Cumulative and Chronic Effects in the Gulf of Mexico

Estimating Reduction of Listening Area and Communication Space due to Seismic Activities in Support of the BOEM Geological and Geophysical Activities Draft Programmatic Environmental Impact Statement

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Executive Summary

This report presents a chronic and cumulative effects assessment of noise exposures caused by oil and gas exploration activities in the United States (U.S.)–managed areas of the Gulf of Mexico by assessing changes in listening area, applicable to all marine mammal species, and communication space for Bryde's whale (*Balaenoptera edeni*). This assessment considers four levels of activity, which correspond to the alternatives defined in Chapter 2 of the Gulf of Mexico Geological and Geophysical Activities Draft Programmatic Environmental Impact Statement (G&G EIS) (NOAA 2016).

The two relatively new methods of assessing changes in listening area and communication space are explained in detail in Sections 2.5 and 2.6 of this report. The change in listening area method follows an approach applied to an effects assessment for in-air sounds to birds (Barber et al. 2009), but it had not previously been applied to underwater noise and marine fauna. To our knowledge, this study, and a related assessment of chronic and cumulative effects of noise in arctic waters, are the first applications of the listening area method to underwater sounds. The communication space assessment implemented the methods previously used for assessing anthropogenic noise effects on blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales by Clark et al. (2009).

The term "listening area" refers to the region of ocean over which sources of sound can be detected by an animal at the center of a space. Sound sources considered by this method can be the same species (such as calls from conspecifics), a different species (such as a predator or prey species), natural sounds (such as breaking surface waves), and anthropogenic sounds. The change in listening area method applied by Barber et al. (2009) calculates a fractional reduction in listening area due to an addition of anthropogenic noise to the environment. It does not provide absolute areas or volumes as does the communication space method; however, a benefit of the change in listening area method is that it does not require the signal source levels. The method only depends on the rate of sound transmission loss. Changes in listening space can be related to the effects of anthropogenic noise on marine fauna.

This communication space assessment considers the region within the ocean surrounding a calling Bryde's whale, in which other Bryde's whales can detect its calls. The relationship between communication space and the well-being of Bryde's whales is presently unknown, but it is reasonable to assume that Bryde's communications serve an important purpose, as it does in other marine mammals, (e.g., attracting mates, identifying and tracking offspring, and maintaining group structure) that could affect an individual's and possibly a population's health. Bryde's whale communication space is limited by the masking of their calls due to natural ambient sounds and/or anthropogenic noise. Communication space is larger for louder calls. Adding ambient and especially anthropogenic noise to the environment surrounding the Bryde's whales leads to a decrease in communication space. Hence, the possible effects of anthropogenic noise on Bryde's whales can be inferred by examining the reduction in communication space.

1. Introduction

This study evaluates potential chronic and cumulative effects to marine mammals from noise exposures caused by oil and gas exploration activities in the Gulf of Mexico in support of the Bureau of Ocean Energy Management (BOEM) Geological and Geophysical Activities Draft Programmatic Environmental Impact Statement (G&G EIS). In this assessment, the methods for calculating a change in listening area by Barber et al. (2009) and communication space by Clark et al. (2009) were applied. Both of these methods require knowledge of ambient and anthropogenic noise levels at receiver positions. JASCO developed a framework to calculate cumulative sound exposure levels (SEL) produced by large numbers of geographically distributed acoustic sources, such as the seismic pulses from multiple seismic surveys using airgun arrays. SELs were calculated for several scenarios for one full year of exploration activities in the Gulf at ten receiver sites (Table 1 and Figure 1). The framework was implemented using scripted Excel spreadsheets, which incorporated acoustic transmission loss tables from sound propagation modeling of an 8000 in^3 airgun array and single 90 in^3 airgun. The same source types (Table 2) were considered in a previous modeling assessment of marine mammal exposures (G&G EIS, Appendix D; NOAA 2016).

BOEM divided the study area into three project management zones (Western, Central, and Eastern Gulf–grey areas, Figure 1). For the purpose of this assessment, we subdivided these zones into six activity zones based on the water depth. The 200 m isobaths was chosen as the divider of coastal and offshore areas.

Table 1. Modeled receiver site locations and water depths.

Site	Receiver Site	Latitude	Longitude	Water Depth (m)
1	Western Gulf	27.01606	−95.7405	842
2	Florida Escarpment	25.95807	−84.6956	693
3	Midwestern Gulf	27.43300	−92.1200	830
4	Sperm Whale Site	24.34771	−83.7727	1053
5	Deep Offshore	27.64026	−87.0285	3050
6	Mississippi Canyon	28.15455	−89.3971	1106
7	Bryde's Whale Site	28.74043	−85.7302	212
8	De Soto Canyon	29.14145	−87.1762	919
9	Flower Garden Banks National Marine Sanctuary	27.86713	−93.8259	88
10	Bottlenose Dolphin Site	29.40526	−93.3247	12

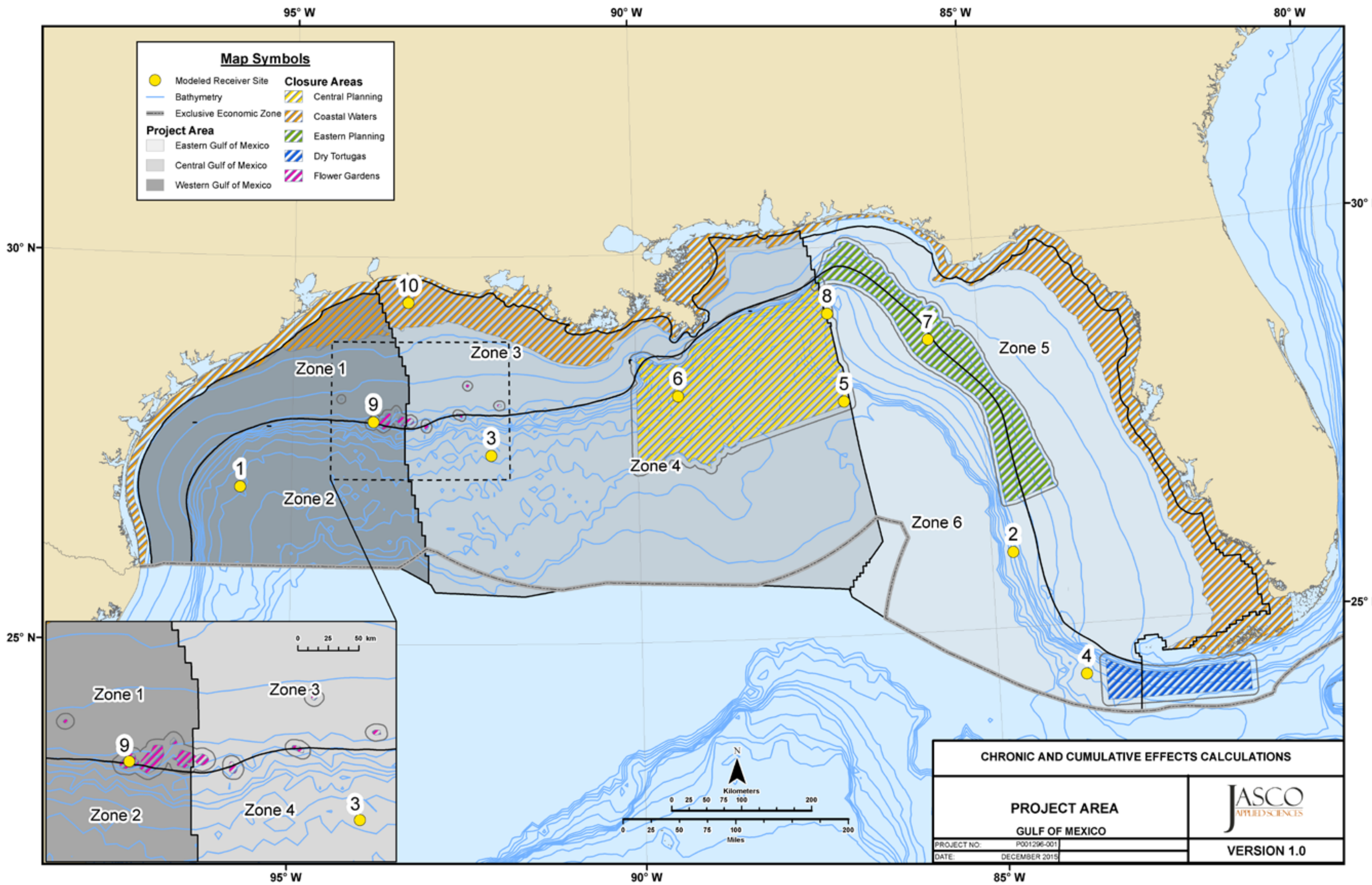

Figure 1. G&G EIS project area with ten modeled receiver sites (yellow dots), project management zones (grey shaded areas), activity zones (1–6), and closure areas (hashed arears). The inset shows a zoom into the Flower Gardens closure area.

Table 2. Survey types and sources used to represent the modeled activities.

Survey Type	Representative Airgun Array	Pulse Spacing (m)
2-D seismic	1 × 8000 in³	50
3-D NAZ seismic	2 × 8000 in³	37.5
3-D WAZ seismic	4 × 8000 in³	37.5
3-D Coil seismic	4 × 8000 in³	50
Geotechnical	1 × 90 in³ (single airgun)	0.7*

* Assumes 3 pulses per second and a tow speed of 4 knots, which is a surrogate for boomer-type sources.

Chapter 2 of G&G EIS (NOAA 2016) describes a number of alternatives that represent different survey activity levels in the Gulf of Mexico. For this analysis, Alternatives, C, E, and F were chosen to represent a range of activity levels; the content of each of these alternatives is summarized in Table 3. For the purpose of this assessment Alternative F was split into two sub-alternatives, F1 and F2. The later reflects the addition of closure areas (as for F1) and a 25% reduction of the activity level in all activity zones (as for E). Additionally, calculations of change in listening area and communication space require baseline noise levels for reference. We refer to this condition as Alternative A. It is defined by commercial shipping noise and noise from natural sounds produced mainly by wind and breaking waves. It therefore does not include seismic survey activity.

Table 3. Description of survey activity levels for G&G EIS Alternatives.

G&G EIS Alternatives	Description
A	No seismic survey activities. Noise consists of natural sounds and commercial vessel noise.
C	All activities uniformly distributed throughout the project area, over 12 months, except for coastal water closures (Figure 1) beginning of February to end of May.
E	Same as Alternative C, with a 25% reduction of the activity level in all activity zones.
F1	Same as Alternative C, with the addition of closure areas (Flower Gardens, Central Planning, De Soto, and Dry Tortugas closure areas; Figure 1) and 25% of the activity that would have occurred in the closure areas redistributed in non-closure areas of the same activity zone.
F2	Same as Alternative F1, with a 25% reduction of the activity levels in all activity zones.

In addition to the survey and source types (Table 2), BOEM provided the anticipated annual (2017–2026) survey lengths (km) for each type of activity and project management zone. The survey lengths were annually averaged for each type of activity, in each activity zone, and for all alternatives (Table 4). These lengths were used to calculate the survey distributions across the study area.

Table 4. Survey lengths (km) associated with each alternative for each activity zone. A dash means no survey of this type is expected within the activity zone.

Activity Zone	Alternative C					Alternative E				
	2-D	3-D NAZ	3-D WAZ	3-D Coil	Geotechnical	2-D	3-D NAZ	3-D WAZ	3-D Coil	Geotechnical
1	-	5,391	-	-	154	-	4,043	-	-	116
2	-	25,698	9,995	4,284	237	-	19,274	7,496	3,213	178
3	-	53,921	7,695	3,297	3,176	-	40,441	5,771	2,473	2,382
4	12,038	112,190	-	28,031	12,149	9,029	84,143	-	21,023	9,112
5	-	-	-	-	505	-	-	-	-	379
6	10,001	23,706	7,260	3,111	2,528	7,501	17,780	5,445	2,333	1,896
Activity Zone	Alternative F1					Alternative F2				
	2-D	3-D NAZ	3-D WAZ	3-D Coil	Geotechnical	2-D	3-D NAZ	3-D WAZ	3-D Coil	Geotechnical
1	-	5,344	-	-	150	-	4,008	-	-	113
2	-	25,663	9,981	4,278	236	-	19,247	7,486	3,209	177
3	-	53,719	7,666	3,285	3,134	-	40,289	5,750	2,463	2,351
4	9,191	85,659	-	21,402	9,256	6,893	64,244	-	16,052	6,942
5	-	-	-	-	444	-	-	-	-	333
6	8,982	21,290	6,520	2,794	2,186	6,736	15,968	4,890	2,095	1,639

1.1. Acoustic Metrics

Underwater sound pressure amplitude is commonly measured in decibels (dB) relative to a fixed reference pressure of p_o = 1 μPa. Because the loudness and other exposure effects of impulsive (pulsed) noise, e.g., shots from seismic airguns, are not generally proportional to the instantaneous acoustic pressure, several sound level metrics are commonly used to evaluate impulsive sound effects on marine life.

