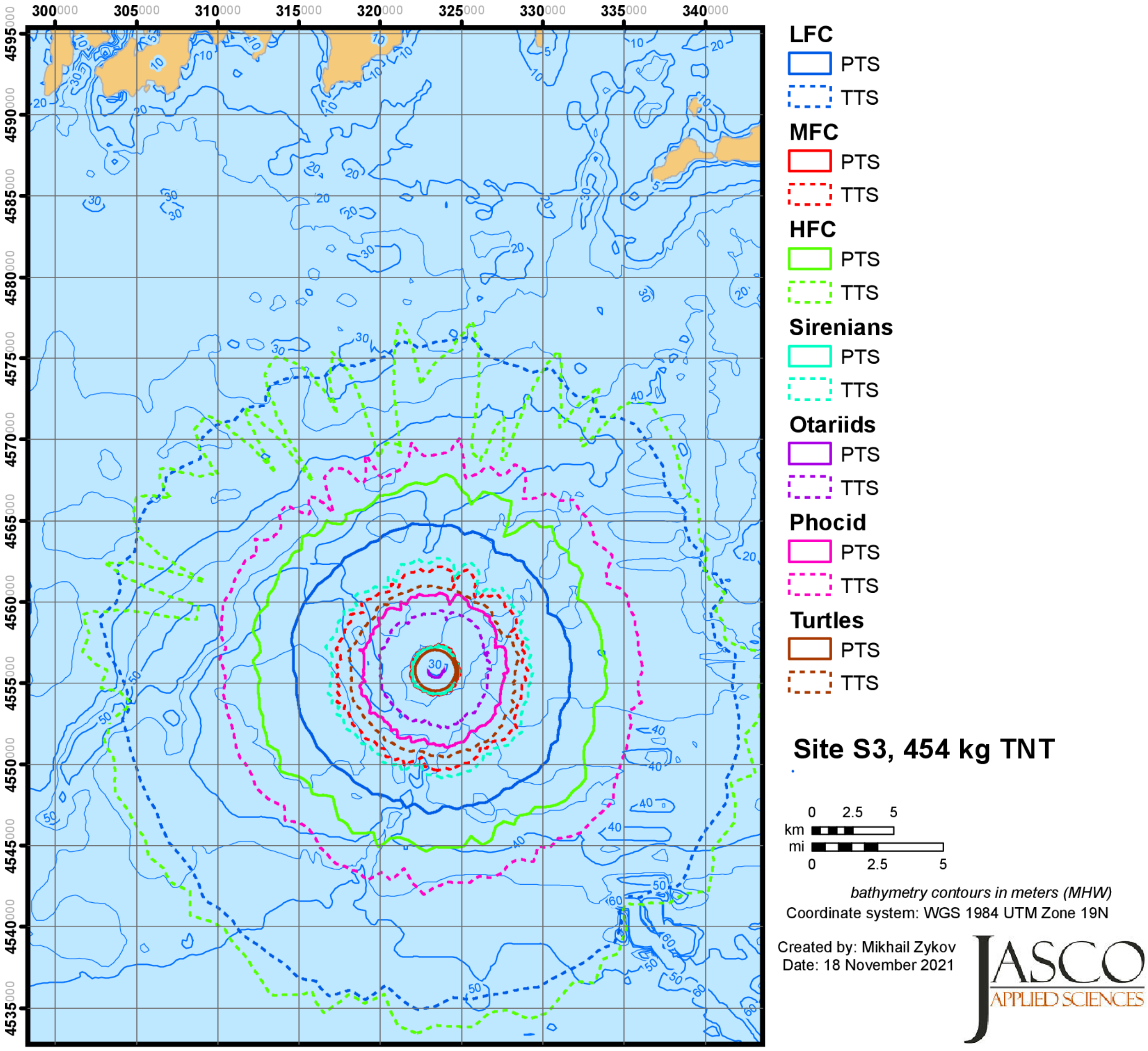

Figure A-6. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S3.

