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INCREASED UNDERWATER NOISE LEVELS IN THE SANTA BARBARA CHANNEL FROM COMMERCIAL SHIP TRAFFIC AND THE POTENTIAL IMPACT ON BLUE WHALES (*BALAENOPTERA MUSCULUS*)

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Abstract—The Channel Islands National Marine Sanctuary (CINMS) and the surrounding waters are considered an urban coastal environment, yet home to a diversity of marine organisms. Understanding the interactions between human activity and the marine ecosystem is vital to its sustainability. In our study, we investigated the acoustic environment in the region, focusing primarily on the addition of anthropogenic sound produced by commercial ship traffic. Our study used a passive, broadband, high-frequency acoustic recording package (HARP) to record ambient noise levels and the contribution of noise from commercial ship traffic to the acoustic environment. Recorded ship sound levels were identified using ship-passage records known as Automatic Identification System (AIS). Our analyses of ambient noise levels from July to October 2007 showed elevated levels of 15–25 dB in the 10–150 Hz frequency band when ships were nearby (<4 km). There were on average 18 ships passing through the channel every day, resulting in approximately three hours per day of elevated noise levels from commercial ship traffic. The shipping activity in the Santa Barbara channel was highest at noon and midnight. Increased background noise levels from the ships have the potential to impact the endangered blue whales utilizing the Santa Barbara Channel. When ships were nearby, blue whale calls were not detected. Although it is unclear whether the whales ceased calling when a ship was present, or the calls were masked by the increased noise, both situations have the potential to impact the whales' ability to carry out normal behaviors in the Santa Barbara Channel. The results of this research will advance scientific understanding of human noise in the marine environment, inform policy decisions for noise in the Sanctuary, and serve as a model for addressing noise pollution in other marine sanctuaries.

INTRODUCTION

The pervasive nature of noise pollution from commercial ships threatens the health of many coastal regions, including the Channel Islands National Marine Sanctuary (CINMS or Sanctuary). Given the Sanctuary's ecologically important and sensitive habitats and populations of marine mammals, large vessel traffic is an ongoing management concern. The shipping lanes of the Santa Barbara Channel (SBC) overlap the eastern portion of the CINMS, with at least 6500 vessels (43% of all U.S. shipping trade) passing through the Sanctuary annually (CINMS January 2009). Our research focuses on the potential acoustic effects of commercial ship traffic, which range from interference with communication in marine mammals and fishes to degradation of habitat quality and/or prevention of recovery in protected systems. It is important to characterize local shipping traffic in the SBC and determine the level of noise added to the marine environment by commercial ships, in order to assess the level of threat to marine organisms.

As the global commercial shipping fleet increases its size and speed, noise added to the marine environment has intensified; background levels are now elevated at some sites by at least 10 times what they were in the 1960s and have doubled in intensity every decade for the past 40 years (Andrew et al. 2002; McDonald et al. 2006). In the Pacific basin where low frequency sounds can propagate for hundreds of kilometers, this trend is attributed to noise from local and distant ships. However, because of the complex bathymetry in coastal regions like the Southern California Bight, most noise from distant ships will not propagate into the shallow regions. Thus, local shipping traffic is the dominant source of ship noise in the SBC (McDonald et al. 2008). The objective of this study is to establish noise levels in the SBC, and assess how these levels are influenced by local ship traffic. Results will be discussed in the context of potential impacts on the endangered North Pacific blue whale (*Balaenoptera musculus*).

The SBC includes not only one of the busiest shipping lanes in the world, but is also an important summer foraging region for the endangered North Pacific blue whale population. The whales tend to aggregate in cold, up-welled coastal waters to feed primarily on subsurface concentrations of euphausiids (Croll et al. 1998; Fiedler et al. 1998). Blue whale populations were decimated by commercial whaling from around 300,000 to fewer than 10,000 and are slowly recovering (Barlow 1995). The North Pacific stock estimates are around 2000 and may be one of the largest populations in the world (Barlow 1995; Calambokidis and Barlow 2004). During the feeding months, whales continuously interact with both commercial and recreational vessels in the channel.

