A quieting ocean: Unintended consequence of a fluctuating economy

M. F. McKenna[a)]
Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0208
megan.mckenna@gmail.com

S. L. Katz
Channel Islands National Marine Sanctuary, National Oceanographic and Atmospheric Administration, 735 State Street, Suite 619, Santa Barbara, California 93101
steve.katz@noaa.gov

S. M. Wiggins
Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0208
swiggins@ucsd.edu

D. Ross
2404 Loring Street, Box 101, San Diego, California 92109
donaldnmiross@mac.com

J. A. Hildebrand
Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0208
jahildebrand@ucsd.edu

Abstract: Simultaneous long-term monitoring of underwater sound and ship traffic provided an opportunity to study how low-frequency noise correlated with ocean-based commercial shipping trends. Between 2007 and 2010 changes in regional shipping off southern California occurred as a consequence of economic and regulatory events. Underwater average noise levels measured before and during these events showed a net reduction of 12 dB. Statistical models revealed that a reduction of 1 ship transit per day resulted in 1 dB decrease in average noise. This synthesis of maritime traffic statistics with ocean noise monitoring provides an important step in understanding the magnitude and potential effects of chronic noise in marine habitats.

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1. Introduction

Underwater radiated noise is an incidental by-product of standard ship operations.[1,2] On ocean basin scales, measurements of low-frequency noise show an increasing trend that is attributed to growth in maritime shipping to support the global economy.[3,4] Increased ocean noise poses a potential threat to marine animals that depend on sound for myriad ecological functions.[5,6] Studies investigating the relationship between levels of anthropogenic activity and noise levels are needed to better understand and mitigate noise in marine habitats. In this study, we have taken advantage of an unplanned

[a)]Author to whom correspondence should be addressed. Also at: U.S. Marine Mammal Commission, 4340 East-West Highway, Suite 700, Bethesda, MD 20814.

change in oceanic commercial shipping to evaluate the coupled system of economic dynamics and chronic sources of anthropogenic noise from large commercial ships in a region off the coast of California. We examined the statistical correlations between regional commercial ship traffic and measurements of low-frequency sound to evaluate the covariance of these data with two *de facto* experimental treatments applied to the system. The first treatment was the "great recession" that lasted from December 2007 to June 2009.[7] A second change in shipping occurred after the California Air Resources Board (CARB) passed an air-quality improvement rule on July 1, 2009; the rule required ships within 24 nautical miles of the coastline to use low-sulfur emitting fuel.[8] The natural experiment provided by the combined effects of large-scale economic forcing and regional air-quality regulation allowed us to estimate the magnitude of, and variability in, ocean noise and demonstrate its relationship to ocean shipping. In addition, we were able to evaluate the trade-offs in noise pollution mitigation with economic drivers to make a first estimate of the costs of reducing ocean noise.

2. Methods

Based on the known changes that occurred in maritime shipping, we established three time periods *a priori* that were treated as categorical factors in an analysis of covariance via a generalized linear model (GLM): (1) *Pre* (February 2007–July 2007), (2) *recession* (April 2008–June 2009), and (3) *CARB* (July 2009–2010). The passage of time and two independent ship traffic metrics [monthly counts of containers entering and leaving the Port of Long Beach (POLB) and monthly average ship transits] were treated as continuous predictors in the statistical model to estimate monthly sound spectrum levels. Parameter estimation and quality of fit were performed with the R statistical software package (version 2.7.1, 2008). Model selection was performed using an exhaustive search. Model performance and discrimination between models was based on corrected Akaike Information Criterion (AIC_c),[9] and models were deemed preferred when the difference in AIC_c was greater than 2. Quality of fit was also reported with an adjusted coefficient of determination (adj-r^2).

