Low-frequency ambient sound in the North Pacific: Long time series observations

Keith R. Curtis, Bruce M. Howe, and James A. Mercer

Applied Physics Laboratory, College of Ocean and Fishery Sciences, University of Washington, Seattle, Washington 98105

(Received 27 May 1998; revised 28 May 1999; accepted 8 July 1999)

Long-term statistics of ambient sound in an ocean basin have been derived from 2 years of data collected on 13 widely distributed receivers in the North Pacific. The data consist of single hydrophone spectra (1–500 Hz in 1-Hz bands) averaged over 170 s and recorded at 5-min intervals. Cumulative probability distributions of the ambient sound level show that for the open-ocean arrays at 75 Hz, sound levels are 3 dB higher than the median level 10% of the time and 6 dB higher 1% of the time. For the coastal arrays, sound levels are 7 dB higher than the median level 10% of the time and 15 dB higher 1% of the time. The clearest feature in many of the spectrograms is a strong annual cycle in the 15–22 Hz band with peak signal levels up to 25 dB above the sound floor; this cycle is attributed to the presence and migration of blue and fin whales. On average, whales are detected 43% of the time. Ships are heard 31%–85% of the time on the coastal receivers and 19%–87% of the time on the open-ocean receivers, depending on the receiver. On average, ships are detected 55% of the time. The correlation coefficient between the sound level in the 200–400 Hz band and wind speed, determined from satellite and global meteorological analysis, is on average 0.56 for the coastal receivers and 0.79 for the open-ocean receivers. For some receivers, the sound level in the 12–15 Hz band is correlated with the sound level in the 200–400 Hz band, with a correlation coefficient of 0.5.

PACS numbers: 43.30.Nb, 43.30.Pc [DLB]

INTRODUCTION

Understanding the variability of ambient sound in the ocean is essential for investigating air–sea interface processes, such as wind, rainfall, snowfall, and breaking waves,1–4 as well as for monitoring submarine seismic events and ship traffic.5–7 Understanding ambient sound variability is necessary for many naval applications. The effect of ambient and anthropogenic sound, e.g., shipping traffic, on marine animals has recently been of concern.

Ambient sound has traditionally been characterized by short-term sound measurements at many locations.8–10 The goal of the present study is to use long time series of ambient sound at fixed locations to extend our understanding of the variability of the sound field and the causes thereof.

In the frequency band 5–500 Hz, the most common sources of sound are seismic events, whales, ships, and wind-generated breaking waves. Blue and fin whales vocalize primarily in the range 15–35 Hz,11 only the lower-frequency (15–35 Hz) sounds are addressed here. The most distinctive characteristic of ship-generated sound is the acoustic energy from propeller cavitation at blade-rate harmonics (the fundamental frequency is typically around 8 Hz); additional energy, both broadband and tonal, is produced by machinery and shaft rotation. The sound from breaking waves covers a wide band (at least 0.1–20 kHz), but the peak frequency ranges from 200 Hz to 2000 Hz, depending on the type of breaking wave.14 It has been shown that the sound level in the range 200–500 Hz is primarily a function of wind speed and correlates well with the energy dissipated by breaking waves.15,3,16 Sound level is not related to wave height,17 probably because nonbreaking waves contribute to the wave-height estimate. If swell is removed from the wave-height estimate, then the correlation of sound level with wave height increases significantly.17

Most observations of low-frequency ambient sound have been sparse and isolated in time and space. Exceptions are a 1-year time series (0.4–30 Hz) from hydrophones near Wake Island,18 a 3-year time series of sonobuoy data (at frequencies of 50, 100, 200, 440, 1000, and 1700 Hz),19 and a 2–3-year study (10–400 Hz) that used several of the same receivers used here (the last data, taken by Wenz20 in 1963–1966, have only recently become available to the general public). Another relevant observation where the results of acoustic modeling of the meteorological conditions were correlated with the ambient sound is a 1-year time series (at 200–300 Hz) from the Greenland Sea.21

The work reported here is a component of the Acoustic Thermometry of Ocean Climate (ATOC) project.22 Concern that the acoustic signals used for measuring ocean temperature change might adversely affect marine mammals led to obvious questions such as, what fraction of the time does the ambient sound level exceed a given level, and how does the ATOC signal level compare with ambient sound levels, levels that were known (in an almost anecdotal fashion) to fluctuate significantly depending on time and location? The original motivation for the present work is that the data needed to answer these simple questions did not exist or were not available. The ambient sound time series reported here may also be used to address other related questions about shipping and marine mammal behavior.