Besides the increased risk of direct interaction between ships and whales, the potential acoustic impacts are also heightened. Blue whale calls are predominantly in the low frequencies (15–100 Hz); a frequency range similar to the dominant acoustic energy of ships (Richardson et al. 1995). Most noise generated by large ships is from propeller cavitation, and machinery noise causing vibrations in the hull is a less dominant source. Propeller cavitation results from the formation and collapse of bubbles at the propeller blade tips (Ross 1976). These sounds are radiated into the water column and will propagate to distances dependent on the bathymetry and water column characteristics. Although the sounds lose intensity as the distance from the source increases, the noise from ships has the potential to mask the calls of whales. Blue whales in the North Pacific are known to produce at least four call types (McDonald et al. 1995; Thompson et al. 1996): A and B calls (16 Hz, ~20 s duration), D calls (down sweep from 90–25 Hz, 1–4 s duration), and highly variable amplitude and frequency modulated calls. A and B calls are songs produced by males and possibly function in mate

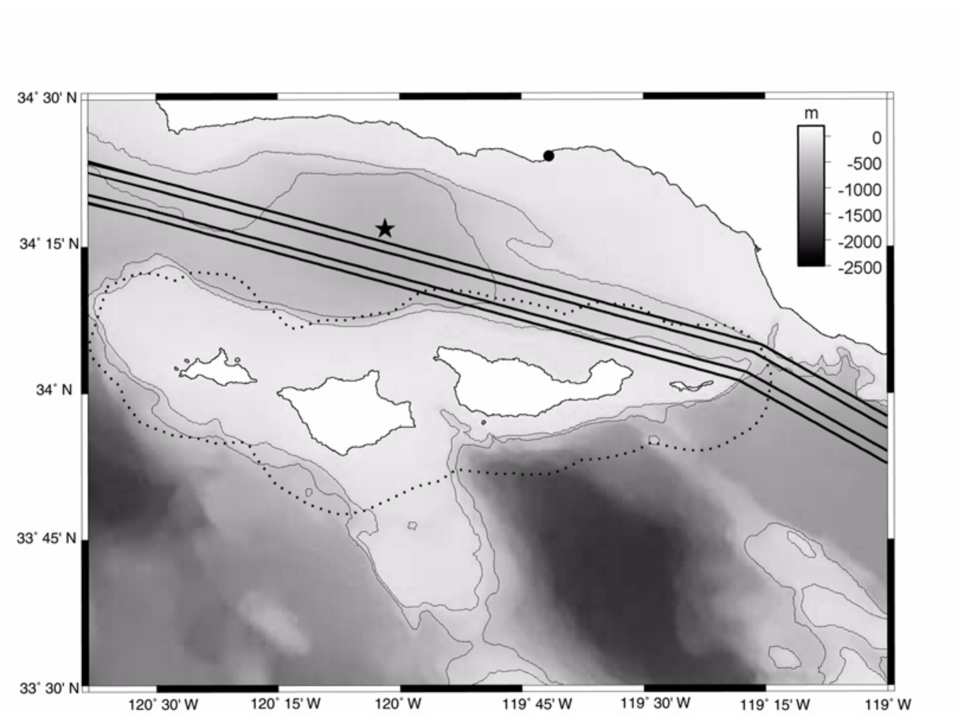

Figure 1. Map of Santa Barbara Channel and the Channel Islands National Marine Sanctuary (CINMS). The dotted line represents the borders of CINMS. The star is the location of the seafloor HARP in the SBC. The contour lines are at 200 and 400 m. The circle is the location of the AIS receiver in Santa Barbara harbor. The solid black lines represent the commercial shipping lanes.

attraction (McDonald et al. 2001). The D calls are recorded from both males and females and are usually associated with feeding behaviors (Oleson et al. 2007a).

The primary goal of this study is to establish background noise levels for the region, in the frequencies utilized by blue whales. Because the region is frequented by ship traffic, the change in noise levels by commercial ships can be characterized. Ultimately, this information can be used to assess the potential threats to the whales.