Underwater sound was monitored in the Santa Barbara Channel (SBC) during the observed changes with autonomous ocean-bottom hydrophones [High-frequency Acoustic Recording Packages (HARPs)][10] in close proximity to local ship traffic (Fig. 1). Acoustic data were decimated to a sampling frequency of 2 kHz and processed to determine monthly sound spectrum averages. For each 225 s interval, the time series was processed using a fast Fourier transform (FFT) and a Hanning window

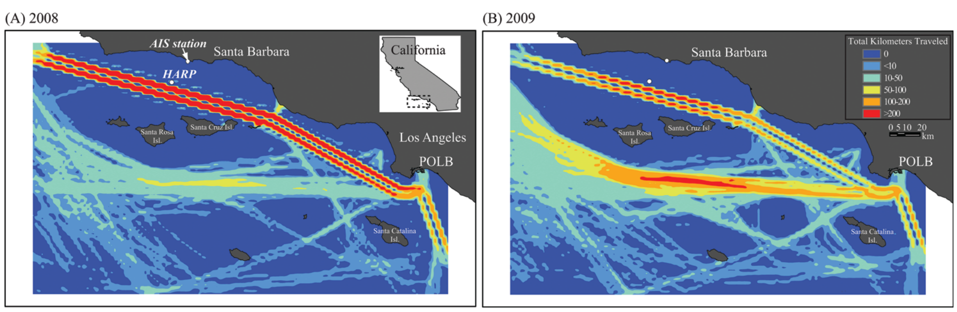

Fig. 1. Commercial ship traffic density off the coast of southern California: (A) 2008, (B) 2009. Maps show the locations of the HARP and AIS shore receiving station as white dots. In 2008 and 2009, AIS data from September 15th to November 1st for cargo and tanker vessels were converted to ship track lines and summed in each 2 km by 2 km grid cell. Colored surfaces represent total kilometers traveled per grid cell. Changing traffic pattern following the CARB ruling on ship fuel use, with increased traffic outside the SBC, is indicated by the enlarged orange-red areas south of the Channel Islands in 2009 (B). POLB label indicates the location of the Port of Long Beach and the Port of Los Angeles.

with a FFT length of 2000 samples and 0% overlap. Samples of 225 s were chosen for consistency with previous ambient noise measurements[4,11,12] and allowed us to minimize contributions from any transient signals, if present. Monthly statistics (mean, 1st, 10th, 90th, and 99th percentiles) of sound levels at 40 and 90 Hz were computed. These 1 Hz bands captured the dominant frequency of ship noise and avoided frequencies with transient signals from blue and fin whale calls.

Ship traffic data from the POLB provided metrics of regional ship traffic for the duration of our acoustic monitoring.[13] The port records monthly totals of the number of containers, measured as the number of twenty-foot equivalent units (TEU), which arrive and depart from port. TEU index is useful for quantifying the amount of traffic in the region and is a coarse indicator of large-scale economic processes (e.g., trade balance, infrastructure development[14]). This metric, however, does not provide spatial information on individual ship transits and only represents a single ship type (container ships). Individual, spatially explicit, ship transits in the region were monitored using the Automatic Identification System (AIS)[15] beginning in September 2008, when data became available. AIS data provided more complete spatial information on individual ship transits, but data were only available for the *recession* and *CARB* periods. AIS transponders are required onboard ships >300 gross tons and broadcast ship transit information (e.g., ship speed, longitude, latitude, identifier, ship name, ship type) via a very-high frequency (VHF) radio signal. From the AIS data, individual ship transits per day within the SBC were used to estimate monthly ship transits and shipping density was quantified as the total kilometers traveled per 2 km by 2 km grid cell based on individual ship tracks. AIS point data were converted to unique linear tracks, defined as a sequence of AIS transmissions from a unique ship without a >24 h time gap or with a time gap of >1 h with a concurrent change in heading of >30°.

3. Results

Regionally, ship traffic varied between the three, *a priori*-defined time periods. In the *pre*-recession period (pre-AIS data) container traffic averaged ∼600 000 TEU per month (∼400 000 loaded), with a small positive temporal trend. During the *recession*, ship traffic decreased in both the number of TEU and monthly ship transits derived from AIS. TEU increased slightly during the *CARB* period (3%); however, AIS data indicated a spatial shift in traffic occurred during this time which resulted in a 70% decrease in monthly ship transits within the SBC (Fig. 1). Ship operators, reluctant to switch to a cleaner but more expensive fuel, altered their transits to stay outside the CARB footprint for a longer portion of their voyage and traveled a more southerly route on their approach to or departure from Los Angeles[16] [Fig. 1(B)].

