Quantifying Loss of Acoustic Communication Space for Right Whales in and around a U.S. National Marine Sanctuary

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Abstract: *The effects of chronic exposure to increasing levels of human-induced underwater noise on marine animal populations reliant on sound for communication are poorly understood. We sought to further develop methods of quantifying the effects of communication masking associated with human-induced sound on contact-calling North Atlantic right whales* (Eubalaena glacialis) *in an ecologically relevant area ($\sim$10,000 km^2) and time period (peak feeding time). We used an array of temporary, bottom-mounted, autonomous acoustic recorders in the Stellwagen Bank National Marine Sanctuary to monitor ambient noise levels, measure levels of sound associated with vessels, and detect and locate calling whales. We related wind speed, as recorded by regional oceanographic buoys, to ambient noise levels. We used vessel-tracking data from the Automatic Identification System to quantify acoustic signatures of large commercial vessels. On the basis of these integrated sound fields, median signal excess (the difference between the signal-to-noise ratio and the assumed recognition differential) for contact-calling right whales was negative (-1 dB) under current ambient noise levels and was further reduced (-2 dB) by the addition of noise from ships. Compared with potential communication space available under historically lower noise conditions, calling right whales may have lost, on average, 63–67% of their communication space. One or more of the 89 calling whales in the study area was exposed to noise levels $\geq$120 dB re 1 μPa by ships for 20% of the month, and a maximum of 11 whales were exposed to noise at or above this level during a single 10-min period. These results highlight the limitations of exposure-threshold (i.e., dose-response) metrics for assessing chronic anthropogenic noise effects on communication opportunities. Our methods can be used to integrate chronic and wide-ranging noise effects in emerging ocean-planning forums that seek to improve management of cumulative effects of noise on marine species and their habitats.*

Keywords: endangered species, marine protected area, marine spatial planning, underwater noise

Cuantificación de la Pérdida de Espacio de Comunicación Acústica para Ballenas Francas Dentro y Alrededor de un Santuario Marino Nacional en E. U. A.

Resumen: *Los efectos de la exposición crónica a niveles cada vez mayores de ruido submarino inducido por humanos sobre poblaciones de animales marinos dependientes del sonido para comunicarse están poco entendidos. Buscamos desarrollar métodos para cuantificar los efectos del enmascaramiento de la comunicación asociados con sonidos inducidos por humanos sobre el llamado de contacto de ballenas francas*

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14. ABSTRACT
The effects of chronic exposure to increasing levels of human-induced underwater noise on marine animal populations reliant on sound for communication are poorly understood. We sought to further develop methods of quantifying the effects of communication masking associated with human-induced sound on contact-calling North Atlantic right whales (Eubalaena glacialis) in an ecologically relevant area ($\sim$10,000 km2) and time period (peak feeding time). We used an array of temporary, bottom-mounted, autonomous acoustic recorders in the Stellwagen Bank National Marine Sanctuary to monitor ambient noise levels, measure levels of sound associated with vessels, and detect and locate calling whales. We related wind speed, as recorded by regional oceanographic buoys, to ambient noise levels. We used vessel-tracking data from the Automatic Identification System to quantify acoustic signatures of large commercial vessels. On the basis of these integrated sound fields, median signal excess (the difference between the signal-to-noise ratio and the assumed recognition differential) for contact-calling right whales was negative (-1 dB) under current ambient noise levels and was further reduced (-2 dB) by the addition of noise from ships. Compared with potential communication space available under historically lower noise conditions, calling right whales may have lost, on average, 63?67% of their communication space. One or more of the 89 calling whales in the study area was exposed to noise levels $\geq$120 dB re 1 μPa by ships for 20% of the month, and a maximum of 11 whales were exposed to noise at or above this level during a single 10-min period. These results highlight the limitations of exposure-threshold (i.e., dose-response) metrics for assessing chronic anthropogenic noise effects on communication opportunities. Our methods can be used to integrate chronic and wide-ranging noise effects in emerging ocean-planning forums that seek to improve management of cumulative effects of noise on marine species and their habitats.

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(Eubalaena glacialis) *en un área ecológicamente relevante (∼ 10,000 km²) y período de tiempo (tiempo pico de alimentación). Utilizamos un conjunto de grabadoras acústicas autónomas, temporales, montadas en el fondo en el Santuario Marino Nacional Banco Stellwagen para monitorear los niveles de sonido ambiental, medir los niveles de sonido asociados con embarcaciones y detectar y localizar llamadas de ballenas. Relacionamos la velocidad del viento, registrada por boyas oceanográficas regionales, con los niveles de sonido ambiental. Utilizamos datos de embarcaciones rastreadoras del Sistema de Identificación Automática para cuantificar las sintonías de embarcaciones comerciales mayores. Con base en estos campos de sonido integrados, la mediana del exceso de señal (la diferencia entre la relación señal-ruido y el diferencial de reconocimiento asumido) para contactar ballenas francas llamadoras fue negativo (−1 dB) bajo niveles de sonido ambiental actuales y disminuyó (−2 dB) con la adición del ruido de los barcos. En comparación con el espacio de comunicación potencial disponible bajo condiciones de ruido históricamente más bajas, las ballenas pueden haber perdido, en promedio 63–67% de su espacio de comunicación. Una o más de las 189 ballenas llamadoras en el área de estudio estuvieron expuestas a niveles de ruido ≥120dB re1μPa de barcos durante 20% del mes, (y un máximo de 11 ballenas estuvo expuesto a ruido en o por arriba de este nivel durante un solo período de 10 minutos. Estos resultados resaltan las limitaciones de las medidas de exposición-umbral (i.e., dosis-respuesta) para evaluar los efectos del ruido antropogénico crónico sobre las oportunidades de comunicación. Nuestros métodos pueden ser utilizados para integrar los efectos de ruido crónico y de amplio rango en los foros emergentes sobre planeación marina que buscan mejorar el manejo de los efectos acumulativos del ruido sobre especies marinas y sus hábitats.*

Palabras Clave: área marina protegida, especies en peligro, planificación espacial marina, ruido submarino

Introduction

The potential effects of underwater noise produced by human activities on marine animals have been recognized for over 40 years (Payne & Webb 1971; Myrberg 1980; Møhl 1981). Most attention has focused on short-term effects associated with high-intensity sounds from purposeful signals (e.g., seismic air guns, military active sonars) and incidental noises (e.g., pile driving, bow thrusters) produced by human activities in close proximity to marine animals (e.g., NRC 2000; Southall et al. 2007). More recently, several reports and studies addressing ocean noise have highlighted effects associated with longer-term exposure to lower-intensity human-induced noise sources that affect animals over much larger spatial extents (e.g., Clark et al. 2009; Hatch & Fristrup 2009). These chronic effects may be more substantial than short-term acute effects over spatial and temporal extents relevant to marine animals that rely on acoustic communication (e.g., Clark et al. 2009).