METHODS

Data Collection

To monitor the acoustic environment within the SBC shipping lanes, a high-frequency acoustic recording package (HARP) was placed in the SBC at 34.32W 120.03N in 530 meters of water (Fig. 1). HARPs are autonomous seafloor-mounted instruments used to provide long-term acoustic recordings, and contain a battery power supply, data acquisition system, hydrophone sensor, acoustic release system, ballast weights, and flotation (Wiggins and Hildebrand 2007). The hydrophone is tethered to the instrument package and buoyed 10 m off the seafloor. The hydrophone employs a two transducer design to provide a high-sensitivity broadband (10 Hz–100 kHz) response, which allows the data acquisition system to record a wide range of sounds, from low frequency ships and baleen whales to high frequency toothed whales and dolphins. HARPs currently store 1920 GB of acoustic data, allowing continuous recording at 200 kHz sample rate (or 200,000 samples per second) for 55 days. The instrument was deployed by the R/V Shearwater on July 13, 2007 and began recording the same day. The instrument stopped recording on October 30, 2007 and was subsequently recovered from the seafloor.

Commercial vessel activity in the SBC was monitored through the Automatic Identification System (AIS) (http://www.navcen.uscg.gov/enav/ais/). AIS is required by all ships over 300 tons to transmit the vessel's characteristics as well as location, speed, and heading information via a VHF signal. An AIS receiving station was set up in Santa Barbara Harbor to continuously archive all ship AIS transmissions in the SBC (Fig. 1). The VHF signal was received with a 124WB Boomer 4 element broadband 2 meter Yagi antenna (Cushcraft Corporation). The strength of VHF signal transmission is dependant on line of sight and atmosphere conditions; therefore some AIS transmissions were not received. The AIS signal was fed through a radio(Icom IC-PCR1500 receiver, 1 channel) into a computer. Using the program ShipPlotter (http://www.coaa.co.uk/shipplotter.htm), the signal was decoded, played in real time, and archived for later analysis. The archived data from July 13, 2007 to October 30, 2007 were downloaded and analyzed using specific functions developed in MATLAB (version 2007b, The MathWorks, Natick, MA). For this analysis, only ships in the shipping lanes were analyzed. Although other vessels utilize the region and contribute noise to the environment, they are not required to have AIS, making it difficult to quantify the contribution of noise from these smaller vessels.

Data Analysis

The broadband acoustic data from the HARP were processed to determine average ambient noise levels, both with and without ships nearby, to characterize ship traffic, and to detect blue whale calls. All data were calibrated based on the frequency response curve of the hydrophone from calibration measurements performed in our laboratory and at the U.S. Navy's Transducer Evaluation Center (TRANSDEC) facility in San Diego. The AIS data were processed to identify times ships were nearby the HARP, and to characterize ship traffic.

To determine the background noise levels in the SBC from July through October 2007, times when ships were distant (at least 9 km distance from the instrument) were manually selected from the data. Noise levels are expressed as the distribution of mean square pressure per unit frequency. To calculate these levels, a fast-Fourier transform was performed on 20 seconds of time (400,000 samples). The fast-Fourier transform results in mean pressure squared values for 0–10,000 Hz. The data are then converted to sound pressure levels expressed as decibels referenced to a unit pressure density. A total of 366 different 20-second samples were analyzed at random from July through October 2007. To get the average noise level, each frequency bin was averaged together for all selected 20-second samples.

Average noise levels when a ship was near the HARP (less than 4 km) were determined by combining the AIS data with the acoustic recordings. From the AIS, the time of the closest point to the HARP for a given ship was determined. The time that corresponded to an individual ship was then manually selected in the acoustic data. A total of 80 ships were analyzed using the same protocol as described above to determine the average noise level when ships are nearby.

Both the AIS and acoustic data were used to characterize ship traffic in the SBC. The mean number of ships, standard deviations, and standard errors are reported from both the AIS and acoustic data. The mean ship speed, standard deviation, and standard errors from the AIS data are reported. The AIS data includes geographical information; therefore analyses of the number and speed of ships were performed on ships in the entire channel and ships in just the shipping lanes. AIS data contains information on ship type, so percentages of ship types in the channel are disclosed.

The number of ships that passed the instrument was determined by an analyst scanning the acoustic data for periods when a distinct acoustic signature from a ship was present. This served as a comparison to the mean number of ships per day detected by AIS. In addition, the time of acoustic detections of ships was analyzed to investigate daily shipping patterns. For this analysis, the data set was expanded to include ships from November 2006 to October 2007.