This paper is organized as follows. A brief description
I. DATA ACQUISITION AND PROCESSING

Time series of ambient sound spectra have been collected using 13 distributed receivers, including U.S. Navy Sound Surveillance (SOSUS) arrays in the North Pacific (Fig. 1 and Table I). The measurement equipment at each site consists of two systems, the receiver (hydrophones, cable, and amplifier) and a signal-conditioning/data-acquisition system installed by the Applied Physics Laboratory, University of Washington, as part of ATOC.22

The spectra have been corrected for the frequency response of the receiver using terminal sensitivity curves provided by the U.S. Navy. With one exception, no recent calibrations of the receiver systems exist. A calibration from 1 to 200 Hz of receiver d (Ref. 23) compares well with the original calibration. However, the measured absolute sound levels are obviously in error for many of the receivers. Therefore, all the spectra are plotted on a relative scale, where the median level at 75 Hz is arbitrarily shifted to 0 dB (i.e., the units are dB re: median level at 75 Hz). When comparisons are made, residuals of the spectrum are used, by either subtracting out a median/mean level or removing a sound floor (as will be discussed in Sec. II).

The response of the receivers is given by the terminal sensitivity as a function of frequency. Signals are band-passed filtered between 2 Hz and 500 Hz, where the high-pass filter is due to ac coupling and the low-pass filter consists of a set of two filters. The first is a two-pole Butterworth filter with the −3-dB point at 1000 Hz; the second is another two-pole Butterworth filter with the −3-dB point at 500 Hz. Signal amplification and analog-to-digital conversion are independent of frequency from 5 to 1000 Hz.

At 5-min intervals, 170 s of data are sampled at 2000 points per second from three hydrophones. Each sound sample, or record, is subdivided into 10 groups of 32 768 samples, for a total length of 163.84 s. Power spectra for each group are ensemble averaged and smoothed over 1-Hz bins from 0 to 500 Hz. The resulting 501-point spectrum is saved, and the original sound sample is discarded. Only data from a single hydrophone on each receiver are discussed here (in this context there is little difference between the data collected from the three hydrophones on a particular receiver). Outliers occur when hydrophones fail or when 60-Hz signals are present; the affected spectra are discarded. Large gaps occur in the time series because of equipment malfunctions on site or damage to the submarine cables connecting the hydrophones to shore. Small gaps occur during ATOC receptions and system administration tasks.

II. OBSERVATIONS—GENERAL OVERVIEW

One of the simplest ways to quantify variability is with a probability density function (PDF) and its integral, the cumulative probability distribution function (CPDF). The CPDF of 1-Hz-wide spectral levels (in decibels) for the data collected here was computed for the frequency range 5–500 Hz. The results for receiver d are given in Fig. 2. The curves...
show the sound levels that are exceeded a certain fraction of time as a function of frequency relative to the median level at 75 Hz. The measured median levels at 75 Hz for receivers $j, k, l, m,$ and $n$ are 81.2, 80.5, 80.2, 82.6, and 83.7 dB, which are within a reasonable range of values for ocean ambient sound. The measured median levels for the other receivers differ from these by more than 10 dB and are considered unrealistic. The CPDFs for all the receivers are shown in Fig. 3. The “whale” peak near 17 Hz is evident even in the median curve; such a peak indicates that the sound level at 17 Hz is greater than the levels at other frequencies for the same percentage of time. The relative increase in spectral level in the 30–100 Hz band reflects the ubiquity of ship sounds. The skewness of the probability distribution varies with frequency. For the lower frequencies, the distribution is positively skewed, similar to a Rayleigh distribution. For the higher frequencies, the distribution is almost symmetrical.