Recent studies have focused on characterizing how chronic noise reduces the area over which species such as large whales are able to exchange information or hear important environmental cues. Møhl (1981) considered the loss in a receiving animal's ability to detect signals in the face of increased ambient noise. Clark et al. (2009) quantified the loss of acoustic habitat or "communication space" available to calling, not receiving, baleen whales due to the obscuring of their signals by low-frequency anthropogenic noise sources, a phenomenon referred to as "communication masking." Due to their endangered status in most international waters, the reliance of baleen whales on low-frequency sounds for feeding, navigating, and reproducing and the overlap between their communication frequencies and the frequencies of most chronic noise produced by human activities, the effects of masking on baleen whales have been identified as a primary concern. Noise from large commercial vessels dominates low-frequency underwater background noise (Richardson et al. 1995) and is increasing (Andrew et al. 2002; McDonald et al. 2006); thus, commercial shipping has been identified as a primary noise-management concern.

Ships introduce a variety of noise-exposure patterns that vary in intensity over space, time, and frequency. In areas with UN International Maritime Organization (IMO) routes for commercial vessels (i.e., shipping lanes), the density of transient-noise peaks is proportional to the number of ships, whereas the levels of transient-noise peaks are primarily dependent on ship distances. The overall effect is that cumulative noises from vessels in high-traffic areas near shipping lanes and ports generate a variable pattern of transient-noise peaks on top of an elevated background noise level that, on average, is omnipresent. These variances in cumulative noise determine the communication spaces available to calling and listening baleen whales. To assess the effects of changes in communication space, communication masking must be quantified (Clark et al. 2009) over sufficiently long periods and large areas so as to be biologically relevant and to accurately represent natural and human-induced noise contributions at those scales. We characterized the effects of communication masking on calling North Atlantic right whales (*Eubalaena glacialis*) in an ecologically relevant area (approximately 10,000 km² surrounding and including the Stellwagen Bank National Marine Sanctuary [SBNMS]) and period (peak month in feeding season).

Figure 1. Study area in and around the Stellwagen Bank National Marine Sanctuary (SBNMS), distribution of large commercial vessels tracked with the Automatic Identification System (AIS) (black lines), locations of the 9 marine acoustic recording units (MARUs) in April 2008, locations of 2 fixed oceanographic buoys, and the boundary of the SBNMS.

Methods

Data Collection

To maximize the number of foraging right whales present in the study area and the percentage of overall traffic in the area that could be accounted for with available tracking data, we choose April 2008 for this study (Supporting Information). Our study area encompassed all waters within the SBNMS and surrounding waters (Fig. 1). An array of 9 marine autonomous recording units (MARUs) was deployed from 7 March to 28 May 2008 to record continuously low-frequency sound (Fig. 1 & Supporting Information). We compared empirical measurements of received sound levels with levels predicted from multiple sound propagation models (D. Cholewiak & A.S.F., unpublished data). Subsequently, we used the Bellhop model (Porter 1992), informed by several environmental variables that influence sound propagation, to predict transmission loss (loss of sound energy over distance between source and receiver) for both vessel and whale sound sources (Supporting Information).

We identified and tracked all large commercial vessels present within the study area in April 2008 with the U.S. Coast Guard's Automatic Identification System (AIS) (Fig. 1 & Supporting Information). We calculated minimum great-circle distances (shortest distance between any 2

points on the surface of a sphere measured along a path on the surface of the sphere) between vessel locations and MARU locations to determine each vessel's closest point to the MARU.

Data Analyses

We divided the 9576 km^2 (90 km lat, 106 km long) study area into 1-km^2 cells for modeling and thus had 7538 unique locations (locations on land were discarded). We used the Acoustic Integration Model (Frankel et al. 2002) to predict month-long series of 1-second/10-min ($n =$ 4320) received sound levels (root mean square dB re 1 μPa unless otherwise noted) associated with vessel and whale sound sources throughout the modeling area and within the frequency band containing the majority of sound energy in right whale contact calls (71–224 Hz) (Urazghildiiev & Clark 2006).

NOISE

We calculated the bottom 5th percentile received sound levels for the 2 MARUs located closest to fixed oceanographic buoys in Massachusetts Bay (GMOOS A01 and NDBC 44013) (Fig. 1). We regressed these received sound levels against wind speeds recorded at buoys and used results to estimate present-day ambient noise

levels (1-second/10-min) in the absence of AIS-tracked discrete vessel signatures. In addition to contributions from wind as a natural source of noise, estimates of ambient noise levels retain contributions from nondiscrete anthropogenic noise sources, including more distant ships. We subtracted 10 dB from 1-second/10-min present-day ambient noise estimates to represent hypothetical levels of historical ambient noise. We used these approximations to represent the change in low-frequency ambient noise levels since the mid 20th century, a period within the lifetimes of many extant North Atlantic right whales.

The only time-series data sets on low-frequency ambient noise levels in Northern Hemisphere coastal waters are from locations off the west coast of the United States (Andrew et al 2002; McDonald et al. 2006), where these levels include ocean-basin scale transmission of shipping noise. Our study area was on the continental shelf where most noise from ships occurs when they transit through shelf waters.

