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Low frequency deep ocean ambient noise trend in the Northeast Pacific Ocean

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Abstract: Concern about effects of anthropogenic noise on marine life has stimulated new studies to establish present-day ocean noise levels and compare them to noise levels from previous times. This paper reports on the trend in low-frequency (10–400 Hz) ambient noise levels and presents measurements made using a calibrated multi-element volume array at deep ocean sites in the Northeast Pacific from 1978 to 1986. The experiments provided spectral noise levels as well as horizontal and vertical noise directionality. The data presented here provide evidence that the trend derived from 1960s data extended to around 1980, but has since continued at a lower rate.

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1. Introduction

Concern about effects of anthropogenic sound generated by sources such as ships, seismic exploration, naval operations, and ocean acoustic research on marine life has stimulated new studies of marine bioacoustics and the ambient noise background in the oceans. The central focus is to understand the impact of noise on marine animal behavior. An underlying issue in assessing the noise impact is to determine the background noise level at the present time and its relationship in comparison to noise levels from previous times.

At low frequencies, <300 Hz, ambient noise in most areas of the ocean is dominated by noise due to shipping. Since the 1960s, the number of ships has nearly doubled, and the vessel size and propulsion power have generally increased. Not surprisingly, ambient noise levels have correspondingly increased over the same period. The most generally accepted prediction of noise level trend at low frequencies is due to Ross,[1,2] who used noise levels from the 1950s and data published by Wenz[3] from the mid 1960s to predict an increase of about 3 dB/decade or 0.55 dB/yr. Recent studies by Andrew *et al.*[4] and McDonald *et al.*[5] using decommissioned navy arrays off the California coast at Point Sur and an autonomous acoustic recording system near San Nicolas Island, respectively, have been carried out to relate present-day noise measurements to the predicted trend, using the Wenz[3] data as reference values. However, their studies address only the magnitude of the increase in noise level between the two times.

This paper addresses the trend in low-frequency ambient noise levels in the ocean and presents measurements taken in the intermediate years between the Wenz[3] data and the present time. The measurements were made using calibrated hydrophone arrays at deep ocean sites in the Northeast Pacific from 1976 to 1986. Array directionality data are used to analyze the sources of the low frequency noise. The measured noise levels provide evidence that the trend predicted by Ross[1,2] extended at least into the early 1980s, but afterward the increase has been more gradual.

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2. Ambient noise measurements

The measurements reported here were made at deep water sites in the Northeast Pacific Ocean at 46° 30′ N 143° 30′ W (August 1978) and 51° 29′ N 136° W (July 1980) in experiments to characterize the low frequency noise background. The data were recorded by a multi-element volume array (MEVA) that consisted of a 6-element horizontal hexagonal planar array with a diagonal length of 2 m through the array center and a 10-element vertical line array (VLA) with hydrophones spaced at 6 m intervals directly below the horizontal array.[6] The arrays were deployed from the monitoring ship, Canadian Forces Auxiliary Vessel (CFAV) endeavour, so that the horizontal array was suspended near the sound channel axis at a nominal depth of 330 m. Additional noise data are included from similar silent period measurements in June 1986 at 44° N 137° W, with the MEVA configured as a single 16-element VLA with 3-m element spacing.

The MEVA provided reliable measurements of the noise level and directionality over the frequency band from 10 to 400 Hz. Mechanical decoupling from the sea surface motion was achieved by a two-stage suspension system comprising a damper plate and a sub-surface float that suspended the arrays and was connected to the damper plate by a neutrally buoyant line. The damper plate was suspended beneath a surface float from a cable that included a distributed buoyancy system at the sea surface. Heading and orientation of the horizontal array were monitored by a compass and tilt meters on the array frame. The acoustic data were digitized at a sampling rate of 1500 samples/s using 12-bit analog-to-digital conversion in a sub-surface electronics unit, and subsequently transmitted to the monitoring ship by a radio frequency link from the surface float. The hydrophone sensitivity was −187 dB re 1 V/μPa, and the system calibration was known to be within 1.0 dB over the measurement frequency band.

