The following supplements accompany the article

Communicating amidst the noise: modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a national marine sanctuary

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Supplement 1: Source Level Calculations

Acoustic data were collected in Massachusetts Bay, in and around the Stellwagen Bank National Marine Sanctuary. Recordings were made using arrays of up to 10 marine autonomous recording units (MARUs) (Calupca et al. 2000). Each MARU was equipped with an HTI-94-SSQ hydrophone (High Tech Instruments; sensitivity: −168 dB re 1 V/ µPa), connected to a pre-amplifier and A/D converter with 12 bit resolution, resulting in an effective system sensitivity of −151.7 dB re 1 V/µPa. All units recorded continuously at a sampling rate of 2000 Hz, yielding an effective analysis bandwidth of 10 to 1000 Hz, with a flat frequency response (±1 dB) between 55 and 585 Hz.

The units were moored 1 to 2 m above the sea floor in water depths ranging from 30 to 100 m, and were typically spaced 5- 12 km apart (Figure S1). Each deployment lasted 1-3 months; the position and spacing of arrays varied between deployments depending on the time of year and target species. Sound velocity profile data were collected 2-4 times during each deployment using a Seabird SBE 19 CTD, deployed by hand to the seafloor. The resultant sound speed data were used in subsequent baleen whale localization analyses. Once the MARUs were recovered, acoustic data were extracted, synchronized to ±1 ms, and merged to create multi-channel files.

Section 1: Calculation of baleen whale source levels

Sound files were browsed either manually or using automated detectors to identify periods with vocalizations of interest. Clear vocalizations that were not overlapped by other signals and appeared across multiple channels in the recording were selected for localization. Individual vocalizing animals within the MARU array were localized using time-of-arrival differences via the correlation sum estimation method, which uses an iterative process to identify the source position that results in highest sum of correlation values across channels (Cortopassi and Fristrup 2005). This method has been used in several previous studies (Hatch et al. 2012, Stanistreet et al. 2013, Risch et al. 2014). To improve the likelihood of measuring signals from a number of different individuals, calls were selected from a period of 3 – 7 days. Mean distances between a vocalizing animal and the nearest MARU ranged from ~2350 m to 5000 m (Table S1; see Figure S1 for an example).

The relevant frequency band for each sound type (Table S1) was chosen based on previously published reports and spectrographic analyses of the MARU data. Received signal levels (dB rms re: 1µ Pa at 1 m) within the frequency band of interest for each call type were calculated using the software package Raven (Charif et al. 2007); ambient noise levels were calculated immediately prior to each sound and were subtracted from the received levels (RLs).

Source level was estimated using a simple transmission loss model (SL = RL + 17 * $\log_{10}$ (r)), taking into account the range (r) between the animal and the nearest MARU, and the RL at that MARU. Transmission loss experiments were conducted twice during our study period to evaluate low-frequency sound propagation within the Stellwagen Bank National Marine Sanctuary (Cholewiak and Frankel, unpublished). The results indicated that the empirical data fit the 17*log(r) TL model well over distances of up to 10 km. The average SL per sound type was used in calculating loss of communication space.

Tests to verify localization accuracy were performed during four of the five acoustic deployments used in this analysis. Synthetic signals were transmitted from known locations (4-17 sites) within each array, usually on 1-2 days during the deployment period. During the data analysis phase, these signals were localized multiple times, using different combinations of channels to test channel alignment and localization accuracy. Overall, average localization error ranged from 53 – 877 m for these arrays (Table S1); however, the results from these tests were used to inform and improve localization analyses of baleen whales. If testing revealed that a particular channel or combination of channels were poorly aligned or produced high levels of localization error, for example, they were excluded from baleen whale localization analyses.

The source levels measured in this study (Table S1) are within or near published ranges for humpback, fin and minke whale sounds (e.g. Thompson et al. 1986; Charif et al. 2002; Au et al. 2006; Širović et al. 2007; Risch et al. 2014). For NARW gunshots, the SLs reported in this study are within the maximum range reported in Parks& Tyack (2005), but higher than their median levels. It's possible that this difference may be due to differences in sample size (Parks & Tyack 2005 included 12 sounds, while this study includes 85 sounds) or propagation modeling.

We calculated empirical measurements of source levels for each of the sound types analyzed to ensure that our results are relevant to our specific study area and vocalization contexts. Source level calculations are vital for understanding different components of sound, such as how far it can be detected, how it is masked and even how it may be perceived. Despite the importance of this metric, empirical source level measurements are rarely presented in the literature, likely because they require both the capacity to localize sounds and appropriate propagation loss models. This work contributes to a growing body of information regarding SLs for a variety of call types for baleen whales.

Section 2: Calculation of vessel source levels

Source levels for each of the three vessel types (AIS, fishing, and whale-watching) were calculated empirically for a subset of vessels in each category and then applied to the remaining vessels. In all cases where empirical data were available, RLs for a known vessel were calculated in $1/3^{rd}$ – octave bands using the closest point of approach (CPA) of the vessel to a MARU. For AIS vessels, a CPA was identified if the vessel passed within 3 km of a MARU. Transmission loss (TL) over the range between the vessel and MARU was calculated using the Bellhop propagation model (Porter & Liu 1994). Individual vessel SLs were used in subsequent modeling steps. For the AIS vessels for which it was not possible to calculate the SL, the average SL from vessels of the same size category was used.

Source levels for both the fishing and whale-watching vessel categories were calculated using a TL model of $17 \times \log_{10}(r)$, where "r" is the CPA range of the vessel to a MARU. CPA ranges for fishing vessels were calculated using data from two different types of events: trawling events, in which a MARU was contacted by a vessel's fishing gear shortly after its CPA, and vessel transit events recorded from the Vessel Monitoring System (VMS), in which approximate GPS positions indicated nearby approaches to a MARU. In the former case, vessels were assumed to pass directly over the MARU, and the range at CPA was considered to be the depth of the water column. In the latter case, the range at CPA was extracted from VMS data. For fishing vessels for which it was not possible to calculate the SL, a SL was randomly assigned from the distribution of empirical fishing vessel measurements.

For whale-watching vessels, SLs were calculated similarly to the fishing vessel transit events, using GPS tracks collected from a subset of whale-watching trips by the U.S. Coast Guard in 2008 & 2009 to determine CPAs. Periods in which a whale-watching vessel passed within 1.5 km of a MARU were examined for CPA events, and those with clear CPAs were used for SL calculations. Due to the paucity of available data, the median SL from these empirical measurements was applied to all whale-watching vessels in subsequent modeling steps.