Contemporary measurements taken in our study site and from similar shallow water sites off the U.S. eastern seaboard show a 13 dB (Hatch et al. 2008, 2009) to over 20 dB (Schiefele & Darre 2005) difference in average 71–224 Hz background noise between sites with less versus more local vessel traffic. Rolland et al. (2012) recorded an over 10 dB drop in background noise levels at frequencies below 150 Hz at a location just north of our study area after a short-term cessation of large commercial vessel traffic following the terrorist attacks on 11 September 2001. Ambient noise levels recorded in wind-only versus shipping-traffic conditions in 1982–1983 in a shallow area also just north of our study site differed by 10–15 dB in the 100–200 Hz band (Urick 1984). Conditions labeled quiet during earlier studies often included noise from shipping, although at nonquantifiable levels. Commonly referenced predictions for low-frequency background noise levels derived from measurements taken in the 1960–1980s are thus consistent with contemporary empirical evidence that 10 dB is a conservative delta value for low versus high traffic on the continental shelf (for further discussion see Supporting Information). Acknowledging uncertainty due to lack of time-series data, but noting that motorized vessel traffic was already well-established in coastal Massachusetts waters in the 1950s (Morry 1987), we also used historical ambient noise levels 20 dB below modern-day levels in calculations to explore the sensitivity of results to the choice of historical-reference level.

We used times and locations of vessels passing within 10 km (5.4 nm) of a MARU to match vessel tracks with acoustic records. When possible, we calculated average received sound levels centered at the time of closest approach and used the Acoustic Integration Model to estimate vessel source levels (intensity of sound at the vessel) in the 71–224 Hz frequency band (Supporting Information). The Acoustic Integration Model was subsequently applied to predict source levels associated with the duration of each vessel's transit through the area. We modeled vessel sources 7 m below the surface to represent average propeller depth across vessel types in the study area. We applied directivity to the Acoustic Integration Model's calculation of noise levels produced by selected vessels to account for known differences in sound propagating from the bow, stern, and sides of ships. We calculated transmission loss for every 15° of relative bearing from the ship's bow (Supporting Information). We used Matlab to sum all coincident vessel noise fields and thus created a 1-second noise-field grid every 10 min throughout the month (4320 frames). These frames collectively represented a time series of cumulative noise from multiple AIS-tracked large commercial ships.

WHALES

We used an automatic detector (ISRAT) to identify all right whale contact calls within the array (Urazghildiiev et al. 2009). We used XBAT and correlation sum estimation (Supporting Information) (K. Fristrup & K. Cortopassi, unpublished) to compute locations (x, y) for 744 calls with good signal-to-noise ratios (generally >10 dB). Localization was used to identify the spatial and temporal characteristics of contact-calling whales. We calculated noise-corrected received sound levels for 100 calls located within 2 km of a MARU and estimated call source levels on the basis of locations of calling whales and Acoustic Integration Model calculations of transmission loss (Supporting Information). We integrated the MARU-derived acoustic detections of contact calls with visual-sighting information from the U.S. National Oceanic and Atmospheric Administration Northeast Fisheries Science Center's aerial surveys to create coarse estimates of density and distribution of calling right whales. We then used the Acoustic Integration Model to model the acoustic behavior and movements of 89 artificial animals, referred to as animats, on the basis of position and movement data governed by preset parameters (Supporting Information) (Frankel et al. 2002).

Data Integration

We used Matlab to sum 1-second/10-min gridded surfaces for contact-calling right whales, hypothesized historical ambient noise, present-day ambient noise, and present-day AIS-tracked shipping noise to create month-long, empirically based, 1 km²-resolution animations of predicted signal and noise-level variation. Signal excesses for calling right whales relative to hypothesized historical ambient, present-day ambient, hypothesized historical ambient and present-day shipping, and present-day ambient and present-day shipping noise levels were calculated as in Clark et al. (2009). We incorporated a detection threshold of 10 dB and a signal-processing gain of 16 dB,

resulting in a recognition differential of 6 dB (see Clark et al. [2009] eqs. 10a–c). The recognition differential term accounts for a right whale's ability to successfully detect and recognize a contact call in some circumstances in which ambient noise levels exceed signal noise levels (Clark et al. 2009). The benefits of this recognition term are expressed as signal excess; the difference between the signal-to-noise ratio and the recognition differential. There is uncertainty in this parameter, although 6 dB is likely a generous recognition differential for a mammalian auditory system. Nevertheless, we also calculated recognition differentials of 0 dB and 3 dB. For each 10-min frame, we mapped summed noise levels (NLs) and signal excesses under various noise levels. Spatial variation in signal excess over all grid points and temporal variation over all 10-min frames were summarized as bottom 5th (quietest), 50th (median), and upper 95th (noisiest) percentiles. We selected 2 10-min frames from the month-long series to illustrate noisier versus quieter periods.

We calculated indices of communication space and communication masking for the modeled right whale animats as a group (rather than as multiple individual senders) by modifying the approach of Clark et al. (2009). Signal-excess values per receiver grid point were scaled and weighted by a probability of recognition term (see eq. 12 in Clark et al. [2009]). This recognition term accounts for an expected decrease in actual communication occurring as the distance between senders and receivers increases. We calculated indices of communication masking for every 10-min sample throughout the month; the masking metric was the change in communication space available to calling whales under hypothesized historical noise levels relative to the communication space available under present-day ambient, shipping, and ambient plus shipping levels. Masking values ranged from 0 (no difference from historical) to 1 (complete loss of communication space available relative to hypothesized historical ambient levels). We averaged spatial variation over all receiver grid points and temporal variation over all 10-min frames and summarized results as 5th, 50th, and 95th percentiles.

To provide a comparison between assessments of noise effects derived from currently applied, exposure-threshold-based metrics versus communication-space quantifications, we calculated, for every 10-min frame under present-day levels of shipping noise, the number of right whales exposed to unweighted ambient noise levels ≥120 dB in the 71–224 Hz band. Noise levels at grid locations were converted from decibels to intensity and linearly interpolated to determine noise levels at animat locations (latitude and longitude only) per 10-min frame. These methods did not allow us to differentiate between unique and repeated events experienced by individual animats over sequential 10-min samples. However, total number of exposure events per day (number of whales exposed to noise levels ≥120 dB in the 71–224

Hz band summed over all 10-min samples in a day) was tabulated for the month. We used masking calculations to compare percent loss of communication space for calling whales under present-day shipping and present-day shipping plus ambient noise levels with the number of right whales exposed to noise levels ≥120 dB in the 71–224 Hz band over all 10-min samples in the month.