The spectra for coastal receivers $e - l$ have a peak at about 350 Hz (Fig. 3) which has a level similar to the band where ship sound is dominate, i.e., 30–100 Hz. Receiver $d$ is also near the coast but shows no peak of similar strength. Interestingly, ambient sound spectra measured by Wenz more than 30 years previously, using some of the same coastal receivers as used in this study, show that the ship sound peak near 50 Hz was about 10 dB higher than the level at 300 Hz. Also sound due to ship traffic has increased on the long term. At this time we do not have an explanation for the anomalous strength of the peaks at 350 Hz in the spectra for receivers $e - l$.

Since our primary concern is the variability in sound level with time, we first subtracted the “sound floor” (the site-dependent, frequency-dependent threshold that is exceeded 99% of the time) to make this variation clearer. When looking at the resulting spectrogram for receiver $o$ (Fig. 4), the eye is first drawn to the feature at 15–22 Hz that has an annual cycle with a peak-to-peak amplitude of approximately 25 dB. This feature is attributed to the vocalizations of fin whales. The ridge is very clear and peaks roughly at 17 Hz. Although this feature covers 7 Hz, the signal is loudest at roughly 17 Hz. The variation in bandwidth is most likely due to the nature of the different whale calls. In spectrograms for receivers $d, e,$ and $f$, harmonics of 17 Hz can also be seen which are characteristic of blue whales. The lack of harmonics at receiver $o$ [Fig. 4(bottom)] suggests that only fin whales are vocalizing near this receiver. It is not known if these vocalizations are from many whales, a few whales vocalizing nearly continuously, or some combination thereof. Calls of other whale species are not prominent in these data, and no work has yet been done on identifying signatures of other species.

Another noticeable feature in Fig. 4 is intermittent periods of increased sound level that are highly correlated over 200–500 Hz and have time scales of 1 day. These high sound levels are caused by high winds associated with storms. To obtain a different perspective on the variability of ambient sound, we also computed the covariance matrix, $C = C(f_1, f_2)$, which gives the covariance of the spectral levels at frequencies $f_1$ and $f_2$. For receiver $k$ [Fig. 5(top)], the variance at 200–500 Hz is highly correlated over the whole band (correlation coefficient $>0.8$) and is also correlated with the energy in the 12–15 Hz band (correlation coefficient 0.6). It has been suggested that this low-frequency component is associated with distant wind events; using data from hydrophones near Wake Island, McCreery et al. obtained correlation coefficients of 0.66 and 0.7 between wind speed and the sound levels at 10–12 Hz and 12–14 Hz. While shipping noise is not very evident in the record for receiver $k$, the whale component at 17 Hz is clear, with no correlation with other frequencies. In contrast, the covariance for receiver $i$ [Fig. 5(bottom)] is largely dominated by shipping, with the fundamental frequency (9 Hz), the higher harmonics, and the wide-band noise quite evident.

In the high-temporal-resolution spectrograms, the presence of tonals at ship blade rates shows up as bright lines, typically at the lower harmonics (8 Hz, 16 Hz, 24 Hz, etc.). The lines are too intermittent to show up in the long-term averaged spectrograms because the duration of a ship event is typically about an hour. In high-resolution spectrograms, one can see a correlation between the ship tonals and the broadband sound associated with them.