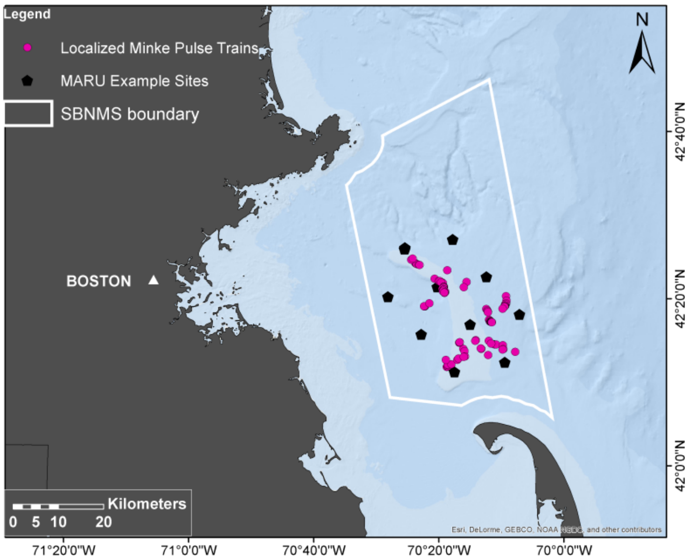

Figure S1.Locations of MARUs during the fall 2009 deployment (black pentagons). Pink dots indicate localizations of individual minke whale pulse trains used for SL analyses.

Table S1.Source level and localization data for each call type. Frequency bands are center frequency for 1/3–octave bands. Mean distances between a vocalizing whale and the MARU used for SL analysis are reported. Localization tests were performed during four the deployments; the number of sites used for localization testing and the mean localization error (in meters) are also reported.

Spp.	Sound Type	Lower Band Limit (Hz)	Upper Band Limit (Hz)	# Sounds for SL Analysis	Mean SL±sd (dB rms)	Mean whale distance (meters)	# Sites for loc testing	Mean loc error ±sd (meters)
Bp	Song	22	891	215	180 (5.4)	3210	16	577 (551)
Mn	Song	36	355	281	170 (2.9)	2560	4	53 (31)
Mn	Social	36	355	99	164 (5.5)	2356	17	239 (164)
Ba	Pulse train	56	355	87	163 (3.9)	3666	17	877 (475)
Eg	Gunshot	36	891	85	206 (4.5)	4910	N/A	N/A

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Supplement 2: Additional Model Description and Simulations

Section 1: Modeling Example for Humpback Whales

To model potential communication masking in baleen whales, an agent-based model was constructed that allowed for the calculation of communication space (and loss thereof under different noise conditions) on a per-individual basis, in 10-minute time steps over a 24h analysis day. The model is comprised of data layers including baleen whale animats, ambient noise, vessel noise, and an underlying grid of receivers, following the framework described by Clark et al. (2009). It is important to recognize that our model is calculating *potential* communication space and masking, based on a distribution of *potential* receivers; actual measures of communication masking would depend on actual receiver locations. The basic model is described in the body of the manuscript; a more detailed example is given here for foraging humpback whales producing social sounds.

The Stellwagen Bank National Marine Sanctuary (SBNMS) is an important summer foraging ground for humpback whales in the western North Atlantic. The number of humpback whales and their distributions were estimated based on prior knowledge and typical aerial survey sightings. July 16^{th} was chosen as an appropriate day for modeling the communication space of humpback whales within the context of foraging activity in this region. Within the larger study area, two sub-regions that are known to be heavily utilized by foraging individuals were identified. A total of fifty humpback animats were randomly distributed within these sub-regions (20 in the northern region and 30 in the southern region), and their movements were constrained to remain within them (Figure S2). Animats were programmed to wander according to predefined movement parameters. Initial locations within the bounding areas were selected randomly; if an animat hit the boundary of the study area or moved into an area with a water depth of < 10 m, it was randomly relocated within the bounding box to an area of water depths great than 10 m. Speed and turning radii were selected randomly from distributions of 3.7-9.3 km/h and 22.5-45°, respectively.

<u>*Construction of Vocalization and Noise layers*</u>

For humpback whales, the frequency band 36 – 355 Hz was chosen for the analyses. Wandering animats were simulated to produce calls at a depth of 5 m from their location every 10 minutes. Average source levels derived from the empirical analyses described in Supplement 1 were assigned to each animat, and calls were propagated across the study area using the Bellhop propagation model.

Ambient noise levels (defined as "Present Ambient", ***PrA***) were calculated for each 10-minute period, as described in the manuscript. Masking indices were computed with respect to a "Reference Ambient" noise level **(*RA*)**, which was set at 10dB less than PrA for each 10-minute time period.

To model the contribution of vessel noise to the acoustic environment, three categories of vessels were included in the analyses: "AIS vessels", fishing vessels, and whale-watching vessels. Procedures for estimating vessel locations, tracks and source levels are described in the body of the manuscript. All three vessel layers were present on July 16^{th}, and were estimated to include 23 AIS vessels, 729 fishing vessels, and 29 whale-watching vessels. Source levels within the 36 – 355 Hz frequency band were assigned to all vessels and propagated across the study area using the Bellhop propagation model. Intensity values were summed and converted to noise levels in the specified frequency band in 10-minute bins, to create cumulative vessel noise layers defined as "Present Shipping" ***(PrS)***.

Figure S3a shows the distribution of received levels for calling animats during one time step of the model (21:00h), under reference ambient (left) and present ambient noise conditions (middle), and shows the added noise contribution from AIS vessels passing through the area at that time slice (right panel; fishing and whale-watching vessels not shown here).

Model Construction

Calculation of Signal Excess

To calculate communication space, an underlying grid of potential receivers was constructed. The grid was designed to be large enough such that it extended at or beyond the predicted maximum range of communication for any of the agent locations under reference ambient conditions. For the humpback whale model, the 90 km x 90 km study area encompassing the SBNMS and surrounding waters was divided into 1x1 km grid cells; this comprised the "receiver grid", which was used to calculate potential communication space for each animat (Figure S2). For humpback whales producing social sounds in the SBNMS, the maximum theoretical communication range was estimated as 5 km, the area of which encompasses approximately 79 potential receivers.

For each potential receiver within the 5 km radius of a calling animat, signal excess was calculated every 10 minutes, using the formula *SE = SNR – RD*, where *RD* is the "recognition differential" (Clark et al. 2009). The recognition differential is a product of three terms; detection threshold (DT), directivity index (DI), and signal processing gain (SG), where *RD= DT- (DI + SG)*. These terms were set to 10, 0, and 16 dB, respectively, resulting in an RD of – 6 dB. The import of this negative RD value is that it improves a receiver's ability to detect a signal that is below background noise levels. See Supplement 3 for a sensitivity analysis in which the value for RD is varied.

Figure S3 (b) shows the Signal Excess experienced by each of the potential receivers for one animat (agent #28) under reference ambient and present ambient noise conditions (left, middle), and under present noise conditions plus the contribution from AIS vessels (right). The broad-scale impact of changing noise conditions on communication for all animats can be visualized by mapping the overall SE for potential receivers (Figure S3c), though it is important to note that the masking metrics presented here assess communication space for each sender (animat) individually.