Noise measurements were made regularly every 4–6 h during "silent" periods when the ship power was completely shut off for about 30 min. The data reported here comprise 13 silent periods over 3 days in August 1978, 15 silent periods over 4 days in July 1980, and 11 silent periods over 3 days in 1986. The measurements include both day- and night-time conditions and ocean wind speeds from 1 to 8 m/s. The data exclude any periods where there was evidence of nearby ships or seismic survey from either the vertical or the horizontal directionality data.

3. Deep ocean ambient noise trends: 1965–present

The MEVA measurements are reported as single hydrophone spectral levels in decibels (dB re 1 μPa^2/Hz) for third octave bands centered at specific frequencies. Mean spectral levels were obtained from 1-min averages of noise data from each VLA hydrophone, and these were averaged over all the silent periods from each site. The results for the two sites are plotted versus frequency in Fig. 1(a). For comparison, the Wenz[3] data from 1965 and the 1994–2001 measurements of Andrew *et al.*[4] from the Point Sur site are also plotted to represent limiting values of ambient noise in the Northeast Pacific between 1965 and the present time. The MEVA values are generally within 1–2 dB at each frequency, and they lie roughly in the mid-range between the two other sets. Compared to the 1965 values, the MEVA values are 6–8 dB greater between 10 and 50 Hz and 1–3 dB greater from 50 to 400 Hz, respectively. The standard deviations of the measurements within each silent period are small, around 1 dB or less. At the higher frequencies (>200 Hz) where the impact of noise due to sea surface winds is greater, the data set is limited by the small number of measurements and the seasonal bias. For the 1978 data, the mean wind speed was 6 m/s, whereas in 1980, the mean wind speed was 4 m/s. The mean noise levels and standard deviations over all the measurements at the 1978 and 1980 sites are listed in Table 1. The standard deviations are similar for the two data sets over the entire frequency band.

The spectral levels from the three data sets for the band centered at 31 Hz are plotted versus year in Fig. 1(b) to display the trend in low frequency noise values due to shipping. Assuming the predicted increase of 0.55 dB/yr, the MEVA data are

