Acoustic Masking in Marine Ecosystems as a Function of Anthropogenic Sound Sources

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ABSTRACT

Acoustic masking from anthropogenic sound sources is recognized as a potential threat to low-frequency specialists such as the baleen whales. Masking from chronic noise sources has been difficult to quantify and measure at both the individual and population levels. There is evidence for increases in low-frequency ocean noise and sound clutter, often in habitats with whale populations. This raises concern that such sound sources could be a chronic factor in the life histories of individuals and populations. This paper presents and extends a recent analytical paradigm focused on masking from vessel noise to include sounds from seismic airgun arrays. The algorithm quantifies changes in an animal's acoustic communication space as a result of spatial, spectral, and temporal changes in background sound levels. The result is both a functional definition of communication masking for whales, and a metric to quantify the potential for acoustic masking. We apply the method to calculate time-varying measures of masking for singing fin whales, singing humpback whales, singing bowhead whales, and calling right whales.

The primary messages in this paper are:

1. The mechanical and analytical tools exist by which to measure and quantify the spatio-spectral-temporal variability in whale acoustic habitats.
2. We have developed an algorithm to quantify a relative measure of acoustic masking for individuals and populations, and this method also addresses the issue of cumulative impact from multiple sources of masking.
3. By applying these tools to an acoustic data set from a habitat with known levels of shipping traffic we calculate the extent of acoustic masking for different species.

4. The same process can be applied to other sound sources, such as seismic airgun surveys, which are known to occur in and influence whale acoustic habitats.
5. Overall, the results lead to and support the concept of a marine acoustic ecology and the notion that individuals and thus populations incur a cost when there are changes to their acoustic habitats, and those costs are of particular concern when the ecological changes occur at rates and levels to which animals are poorly adapted.

INTRODUCTION

We all know from experience how difficult it is to have a conversation when the noise at a social occasion becomes too loud, or how much better we can hear from a distance when it is quiet outside compared to when it is noisy. The effect of increased noise is basically the same, whether it comes from the wind roaring through the trees, the jet engines of the plane as we take off in flight, the collective din from a nearby highway, or the pounding beat of a sub-woofer in a teenager's car. All such changes in our acoustic milieu make it more difficult to hear and pay attention to acoustic events of importance or interest.

Acoustic interference can be categorized as masking in the clinical sense when the interfering noise is above one's hearing threshold so much so that the sound of interest cannot be perceived or recognized. In some cases, for example in an industrialized work place, prolonged exposure to elevated noise levels can lead to repeated bouts of temporary hearing loss or even permanent hearing loss unless mitigating actions, such as ear protection, are taken. Much of what is known scientifically concerning the short- and long-term consequences of acoustic interference re communication comes from studies with humans. Most of us are aware of the these types of masking scenarios, which are often referred to as "energetic masking' in that the energy of the sound (i.e., sound intensity over time), as well as its general spectral and temporal characteristics, result in a loss on one's ability to perceive sound signals.

The notion that noise from anthropogenic sources night be having an impact on marine mammals was first articulated in a paper by Payne and Webb (1971) in which they proposed that the collective, very-low-frequency noise (< 100Hz) from ocean shipping might reduce the range over which some of the great whales are able to communicate. In a recent paper (Clark et al. in review) we extend that concept of acoustic masking in the marine environment and develop a formalized algorithm to quantify masking at both the level of the individual and population, and the algorithm is generalized so as to calculate a cumulative measure of masking for multiple sound sources. Here we provide a distilled version of that paper because: 1) the review process is not completed so the paper cannot be provided in a "for info" version, 2) we believe the underlying conceptual framework and outcomes of the algorithm's implementation are of importance to the SC's deliberations with respect to long-term and chronic anthropogenic sound impacts on whale populations, and 3) this paper (E10) has some bearing on how the working group might decide to proceed in the coming year in preparation for a renewed conversation on the issue of anthropogenic noise and whales.

The discussion and debate over how marine mammals may be affected by human noise in the ocean (see: National Research Council 2000, 2003, 2005, Cox et al. 2006, Southall et al. 2007), has mostly been directed at understanding the physiological impacts from short-term, small-scale (i.e., acute), high intensity exposures. There is recognition that long-term, large-scale (i.e., chronic), low intensity exposures might also be affecting individuals and populations, and acoustic masking is often mentioned or implied as a probable mechanism (Payne & Webb, 1971, NRC 2000, 2003, Southall 2005, McDonald et al. 2006, Nowacek et al. 2007, Hatch et al. 2008). Models have been created to estimate the spatial extent of masking. One such model for beluga whales (*Delphinapterus leucas*) considered the physical environment as well as both the acoustic behavior and hearing ability of the animal (Erbe & Farmer 2000). Clark et al. (in review) presents an overarching paradigm for measuring the potential for acoustic masking on free-ranging animals, particularly the low-frequency specialists, baleen whales, because this is the group at highest risk from chronic exposure to anthropogenic sounds.

We start by recognizing that there is substantial evidence supporting the conclusion that the mysticetes are highly adapted for producing and perceiving sounds in the low-frequency (< 1000Hz) and very-low-frequency (<100Hz) bands. The physics of sound (i.e., signal propagation and ambient noise) combined with Darwinian selection (natural and sexual, for distance and honest signaling) has resulted in long-distance communication signals that are constrained into low- and very-low-frequency bands (Clark and Ellison 2004). The very same propagation physics to which the whales adapted so as to communicate over great distances via low- and very-low-frequency sounds is the same physics that enables the noisy bi-products and intentional signals produced by humans to persist over very great areas of the ocean. In Clark et al. (in review) we applied and combined the procedures of ocean sound propagation and acoustic communication to derive a metric for acoustic masking. This process is informed by species-specific sound characteristics and several assumptions about signal recognition thresholds. The model is exercised with some empirical ship noise data to reveal how the process results in a standardized metric for communication masking. The results for three different species revealed how different species are impacted differently given the same anthropogenic noise activity. Independent of species, what emerges is the notion that individuals and therefore populations rely on an acoustic habitat for establishing and maintaining normal communications and when their acoustic habitat is degraded, acoustic communication is degraded. This then leads to the concept of an acoustic ecology – the acoustic landscape within which the acoustic communication functions and without which the social system can become dysfunctional. It further leads to the conclusion that there are costs associated with the loss of acoustic habitat (e.g., in the reduction of feeding efficiency, mating success, predator avoidance), and these costs can affect individuals and populations.

