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PROFILE

Characterizing the Relative Contributions of Large Vessels to Total Ocean Noise Fields: A Case Study Using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary

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Abstract In 2006, we used the U.S. Coast Guard's Automatic Identification System (AIS) to describe patterns of large commercial ship traffic within a U.S. National Marine Sanctuary located off the coast of Massachusetts. We found that 541 large commercial vessels transited the greater sanctuary 3413 times during the year. Cargo ships, tankers, and tug/tows constituted 78% of the vessels and 82% of the total transits. Cargo ships, tankers, and cruise ships predominantly used the designated Boston Traffic Separation Scheme, while tug/tow traffic was concentrated in the western and northern portions of the sanctuary. We combined AIS data with low-frequency acoustic data from an array of nine autonomous recording units analyzed for 2 months in 2006. Analysis of received sound levels (10–1000 Hz, root-mean-square pressure re 1 μPa ± SE) averaged 119.5 ± 0.3 dB at high-traffic locations. High-traffic locations experienced double the acoustic power of less trafficked locations for the majority of the time period analyzed. Average source level estimates (71–141 Hz, root-mean-square pressure re 1 μPa ± SE) for individual vessels ranged from 158 ± 2 dB (research vessel) to 186 ± 2 dB (oil tanker). Tankers were estimated to contribute 2 times more acoustic power to the region than cargo ships, and more than 100 times more than research vessels. Our results indicate that noise produced by large commercial vessels was at levels and within frequencies that warrant concern among managers regarding the ability of endangered whales to maintain acoustic contact within greater sanctuary waters.

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Introduction

The anthropogenic components of underwater noise and their potential impacts on marine resources are topics of substantial interest and concern among scientists and the public (NRC 1994, 2000, 2003, 2005). In the past 5 years, many national and international policy forums have addressed ocean noise concerns (ACCOBAMS 2003; ASCOBANS 2003; World Conservation Union [IUCN] 2004; IWC 2005; U.K. IACMST 2006; U.S. MMC 2007). These concerns have mainly focused on injury and/or behavioral disturbance of whales exposed to impulsive (e.g., short-duration) sounds, such as sonars utilized for naval defense and seismic sources used for oil and gas exploration (NRC 2000, 2003). However, possible impacts to marine animals exposed to continuous sources, such as commercial shipping, have recently begun to garner more attention (Southall 2005, 2007).

Evidence of increasing levels of underwater noise associated with shipping has heightened concerns regarding the “masking” of marine animal signals, particularly low-frequency vocalizations, with possible negative effects including diminished abilities to find mates, maintain social structure, forage, navigate, and/or evade predation (Payne and Webb 1971; Erbe and Farmer 1998, 2000; Southall and others 2000; Erbe 2002; Morisaka and others 2005; Nowacek and others 2007). Due to the concentration of acoustic energy from large commercial vessels within low-frequency bandwidths, and the efficiency of the propagation of low frequencies underwater, distant commercial shipping dominates low-frequency, omnipresent background or “ambient” noise in many parts of the world’s oceans (Wenz 1962, 1969; Gray and Greeley 1980; Ross 1993; Greene and others 1995). The relative contribution of vessel noise to ambient ocean noise varies with the distribution of vessel traffic, with areas such as shipping lanes (Andrew and others 2002; McDonald and others 2006) and the northern hemisphere in general (Cato 1976) showing higher noise levels. In such areas, increasing commercial maritime transport over the past 30 years is correlated with 10 decibel (dB) re 1 micropascal (μPa) increases in low-frequency noise levels (Andrew and others 2002; Cato and McCauley 2002; McDonald and others 2006).

A key recommendation of reports dealing with anthropogenic noise is the need to establish “noise budgets,” defined as the sum of the relative contributions made by identified sound sources to total noise fields, for areas of the ocean (NRC 2003). The NRC specifically identified the need to define the sound contributions of different vessel types within the major category of shipping and to characterize the temporal (e.g., annual, seasonal, monthly, and daily) and spatial variation of noise production and sound fields (NRC 2003). This information can then be used to understand the potential impact of anthropogenic noise on local marine animals.

Our study site was the Stellwagen Bank National Marine Sanctuary (SBNMS or sanctuary). The sanctuary is a federally designated marine protected area located to the east of Boston, Massachusetts, USA, and in close proximity to a densely populated coastal zone (Fig. 1). Because of this, substantial commercial shipping transits the sanctuary to and from the port of Boston, and the sanctuary hosts a United Nations’ International Maritime Organization (IMO) recommended route for commercial vessels (the Boston Traffic Separation Scheme; BTSS). The sanctuary is also an important feeding ground for endangered marine mammals such as the North Atlantic right whale (*Eubalaena glacialis*), humpback whale (*Megaptera novaeangliae*), and fin whale (*Balaenoptera physalus*), which are vulnerable to collisions with vessels and persistent exposure to shipping-generated noise. As a result, the sanctuary makes an ideal

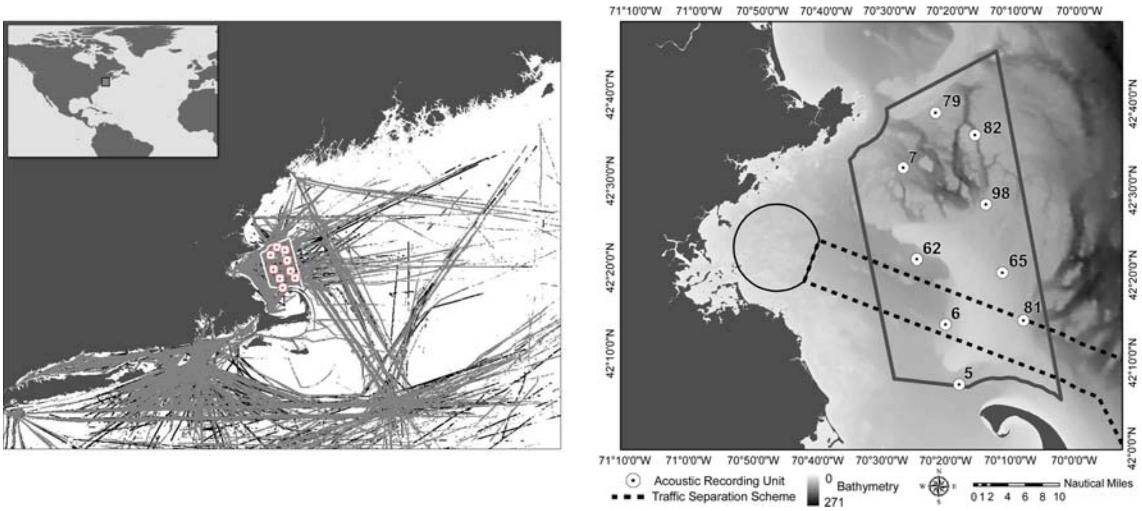

Fig. 1 The upper-left inset shows the location of the Gerry E. Studds Stellwagen Bank National Marine Sanctuary (SBNMS) in Massachusetts Bay, off the northeast coast of the United States. Both regional maps show the boundaries of the SBNMS and the locations of the nine Autonomous Recording Units (ARUs) deployed between April 7 and May 24, 2006. All vessel traffic tracked using the U.S. Coast Guard’s Automatic Identification System during the months of April and May 2006 using four receivers located on Fisher Island near Groton, CT, on Cape Cod near Provincetown, MA, in downtown Boston, MA, and at SBNMS headquarters in Scituate, Massachusetts has been plotted on the left. April’s traffic is plotted in black and May’s traffic is in gray. The map at the right allows the reader to reference the ARU numbers referred to in the text, the location of the 2006 Boston Traffic Separation Scheme (dashed line), and the bathymetry of the study area

study site for the investigation of anthropogenic noise and its potential impact on endangered large whales.

For this investigation, we used the U.S. Coast Guard's Automatic Identification System (AIS) to track individual vessels transiting the SBNMS throughout 2006. For April and May 2006, we combined ship transit data with acoustic data collected from autonomous recording units (ARUs) placed throughout the sanctuary. Our goal was to establish a noise budget for the sanctuary by (1) quantifying the temporal and spatial vessel traffic patterns in the sanctuary, including variation in vessel size and speed, (2) quantifying the noise produced by specific vessel classes, and (3) extrapolating those data to the entire sanctuary area for a 1-year period. We also used data on historic distribution of marine mammals in the sanctuary to quantify the acoustic consequences of the sanctuary's recent shifting of the BTTS from areas of high whale density to low-density areas.

Methods

Acquisition of Automatic Identification System Data

Under the IMO's current mandates, all ocean-going commercial traffic >300 gross tons or carrying more than 165 passengers, as well as all tug/tows, are required to carry AIS transmitters (Federal Register 2003; IALA 2004). The AIS is a VHF "line-of-sight" transmitter that broadcasts a vessel's position, identity, and various characteristics (including but not limited to length, beam, draught, cargo type, destination, and speed) as often as every 2 s. Four AIS receivers, located near Provincetown, Boston, and Scituate, Massachusetts, USA, as well as on Fishers Island, New York, USA, allowed for the tracking of all vessels carrying AIS transmitters as they transited the study area and beyond (Fig. 1). Through collaboration with the U.S. Coast Guard, vessel tracking data from these receivers were continuously archived for the entire year of 2006 on a server at the SBNMS and available for real-time viewing as well as post hoc analysis.