In the last few years there has been considerable interest in the effect of manmade sounds on marine mammals. One of the original motivations for this study was to compare the ATOC signal with ambient sound. ATOC signals are broad-
band \( m \)-sequences\(^{28} \) with a center frequency of 75 Hz, a bandwidth of 37.5 Hz, and a source level of 260 W, or 195 dB re: 1 \( \mu \)Pa at 1 m. The range from the ATOC source on Pioneer seamount to receiver \( d \) is 148 km. Measurements of the ATOC signal at receiver \( d \) show that the ambient sound at receiver \( d \) is louder than the ATOC signal about 8\% of the time, or 120 min per day (Fig. 6). For the particular spectrum shown, shipping and possibly fin or blue whale harmonics dominate the spectrum. At a range of 34 km (18 nautical miles) from the source, the ambient sound level would be greater than or equal to the ATOC signal level 2\% of the time (assuming cylindrical spreading and the same ambient sound statistics as along the path between the source and receiver \( d \)). For an average ATOC source duty cycle of 2\%, or 30 min per day, the ATOC signal level is not anomalous (i.e., higher than the range of ambient sound levels) until the range to the ATOC source is less than 34 km.

In the following sections, we discuss the statistics of ambient sound due to whales, ships, and wind in more detail.

### III. WHALE AND SHIPPING SOUND

Fin whales produce series of pulses which, after averaging, show as a peak in the spectrum at 15–22 Hz.\(^{29} \) Blue whales produce long patterned sequences of a part A (amplitude modulated series of pulse) and a part B (downsweep with strong harmonics) signal.\(^{30–34} \) This is evident as a peak at 15–22 Hz, as well as harmonics at 34, 51, and 68 Hz which can be quite visible in a spectrogram. Figure 7 shows receptions at 17 Hz, which was used to represent whale vocalizations. Some receivers \( (n,o,p) \) show large changes with time, of the order of 25 dB peak to peak, while others \( (g,h,i) \) show little or no changes. The northern coastal receivers \( (h \text{ and } i) \) show a small seasonal variation at 17 Hz.
Although not shown, only the coastal receivers off California (d,e,f) show evidence (i.e., harmonics) of a strong blue whale signature.

Preliminary work has been done on classifying spectra based on the presence of whale and shipping sound. In an experiment run on the Stuttgart Neural Network simulator,\textsuperscript{35} we trained a simple neural network to classify whether whale or ship sound was present in a spectrum. The experiment utilized a two-layer feed-forward neural network with an input layer consisting of normalized spectral levels from 5 to 104 Hz in 1-Hz increments. The average spectral level was removed, and the input values were then normalized with the peak value before being used. The training data were selected subjectively; spectra were identified by eye as to whether ship or whale (blue and/or fin) signatures were present or absent. Sample spectra were collected from the data sets for each receiver and then combined to form the training and validation sets. The network correctly classified 92\% of the spectra used in training and 90\% of the validation spectra that were held in reserve for evaluating the performance of the network (Fig. 8). The neural network produces a continuous measure of detection, $0 < D < 1$, with a 0 being a perfect nondetection and a 1 being a perfect detection. We take $D = 0.5$ to indicate a detection.

Because the training and validation data were selected by eye, it is quite possible that the subjective classifications were not always correct. An attempt was therefore made to avoid overfitting the network, i.e., to accept a less than perfect performance on the training data. By avoiding overfitting, it was hoped that the neural network would generalize to other spectra that it was not trained on.\textsuperscript{36} As can be seen in Fig. 8, the resulting network can detect whether a spectrum contains ship or whale components.

Figure 9 shows the neural network response when clasi-
sifying whale receptions at receivers e and p. Receiver e shows a definite seasonal signal [Fig. 9(top)]. The “whale season” starts quite abruptly in mid-July and ends in January. For receiver p, the whale season starts in late August and ends in March [Fig. 9(bottom)]. Surprisingly, there appear to be more ship detections for receiver p, an open-ocean receiver, than for receiver e, a coastal receiver. Receiver p is near the United States–Far East shipping lane, whereas receiver e is seaward of San Nicolas Island and may be shielded from shipping lanes by local bathymetry.20

The whale detections have a distinct bimodal appearance: in most cases, the algorithm is sure that whale vocalizations are or are not present [Fig. 10(a)]. In general, the whale season starts in the summer and ends in the winter; in most cases, the beginning and end are distinct events. On average, whales are detected 43% of the time (Table II). The average increase in level at 17 Hz varies from 2 dB at receiver g to 9 dB at receiver o.

