Ocean ambient sound south of Bermuda and Panama Canal traffic

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Comparisons of current and historic ocean ambient noise levels are rare, especially in the North Atlantic. Recent (2013–2014) monthly patterns in ocean ambient sound south of Bermuda were compared to those recorded at the same location in 1966. Additionally, trends in ocean traffic, in particular, Panama Canal traffic, over this time were also investigated. One year of ocean ambient noise measurements were collected in 1966 using cabled, omnidirectional hydrophones at the U.S. Navy Tudor Hill Laboratory in Bermuda, and repeat measurements were collected at the same location from June 2013–May 2014 using a High-frequency Acoustic Recording Package. Average monthly pressure spectrum levels at 44 Hz increased 2.8 ± 0.8 dB from 1966 to 2013, indicating an average increase of 0.6 dB/decade. This low level of increase may be due to topographic shielding at this site, limiting it to only southern exposure, and the limit in the number of ship transits through the Panama Canal, which did not change substantially during this time. The impending expansion of the Canal, which will enable the transit of larger ships at twice the current rate, is likely to lead to a substantial increase in ocean ambient sound at this location in the near future. © *2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1121/1.4947517]

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I. INTRODUCTION

Sources of ocean ambient sound vary in origin, frequency, and temporal character (Hildebrand, 2009). Generally, low frequency sounds (<10 Hz) are of natural physical origin, and are produced by earthquake activity and surface wave interactions. Anthropogenic sounds from distant large ships are a dominant source across the 10–200 Hz band of deep ocean ambient sound (Wenz, 1962), while nearby ships contribute sounds up to 10 s of kHz (McKenna *et al.*, 2012b). Wind-driven surface waves are a dominant sound source above 200 Hz, with about 6 dB/octave decrease in levels above 500 Hz (Knudsen *et al.*, 1948; Wenz, 1962; Urick, 1983). Finally, marine animals, in general, and marine mammals, in particular, can be seasonally important contributors of ambient sound across a range of frequencies (Širović *et al.*, 2013).

Increase in ocean ambient sound is a persistent trend in the world's oceans. Based on the data collected in the North Atlantic and the North Pacific from the 1950s through the 1970s, Ross (2005) showed an average noise at 50 Hz (mainly due to shipping) was increasing 5.5 dB/decade. When we take into account more recent data, deep-ocean noise levels in the eastern North Pacific have been increasing at an average rate of 2.5–3 dB/decade at 30–50 Hz since the 1960s (Andrew *et al.*, 2002; McDonald *et al.*, 2006; Chapman and Price, 2011). If we consider just the last decade, however, ocean traffic noise in the North Pacific has become variable (Andrew *et al.*, 2011; McKenna *et al.*, 2012a).

The North Atlantic is generally a noisy ocean basin (Ross, 1993, 2005), but to our knowledge, no comparisons between current and past noise levels exist. Much of the low frequency noise in the North Atlantic is driven by shipping and oil and gas exploration, both of which are prevalent across the basin (Ross, 2005; Klinck *et al.*, 2012; Nieukirk *et al.*, 2012). In this paper, we present recent (2013–2014) monthly patterns in ocean ambient sound south of Bermuda and compare them to recordings collected at the same location in 1966 (Perrone, 1976). We discuss the trends in the recorded ambient sound levels in relation to changes in ocean traffic, in particular, traffic through the Panama Canal, over this time.

II. METHODS

A. Acoustic recordings

1. Cabled hydrophone data collection (1966)

One year of ambient noise measurements were collected in 1966 using cabled, omnidirectional hydrophones at the U.S. Navy Tudor Hill Laboratory in Bermuda (Perrone, 1976). Hydrophones were deployed at five depths: 30, 400, 1100, 2400, and 2500 fathoms, each located a few meters above seafloor. The data from each hydrophone were recorded on magnetic tapes for 2 min every 2 h. The signal was sequentially scanned and the output was fed to a bank of seven logit filters (centers at 11, 22, 56, 141, 354, 891, and

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1414 Hz). The signal level output from each filter was recorded on Sanborn Tape Recorder (Waltham, MA). To calculate the average noise level, the mean value was computed using 100 1 s root-mean-square (RMS) levels in each logit filter band over the sampled range. Records with high levels of biological or anthropogenic noise were discarded. The system was calibrated throughout the year to verify that the system gain was within 1 dB (Perrone, 1976).