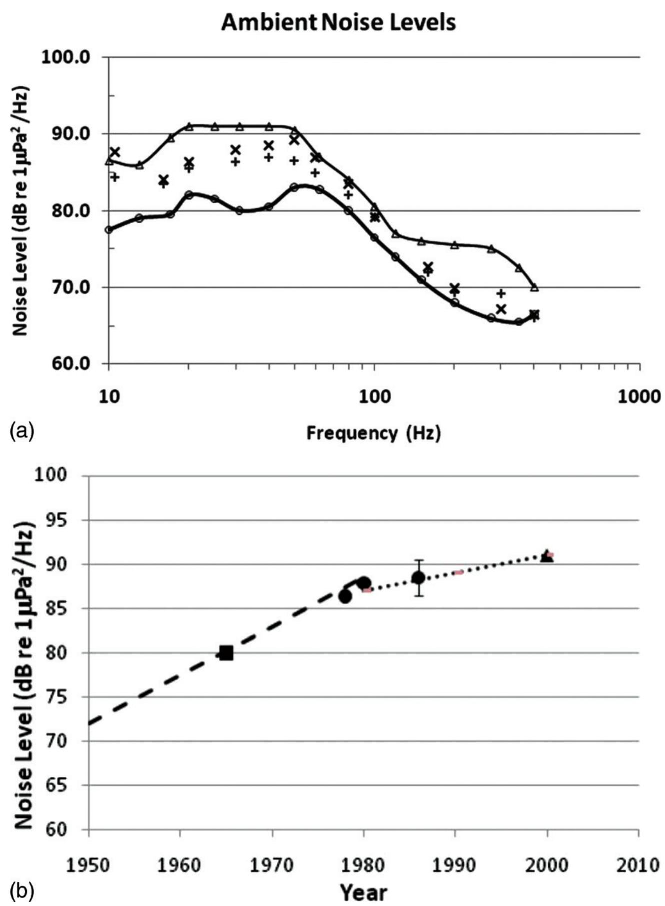

Fig. 1. (Color online) (a) Noise level in 1/3 octave bands: (+) 1978 MEVA; (×) 1980 MEVA. The open triangles show the recent measurements by Andrew *et al.* (Ref. 4) at Point Sur, and the open circles show the 1965 noise levels from Wenz (Ref. 3). (b) Noise measurements for the 1/3 octave band at 31 Hz. The closed circles are the deep ocean MEVA data, the solid triangle is the result from Andrew *et al.* (Ref. 4) and the solid square is the Wenz (Ref. 3) measurement from 1965. The broken line is the Ross (Ref. 1) predicted trend of 0.55 dB/yr, and the dotted line shows a more gradual trend of 0.25 dB/yr.

consistent with the Ross[1,2] trend, and the figure shows that the trend persisted at least to around 1980. Over the remainder of the century, the increase in noise level is only about 5 dB, corresponding to a slower trend of ~0.2 dB/yr. The 1986 noise levels are consistent with the more gradual trend starting around 1980. The decrease in noise trend was suggested by Ross[2] who reasoned that factors such as better design of propulsion systems and economic conditions affecting the price of oil would contribute to a reduced rate of noise level increase.

Another comparison of noise levels can be made using the results of McDonald *et al.*[5] from the San Nicolas Island site. The noise levels at this site are consistently lower than those at Point Sur by about 10 dB in the low frequency shipping band, but the increase from 1965 is about the same at each site. The lower levels at San Nicolas may be due to its greater distance from the northern shipping lanes or local conditions that affect the coupling with the sound channel. McDonald *et al.*[5] obtain a trend of 0.3 dB/yr increase in noise level, similar to the more gradual trend derived from the MEVA data for the period from 1980.

4. Deep ocean noise directionality

Vertical directionality of the MEVA data was reported previously in connection with measurements of noise level due to sea surface winds.[6] For all the data reported here,

Table 1. Ambient noise levels from MEVA data.

Frequency band (Hz)	1978 site (dB re 1 μPa^2/Hz)	1980 site (dB re 1 μPa^2/Hz)
10	84.4 ± 3.2	87.7 ± 1.1
16	83.4 ± 0.8	84.0 ± 1.1
20	85.5 ± 1.2	86.3 ± 1.4
31	86.4 ± 1.3	87.9 ± 2.4
40	86.9 ± 1.2	88.5 ± 2.8
50	86.5 ± 2.2	89.3 ± 1.4
62	84.9 ± 1.3	86.9 ± 1.2
80	82.0 ± 0.8	83.5 ± 0.9
100	79.1 ± 0.6	79.1 ± 1.1
160	72.0 ± 1.0	72.7 ± 1.0
200	69.3 ± 1.2	69.9 ± 1.3
400	66.0 ± 2.9	66.4 ± 2.0

the vertical directionality at the deep ocean sites was dominated by the high intensity "pedestal" at small angles, which is characteristic of distant shipping noise propagated at shallow angles in the sound channel. There are two mechanisms that can account for the high intensity at shallow propagation angles in low frequency deep ocean noise. Sound from surface ships is coupled to the sound channel by downslope conversion that occurs at continental margins where steep-angle bottom-interacting rays from ships transiting over the continental slope are converted to shallow angle paths that propagate sound throughout the ocean basin with relatively low loss.[7–9] Thus, the noise observed at deep ocean sites is generated by distant ships entering and leaving major ports along the coast. In the Northeast Pacific, another effective source of sound in the sound channel is due to ships at high latitudes. The shipping lanes between Asia and North America follow great circle routes that pass through high northern latitudes where the axis of the sound channel is relatively shallow. The sound from surface ships is coupled efficiently into the sound channel at the high latitude portions of the great circle routes. Bannister[10] has suggested that low frequency sound generated at the surface by wind is also efficiently converted into the shallow sound channel at high latitudes, so both types of sources may contribute to the low-angle noise pedestal by this mechanism. However, it is also possible that the high latitude wind noise and the surf noise generated by breaking waves at the Aleutian Island chain are coupled into the sound channel by downslope conversion along the Island chain.