Analysis of AIS Data

An area defined by the boundaries of the SBNMS extended by 5 nautical miles (nmi) was chosen for analysis. This spatial extent was chosen as a course estimate of the area within which ships with source levels (SLs) $\geq$ 180 dB re 1 μPa would ensonify the sanctuary at levels >120 dB re 1 μPa. Source levels for the majority of large commercial vessels range from 170 to 190 dB (Wenz 1962; Gray and Greeley 1980; Greene and others 1995). For a SL of 180 dB, a course estimate of transmission loss (TL) of 60 dB (bringing received levels [RL] to 120 dB), using TL = 15 log10 (distance), would occur approximately 5.4 nmi (10 km) from the source. As discussed further below, this simplified TL equation was chosen to represent the average sound field during our study, while retaining dependence on the principle features of the environment.

Archived AIS data collected in 2006 were extracted, reformatted, filtered, and quality controlled. Reformatting was necessary to provide a continuous data stream rather than daily log files collected for the U.S. Coast Guard's purposes, and filtering was necessary to extract only the vessel information that was necessary for this study. Extraction and filtering were completed using the U.S. Coast Guard's newly updated software (U.S. Coast Guard Research and Development 2007) and custom software written in Python v2.5.1 (Python Software Foundation 2007) added to the noaadata package (Schwehr 2007).

Ship positions were loaded in PostgreSQL/PostGIS (Santilli and Leslie 2007) for transit analysis. Using the database, each vessel's position reports were grouped into transits. A vessel's transit was defined as a set of chronologically ordered position reports preceded and followed by not receiving a position report from the vessel within the study area for 1 h. Noaadata then generated a report of all transits. Following extraction from AIS Miner (U.S. Coast Guard Research and Development 2007) and ArcGIS (ESRI 2006), AIS data were manipulated and/or graphed in Microsoft Excel (Microsoft Office 2003) and/or Microsoft Access (Microsoft Office 2003), depending on the file size.

Finally, because some AIS data fields (e.g., ship identification numbers, ship name, ship type, cargo type, and dimensions) rely on manual input from shipboard users, they are more likely to contain errors (Harati-Mokhtaria and others 2007). Thus, information on each of the 541 vessels was reviewed by hand, with additional information (including gross tonnage, flag of ship, and year built) and any errors identified by cross-checking information provided with that available from Web-based ship registries (e.g., Equasis and individual company websites). Ship type categories were taken directly from the International Association of Marine Aids to Navigation and Lighthouse Authorities' Guidelines for AIS (IALA 2004), with further specificity provided through Web-based research. Once ships were classified, the separate groups of ships were gridded using noaadata. The study area was divided into a grid with 1 × 1 nmi (1.85 × 1.85 km) cells. Each transit was linearly interpolated across the gridded region based on all of the received ship position reports. A cell was incremented by one for each time the ship entered the cell. If a ship left and re-entered a cell, the cell was again incremented. The amount of time a ship resided within a cell was not considered for the cell counts. The total counts were then written to an ArcASCII grid and imported into ArcGIS for display.

AIS data were visualized and spatially analyzed either using custom queries added to the noaadata software or ArcGIS. Minimum great circle distances (meters) between vessel locations and ARU locations were calculated to determine each vessel's closest point of approach (CPA) to the array. Each transit of the sampled area per vessel was then further documented by recording the times and dates of entries and exits. Vessels' speeds over ground were analyzed, and results are presented by Wiley and others (2008). As discussed by Wiley and others (2008), calculations of average speed over ground in a specified area using AIS data must account for covariance between the number of data points received and the speed of the transmitting vessel. For this paper, two summary statistics that are robust to non-uniform sampling rates were calculated for each vessel transit: minimum speed over ground and maximum speed over ground (as knots or nmi/h and as km/h). Number of hours spent and number of nautical miles/kilometers transited within the sampling region were calculated per transit. The numbers of transits approaching within 5-nmi (9.26-km) radii of each of the ARUs were calculated. Finally, each-nmi^2 (3.42-km^2) block of the SBNMS was coded per day according to the presence/absence of vessels falling into five broad categories (e.g., cargo, tanker, services and research, passenger, and tug/tows). These daily presence/absence grids were then summarized as density plots to show the distribution of vessel types within the SBNMS.

Acquisition of Acoustic Data

Acoustic data (10–1000 Hz) were collected using an array of 9 or 10 ARUs (ARUs) deployed in the Stellwagen sanctuary from January 2006 to January 2007 (Fig. 1). All units were synchronized just prior to deployment and just after recovery. These ARUs, or "pop-ups," were developed by Cornell University's Bioacoustics Research Program and are comprised of an external hydrophone attached to a glass sphere containing a battery, computer electronics, and memory which is temporarily anchored to the ocean floor with sandbags (Calupca and others 2000). The ARU hydrophones were calibrated at U.S. Naval facilities in New London, Connecticut, USA, and the operational ARUs were calibrated at a U.S. Naval facility on Seneca Lake, New York, USA. Operational ARUs had flat frequency responses (±1-dB variation) in the 55- to 1000-Hz range. To retrieve data from the ARUs, the release of their anchorage was acoustically triggered using a shipboard transponder allowing surface retrieval. ARUs were retrieved and redeployed every 2–3 months in order to download data and replenish batteries. The units recorded continuously at a 2000-Hz sampling rate; raw binary acoustic data files, as well as finalized multichannel AIFF files, were archived onto 160- to 320-GB hard drives.

Analysis of Acoustic Data

The months of April and May 2006 were chosen for integration of acoustic and AIS data because many non-commercial shipping activities that are presumed to impact the SBNMS's acoustic environment (e.g., fishing vessels, fishing activities, and small recreational craft) were either prohibited (most fishing activity) or reduced (recreational activity) during that period. This time period was slightly restricted by late deployment and earlier retrieval of a few ARUs in the array. Thus, the analysis period, during which the full ARU array was deployed, was April 7–May 24, 2006 (48 days). In addition, one ARU (no. 6) was found to have malfunctioned on May 4, 2006. Thus, analysis at this location was only possible for 27 days.

Archived raw acoustic data from all nine ARUs were processed to create synchronized, nine-channel, time-aligned files. Synchronized acoustic data were then visualized using an open-source extensible sound analysis application for developing sound analysis tools written in Matlab (The Mathworks Inc. 2006) called XBAT (Mills and Figueroa 2005; Figueroa 2007). Daily, weekly, and monthly RLs for 3 broad-frequency bandwidths (10–1000, 10–400, and 71–141 Hz) and 17 third-octave bandwidths (center frequencies at 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, and 400 Hz) were calculated. Total bandwidth RLs were also broken down by percentages of the time period analyzed, with RL thresholds for 5, 25, 50, 75, and 95% of the sampling period reported. These calculations were performed using a Matlab program called LTspec (Cortopassi 2007). LTspec uses a Fourier transform and time aggregation to generate a long-term root-mean-square (RMS) spectrogram which contains RMS magnitude values for each frequency band of width Δf over the total spectrogram bin interval Δt. RMS spectrograms were created using a sampling rate of 2000 Hz, a FFT size of 2048, $\Delta t = 1.024$ s (aggregated over hours, days, weeks, and months), $\Delta f = 0.98$ Hz, a Hanning window function, and a calibration reference level of 85.5 dB re 1 μPa with a reference bit depth of 12.

Spectrograms and power curves for each ARU location were generated to display variation in received frequencies and acoustic intensity (dB re 1 μPa) over days, weeks, and each of the 2 months sampled.

Integration of AIS and Acoustic Data

AIS data were integrated with acoustic data in two ways: (1) RLs were examined relative to the number of vessels transiting each of the ARUs over multiple temporal scales; and (2) the acoustic footprints of 17 vessels representing all vessel types in our 2-month sample were characterized at their points of closest approach to ARUs in the array.

Standard errors were calculated to accompany all averages reported in this paper. For the first analysis, low-frequency acoustic events identified within the daily, weekly, and monthly acoustic records for each ARU were matched in time with close approaches by AIS-tracked vessels tracked. The total and average numbers of each type of AIS-tracked vessel passing within a 5-nmi (9.26-km) radius of each of the ARUs were calculated. The relationship between the numbers of closely approaching vessels and the variation in RMS RLs recorded by each of the ARUs during the months of April and May 2006 was evaluated statistically in a number of ways. First, the average number of vessels within 5 nmi (dependent variable) was assessed relative to average received levels in the 10- to 400-Hz band (independent variable) for each ARU in April and May 2006 using linear regression. Analyses were also completed using daily RMS RLs and the daily close approaches by each vessel type, to determine whether some vessel types were stronger determinants of received levels than others. All statistical analyses were completed in JMP v5.0.1a (SAS Institute Inc. 2002).