The variation in the network’s response is much more continuous for ship detections [Fig. 10(b)]. Perhaps this is not so surprising given the wider variety of ships compared to whales. On average, ships are detected 55% of the time; this varies from a low of 18% for receiver o to a high of 87% for j. As with receiver p, receiver j is probably hearing the shipping going between the United States and the Far East, whereas receiver o is an open-ocean receiver between California and Hawaii where little ship traffic is expected. A seasonal cycle may be present for receivers n and o [Fig. 10(b)].

IV. WIND SOUND

In Fig. 4 the sound due to high wind is evident as events several days long in the frequency range of 150–500 Hz. Since the wind speeds above the receivers vary seasonally, this suggests that the ambient sound level would also vary seasonally. A seasonal cycle is found in sonobuoy data (of the order of 10 dB peak to peak)19 and in the earlier work of
Wenz (5 dB peak to peak on some receivers). However, a seasonal cycle is not evident in the data for most of the receivers (exceptions may be \( n \) and \( p \)), possibly because of sizable gaps in the time series.

In the following subsections we first describe a very simple model to predict the sound level due to wind. This model integrates the effect of the wind over the ocean surface. The variations of the model-predicted sound level are compared to the variations of the observed sound level in the 200–400 Hz band. We also compare the variation in sound level measurements in the 200–400 Hz band with independent estimates of wind speed.

A. Zeroth-order model

In the zeroth-order approximation, sound propagates in a straight line from a source on the surface to a receiver in the water. Thus any surface sound source, such as breaking waves, contributes to the signal received at a hydrophone located on the ocean floor. As the distance from the hydrophone increases, the signal received from any single source decreases, but the area of possible contributing sources increases. Because of chemical absorption of sound, there is a range at which the presence or absence of sources ceases to be significant. We consider this range the effective listening radius (see the Appendix).

The effective listening radius imposed by absorption is an upper bound, as the sound also undergoes attenuation due to scattering by internal and surface waves. This upper bound could be used to truncate numerical integration in ocean acoustic propagation models. Thorp’s expression for the attenuation coefficient gives the effective listening radii for frequencies of 200 Hz and 400 Hz as 1650 km and 650 km, respectively (Fig. 11).

Because significant energy is contributed from sources at long ranges (until the energy is attenuated by chemical absorption), such sources should be considered when predicting the received level \( I_r \). If sources with intensity \( I_i \) are specified on a grid, then a crude estimate of the intensity at a receiver is
where $\alpha_i$ is the attenuation due to spreading and absorption along a path connecting the receiver and grid point $i$. If the $I_i$ values are known from a specified distribution of wind speed, then this method should be superior to simply using the intensity predicted from the wind speed above the receiver to obtain $I_r$.

\[ I_r = \sum_i \alpha_i I_i, \quad (1) \]

B. Long-term comparisons: SSM/I winds and NCEP winds

Wind fields have been obtained using data from two or three satellites equipped with Special Sensor Microwave Imagers (SSM/I$s$) and from a reanalysis project at the National Center for Environmental Prediction (NCEP) (where data gathered over the past few decades have been reanalyzed using one consistent methodology). The wind speeds determined from the SSM/I data cover a 50-km-wide swath and are available twice a day, but values are not available for pixels where there is rainfall. The satellite orbit is sun-
synchronous with a period of 102 min. The SSM/I data files were processed using the Wentz algorithm \(^{38}\) and formatted into quarter-degree pixels (courtesy of Remote Sensing Systems).

The NCEP wind data have a 12-h time step and are formatted into approximately \(1°\) pixels. Unlike the SSM/I wind data, the NCEP data do not contain pixels with missing data. The NCEP data were thus easier to use, but in order to ensure that the same time scales were being compared, the acoustic data were low-passed filtered (over 12 h) before being compared with the NCEP data. The NCEP analysis does not include SSM/I data.