Calculation of Communication Space

Successful communication is not guaranteed to occur if signal excess is greater than zero; as SE decreases and approaches zero, the probability of a receiver recognizing the signal also decreases. Therefore, to calculate potential communication space for any given animat, the actual area over which potential receivers experience SE > 0 is weighted by a probability-of-recognition term (PR). For each animat, this potential communication space (CS) is summed for each time slice:

$$\mathrm{CS} = \sum_{i=1}^{R} f(SE)_i * PR(SE)_i$$

where R is the number of receivers, and $f(SE)_i = 0$ for SE < 0 dB, $f(SE)_i = 1$ for SE ≥ 0 dB, and $PR(SE)_i = 0.5$ at SE = 0 dB, and $PR(SE)_i = 1$ at SE ≥ 18 dB, and $PR(SE)_i = 0.5 + \frac{(1-0.5)}{18} * \mathrm{SE}$ where 0 dB ≤ SE ≤ 18 dB (see Clark et al. 2009 for further explanation).

The resultant potential communication space is calculated based on reference ambient conditions, present ambient conditions, noise contribution from vessels alone, and the aggregation of vessels and ambient noise. Figure S4 shows the time-varying potential communication area for all 50 humpback whale animats in one model run over 24h, for reference ambient, present ambient and aggregate noise conditions.

Calculation of the Masking Index

Masking for a given animat under present noise conditions at any one point in time is then calculated as 1 minus the ratio of current communication space (under various scenarios) to potential communication space under reference ambient noise conditions (CS_{max}).

$$\mathrm{M} = 1 - \left(\frac{\sum_{i=1}^{R} f(SE)_i * PR(SE)_i}{CS_{max}}\right)$$

(adapted from equation 13, Clark et al. 2009).To calculate masking for multiple senders, all animat communication spaces are summed and divided by their summed potential communication spaces. This calculation is repeated for each time slice.

This "Masking Index" is a value between 0 and 1, and is quantified to represent the proportion of communication space available according to three different scenarios, all relative to the reference ambient conditions: (1) change in communication space due to levels of present ambient noise alone; (2) change in communication space due to discrete vessel noise; and (3) change in communication space due to the aggregate effects of present ambient noise and discrete vessel noise.

For humpback whales producing social sounds, this model run resulted in a median loss of 55% of communication space under present ambient noise conditions, and a 99% loss of communication space when vessels were included into the calculation.

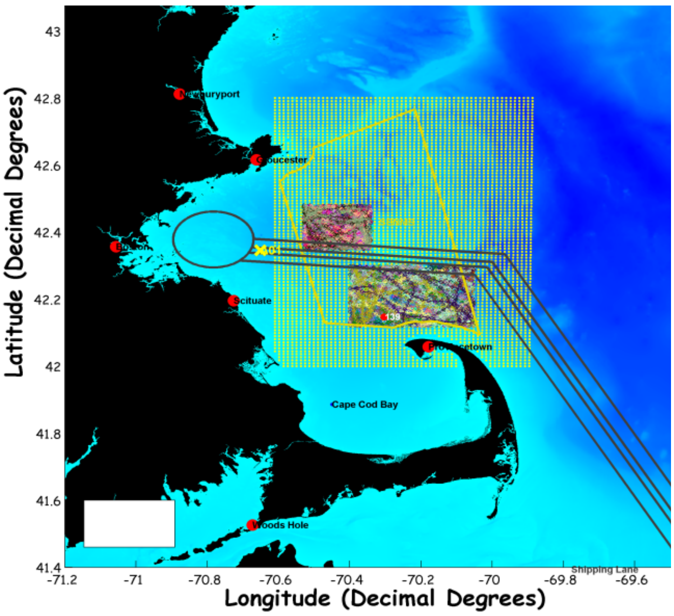

Figure S2. Map of Massachusetts Bay showing the Stellwagen Bank National Marine Sanctuary (outlined in yellow), the Traffic Separation Scheme for Boston shipping lanes (black), the underlying receiver grid (yellow), and the two sub-regions that represent the typical distribution of humpback whales during summer foraging months. Fifty humpback whale animats were confined to move within these regions.