It is likely that for a broad range of marine mammals, acoustic masking is having an increasingly prevalent impact on acoustic information transfer including both communication and other key activities such as navigation and prey/predator detection. In an evolutionary time frame relevant to species adaptations, these impacts are both quite recent and relatively rapid. Furthermore, we believe that masking acts on different spatio-spectral-temporal scales, primarily depending on the spatial, frequency and temporal features of the species' communication system. The proximate motivation for this paper is to make the scientific committee aware of the recent development of an intuitive yet quantitative approach for evaluating this acoustic communication masking within a scientific framework.

The Clark et al. (in review) approach expands on some previous syntheses and recent research (*e.g.*, Clark & Ellison 2004, Southall et al. 2007, Hatch et al. 2008). It merges these ideas to introduce the concept of a dynamic spatio-spectral-temporal acoustic habitat and uses this perspective to introduce analytical representations by which to study acoustic masking. In a series of steps, we formalized a protocol that integrates a form of the sonar equation (Urick 1983) with biological knowledge to quantify the affects of masking noise from a single source on the area over which an animal's acoustic communication signal might be recognized by a conspecific. This procedure for a single animal was then expanded to a population of calling animals to quantify the spatio-spectral-temporal distribution and variability of masking and to predict the affect that masking might have on the ability of a population of calling animals to communicate throughout a habitat region. Finally, we generalized the algorithm to include multiple noise sources so as to formalize a method for quantifying the cumulative effects of varying numbers and types of anthropogenic sources.

Concepts

Primary concepts in Clark et al. (in review):

1. *Communication space* is the volume of space surrounding an individual within which acoustic communication with other conspecifics can occur. The size and shape of any particular communication space is influenced by multiple factors which vary over time, some more rapidly than others, such that one must envision the space as fluctuating[1].
2. A central consideration is the effective three-dimensional space over which a bioacoustical activity occurs. This is referred to as the bioacoustic space, and different types of bioacoustic space are characterized by different volumes of ocean within which the acoustic activity occurs, and by the characteristics of the animal attempting to detect that acoustic activity.

[1] The communication space of a caller will vary considerably depending on the source level and directionality of the caller's sound, the caller's depth and orientation, the receiving animal's depth, the sound transmission path between the sender and receiver, and the variability of the ambient noise and other possible interfering sound sources at the receivers' ears over the time period of the sender's communication sound. The spatio-spectral-temporal features of communication space will vary considerably for different species. For example, the communication space of a pilot whale whistling in the 7-15 kHz frequency band will be much smaller than the communication space of a fin whale calling in the 30-80 Hz band, even if the output levels are similar, simply as a result of physical acoustics.

3. The model is quantitative, empirical-data-driven, and tunable for specific species, ocean environments, and noise regimes. Results from the model identify which combinations of physical and environmental variables predict the greatest levels of communication masking and account for the greatest proportions of uncertainty in the spatio-spectral-temporal noise distribution. They also identify which model variables have the greatest influence on the uncertainties in the model's predictions, thereby pointing to research priorities (e.g., metrics for ambient noise prior to or without anthropogenic sound sources, the distances over which whales acoustically communicate).
4. The results quantify the spatio-spectral-temporal dynamics of an ocean volume given the different parameters associated with any particular bioacoustic space and species, where the parameters are a complex mix of biological and physical features.

There are four sub-sets considered in the communication space: *potential*, *actual*, *sender*, and *receiver* communication spaces[2]:

Potential communication space is the volume of space surrounding an individual within which acoustic communication with other conspecifics could occur under ideal conditions.

Actual communication space is the volume of space surrounding an individual within which acoustic communication with other conspecifics actually occurs under natural conditions. Many of the features of actual communication space must be determined empirically, and there are few data quantifying actual communication space for any marine mammal.

Sender communication space is the volume of space surrounding a sound producing animal within which acoustic communication with listening conspecifics could occur.

Receiver communication space is the volume of space surrounding a listening animal within which that animal could recognize the sounds from conspecifics.

The model includes the basic components of source characteristics, acoustic propagation and relative sound exposure, and the result is cast in metrics that provide a methodology for assessing the relative affects of masking on an individual animal's bioacoustic space. The key elements in the model extend from the noise(s) and/or sound(s) experienced by an animal through the initial stage of the animal's auditory process when the sound of interest is recognized.

A series of examples is used to illustrate some of the important concepts and dimensions of masking. Metrics associated with quantifying the masking process are developed. These are

[2] These are not mutually exclusive. Here we simplify the dimensionality of communication space to be an area while recognizing that in many situations it is actually a volume. We also constrain the discussion to noise masking and do not include the condition when clutter is the source of interference.

focused on baleen whales that communicate in species-specific portions of the low-frequency band (< 1000Hz).

Conversion of acoustic scenes into measures of masking requires careful consideration and inclusion of variability in the temporal, spectral and spatial dimensions of the acoustic environment at biologically meaningful resolutions. Therefore, the temporal resolution of the analysis should match the durations of the sounds produced by the species of concern, the spectral resolution should match the frequency bands in which the species communicates, and the spatial resolution should match the area over which the animal communicates.

The noise field around a listening animal is not symmetrical and varies as a function of direction. Furthermore, the spatial directivity of each sound source contributing to an auditory scene varies; some sources are fairly omnidirectional (e.g., very low-frequency whale calls or the rumbling of distant shipping traffic), some are more directional (e.g., high pitched pilot whale whistles or the noise from a small boat passing overhead)[3].

To gain a sense of how sound is distributed throughout the acoustic environment in which a population of whales occurs, one needs to spatially sample a large area that encompasses a representative portion of their acoustic habitat, thus adding the critical dimension of spatial variability to the masking process.

The three primary factors for evaluating the potential that noise masking could occur include the degree to which the noise and the signal overlap along the dimensions of frequency, time and space. The explicit application of biological considerations to tune the selection of parameters representing the degree to which signals and noise overlap in frequency, time and space results in calculations of signal-to-noise ratios (SNR) that are adjusted to species-specific parameters. This yields a biologically informed metric for evaluating the ability of the animal to detect and recognize communication signals under different noise conditions; or, in other words, a metric for estimating the amount by which noise reduces the ability of an animal to hear the sounds of a conspecific or to be heard by a conspecific. The terms for these three factors relative to acoustic communication are:

a. Frequency band: a frequency range covered by a set of 1/3rd-octave frequency bands within which ambient noise could mask a biologically meaningful sound. Here the value of this frequency band is based on the set of 1/3rd-octave bands that span the species-specific communication sounds produced by the species of interest and is recognized as a proxy for the nominal critical bandwidth (Fay 1988).
b. Integration-time: the duration over which ambient noise could mask the recognition of a biologically meaningful sound. The value of this sound recognition, integration-time factor is based on the assumed functional duration of

[3] We are all intimately familiar with this dynamic feature of spatial directivity for noise in our communication space as we constantly contend with it while attending to one speaker against a background of multiple sound sources. Here we recognize that whales have the ability to spatially segregate signals and noise, but we do not specifically include a directionality term in our model of communication space or our calculations of a masking index.

the types of communication sounds produced by the species of interest. In the simple cases addressed here we assume that the noise occurs simultaneously with and throughout the entire duration of the sound, while recognizing that masking can occur when the noise and sound of interest only partially overlap in time or when the noise precedes the sound.

c. Space: the Euclidean space over which ambient noise could mask a communication sound. The value of this acoustic-space factor is based on the assumed functional communication range for the type of sound produced by the species of interest.