Wind speed was also measured 3–8 km from the locations of each hydrophone using an anemometer positioned 46 m above the sea surface on the Argus Tower. Average wind speed corresponding to each ambient noise recording period was calculated by averaging the recorded wind speed over a time interval of ~12 min before and after the ambient noise recording. Mean spectrum levels were then grouped according to wind speed into eight 5 kn wind speed groups (0–2, 3–7, 8–12, 13–17, etc.). Average monthly values were grouped by wind speed group and overall medians for each group were plotted against frequency (Perrone, 1976), and these data were used for comparison with contemporary data.

2. Autonomous recorder data collection (2013–2014)

Autonomous, bottom-mounted High-frequency Acoustic Recording Packages (HARPs; Wiggins and Hildebrand, 2007) were deployed at a site south of Bermuda, where previous ambient sound recordings were collected (Fig. 1). The hydrophone was deployed at ~720 m depth for comparison to the 400 fathom recordings collected in 1966 (Perrone, 1976). Data were recorded continuously, sampling initially at 200 kHz, but to allow for more efficient data analysis, the recordings were low-pass filtered and downsampled to 2 kHz for an effective bandwidth from 15 Hz to 1000 Hz. Hydrophones were calibrated at the U.S. Navy's Transducer Evaluation Center (TRANSDEC) in San Diego, CA. Analyzed data spanned the period from 10 June 2013 through 24 May 2014, with a gap in recording on 12 March 2014.

B. Acoustic data analysis

Monthly spectral plots from Perrone (1976) were digitized and imported into Adobe Illustrator (San Jose, CA). A grid was superimposed on the spectral plots to allow more precise reading of the spectral values. The grid consisted of vertical lines at each logit center frequency The plots for the 400 fathom recordings covered frequencies from 11 Hz to 276 Hz. Horizontal grid lines were spaced 2 dB apart and spectral readings were done with resolution 0.5 dB. Separate spectral plots were created for different sea states by Perrone (1976), and we used the lowest sea state group (0–2) for extracting the values because often the individual lines were blurred and formed one thick line, thus, it was easiest to obtain the reading on the low end of the line. This tight clustering of the lines, however, indicated there was little variability in spectral levels, especially at lower frequencies where the variability across sea states was relatively low (maximum 3 dB, and generally <1 dB at frequencies below 100 Hz).

Spectrum levels from contemporary recordings were computed first by calculating 5 s spectral averages with 1 Hz frequency resolution from average energy in five 1 s blocks of data (calculated using Hanning window and with no overlap). They were additionally averaged over 100 s for consistency with previous ocean noise measurements from this location. Monthly and weekly average power spectral densities were