1.1.1. Root-Mean-Square Sound Pressure Level

The root-mean square (rms) SPL (L_p, dB re 1 μPa) is the rms pressure level in a stated frequency band over a time window (T, s) containing the pulse:

$$L_p = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_o^2\right) \quad (1)$$

The rms SPL can be thought of as a measure related to the average sound intensity or as the effective pressure intensity over the duration of an acoustic event, such as the emission of one acoustic pulse. Because the time window length, T, is a divisor, pulses having the same total acoustic energy, but more spread out in time, will have a lower rms SPL. The value of T for the purpose of the rms SPL calculation can be selected using different approaches. According to one, T is defined as the 90% energy pulse duration, containing the central 90% (from 5% to 95% of the total) of the cumulative square pressure (or sound exposure level) of the pulse, rather than over a fixed time window (Malme et al. 1986, Greene 1997, McCauley et al. 1998). The 90% rms SPL (L_{p90}, dB re 1 μPa) in a stated frequency band is calculated over this 90% energy time window, T_{90}:

$$L_{p90} = 10\log_{10}\left(\frac{1}{T_{90}}\int_{T_{90}} p^2(t)dt \Big/ p_o^2\right) \tag{2}$$

The other approach for rms SPL calculation of a pulse is to use fixed time window. In this study, a sliding window was used to calculate rms SPL values for a series of fixed window lengths within the pulse. The maximum value of rms SPL over all time window positions is taken to represent the rms SPL of the pulse.

1.1.2. Sound Exposure Level

The sound exposure level (SEL) (L_E, dB re 1 µPa^2·s) is the time integral of the squared pressure in a stated frequency band over a stated time interval or event. The per-pulse SEL is calculated over the time window containing the entire pulse (i.e., 100% of the acoustic energy), T_{100}:

$$L_E = 10\log_{10}\left(\int_{T_{100}} p^2(t)dt \Big/ T_o p_o^2\right) \tag{3}$$

where T_o is a reference time interval of 1 s by convention. The per-pulse SEL, with units of dB re 1 µPa·√s, or equivalently dB re 1 µPa^2·s, is related, at least numerically, to the total acoustic energy flux density delivered over the duration of the acoustic event at a receiver location. SEL, unlike energy flux density, neglects the acoustic impedance of the medium (here water), which depends on density,sound speed, and on proximity to reflective surfaces and position within refractive environments. SEL is a measure of sound exposure through time rather than just sound pressure.

SEL is a cumulative metric; it can be accumulated over a single pulse, or calculated over periods containing multiple pulses. To accumulate multiple pulse cumulative SEL (L_{Ec}), the single pulse SELs are summed. If there are N such pulses having individual SELs of (L_{Ei}), then:

$$L_{Ec} = 10\log_{10}\left(\sum_{i=1}^{N} 10^{\frac{L_{Ei}}{10}}\right) \tag{4}$$

The SEL is related to the total acoustic energy flux density delivered over the duration of the set period of time, i.e., 24 h. It is a representation of the accumulated SEL delivered by multiple acoustic events, e.g., multiple pulses of a single acoustic source.

Because the rms SPL and SEL of a single pulse are computed from the same time integral of square pressure, these metrics are related numerically by a simple expression, which depends only on the duration of the 90% energy time window T_{90}:

$$L_E = L_{p90} + 10\log_{10}(T_{90}) + 0.458 \tag{5}$$

where the factor of 0.458 dB accounts for the missing 10% of SEL due to consideration of just 90% of the cumulative square pressure in the L_{p90} calculation. It is important to note that the decibel reference units of L_E and L_{p90} are not the same, so this expression must be interpreted only in a numerical sense. No similar relationship exists when SPL is calculated using fixed time windows shorter than the full pulse duration, T_{100}; however, if the window length T is equal to or greater than T_{100} then the relationship is simply:

$$L_E = L_p + 10\log_{10}(T) \tag{6}$$

1.1.3. Energy Equivalent Sound Pressure Level

Energy equivalent SPL (dB re 1 µPa, denoted L_{eq}) is the measure of the average amount of energy carried by a time-dependent pressure wave, $p(t)$, over a period of time T. It is defined as the rms SPL over a fixed duration time window:

$$L_{eq} = 10\log_{10}\left(\frac{1}{T}\int_T p^2(t)dt \Big/ p_o^2\right) \tag{7}$$

The L_{eq} is numerically equal to the rms SPL of a steady sound that has the same total energy as the sound measured over the given time window. The expressions for L_p and L_{eq} are numerically identical; conceptually, the difference between the two metrics is that the former is computed over short time periods, usually one second or less, and tracks the fluctuations of a non-steady acoustic signal, whereas the latter reflects the average SPL of an acoustic signal over tens of seconds or longer. The integration time should be specified for both L_p and L_{eq}.

1.2. Marine Species and Auditory Bands

Within this assessment, a number of species were considered, with a variety of hearing acuities and frequency-dependent sensitivities. Twenty-one cetacean species are listed in Appendix D in the G&G EIS (NOAA 2016). These include low-, mid-, and high-frequency cetaceans. Hence, the corresponding M-weighting filters defined by Southall et al. (2007) were applied in the assessment of change in listening area. Because Bryde's whales are the only low-frequency cetacean, the most common mysticete in the Gulf, and appear to be present year-round (G&G EIS, Appendix E; NOAA 2016), this species was selected for the communication space assessment.

1.3. Chronic and Cumulative Effects

Historically, studies focused on short-term effects from high-intensity sounds (e.g., the near-field sounds from seismic airguns, sonars, and pile driving) when researching the effects of anthropogenic noise on marine mammals. More recently, focus has shifted to effects of long-term exposure that affect marine mammals over larger spatial and temporal extents (Clark et al. 2009, Hatch et al. 2012). These long-term exposures, or chronic effects, may in some cases be more relevant to marine animals than short-term acute effects, especially for communication between conspecifics (e.g. Hatch et al. 2012).

2. Methodology

2.1. Acoustic Source Models

The source levels and directivity of the airgun array were predicted with JASCO's Airgun Array Source Model (AASM; MacGillivray 2006). This model is based on the physics of oscillation and radiation of airgun bubbles described by Ziolkowski (1970). The model solves the set of parallel differential equations that govern bubble oscillations. AASM also accounts for nonlinear pressure interactions between airguns, port throttling, bubble damping, and generator-injector (GI) gun behavior that are discussed by Dragoset (1984), Laws et al. (1990), and Landro (1992). AASM includes four empirical parameters that were tuned so model output matches observed airgun behavior. The model parameters fit to a large library of empirical airgun data using a "simulated annealing" global optimization algorithm. These airgun data are measurements of the signatures of Bolt 600/B guns ranging in volume from 5 to 185 in^3 (Racca and Scrimger 1986).

AASM produces a set of "notional" signatures for each array element based on:

- Array layout
- Volume, tow depth, and firing pressure of each airgun
- Interactions between different airguns in the array

These notional signatures are the pressure waveforms of the individual airguns at a standard reference distance of 1 m; they account for the interactions with the other airguns in the array. The signatures are summed with the appropriate phase delays to obtain the far-field source signature of the entire array in all directions. This far-field array signature is filtered into 1/3-octave-bands to compute the source levels of the array as a function of frequency band and azimuthal angle in the horizontal plane (at the source depth), after which it is considered a directional point source in the far field.

A seismic array consists of many sources and the point-source assumption is invalid in the near field where the array elements add incoherently. The maximum extent of the near field of an array (R_{nf}) is:

$$R_{\mathrm{nf}} < \frac{l^2}{4\lambda} \tag{8}$$

where λ is the sound wavelength and l is the longest dimension of the array (Lurton 2002, §5.2.4). For example, an airgun array length of l = 16 m yields a near-field range of 85 m at 2 kHz and 17 m at 100 Hz. Beyond this R_{nf} range, the array is assumed to radiate like a directional point source and is treated as such for propagation modeling.

The interactions between individual elements of the array create directionality in the overall acoustic emission. Generally, this directionality is prominent mainly at frequencies in the mid-range between tens of hertz to several hundred hertz. At lower frequencies, with acoustic wavelengths much larger than the inter-airgun separation distances, the directionality is small. At higher frequencies, the pattern of lobes is too finely spaced to be resolved and the effective directivity is less.

2.2. Transmission Loss Models

The acoustic fields at the receiver sites were modeled at frequencies from 10 Hz to 5 kHz, for sources up to 500 km away, using JASCO's Marine Operations Noise Model (MOMN; Racca et al. 2015). MONM computes received per-pulse SEL for directional impulsive sources at a specified source depth.

MONM computes acoustic propagation from 10 Hz to 1 kHz via a wide-angle parabolic equation solution to the acoustic wave equation (Collins 1993) based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed (Zhang and Tindle 1995). It computes acoustic propagation above 1 kHz via the BELLHOP Gaussian beam acoustic ray-trace model (Porter and Liu 1994).

The parabolic equation method has been extensively benchmarked and is widely employed in the underwater acoustics community (Collins et al. 1996). MONM accounts for the additional reflection loss at the seabed 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. At frequencies above 1 kHz, MONM also accounts for sound attenuation due to energy absorption through ion relaxation and viscosity of water in addition to acoustic attenuation due to reflection at the medium boundaries and internal layers (Fisher and Simmons 1977). The version of MONM used in this assessment was validated with real data from marine seismic survey projects near Sakhalin Island (Racca et al. 2015) that used large airgun arrays similar to the ones considered in this report.

MONM incorporates the following site-specific environmental properties: a bathymetric grid of the modeled area, underwater sound speed as a function of depth, and a geoacoustic profile based on the overall stratified composition of the seafloor.

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

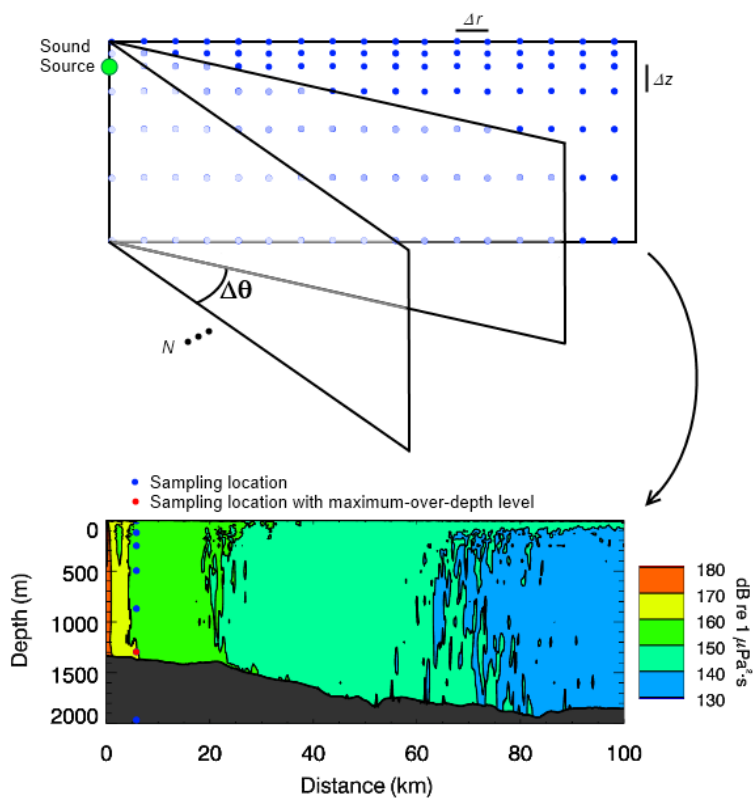

Figure 2. The N×2-D and maximum-over-depth modeling approach used by MONM.

MONM treats frequency dependence by computing acoustic transmission loss at the center frequencies of 1/3-octave-bands. Sufficiently many 1/3-octave-bands, starting at 10 Hz, are modeled to include the majority of acoustic energy emitted by the source. At each center frequency, the transmission loss is modeled within each of the N vertical planes as a function of depth and range from the source. The 1/3-octave-band received per-pulse SELs are computed by subtracting the band transmission loss values from the directional source level in that frequency band. Composite broadband received SELs are then computed by summing the received 1/3-octave-band levels.

The received per-pulse SEL sound field within each vertical radial plane is sampled at various ranges from the source, generally with a fixed radial step size. At each sampling range along the surface, the sound field is sampled at various depths, with the step size between samples increasing with depth below the surface.