The observed sound levels, integrated over the band 200–400 Hz, were compared with the different wind products in two ways: The sound levels measured at each receiver were compared with wind estimates derived from the overhead pixel, and with the levels predicted when using a simple model incorporating the SSM/I or NCEP wind estimates. The correlations between the observed sound levels and the NCEP winds estimated from the overhead pixels are generally the same as the corresponding correlations for the SSM/I winds (Table III). There is slightly more scatter in the relationship between NCEP wind speed versus sound level than in SSM/I wind speed versus sound level. For each receiver, correlations were computed for when the wind speeds were greater than 5 m/s and when they were less than 5 m/s. In general, the time series of wind speed in the overhead pixel of any receiver correlated well with the integrated sound level in the band 200–400 Hz (Fig. 12).

Figure 13 shows the relation between the sound level and the logarithm of the wind speed estimated from the SSM/I data. There is a clear difference in the slope of the relation for wind speeds less than 5 m/s and for wind speeds over 5 m/s. Below 5 m/s there is little if any correlation. For the SSM/I data, receivers \(h\), \(i\), \(j\), \(k\), \(l\), and \(m\) had correlations less than 0.1 at low wind speeds (see Table III). Receivers \(e\) and \(p\) had the highest correlations at low wind speeds, 0.3 and 0.4, respectively. This suggests that for low wind speeds and frequencies of 200–400 Hz the source level could be considered a constant or at least unrelated to wind speed.

Above 5 m/s, receivers \(d\), \(g\), \(h\), and \(i\) had low correlations with the SSM/I winds, less than or equal to 0.5; the balance of the receivers had correlations between 0.6 and 0.8. The correlations reached the 0.8 level for receivers \(k\), \(l\), \(m\), \(n\), and \(p\). Using NCEP data, all the receivers except \(d\), \(h\), and \(i\) have correlations in the range 0.6–0.8.

Some of the overhead comparisons with SSM/I data are poor, specifically \(d\), \(g\), \(h\), and \(i\). Those receivers are near land, and the presence of nearby land is likely contaminating the SSM/I wind estimate. The NCEP winds at the land/sea boundary have larger errors also. For receiver \(d\), the number of SSM/I data points is small, and that would limit the correlation as well.

When running the simple model to predict the received sound level due to wind distributed over the ocean surface, we used SSM/I pixels within 1000 km of a receiver to find wind speeds at several time periods during a day. The wind speeds were then averaged over all data available for that day for a particular pixel to produce a daily average for that pixel. Using the Chapman and Cornish\(^{15}\) relationship \((NL = B + 20\gamma \log \nu\) where \(NL\) is the sound level, \(\nu\) is the wind speed, and the other parameters \((\gamma, B)\) are determined em-