Seventeen vessels which closely approached the location of an ARU in the array and represented the diversity of vessel types in the sample were chosen for the second analysis. The locations and times of their CPAs to the ARUs in the array were used to match the vessel tracks to the acoustic records. Once matched, three estimates of RLs (1-s peak RL, 10-s peak RL, and 5-min RMS RL) were calculated at the time of the CPA to each ARU in the array, and in a frequency bandwidth (71–141 Hz) important for vocalizing North Atlantic right whales in the SBNMS (Urazghildiiev and Clark 2006). The average of these values was used as the empirical basis for interpolating the levels of sound inside the boundaries of the array. Kriging (a group of geostatistical techniques used to interpolate the value of a random field at an unobserved location from observations of its value at nearby observed locations [see Cressie 1993]) was used to compute the best linear unbiased estimator of the RLs based on a stochastic model of the spatial dependence quantified by a variogram of the empirically measured levels. Parameter settings used to krige the acoustic data were as follows: Xmin = –70.4568, Xmax = −70.1362, Ymin = 42.1204, Ymax = 42.6455, dx = 0.0168737, and dy = 0.0276368. Variogram settings included the selection of a spherical model type with a range of 1.4142, length of 1.4142, resolution of 0.025, power of 3.3973, sill of 2.2495, and nugget of 0. The intensity of the kriged sound field in the 71- to 141-Hz frequency band was represented on a gray scale from black (high) to white (low), with a grid size of 13 × 18 points. The final image was refined using a smoothing interpolation function in Matlab.

Interpolating RLs necessitated identifying a simplified estimate of TL (decreasing sound energy over distance from source) that could be used to characterize the average sound field in our study area during the months analyzed here. To estimate TL, we referred to equations devised by Marsh and Schulkin (1962) which represent average sound fields in areas where conditions gradually transition between spherical spreading in the near field to cylindrical spreading in the far field. Based on the range of bottom depths and thermocline depths (referenced from Valentine and others 1999) in our study area during April and May, our conditions were characterized as “intermediate” and are described by the simplified equation $\mathrm{TL} = 15\log(\mathrm{distance}) + 5\log(H) - K$, where H represents the skip distance of a propagating wave and K represents the contribution by bottom and surface reflections (Marsh and Schulkin 1962). H (as kiloyards) is further defined to equal $[1/8(\text{depth to bottom in feet} + \text{depth to thermocline in feet})]^{1/2}$ (Marsh and Schulkin 1962). By calculating TL over the appropriate range of empirical and reference-based bottom and thermocline depths, we determined that accounting for the H term could increase our TL estimates (and thus raise our SL estimates) by no more than 4 dB. Further accounting for K would likely offset this theoretical maximum to some unknown degree. Thus, in the absence of the data necessary to accurately calculate H, we relied on the main term 15 log(distance), noting that our results are conservative by as much as, but likely far less than, 4 dB.

Using this equation for TL, the SL of a vessel was calculated as its RL plus TL over the distance between the source and the receiver (Ross 1976; Urick 1983). Three estimates of the SLs (associated with the three estimates of RL) for each vessel at its CPA and three estimates of distances from CPA locations to isopleths (contours that map the spatial extent of a sound within specified intensity bounds) of interest were calculated.

To estimate the total relative contributions of different sampled vessel types to the low-frequency (71- to 141-Hz) band of the sampled region during 2006, average SLs for vessels of each type were converted from decibels to absolute intensity (watts). Absolute intensity per vessel type was then multiplied by the total number of hours that each type spent in the sampling region in 2006. These estimates of total absolute intensity per year per vessel type were then converted back to decibels and scaled relative to the lowest contributing vessel type.

Results

Automatic Identification System Data

Number and Types of Vessels

Commercial vessels accounted for 78% of AIS-tracked vessels transiting the study area in 2006, with the remaining

22% comprised of passenger carriers (16%), service and research vessels (6%), and fishing vessels (1%) (Table 1). AIS Carriage A requirements exempt the majority of fishing vessels, local/regional passenger ferries, and private yachts that utilize the study area; thus, the number of those vessels and their relative abundance are underestimated to a large, but unknown degree. These vessels were retained in the sample to provide information on vessel behavior and acoustic footprints which may be useful to extrapolations based on external estimates of small and medium size vessel activity in Massachusetts Bay.

Commercial vessels accounted for 82% of vessel transits, representing 60% of the total time and 80% of the total distance that vessels spent in the study area (Table 1). Research and sailing vessels traveled longer distances on average, while research vessels, marine service vessels, and private yachts averaged the longest time within in the region. Variance in transiting distance varied significantly among vessel types (O'Brien's test, $F = 6.5$, df $= 13$, $p < 0.0001$), with tankers showing the lowest variance in transiting distance (standard deviation [SD] = 11 km; $n = 793$), while research vessels (SD = 128 km; $n = 122$) and law enforcement vessels (SD = 74 km; $n = 69$) showed the highest variance. The largest vessels, in both gross tonnage and length, were liquefied gas carriers, cruise ships, and a U.S. Navy medical transport vessel (Table 1).

Temporal and Spatial Use

The temporal distributions of vessel types transiting the SBNMS varied significantly in 2006. Tankers carrying oil and natural gas were marginally significantly more common in the fall and winter than in the spring and summer ($\chi^2 = 3.4$, df $= 1$, $p = 0.06$), while passenger carriers (cruise ships, ferries, sailing vessels, and pleasure craft) were significantly more common in the summer and fall than in the winter and spring ($\chi^2 = 222.7$, df $= 1$, $p \ll 0.0001$).

The spatial distributions of vessel types were also found to be nonuniform within the sampled area was (Fig. 2). Tankers, cargo ships, and passenger vessels (e.g., cruise ships) predominantly used the Boston shipping lanes (BTSS), while service and research vessels were less concentrated and tug/tow activity was concentrated in the western and northern sanctuary (on the outer boundary of the acoustically monitored area). Differences among vessel

Table 1 Numbers and sizes for each vessel type tracked in this study, as well as numbers and total and average distances and times for transits of the study area made by these vessels (SE = standard error)

Vessel class	Vessel type	No. vessels	Average gross tonnage (ft^3 ± SE)	Average length (m ± SE)	No. transits	Total transit distance (km)	Average transit distance (km ± SE)	Total transit time (h)	Average transit time (h ± SE)
Commercial	Tug	113	334 ± 24	34 ± 1	1,102	44,033	40 ± 0.8	2,956	3 ± 0.06
	Cargo/container	113	29,002 ± 1,097	205 ± 4	599	33,767	56 ± 1.3	1,243	2 ± 0.07
	Other cargo	31	34,060 ± 3,234	189 ± 7	110	5,639	52 ± 2.4	238	2 ± 0.1
	Oil/chemical tanker	151	24,463 ± 623	178 ± 2	793	41,915	53 ± 0.4	1,702	2 ± 0.1
	LNG tanker	9	66,570 ± 9,947	246 ± 14	163	8,552	52 ± 2.2	1,065	7 ± 1.3
	Other tanker	2	17,315 ± 11,023	146 ± 37	40	1,699	42 ± 0.9	74	2 ± 0.07
Passenger	Ferry	1	6,556 ± 0	78 ± 0	2	125	62 ± 0.7	2	1 ± 0.2
	Cruise ship	23	59,841 ± 9,588	220 ± 19	187	10,485	56 ± 0.9	394	2 ± 0.07
	Sailing	14	117 ± 30	31 ± 4	36	2,306	64 ± 7.8	226	6 ± 1.3
	Private yacht	49	566 ± 83	38 ± 2	127	5,919	48 ± 5.8	2,343	18 ± 10
Service and research	Law enforcement	10	1,091 ± 248	61 ± 8	70	3,806	55 ± 8.9	217	3 ± 0.4
	Medical transport	1	54,367 ± 0	273 ± 0	2	125	62 ± 2.9	6	3 ± 0.5
	Research	9	1,093 ± 358	51 ± 6	122	9,117	75 ± 12	999	8 ± 1.8
	Training ship	7	35,765 ± 13,651	176 ± 43	21	1,162	55 ± 4.3	64	3 ± 0.3
	Marine service	4	4,275 ± 2,702	79 ± 23	14	739	53 ± 5.4	457	33 ± 19
Fishing	Fishing	4	NA	38 ± 9	25	1,186	47 ± 6.5	95	4 ± 0.6
Total		541			3,413	170,573		12,079	