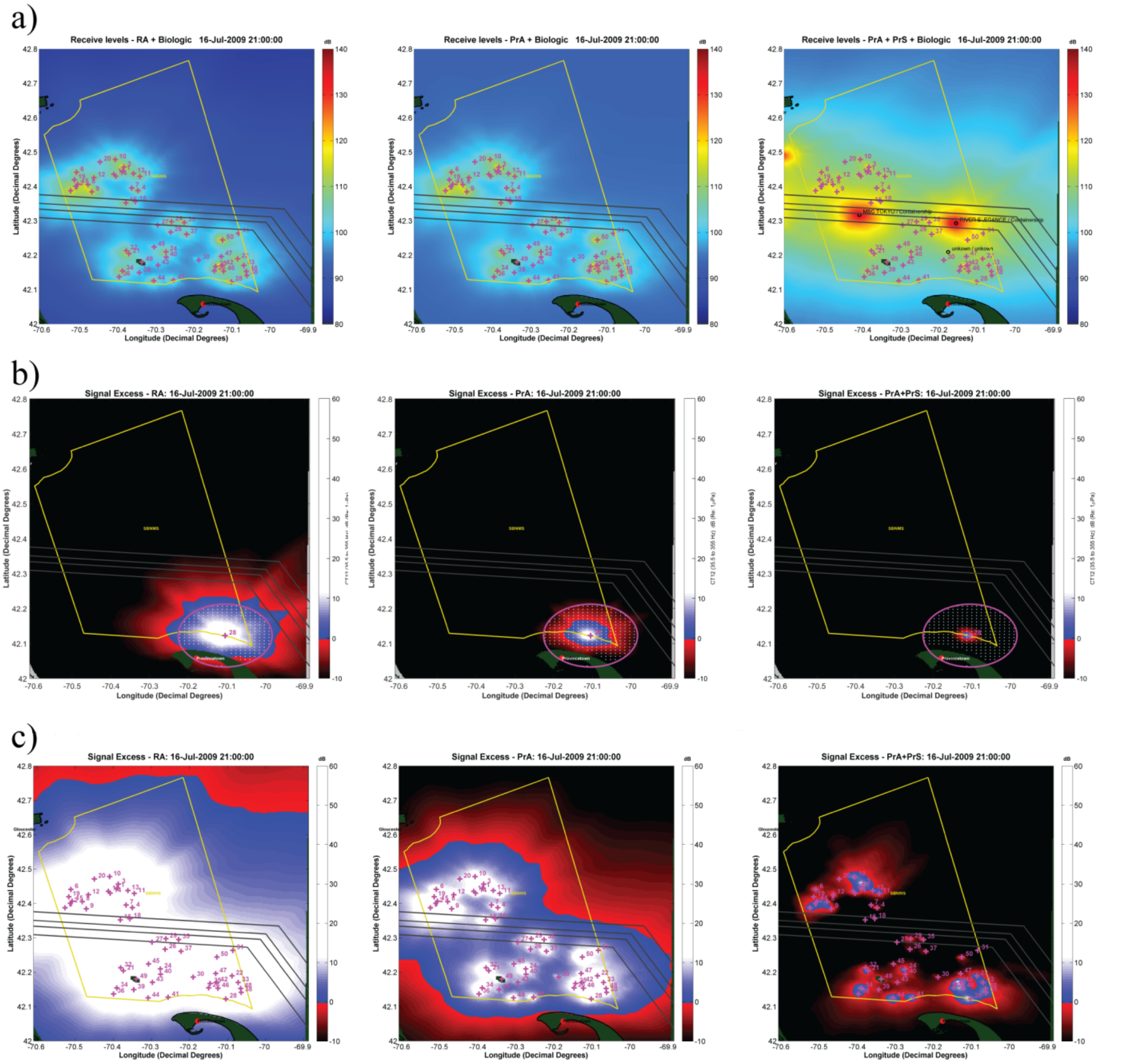

Figure S3. Visualization of several components of the communication space model for humpback whales producing social sounds at the 21:00h time step. The panels represent the following noise conditions: reference ambient noise (left), present ambient noise (middle), and present ambient noise plus the noise contribution from AIS vessels (right). a) Distribution of received levels across the study area, for 50 animats distributed within two sub-regions of the SBNMS. b) Signal Excess experienced by all of the receivers for one animat (agent #28) under the three noise conditions; c) Cumulative signal excess for all receivers for all animats (for visualization purposes only; masking metrics were calculated on a per-individual basis).

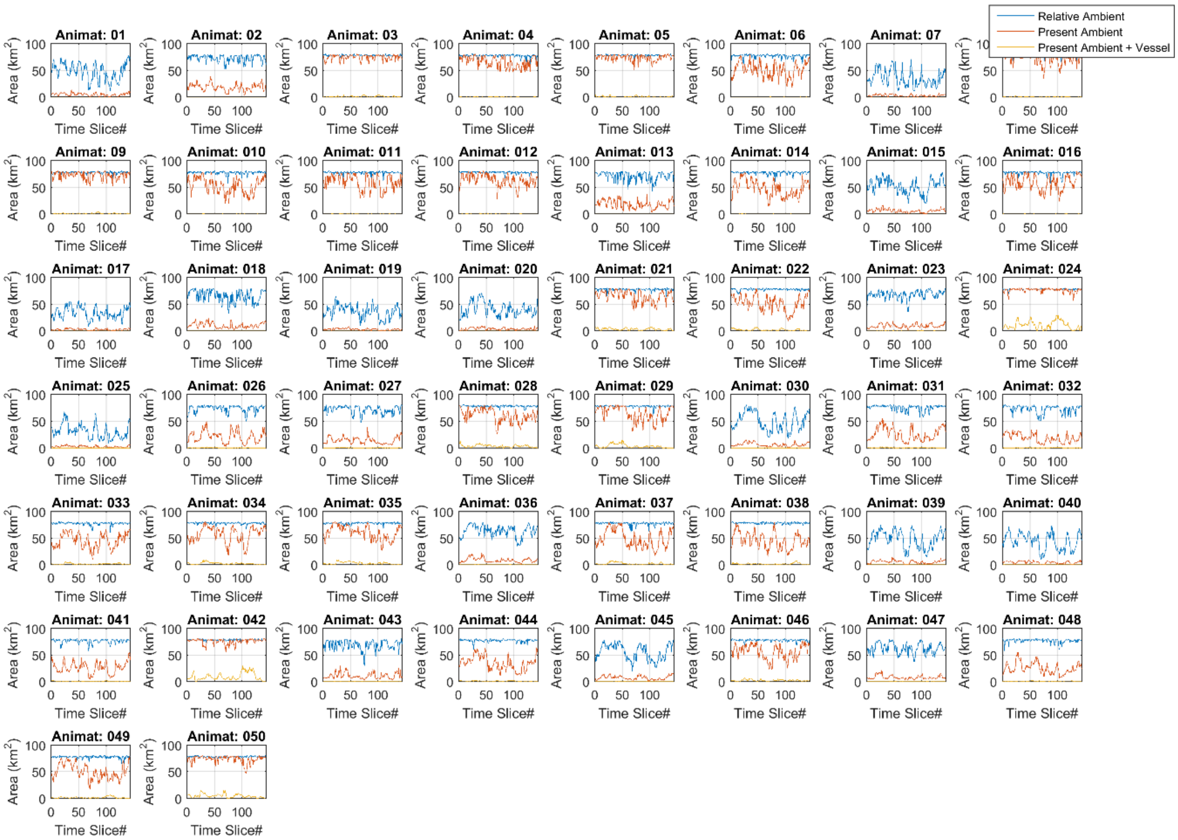

Figure S4. Time-varying measures of communication area over the 24 h analysis day for each of the 50 humpback whale animats in one model simulation, where the three line colors represent the three different noise conditions.

Section 2: Additional Model Simulations

One of the strengths of an agent-based modeling framework is the ability to repeat a model simulation multiple times, while varying input parameters of interest, to examine their effects on the overall conclusions of the study. To examine the sensitivity of the model to initial animat position, we conducted additional model simulations for humpback whales (producing social calls) and fin whales (singing). For each species, we ran the model 10 times, each time varying the random starting points for all animats, so that they would move throughout different areas within the study region. For humpback whales, all animats were still confined to the sub-regions described previously. All other variables, including ambient and vessel noise layers, were held constant.

For humpback whales producing social sounds, the results indicated that the mean potential communication area under current ambient noise conditions ranged from 20 (±16) km^2 to 37 (± 28) km^2. This area decreased to 1 (±3) km^2 or less in all 10 model runs (Table S2) when vessels were included. The variation in communication area for all animats in the 10 model runs can be seen in Figure S5; note that the data for Run 1 are the same as those presented in the main body of the manuscript. Their median proportion of lost communication space ranged from 55-76% under ambient conditions alone. This range of variation demonstrates the importance of a sender's location and resulting signal transmission loss when considering the area over which individuals can communicate. However, once the vessel noise layers were added into the equation, the median masking rose to 99% in all model runs. These results suggest that, despite an individual's location, the vessel noise included in this model is pervasive and impacts the communication space for all individuals.

Similar patterns were seen for fin whales. Fin whale communication area ranged from an average of 25 (±60) km^2 to 464 (± 630) km^2 under current ambient noise conditions (Table S3). Because the fin whale model included only 4 animats, variation in their placement had a greater effect on these estimates of their communication area. However, even in the best-case scenario, their modeled communication space was still just a fraction of that modeled under reference noise conditions; median masking for fin whales under current ambient noise conditions was 90% - 99% across all model runs. The effect of vessel noise alone was more variable in its contributions to masking; median masking from vessel noise ranged from 81-97%. However, once vessel noise and current ambient noise were combined, average communication areas decreased to between 6 (±13) km^2 and 101 (±101) km^2, and the corresponding median levels of masking exceeded 98% across model runs (Table S4).