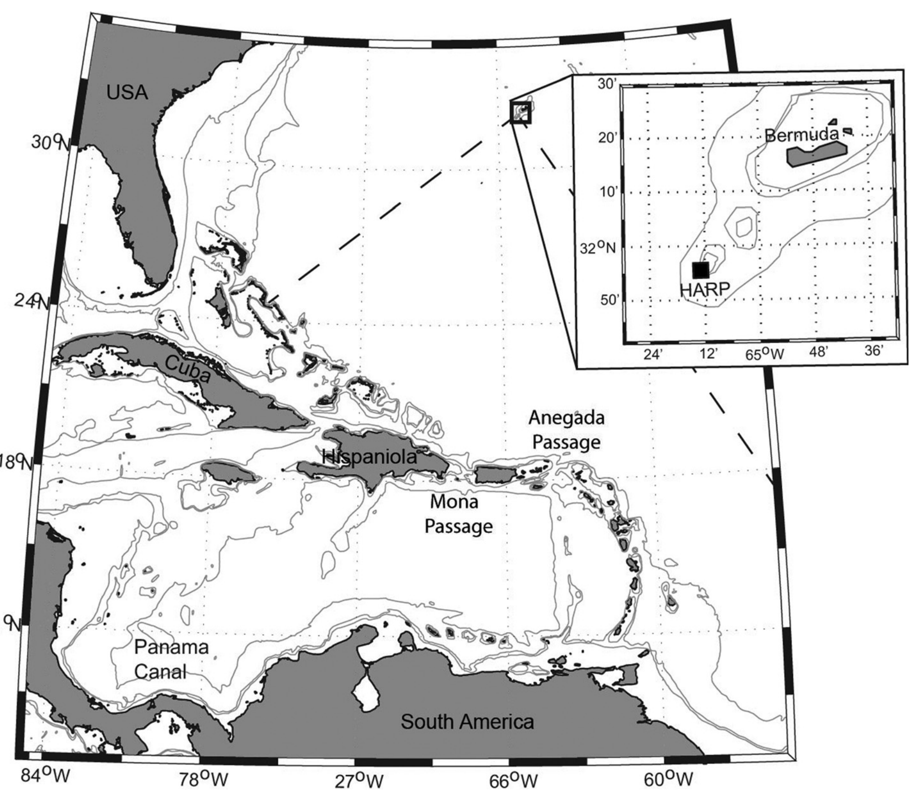

FIG. 1. Location of the HARP deployment site, which coincided with the location of the cabled hydrophone deployed in 1966, on the south side of Bermuda (inset) in the context of the North Atlantic Ocean. Grey lines are 500, 1000, 2000, and 3000 m depth contours. Broken lines denote area of acoustic window from the HARP site.

computed in logarithmic (dB) realm over the 15–1000 Hz band. Also, variation in noise over the course of a day was investigated by comparing hourly average power spectral densities in the same frequency band during each month of deployment. Periods with consistent low frequency flow noise and instrument self-noise were removed, but transient signals (e.g., whale calls, ship passages) were included as, at times, they were major contributors of ocean ambient sound. This removed noise comprised 1.3% of the total samples. All spectrum levels are reported as dB re: 1 μPa^2/Hz.

Spectral levels at 44 Hz [closest to the logit center frequency reported by Perrone (1976) that was deemed best representative for shipping noise, 43.8 Hz] were compared between the two sets of recordings by subtracting the monthly median value of contemporary data from the digitized value for the same month in 1966. The average of all the differences was calculated to estimate average decadal change (in dB) of spectral levels at 44 Hz at this site south of Bermuda. Since the 1966 data were based on sea state 0–2 ambient sound levels, this average might be a slight overestimate of the total average change rate.

In addition, in contemporary data, we also calculated basic statistics of noise levels for two frequencies chosen as representative, 50 Hz for ship-dominated noise and 500 Hz for weather dependent noise, based on the cumulative probability distributions of 100 s averages. Median (50th percentile), 1st, 10th, 90th, and 99th percentiles were calculated from the probability distributions. Skewness, third standardized moment and a measure of asymmetry of the probability distribution, and kurtosis, fourth standardized moment and a measure of "peakedness" in the probability distribution, were also calculated. All averaging statistics were calculated on a logarithmic scale.

C. Shipping data

To evaluate changes in global shipping trends between 1966 and 2013–2014, we used records from the Lloyd's Register of Shipping (London, UK). Lloyd's maintains information on self-propelled merchant vessels 100 gross tons or higher in the world's fleet. The annual total number and gross tonnage of all ships from 1965 to 2014 are reported. In addition, the information on the number of annual ocean-going (commercial vessels of 300 net tons or greater) ship transits through the Panama Canal was obtained from annual reports of the Panama Canal Company provided to the U.S. Congress prior to 1978 (Panama Canal Company, 1979), the Panama Canal Commission for 1979–1999 (Panama Canal Commission, 1989; Eriksen, 2000), and the Panama Canal Authority since 2000 (Panama Canal Authority, 2014). Also, the number of monthly transits for the period of the contemporary study was obtained from the Panama Canal Authority website (https://web.archive.org/web/20150426102835/http://www.pancanal.com/eng/op/transit-stats/2014/2014-Table10%5B1%5D.pdf, last viewed 11/16/2015). We used these data to assess overall global shipping trends during the period of our recording, as well as evaluate the changes in traffic through the Panama Canal around the times of our and historic recordings.