Note: SE, standard error

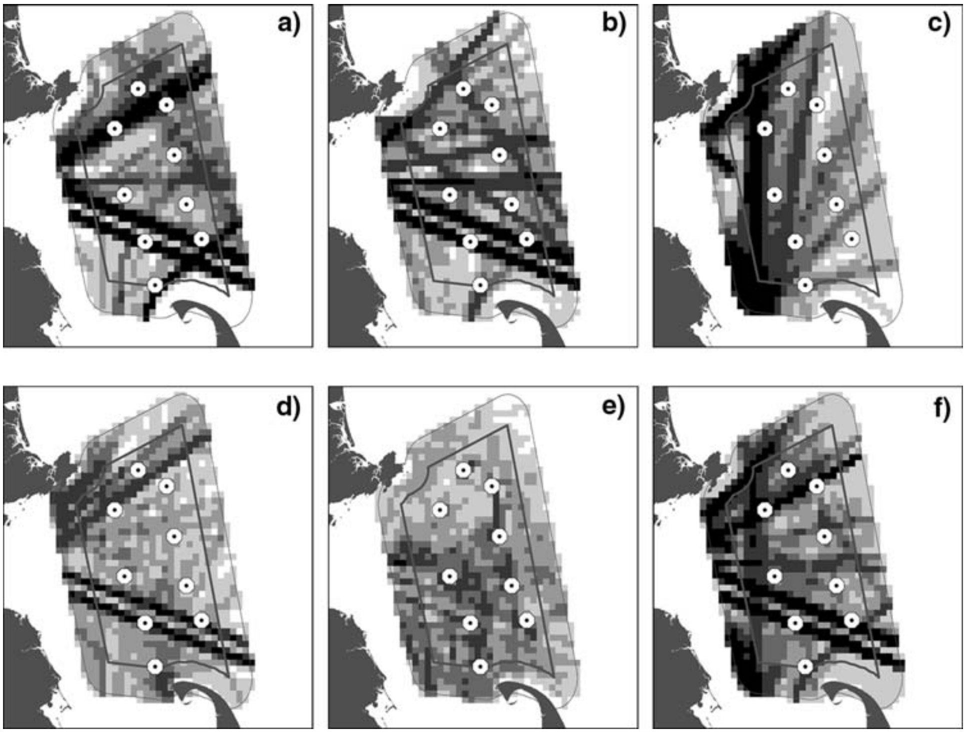

Fig. 2 Distributions of five vessel types (**a–e**) and all (except fishing) vessels (**f**) within the sampling region in 2006, with (**a**) all tankers (including liquefied gas; *n* = 162), (**b**) all cargo ships (*n* = 144), (**c**) all tug/tows (*n* = 113), (**d**) all passenger vessels (including cruise ships, sailing boats, fast ferries, and private yachts; *n* = 87), and (**e**) all service and research vessels (also including training, medical, and law enforcement vessels; *n* = 31). Cell density scores for tugs/tows (the vessel type with the highest density score per cell) were ordered, and all nonzero values were divided into quintiles. These quintiles were used to bin density scores and color-code cell grids for individual vessel types (**a–e**). White cells had no vessel activity. Cells with vessel activity were color-coded as follows: 20% gray, >0 to 4; 40% gray, >4–10; 60% gray, >10–17; 80% gray, >17–43; and black, >43–244. Quintiles for the grid of all vessels were as follows: 20% gray, >0 to 35; 40% gray, >35–53; 60% gray, >53–77; 80% gray, >77–131; and black, >131–557. White dots with black centers represent Autonomous Recording Unit (ARU) locations

types in the spatial distributions within the sanctuary were also associated with significant differences in their transiting speeds. A thorough analysis of speed variation within the sanctuary is presented by Wiley and others (2008), however, average minimum and maximum speeds over ground for transits by vessels of each type are reported in Table 2. These averages (and their standard errors) are course representations of the ranges over which speeds varied among vessel types. Research vessels showed the lowest minimum average speeds but also displayed a wider range of speeds than all other sufficiently sampled vessel types. In contrast, differences between average minimum and average maximum speeds for large commercial vessels (tankers, cargo/container ships, and cruise ships) were relatively small.

Acoustic Data

All intensity levels reported here are RMS values referenced to 1 μPa. Figure 3 shows the average RMS RLs for several low-frequency bandwidths at each of the ARUs in relation to the average number of vessels passing within 5 nmi of each of the ARUs over the 2-month sampling period. As can be seen, although low-frequency bandwidth RLs at each ARU location varied within the 2-month period, relative differences among ARUs were largely reflective of the number of AIS-tracked vessels that closely approached each location. The loudest average RLs in the 10- to 400-Hz band were recorded at ARUs no. 6 (120.6 ± 0.4 dB) and no. 81 (118.1 ± 0.4 dB), which were positioned adjacent to or directly within the BTSS (see Fig. 1) and, thus, had the highest levels of closely approaching vessel traffic. Intermediate RLs in the same frequency band were recorded at ARU no. 65 (113.6 ± 0.8 dB) and no. 79 (112.5 ± 0.6 dB), both of which were located north of the BTSS but in areas commonly utilized by traffic en route between Boston and Europe and Maine/Canada, respectively. Average RLs in the 10- to 400-Hz band at all other ARU locations were lower, with ARU no. 5 representing the quietest location (110.4 ± 0.6 dB). Although the levels of traffic closely approaching ARU nos. 7 and 62 were also relatively high, this traffic was comprised mainly of tug/tows, which (as discussed below) were not significantly related to RLs.

Table 2 Average of minimum (min.) and maximum (max.) speeds over ground (SOG) for transits of the study area by vessels of each type, in both knots (kt; nautical miles per hour) and kilometers per hour

Vessel class	Vessel type	Average min. SOG (kt ± SE)	Average min. SOG (km/h ± SE)	Average max. SOG (kt ± SE)	Average max. SOG (km/h ± SE)
Commercial	Tug	7 ± 0.1	13 ± 0.2	9 ± 0.1	17 ± 0.2
	Cargo/container	13 ± 0.3	24 ± 0.6	17 ± 0.2	32 ± 0.4
	Other cargo	12 ± 0.4	22 ± 0.7	15 ± 0.3	28 ± 0.6
	Oil/chemical tanker	12 ± 0.1	22 ± 0.2	15 ± 0.07	28 ± 0.1
	LNG tanker	10 ± 0.5	19 ± 0.9	14 ± 0.4	26 ± 0.7
	Other tanker	12 ± 0.3	22 ± 0.6	14 ± 0.2	26 ± 0.4
Passenger	Ferry	25 ± 8.8	46 ± 16	41 ± 1.8	76 ± 3.3
	Cruise ship	13 ± 0.4	24 ± 0.7	17 ± 0.3	32 ± 0.6
	Sailing	5 ± 0.6	9 ± 1.1	10 ± 0.4	19 ± 0.7
	Private yacht	8 ± 0.6	15 ± 1.1	13 ± 0.5	24 ± 0.9
Service and research	Law enforcement	6 ± 0.9	11 ± 1.7	12 ± 1.4	22 ± 2.6
	Medical transport	10 ± 1.7	19 ± 3.1	14 ± 2.2	26 ± 4.1
	Research	4 ± 0.8	7 ± 1.5	13 ± 0.8	24 ± .15
	Training ship	8 ± 0.9	15 ± 1.7	12 ± 0.7	22 ± 1.3
	Marine service	8 ± 1.3	15 ± 2.4	11 ± 0.5	20 ± 0.9
Fishing	Fishing	6 ± 1.1	11 ± 2	10 ± 0.9	19 ± 1.7

Note: SE, standard error

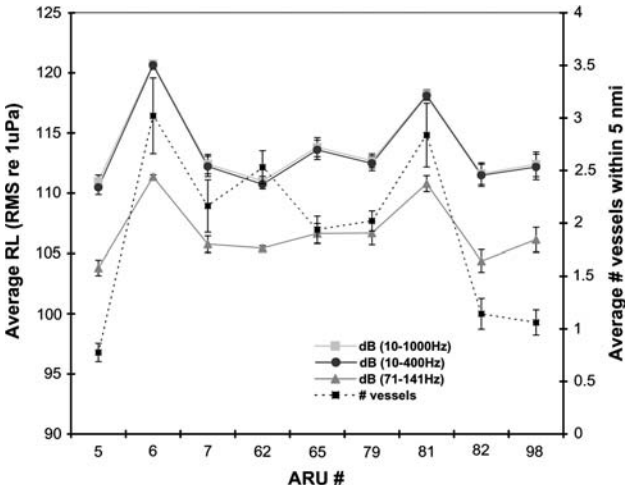

Fig. 3 Average (±SE) received levels recorded in April and May 2006 in three low-frequency bandwidths (71–141, 10–400, and 10–1000 Hz) at each of the nine Autonomous Recording Units (ARUs), with the average number (±SE) of Automated Identification System (AIS)-tracked vessels passing within 5 nmi (9.26 km) of each of the ARUs plotted on the second *y* axis

Examples of acoustic analyses for 1 week (April 21–27, 2006) of low-frequency data recorded at ARU no. 6 in the BTSS is shown in Fig. 4 as a spectrogram, two sets of power curves, and RL quartiles. The top panel in Fig. 4 shows a spectrogram in which higher-intensity, low-frequency acoustic events are evident as black peaks of color against lower background intensities (white to light-gray). The second panel shows RLs at this ARU over the course of the week for three frequency bands: the total frequency band sampled (10–1000 Hz), a low-frequency band (10–400 Hz) that contains the peak frequencies produced by vocalizing fin, humpback, and right whales, and a low-frequency band (71–141 Hz) that contains the peak frequencies of the contact call of North Atlantic right whales in the SBNMS region (Urazghildiiev and Clark 2006). As can be seen, RL estimates for the 10- to 1000-Hz and 10- to 400-Hz bands were nearly identical, indicating the concentration of acoustic energy in the 10- to 400-Hz band (a consistent finding in this study). The third panel depicts RLs for six third-octave bandwidths and shows peak RLs (113 dB) in the 31.5- and 50-Hz bandwidths. The bottom panel depicts percentages of the week (5, 25, 50, 75, and 95%) during which RLs across all sampled frequencies exceeded various intensity thresholds. As shown here for ARU no. 6 (the most highly trafficked ARU location in this study), RLs at frequencies between 30 and 50 Hz were above 85 dB 50% of the week and above 98 dB 5% of the week.