Collectively, the results from these additional modeling simulations support the conclusion that the combined effects of current ambient noise conditions and vessel noise in our region are pervasive and strongly impact the area over which multiple species can communicate. While the location of a vocalizing animal is important in assessing its communication space, variation in animat placement had negligable effect on estimates of communication masking under aggregate noise conditions. The two models that we chose for these additional simulations had relatively different input parameters: 50 animats utilizing a broader frequency range for their communication sounds vs. 4 animats with relatively narrow-band song notes. The model results did capture variation between individuals and demonstrate that the overall results and conclusions are robust.

Table S2. Modeled communication range and area for humpback whales producing social sounds under reference ambient noise conditions, current ambient noise conditions, and current noise conditions including ambient noise and discrete vessel noise. Ten model simulations were performed; results are mean values (+/- SD) for the 24-hour analysis day for each model run.

	Modeled Communication Range (km); mean (SD)			Modeled Communication Area (km^2); mean (SD)		
Model Run	Reference Ambient	Current Ambient	Ambient + Vessels	Reference Ambient	Current Ambient	Ambient + Vessels
Run 1	4.8 (0.5)	3.4 (1.6)	0.8 (0.6)	69 (16)	37 (28)	1 (3)
Run 2	4.9 (0.1)	4 (0.9)	0.7 (0.4)	63 (10)	25 (11)	1 (1)
Run 3	5 (0.03)	3.8 (1)	0.6 (0.3)	77 (5)	35 (17)	1 (0.9)
Run 4	5 (0.04)	3.7 (1)	0.6 (0.3)	77 (5)	33 (16)	1 (0.8)
Run 5	5 (0.04)	3.6 (1)	0.5 (0.3)	76 (5)	32 (16)	1 (0.8)
Run 6	4.8 (0.4)	2.6 (1.3)	0.5 (0.3)	67 (14)	20 (16)	0.2 (0.6)
Run 7	4.9 (0.3)	2.9 (1.2)	0.5 (0.3)	70 (12)	22 (16)	0.3 (0.7)
Run 8	4.8 (0.3)	2.9 (1.3)	0.6 (0.3)	68 (14)	23 (18)	0.3 (0.7)
Run 9	4.8 (0.4)	2.7 (1.3)	0.5 (0.3)	68 (14)	21 (17)	0.3 (0.7)
Run 10	4.9 (0.3)	3 (1.3)	0.6 (0.3)	71 (12)	25 (18)	0.3 (0.8)

Table S3. Modeled communication range and area for fin whales producing songs under reference ambient noise conditions, current ambient noise conditions, and current noise conditions including ambient noise and vessel noise. 10 model simulations were performed; results are mean values (+/- SD) for the 24-hour analysis day for each model run.

	Modeled Communication Range (km); mean (SD)			Modeled Communication Area (km^2); mean (SD)		
Model Run	Reference Ambient	Current Ambient	Ambient + Vessels	Reference Ambient	Current Ambient	Ambient + Vessels
Run 1	29.7 (0.8)	14.9 (11.3)	8.5 (9.8)	2145 (733)	173 (322)	30 (65)
Run 2	29.8 (0.04)	21.5 (8.7)	12.5 (9.3)	2477 (378)	464 (630)	101 (197)
Run 3	29.5 (1.8)	7.98 (8.4)	3.6 (4.8)	1788 (855)	46 (102)	9.9 (23)
Run 4	29.8 (0.1)	13.1 (9.1)	6.8 (7.2)	2423 (436)	144 (267)	28 (61)
Run 5	29.8 (0.1)	17.3 (11.1)	9.7 (9.7)	2414 (450)	283 (426)	46 (95)
Run 6	29.6 (1.4)	11 (9.9)	5.1 (6.6)	2141 (743)	99.7 (224)	16 (41)
Run 7	29.8 (0.1)	18.4 (10.1)	10.6 (10.1)	2381 (380)	336 (526)	81 (170)
Run 8	28.4 (4.1)	5.8 (7.2)	2.3 (3.7)	1601 (907)	25 (60)	6 (13)
Run 9	29.8 (0.03)	21.1 (8.9)	12.9 (9.6)	2546 (355)	430 (524)	95 (184)
Run 10	29.8 (0.1)	19.0 (9.7)	11.1 (8.8)	2497 (370)	335 (433)	72 (125)

Table S4. The Communication Masking Index, or overall proportion of lost communication space for humpback whales and fin whales for 10 model simulations each. Results are median values for each 24-hour analysis day. Masking due to current ambient conditions, masking from vessel noise alone, and masking from the combination of ambient noise and vessels are included.

	Humpback whales			Fin whales		
	Ambient	**Vessels**	**Ambient + Vessels**	**Ambient**	**Vessels**	**Ambient + Vessels**
Run 1	0.55	0.99	0.99	0.96	0.90	0.99
Run 2	0.66	0.99	0.99	0.91	0.81	0.99
Run 3	0.63	0.99	0.99	0.99	0.96	0.996
Run 4	0.65	0.99	0.995	0.98	0.92	0.99
Run 5	0.66	0.99	0.995	0.95	0.88	0.99
Run 6	0.76	0.997	0.997	0.98	0.94	0.999
Run 7	0.74	0.997	0.997	0.93	0.81	0.99
Run 8	0.71	0.997	0.997	0.99	0.97	0.997
Run 9	0.74	0.996	0.996	0.90	0.81	0.98
Run 10	0.71	0.996	0.996	0.94	0.85	0.99

Figure S5. Time-varying communication area for 50 humpback whale animats across 10 model runs. The solid lines represent mean communication area under reference ambient conditions (blue), current ambient conditions (red), and current noise conditions including ambient + vessels (yellow), with +/- 1 SD shown in colored shading. Each panel represents a separate model simulation in which the animats were randomly re-distributed within their pre-defined regions. Note that the panel in the upper left (i.e. “Run 1”) is the same as the upper right panel in the main paper’s Figure 4.