A visual entrée into the description and quantification of masking is shown in Figure 1. The top two panels in the figure show 24h spectrograms (i.e., acoustic scenes) based on acoustic data collected with identical recorders in two different habitats with known populations of fin whales; the Gulf of California, a habitat with present-day, low ambient noise conditions, and the Mediterranean Sea, a habitat with high noise conditions. Fin whales were singing in both samples and are very evident in the Baja habitat (Fig. 1A), but barely evident in the Mediterranean habitat which is dominated by shipping noise (Fig. 1B). Panels 1C and 1D quantify spectral energy distributions for the two acoustic scenes with 1C for Baja showing a dominant 20 Hz peak representing the collective voices of fin whale singers, while for the Mediterranean habitat (Fig. 1D) there is no apparent 20 Hz peak, and the contribution of singers to the spectral energy distribution is hidden within a broader, 15-80 Hz band of shipping noise.

The application of arrays of autonomous seafloor acoustic recorders is now allowing us to map spatio-spectral-temporal ambient noise variability. Figure 2 shows examples of the spatial distribution of acoustic power in four different frequency bands for a 1-minute sample as collected by an array of 19 seafloor recorders off Massachusetts. The relatively high noise levels (dark red) at the center recorder (approx. 42.4N/70.6W) in A, C and D are a result of noise associated with the construction of a liquefied natural gas terminal offshore of Boston, MA, while the higher level in B is from a singing fin whale located at 42.47N/70.55W. There were no singing humpback whales or calling right whales in the area during this 1-minute sample.

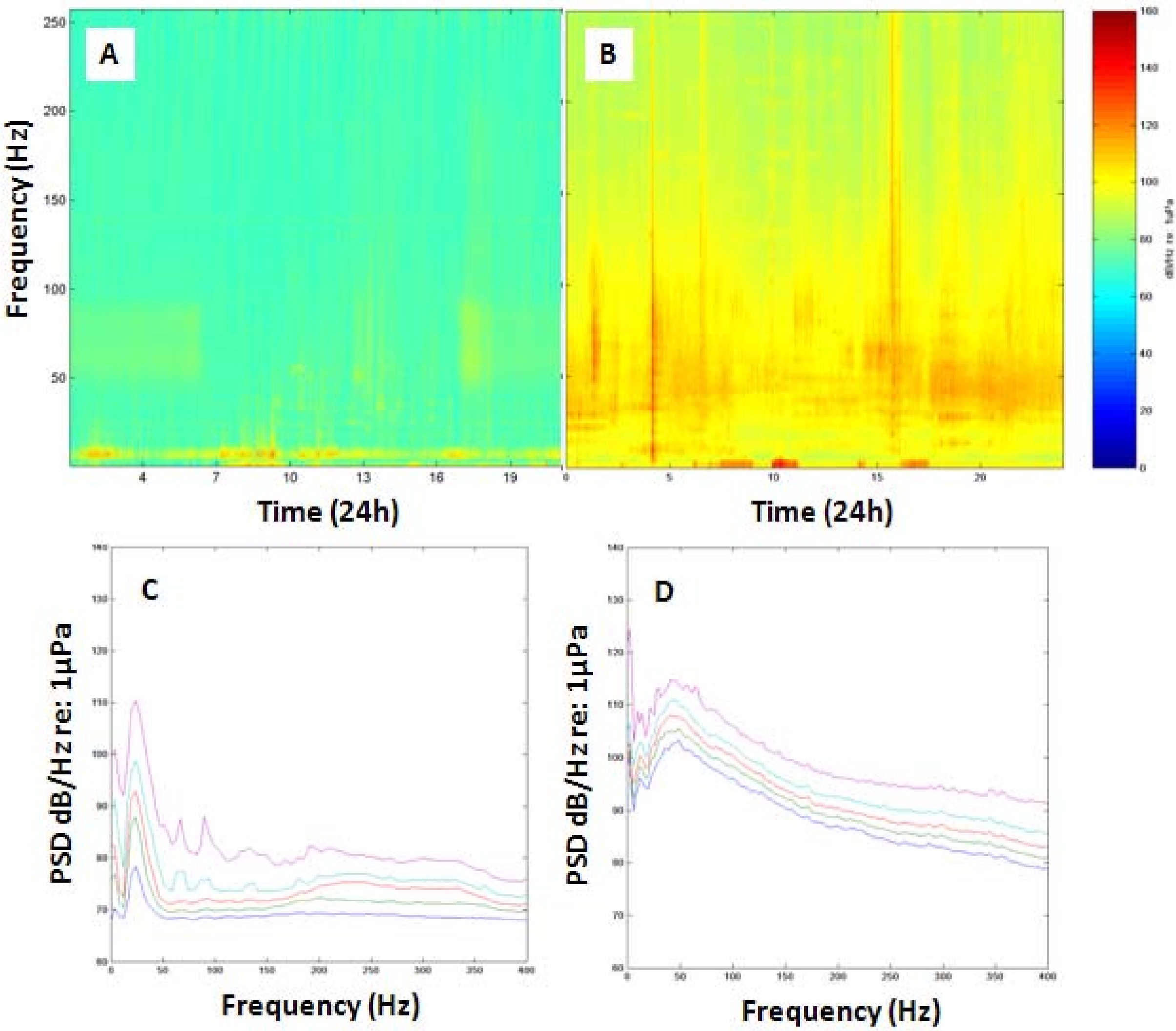

Figure 1. Examples of 24-h acoustic scenes for two habitats in which male fin whales were singing: (A) Gulf of California and (B) Mediterranean Sea. Both recorders were identical with flat (± 1.0 dB) frequency response between 10 – 585 Hz (2 kHz sampling rate, 1024 pt FFT, 50% overlap, Hanning window). Order statistic analysis for the 24-h acoustic samples in which fin whales were singing (C) Gulf of California and (D) Mediterranean Sea [order statistics: 5% (dark blue), 50% (red), and 95% (purple)]. Color bar indicates rms pressure level in dB re 1 µPA.