2.3. Chronic and Cumulative Exposure (CCE) Calculator

A Chronic and Cumulative Exposure (CCE) calculator was developed to assist with assessing chronic seismic exploration noise received by marine mammals at the 10 receiver sites. This calculator is implemented as Microsoft Excel spreadsheets with scripting to provide a flexible tool for evaluating cumulative SELs generated by scenarios of seismic activity distributed over wide areas. The modeling geometry implemented in the CCE calculator makes use of acoustic reciprocity, whereby the model was run with the source and receiver positions interchanged—an efficient approach when there are more potential source sites than receiver sites.

The acoustic transmission loss results and the modeled source levels for each activity type are stored in the spreadsheets of the CCE calculator. The CCE calculator contains sets of marine mammal hearing frequency weighting filter coefficients that can be applied to the received levels. For change in listening space calculations, we applied filters for low-, mid-, and high-frequency cetaceans as defined by Southall et al. (2007). The CCE calculator also contains baseline (ambient) level spectrum for all receiver sites and depths (Section 2.4).

The CCE calculator computes three values: cumulative SELs, L_{eq}, and L_{eq} above ambient at the selected receiver site resulting from all pulses from the seismic surveys specified for each alternative.

2.3.1. Survey Distribution

Since the activity locations were unknown, the survey source pulses were uniformly distributed throughout each activity zone according to the respective survey line lengths within the activity zones (Table 4) and pulse intervals. Rather than modeling every pulse position throughout each activity zone, the seismic surveys were divided into several survey cells, each representing a portion of the overall project area. The number of pulses contained within each cell was based on the average pulse density in each activity zone (Table 5) and the cell areas. The cumulative levels estimated using this approach are accurate when the cell dimensions are small, relative to the source-receiver separation.

Table 5. Maximum average pulse density (annual number of pulses per km^2; Alternative C) per airgun array in each activity zone.

Representative Airgun Array	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
8000 in^3	5.5	43.9	57.5	42.2	0	20.0
90 in^3	14.1	58.2	67.3	88.4	1.6	2.9

The coordinates of the center of each cell were entered in the CCE calculator with the number of pulses represented by the corresponding cell. The calculator assumed this number of pulses occurred at the cell's geometric center. The error in cumulative SEL due to approximating all shot locations within the cell by the cell's center location is expected to be negligible.

To minimize the number of cells throughout the project area and to minimize the error in the cumulative level estimates, the cell dimensions were defined so that the distances of the closest side to the most distant side of a cell from any receiver had a ratio of less than 1.5. This approach limited the difference in transmission loss between any point in the cell and its center to less than ~ 2 dB assuming 20×log(R) transmission loss. Thus, cells closest to a receiver represented smaller areas than more distant cells. The entire project area was divided into 1706 cells (Figure 3). The coordinates of the center of each cell were entered in the CCE calculator with the number of pulses contained within the cell.

The number of pulses in each cell in activity zones along the coast accounted for a 4-month coastal-water closure area (orange hashed; Figure 3). Alternatives F1 and F2 include additional closure areas also shown in Figure 3. For these alternatives, we removed activity from areas consisting of the actual closure areas and from a surrounding spatial buffer designed to maintain sound pressure levels (SPL) below 160 dB re 1 μPa (90% rms) at the closure area boundaries. The effect on activities due to closures might be the redistribution of a fraction of the excluded surveying activity. To account for this possibility, 25% of the survey pulses excluded from a closure area were redistributed outside the closure area, but within the same activity zone. The spatial buffer widths varied from 4.8 to 8.4 km for the 8000 in^3 airgun array, depending on the closure area (grey line around closure areas in Figures 1 and 3). No buffers were applied for the 90 in^3 airgun source since its 160 dB re 1 μPa (rms) distance was estimated at less than 100 m for the modeled receiver depths.

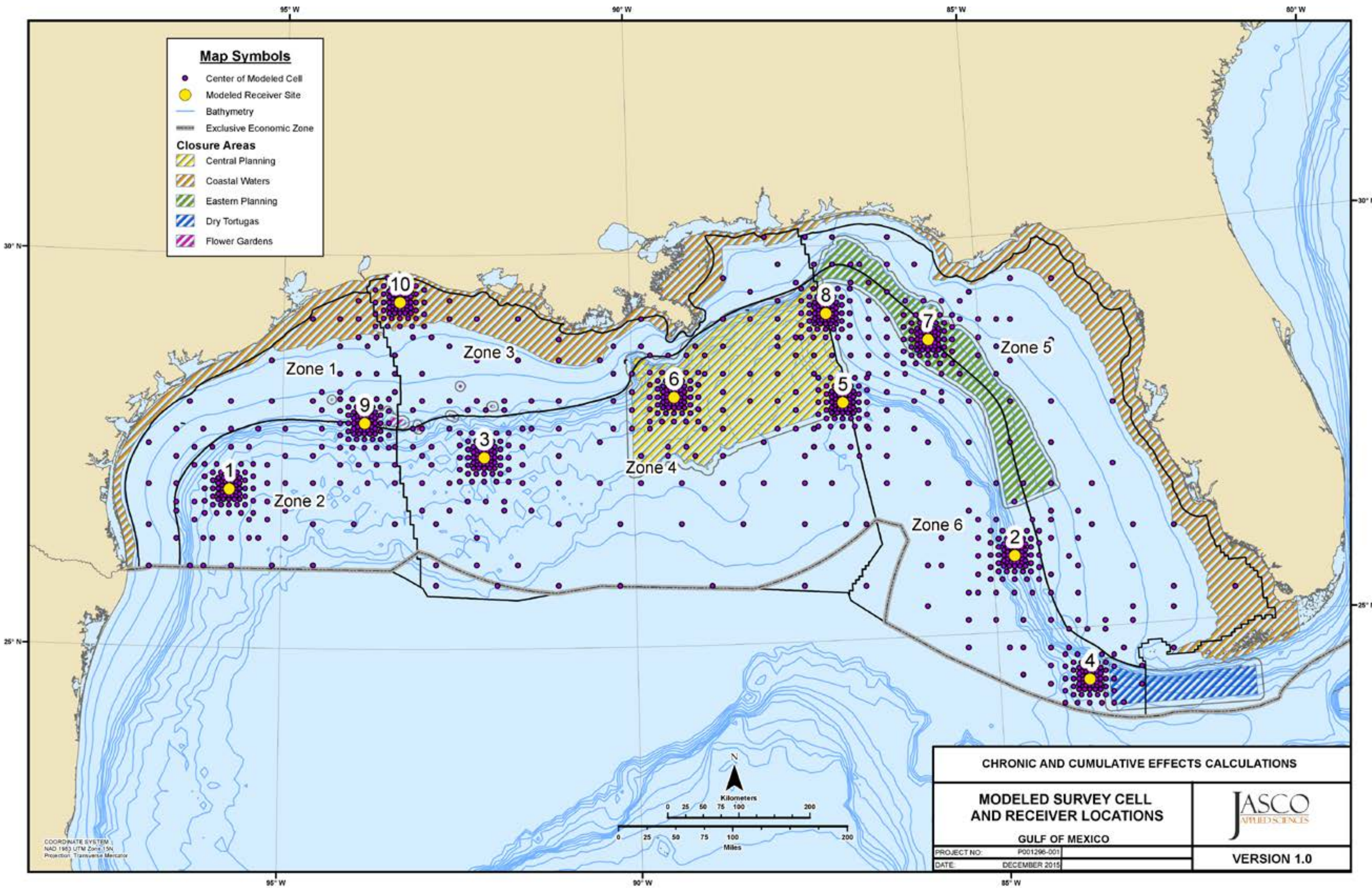

Figure 3. Location of the modeled survey cells (purple dots) and receiver (yellow dots). Survey source pulses were uniformly distributed throughout each activity zone according to the respective survey line lengths within the activity zones. Each modeled survey cell location is associated with a number of pulses proportional to the cell area (not shown here).

2.3.2. Removal of Top 10% of Pulse Exposures

A feature of underwater sound propagation is that nearby sources generally contribute substantially more SEL than more distant sources of the same type, since the exposure levels decay approximately with the square of distance from the source. This causes cumulative SEL received from spatially distributed and moving seismic sources to be dominated by the source pulses generated closest to a receiver. However, the time period of exposures from nearby sources is typically quite short. While exposures from nearby sources are important for assessing acute effects, their inclusion in a chronic effects assessment can be unrepresentative. To avoid this problem, this analysis neglected the highest seismic pulse exposures received during a fraction (10%) of the year-long analysis period.

The specific method for removing the highest pulse contributions first involved sorting cells based on their received per-pulse SEL. Since the pulses were uniformly distributed through each activity zone, the time required to survey each cell was assumed proportional to the number of pulses in the cell. The SEL-ordered cells corresponding to 10% of the 1-year study duration (36.5 days) were neglected prior to calculating cumulative SEL, L_{eq} and L_{eq} above ambient.

2.4. Baseline Levels

To estimate changes in listening area and communication space for various levels of seismic activities, we calculated a baseline noise level containing mainly commercial shipping noise and noise from natural sounds produced mainly by wind and breaking waves. The commercial shipping noise levels were obtained from the SoundMap mapping tool (SoundMap Working Group 2015). SoundMap produces commercial shipping noise levels over the Gulf of Mexico region in 1/3-octave frequency bands between 50 and 800 Hz. Natural ambient noise levels were calculated from the formulas of Wenz (1962) and Cato (2008) for a wind speed of 8.5 knots. The natural noise levels were added to all available vessel noise levels to generate composite 1/3-octave-band baseline levels between 10 Hz and 5000 Hz. Since no data for commercial shipping noise were available outside the frequency range of the SoundMap results, shipping noise outside the 50-800 Hz bands was excluded (Figures 4–6).

Broadband baseline levels varied between 94.3 and 102.3 dB re 1 µPa, depending on the receiver location and depth. Third-octave band baseline levels were entered in the CCE calculator. L_{eq} and L_{eq} above ambient were then calculated in 1/3-octave bands using low-, mid-, and high-frequency cetacean filters and without frequency weighting. Baseline levels in the 100 Hz 1/3-octave band, which varied between 76.1 and 86.7 dB re 1 µPa, were used to calculate Bryde's whale communication space under Alternative A.

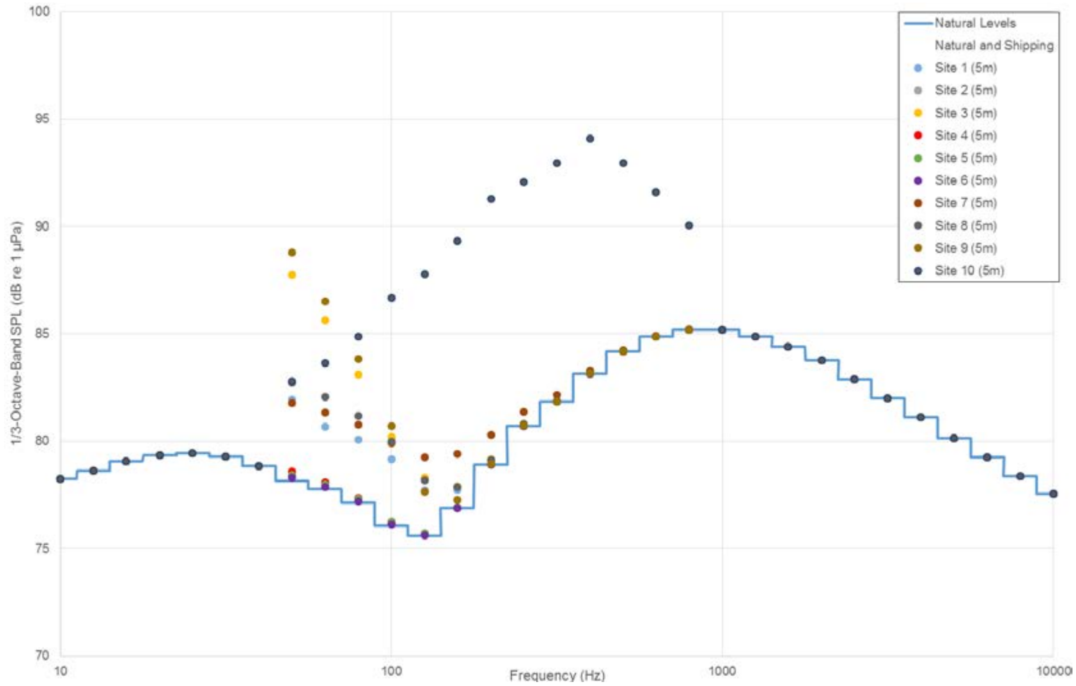

Figure 4. Summed levels for frequency bands of 10 Hz to 10 kHz for all sites at 5 m receiver depth. The natural interpolated sound levels (blue line; Wenz (1962), Cato (2008)) and SoundMap data were summed for frequency bands between 50 and 800 Hz. Beyond these limits the interpolated natural levels were used.