Results

Whales

We detected 22,423 right whale contact calls within the MARU array (average [SD] = 747 calls/day [294]). Average contact-calling rate was 0.47 calls/min (0.38) ($n = 86$ calling bouts). Average contact call source level was 172 dB [6.6] in the 71–224 Hz band ($n = 100$ calls). Eighty-nine representative right whale animats were distributed as follows: 27 in the southern sanctuary and Cape Cod Bay (first region), 37 in a region surrounding the first region that encompassed the remainder of the sanctuary and some additional inshore waters (second region), and 26 outside the second region, but within the remainder of the modeling area. The median received sound levels of the 89 contact-calling right whale animats, evaluated over both the area and month of study, was 90 dB (minimum 76, maximum 150) in the 71–224 Hz band.

Noise

The bottom 5th percentile received sound levels for the 2 MARUs closest to the oceanographic buoys averaged 99 dB (SD 4.6) in the 71–224 Hz band. Measured wind speeds (average 4.9 m/s [2.9]) correlated significantly with 5th percentile received sound level summary statistics ($R^2 = 0.034$; analysis of variance $F = 5.7$, $p = 0.02$; slope 0.16, intercept 96.1). We used this linear relation to compute spatially uniform, but time-varying (10-min sample rate), present-day ambient noise levels in the 71–224 Hz band (median 98 dB, minimum 97, maximum 99). Present-day ambient noise levels were similar to contemporary noise levels recorded at other shallow locations along the U.S. east coast with moderate to heavy vessel traffic. Hypothesized historical ambient noise levels (median 88 dB, minimum 87, maximum 89) were higher than (and thus conservative relative to) noise levels recorded at several low-traffic shallow locations similar to, within, or predicted for our study area (Supporting Information).

The median noise level produced by all AIS-tracked ships was 73 dB in the 71–224 Hz band (minimum 0, maximum 196). The model analyses included transiting of 117 vessels: 45 tugs or tows, 27 cargo or container ships, 23 tankers, 10 military or law enforcement vessels, 5 service or research vessels, 4 passenger vessels (cruise ships, ferries, or yachts), and 3 fishing vessels. On the basis of signal-to-noise ratio criteria, received sound

Table 1. Summary of noise-level data by vessel type or class in the Stellwagen Bank National Marine Sanctuary study area in April 2008.

Vessel type or class	n	Source sound level[a]	Average (SD) source sound level[a] (measured)	Average (SD) source sound level[a] (measured + estimated)	Average (SD) speed over ground[b]	Average (SD) minimum draught (m)	Average (SD) maximum draught (m)
Cargo	27	21	191 (6)	190 (6)	4	9 (2)	11 (2)
Liquified natural gas tanker	3	3	188 (8)	188 (8)	5	10 (0.4)	11 (1)
Large tanker	16	14	192 (8)	192 (8)	3	8 (1)	11 (1)
Medium tanker	4	2	188 (6)	187 (4)	1	5 (0.5)	8 (1)
Large cruise	1	1	191	191	0	7	7
Small cruise	1	1	171	171	1	5	5
Ferry	1	0		168	2	na[c]	na[c]
Yacht	1	0		150	0	3	3
Large military	1	0		185	0	na[c]	na[c]
Medium military	9	1	162	159 (1)	1	8 (5)	8 (5)
Marine service	2	0		183 (3)	3	4 (3)	4 (3)
Pilot	1	0		165	11	1	1
Research	2	1	174	168 (8)	4	5	5 (0.4)
Tug	43	9	180 (11)	180 (1)	1	6 (3)	7 (3)
Pusher tug	2	1	179	177 (5)	0	6 (2)	8 (2)
Fishing	3	1	166	168 (3)	4	6	7 (1)

[a] *Unit of measure: dB root mean square 71–224 Hz re 1 μPa.*
[b] *Knots (nautical miles/h).*
[c] *Data not available.*

levels at points closest to MARUs were used to estimate source levels for 55 of the 70 vessels that transited within 10 km (5.4 nm) of an MARU. Empirical source levels were highest for large tankers, cargo or container ships, and large cruise ships and lowest for medium-sized military or law enforcement vessels (Table 1). Empirically based source levels were calculated for 22% of the tug or tows, 78% of the cargo or container ships, 83% of the tankers, 50% of the passenger vessels, 10% of the military or law enforcement vessels, 20% of the service or research vessels, and 33% of the fishing vessels. Average source levels for all vessels of the same type (drawing from both empirical and estimated or literature values) were similar to averages for those measured empirically (Table 1).

For 9 of the 16 types of vessels, the average SD for speed over ground (hereafter speed) was <1.03 m/s (Table 1). For 6 other vessel types, average speed SD was 1.5–2.6 m/s, and for a single-pilot vessel the speed SD was 5.7 m/s. Differences between average minimum and average maximum draughts per vessel type ranged from 0 to 3 m (AIS data) (Table 1).

Five cargo vessels and 2 cruise ships closely approached MARUs and had similar patterns of received sound levels relative to bearing to the MARU: broadside measures (30–140°) were on average 5 dB higher than stern and bow measures (0–30° and 140–180°). We used this pattern to model sound propagation for all cargo ships ($n = 27$) and cruise ships ($n = 2$). Directivity patterns among the other vessel types were either not consistent or sample sizes were too small to support altering the default omnidirectional modeling pattern.

Signal Excess, Communication Masking, and Exposure to Noise

Median signal excess for contact-calling right whales under present-day ambient noise levels without shipping noise was -1 dB (Fig. 2a), whereas median signal excess for the same calling whales evaluated over the same area and period under hypothesized historical ambient noise levels was 9 dB (Fig. 2a). Median signal excess was positive (7 dB) in the presence of hypothesized historical ambient noise plus noise from ships (Fig. 2a), but was negative (median –2 dB) when noise from ships was added to present-day ambient noise (Fig. 2a).