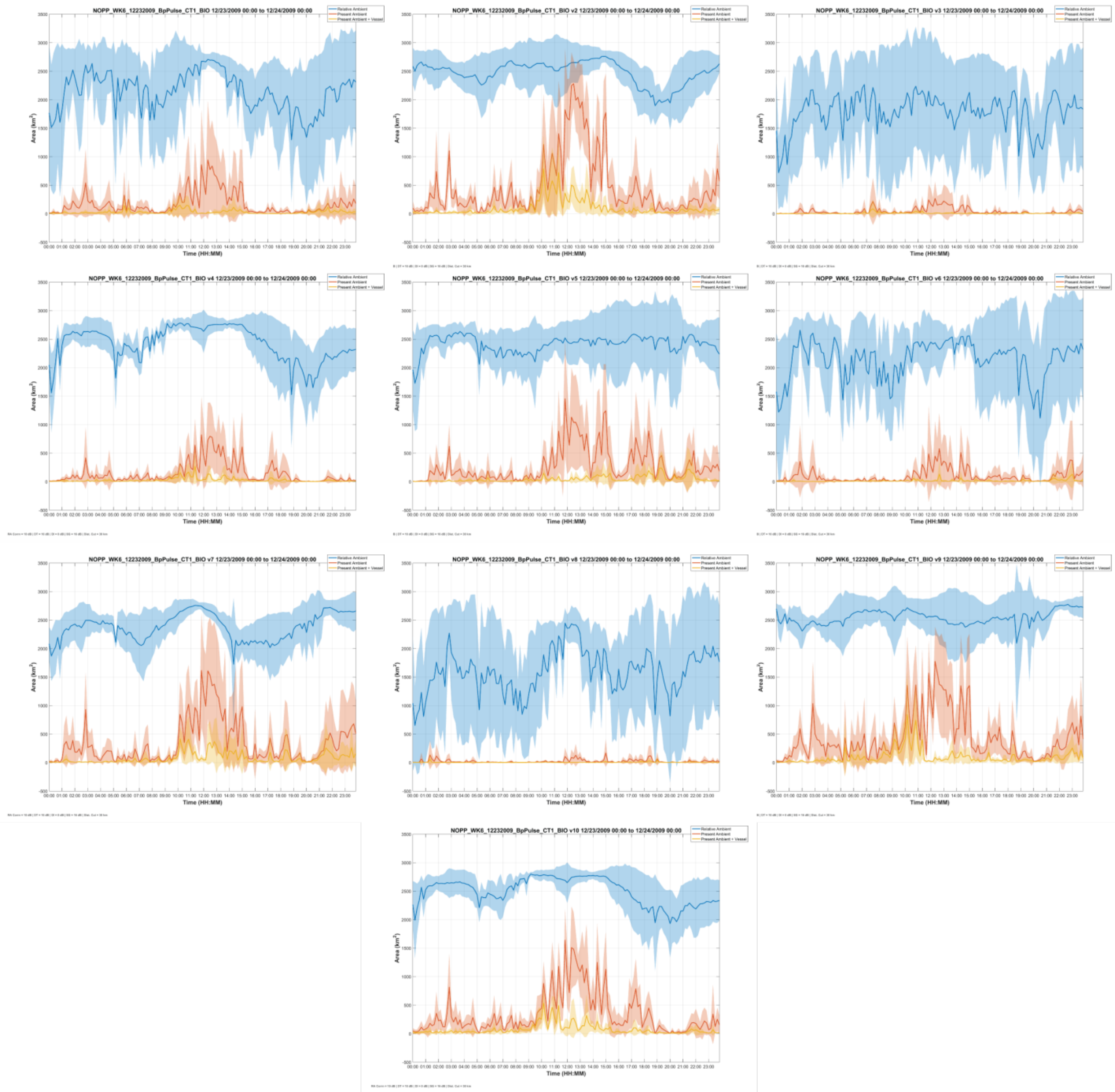

Figure S6. Time-varying communication area for 4 fin whale animats across 10 model runs. The solid lines represent mean communication area under reference ambient conditions (blue), current ambient conditions (red), and current noise conditions including ambient + vessels (yellow), with +/- 1 SD shown in colored shading. Each panel represents a separate model simulation in which the animats were randomly re-distributed within their pre-defined regions.

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Supplement 3: Sensitivity Analysis – Varying the Recognition Differential

The calculation of communication masking is essentially a problem of signal-to-noise ratio (SNR) and detection threshold (DT), when considering a signal from the point-of-view of the receiver. However, for communication to be successful, most signals need not only to be detected, but also *recognized* by a receiver. The difference in thresholds between signal detection and signal recognition has been measured at up to 6 dB for birds in some studies (Lohr et al. 2003, Dooling et al. 2015), significantly limiting the area over which successful communication may occur. On the other hand, receivers also utilize a variety of behavioral and physiological mechanisms to improve both the detection and recognition of a signal under a variety of noise conditions (Brumm & Slabbekoorn 2005). Controlled studies have elucidated the mechanisms behind several neurophysiological adaptations, such as selective filtering and gain control, particularly in insects (e.g. Schmidt & Hömer 2011).

In the current study, communication space for a given vocalizing individual is defined as the area within which potential receivers will experience a signal excess (SE) of greater than zero. SE depends on both the SNR and on a term we are calling the recognition differential (RD). The latter includes the DT, as well as two variables that may improve the detection and recognition of a signal: directivity index (DI) and signal processing gain (SG). DI can account for the gain afforded by directional hearing, while SG can account for the gain afforded by a matched filter within a species' signal processing mechanisms. The theoretical gain from a matched filter can be approximated as 10 * log (time-bandwidth product) for a signal *(10 log (TW))*. For example, a matched filter for a one-second signal with a frequency bandwidth of 100 Hz would lead to a signal gain of 20 dB.

The calculation of SE is derived from Clark et al. (2009), such that $SE = SNR - RD$ (Eqn. 5), where $RD = DT - (DI + SG)$ (Eqn. 6). The theoretical DT, DI and SG values were set to 10, 0, and 16 dB, respectively, resulting in an overall RD of -6 dB. Although cetaceans' adaptive mechanisms for dealing with signal detection in noise are unknown, these values are considered reasonable starting points, particularly for baleen whales. This approach equates to a 6 dB gain in signal excess due to the signal processing capabilities of the receiver, allowing for detection of signals that fall below background noise levels.

Our study used the same theoretical recognition differential across species and call types. However, as changes in any of the underlying variables will affect RD, it is informative to examine how variation in this parameter affects the downstream calculation of communication masking within our model framework. A sensitivity analysis was undertaken for two species and their respective vocalizations: fin whales (20-Hz song units) and humpback whales (social sounds) to examine the effect that RD has on the overall masking metric. For both species, RD was varied from 0 dB to –12 dB, in increments of 3 dB. As in the modeling presented in the main body of the manuscript, masking was quantified according to three different scenarios: change in communication space due to levels of present ambient noise alone; change in communication space due to discrete vessel noise alone; change in communication space due to the combined effects of present ambient and discrete vessel noise. For each RD level, the time-varying communication range, communication area and the communication masking index were calculated per animat per 10 minute period, and averaged across all animats.