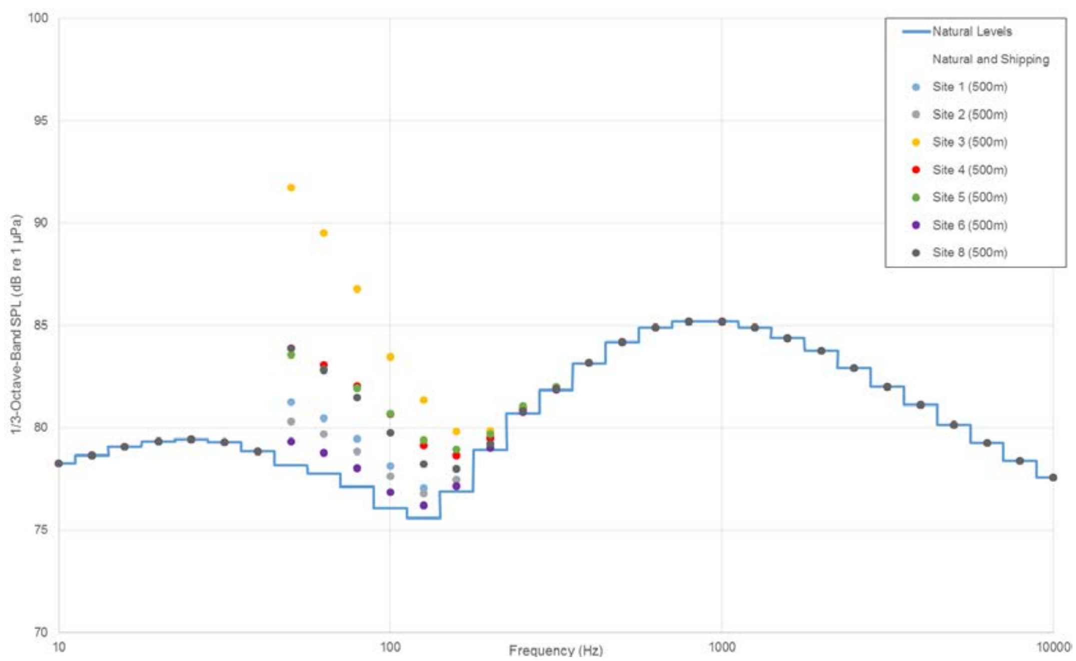

Figure 5. Summed levels for frequency bands of 10 Hz to 10 kHz for nine sites at 30 m receiver. The natural interpolated sound levels (blue line; Wenz (1962), Cato (2008)) and SoundMap data were summed for frequency bands between 50 and 800 Hz. Beyond these limits the interpolated natural levels were used. Note that not all sites have water depth reaching this receiver depth.

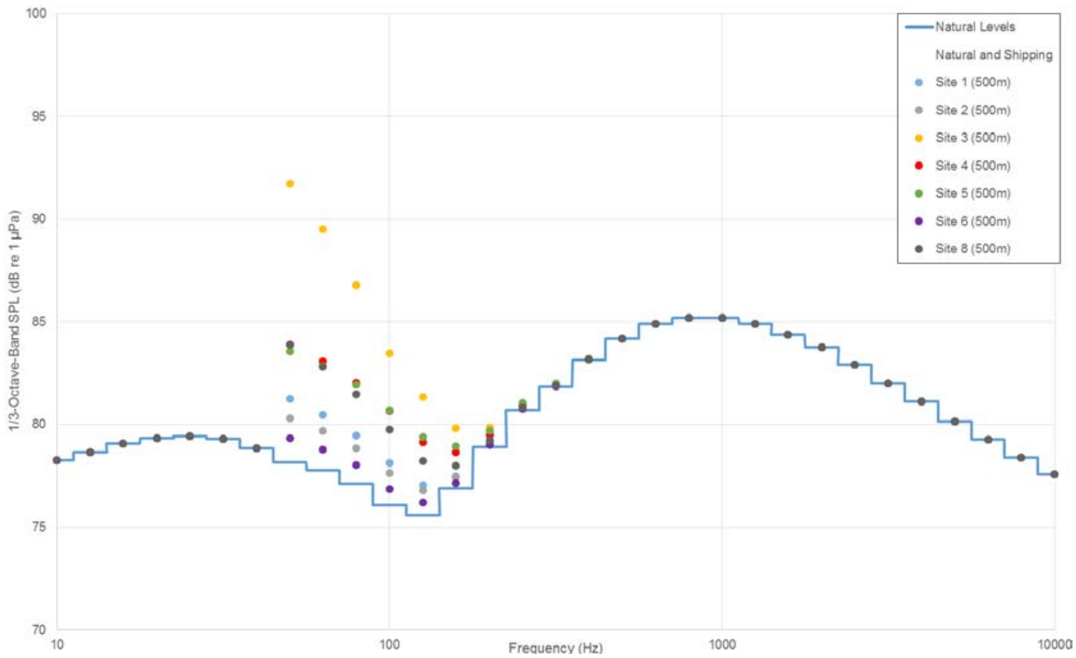

Figure 6. Summed levels for frequency bands of 10 Hz to 10 kHz for seven sites at 500 m receiver depth. The natural interpolated sound levels (blue line; Wenz (1962), Cato (2008)) and SoundMap data were summed for frequency bands between 50 and 800 Hz. Beyond these limits the interpolated natural levels were used. Note that not all sites have water depth reaching this receiver depth.

2.5. Listening Area

The term listening area refers to the area associated with the maximum detection distance of a signal by an animal. A listening area assessment considers the region of ocean where marine fauna can detect sound from conspecifics, as well as from predators and prey (Figure 7). The introduction of noise in the same frequency band as the signal may reduce an animal's ability to detect the signal, and therefore decreases the maximum detection distance and reduces the listening area.

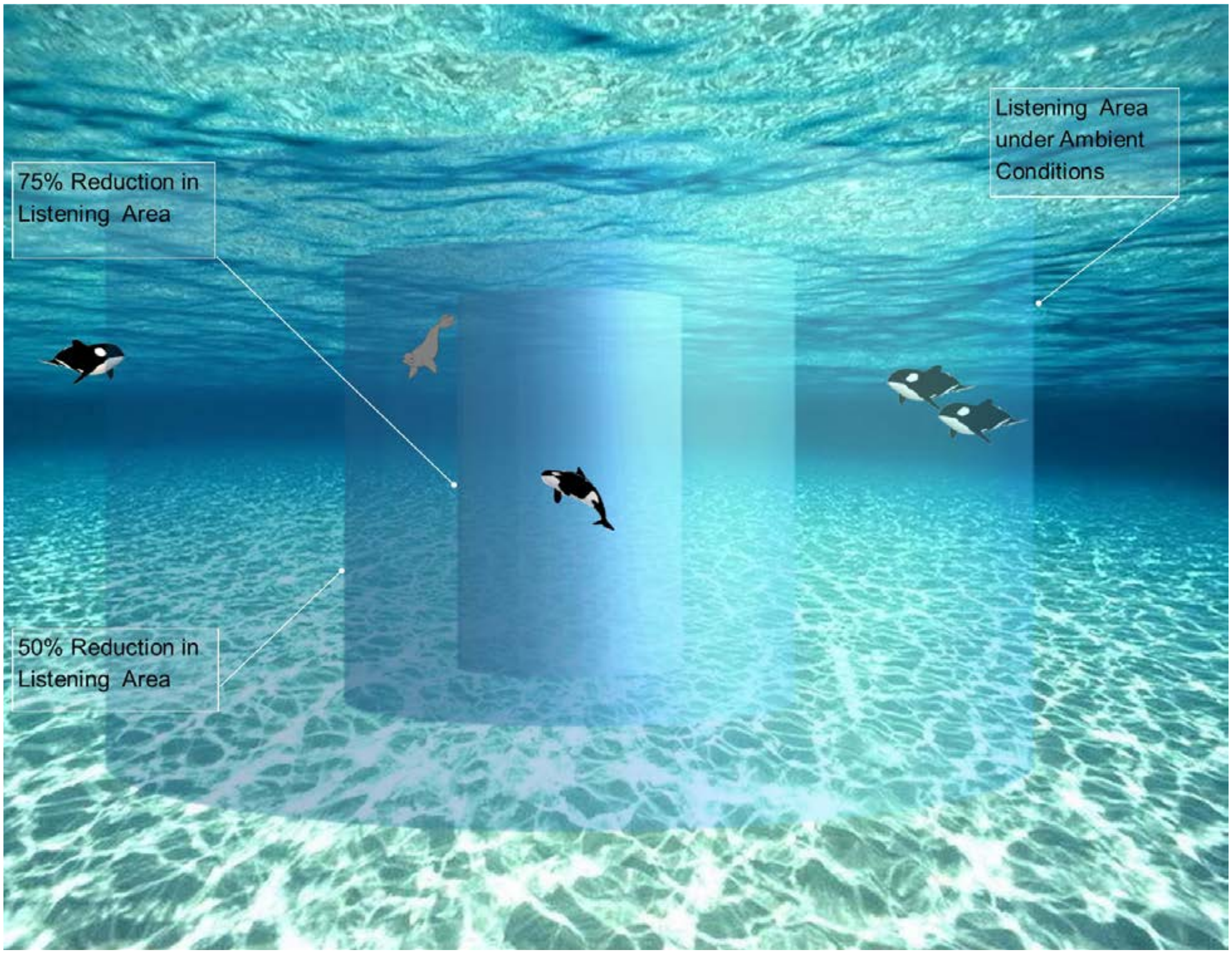

Figure 7. Schematic representation of changes in listening area around a marine mammal. Under ambient conditions, an animal may be able to listen to conspecifics, as well as predators and prey. When the noise level increases, the listening area is reduced. (Figure adapted from NPS 2010.)

The remaining fraction of the listening area after an increase in noise level can be calculated without prior knowledge of the signal source level and detection distance by approximating the transmission loss (*TL*) as:

$$TL = N \log_{10}(R). \tag{9}$$

The maximum detection distance of the signal (R_o), associated with a source level *SL*, will result in a received level RL_o:

$$RL_o = SL - N \log_{10}(R_o). \tag{10}$$

The maximum detection distance (*R*) associated with an increase in noise level will result in a received level (*RL*):

$$RL = SL - N \log_{10}(R). \tag{11}$$

The remaining fraction of listening area after an increase in noise level is therefore:

$$\frac{\pi R^2}{\pi R_o^2} = \frac{10^{2(RL-SL)/N}}{10^{2(RL_o-SL)/N}} = 10^{-2\Delta/N} . \quad (12)$$

Where Δ is equal to the increase in noise level, in dB. Results are presented in fractions (percentage) of the listening area that is left, relative to the original, after an increase in noise level.

This concept was applied by Barber et al. (2009) to terrestrial organisms. To our knowledge, this concept has not previously been applied to marine animals. Unlike the assessment of communication space (Section 2.6), the assessment of change in listening area does not require prior knowledge parameters such as the signal source levels, detection thresholds based on the receiver perception capabilities, signal directivity, noise and signal duration, and band-specific (spectral) noise levels. This assessment can be done for specific frequency bands, or by taking into consideration the animal's auditory system and applying a relevant filter to the noise level.

This equation is expected to overestimate the reduction in listening area at most sites, where the ***TL*** is better estimated by an equation of the form:

$$TL = N\log_{10}(R) - \alpha R . \quad (13)$$

In this study, we estimated *N* at each of the receiver sites by curve fitting the modeled *TL* from the receiver at ranges ≤ 75 km. The noise level increase, Δ, is the difference between the estimated ambient level and L_{eq} or between two alternatives being compared. The approach considers the additive nature of ambient noise to L_{eq} in decibel space (for example, if L_{eq} and ambient level were equal, then Δ would be 3 dB). While that may seem counterintuitive, recall that the decibel sum of two equal sound levels is their individual value plus 3 dB. Changes in listening area were calculated for unfiltered broadband (10–5000 Hz) noise levels, as well as by applying low-, mid-, and high-frequency cetaceans weighting to the noise levels.

2.6. Bryde's Whale Communication Space

A communication space assessment considers the region of ocean within marine fauna can detect calls from conspecifics. Masking can be defined as a reduction in communication space (active acoustic space) that an individual experiences due to an increase in background noise (ambient and anthropogenic) in the frequency bands relevant for communicating. Reduction in communication space due to anthropogenic sounds cannot be determined based on the broadband cumulated sound exposure level, because the effect depends on the spectral noise level within the frequency band of the sounds in question and therefore varies dynamically with receiver distance from the sound (noise) source. To estimate the communication space quantitatively, it is necessary to account for parameters such as call source levels, detection thresholds based on the receiver perception capabilities, signal directivity, band-specific (spectral) noise levels, and noise and signal duration.