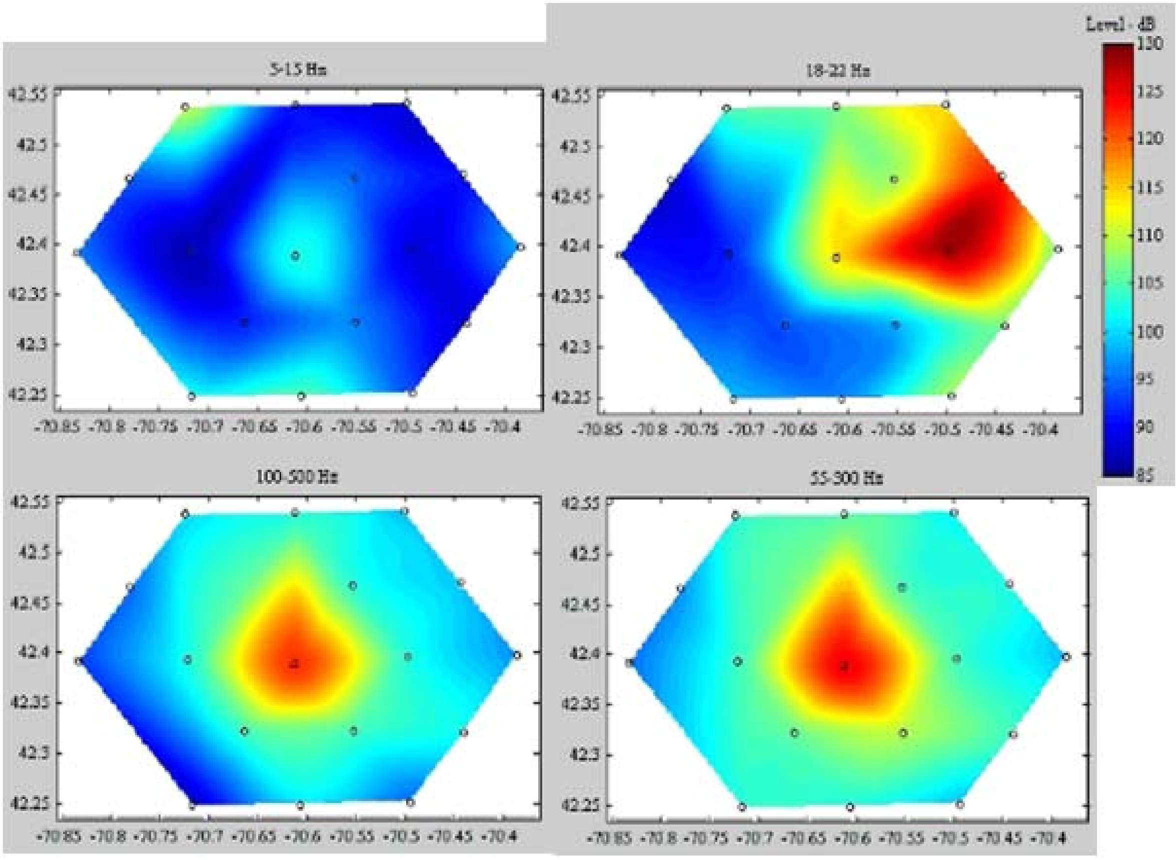

Figure 2. Example of ambient noise fields for four different frequency bands in a 1-minute sample from an array of 19 autonomous seafloor recorders (small open circles) deployed in Massachusetts Bay and centered on a liquefied natural gas construction site: (A) acoustic noise field in the 5-15Hz frequency band; (B) acoustic noise field in the 18-22Hz fin whale band; (C) acoustic noise field in the 100-500Hz humpback whale band; (D) acoustic noise field in the 55-300Hz right whale band.

These considerations (Figs. 1-2) elicit questions such as: is there an impact on fin whale communication in the Mediterranean Sea from these high levels of low-frequency noise? What is the effect of noise from a passing ship passing on right whales communication? How does a whale's communication space vary as a noise source, natural or anthropogenic, varies? What is the impact of a loss of communication space on individual breeding success and the population, and how does this vary by species?

To address these types of questions and provide quantitative answers, we:

1. developed a series of sonar equations to quantify the noise field within which a sending animal could potentially communicate with receiving animals,
2. extended this quantification over the dimensions of space and time so as to quantify the spatial and temporal characteristics of the noise field, including its variability, and

3. decomposed noise into its basic components of ambient noise, specific man-made noise sources, and animal sound sources,
4. accounted for spectral overlap between whale communications and anthropogenic sounds by calculating received levels (RL) and SNR levels in the 1/3rd octave bands bounding the communication signal of interest (e.g., a contact call or song),
5. accounted for temporal overlap by calculating RLs and SNR levels in the 1/3rd octave bands bounding the communication signal of interest for time windows matching the durations of the communication signal of interest (e.g., 2 seconds for a right whale contact call or 10 seconds for a humpback song phrase), and
6. accounted for spatial overlap by limiting the masking area by an assumed communication distance for the signal of interest (e.g., 20 km).

Given that one constrains masking to overlapping spectral, temporal and spatial dimensions, the masking metric is primarily a matter of SNR at a receiver, *R*, for a signal from a sender, *S*, where SNR is calculated for the species-specific frequency band and measured as:

$SNR_R = RL_R – NL_R$, in dB (this is a ratio, so no reference unit) (1a)
RL_R = 10Log[Received Signal Intensity at receiving whale /Reference Intensity] (1b)
NL_R = 10Log[Noise Intensity at receiving whale/Reference Intensity] (1c)
$RL_R = SL_S – TL_S$, where (1d)

SL = Source level of sound as emitted with reference to a 1m distance, dB re 1µPa @1m.
RL = Receive level of sound at a receiver some distance from the source, dB re 1µPa.
TL = One way transmission loss between sound source and receiver inclusive of spreading losses, refraction, scattering, absorption and other boundary losses, in dB (ratio, there is no reference unit).
NL = Noise band level in dB re 1µPa at a receiver, where NL is the sum of ambient noise and noise from specific sources with distinctive spatial and temporal parameters (e.g., ships).