Figure 5 shows average third-octave bandwidth RLs for all ARUs in April and May 2006. The pattern depicted in Fig. 4 for 1 week at ARU no. 6 is consistent across the full time period analyzed at that highly trafficked location: 31.5- and 50-Hz bandwidths showed the highest RLs among the octaves measured. Two additional highly trafficked ARUs, nos. 65 and 81, showed the same pattern. ARU nos. 5, 7, 62, and 98 showed relatively consistent RLs for bandwidths between 40 and 63 Hz. Finally, ARU nos. 79 and no. 82, both of which were located in the northeastern corner of the sanctuary, showed peak RLs at 63 and 80 Hz.

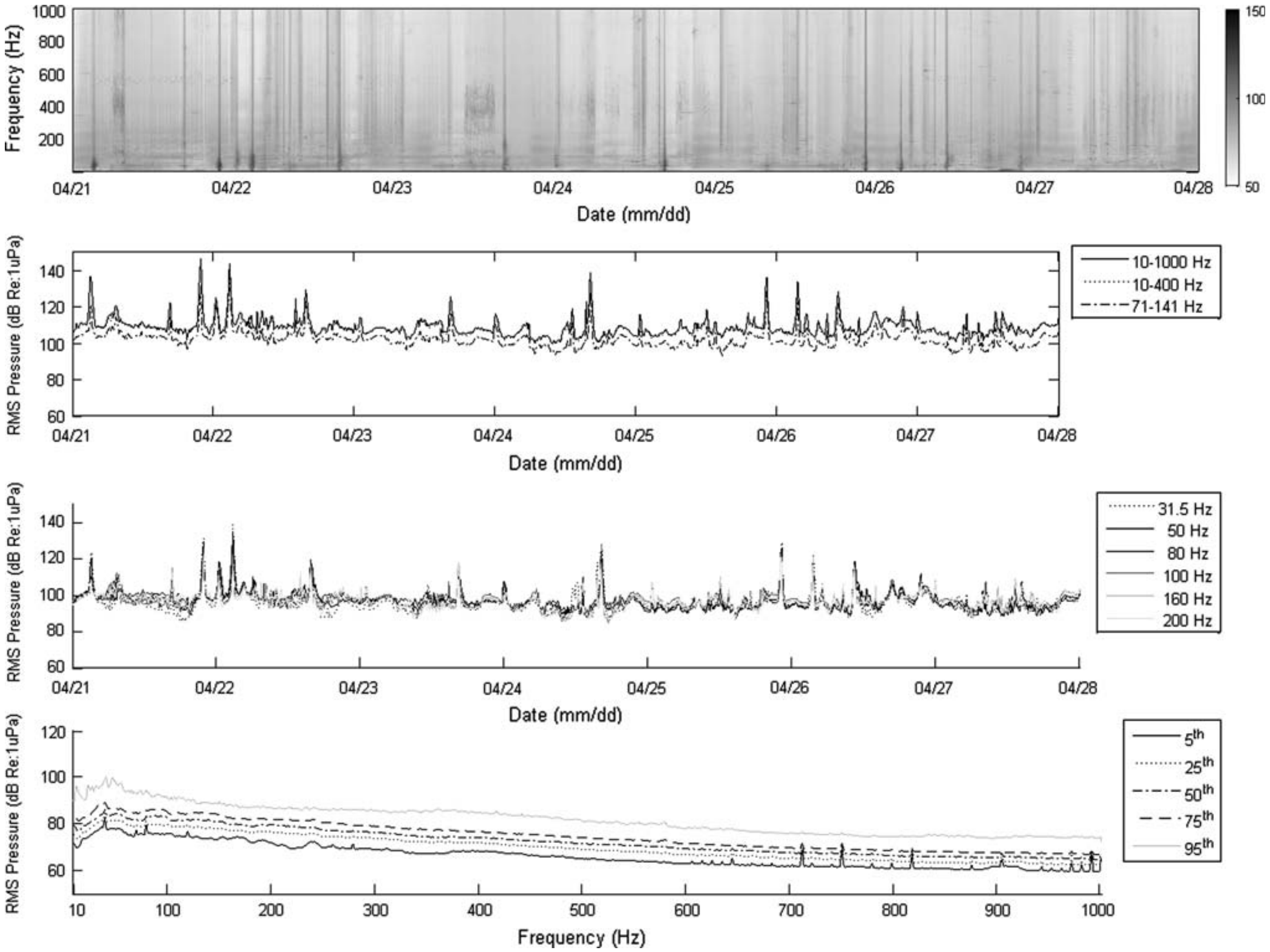

Fig. 4 Four panels depicting spectrograms (frequency over time, with high-intensity received levels in black and lower intensities in light-gray), received levels over time for frequency bandwidths and six third-octave frequencies, and percentiles for received levels across the range of frequencies sampled, all recorded at a single Autonomous Recording Unit (ARU no. 6) during the week of April 21–27, 2006

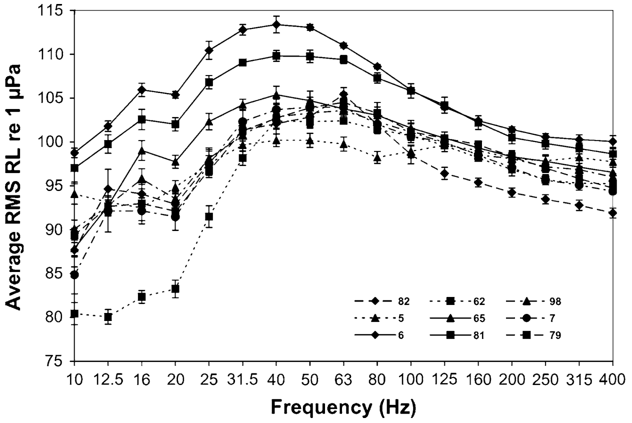

Fig. 5 Average (±SE) received levels (RMS re 1 µPa) recorded in April and May 2006 in 17 third-octave bandwidths at each of the nine Autonomous Recording Units (ARUs)

Integration of Automatic Identification System and Acoustic Data

All vessel positions in the study area reported during the week of April 21–27, 2006, are shown in ArcGIS in Fig. 6, along with average RLs at each ARU in the 10- to 400-Hz frequency band. As can be seen, higher RLs correspond with more highly trafficked locations, with the times of peaks in low-frequency RLs (shown in the first panel in Fig. 6) matching the times of closest points of approach by AIS-tracked vessels. Linear regression analysis supported this correlation statistically, showing the total numbers of vessels transiting within 5 nmi (9.26 km) of each of the ARUs to be significantly, positively related to their RLs in the 10- to 400-Hz band in both April and May (see Supplementary Table S online).

Fig. 6 A snapshot from ArcGIS showing the distribution of Automated Identification System (AIS) vessels and root-mean-square received levels in the 10- to 400-Hz band at each Autonomous Recording Unit (ARU) location for the same week (April 21–27, 2006) that is depicted in Fig. 4. The sizes of the circles at each ARU location are scaled relative to received levels. The white line represents the boundaries of the sanctuary. Vessel position reports (in black) are shown within the boundaries of the study area (the area of the sanctuary buffered by 5 nm)

The strength of the relationship between RLs and number of transiting vessels was further examined by vessel type. All results are provided in Supplementary Table S (online). The numbers of transits by cargo ships and tankers within 5 nmi of the ARUs were significantly, positively related to RLs recorded at the ARUs in both months. Significant, positive relationships were also detected between RLs and the number of transits within 5 nmi (9.26 km) by passenger vessels (a category dominated by cruise ships) in May, though not in April. For both tug/tows and service/research vessels, linear regression analyses of the numbers of approaches within 5 nmi (9.26 km) of each of the ARUs against their RLs revealed no significant relationships.

Estimates of two-dimensional acoustic "footprints" for two of the sampled vessels that transited the sanctuary, a liquefied natural gas carrier and a NOAA research vessel, are shown in Fig. 7. Multiple estimates of RLs within the 71- to 141-Hz frequency band (1-s peak, 10-s peak, and 5-min RMS) at the time of each sampled vessel's CPA were used to estimate average SLs and average distances to isopleths of interest for each vessel (Table 3). Distances over which RLs are expected to decrease to 160 and 120 dB due to TL were chosen for this analysis, since these levels are currently used by NOAA Fisheries as threshold values for assessing impacts to marine mammal species (U.S. NOAA 2005). As can be seen, average SL estimates in the 71- to 141-Hz bandwidth varied between 158 ± 2 dB (research vessel) and 186 ± 2 dB (oil and/or chemical product tanker). Corresponding estimates of the average distances over which SLs reach 160 dB ranged from 1 ± 0.2 m (average area ensonified = 3.14 m^2), associated with the quietest ship, to 57 ± 15 m (average area ensonified = 0.01 km^2/0.003 nmi^2), associated with the loudest ship. Average distances to 120-dB isopleths ranged from 379 ± 103 m (average area ensonified = 0.45 km^2/0.13 nmi^2), associated with the quietest ship, to 26,266 ± 6,966 m (average area ensonified = 2167 km^2/632 nmi^2), associated with the loudest ship.