The communication space for Bryde's whales was estimated using a similar approach to that employed by Clark et al. (2009). This approach calculates the horizontal area in square kilometers over which a call can be detected, recognizing that the true call could originate within a 3-D volume of ocean. The primary difference between our approach and Clark et al.'s is that we a applied the analysis in a single representative 1/3-octave-band rather than to broadband levels. This approach is based on a form of the sonar equation that considers the maximum distance an animal can detect a signal in the presence of masking noise. The form of the sonar equation employed here was:

$$SE = SL - TL - NL - DT + DI + SG \quad . \tag{14}$$

The signal excess (*SE*) is the signal excess above detectability. The source level (*SL*) is the animal call source level. *TL* is the acoustic transmission loss between the calling and listening Bryde's whales (a function of the distance of their separation). *NL* is the noise level in the same frequency band as the source level. *DT* is the detection threshold of the animal, representing the amount above ambient level the sound must be in order for it to be detected. The directivity index (*DI*) represents the animal's ability to discriminate sounds coming from a specific direction, in the presence of masking noise arriving uniformly from all directions. *SG* is the signal gain that indicates the ability of the animal to use its knowledge of the time-frequency structure of the call to differentiate it from background noise.

3. Modeled Parameters

3.1. Acoustic Environment

The environmental parameters used by the transmission loss model (MONM; Section 2.2) were the same ones used in the 2016–2025 Annual Acoustic Exposure Estimates for Marine Mammals (Appendix D of the G&G EIS; NOAA 2016). Water depths throughout the modeled area were obtained from the National Geophysical Data Center's U.S. Coastal Relief Model l (NGDC 2014). Sound speed profiles for February for each receiver site were used to estimate the transmission loss for the entire year. This adds a level of conservativeness since the winter profiles include an isovelocity layer and, at some sites, a surface sound channel; both can enhance sound propagation for the near-surface sources considered here. Three of the four sets of geoacoustic parameters (Center-West Shelf, Slope, and Deep) from the G&G EIS, Appendix D (NOAA 2016) were used in this assessment. A fourth set of parameters (Table 6) was developed to model transmission loss at receiver sites on the eastern slope (offshore Florida), based on the information previously acquired (G&G EIS, Appendix D; NOAA 2016).

Table 6. Eastern Slope: Geoacoustic properties of the sub-bottom sediments as a function of depth, in meters below the seafloor (mbsf). Within each depth range, each parameter varies linearly within the stated range.

Depth below seafloor (m)	Material	Density (g/cm^3)	P-wave speed (m/s)	P-wave attenuation (dB/λ)	S-wave speed (m/s)	S-wave attenuation (dB/λ)
0–20	Silt *φ*=6	1.44	1532	0.41	200	0.22
20–50		1.7	1725	1.00		
50–200		1.7	1826	1.30		
200–600		1.87	2105	1.75		
> 600		2.04	2466	2.11		

3.2. Acoustic Sources

The source levels and directivity of the two types of airgun arrays were predicted with AASM (Section 2.1). Source levels in 1/3-octave frequency bands for each source were determined and input in the acoustic propagation model. Directivity was purposely removed by averaging the direction-dependent levels modeled with AASM because here we assumed randomly oriented surveys. The averaging preserved total acoustic energy emitted.

The acoustic source levels used in the CCE calculator (Section 2.3) were derived from the Appendix D of the G&G EIS (NOAA 2016).

3.3. Transmission Loss and CCE Calculator

Sixteen vertical planes were modeled around each receiver site, providing an angular spacing of 22.5 degrees. The modeled radial lengths were limited to 500 km. Seismic pulses originating more than 500 km from a specified receiver were estimated to have little influence on the cumulative sound field and were excluded. Receiver depths were modeled at 5, 30, and 500 m. The surrogate sources (90 in^3 and 8000 in^3 arrays) were modeled at 4 and 8 m depths.

The L_{eq} was based on the accumulation period of 1 year, and T was 31.45×10^6 seconds.

3.4. Bryde's Whale Communication Space

A representative source level was estimated from the median Bryde's whale source level reported by Širović et al. (2014). Under the assumption that the call bandwidth spanned two 1/3-octave-bands, a source level of 152 dB re 1 µPa at 1 m was specified for the 100 Hz band based on the broadband source level for Bryde's moans of 155 dB re 1 µPa at 1 m. All communication space calculations were performed in the single 1/3-octave frequency band centered at 100 Hz.

A 1/3-octave-band analysis is relevant for assessing audibility of a signal, as it is often used to approximate the critical bandwidth of the mammalian ear. We used a signal excess of $SE = 0$, to represent the onset of detectability. Transmission loss was obtained at each receiver site from the transmission loss model results. The noise levels were calculated with the CCE calculator as described in Section 2.3. The detection threshold was assumed to be 10 dB and the detection index was assumed to be zero (Clark et al. 2009). The signal processing gain ($SG = 10\log(TW)$), which accounts for the animal's ability to detect and recognize a signal from conspecifics, was estimated as 12.36 dB, based on a median frequency bandwidth (W) of 43 Hz and call length (T) of 0.4 seconds (Širović et al. 2014).

4. Results

This section presents the modeled results of cumulative sound exposure levels (Tables 8–11) and time-averaged equivalent sound pressure levels (Tables 12–19) for all modeled scenarios. Scenario estimates are then compared to each other, as well as to baseline noise level. Relative differences are calculated and ranked. Results are then presented as changes in listening area (Tables 20–27) and changes in communication space for Bryde's whales (Tables 28–36). Communication space and listening area calculations use baseline noise levels (Alternative A) for reference (Table 7). Alternative A is comprised of commercial shipping noise and natural sounds produced mainly by wind and breaking waves.

Table 7. Broadband (10–5000 Hz) baseline (Alternative A; no activity) SPL (dB re 1 µPa) for each receiver site and depth.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	96.1	95.9	96.9	95.9	95.9	95.9	96.3	96.3	97.2	102.2
	30	96.1	95.9	96.3	95.9	96.0	95.9	96.6	96.3	97.2	
	500	96.1	96.0	98.3	96.5	96.5	95.9		96.4		
Mid-Frequency Cetaceans	5	94.6	94.6	94.7	94.6	94.6	94.6	94.7	94.7	94.7	100.3
	30	94.6	94.6	94.7	94.6	94.6	94.6	94.7	94.6	94.7	
	500	94.6	94.6	94.8	94.7	94.7	94.6		94.7		
High-Frequency Cetaceans	5	94.3	94.3	94.4	94.3	94.3	94.3	94.4	94.3	94.3	99.6
	30	94.3	94.3	94.4	94.3	94.3	94.3	94.4	94.3	94.4	
	500	94.3	94.3	94.4	94.4	94.4	94.3		94.3		
Unweighted	5	96.3	96.1	97.1	96.1	96.1	96.1	96.5	96.5	97.3	102.3
	30	96.3	96.1	96.5	96.1	96.2	96.1	96.8	96.5	97.4	
	500	96.3	96.2	98.5	96.7	96.7	96.1		96.6		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

4.1. Cumulative Sound Exposure Levels

Tables 8–11 present the results for cumulative SELs (dB re 1 µPa²s) for each receiver site and depth for all modeled alternatives. These levels were filtered for low-, mid-, and high-frequency cetaceans. These results are based on the total number of pulses (shots) for a one-year duration.

Table 8. Alternative C: Cumulative SEL (dB re 1 µPa²s) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	173.8	170.8	169.1	164.8	189.6	165.1	123.7	164.8	175.8	157.0
	30	176.8	179.4	174.8	174.6	193.8	168.6	138.8	167.9	174.3	
	500	180.9	179.8	178.2	173.8	191.9	174.8		170.9		
Mid-Frequency Cetaceans	5	173.2	160.3	167.1	158.3	186.5	163.6	102.3	161.5	175.7	156.9
	30	172.3	162.4	159.6	161.0	185.1	149.7	113.5	149.3	174.2	
	500	164.7	164.4	163.4	160.2	180.9	155.3		152.0		
High-Frequency Cetaceans	5	172.7	158.1	166.7	156.6	185.9	163.5	99.1	160.9	175.5	156.8
	30	172.0	160.3	157.2	158.2	184.3	146.7	109.6	146.3	174.0	
	500	162.4	162.6	161.0	157.9	179.1	152.7		149.3		
Unweighted	5	173.8	171.2	169.3	165.0	189.6	165.2	125.1	165.1	175.9	157.0
	30	177.6	180.4	175.3	175.2	194.1	169.5	140.0	168.9	174.4	
	500	182.0	181.0	179.2	174.7	193.1	176.2		172.1		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 9. Alternative E (25% reduction): Cumulative SEL (dB re 1 µPa²s) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	172.5	169.5	167.9	163.5	188.3	163.9	122.5	163.6	174.6	155.7
	30	175.6	178.2	173.5	173.4	192.5	167.3	137.6	166.6	173.1	
	500	179.6	178.6	177.0	172.6	190.7	173.6		169.7		
Mid-Frequency Cetaceans	5	171.9	159.0	165.8	157.1	185.3	162.3	101.1	160.2	174.4	155.7
	30	171.1	161.2	158.4	159.8	183.9	148.5	112.2	148.1	172.9	
	500	163.5	163.1	162.1	159.0	179.6	154.0		150.7		
High-Frequency Cetaceans	5	171.5	156.8	165.5	155.4	184.7	162.2	97.8	159.6	174.3	155.6
	30	170.8	159.1	156.0	157.0	183.1	145.5	108.4	145.1	172.8	
	500	161.2	161.3	159.8	156.6	177.8	151.4		148.0		
Unweighted	5	172.6	169.9	168.1	163.8	188.4	164.0	123.8	163.9	174.6	155.8
	30	176.4	179.1	174.1	174.0	192.8	168.3	138.8	167.7	173.2	
	500	180.8	179.7	177.9	173.5	191.9	174.9		170.9		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 10. Alternative F1 (area closures): Cumulative SEL (dB re 1 µPa²s) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	174.8	171.4	171.3	165.0	193.4	163.2	123.1	160.3	176.5	158.3
	30	178.9	179.4	177.4	174.9	197.1	166.2	138.1	164.2	175.2	
	500	182.2	179.9	180.9	174.1	195.0	173.3		166.7		
Mid-Frequency Cetaceans	5	174.2	160.8	169.1	158.5	188.9	161.8	101.1	157.5	176.3	158.2
	30	173.3	162.7	162.4	161.2	188.9	142.4	112.1	144.2	174.9	
	500	166.6	165.1	165.5	159.3	184.9	149.1		145.6		
High-Frequency Cetaceans	5	173.8	158.7	168.6	156.8	187.0	161.7	98.3	156.9	176.2	158.2
	30	173.1	160.5	160.0	158.4	187.4	138.9	108.3	140.7	174.8	
	500	164.7	162.9	163.6	157.1	183.4	146.3		142.9		
Unweighted	5	174.9	171.5	171.5	165.2	193.5	163.4	124.5	160.6	176.6	158.4
	30	179.5	180.5	178.2	175.5	197.4	167.0	139.6	165.2	175.2	
	500	183.3	181.0	182.5	175.0	195.6	173.6		168.0		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 11. Alternative F2 (area closures and 25% reduction): Cumulative SEL (dB re 1 µPa²s) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	173.6	170.2	170.1	163.7	192.2	162.0	121.9	159.1	175.3	157.1
	30	177.7	178.2	176.1	173.6	195.8	165.0	136.9	163.0	173.9	
	500	181.0	178.7	179.6	172.8	193.8	172.0		165.4		
Mid-Frequency Cetaceans	5	172.9	159.5	167.8	157.3	187.7	160.6	99.9	156.2	175.1	157.0
	30	172.0	161.5	161.2	160.0	187.7	141.2	110.8	143.0	173.7	
	500	165.3	163.9	164.3	158.1	183.6	147.8		144.3		
High-Frequency Cetaceans	5	172.5	157.4	167.4	155.6	185.8	160.4	97.1	155.6	174.9	156.9
	30	171.8	159.3	158.8	157.2	186.1	137.6	107.1	139.4	173.5	
	500	163.5	161.6	162.3	155.9	182.1	145.1		141.6		
Unweighted	5	173.6	170.3	170.3	164.0	192.2	162.1	123.3	159.3	175.3	157.1
	30	178.2	179.3	176.9	174.2	196.2	165.7	138.4	164.0	174.0	
	500	182.0	179.7	181.3	173.7	194.3	172.3		166.8		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

4.2. Time-Averaged Equivalent Sound Pressure Levels

Tables 12–19 present the time-averaged equivalent SPLs for each receiver site and depth for all modeled alternatives. The time-averaged equivalent SPLs were calculated by applying the cumulative SELs and the filtered baseline noise levels (Table 7) with a time average of 31.45 × 10^6 seconds. The values in the tables represent time-averaged equivalent SPLs above and below the baseline levels (Alternative A - Table 7).