Given that there are multiple sources of noise in addition to ambient noise,

$$NL = NL_A + \sum_1^n NL_n \quad (2)$$

where NL_A is the ambient noise level, and NL_n is the noise level for the nth noise source, the total SNR for a sender's signal at a receiver is:

$$SNR_R = RL_R - NL_A – \sum_1^n (NSL_n – NTL_n) \quad (3)$$

Due to the natural fluctuations of background noise and related features of sounds, communication signals are not normally perceived at a value of SNR = 0, but at some value (receiver system specific) greater than zero. This difference is termed the detection threshold, or

DT, and the relation between DT and SNR is undertaken by another term called signal excess, or SE. This leads to three different expressions for SE at a receiver under different noise conditions.

$$\mathrm{SE}_{\mathrm{AA}} = \mathrm{RL}_R - \mathrm{DT} + 16 - \mathrm{NL}_{\mathrm{AA}} \quad (4a)$$

$$\mathrm{SE}_{\mathrm{PrA}} = \mathrm{RL}_R - \mathrm{DT} + 16 - \sum_1^n(\mathrm{NSL}_n - \mathrm{NTL}_n) \quad (4b)$$

Where the subscript AA refers to ancient ambient, the term (RL_R - DT + 16) defines the condition under which the signal could possibly be perceived by the receiver under ancient ambient noise conditions (i.e., $\mathrm{SE}_{AA} > 0$ dB)[4], PrA is a reference to present conditions, and n is the number of different discrete noise sources.

Quantifying Communication Area for a Single Sender: Figure 3 illustrates Eqs. (4) assuming a normal mode transmission loss function (Porter and Reiss 1985) for two different ambient noise levels; 75 dB representing the ancient ambient noise level in the right whale communication band and 90 dB representing an ambient noise level under present conditions.

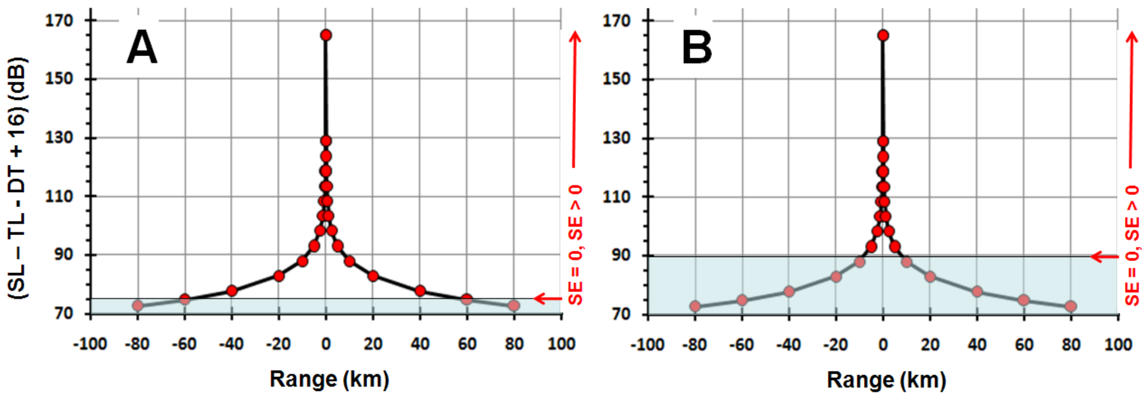

Figure 3. Examples to illustrate the change in communication range under different levels of omnidirectional ambient noise and assuming TL = 20Log[range/1m] for range ≤ 1 km and TL = 60dB + 17Log[range/1km] for range > 1km: (A) NL = 75 dB, range = 60 km, area = 1310 km^2; (B) NL = 90 dB, range = 8 km, area = 201 km^2.

In these simplified cases, the communication area is the area of the circle for which the radius is the range at which SE > 0 dB. This figure illustrates several important features of communication area: 1) the influence of transmission loss on the shape of the SE curve; where TL is always dominated by logarithmic sound attenuation, 2) the resultant rapid fall off in RL, c) the importance of DT and PG, and d) the influence of noise level on the range out to which SE > 0.

[4] An appropriate placeholder for DT common to many sonar systems as well as marine mammals is 10dB (e.g., Kastelein et al. 2007).

We assume that the area within which $SE_{AA} > 0$ dB under ancient ambient conditions defines the area within which communication could possibly occur. We refer to this area as the ***potential sender communication area***. In contrast, we refer to the area within which whales would actually communicate under ancient ambient conditions as the ***actual*** **sender communication area**, which is determined from the range out to which the animals are able to communicate under present noise conditions. For mysticete whales there is a paucity of information about actual communication ranges, and this is an issue that needs research attention.

An important development here is that the value of SE under the ancient ambient noise condition, SE_{AA}, is used as the standard by which to determine the relative area over which communication takes place under a present noise condition. To simplify calculations we assumed that under ancient ambient noise conditions the maximum communication range for fin, humpback and right whales is 20km, for a maximum sender communication area, CA_{Smax}, of 1258 km^2.

Quantifying Communication Space: As the range between a sender and receiver increases and SE approaches 0 dB, the probability of the receiver recognizing the sender's signal decreases. To account for this range dependency, the SE values were weighted throughout the area by a probability-of-recognition term, PR. The weighted maximum communication area for a single animal under ancient ambient noise conditions is referred to as the *maximum sender communication space,* while the weighted communication area for a single animal under present noise conditions is referred to as the *communication space*.

This term *maximum sender communication space* is very important. It serves as the reference against which changes in communication space under different ambient noise conditions are compared. Its value depends on the source level of the sound produced by the sending whale and the environmental conditions under which that signal propagates to a potential population of receivers under ancient ambient noise conditions. It is the relative basis for quantifying communication space under present day noise conditions.

When specific noise sources that have spatial and temporal properties are considered, the noise level surrounding a receiver is dynamic and varies over space through time. That is, the noise terms in Eq. (4) are function of time and the relative positions of the receiver and the noise source(s). Given these considerations one can calculate how much noise from a noise source masks the signal from a sending whale at a receiving whale as the noise source moves through the whales' acoustic space. By using propagation equations to estimate both the RL of the sound from the calling whale and the RL from the noise source at the receiving whale, and by entering these values into Eq. (4) we determine the SE_{PrA} at the receiving whale during the brief moment in time when the whale called. If the $SE_{PrA} < 0$, the noise from the noise source masked the sound from the sending whale. However, even for this static case, this evaluation does not actually provide a full measure of the masking effect of the noise source because it does not include the total loss to the calling whale's communication space as a result of the noise source's passage through the communication area. To adequately quantify masking, we extended this simple notion of masking to include SE_{PrA} variability over a) the entire potential communication space of the calling animal, not just for the geometry of the single pair of animals and b) throughout the period of time when the noise source could potentially interfere with communication between the calling and receiving animals.