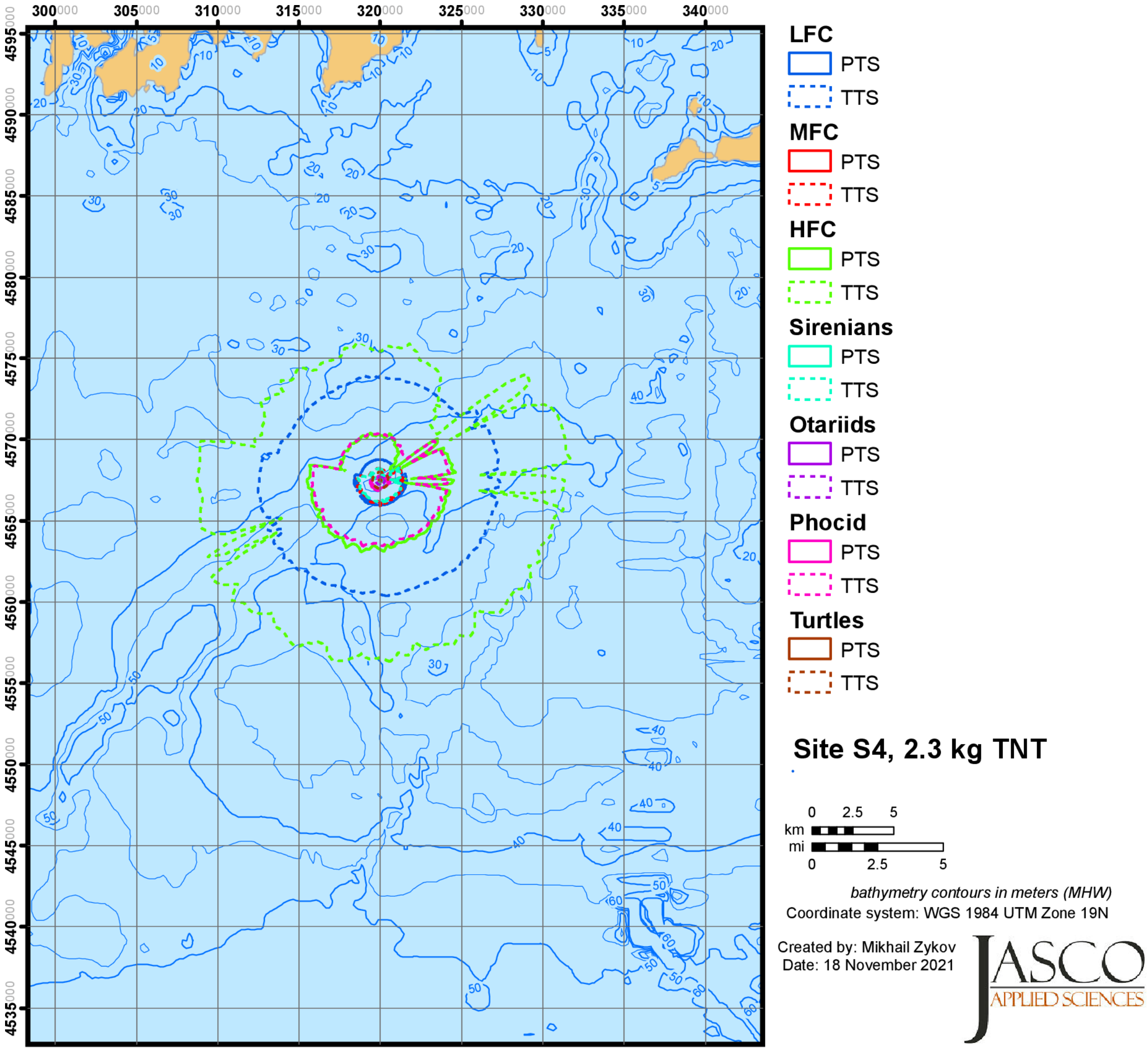

Figure A-7. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 2.3 kg charge size at Site S4.