The contribution of ship noise to the environment was calculated based on the difference in average sound pressure levels in each frequency (10–1000 Hz) when local ships were nearby (<4 km) to when ship traffic is low. This difference served as a metric to quantify the increase in noise levels as a result of ship traffic. To estimate the average number of hours per day that sound levels were increased from ships, the average duration (d) of increased noise levels as the ship passed the instrument was multiplied by the number of ships per day (n) to arrive at the percent of the day ambient noise levels are elevated: $n * (d / 60) =$ hours. The duration that sound pressure levels are elevated depends mainly on the size and speed of the ship; the duration that levels were elevated by at least 15 dB averaged 10 minutes for all ships analyzed.

The acoustic data were also scanned for the presence of blue whale calls. The calls of many baleen whale species are stereotyped and well known. Detection and classification of stereotyped mysticete calls are carried out using automatic detectors (Oleson et al. 2007b). The acoustic data from September 2007 and archived data from the same location in September 2005 were analyzed for the presence of blue whale B calls using the spectrogram correlation function within the software program Ishmael (Mellinger 2002). From previous studies with blue whale B calls (Oleson et al. 2007b), this has proved to be an effective detection method.

RESULTS

A four month average of acoustic energy in the SBC when local ships were not nearby (>9 km) shows that the sound levels in the low frequency band (10–1000 Hz) ranged from 56 to 90 dB re: $1Pa^2/Hz$ (Fig. 2). During this period the blue whales calls are a dominant source of acoustic energy, and are elevated above the background by 10 dB re: $1Pa^2/Hz$ at 16 Hz (the fundamental frequency of the blue whale B song call). The subsequent peaks are harmonics of the fundamental frequency (32 Hz and 48 Hz). The number of automatic detections of B calls per day ranged from 609 to 919.

When local ships are nearby (<4 km), sound pressure levels in the lower frequencies (0–150 Hz) increase by 15–25 dB when compared to normal background levels. The fundamental frequency of the blue whale call (16 Hz) is no longer detected above the background levels when a ship is within 4 km of the recording instrument (Fig. 2). However the third harmonic of the blue whale call is slightly above the background (Fig. 2), suggesting that the whales are calling when a ship is present, but the fundamental frequency of the call is masked.

Based on detections of ships in the acoustic data, there are ~19 ships per day passing the acoustic instrument, compared to ~15 ships detected by the AIS (Table 1). The majority of ships detected by the AIS were cargo ships transiting the channel (Table 2). The average speed from the AIS over this four-month period was ~15 knots in the entire channel; however the average speed for ships in the lanes was higher (~20 knots) (Table 1).