For our measure of ancient ambient noise we used a 5^{th} % order statistic noise level value (in the communication frequency band) based on the analysis of at least a month of data under normal conditions. We calculated a sender's maximum communication space under a present noise condition, CS_S, by considering a single sending animal and a hypothetical population of receiving animals, uniformly distributed over an ecologically meaningful area.

By this process, CS_S represents the portion of the communication space (i.e., a value between 0 and 1) available to a sender under the existing noise conditions relative to a sender's maximum communication space under ancient ambient noise conditions. To estimate temporal variation in the communication space for a single sender over a given time period, CS_S values are calculated at regular time intervals through periods when a noise source is possibly influencing the communication space.

Empirical Measures of *Actual* Communication: To exercise the model for calculating an *actual* communication space for a single sender and a population of senders, we used data from an ongoing project in the Stellwagen Bank National Marine Sanctuary (SBNMS). We applied oceanographic data (e.g., bathymetry, seasonal sound velocity profiles), marine mammal data (e.g., acoustic locations and tracks of vocally active whales), commercial shipping data (e.g., tracks, speeds, source levels), and the KRAKEN sound propagation model inside the Acoustic Integration Model for propagation sound field calculations (Frankel et al. 2002). We used two different areas centered on the SBNMS (Fig. 4). One area was considered the area containing all potential senders. This was an area within a circle with a radius that is the range out to which the species is assumed to communicate under ancient ambient conditions (i.e., 20 km). In our examples, this area was gridded into a matrix of 4 km^2 cells, with one sending whale per cell. The second area contains all potential receivers, and is the area within a circle of radius that is equal to twice the species' communication range. This area was also gridded into 4 km^2 cells, with one sending whale per cell. The two matrices were offset and interlaced such that there was a sender in the center of each receiver's 4 km^2 cell, and there was a receiver in the center of each sender's 4 km^2 cell. By this procedure there were 316 receivers in each sender's space and a total of 313 senders in the population. In all these analyses an ancient ambient band level noise value of 75 dB was used for fin, humpback and right whales. The source levels of the ship's noise in the fin, humpback and right whale frequency bands were 181dB, 167dB and 173dB, respectively.

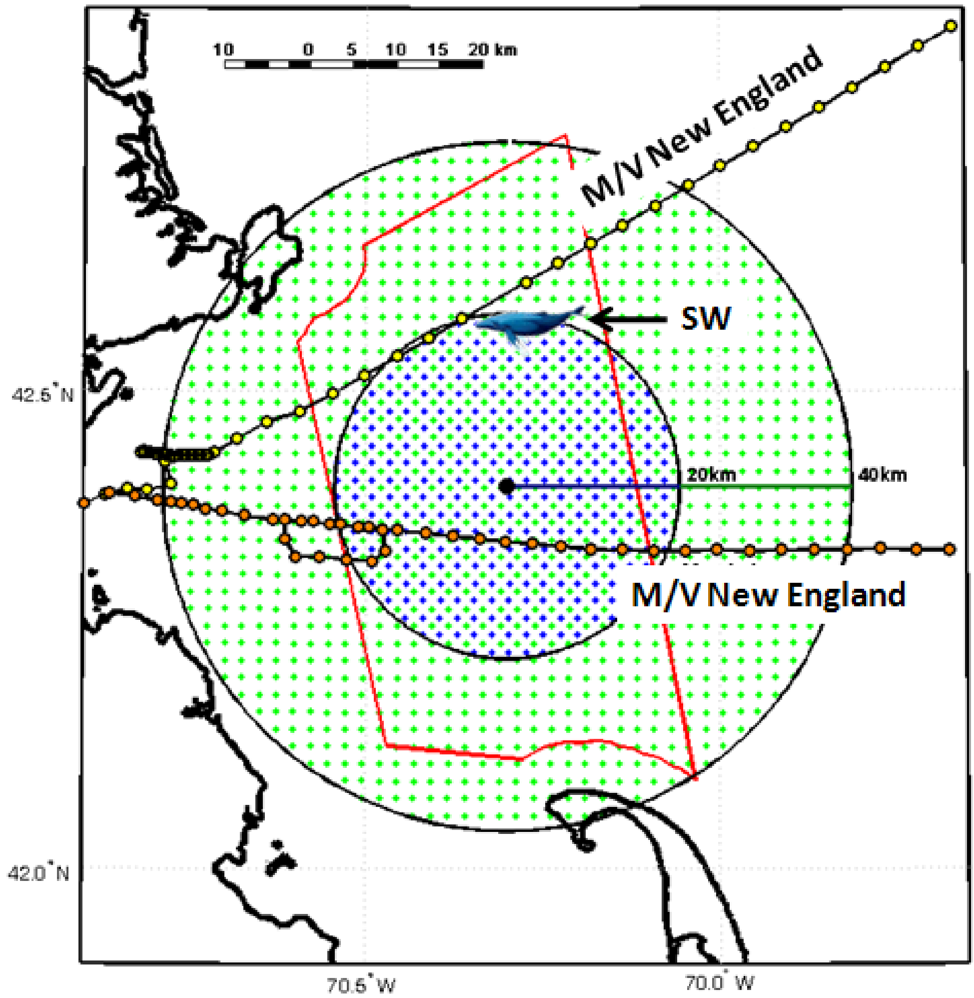

Figure 4. Map showing the distribution of hypothetical population of sending whales (n = 313, light dots) distributed over a circular area of radius = 40km and the distribution of hypothetical population of receiving whales (n = 1258, dark dots) distributed over a circular area of radius = 80km. The tracks of two commercial vessels, the *M/V New England* and the *M/V Marchekan*, that transited through the area on 27 December 2007are shown. Also shown is the position of a calling whale (SW) as used in our example here [Figure 6].

Masking of sender communication space is defined as *the amount of change in a sender's communication space caused by the presence of other sounds, relative to a pre-industrial ambient noise condition*. By the proposed algorithm, measures of communication space masking can be calculated for multiple sound sources, where masking is calculated as the relative difference between masking under ancient ambient noise conditions and a present noise condition. Given all these considerations, the *basic metric for masking is the portion of the communication space that is unavailable for communication*.