III. RESULTS

Average monthly pressure spectrum level at 44 Hz increased 2.8 ± 0.8 dB from 1966 to 2013 at this location, indicating an average increase of 0.06 dB/yr or 0.6 dB/decade. Over the same time, the number of ships worldwide increased about two and a half times [Fig. 2(A)]. The increase in ship numbers alone would lead to a predicted ambient noise increase of 4 dB, which is substantially more than the increase measured here. We postulate that the lower increase evidenced in our recordings is the result of topographic shielding of our recording site, limiting its exposure to southerly directions, and the limitation in the number of ship transits through the Panama Canal, which remained relatively steady between 1966 and 2013–2014 [Fig. 2(A)]. The number of monthly ship passages through the Panama Canal was positively correlated with the average weekly spectral levels at 50 Hz for that month during 2013–2014 [$r = 0.309$; $p = 0.029$; Fig. 2(B)].

A. Anthropogenic and natural sounds

The dominant source of ambient sound at frequencies <100 Hz during all seasons was shipping, although those levels have changed little since 1966 (Fig. 3). In general, those levels were not very high, generally around 78 dB in the frequency band from 30 Hz to 80 Hz. Even though most

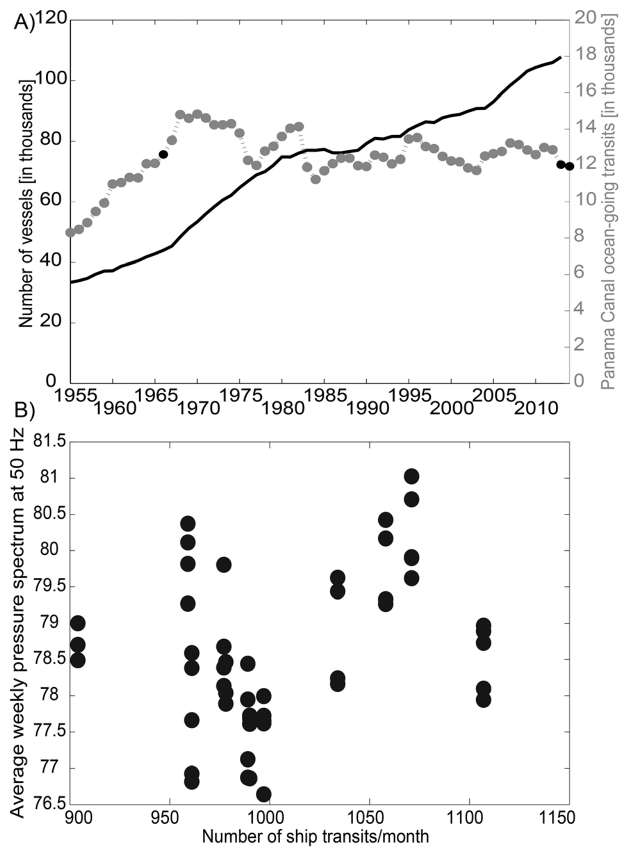

FIG. 2. (A) Shipping trends since 1955 as total number of vessels (black solid line) and total annual number of ocean-going ship passages through the Panama Canal (light grey dots; with 1965, 2013, and 2014 data highlighted as black dots). (B) Number of monthly ship transits through the Panama Canal compared to the average weekly pressure spectrum levels at 50 Hz.