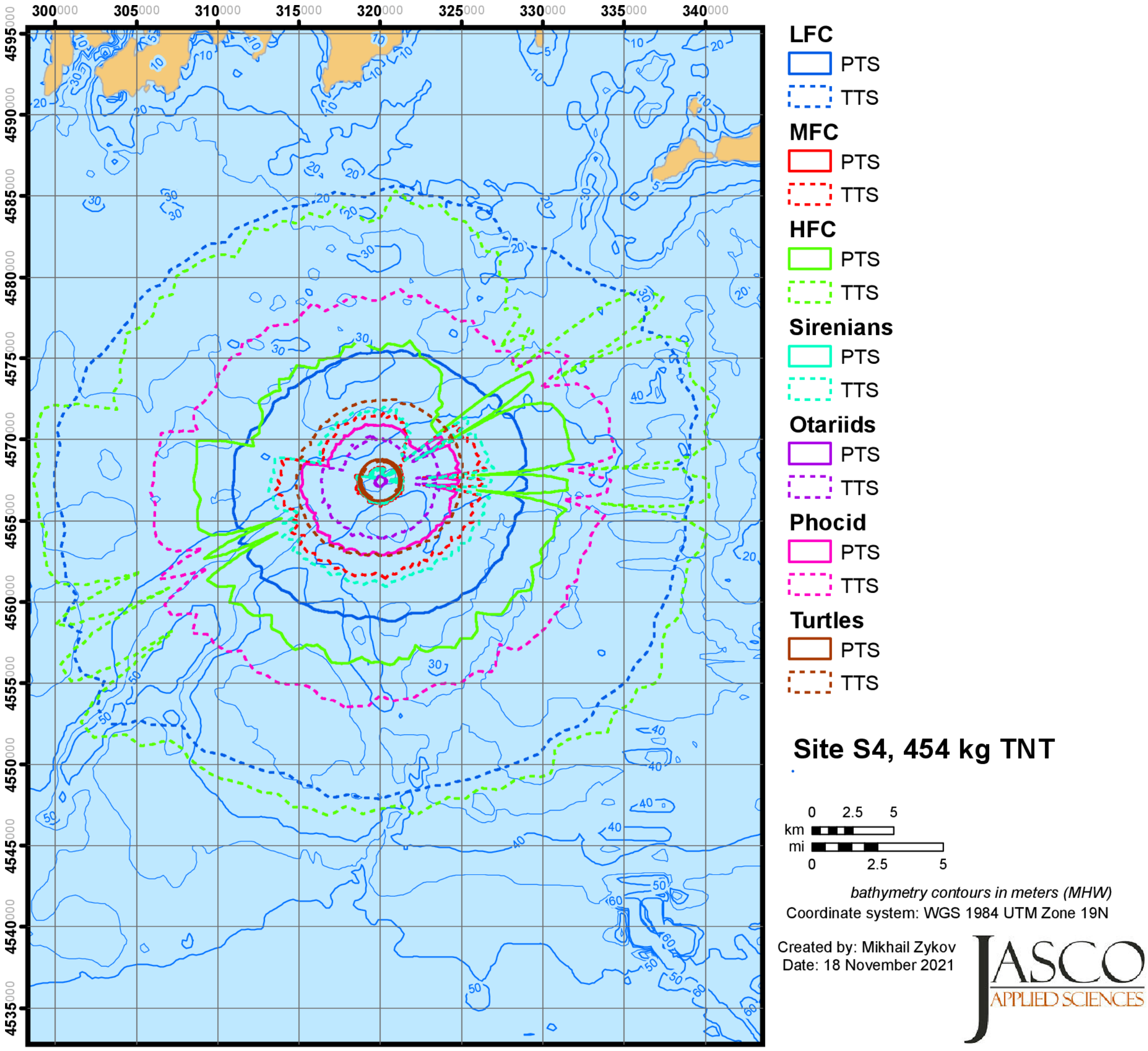

Figure A-8. Map of frequency-weighted SEL PTS and TTS exceedance zone for each species group for the 454 kg charge size at Site S4.