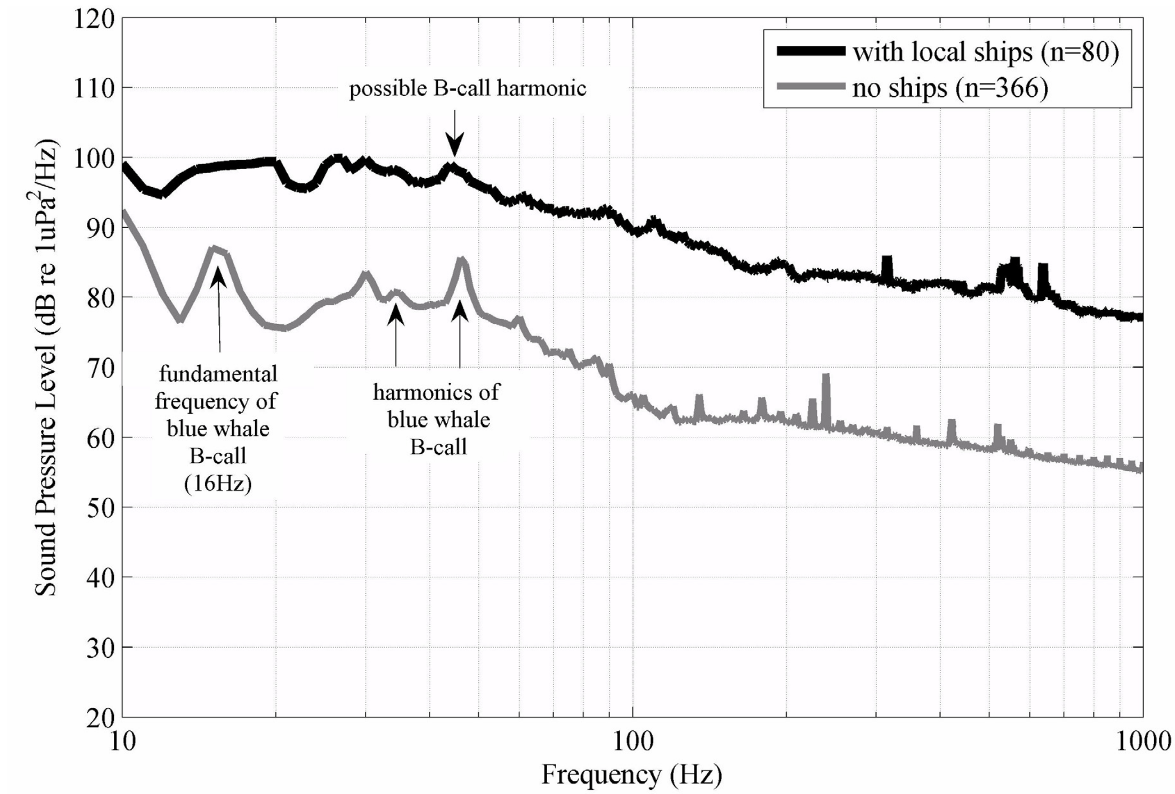

Figure 2. Comparison of sound pressure levels in the Santa Barbara Channel when ships are nearby (<4 km) and ships are distant (>9 km). The data are from July 2007 to October 2007.

Based on the number of ships and the duration of the elevated noise levels, the ambient noise levels are elevated by 15–25 dB for an estimated 3.1 hours per day. The increased levels of noise do not appear to be evenly distributed throughout the day; distinctive peaks in shipping activity exist at noon and midnight (Fig. 3).

DISCUSSION

The level of ambient noise in the SBC is elevated by 15–25 dB when a commercial vessel traveling in the northbound lane is <4 km from our acoustic recorder. The duration of the increased background noise is approximately 3.1 hours per day. This pattern is likely true for a 4 km distance outside the shipping lanes as a ship is transiting the channel. As distance to the shipping lanes decreases the levels will increase; likewise as one moves greater than 4 km from the lanes, the increase in sound levels will diminish as a function of that distance.

When ships were < 4 km, the fundamental frequency of blue whale B calls was no longer detected above ambient noise levels. This result might indicate that blue whales are either not present or do not call when ships are nearby. However, results of blue whale detections from the acoustic data show that calling animals were present during this time, and aerial surveys corroborate this finding (http://channelislands.noaa.gov/). Furthermore, the harmonic at 48 Hz was slightly elevated above the background, suggesting that whales are calling but their calls are masked by the increased noise from commercial ships (Fig. 2).

Peaks in shipping activity occur at noon and midnight, and are most likely related to patterns of activity at the ports of Los Angeles and Long Beach. Blue whale B calls are primarily made during crepuscular hours (Oleson et al. 2007b; Wiggins et al. 2005), when ship traffic in SBC appears to be the least intense, so it is possible that noise from commercial ships will have minimal impacts on the mating calls of blue whales. Blue whale D calls

Table 1. Comparison of ship traffic: July 13 to October 31, 2007.

	Data	Location	Mean	Standard deviation	Standard error
# Ships	AIS	Channel	15.6	4.5	0.46
# Ships	AIS	Shipping lanes	11.7	4.3	0.44
# Ships	Acoustics	HARP	18.8	10.8	1.9
Speed (knots)	AIS	Channel	15.2	2.6	0.26
Speed (knots)	AIS	Shipping lanes	19.7	2.2	0.23

associated with feeding peak at dawn and dusk, but also are detected throughout the day (Oleson et al. 2007b). Therefore, if the noise from shipping traffic masks blue whale D calls in a manner similar to B calls, the increased ship activity at midday might interfere with some blue whale feeding behavior.