Change in RD had a greater effect on fin whale communication range and area than for humpback whales (Tables S5,S6), likely because the maximum theoretical range over which humpback whale social sounds can be detected is much smaller. Varying the RD for fin whales resulted in a modeled communication area under current ambient noise conditions ranging from 5 km^2 (±6 km^2) to 1386 km^2 (±1032 km^2), which was reduced to between 2 (±2) km^2 and 782 (±789) km^2 when vessel noise was included (Table S5). The change in RD also led to greater variation in communication masking under ambient noise conditions alone than under ambient noise conditions including vessels. When vessel noise was included, the loss of communication space ranged from over 99% (with RD = 0 dB), to 79% in the “best-case” scenario, where receivers are afforded an additional 12 dB in signal excess (Table S7). Figure S7 shows the change in fin whale modeled communication area over time for each of the five RD values.

For humpback whales producing social sounds, the variation in RD had a somewhat substantial effect in the absence of vessels (considering ambient noise only), but had a negligible effect once noise from discrete vessels was taken into account (Figure S8). Their average modeled communication range under current ambient noise conditions including vessels ranged from less than a kilometer (0.5 ±0.3 km) to just over a kilometer (1.5 ±1.1 km) (Table S6). Their loss of communication space in the absence of vessels ranged from 37-75%, but in the presence of vessels their communication space was reduced by 95% or more under all variations in RD (Table S7).

Combined, these results demonstrate how variation in the parameters underlying the calculation of signal excess can affect the estimation of communication space and loss thereof under different noise conditions, for two baleen whale species with very different vocalization characteristics. The impact of the recognition differential, or essentially the improvement in a potential receiver’s ability to detect and recognize a signal, is greatest under ambient conditions alone, and can lead to a modest improvement in communication space in the absence of discrete vessel activity. However, in our environment, these gains are essentially wiped out once vessel noise is considered in the equation, indicating that within this noisy habitat, there may be little that a receiver can do to decrease communication masking.

Table S5**.** Modeled communication range and area for fin whales producing 20-Hz song units using a recognition differential that varies from 0 dB to – 12 dB. Ranges and areas are calculated under reference ambient noise conditions, current ambient noise conditions, and current noise conditions including ambient noise and vessel noise. Results are mean values (+/- SD) for each 24-hour analysis day. An RD of – 6 dB was used in the manuscript; those results are in bold below.

	Modeled Communication Range (km); mean (SD)			Modeled Communication Area (km^2); mean (SD)		
Recognition Differential (dB)	Reference Ambient	Current Ambient	Ambient + Vessels	Reference Ambient	Current Ambient	Ambient + Vessels
RD 0	23.3 (9.7)	2.6 (4.4)	0.99 (1.4)	929 (902)	5 (6)	2 (2)
RD -3	27.8 (5.2)	7.4 (8.9)	2.9 (4.8)	1591 (1014)	24 (52)	5 (7)
RD -6	**29.7 (0.8)**	**14.9 (11.3)**	**8.5 (9.8)**	**2145 (733)**	**173 (322)**	**30 (65)**
RD -9	29.8 (0.03)	21.5 (10.5)	16.5 (12.1)	2480 (373)	685 (768)	199 (328)
RD -12	29.8 (0.03)	26.4 (6.9)	22.3 (10.4)	2560 (278)	1386 (1032)	782 (789)

Table S6. Modeled communication range and area for humpback whales producing social sounds using a recognition differential that varies from 0 dB to – 12 dB. Ranges and areas are calculated under reference ambient noise conditions, current ambient noise conditions, and current noise conditions including ambient noise and vessel noise. Results are mean values (+/- SD) for each 24-hour analysis day. An RD of – 6 dB was used in the manuscript; those results are in bold below.

	Modeled Communication Range (km); mean (SD)			Modeled Communication Area (km^2); mean (SD)		
Recognition Differential (dB)	Reference Ambient	Current Ambient	Ambient + Vessels	Reference Ambient	Current Ambient	Ambient + Vessels
RD 0	4.1 (1.3)	2.2 (1.5)	0.5 (0.3)	51 (28)	15 (17)	0.2 (0.5)
RD -3	4.5 (0)	2.8 (1.7)	0.7 (0.5)	60 (23)	25 (24)	0.5 (1.3)
RD -6	**4.8 (0.5)**	**3.4 (1.6)**	**0.8 (0.6)**	**69 (16)**	**37 (28)**	**1 (3)**
RD -9	4.9 (0.2)	3.9 (1.4)	1.1 (0.9)	74 (9)	48 (28)	3 (6)
RD -12	5 (0.03)	4.4 (1)	1.5 (1.1)	77 (5)	57 (25)	6 (10)

Table S7. The Communication Masking Index, or overall proportion of lost communication space for fin whales and humpback whales across RD values that vary from 0 dB to -12 dB. Results are median values for each 24-hour analysis day. Masking due only to current ambient conditions, as well as masking resulting from the combination of all vessel layers and ambient noise conditions are also presented.

	Fin whales (20-Hz song units)		Humpback whales (social sounds)	
Recognition Differential (dB)	Ambient only	Vessels + Ambient	Ambient only	Vessels + Ambient
RD 0	0.995	0.997	0.75	0.998
RD -3	0.99	0.997	0.65	0.99
RD -6	**0.96**	**0.99**	**0.55**	**0.99**
RD - 9	0.80	0.95	0.46	0.97
RD - 12	0.59	0.79	0.37	0.95