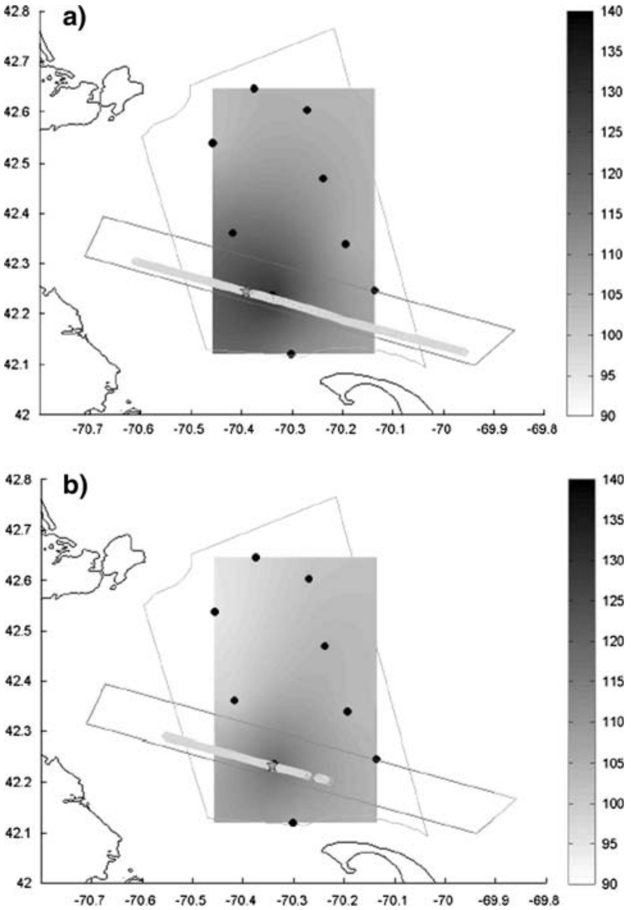

Fig. 7 The kriged acoustic footprints of two vessels at their closest points of approach (CPAs) to an Autonomous Recording Unit (ARU) in the array (represented by stars): (**a**) a liquefied natural gas carrier and (**b**) a NOAA research vessel. The gray scale, from white (low) to black (high), represents interpolated received levels in the 71- to 141-Hz bandwidth at each location (dB re 1 μPa), based on an average of three received level estimates taken at each ARU location (1-s peak, 10-s peak, and 5-min root mean square). The light-gray rectangle represents the Boston Traffic Separation Scheme in 2006, and the dots represent the track of the vessel through the sampling region

Finally, analysis of the relative predicted contributions by vessels of various classes to the low-frequency RLs of the sampled region identified oil/chemical product tankers as the largest contributors of acoustic energy to the

Table 3 Multiple estimates of received levels (RLs) at the times of closest points of approach (CPAs) to autonomous recording units (ARUs) in the array for all 17 sampled vessels. RLs then used to calculate average (±SE) source levels (SLs), and average (avg ± SE) distances to isopleths of interest using SL = RL + transmission loss (TL), with TL = 15log(distance at time of CPA)

Vessel name	Vessel type	CPA distance (m)	CPA date	CPA time (h:min:s)	5-min RMS RL (dB 71–141 Hz)	10-s max RL (dB 71–141 Hz)	1-s max RL (dB 71–141 Hz)	Avg SL ± SE (dB 71–141 Hz)	Avg distance to 160 dB ± SE (m)	Avg distance to 120 dB ± SE (m)
Atlantic Service	Tug	739	5/8/06	3:18:35	125	132	136	174 ± 3	11 ± 4	4,980 ± 2,023
Wilf Seymour	Tug	876	5/5/06	11:26:56	126	131	134	175 ± 2	11 ± 3	4,992 ± 1,599
King Phillip	Tug	399	5/5/06	7:00:10	123	128	129	166 ± 2	3 ± 0.6	1,192 ± 299
Delaware 2	Research	456	4/21/06	16:40:33	116	118	122	158 ± 2	1 ± 0.2	379 ± 103
RV Albatross	Research	483	4/17/06	22:33:56	118	122	124	161 ± 2	1 ± 0.3	627 ± 171
Freedom of the Seas	Cruise ship	577	4/19/06	4:17:26	131	138	140	178 ± 3	18 ± 6	8,260 ± 2,877
Norwegian Majesty	Cruise ship	1,685	5/14/06	2:31:32	132	134	139	183 ± 2	41 ± 14	19,134 ± 6,579
Stamford	Private yacht	1,285	5/21/06	9:21:29	113	116	117	162 ± 1	1 ± 0.2	655 ± 108
The Cat	Fast ferry	1,164	5/22/06	8:30:31	119	124	126	169 ± 2	5 ± 1	2,127 ± 601
Great Eastern	Oil/chemical tanker	1,821	4/12/06	15:32:36	125	131	133	179 ± 3	20 ± 6	9,461 ± 3,003
Eland	Oil/chemical tanker	1,645	5/16/06	15:46:49	126	132	134	179 ± 3	20 ± 6	9,401 ± 3,020
Jasmine Express	Oil/chemical tanker	3,375	4/12/06	4:22:50	128	132	134	184 ± 2	43 ± 10	19,977 ± 4,596
Energy Challenger	Oil/chemical tanker	3,395	4/22/06	2:55:27	129	133	136	186 ± 2	57 ± 15	26,266 ± 6,966
Berge Everett	LNG tanker	2,940	4/25/06	22:15:43	126	131	134	182 ± 2	35 ± 11	16,185 ± 5,359
Kent Explorer	Cargo/ container	1,543	4/28/06	4:22:35	124	127	130	175 ± 2	10 ± 2	4,721 ± 1,137
MSC Elena	Cargo/ container	2,712	4/20/06	5:49:20	126	131	133	181 ± 2	30 ± 9	13,870 ± 4,171
Port Pirie	Cargo/ container	1,273	4/14/06	13:42:37	131	134	137	181 ± 2	26 ± 7	12,056 ± 3,204

Table 4 Relative noise contributions of different vessel types to the sampling region's total ocean noise budget, based on average source level (SL) estimates, and total time spent in the sampling region within (w/in) 2006 and normalized to the vessel type with the lowest decibel contribution to facilitate comparison

Vessel type	*N*	Avg SL ± SE (dB)	Avg SL (W)	Total time w/in SBNMS (h)	Total SL w/in SBNMS (W)	Total SL w/in SBNMS (dB)	Relative SL w/in SBNMS (dB)
Oil/chemical tanker	4	182 ± 2	1.6E+18	1702	2.7E+21	214	24
LNG tanker	1	182	1.6E+18	1065	1.7E+21	212	22
Cargo/container	3	179 ± 2	7.9E+17	1481	1.2E+21	211	21
Tug	3	172 ± 3	1.6E+17	2956	4.7E+20	207	17
Cruise ship	2	181 ± 3	1.3E+18	394	5.0E+20	207	17
Private yacht	1	162	1.6E+16	2343	3.7E+19	196	6
Research	2	160 ± 2	1.0E+16	999	1.0E+19	190	0

Note: Avg, average

sampling region's annual noise budget (Table 4). Based on the total amount of time spent by vessels of this type in the region in 2006 (1702 h) and their average estimated SL in the 71- to 141-Hz bandwidth (182 ± 2 dB or 1.6 × 10^{18} W), these vessels can be estimated to have produced 2.7 × 10^{21} W or 214 dB re 1 μPa of sound over the course of the year. The estimate for tankers is 3 dB greater than the estimate for cargo ships, which spent 1481 h in the sampling region, with an average SL of 179 dB ± 2 dB, for a total of 211 dB over the course of the year. The logarithmic nature of the decibel scale means that a 3-dB increase represents a doubling of acoustic power. The smallest estimated contribution to the region's noise budget was from research vessels, whose contribution was a full 24 dB less than that of oil/chemical product tankers, representing more than 100-fold less in acoustic power.

Discussion

Using passive acoustic monitoring and AIS ship tracking data, we were able to simultaneously and continuously monitor an area averaging over 500 nmi^2 (assuming, on average, 6-nmi reception of signals below 400 Hz [Clark, personal communication, 2007]) for an entire calendar year. We found Stellwagen Bank National Marine Sanctuary (SBNMS) to be a dynamic acoustic landscape with significant peaks and troughs in the relative intensity of sound within frequency bandwidths important to the communication capabilities of resident species. Median RLs over the full sampled bandwidth (10–1000 Hz) were 3 dB greater at the loudest locations in the sanctuary (within or adjacent to the Boston shipping lanes) than those recorded at less trafficked locations. Because of the logarithmic nature of the decibel scale, this difference in levels of low-frequency noise represents double the acoustic power more than 50% of the time at highly trafficked locations in the sanctuary, relative to less trafficked locations.

Acoustic data from this case study are relevant to ongoing debates regarding increasing levels of ambient noise in the ocean, particularly in heavily trafficked areas (Wenz 1962, 1969; Piggott 1964; Cato 1976; Ross 1976; Worley and Walker 1982; Zakarauskas 1986; Bachman and others 1996; Zakarauskas and others 1990; Curtis and others 1999, Andrew and others 2002; Cato and McCauley 2002; Heitmeyer and others 2004; McDonald and others 2006). Our data indicate that noise generated by ships, and commercial shipping in particular, contributes greatly to total noise levels in the SBNMS. Our study found average 50% quartiles (RLs that were exceeded during half of the sampled time) among all the ARUs to be 83 ± 3 dB at 30–50 Hz, 78 ± 4 dB at 100 Hz, and 76 ± 4 dB at 200 Hz. These RLs from our study site in the northwestern Atlantic Ocean compare well with recent measurements taken in the northeastern Pacific Ocean, and are considerably higher than estimates of ambient ocean noise reported for the 1960s and 1970s (Wenz 1969; Cato 1976; Andrew and others 2002; McDonald and others 2006). Studies that have compared RLs recorded 30–50 years apart in the same geographic locations have shown a 10- to 20-dB increase ambient noise in the 30- to 50-Hz frequency range (Andrew and others 2002; McDonald and others 2006). Estimates of ambient levels from the 1960s are not available for the SBNMS; however, our present-day estimates are within the range of those reported for areas where increasing commercial shipping has been invoked as a possible determinant of rising ocean low-frequency noise.