The biological significance of the elevated ambient sound pressure levels is not clear; comparisons of background noise measurements in other regions, with different levels of ship traffic, put the results for SBC in perspective, in terms of the levels of exposure to the animals utilizing the region. Sound pressure levels from North Pacific offshore deep sites (off Point Sur and San Nicolas Island) are similar to SBC without ships nearby (Andrew et al. 2002; McDonald et al. 2006). However, when ships are nearby the sound pressure levels in the SBC are ~5–10 dB greater than those of the North Pacific sites (Fig. 4). When local ships are present in the SBC, the levels are 0–5 dB greater than the average levels in the highly industrialized Gulf of Oman (Wagstaff and Aitkenhead 2005). The Scotian Shelf measurement, made in the 1960s (Piggott 1964), is from an area of low local ship traffic, and as expected the sound levels are below those in the SBC; without nearby ships by 0–15 dB (10–200 Hz) and 15–35 dB below SBC when a ship is nearby (Fig. 4). This suggests that even when local ships are not present in the SBC, the levels are higher than measurements in the 1960s. The west side of San Clemente Island has little local ship traffic and is shadowed from the propagation of distant shipping by the adjacent deep canyons and shallow banks (McDonald et al. 2008). This site is over 40 dB less than SBC when local ships are present. Because the decibel scale is a logarithmic scale, 40 dB equate to a ten-thousand (10^4) increase in acoustic power. Although we do not have measurements of the pre-human ocean noise levels, when the animals evolved, the site off San Clemente offers a potential baseline to compare ambient noise levels that animals are exposed to today.

The level of noise generated by ships is related to the size, speed, and power of a ship along with a number of other factors, including type, propeller, engine, age, and any damage. In general, larger, faster ships generate more noise because they produce more propulsion power which is converted into acoustic power (noise) via bubble cavitation (Ross 2005). Reducing ship speed has been a possible management strategy to reduce noise levels and ship strikes (Laist et al. 2001). Although this will result in decreased noise levels, the degree of the reduction is frequency dependent. Arveson and Vendittis (2000) compared sound levels from the

Table 2. Types of ships in Santa Barbara Channel (July 13 to October 31, 2007).

Ship type*	Total number	Percentage
Anti-pollution	3	0.56%
Cargo ship	404	75.94%
High speed craft	1	0.19%
Other ship	23	4.32%
Passenger	7	1.32%
Tanker	52	9.77%
Tug	7	1.32%
Dreg vessel	2	0.38%
Fishing vessel	1	0.19%
Military vessel	1	0.19%
Pleasure vessel	8	1.50%
Research vessel	23	4.32%

*Ship types defined based on AIS data designation.

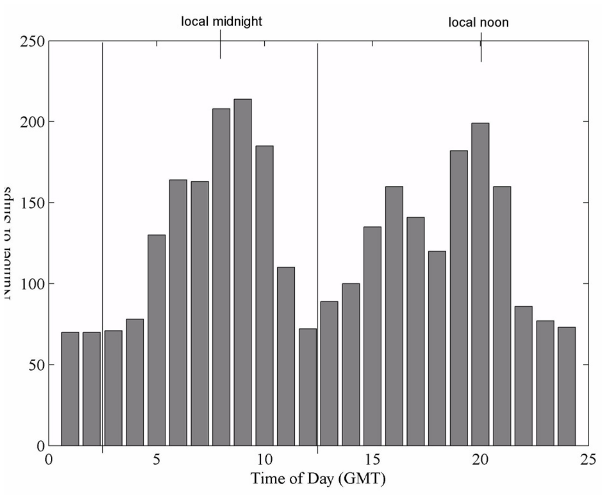

Figure 3. Acoustic daily ship activity patterns. The time a ship was closest to the HARP was used for this analysis. The y-axis describes the total number of ships observed at the subsequent time of day. Data set was expanded to include ships from November 2006 to October 2007.

same ship as it changed speed. By controlling for ship speed they found that at low frequencies (<150 Hz, the frequencies of blue whale calls), there was a 21 dB decrease as the ship slowed from 14 knots to 8 knots; however, at 10,000 Hz (the frequency of dolphin whistles), there is only a 10 dB decrease in noise for the same speed reduction. Therefore, management strategies should determine the frequencies that they are interested in reducing before advocating for speed reduction of ships to lower noise levels.