Table 12. Alternative C: Time-averaged equivalent sound pressure levels (L_{eq}) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	100.7	98.9	98.8	96.8	114.6	96.9	96.3	97.2	102.4	102.3
	30	102.9	105.0	101.4	101.2	118.8	97.9	96.6	98.0	101.4	
	500	106.3	105.4	104.5	100.8	117.0	101.3		99.2		
Mid-Frequency Cetaceans	5	99.8	95.1	96.6	94.9	111.6	95.6	94.7	95.3	101.7	100.4
	30	99.2	95.4	95.1	95.2	110.3	94.7	94.7	94.7	100.5	
	500	95.9	95.8	95.7	95.1	106.2	94.8		94.7		
High-Frequency Cetaceans	5	99.4	94.6	96.3	94.6	111.0	95.3	94.4	94.9	101.5	99.6
	30	98.9	94.8	94.6	94.7	109.5	94.3	94.4	94.4	100.3	
	500	95.1	95.2	95.0	94.7	104.5	94.4		94.4		
Unweighted	5	100.8	99.1	99.0	97.1	114.7	97.1	96.5	97.4	102.5	102.3
	30	103.5	105.9	101.9	101.7	119.1	98.4	96.8	98.4	101.5	
	500	107.4	106.5	105.2	101.5	118.2	102.4		99.9		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 13. Alternative C: Time-averaged equivalent sound pressure levels (L_{eq}) above ambient at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	4.5	3.0	1.8	1.0	18.7	1.0	0	0.9	5.2	0
	30	6.7	9.1	5.1	5.2	22.9	2.0	0	1.6	4.2	
	500	10.2	9.4	6.1	4.4	20.5	5.4		2.8		
Mid-Frequency Cetaceans	5	5.1	0.5	1.9	0.3	17.0	1.0	0	0.6	7.0	0.1
	30	4.6	0.8	0.4	0.6	15.6	0	0	0	5.8	
	500	1.2	1.1	0.9	0.5	11.5	0.2		0.1		
High-Frequency Cetaceans	5	5.1	0.3	1.9	0.2	16.7	1.0	0	0.6	7.1	0.1
	30	4.6	0.5	0.3	0.3	15.1	0	0	0	6.0	
	500	0.8	0.8	0.6	0.3	10.2	0.1		0		
Unweighted	5	4.4	3.1	1.8	1.0	18.6	1.0	0	0.9	5.1	0
	30	7.2	9.8	5.3	5.5	23.0	2.3	0	1.9	4.2	
	500	11.1	10.2	6.7	4.8	21.5	6.2		3.3		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 14. Alternative E (25% reduction): Time-averaged equivalent sound pressure levels (*Leq*) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	99.9	98.3	98.4	96.6	113.4	96.7	96.3	97.0	101.6	102.2
	30	101.9	104.0	100.6	100.4	117.6	97.5	96.6	97.6	100.7	
	500	105.2	104.3	103.5	100.1	115.8	100.5		98.6		
Mid-Frequency Cetaceans	5	99.0	95.0	96.2	94.8	110.4	95.4	94.7	95.1	100.7	100.3
	30	98.4	95.2	95.0	95.0	109.0	94.6	94.7	94.7	99.6	
	500	95.6	95.5	95.5	95.0	105.0	94.7		94.7		
High-Frequency Cetaceans	5	98.6	94.6	95.9	94.5	109.8	95.1	94.4	94.8	100.5	99.6
	30	98.1	94.7	94.6	94.6	108.3	94.3	94.4	94.4	99.4	
	500	95.0	95.0	94.9	94.6	103.4	94.4		94.4		
Unweighted	5	100.0	98.6	98.6	96.8	113.5	96.9	96.5	97.2	101.6	102.3
	30	102.6	104.8	101.0	100.8	117.9	97.9	96.8	98.0	100.8	
	500	106.3	105.3	104.3	100.7	116.9	101.5		99.3		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 15. Alternative E (25% reduction): Time-averaged equivalent sound pressure levels (*Leq*) above ambient at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	3.8	2.4	1.4	0.7	17.5	0.8	0	0.7	4.4	0
	30	5.8	8.1	4.2	4.4	21.6	1.6	0	1.3	3.5	
	500	9.1	8.3	5.2	3.6	19.3	4.5		2.2		
Mid-Frequency Cetaceans	5	4.3	0.4	1.5	0.2	15.8	0.7	0	0.5	6.0	0
	30	3.8	0.6	0.3	0.4	14.4	0	0	0	4.9	
	500	0.9	0.9	0.7	0.4	10.4	0.1		0.1		
High-Frequency Cetaceans	5	4.2	0.2	1.5	0.2	15.5	0.8	0	0.4	6.2	0.1
	30	3.8	0.4	0.2	0.2	13.9	0	0	0	5.1	
	500	0.6	0.6	0.5	0.2	9.1	0.1		0		
Unweighted	5	3.7	2.5	1.4	0.7	17.4	0.8	0	0.7	4.3	0
	30	6.2	8.7	4.5	4.7	21.7	1.8	0	1.5	3.4	
	500	10.0	9.1	5.8	4.0	20.3	5.3		2.7		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 16. Alternative F1 (area closures): Time-averaged equivalent sound pressure levels (*Leq*) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	101.4	99.2	99.7	96.9	118.4	96.6	96.3	96.6	102.9	102.3
	30	104.6	105.0	103.3	101.3	122.1	97.2	96.6	97.1	102.0	
	500	107.6	105.5	106.6	101.0	120.1	100.3		97.7		
Mid-Frequency Cetaceans	5	100.5	95.1	97.4	94.9	114.0	95.3	94.7	94.9	102.2	100.4
	30	99.9	95.4	95.4	95.2	114.0	94.6	94.7	94.7	101.1	
	500	96.4	96.0	96.2	95.1	110.0	94.7		94.7		
High-Frequency Cetaceans	5	100.1	94.7	97.0	94.6	112.1	95.0	94.4	94.6	102.0	99.6
	30	99.6	94.9	94.8	94.7	112.5	94.3	94.4	94.3	100.9	
	500	95.6	95.2	95.4	94.6	108.6	94.3		94.4		
Unweighted	5	101.5	99.3	99.9	97.1	118.5	96.8	96.5	96.8	103.0	102.3
	30	105.1	106.0	104.0	101.9	122.5	97.5	96.8	97.4	102.1	
	500	108.6	106.4	108.0	101.6	120.6	100.5		98.2		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 17. Alternative F1 (area closures): Time-averaged equivalent sound pressure levels (*Leq*) above ambient at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	5.2	3.3	2.7	1.0	22.6	0.7	0	0.3	5.7	0.1
	30	8.5	9.1	7.0	5.4	26.1	1.3	0	0.8	4.8	
	500	11.5	9.4	8.2	4.5	23.6	4.3		1.3		
Mid-Frequency Cetaceans	5	5.9	0.5	2.7	0.3	19.4	0.7	0	0.3	7.5	0.1
	30	5.2	0.8	0.8	0.6	19.4	0	0	0	6.4	
	500	1.7	1.3	1.4	0.4	15.3	0		0		
High-Frequency Cetaceans	5	5.8	0.4	2.7	0.2	17.8	0.7	0	0.2	7.7	0.1
	30	5.3	0.5	0.5	0.3	18.1	0	0	0	6.5	
	500	1.3	0.9	1.0	0.3	14.2	0		0		
Unweighted	5	5.2	3.2	2.7	1.0	22.5	0.7	0	0.3	5.6	0.1
	30	8.8	9.9	7.5	5.7	26.3	1.4	0	0.9	4.7	
	500	12.3	10.2	9.5	5.0	24.0	4.4		1.6		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 18. Alternative F2 (area closures and 25% reduction): Time-averaged equivalent sound pressure levels (*Leq*) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	100.6	98.6	99.1	96.7	117.2	96.4	96.3	96.6	102.0	102.3
	30	103.6	103.9	102.4	100.5	120.9	96.9	96.6	96.9	101.2	
	500	106.4	104.4	105.5	100.2	118.8	99.6		97.4		
Mid-Frequency Cetaceans	5	99.6	95.0	96.9	94.9	112.8	95.1	94.7	94.8	101.2	100.4
	30	99.0	95.2	95.2	95.1	112.8	94.6	94.7	94.7	100.2	
	500	96.0	95.7	95.9	95.0	108.8	94.6		94.7		
High-Frequency Cetaceans	5	99.2	94.6	96.5	94.5	110.9	94.9	94.4	94.5	101.0	99.6
	30	98.8	94.7	94.7	94.6	111.2	94.3	94.4	94.3	100.0	
	500	95.3	95.0	95.2	94.5	107.4	94.3		94.4		
Unweighted	5	100.7	98.7	99.3	96.9	117.3	96.6	96.5	96.8	102.1	102.3
	30	104.0	104.9	103.0	101.0	121.2	97.2	96.8	97.2	101.3	
	500	107.4	105.3	107.0	100.8	119.4	99.8		97.8		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 19. Alternative F2 (area closures and 25% reduction): Time-averaged equivalent sound pressure levels (*Leq*) above ambient at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	4.4	2.7	2.2	0.8	21.3	0.5	0	0.3	4.9	0
	30	7.4	8.0	6.0	4.6	24.9	1.0	0	0.6	4.0	
	500	10.3	8.4	7.2	3.7	22.3	3.6		1.0		
Mid-Frequency Cetaceans	5	5.0	0.4	2.2	0.2	18.2	0.5	0	0.2	6.5	0.1
	30	4.4	0.6	0.6	0.4	18.1	0	0	0	5.5	
	500	1.4	1.0	1.1	0.3	14.1	0		0		
High-Frequency Cetaceans	5	4.9	0.3	2.1	0.2	16.5	0.5	0	0.2	6.7	0.1
	30	4.4	0.4	0.4	0.3	16.9	0	0	0	5.6	
	500	1.0	0.7	0.8	0.2	13.0	0		0		
Unweighted	5	4.3	2.6	2.2	0.8	21.2	0.5	0	0.3	4.8	0
	30	7.7	8.8	6.5	4.8	25.1	1.1	0	0.7	3.9	
	500	11.1	9.1	8.4	4.2	22.7	3.6		1.2		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

4.3. Listening Area

Tables 20–27 present the calculated change in listening area for each receiver site and depth for all modeled alternatives.