Horizontal directionality of the noise at each site was determined over the band between 30 and 250 Hz using the horizontal planar array. The data were processed to obtain superdirective cardioid beams from first order pressure gradients between pairs of hydrophones on opposite sides of the array. Directionality for the 1/3 octave band at 31 Hz is shown in Fig. 2. The 1978 data show highest intensity toward the east and northwest. The eastern direction is consistent with the expected source of deep ocean shipping noise due to downslope conversion at continental margins off the west coast ports of North America (San Francisco, Los Angeles, Vancouver/Seattle). The northwest direction points toward the Aleutian Islands where sound from ships traversing the northern great circle route would be coupled efficiently into the sound channel. For the 1980 site which is $\sim 5^\circ$ farther north, the highest sensitivity is toward the northwest for all the 1/3 octave bands from 31 to 250 Hz, consistent with conversion from high latitude sources. This observation may be explained by the Bannister model related to the efficient conversion of distant shipping or wind noise at high latitudes.[10] However, it may also be explained by downslope conversion of broadband noise generated by surf along the coasts of the Aleutian Island chain.

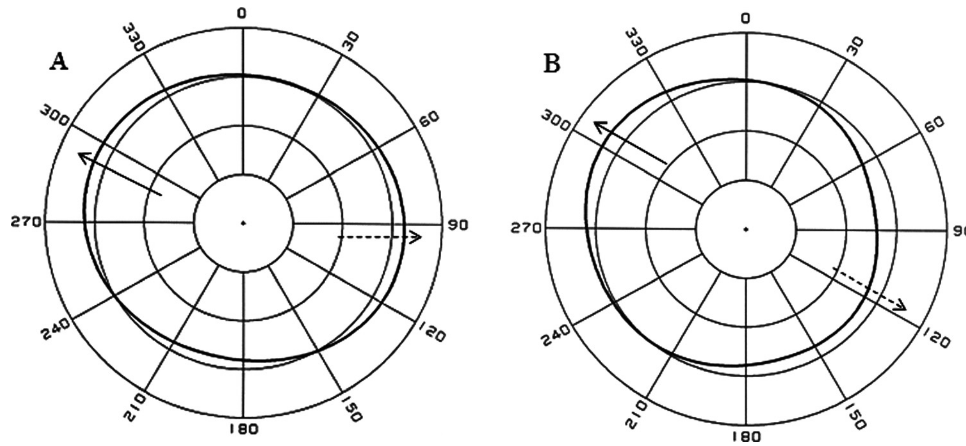

Fig. 2. Horizontal directionality for 1/3 octave band noise data at 31 Hz: (a) 1978 data and (b) 1980 data. The center of each scale is 75 dB re 1 $\mu Pa^2/Hz$ and each ring increased by 5 dB. The solid line in each panel points to the high latitude noise sources and the broken line to the west coast noise sources from each site.

5. Summary and conclusions

Ambient noise data from deep water sites in the Northeast Pacific Ocean between 1978 and 1986 provide new information about the shipping noise level increase in the latter part of the 20th century. The measurement system, a combined vertical line and horizontal planar hydrophone array, was fully calibrated. Although the data set is limited, the statistical variation of the noise at each of the two main sites is similar, and the results from the experiments are representative of distant shipping noise. The data indicate that the trend of 0.55 dB/yr predicted by Ross[1,2] persisted until at least around 1980. Afterward, the increase per year was significantly less, about 0.2 dB/yr.

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