### Table III. Correlations of SSM/I and NCEP winds with observed sound levels.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>SSM/I</th>
<th></th>
<th></th>
<th>NCEP</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;5 m/s</td>
<td>&gt;5 m/s</td>
<td>+Model</td>
<td>&lt;5 m/s</td>
<td>&gt;5 m/s</td>
<td>+Model</td>
</tr>
<tr>
<td>(d)</td>
<td>0.11</td>
<td>0.34</td>
<td>0.29</td>
<td>0.01</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>(e)</td>
<td>0.30</td>
<td>0.61</td>
<td>0.72</td>
<td>0.35</td>
<td>0.62</td>
<td>0.73</td>
</tr>
<tr>
<td>(f)</td>
<td>0.23</td>
<td>0.63</td>
<td>0.68</td>
<td>0.40</td>
<td>0.64</td>
<td>0.72</td>
</tr>
<tr>
<td>(g)</td>
<td>0.25</td>
<td>0.49</td>
<td>0.49</td>
<td>0.06</td>
<td>0.71</td>
<td>0.65</td>
</tr>
<tr>
<td>(h)</td>
<td>-0.02</td>
<td>0.42</td>
<td>0.41</td>
<td>0.08</td>
<td>0.53</td>
<td>0.49</td>
</tr>
<tr>
<td>(i)</td>
<td>0.07</td>
<td>0.39</td>
<td>0.46</td>
<td>0.21</td>
<td>0.48</td>
<td>0.49</td>
</tr>
<tr>
<td>(j)</td>
<td>0.05</td>
<td>0.72</td>
<td>0.65</td>
<td>0.09</td>
<td>0.69</td>
<td>0.75</td>
</tr>
<tr>
<td>(k)</td>
<td>-0.01</td>
<td>0.82</td>
<td>0.66</td>
<td>-0.01</td>
<td>0.74</td>
<td>0.82</td>
</tr>
<tr>
<td>(l)</td>
<td>-0.06</td>
<td>0.82</td>
<td>0.60</td>
<td>0.05</td>
<td>0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>(m)</td>
<td>0.07</td>
<td>0.84</td>
<td>0.60</td>
<td>0.05</td>
<td>0.71</td>
<td>0.75</td>
</tr>
<tr>
<td>(n)</td>
<td>0.15</td>
<td>0.79</td>
<td>0.73</td>
<td>0.20</td>
<td>0.83</td>
<td>0.86</td>
</tr>
<tr>
<td>(o)</td>
<td>0.18</td>
<td>0.73</td>
<td>0.69</td>
<td>0.25</td>
<td>0.66</td>
<td>0.79</td>
</tr>
<tr>
<td>(p)</td>
<td>0.38</td>
<td>0.83</td>
<td>0.72</td>
<td>0.20</td>
<td>0.75</td>
<td>0.84</td>
</tr>
<tr>
<td>all</td>
<td>0.65</td>
<td>0.59</td>
<td>0.69</td>
<td>0.65</td>
<td>0.65</td>
<td>0.69</td>
</tr>
</tbody>
</table>
between wind speed and sound source level, we converted the daily averaged wind speed field to a sound intensity field and calculated the sound level at a receiver from Eq. (1). The time series of observed sound levels were low-passed filtered (1 day for SSM/I and 12 h for NCEP) and compared with the levels predicted from the SSM/I and NCEP wind fields. Numerical results are given in Table III, and the results for the NCEP winds and receiver \( p \) are shown in Fig. 14. The NCEP/model values correlate slightly better than the NCEP wind speeds in the overhead pixel with the observed levels; the average correlations are 0.69 and 0.65, respectively. However, the reverse is true for the corresponding SSM/I comparisons, with wind speed in the overhead pixel being correlated slightly better than the SMM/I model values; the average correlations are 0.65 and 0.59, respectively.

For all the receivers, the model predictions when using the NCEP wind fields are better than the corresponding SSM/I predictions. The model predictions when using the NCEP winds had better correlations than the predictions when using the SSM/I winds for receivers \( e, f, i, j, n, o, \) and \( p \), sometimes as much as 0.1 better. In some cases, though, the model/NCEP correlation was less than that for the other receivers, as much as 0.1 less.

According to the model, almost all the sound is from distant and not overhead sources. In fact, the depth of the receiver is almost irrelevant, as the ratio of the energy received from sources within 12 km (one SSM/I pixel) to the energy received from sources beyond 12 km is about 1:25 irrespective of any reasonable receiver depth. If the local sound sources were in-phase and the distant sources were out-of-phase, then the local sources might dominate the measured sound level. The correlations for the overhead data and for the model data are similar; this probably indicates that the correlation length of the wind field is large.

It is conceivable that high-frequency noise associated with shipping might affect the correlation estimates. Using the neural network described earlier, we removed the spectra in which shipping sound was detected \( (D > 0.5) \) from the wind data set before correlating the measured data sound levels with the SSM/I wind time series in the pixel above the receiver. For receivers \( j, k, \) and \( l \), the presence of shipping was so high that the amount of data available for the correlation estimate was significantly reduced, and the correlation between the observed level and the SSM/I wind was smaller. Otherwise, the presence or absence of spectra with shipping noise did not affect the correlation between the observed sound level and wind speed.

V. DISCUSSION AND CONCLUSIONS

In this paper we have investigated the long-term statistics of whale, shipping, and wind-generated sound in the North Pacific Ocean using data from many geographically distributed, fixed receivers. The CPDFs that are now available are powerful reference data for designing acoustic experiments.