Table 20. Alternative C relative to Alternative A (no activity): Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	22.1	43.7	55.7	76.0	0.6	72.2	100	75.5	17.7	98.6
	30	13.6	7.7	22.9	21.6	0.2	55.0	100	61.2	29.7	-
	500	6.2	7.1	17.6	29.9	0.3	21.9	-	45.8	-	-
Mid-Frequency Cetaceans	5	18.0	87.5	54.4	91.3	0.9	73.5	100	82.2	9.9	97.9
	30	25.8	80.7	88.7	84.8	1.2	98.7	100	98.8	18.8	-
	500	71.8	72.3	77.4	87.8	4.1	95.7	-	98.0	-	-
High-Frequency Cetaceans	5	18.5	91.6	54.6	93.6	1.0	72.5	100	83.1	9.4	97.6
	30	25.8	86.4	92.7	90.9	1.4	99.3	100	99.4	18.1	-
	500	80.3	78.9	84.5	92.0	5.9	97.4	-	98.8	-	-
Unweighted	5	22.7	42.6	55.8	75.7	0.6	72.6	100	75.0	18.4	98.6
	30	11.9	6.4	21.2	19.7	0.2	50.4	100	56.2	30.3	-
	500	4.9	5.5	14.7	26.3	0.3	17.2	-	39.9	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 21. Alternative E (25% reduction) relative to Alternative A (no activity): Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	28.5	51.3	63.1	80.9	0.8	77.8	100	80.6	23.3	99.0
	30	18.1	10.4	29.1	27.5	0.2	62.4	100	68.1	36.7	-
	500	8.4	9.6	22.7	36.7	0.5	27.8	-	53.4	-	-
Mid-Frequency Cetaceans	5	23.7	90.3	61.9	93.4	1.3	78.9	100	86.1	13.7	98.4
	30	32.5	84.9	91.3	88.2	1.7	99.0	100	99.1	24.2	-
	500	77.4	77.8	82.1	90.6	5.6	96.7	-	98.5	-	-
High-Frequency Cetaceans	5	24.4	93.6	62.0	95.1	1.4	78.0	100	86.8	13.1	98.2
	30	32.4	89.5	94.5	93.1	2.0	99.5	100	99.5	23.4	-
	500	84.5	83.3	87.9	93.9	8.1	98.0	-	99.1	-	-
Unweighted	5	29.2	50.1	63.2	80.7	0.8	78.2	100	80.2	24.1	99.0
	30	15.9	8.7	27.1	25.4	0.2	58.0	100	63.5	37.4	-
	500	6.7	7.6	19.3	32.8	0.4	22.3	-	47.4	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 22. Alternative F1 (area closures) relative to Alternative A (no activity): Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	17.4	39.9	41.9	75.1	0.2	80.3	100	89.9	15.0	98.1
	30	8.2	7.8	13.0	20.6	0.1	68.2	100	79.1	25.4	-
	500	4.5	6.9	9.6	28.6	0.1	29.2	-	70.1	-	-
Mid-Frequency Cetaceans	5	14.2	86.1	42.0	91.0	0.5	80.8	100	92.1	8.3	97.2
	30	21.3	79.6	80.4	84.2	0.4	99.8	100	99.6	16.0	-
	500	62.3	68.7	67.4	89.8	1.4	98.9	-	99.5	-	-
High-Frequency Cetaceans	5	14.6	90.4	42.7	93.3	0.7	80.3	100	92.7	7.9	96.8
	30	20.9	85.9	86.9	90.5	0.6	99.9	100	99.8	15.4	-
	500	70.5	77.7	75.0	93.2	1.9	99.4	-	99.7	-	-
Unweighted	5	17.9	40.5	41.9	74.8	0.2	80.4	100	89.8	15.6	98.2
	30	7.5	6.2	11.2	18.8	0.1	65.4	100	75.8	26.2	-
	500	3.6	5.6	6.6	25.2	0.1	28.8	-	64.1	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 23. Alternative F2 (area closures and 25% reduction) relative to Alternative A (no activity): Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	23.0	47.4	49.7	80.2	0.3	84.6	100	92.3	20.1	98.6
	30	11.2	10.5	17.3	26.4	0.1	74.3	100	83.5	31.9	-
	500	6.1	9.4	12.9	35.4	0.2	36.1	-	75.9	-	-
Mid-Frequency Cetaceans	5	19.1	89.2	49.9	93.1	0.7	85.0	100	94.0	11.6	97.9
	30	27.3	83.9	84.6	87.7	0.6	99.8	100	99.7	20.9	-
	500	69.0	74.7	73.5	92.2	2.0	99.2	-	99.6	-	-
High-Frequency Cetaceans	5	19.6	92.7	50.6	94.9	1.0	84.5	100	94.4	11.1	97.5
	30	26.8	89.1	89.9	92.7	0.8	99.9	100	99.9	20.1	-
	500	76.2	82.3	80.1	94.9	2.7	99.5	-	99.8	-	-
Unweighted	5	23.6	48.0	49.8	80.0	0.3	84.6	100	92.2	20.8	98.6
	30	10.2	8.4	15.0	24.3	0.1	71.8	100	80.8	32.8	-
	500	4.9	7.6	9.1	31.5	0.2	35.7	-	70.6	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 24. Alternative E (25% reduction) relative to Alternative C: Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	129.1	117.4	113.3	106.5	140.7	107.7	100	106.7	131.8	100.3
	30	132.5	135.3	127.0	127.7	142.0	113.4	100	111.2	123.5	-
	500	135.2	136.0	129.5	123.1	141.0	127.1	-	116.5	-	-
Mid-Frequency Cetaceans	5	131.8	103.3	113.8	102.2	140.3	107.3	100	104.8	137.7	100.5
	30	125.6	105.1	102.9	104.0	140.7	100.3	100	100.3	129.0	-
	500	107.7	107.6	106.1	103.2	137.6	101.1	-	100.5	-	-
High-Frequency Cetaceans	5	131.4	102.2	113.7	101.6	140.2	107.7	100	104.5	138.2	100.6
	30	125.7	103.5	101.9	102.3	140.5	100.2	100	100.2	129.3	-
	500	105.2	105.7	104.1	102.1	136.2	100.7	-	100.3	-	-
Unweighted	5	128.8	117.8	113.3	106.6	140.6	107.6	100	106.9	131.4	100.3
	30	133.7	136.2	127.9	128.7	142.0	115.1	100	113.0	123.2	-
	500	136.1	137.1	131.1	124.7	141.1	129.6	-	118.9	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 25. Alternative F1 (area closures) relative to Alternative C: Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	78.7	91.3	75.2	98.8	34.7	111.2	100	119.1	84.8	99.5
	30	60.0	100.9	57.0	95.4	39.9	124.0	100	129.1	85.6	-
	500	72.1	97.4	54.6	95.9	42.7	133.8	-	153.1	-	-
Mid-Frequency Cetaceans	5	78.9	98.4	77.3	99.6	51.7	110.0	100	112.2	84.1	99.3
	30	82.6	98.6	90.6	99.2	34.9	101.1	100	100.8	85.0	-
	500	86.8	95.0	87.0	102.3	34.5	103.4	-	101.6	-	-
High-Frequency Cetaceans	5	78.6	98.7	78.3	99.7	74.2	110.8	100	111.6	84.0	99.1
	30	81.1	99.4	93.7	99.5	42.8	100.6	100	100.5	84.8	-
	500	87.8	98.5	88.8	101.4	32.8	102.0	-	100.9	-	-
Unweighted	5	78.7	95.1	75.2	98.8	34.4	110.7	100	119.7	84.9	99.5
	30	62.9	96.9	52.9	95.3	38.9	129.7	100	134.9	86.2	-
	500	72.7	100.7	45.0	95.6	50.5	167.6	-	160.9	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 26. Alternative F2 (area closures and 25% reduction) relative to Alternative E (25% reduction): Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	80.6	92.4	78.8	99.1	34.8	108.7	100	114.5	86.0	99.6
	30	61.7	100.9	59.5	95.8	39.9	119.2	100	122.6	87.0	-
	500	72.8	97.5	56.6	96.3	42.8	130.0	-	142.2	-	-
Mid-Frequency Cetaceans	5	80.5	98.8	80.6	99.7	51.9	107.8	100	109.2	85.0	99.4
	30	84.1	98.9	92.6	99.4	35.1	100.8	100	100.6	86.0	-
	500	89.2	96.0	89.5	101.8	35.1	102.6	-	101.2	-	-
High-Frequency Cetaceans	5	80.3	99.0	81.5	99.8	74.3	108.4	100	108.8	84.8	99.3
	30	82.8	99.5	95.1	99.6	43.1	100.4	100	100.4	85.9	-
	500	90.2	98.8	91.1	101.0	33.5	101.5	-	100.7	-	-
Unweighted	5	80.6	95.8	78.8	99.1	34.5	108.3	100	115.0	86.2	99.6
	30	64.4	97.0	55.4	95.7	39.0	123.8	100	127.3	87.6	-
	500	73.2	100.7	46.8	96.1	50.5	160.0	-	149.1	-	-

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 27. Alternative F2 (area closures and 25% reduction) relative to Alternative F1 (area closures): Remainder of listening area (%) at each receiver site with M-weighting for low- , mid-, and high-frequency cetaceans and without weighting.

Hearing Group	Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
Low-Frequency Cetaceans	5	132.2	118.9	118.7	106.8	141.1	105.3	100	102.6	133.7	100.5
	30	136.3	135.2	132.6	128.3	142.1	108.9	100	105.6	125.5	-
	500	136.4	136.1	134.3	123.6	141.3	123.5	-	108.3	-	-
Mid-Frequency Cetaceans	5	134.5	103.6	118.7	102.3	140.8	105.2	100	102.0	139.2	100.7
	30	128.0	105.5	105.3	104.2	141.6	100.1	100	100.1	130.6	-
	500	110.7	108.7	109.2	102.6	139.9	100.3	-	100.1	-	-
High-Frequency Cetaceans	5	134.2	102.5	118.4	101.7	140.5	105.3	100	101.9	139.5	100.8
	30	128.2	103.7	103.4	102.4	141.4	100	100	100	130.9	-
	500	108.1	106.0	106.8	101.7	139.4	100.2	-	100.1	-	-
Unweighted	5	131.9	118.6	118.7	106.9	141.1	105.3	100	102.6	133.3	100.5
	30	136.9	136.3	133.8	129.3	142.1	109.8	100	106.6	125.2	-
	500	137.1	137.1	136.4	125.2	141.3	123.7	-	110.2	-	-

* Cells without values indicate that the site was too shallow to place a receiver at the specified depth.

4.4. Bryde's Whale Communication Space

Tables 29–36 present the relative changes in Bryde's whale communication space for all modeled alternatives based on communication in the 1/3-octave band centered at 100 Hz. The baseline levels (SPLs for Alternative A; Table 28) used in these comparisons were calculated for the same frequency band.

Table 28. Baseline (Alternative A; no activity) SPL (dB re 1 µPa) for 100 Hz for each receiver site and depth.

Receiver Depth (m)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7*	Site 8	Site 9*	Site 10*
5	79.18	76.18	80.21	76.26	76.27	76.13	79.93	79.98	80.70	86.66
30	78.15	76.20	78.95	76.44	76.59	76.19	81.66	79.05	80.59	
500	78.12	77.63	83.46	80.66	80.71	76.86		79.75		

* Cells without values correspond to receiver depths that do not exist at shallow sites.