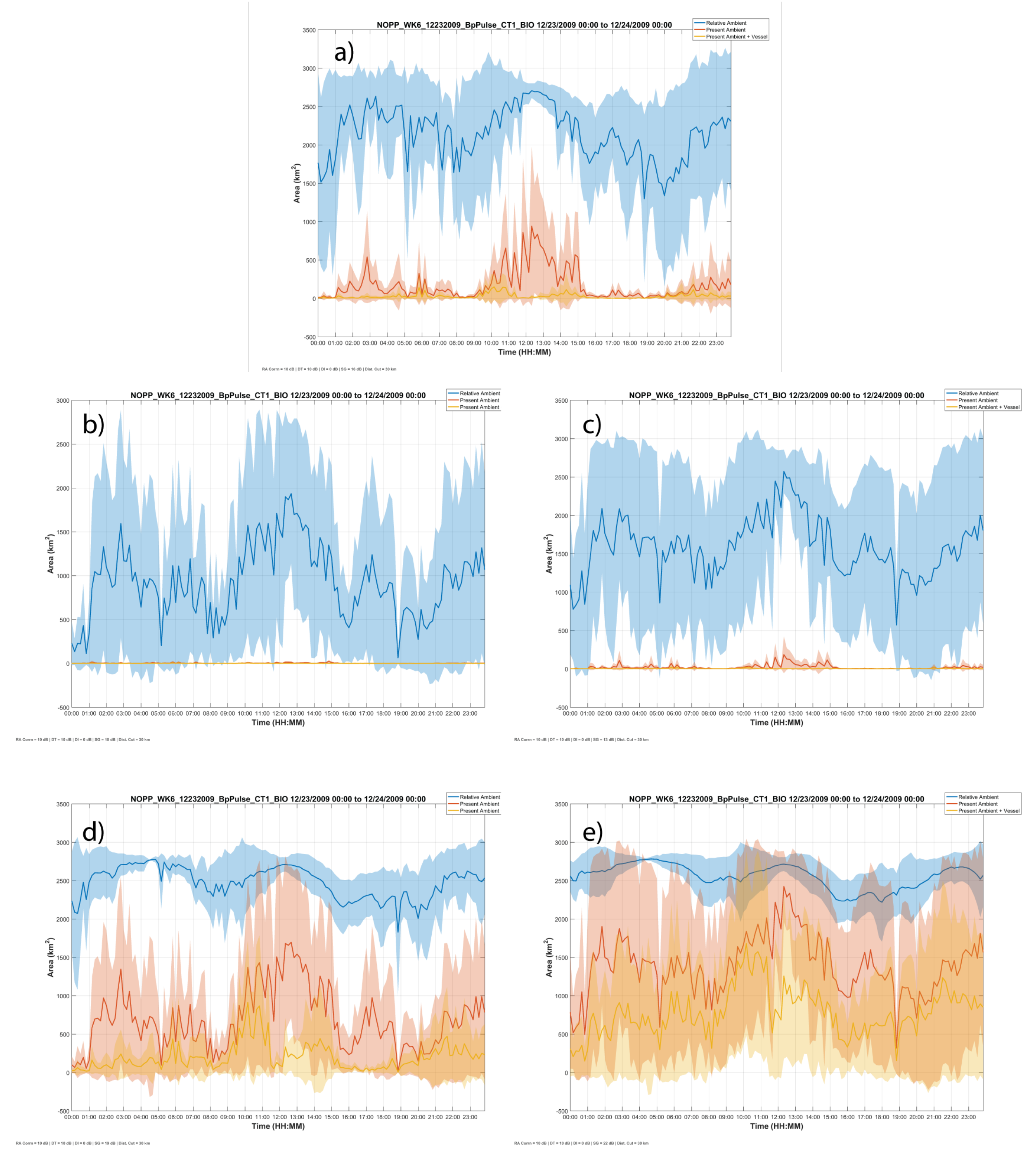

Figure S7. Time-varying change in modeled communication area for fin whales over the 24-hour analysis day. Each panel represents a different RD. a) RD = -6 dB (as in the body of the manuscript); b) RD = 0 dB; c) RD = -3 dB; d) RD = -9 dB; e) RD = -12 dB. The solid lines represent mean communication area under reference ambient conditions (blue), current ambient conditions (red), and current noise conditions including ambient + vessels (yellow), with +/- 1 SD shown in shading.

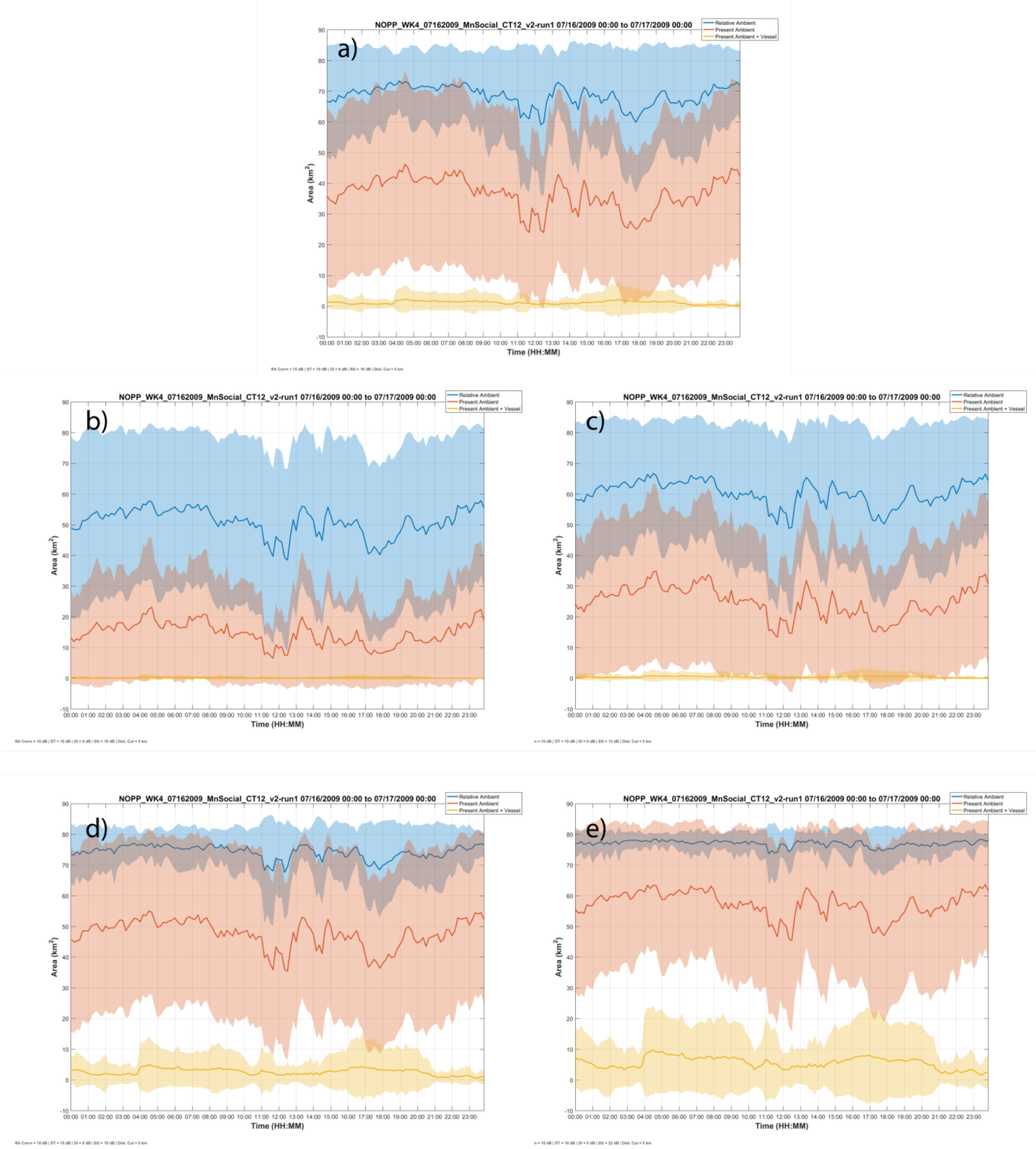

Figure S8. Time-varying change in modeled communication area for humpback whales producing social sounds, over the 24-hour analysis day. Each panel represents a different RD. a) RD = -6 dB (as in the body of the manuscript); b) RD = 0 dB; c) RD = -3 dB; d) RD = -9 dB; e) RD = -12 dB. The solid lines represent mean communication area under reference ambient conditions (blue), current ambient conditions (red), and current noise conditions including ambient + vessels (yellow), with +/- 1 SD shown in shading.

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