Monthly average sound spectrum levels in the SBC correlated well with these observed changes in ship traffic (Table 1; Fig. 2). Decreases in the 40 Hz band began in July 2008 and continued to decrease significantly through May 2009 ($p \ll 0.001$),

Table 1. Results of model selection to determine the best performing statistical model that predicted the observed acoustic data from the available predictor variables.

Model	Number of parameters	*adj*-r^2	AIC_c
	40 Hz		
Time period × total TEU	3	0.930	142.986
Time period × inbound TEU × time	6	0.941	142.845
Time period × total TEU × time	6	0.938	144.845
	90 Hz		
Time period × total TEU	3	0.838	138.975
Time period × inbound TEU × time	6	0.868	137.635
Time period × total TEU × time	6	0.863	138.995

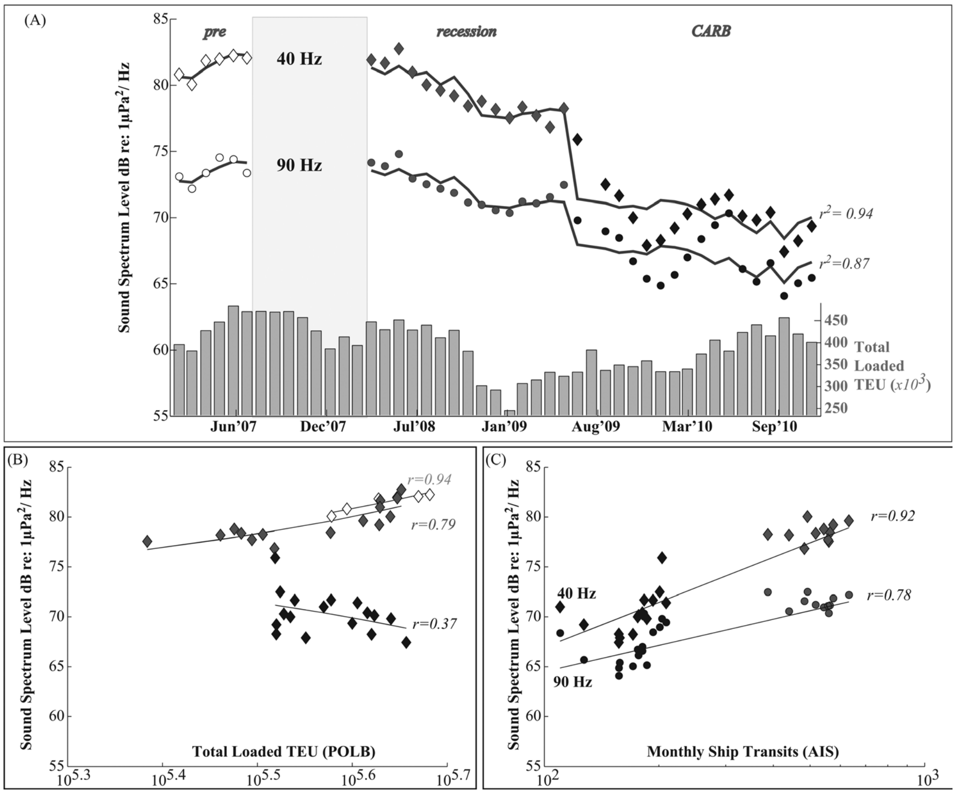

Fig. 2. Changes in low-frequency noise levels and ship traffic. (A) Time series of monthly average sound spectrum levels in the SBC and total TEU. Trend lines are from the predicted values based on estimated coefficients from best fit GLM that included time period and total TEU. (B) Monthly sound spectrum levels at 40 Hz plotted as a function of the total number of total TEU in the corresponding month. (C) Monthly sound spectrum levels (40 and 90 Hz) plotted as a function of the number of ship transits per month in the SBC from AIS data. Trend lines are shown for each frequency band with *R* values indicating the quality of fit. In all panels, symbols for frequency bands are as follows: diamond = 40 Hz, circle = 90 Hz; colors indicate the time periods: light white = *pre,* grey = *recession,* black = *CARB*. The shaded area in (A) indicates times when acoustic data were not available due to problems with the instrumentation.