Communication masking under present-day ambient levels was at least 0.60 for 95% (bottom 5th percentile) of the month, a 60% loss of communication space relative to hypothesized historical ambient levels (Fig. 2b). For 50% of the month, communication masking was ≥0.63, a loss of 63% of the communication space available relative to hypothesized historical ambient noise levels. In the presence of only shipping noise, for 50% of the month, communication masking was 0.14, a 14% loss of communication space relative to hypothesized historical noise levels. For 5% of the month, however, communication masking due to shipping noise alone was ≥0.38, a loss of ≥38% of the communication space relative to hypothesized historical levels (Fig. 2b). Under present-day ambient plus shipping noise, masking resulted in a communication space loss of ≥62% for 95% of the month, ≥ 67% for 50% of the month, and ≥ 74% for 5% of the month (Fig. 2b).

We used a first-order sensitivity analysis to explore the relation of values that parameterized historical
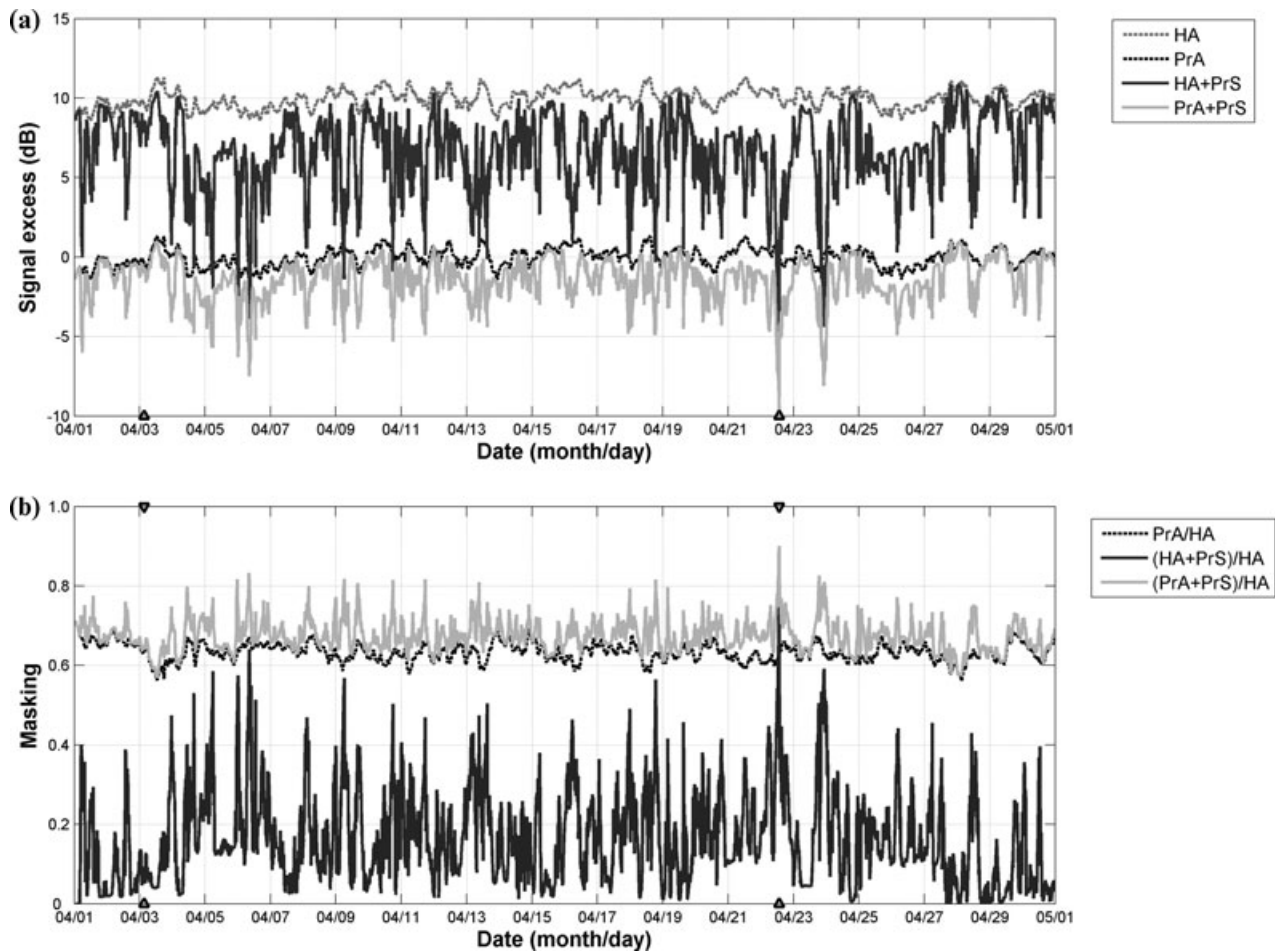
Figure 2. Temporal variation (a) in median signal excess (the difference between the signal-to-noise ratio and the recognition differential) of contact calls of North Atlantic right whales in and around the Stellwagen Bank National Marine Sanctuary per 10-min sample in April 2008 relative to hypothesized historical ambient (HA), present-day ambient (PrA), hypothesized historical ambient plus present-day shipping (HA + PrS), and present-day ambient plus present-day shipping (PrA + PrS) noise levels and (b) in communication masking calculated for the modeled contact-calling North Atlantic right whales per 10-min sample in April 2008 for PrA, HA + PrS, and PrA + PrS noise levels relative to HA noise level. All levels are in the 71–224 Hz frequency band (dB root mean square re 1 µPa), and triangles indicate quieter and noisier 10-min samples, which are shown spatially in Fig. 3.

ambient noise level and recognition differential to communication masking. For a historical ambient noise level of 10 dB below present-day ambient noise levels and recognition differentials of 0, 3, and 6 dB, monthly average lost communication space was 81%, 76%, and 67% respectively. When the historical level of ambient noise was 20 dB below present-day ambient noise and recognition differentials were 0, 3, and 6 dB, the average lost communication space was 90%, 83%, and 74% respectively.

Comparison of received sound level and signal-excess maps for the 89 contact-calling right whales and present-day shipping noise during quiet versus noisy periods illustrates the relative loss of communication space associated with higher densities of nearby large commercial vessels (Fig. 3). Median signal excess during the quiet

period was –2 and –9 dB during the noisy period. This relative difference was quantified by calculating masking for these 2 periods. During the noisy period, communication masking was 0.87, which indicates a loss of 87% of the communication space for calling right whales relative to what they would have had available under hypothesized historical levels of ambient noise. During the quiet period masking was 0.65, which indicates a loss of 65% of communication space relative to hypothesized historical levels of ambient noise for the same callers.