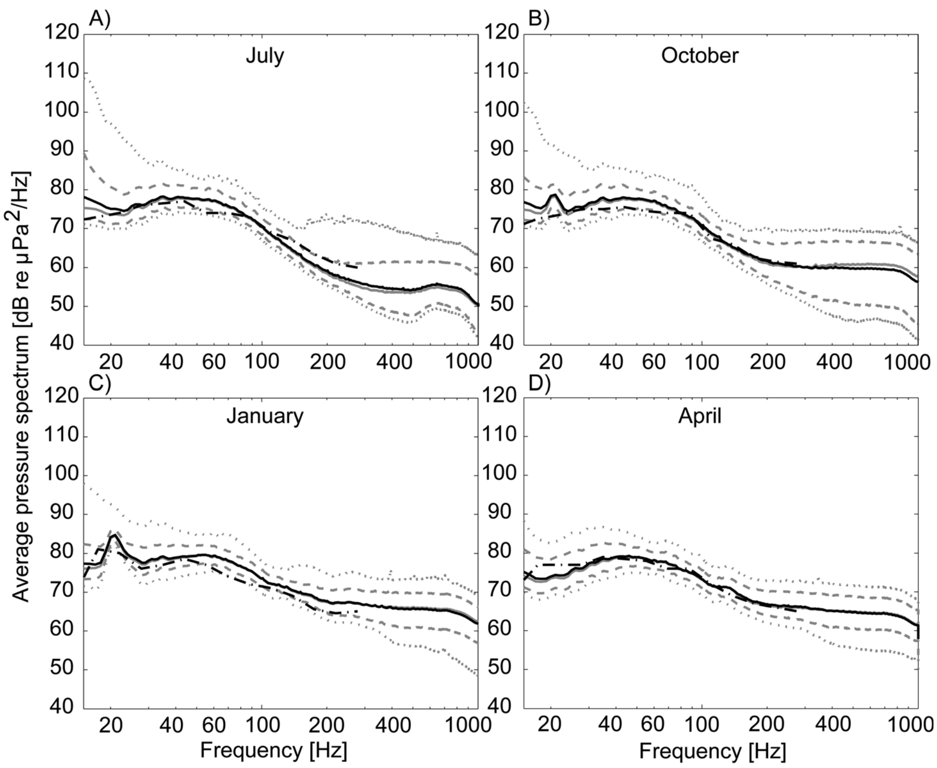

FIG. 3. Representative monthly sound pressure spectrum levels from 15 to 1000 Hz for (A) July (summer), (B) October (fall), (C) January (winter), and (D) April (spring). Solid black line is the 2013–2014 monthly mean and dash dotted black line is the 1966 monthly mean for given month. Solid grey line is the median, dotted grey lines are 10th and 90th percentiles, and broken grey lines are 1st and 99th percentiles.

of that shipping was from distant sources, there were also some local sources, such as small boat activity, that contributed to spectrum levels at frequencies >100 Hz. Specifically, the low amplitude signals visible in the 99th and 90th percentile spectra at frequencies >500 Hz in July and October were from distant small boats, and the increased 1st and 10th percentile spectra in July at 150–400 Hz were from nearby small boating activities (Fig. 3). Ambient sound at 50 Hz was only slightly skewed toward high amplitudes, indicating likely that ship transits contribute to occasional increases in spectrum levels, while high kurtosis indicates that those passages likely contribute to high level outliers, especially in October and April (Fig. 4). Spectra at 50 Hz, corresponding primarily to shipping noise, are about 2 dB higher in the winter and spring than summer and fall, with no strong diel pattern (Fig. 5).

Similar levels of ambient sound at frequencies >200 Hz were recorded in January and April, but they were much lower during the summer, in July (Fig. 3). July was also the only month with positive skewness in the distribution at 500 Hz, indicating that occasional wind events at times raise otherwise low sound levels, while the skewness was negative in other months whose median was much higher (Fig. 4). At this frequency, representative of wind-induced waves, spectrum levels in July were the lowest, about 5 dB lower than in October and about 10 dB lower than in January and April (Fig. 5). A diel wind pattern was visible in July, with winds peaking early in the morning and at dusk, but no clear diel trends were visible other times of the year (Fig. 5).

B. Biological sounds

Calls from several species of baleen whales were detected in the recordings. Fin whale (*Balaenoptera physalus*) 20 Hz calls were the most substantial seasonal biological contributor to low frequency ambient sound. In particular, they were common during the fall and winter months, as seen in peaks at 20 Hz visible both in current October and January spectra, as well as those from January 1966, as they raised the