Table 29. Alternative C relative to Alternative A (no activity): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative A area (km²)	Alternative C area (km²)	Δ area (km²)	% of original area
1	5	98.2	49.4	48.8	50
	30	190.9	31.5	159.4	16
	500	182.2	19.2	163.1	11
2	5	186.8	40.9	145.9	22
	30	286.7	51.7	235.0	18
	500	232.1	28.0	204.1	12
3	5	108.4	76.2	32.2	70
	30	186.7	82.7	104.0	44
	500	81.5	26.3	55.1	32
4	5	164.5	77.0	87.6	47
	30	252.3	55.5	196.9	22
	500	135.1	30.9	104.2	23
5	5	0.8	0	0.8	5
	30	4.3	0.2	4.1	4
	500	26.3	0	26.3	0
6	5	186.1	173.1	13.0	93
	30	290.1	244.4	45.6	84
	500	271.3	117.3	154.0	43
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	81.9	79.4	2.5	97
	30	195.3	167.9	27.4	86
	500	159.3	116.6	42.7	73
9*	5	34.1	34.0	0	100
	30	97.8	97.5	0.3	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 30. Alternative E (25% reduction) relative to Alternative A (no activity): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative A area (km^2)	Alternative E area (km^2)	Δ area (km^2)	% of original area
1	5	98.2	57.9	40.3	59
	30	190.9	43.0	148.0	23
	500	182.2	23.9	158.3	13
2	5	186.8	53.1	133.7	28
	30	286.7	70.6	216.1	25
	500	232.1	37.1	195.0	16
3	5	108.4	83.1	25.3	77
	30	186.7	97.6	89.1	52
	500	81.5	30.8	50.7	38
4	5	164.5	91.3	73.2	55
	30	252.3	77.3	175.0	31
	500	135.1	41.6	93.5	31
5	5	0.8	0	0.8	5
	30	4.3	0.2	4.1	5
	500	26.3	0	26.3	0
6	5	186.1	176.1	10.0	95
	30	290.1	254.9	35.2	88
	500	271.3	141.7	129.6	52
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	81.9	80.1	1.9	98
	30	195.3	174.3	21.1	89
	500	159.3	125.3	34.0	79
9*	5	34.1	34.1	0	100
	30	97.8	97.6	0.2	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 31. Alternative F1 (area closures) relative to Alternative A (no activity): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative A area (km²)	Alternative F1 area (km²)	Δ area (km²)	% of original area
1	5	98.2	34.4	63.7	35
	30	190.9	19.9	171.0	10
	500	182.2	12.9	169.3	7
2	5	186.8	27.3	159.5	15
	30	286.7	57.5	229.2	20
	500	232.1	24.0	208.2	10
3	5	108.4	49.7	58.6	46
	30	186.7	51.8	134.9	28
	500	81.5	19.7	61.8	24
4	5	164.5	74.3	90.3	45
	30	252.3	51.9	200.4	21
	500	135.1	30.3	104.8	22
5	5	0.8	0	0.8	3
	30	4.3	0.1	4.2	3
	500	26.3	0	26.3	0
6	5	186.1	180.2	5.9	97
	30	290.1	276.8	13.2	95
	500	271.3	176.6	94.7	65
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	81.9	81.2	0.8	99
	30	195.3	188.6	6.7	97
	500	159.3	146.4	12.9	92
9*	5	34.1	34.1	0	100
	30	97.8	97.4	0.4	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 32. Alternative F2 (area closures and 25% reduction) relative to Alternative A (no activity): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative A	Alternative F2	Δ area (km²)	% of original area
		area (km²)	area (km²)		
1	5	98.2	41.4	56.8	42
	30	190.9	27.4	163.6	14
	500	182.2	17.5	164.7	10
2	5	186.8	34.9	151.9	19
	30	286.7	77.5	209.2	27
	500	232.1	31.6	200.5	14
3	5	108.4	57.4	50.9	53
	30	186.7	65.8	120.9	35
	500	81.5	22.6	58.9	28
4	5	164.5	88.8	75.8	54
	30	252.3	74.1	178.3	29
	500	135.1	40.8	94.3	30
5	5	0.8	0	0.8	3
	30	4.3	0.2	4.1	4
	500	26.3	0	26.3	0
6	5	186.1	181.6	4.5	98
	30	290.1	280.1	9.9	97
	500	271.3	195.5	75.8	72
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	81.9	81.4	0.6	99
	30	195.3	190.3	5.1	97
	500	159.3	149.4	9.9	94
9*	5	34.1	34.0	0	100
	30	97.8	97.5	0.3	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 33. Alternative E (25% reduction) relative to Alternative C: Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative C area (km²)	Alternative E area (km²)	Δ area (km²)	% of original area
1	5	49.4	57.9	−8.5	117
	30	31.5	43.0	−11.5	136
	500	19.2	23.9	−4.7	125
2	5	40.9	53.1	−12.3	130
	30	51.7	70.6	−18.9	137
	500	28.0	37.1	−9.1	132
3	5	76.2	83.1	−6.9	109
	30	82.7	97.6	−14.9	118
	500	26.3	30.8	−4.5	117
4	5	77.0	91.3	−14.3	119
	30	55.5	77.3	−21.8	139
	500	30.9	41.6	−10.7	135
5	5	0.038	0.043	−0.005	113
	30	0.182	0.212	−0.030	116
	500	0	0	0	
6	5	173.1	176.1	−3.0	102
	30	244.4	254.9	−10.4	104
	500	117.3	141.7	−24.4	121
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	79.4	80.1	−0.6	101
	30	167.9	174.3	−6.4	104
	500	116.6	125.3	−8.7	107
9*	5	34.0	34.1	0	100
	30	97.5	97.6	−0.1	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 34. Alternative F1 (area closures) relative to Alternative C (no activity): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative C area (km^2)	Alternative F1 area (km^2)	Δ area (km^2)	% of original area
1	5	49.4	34.4	15.0	70
	30	31.5	19.9	11.6	63
	500	19.2	12.9	6.2	67
2	5	40.9	27.3	13.6	67
	30	51.7	57.5	−5.9	111
	500	28.0	24.0	4.0	86
3	5	76.2	49.7	26.4	65
	30	82.7	51.8	30.9	63
	500	26.3	19.7	6.7	75
4	5	77.0	74.3	2.7	96
	30	55.5	51.9	3.5	94
	500	30.9	30.3	0.6	98
5	5	0.038	0.023	0.015	61
	30	0.182	0.123	0.059	68
	500	0	0	0	
6	5	173.1	180.2	−7.1	104
	30	244.4	276.8	−32.4	113
	500	117.3	176.6	−59.3	151
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	79.4	81.2	−1.7	102
	30	167.9	188.6	−20.7	112
	500	116.6	146.4	−29.8	126
9*	5	34.0	34.1	0	100
	30	97.5	97.4	0	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 35. Alternative F2 (area closures and 25% reduction) relative to Alternative E (25% reduction): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative E area (km^2)	Alternative F2 area (km^2)	Δ area (km^2)	% of original area
1	5	57.9	41.4	16.5	71
	30	43.0	27.4	15.6	64
	500	23.9	17.5	6.4	73
2	5	53.1	34.9	18.2	66
	30	70.6	77.5	−6.9	110
	500	37.1	31.6	5.5	85
3	5	83.1	57.4	25.6	69
	30	97.6	65.8	31.9	67
	500	30.8	22.6	8.2	73
4	5	91.3	88.8	2.5	97
	30	77.3	74.1	3.3	96
	500	41.6	40.8	0.8	98
5	5	0.043	0.028	0.015	65
	30	0.212	0.151	0.061	71
	500	0	0	0	
6	5	176.1	181.6	−5.5	103
	30	254.9	280.1	−25.3	110
	500	141.7	195.5	−53.8	138
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	80.1	81.4	−1.3	102
	30	174.3	190.3	−16.0	109
	500	125.3	149.4	−24.1	119
9*	5	34.1	34.0	0	100
	30	97.6	97.5	0.1	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

Table 36. Alternative F2 (area closures and 25% reduction) versus Alternative F1 (area closures): Bryde's whale communication space at all receiver sites.

Site	Receiver Depth (m)	Alternative F1 area (km^2)	Alternative F2 area (km^2)	Δ area (km^2)	% of original area
1	5	34.4	41.4	−6.9	120
	30	19.9	27.4	−7.4	137
	500	12.9	17.5	−4.6	135
2	5	27.3	34.9	−7.6	128
	30	57.5	77.5	−20.0	135
	500	24.0	31.6	−7.6	132
3	5	49.7	57.4	−7.7	115
	30	51.8	65.8	−14.0	127
	500	19.7	22.6	−2.9	115
4	5	74.3	88.8	−14.5	120
	30	51.9	74.1	−22.1	143
	500	30.3	40.8	−10.6	135
5	5	0.023	0.028	−0.005	122
	30	0.123	0.151	−0.028	123
	500	0	0	0	
6	5	180.2	181.6	−1.5	101
	30	276.8	280.1	−3.3	101
	500	176.6	195.5	−18.9	111
7*	5	60.4	60.4	0	100
	30	110.1	110.1	0	100
8	5	81.2	81.4	−0.2	100
	30	188.6	190.3	−1.7	101
	500	146.4	149.4	−3.0	102
9*	5	34.1	34.1	0	100
	30	97.4	97.5	−0.1	100
10*	5	3.5	3.5	0	100

* Sites 7, 9, and 10 are located in areas too shallow to place a receiver at the 500 m depth, and Site 10 is located in an area too shallow to place a receiver at the 30 or 500 m depths.

5. Discussion and Conclusion

This assessment applied acoustic modeling to determine changes to Bryde's whale communication space and changes in listening area (all species), caused by the introduction of various seismic survey activities in the Gulf of Mexico. Ten receiver sites were modeled (Table 1, Figure 1) for five alternatives of seismic survey activity (Table 3), representing possible levels of annual survey activity across six geographic activity zones comprising the project area (Figure 1). The assessment results for change in listening area are presented in Tables 20–27, and results for Bryde's whale communication space are presented in Tables 28–36.

The key findings of this acoustic effects assessment are:

- Communication space and listening area decreased for all alternatives relative to the no-activity Alternative A, except at Site 7. Change in listening area was generally greater for low-frequency cetaceans than for mid- and high-frequency cetaceans.
- The largest decreases, by up to 99.9% of listening area (low-frequency cetaceans) and up to 100% of Bryde's whale communication space, occurred at Site 5 for reasons outlined below. The decreases in communication space and listening area at other sites were highly variable (between 0.1% and 95%). The amount of change depended on the location, receiver depth, and marine mammal frequency weighting filter used.
- Bryde's whale communication space and low-frequency cetacean listening area reductions were greater at the 500 m receiver depth than at the shallower receiver depths (5 and 30 m). That was attributed to the downward refracting sound speed profile near the surface, caused by the thermocline steering sound to deeper depths. It was also influenced by surface interactions that increase transmission loss (lower anthropogenic levels) at shallow depths for low frequencies.
- Listening area reductions for mid- and high-frequency cetaceans were substantially lower than for low-frequency cetaceans at most sites. Change in listening areas were generally small (> 75% remaining) except at Sites 1, 5, and 9. The listening area reductions were not systematically greater at depth, and in fact in some cases were less.

5.1. Site-Specific Results

- Site 1 (Western Gulf, 842 m water depth) experienced decreased listening area of up to 93.8% (6.2% remaining) for low-frequency cetaceans. Bryde's whale communication space was decreased by up to 89% (11% remaining), for Alternative C. The proposed area closures and reduced activity alternatives did not appreciably change these results.
- Site 2 (Florida Escarpment, 693 m water depth) experienced decreased listening area of up to 92.9% (7.1% remaining) for low-frequency cetaceans. Bryde's whale communication space was decreased up to 88% (12% remaining), for Alternative C. The proposed area closures and reduced activity alternatives did not appreciably change these results.
- Site 3 (Midwestern Gulf, 830 m water depth) experienced decreased listening area of up to 82.4% (17.6% remaining) for low-frequency cetaceans. Bryde's whale communication space was decreased up to 88% (12% remaining) for Alternative C. The proposed area closures Alternative F1 actually lead to increased noise at Site 3 due to the redistribution of 25% of the activity inside the central planning area into the rest of Zone 4. This resulted in a decreased listening area of 90.4%.
- Site 4 (Sperm Whale Site, 1053 m water depth) experienced decreased listening area of up to 70.1% (29.9% remaining) for low-frequency cetaceans. Bryde's whale communication space was decreased by up to 77% (23% remaining) for Alternative C. The proposed area closures Alternative F1 did not appreciably affect this site even though it lies near the Dry Tortugas closure area.

- Site 5 (Deep Offshore, 3050 m water depth) experienced the largest change to communication space and had the greatest relative reduction in listening area for all alternatives. Communication space was decreased by more than 95% (to less than 5% remaining) for all activity alternatives relative to the no-activity alternative (Alternative A). Listening area was reduced to less than 1% for low-frequency cetaceans and to less than 8% for mid-frequency and high-frequency cetaceans for all alternatives relative to Alternative A. This site experienced the highest anthropogenic noise levels because:
  1. Receiver 5 was located in Zone 4, which has the highest density of seismic pulses.
  2. This receiver site lies in deep water that supports longer-range low-frequency sound propagation than shallower sites. As a result, a larger number of seismic pulses contributed to its accumulated acoustic energy.
- Site 6 (Mississippi Canyon, 1106 m water depth) experienced decreased listening area of up to 78.1% (21.9% remaining) for low-frequency cetaceans. Bryde's whale communication space decreased up to 77% (23% remaining) for Alternative C. Site 6 lies inside the central planning closure area and consequently Alternative F1 led to improved noise conditions, with listening area loss at 70.8% (29.2% remaining) for low-frequency cetaceans compared to the no-activity alternative (Alternative A). This is an increase of the listening area by 7.3% compared to that for Alternative C.
- Site 7 (Bryde's Whale Site, 212 m water depth) experienced the lowest anthropogenic sound levels (L_{eq}) for all alternatives. These L_{eq} were in fact below baseline levels (Alternative A) even for the full activity level described in Alternative C. Consequently, no changes to communication space or listening area were experienced for any of the alternatives. There are three primary reasons for low anthropogenic noise levels at this site:
  1. The ocean sound speed profile is downward refracting and steers sound energy from distant sources into the seabed, where it is absorbed by softer, non-reflective sediments.
  2. Only geotechnical surveys are performed in Zone 5 (Florida shelf), adjacent to this receiver site. The geotechnical surveys are represented by a single small airgun source that produces substantially less acoustic energy than the 3-D airgun array used in other activity zones (see Table 5).
  3. The 2-D and 3-D survey activity levels in Zone 6, in which this receiver resides, are low relative to other sites.
- Site 8 (De Soto Canyon, 919 m water depth) experienced decreased listening area of up to 54.2% (45.8% remaining) for low-frequency cetaceans. Bryde's whale communication space decreased up to 27% (73% remaining) for Alternative C. The proposed area closures for Alternative F1 further improved the noise conditions at this site since it lies on the eastern edge of the central planning closure area. This led to a change in listening area of 24.1% (75.9% remaining) compared to the no-activity alternative (Alternative A).This is an increase of listening area by 30.1% compared to Alternative C.
- Site 9 (Flower Garden Banks National Marine Sanctuary, 88 m water depth) experienced decreased listening area of up to 54.2% (17.7% remaining) for low-frequency cetaceans and up to 90.6% (9.4% remaining) for high-frequency cetaceans. Interestingly, the Bryde's whale communication space decreases did not show this loss and indicated no loss in space for Alternative C. This result was likely due to noise outside of the Bryde's whale call band affecting listening area, but not the Bryde's communication space. The proposed area closures for Alternative F1 did not appreciably change these results even though the site lies in the Flower Garden closure area.
- Site 10 (Bottlenose Dolphin Site, 12 m water depth) was inside the coastal closure area and experienced little low-frequency seismic survey noise and only marginal higher-frequency noise. Its decrease in listening area was by up to 2.4% (97.6% remaining) for high-frequency cetaceans with even smaller decreases for low-frequency cetaceans and mid-frequency cetaceans. The Bryde's whale communication space was unaffected.

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