The number of right whale animats exposed to ambient noise levels ≥120 dB in the 71–224 Hz band due to ship noise was 0.32 whales/10-min (SD 0.8) (minimum 0, maximum 11) (Fig. 4). Thus, an average of <1% of the whales in the study area were exposed to ambient
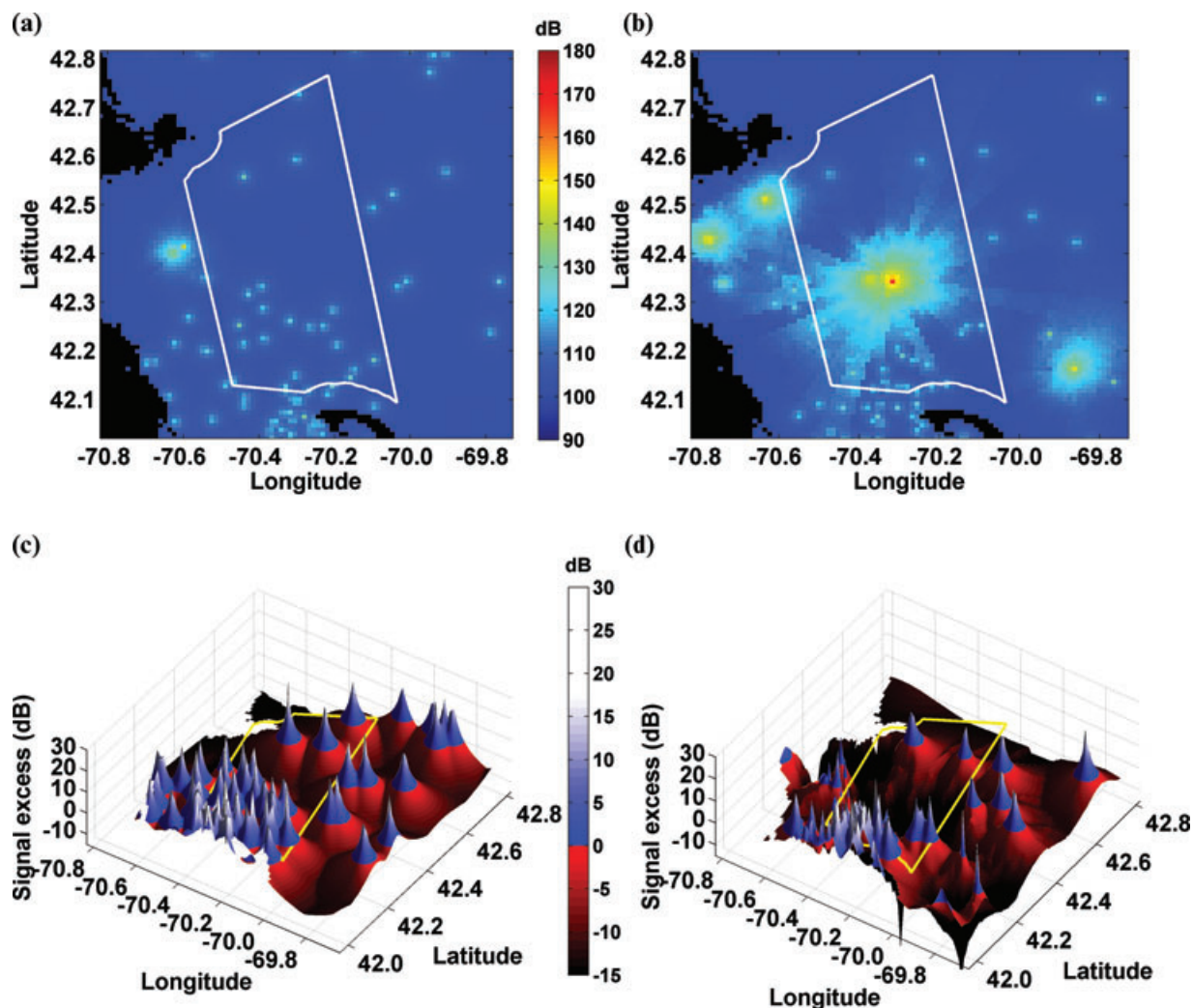
Figure 3. Spatial distribution of (a and b) summed received levels and (c and d) signal excess (defined in Fig. 2) of contact calls of North Atlantic right whales relative to noise from ships (71–224 Hz, dB root mean square re 1 μPa) during 2 10-min sampling periods selected to represent quieter (a and c) and noisier (b and d) periods (triangles in Fig. 2) (white and yellow lines, the boundary of the Stellwagen Bank National Marine Sanctuary).

noise levels ≥120 dB per 10-min sample. The average level of masking to which 89 calling right whales were subjected due to noise from the close passage of ships (per 10-min sample period) was 0.16 (SD 0.12) (minimum 0.0, maximum 0.82). Under the combination of present-day ambient noise and noise from ships, there were, on average, 46 whale-exposure events/day with noise levels ≥20 dB (SD 28) in the 71–224 Hz band (minimum 9, maximum 121), and the average level of communication masking was 0.67 (SD 0.04) (minimum 0.57, maximum 0.90) (Fig. 4). No right whales were exposed to noise levels ≥120 dB in the 71–224 Hz band during the quiet 10-min sample period (Fig. 5a), whereas 5 right whales were exposed to levels ≥120 dB in the 71–224 Hz band during the noisy 10-min sample period (Fig. 5b).