with some monthly fluctuations related to seasonal patterns in ship traffic. Over this period (*recession*), a net 5.1 dB reduction in 40 Hz noise was observed. This same trend was observed in the 90 Hz band ($p \ll 0.001$), with a net decrease of 3.1 dB. Prior to the CARB rule, most ships entering and leaving the POLB transited the SBC and port statistics were well correlated with measured sound spectrum levels within the SBC [Fig. 2(B)]. A comparison of monthly loaded TEU in both the *pre* and *recession* periods with monthly average noise levels in the 40 Hz band showed significant positive correlations ($r_{pre} = 0.94,\ p = 0.003;\ r_{recess} = 0.79,\ p < 0.001$). On average, loaded TEU traffic from *pre* to *recession* decreased by 65 304 TEU (15%) and correlated with a 2.2 dB difference in average noise levels at 40 Hz. Since most of the container ships transiting the SBC are Panamax (250–290 m in length) and post-Panamax (275–305 m in length) generations of container ships, the average TEU per ship is about ∼4000.[17] Therefore, the observed 2.2 dB difference in average noise levels resulted from a reduction of ∼16 monthly container ship transits (or 0.5 ship transits per day) and likely a reduction in other ship types not captured in the TEU metric.

In July 2009, coincident with the CARB rule, the best fit GLM of sound level showed a step-decline [Table 1; Fig. 2(A)]: 5.2 dB in the 40 Hz band; 2.5 dB in the 90 Hz band. After this rapid decrease, there was another period of gradual negative trend in noise levels that had a similar slope in both bands (significant for 40 Hz, $p = 0.023$, but not in the 90 Hz band, $p = 0.051$), but was also characterized by an increase in month-to-month variability. After the CARB rule, the observed decrease in noise level did not correlate as well with the number of loaded TEU [Fig. 2(B)], but correlated with the log of number of ship transits per month from the AIS data [Fig. 2(C): $r_{40\,\mathrm{Hz}} = 0.92$, $p \ll 0.001$; $r_{90\,\mathrm{Hz}} = 0.78$, $p \ll 0.001$]. The number of TEU entering the POLB does not reveal explicitly where the ships are transiting, the metric derived from AIS data proved a more informative indicator of ship activity just within the SBC, and provided an explanation for the changes in both the noise levels and the relationship between loaded TEU and noise level during the *CARB* period. From the *recession* to *CARB* periods, mean monthly ship transits decreased by 350 (or 12 ship transits per day), which correlated with a 9.0 dB difference in average noise levels at 40 Hz. Converting this result to a per 1 dB change, we found on average a reduction of 1 ship transit per day resulted in 1.2 dB decrease in average noise levels.

4. Discussion

The synthesis of port transaction and maritime traffic statistics with ocean noise monitoring has improved our understanding of the connections between shipping activity and ocean noise as well as their economic and regulatory drivers. By monitoring over time, we have been able to evaluate the covariance in these data sets, and this now informs a more mature ability to forecast potential noise reduction mitigation scenarios. Overall, these treatments (*pre*, *recession*, and *CARB*) were associated with a net decrease in monthly average sound levels of 12 dB in the 40 Hz band over the 3 year period. However, this reduction in noise came with a substantial cost; average loaded containers per month entering and leaving the POLB dropped by 15% from the *pre* to *recession* periods. Based on published values per container,[13] this may represent as much as a $19 billion reduction in goods transiting to and from the port. More detailed economic analysis that includes additional factors (i.e., petroleum transport as well as shore-based costs and revenues) may show additional loss to the industry associated with the reduced noise level. Specific mitigation tactics for noise reduction will have to include technical advances in ship quieting that are currently being considered. One can anticipate that potential costs of billion dollars per decibel are perceived already as a significant force driving such technical development.