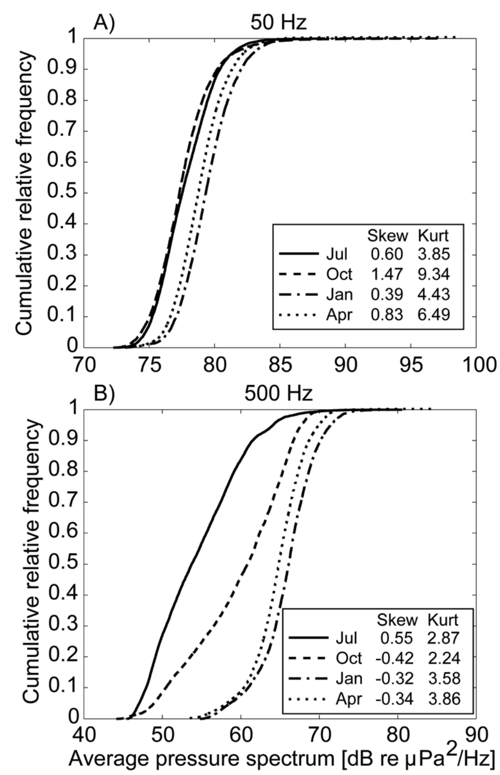

FIG. 4. Cumulative density functions of average sound pressure spectrum levels at (A) 50 Hz and (B) 500 Hz during four representative months. The skewness and kurtosis for each presented month are in the inset.

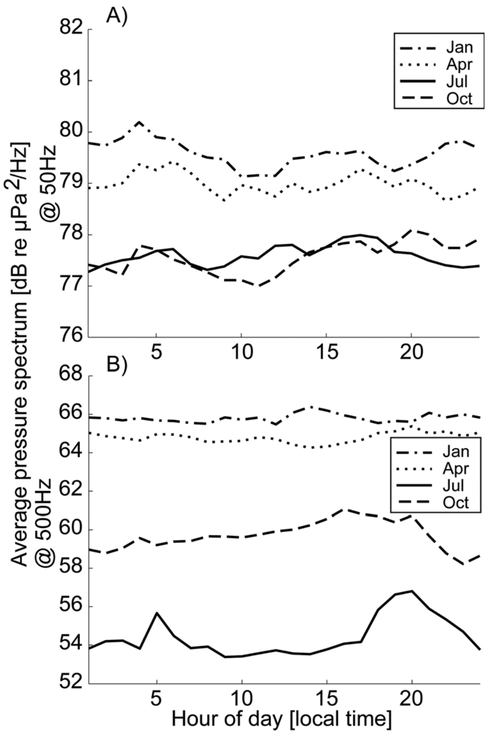

FIG. 5. Examples of hourly average sound pressure spectrum levels at (A) 50 Hz and (B) 500 Hz during four representative months from June 2013 to May 2014.

median levels around 20 Hz (Fig. 3). These calls occurred in a song pattern, as singlets with ~15 s intercall intervals, occasionally also with a higher frequency component around 130 Hz. Humpback whale (*Megaptera novaeangliae*) song was recorded during winter and, as it was not common in January but was generally high amplitude, it was likely occurring near the recorders and it only contributed to elevated ambient sound levels at the 1st percentile. Minke whale (*Balaenoptera acutorostrata*) thump trains (Mellinger *et al.*, 2000) were also recorded during the winter months and were visible as increases at frequencies <400 Hz in the 99th percentile spectrum in January (Fig. 3), as they were still infrequent this early in the season, but became more common during the rest of the winter. They were generally slow-down or speed-up type, although some constant sequences were also detected (Risch *et al.*, 2013).

IV. DISCUSSION

The rate of increase in low frequency ambient sound recorded at this site off Bermuda is about an order of magnitude lower than average noise increases observed at 50 Hz at various locations during the period from the 1950s to the 1970s (Ross, 2005), and substantially lower than the increase measured for the North Pacific from the mid-1960s to 2004 (McDonald *et al.*, 2006). We propose that two major factors can explain this relatively small increase: local bathymetry and the shipping bottleneck created by the Panama Canal. Most of the contribution to the noise at this site probably comes from downslope conversion, a process by which sounds from surface sources (such as ships) enter the deep sound channel at the continental margins due to the conversion of steep-angle rays into shallow angled ones, allowing propagation of low frequency sounds with relatively little loss (Wagstaff, 1981). The recording site was located on the east flank of a ridge that extends south and west from Bermuda. This ridge is likely causing sound shadowing to the west of the recording location, toward the North American continental margin, thus, this site may be shielded from the shipping events occurring north of the Bahamas, along the eastern U.S. seaboard, as well as the traffic between the Gulf of Mexico and Europe that passes to the north of Bermuda. It is likely only exposed to the shipping lanes to the south of Bermuda, which make up only a portion of the traffic that transits through the Canal. So, in this case, ambient noise at this Bermuda location would be affected mostly by the passage of ships through Mona and Anegada Passages, located between Hispaniola and Puerto Rico, and British Virgin Islands and Anguilla, respectively (Fig. 1). This is consistent with the positive but relatively weak link we found between the number of monthly passages through the Canal and weekly noise levels during our recording period, as likely a variable fraction of those ships continues through the two passages.