Discussion

We quantified dramatic losses in the potential communication space available to North Atlantic right whales associated with changes in noise conditions that we hypothesize took place within the lifetimes of many of the whales alive today. We estimated that on average contact-calling right whales in this ecologically important area have conservatively lost 63% of the communication opportunities estimated to have been available to them in the mid 20th century. During the passage of commercial vessels, lost communication space increased to 67%. This supports the claim made by Clark et al. (2009) that compared with other vocally active baleen whales, the lower source levels produced by contact-calling North Atlantic right whales make them particularly vulnerable
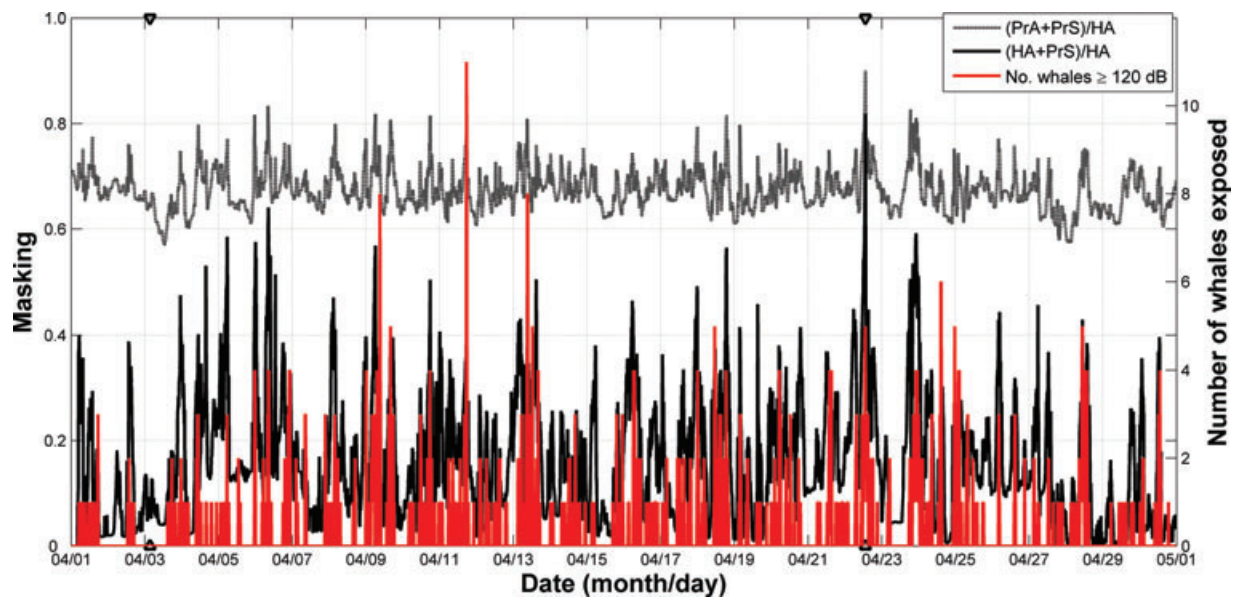
Figure 4. Temporal variation per 10-min sampling period in April 2008 in the number of North Atlantic right whales within the study area exposed to noise levels ≥120 dB (71–224 Hz, root mean square re 1 µPa) from ships and average value of communication-masking index under hypothesized historical ambient plus present-day shipping noise levels (HA + PrS) and under present-day ambient plus PrS noise levels (PrA + PrS), both relative to HA level (triangles indicate quieter and noisier 10-min samples shown spatially in Fig. 5).

to communication masking as a result of chronic noise from vessel traffic.

We identified several parameters that define communication space for calling whales, but many of them are poorly understood. Although further research and modeling efforts are needed to address uncertainty in signal-

recognition processes and long-term, large-scale trends in ambient noise levels, our results also point to the roles population dynamics can play in shaping communication capacity. Baleen whales, like most animals, are not distributed uniformly. Calling was modeled for areas with both high and low densities of whales, and signal
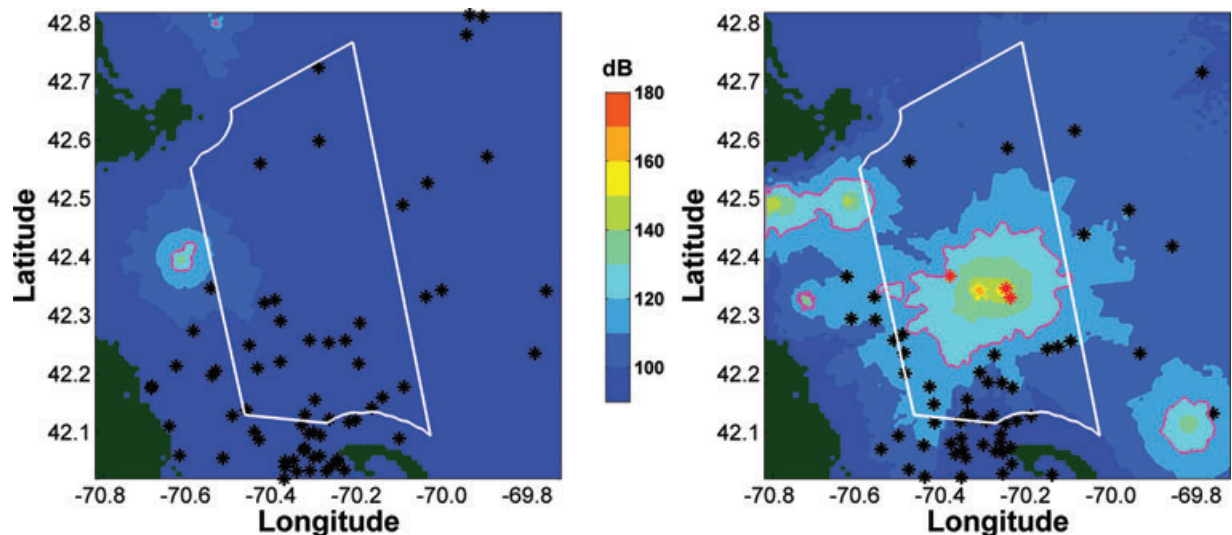

Figure 5. Spatial distribution of cumulative ship noise levels (71–224 Hz, dB root mean square re 1 µPa). Contours are in 10-dB increments (120 dB contour in pink) relative to the locations of 89 modeled North Atlantic right whales (black asterisks) and to whales exposed to noise levels ≥120 dB (red asterisks) during 2 10-min sampling periods selected to represent (a) quieter and (b) noisier periods (triangles in Fig. 4) (white line, boundary of the Stellwagen Bank National Marine Sanctuary).

excess was low in areas with high noise levels and in areas with few or widely spaced calling whales. This underscores the importance of accurately representing the density and distribution of both calling and receiving whales when evaluating communication space and of understanding the effects of changes in population size on probability of communication. Extant North Atlantic right whales are more likely to be subjected to higher levels of communication masking from vessel noise than other baleen whale populations because of their low population size and the low density of calling. In addition, relative to other species of baleen whale, right whales do not produce intense, patterned acoustic displays (i.e., songs), and their call source levels and call rates are relatively low. Thus, even when right whale populations were at prewhaling abundance levels and call density was proportionately greater, greater calling density would not have added substantially to background noise levels or reduced opportunities for communication among individuals.