During the months of April and May when Massachusetts Bay ground fisheries are closed and the recreational boating and whale-watching seasons have not reached their highest densities, we hypothesized that the low-frequency acoustic environment of the sanctuary would be dominated by the transiting of large, AIS-tracked commercial vessels. This hypothesis was supported by our results, which showed RLs to be significantly, positively related to the number of AIS-tracked vessels closely approaching the recording units during both months. Further analysis by vessel type supported the assumption that the largest (in both length and gross tonnage) commercial vessels were particularly strong determinants of RLs, with the number of transits by oil/chemical/LNG tankers and cargo ships showing significant, positive relationships with the RLs. Tug/tows did not contribute significantly to RLs recorded by the array, possibly supporting the claim that tugs with barges typically produce less near-surface sound than other ships due to the recessing of their propellers as protection against grounding (Bartlett and Wilson 2002). Close approaches by passenger vessels (a category dominated by cruise ships under AIS carriage A requirements) showed significant positive relationships with RLs in May but not in April, when the number of transits by passenger vessels was too small to allow a powerful statistical analysis. This result underscores an assumed and yet important finding of this study, which is the significant effect of season in northern latitudes on type of vessel activity. Intensive analysis of April and May RLs relative to the abundance, distribution, and behavior of vessels during these 2 months can be used to educate models to predict acoustic levels in months that were either less heavily sampled or not sampled at all. Such predictions must also take into account seasonal variation in local environmental factors such as temperature and salinity due to their effects on acoustic propagation underwater. Thus, future research will focus on incorporating oceanographic and bathymetric variables into this case study's predictive model to broaden its accuracy as well as utility in disparate marine environments (Ellison and others 1999; Frankel and others 2003).

Additional factors affecting levels of noise in this study are the subject of ongoing research. The remainder of the acoustic data set from 2006 will be analyzed to allow assessment of temporal trends in RLs in the sanctuary, including the impacts of variables associated with northern latitude seasonality, such as wind speeds and temperature.

Studies of ambient noise on Canada's Scotian Shelf, north of Massachusetts Bay, indicate that ambient levels below 300 Hz, though less seasonally variable in areas with consistently high shipping traffic, are 2 to 4 dB higher in the winter months due to higher average wind speeds (Piggott 1964; Zakarauskas and others 1990). In addition, the contribution of marine animal life to the low-frequency intensities analyzed here are being estimated through quantification of calls produced by North Atlantic fin, humpback and right whales, and several fish species (Van Parijs, personal communication, 2007). At some locations and at some times of year, spatial variation among acoustic signatures recorded by ARU locations throughout the sanctuary may reflect concentrated calling behavior by one or more species. Biological contributions to species-specific bandwidths will be quantified and incorporated into multivariant models developed to describe the sanctuary's total underwater noise budget.

Management Implications

The ability to fulfill the U.S. National Marine Sanctuaries Act's (1992) mandate to "identify and mitigate activities that are likely to destroy, cause the loss of, or injure a sanctuary resource" relies heavily on the quality of information regarding the distribution and nature of threats available to managers. In particular, SBNMS's mission, "to conserve, protect and enhance the biodiversity, ecological integrity and cultural legacy of the sanctuary while allowing for compatible use" (U.S. NOAA 2008) points to the importance of research within the sanctuary that will allow managers to balance the needs of multiple users and resources by quantifying risk both spatially and temporally. Here, we discuss the implications of this study for addressing two threats facing endangered whale species in greater sanctuary waters: ship strikes and masking and/or harassment due to vessel noise.

Ship Strikes, Speed, and Noise

Due to predictably coincident densities of feeding-endangered baleen whales and large commercial traffic, SBNMS is a "hot-spot" for vessel-whale collisions (Jensen and Silber 2003). Efforts to eliminate and/or minimize conflicts produced by the high levels of commercial traffic accessing the port of Boston and/or en route to other east coast destinations and the importance of these waters for several endangered whale species are areas of active policy making and debate (U.S. NOAA 2006). In a companion paper, Wiley and others (2008) examine variation in the speeds of the same commercial vessel traffic analyzed here relative to variation in the densities of endangered whale species to estimate spatial and temporal variation in the risk of ship strike within the sanctuary. Speed is often positively correlated with the amplitude of vessel noise (Gray and Greeley 1980; Greene and others 1995; Bartlett and Wilson 2002; Kipple and Gabriele 2003), thus management actions taken to reduce probabilities of lethal ship strikes to endangered large whales by reducing speed may also reduce noise within low-frequency bandwidths used by these species for communication. Future research to assess whether reductions in speed lead to lower contributions by ships to the total noise budgets of discrete areas like the SBNMS must also take into account the longer time periods over which vessels will be transiting these waters when traveling at lower speeds.

Finally, summary statistics presented in this paper show that the differences within the average minimum and maximum speeds reported by large commercial vessels (cargo/container ships, tankers, and cruise ships) in our study area were relatively small and did not differ dramatically among types (Table 2). Thus, although speed must be taken into account in subsequent multivariate predictive models used to examine vessel noise profiles at higher resolution, our use of vessel type to account for gross-level differences in RLs both over the days of our study and extrapolated for an annual year are likely to represent robust initial approximations.

Masking and/or Harassment by Noise

Although acoustic harassment regulations are currently under review by the U.S. government, NOAA Fisheries' Office of Protected Resources currently requires permits under the U.S. Marine Mammal Protection Act (1972) for human activities that could lead to baleen whales receiving impulse sound levels >160 dB re 1 μPa or continuous sound levels >120 dB re 1 μPa (U.S. NOAA 2005). This represents the current basis for regulating the harassment of marine mammals by acoustic sources, as mandated by the U.S. MMPA (1972, as amended through 1997). This regulation does not currently apply to vessels in transit. However, acoustic impacts from vessel traffic are of concern to NOAA and have been the subject of two international symposiums hosted by NOAA's Ocean Acoustics Program (Southall 2005, 2007). Our study begins to quantify the basis for these concerns. According to the simplified model of TL used here for preliminary characterization of vessel signatures, the average area ensonified over 120 dB by an oil/chemical product tanker transiting the SBNMS is 632 nmi^2. Since the area of the SBNMS is 638 nmi^2, this area is roughly equivalent to the size of the sanctuary, and corresponds to a single transit by a single vessel. Oil/chemical product tankers transited the greater SBNMS 793 times in 2006.

Results from the analysis of the relative contribution by vessel types to the annual noise budget of the sanctuary identified oil/chemical product tankers as the largest contributors due to their high SLs and high transiting rate. This was further supported by statistical analysis based on the 2 months for which acoustics were analyzed, which found close approaches by tankers to be the strongest determinant of RLs. As SL estimates reported here do not accurately account for variations in acoustic propagation due to variation in the local marine environment, future research will utilize more elaborate acoustic propagation models to depict the acoustic footprint of vessels in four dimensions (latitude, longitude, depth, and time) (Ellison and others 1999; Frankel and others 2003). Accurate modeling of acoustic sources is critical to ongoing research associated with this study to examine behavioral responses by acoustically active species in the greater SBNMS region in relation to vessel traffic. In addition, a better understanding of the long-term exposure of whales in the region to vessels with different acoustic characteristics provides a stronger basis for evaluating the results of relatively short periods of intensive observation using technologies such as digital tags (Johnson and Tyack 2003).

Debates surrounding the treatment of ships over short distances as impulse sources leading to the harassment of marine mammals are unlikely to resolve the larger debate surrounding the contribution of shipping to pervasive background noise over large spatial scales. Although long-term average RLs presented here did not separate near- and far-field vessel contributions to ambient noise in the sanctuary, background levels versus those representing discrete acoustic events (close approaches by ships) were clearly discernible in the data (see Fig. 4). In addition, less trafficked and highly trafficked locations in the sanctuary presumably receive relatively similar levels of ambient noise from far-field shipping. Thus, an average RL in the 71- to 141-Hz band of 103.8 ± 0.7 dB recorded at the quietest ARU location in this study (ARU no. 5) likely represents the best approximation of the far-field contribution of shipping noise to the bandwidth most heavily utilized by right whales for communication in Massachusetts and Cape Cod Bays. Parks and Tyack (2005) estimated the average RMS (re 1 μPa) SL of North Atlantic right whale contact calls in the 50- to 10,000-Hz bandwidth to be 150 dB (± 4 dB SD). Based on these estimates of (1) ambient noise in the quieter areas of the sanctuary within the bandwidth of the signal and (2) the SL of the right whale call type predicted to be the most common in the sanctuary (Parks and Clark 2005, Van Parijs, personal communication, 2007), and further assuming that (3) TL is equal to 15 log (range) and (4) detection is only possible if the signal is more intense than the background noise within the signal's bandwidth, a calling right whale would only be discernible for a distance of 1.2 km from its location (or a two-dimensional area of 1.4 km^2 or 0.4 nmi^2). Further research will improve the accuracy of communication/hearing range calculations, including evaluating large whales' capabilities to both detect and recognize specific tonal signals overlapped by background noise (Clark and Ellison 2004; Southall and others 2007). However, as this example was based on an estimate of background noise in a less trafficked area of the sanctuary, it is likely to remain relatively conservative for this geographic area. Integrating the results of this study with those from additional research focused on identifying threshold conspecific communication ranges (distances over which animals must be able to communicate in order to make effective and/or energetically efficient choices regarding feeding, mating, or other fitness-related activities) will help managers better understand the more subtle but chronic impacts of rising ambient noise on vocally active species in areas such as the SBNMS.