Another complication with speed reduction in terms of decreasing noise output is the impact on the biology. An animal's perception of a sound plays an important role in determining temporal threshold shifts and/or permanent hearing loss. This is especially important for more resident species that are not capable of leaving an area during increased noise levels. For some fishes it is known that they have significant increased levels in stress hormones when ship noise is present (Wysocki et al. 2006); however more experimental data is needed to determine the impact of a longer quieter sound,

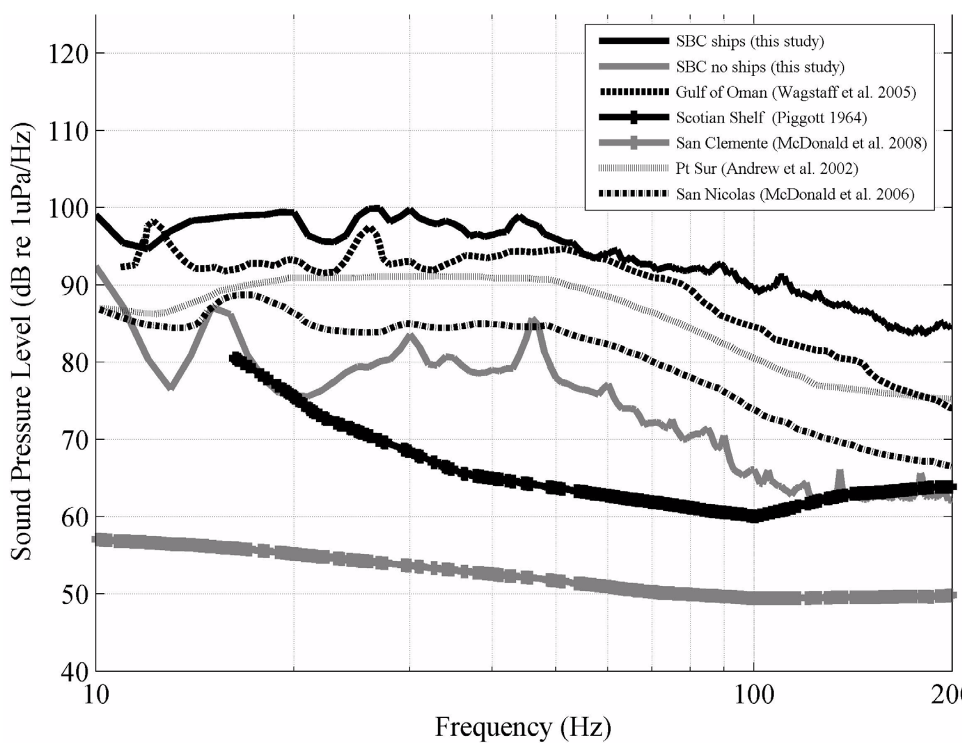

Figure 4. Comparison of low frequency sound pressure levels in the Santa Barbara Channel to other coastal and deep ocean regions.

compared to louder shorter sound (e.g., the result of slowing a ship).

The noise levels in SBC are high compared to other coastal regions, and the potential for impacts on the marine mammals and fishes seems inevitable. Future modeling of sound propagation in the channel will help elucidate characteristics of the basin that might contribute to the high noise levels. A future component to this study will be to compare the SBC to other regions in the Sanctuary to identify quieter regions, either from sound propagation and/or proximity to shipping lanes. If elevated noise levels are influencing the health of the region, the comparison between sites will offer a measure of this impact. Furthermore, determining behavioral and auditory impact on blue whales through the deployment of acoustic tags when a ship is present will also help evaluate the impact of elevated noise levels from commercial ships.

CONCLUSIONS

The results of this study showed that ships within 4 km elevate noise levels by 15–25 dB (10–150 Hz) in the SBC; an elevation in noise of more than 15 dB lasted for approximately 3.1 hours per day, based on the number of ships transiting the channel combined with the average speed of the ships. Compared to another Southern California site that is not exposed to distant shipping and has little local ship traffic, SBC has high sound levels; however compared to the Gulf of Oman, another industrialized site, the sound levels in SBC are only a few dB higher. The impact of these elevated noise levels on the marine ecosystem is still not well understood, but we found that blue whale B calls were not detected when a commercial ship was within 4 km. This suggests that there is a decrease in communication distance for blue whales when a ship is nearby, especially at noon and midnight when ship traffic is the most intense in the SBC.

Current management strategies are focused on the possibility of slowing ships in the channel to reduce noise and decrease the probability of ship strikes. To successfully manage the acoustic impacts on marine mammals from ship noise, managers should define the frequency band for noise level reduction, understand how ship operations may be modified to enact these changes, and understand how marine mammals might benefit from the change.

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