Over decades, the number of recorded Panama Canal transits has varied substantially, as a result of geopolitical changes (e.g., a decrease in transits after 1982 is the result of the completion of the Trans-Panama pipeline that year that facilitated oil transfer between the Pacific and Atlantic coasts, and reduced the number of tanker transits). However, in general, the Canal creates a bottleneck in the total number of ships and limits the size of ships that can pass through. In addition, our recordings were collected in years with lower ship transits than in the previous decade. In 2013 and 2014, the number of transits decreased by more than 8% from their peak in 2007, likely as a result of the global economic downturn. Both of these factors can explain relatively low increase in the ambient sound levels between the 1960s and today at this location.

A systemic bias in our estimate could arise if we were not monitoring at exactly the same location as that of the 1966 recording. Even though Perrone (1976) did not provide exact latitude and longitude for his recordings, we used a local landmark (the Argus Tower) and bathymetry information that was available to identify the location and are confident we deployed the HARP at the same site. As another source of bias, we compared our ambient sound levels, which were averaged over all sea states, to those collected only during low sea states. However, that bias would result in overestimation of the change in sound levels, and even so we show a smaller change than those observed in other similar studies at other locations (Andrew *et al.*, 2002; McDonald *et al.*, 2006; Chapman and Price, 2011). Wind conditions were not substantially different in 2013–2014 from 1966 as seen in comparable ambient sound levels at frequencies characteristic of wind-driven waves in the two sets of recordings, so any difference due to this measurement bias is likely minimal. Thus, it is probable that the local bathymetry and southerly exposure of the site, along with limited traffic through the Panama Canal, explain a relatively small increase in ambient sound observed here relative to recent studies in the North Pacific (e.g., McDonald *et al.*, 2006).

A. Biological sounds

Even though a variety of biological sounds were present in the recordings, most of them did not substantially contribute to the ambient sound levels, as is the case at some other locations (McDonald *et al.*, 2006; Širović *et al.*, 2013). This location off Bermuda is likely a seasonally important winter breeding site for baleen whales. Fin whale singlet song detected in these recordings was similar to the long inter-pulse interval (IPI) song reported by Morano *et al.* (2012), but the timing of its occurrence is different. This type of song peaked from March through May in Massachusetts Bay and New York Bight, but songs with 9.6 s interpulse interval were recorded from September to January (Morano *et al.*, 2012). At the same time, our timing is consistent with the recordings from the Gulf of Maine where songs with ∼15 s IPI were also recorded during the winter and early fall of 2006 (Delarue *et al.*, 2009). Higher frequency components in North Atlantic fin whale calls have been reported previously in the Mediterranean and northeastern Atlantic, but also to the north of the Greater Antilles (Folkow and Blix, 1991; Castellote *et al.*, 2012). Further investigation of these patterns may provide insights into the regional fin whale population structure.

The timing of the minke whale thump train occurrence in this region is consistent with this being one possible wintering ground for the population that spends the summers off the coast of the northeastern U.S., as their calls here occur during winter months when calling was not recorded further north (Risch *et al.*, 2013; Risch *et al.*, 2014). While detailed quantification of different types of thump trains is beyond the scope of this study, it did appear that the slow-down type was also the most common type in our recordings, as was reported by Risch *et al.* (2013) for Massachusetts Bay, U.S.A.

V. CONCLUSION

The relatively small increase of low frequency ambient sound since 1966 reported here may be due to the limit in the number of ship transits through the Panama Canal, which increased by only about 6% during this time. However, the impending expansion of the Canal, which will double its capacity and enable transit of ships about one and a half times the current maximum width and length in 2016, is likely to lead to a substantial increase in ocean ambient sound at this location in the near future. Since this site is an important over-wintering ground for a number of baleen whale species, this expected increase in ambient sound has the potential to reduce their communication range, which could negatively impact their breeding success. Continued monitoring at this location will help in assessing the change in ocean ambient sound levels brought about by the expansion of the Panama Canal and potential impact that may have on baleen whale communication space at this likely breeding ground.

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