Conclusion and Recommendations

Understanding and quantifying human activity in the marine environment is a challenging task. Combining such data with estimates of marine noise and interpreting those data in light of impacts to marine mammals is an even greater challenge. The descriptive statistics and visualizations presented here relating ships to underwater noise do not tell a new story. Taken together with additional research addressing the impacts of these sources on whale behavior, however, this study has begun to quantify the relationships among these metrics in a manner that promotes the kind of careful decision making that is needed to manage multiple uses of the marine environment.

Toward that end, we offer the following three recommendations for future policy and scientific pursuit.

Consolidation and/or Rerouting of Ship Traffic

Efforts to reduce ship strikes have implications for reducing ensonification of whales by shipping noise. For example, efforts to shift the Boston Traffic Separation Scheme (BTSS) to the north were recently reviewed and accepted by the International Maritime Organization (IMO 29). This proposal was developed by personnel at the SBNMS following analyses of the relationships among more than 20 years of visual sighting records for North Atlantic fin, humpback, and right whales, the distribution, behavior, and abundances of the prey types supporting these whale populations, and the physical oceanographic features influencing these prey variables. These analyses identified a theoretical and empirical trough in the distribution of feeding whales within the SBNMS. To reduce the risk of ship strikes, the SBNMS, NOAA Fisheries, and U.S. Coast Guard proposed shifting the BTSS into that trough. In Fig. 8, we overlapped this shift in the shipping lane with course estimates of the 120- and 160-dB isopleths (8260 and 18 m, respectively; see Table 3) of an average

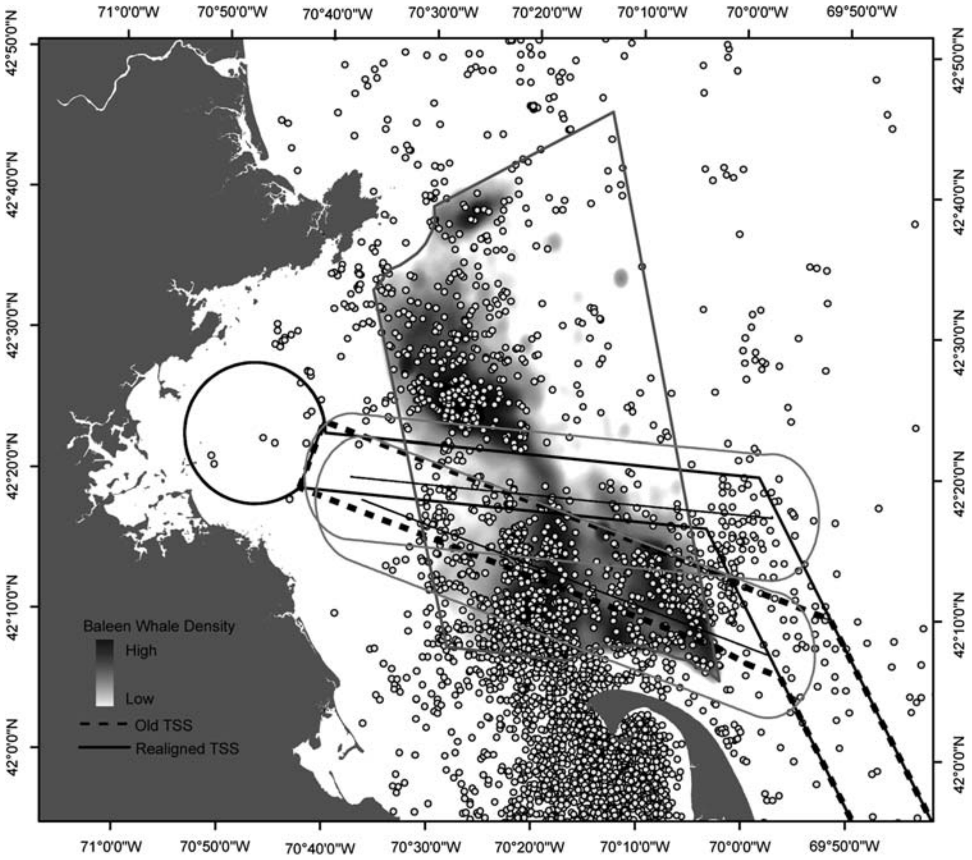

Fig. 8 Distribution of visual sightings of all baleen whales (kriged density grid, with black as high density and white as low density) and North Atlantic right whales (dots) relative to the Boston Traffic Separation Scheme prior to (dashed lines) and following (solid lines) the realignment and narrowing of the lanes in July 2007. The 160- and 120-dB isopleths (∼18 and 8260 m, respectively) associated with a large commercial carrier leaving the port of Boston are show as the two translucent gray rectangles

intensity large commercial vessel (RMS SL = 178 dB re 1 μPa). We then calculated the number of baleen whale and right whale sightings that fell within these isopleths in the pre- and post-shifted BTSS. This analysis showed a 42% reduction in the number of sightings of baleen whales falling within the 120-dB isopleth (from 119,786 to 49,645) and a 28% reduction within the 160-dB isopleth (from 261 to 74). Right whales showed a 54% reduction in the number of sightings falling within the 120-dB isopleth (from 1469 to 798) and a 100% reduction in the 160-dB isopleth (from 2 to 0).

Based on these results we recommend the use of passive acoustic monitoring data to aid regional managers and maritime transport stakeholders in the development of proposals to the IMO, national regulatory agencies, and/or regional/local conventions to reroute and/or consolidate shipping traffic to minimize exposure of sensitive species to noise and risk of ship strike.

Use of Buffers to Enhance the Utility of Marine Protected Areas for Noise Mitigation

A variety of reports and reviews have highlighted the fact that marine protected areas can represent "test beds" to evaluate the efficacy of methods to continuously monitor underwater noise (Van Parijs and Southall 2007) and create policy to regulate anthropogenic sources (McCarthy 2004; Cummings 2007; Firestone and Jarvis 2007; Haren 2007; Scott 2007). In this study we chose to buffer the boundaries of the SBNMS with a 5-nmi (9.26 km) wide area on all sides, so as to ensure sampling of large commercial vessels likely to ensonify sanctuary waters >120 dB. We hypothesized that this would be a conservative estimate, since a 120-dB RL is well above low-frequency ambient measures (Richardson and others 1995) and is currently utilized by NOAA as the basis for regulating harassment of large whale species by continuous sources of underwater noise (U.S. NOAA 2005).

Based on our findings, we feel that this sampling scale was appropriate and we recommend that the utility of buffers for marine protected areas, including National Marine Sanctuaries (with dimensions determined by the sensitivity of local species and local noise conditions), be explored as regulated and/or voluntary "quiet zones" in which methods for reducing noise and/or limiting exposure are tested and/or implemented.

Evaluate the Efficacy of Passive Acoustics for Testing and/or Monitoring the Use of Vessel Quieting Technologies

Recent symposia hosted by NOAA on shipping noise and quieting techniques have highlighted the need for naval architects, physical oceanographers, and marine mammal experts to continue to communicate what they know as well as the uncertainty surrounding the current states of their sciences to the international maritime transport industry, including ship builders, owners/investors, inspectors/regulators, and alliance representatives, to name a few (Southall 2007). As with most large-fleet, global transportation industries, large-scale technological changes such as those that are necessary to produce quieter ships, either through retrofitting ships currently in service or through the commissioning and construction of new ships, will take several decades to implement. If industry acts proactively when presented with vessel quieting options, and if acoustic and marine mammal specialists stay engaged in dialogues with industry to evaluate the efficacy of various options, current estimates of 3- to 10-dB increases in underwater noise below 100 Hz per decade may abate in future decades. Such prolonged engagement in finding vessel-quieting solutions that work will necessitate large-scale and standardized opportunities to evaluate the efficacy of different technologies under different conditions. Although the noise profiles of ships are traditionally quantified in a limited number of Naval and private facilities and/or under controlled conditions, such facilities would not be able to accommodate the kinds of large-scale testing and monitoring necessitated by an industry-wide campaign to reduce noise.

Thus, we recommend that future research explore the potential for using data from quasi-permanent, continuously recording passive acoustic monitoring systems to evaluate differences in ship noise profiles under different “quieting” treatments to identify niches for technological advancement (instrumentation, etc.) and/or to educate the design of ocean observing systems to collect acoustic data applicable to a wide range of marine resource management goals.

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