Baleen whale species use a variety of complex acoustic behaviors to conduct vital activities such as foraging, raising of young, migrating, and selecting mates (Tyack 2008). Thus, increasing levels of background noise within the frequency bands used by whales to send and receive information are likely to affect their abilities to survive and reproduce (Ellison et al. 2012). More generally, higher levels of background noise can affect multiple, hearing-dependent, life-critical behaviors (e.g., foraging, predator detection, navigation), and individuals living in noisier conditions are less able to use sound to detect changes in their environment. Many animals maintain constant auditory vigilance. Sounds that do not awaken sleeping humans but cause physiological arousal are associated with long-term, negative health effects (Spreng 2000; Babisch 2006; Haralabidis 2008), and increases in ambient noise affect development and academic performance in humans (Evans 2003). There is a correlation between reduced ship traffic and decreased baseline levels of stress-related glucocorticoids in North Atlantic right whales (Rolland et al. 2012). This finding provides preliminary evidence that exposure to low-frequency noise may be associated with chronic stress in this species.

Chronic background noise thus diverts attention and disrupts behavior, leads to habituation to background noise, masks auditory signals, and stimulates spurious physiological responses. These problems may compromise physiological function, reduce energy and time available to support critical activities, result in failure to detect important cues, impair transmission of cues and communication, and reduce use of important habitat areas or resources (Hatch & Fristrup 2009). These problems have fitness consequences. Although at least 2 marine mammals will increase call source levels in response to increased noise levels (Holt et al. 2009, Parks et al. 2010), such compensation is constrained by biome-

chanical, behavioral, and sound-propagation limits and incurs potential fitness costs.

The U.S. Endangered Species Act of 1973, as amended through 2004 (ESA), and U.S. Marine Mammal Protection Act of 1972, as amended through 2007) (MMPA), were passed specifically to identify and reduce or eliminate negative fitness effects on species threatened with extinction or otherwise deemed priorities for protection. Under the MMPA, human-induced underwater noise sources that expose baleen whales to continuous noise above 120 dB (frequency bandwidth is not specified in the regulations) are identified as potential sources of disturbance ("acoustic harassment") (Ellison et al. 2012) and must be permitted (NOAA 2005). Although noise from commercial vessels in transit is currently not regulated under the MMPA, we applied the 120-dB threshold to our data to estimate the proportion of right whales in the study area that were behaviorally disturbed by noise from commercial ships. We estimated that as many as 11 out of 89 (12%) of the whales in the model were exposed to unregulated noise from commercial shipping $\geq$120 dB in the 71–224 Hz band during one 10-min period.

The average contribution of discrete nearby ships to levels of communication masking experienced by a sparsely distributed population of right whales was relatively low (16%), as were average levels of acoustic harassment (1%). This is because present-day ambient noise levels throughout the study area are elevated and are now the main contributor to estimates of lost communication space (on average 63% for the month). This highlights the need to incorporate measures of ambient noise in methods that evaluate chronic-noise effects (Ellison et al. 2012). In addition, determining loss of communication space relative to ambient noise levels before large-scale, human-induced alteration of acoustic habitats is important for evaluating long-term population viability. Currently, assessments of chronic noise sources conducted under the ESA largely apply the same metrics used in permitting under the MMPA and thus share the weaknesses of this approach. However, under the ESA there is the opportunity to incorporate assessments of lost acoustic habitat in consultations and long-term assessments of recovery potential.

Interest in developing methods that integrate quantification of acoustic habitat loss and effects from additional stressors that affect listed species is growing (Hatch & Fristrup 2009). It has been 30 years since the National Environmental Policy Act (1969 as amended through 1982) and other cumulative-effect regulations were implemented in the United States and worldwide, and the state of global marine ecosystems is still declining (e.g., Halpern et al. 2008; Foley et al. 2010). This decline has spurred ocean planning initiatives in the United States (Interagency Ocean Policy Task Force 2009) and other countries (Ehler & Douvere 2009) that are designed to comprehensively manage human uses in both nearshore

and offshore waters. Nearly all emerging ocean planning efforts assert the goal of protecting marine ecosystems yet integration of information regarding the ecological implications of human activities continues to lag behind efforts to map human uses (Foley et al. 2010). However, ocean planning represents a promising strategy for incorporating the accumulated effects of wide-ranging stressors, such as chronic noise, in decisions regarding future human activity.

More complete integration of the effects of communication masking on marine mammals and other animals will require the development of methods for translating the effects of masking on ecosystem services. Baleen whales have been given legally codified, cultural value in U.S. waters, support whale-watching businesses, and play a variety of roles in ecosystem dynamics that support commercial and recreational fisheries. Measures of the effects of noise that relate directly to functional consequences for whales can thus be integrated in models that evaluate trade-offs among ecosystem services (e.g., management choices that change the type, magnitude, and relative mix of services provided by ecosystems). Efforts to define such measures for marine mammals and noise continue to focus primarily on disturbance of important, obvious behaviors (e.g., reproduction, foraging). We argue that measures of acoustic communication or degradation of acoustic awareness can document wider-ranging and increasingly relevant functional consequences of increased ambient noise levels for marine animal populations. Thus, we believe research and policy development should explore the individual and population-level costs of habitat loss caused by acoustic masking. Finally, we believe the integration of the effects of noise and the effects of other environmental stressors should be prioritized.

Acknowledgments

Supporting Information

More information on the experimental design (Appendix S1) and methods and modeling (Appendix S2) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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