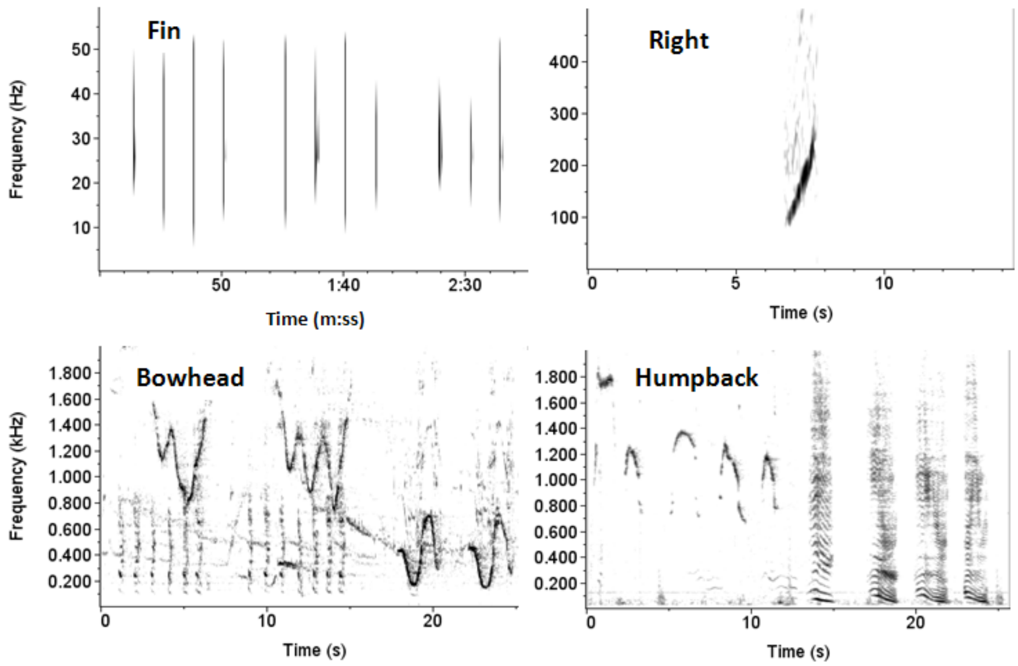

Figure 5. Spectrographic examples of the sounds from fin, humpback, right and bowhead whales

Here, as examples, we first show masking indices for a calling right whale (species in which whales counter-call to maintain contact and initiate social interactions; Clark et al. 2006, Parks et al. 2007), for a singing fin whale and for a singing humpback whale (species in which males produce long sequences of intense sounds that function as male reproductive displays; Payne & McVay 1971, Watkins et al. 1987, Croll et al. 2002), and for populations of senders for all three species; all as a result of two commercial ship moving through the SBNMS area. Figure 5 provides spectrographic examples of the sounds from fin, humpback, right and bowhead whales.

Figure 6 shows the masking indices for the fin, humpback and right whale populations as a result of two ships, the *M/V New England* and the *M/V Marchekan*. The accumulated noise from two ships during the 21h period (01:10h -22:10h) results in masking indices for fin, humpback and right whales of 0.33 (s.d. ± 0.14), 0.11 (s.d. ± 0.06), and 0.84 (s.d. ± 0.16), respectively.

To emulate the potential for masking from seismic airgun survey sounds and the noise from a single ship, we used the same process as above for ship noise masking, but placed the geographic location in the Bering Sea and applied the algorithm to bowhead whales; where the frequency band of interest is 71-224Hz and the whale's rms SL is 170dB. This also assumes the airgun array fires every 10 seconds with source levels 215, 205 and 195 in the 18-28Hz (fin), 71-224Hz (bowhead and right), and 224-708Hz (humpback), respectively. Figure 7 shows spectrographic examples of airgun array sounds as recorded under two contexts; at a range of ca. 20 km in coastal, shallow water and at a range of > 200 km in deep ocean water.

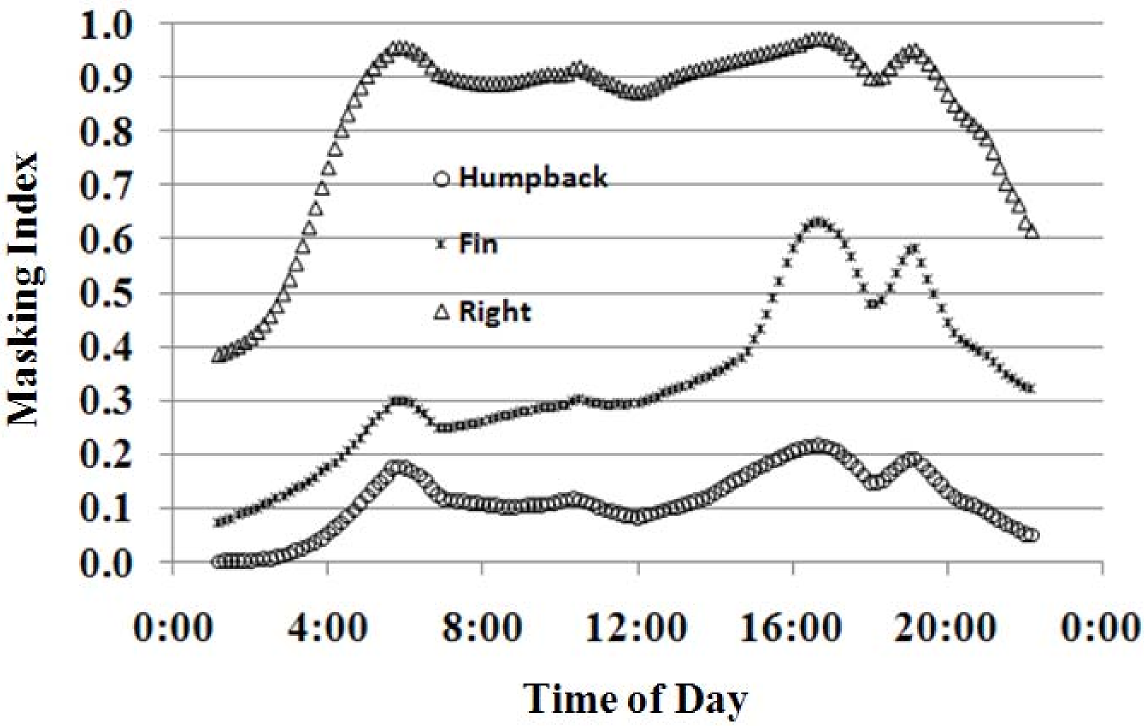

Figure 6. Cummulative masking indices for singing populations of fin and humpback whales and calling right whales on 27 December 2007 as a result of noise from two ships, the *M/V New England* (01:10 – 13:30h) and the *M/V Marchekan* (14:50 – 20:50h). Samples were taken every 10 minutes from 01:10 – 22:10h.