Although we observed an order of magnitude reduction in average noise level in a coastal basin, specifying the ecological impact of underwater sound is complex and depends on many factors in addition to intensity levels measured at a hydrophone. Human-generated sound in the ocean is identified as a threat to marine animals that depend on sound and much concern has been raised over the potential impacts of military sonar[18,19] and seismic air gun surveys[20,21] on marine mammals. Less understood and addressed by ocean resource managers is underwater noise from the global fleet of commercial vessels that is more pervasive, spanning larger spatial and temporal scales.[22,23] In this study, we focused on relatively low-intensity, chronic noise, rather than high-intensity, short duration noise, and there is growing appreciation that this noise may have widespread ecological impacts,[6,24] and perhaps even physiological impacts.[25] Showing the physiological impacts of high-intensity noise has been contentious[19]; demonstrating the ecological impacts of chronic noise will be more challenging.[24] Importantly, the values reported here are conservative in two ways. First, our receiver is located several kilometers from the path of the ships and whales in closer proximity to the ships will experience higher sound pressures. Second, we are presenting time averages, rather than instantaneous, extreme values. Instantaneous received sound pressure values in excess of 100 dB re $\mu\mathrm{Pa}^2$/Hz were occasionally observed, particularly in the *pre-recession* period (Fig. 3).

This study demonstrates that trade-offs between marine transportation services and resulting chronic noise can be quantified, at ship-by-ship resolution and with net

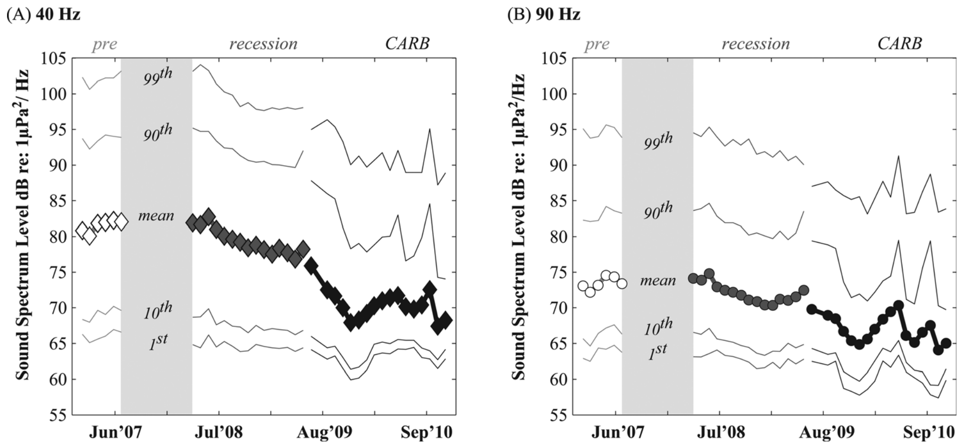

Fig. 3. Statistical distributions of monthly sound spectrum levels over time: (A) 40 Hz band and (B) 90 Hz band. Distributions are represented by the mean (diamonds and circles), 99th, 90th, 10th, and 1st percentiles of observed sound levels. Colors indicate the time periods: light white = *pre,* grey = *recession,* black = *CARB*. The 99th percentile curves represent the highest sound levels measure at this recording site 3 km from a major shipping lane. The shaded areas indicate times when acoustic data were not available due to problems with the instrumentation.

change of almost an order of magnitude in sound pressure level. Our results emerge from a richness of acoustic and ship traffic data combined with the coincidence of these large-scale economic and regulatory forcings. As shipping and acoustic monitoring matures and is integrated into the larger suite of ocean observing systems we can anticipate more complete evaluations of the trade-offs and more precise forecasts of ecosystem impacts from anthropogenic activity.

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