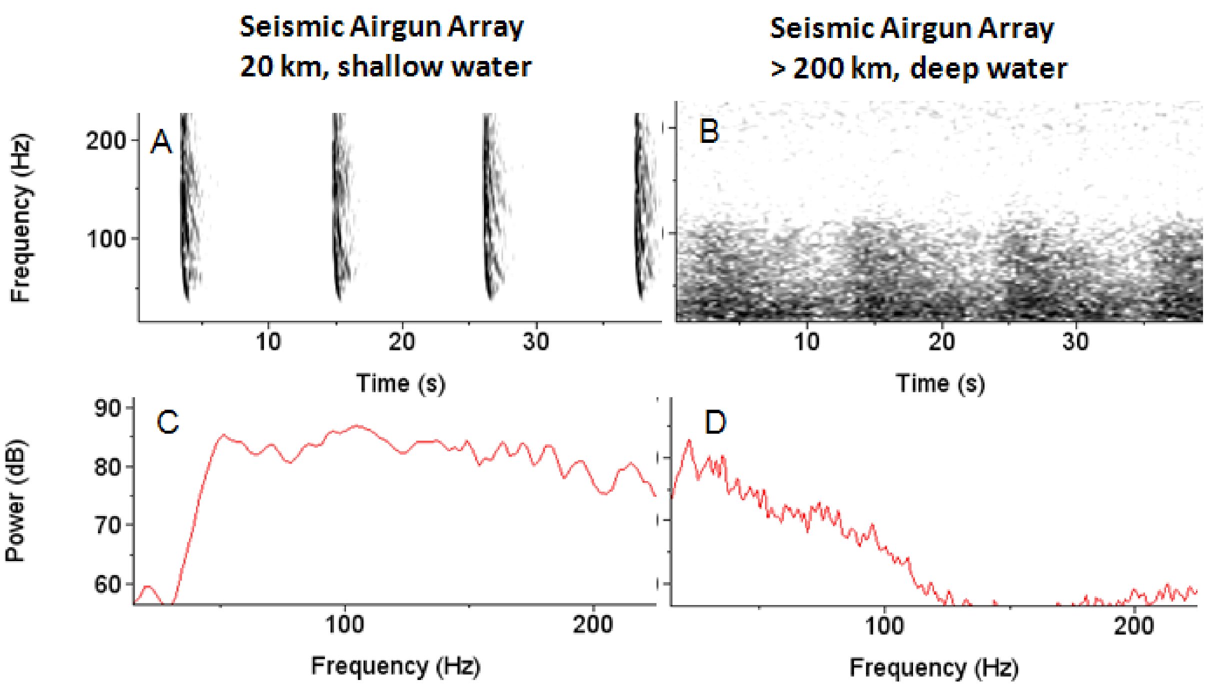

Figure 7. Examples of seismic airgun array sounds as recorded in shallow (< 100m) water and deep water (> 2000m). A and B spectrograms. C and D Power spectral density functions .

Figure 8 shows results when the sounds from a hypothetical seismic airgun array (firing a seismic impulse once every 10 seconds) are added to the noise from a single ship (M/V New England) and the model run for a coastal habitat in the Bering Sea (similar conditions to those off New England).

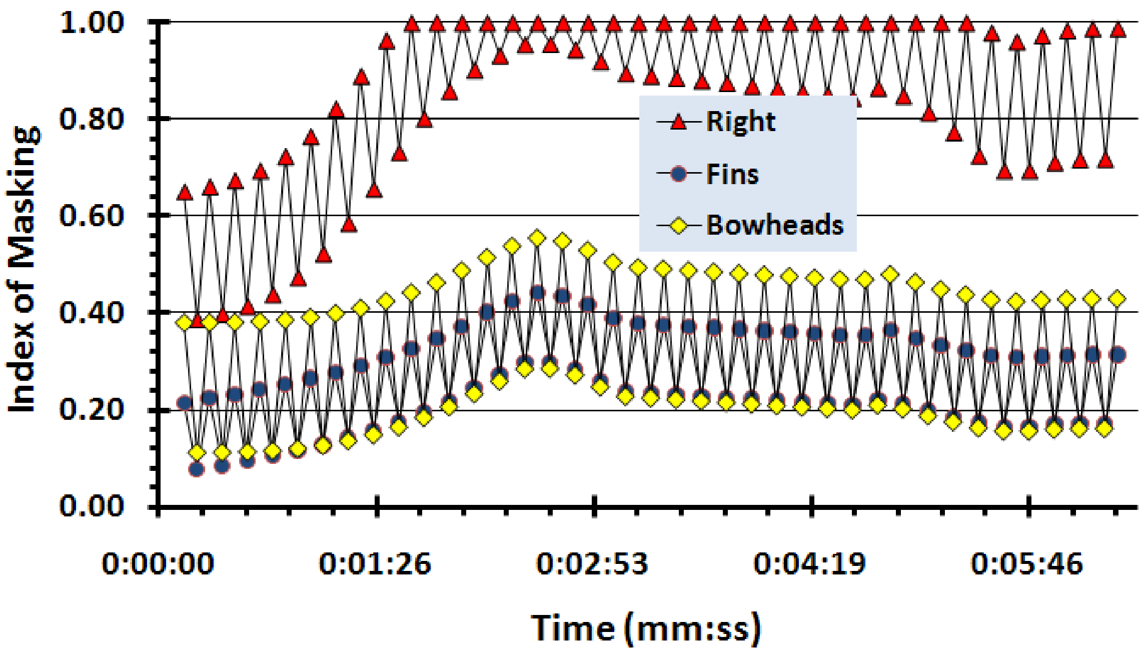

Figure 8. Cummulative masking index for sender populations of fin, right and bowhead whales for a hypothetical situation in the Bering Sea as a result of noise from one ship, the *M/V New England* and sounds from a seismic airgun array. Samples were taken every 5 seconds over a 10 minute period in order to show the temporal details of airgun pulses on the masking index.

SUMMARY

This paper is intended to inform the SC on recent developments of an algorithm for quantifying acoustic masking from commercial shipping (Clark et al. in review) with the added considerations of masking from sounds from seismic airgun surveys, focused on free-ranging baleen whales. The process described provides a mechanism for quantitatively assessing masking for an individual or a population; where masking is the portion of an animal's or population's communication space that is lost during the occurrence of anthropogenic sounds.

This exercise emphasizes the importance of knowing much more about the characteristics of communication sounds, the conditions under which animals actually produce these sounds, and how they might vary their communications under different contexts.

A very important outcome is that this noise masking algorithm can be applied to evaluate the contributions from individual sound sources and the cumulative effect of multiple sources on an individual's or a population's communication space. This issue of cumulative impact has been an intractable issue in the debate regarding noise effects on marine mammals. We believe the algorithm and practical approaches as briefly presented here provide a way forward that is constructive and functional.

We expect that the Clark et al. (now in review) paper will be available as a "For Info" document at next year's SC meeting.

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