The whale component of ocean ambient sound is now becoming more fully appreciated as one of the major sources of sound in the ocean. The fact that, on average, it is detected in 43% of the time in the receiver spectra (the range is 18%–59%, depending on the receiver) indicates its ubiquity. On some receivers the annual variation in level can be as much as 25 dB; on average, the difference is 2–9 dB. The distinct seasonality of the signal suggests questions such as, where are the whales during the quiet times (March–July)? Are they simply not vocalizing? The latter strikes an incongruous chord given their apparent social character. Ideally, there would be a global network of acoustic sensors to monitor migration patterns and to determine whether effects such as El Niño perturb the migrations.

If the sound of whales is ubiquitous, the sound of ships is even more so. On average, ships are detected in 55% of the time in the spectra (the range is 18%–87%, depending on the receiver). The levels of ship sounds received on single hydrophones are typically 10 dB above the background level [Fig. 8(a)], but the levels cover a wide range (Fig. 3).

The wind analysis given here is a large-scale comparison between global-scale wind products (satellite data and meteorological analyses) and measured acoustic sound levels. The analysis indicates that the forward problem of predicting the sound level at a receiver is working reasonably well. In fact, we consider the average correlation of 0.69 between the measured sound levels and the NCEP model results to be quite good. The NCEP product has no formal error bars associated with it, but errors of 1–2 m/s are expected over the open ocean and even larger errors are expected near the coast, especially since so few direct oceanic wind measurements are assimilated into the NCEP meteorological model. Also, the estimated errors for SSM/I winds are 1 m/s and are probably larger near the coast. The average NCEP model correlations are 0.56 for the coastal receivers and 0.79 for the open-ocean receivers.

A natural next step in this analysis will be to use a more sophisticated acoustic propagation model that includes frequency dependence to see if the results are affected. Furthermore it would be worthwhile to compare the ambient sound levels with a modeled surface wavefield as has been done previously with good results.\(^2^1\)
The formula given in Eq. (1) for estimating the received intensity given the distribution of noise sources suggests that it could be inverted to obtain the surface intensity if there were a sufficient number of data points to make the problem "well" determined. We are investigating using beam data from each receiver as one possible way of obtaining sufficient data to reconstruct the distribution of the surface sound field. The distribution of vocalizing whales and shipping could be more successfully determined using the above scheme because of the lower attenuation at lower frequencies.

At the receiver closest to the ATOC source (receiver d, 148 km away), the ambient sound is louder than the ATOC signal, on average, 2 h per day; the ambient sound and the ATOC signal would be of comparable magnitude only at ranges less than 34 km from the transmitter. It is clear that ship sound is a major source of sound in the band 15–100 Hz, and yet the cumulative effect of years of such sound on marine life is unknown.

A failing of the present data set is the lack of absolute calibration of the system. Performing a direct calibration is costly and difficult. It may be worthwhile to investigate the use of the "Holus Spectrum" between 0.4 and 6 Hz to set the absolute level. However, additional questions would still remain; for instance, is the "hump" at 350 Hz shown in Fig. 3 for most of the coastal receivers real or an artifact of the present measurement system? The average spectral curves plotted by Wenz20 start to increase with frequency at 200 Hz, not at 100 Hz as we observe, and show no abrupt peaks at 350 Hz such as we observe.

We did not address ambient sound of seismic origin here, as the data collected consist of average spectra which do not show the details of the typical low-frequency, transient seismic signal. Seismic signals in the ocean have been treated by other researchers.5,6 It is clear that in the future, as we try to split the spectrum further into its components, transient signals, seismic, and others, as well as signals from other whale species, will have to be included in the analysis.

Currently we do not have an explanation for the 12-Hz wind signal observed at receiver k. This is an area for investigation by future research.

With the present data it is difficult to extrapolate results away from the the point receivers. We expect that by using data from beamforming arrays, we will be able to improve our spatial resolution and perhaps even attempt to invert Eq. (1) to obtain the geographic distribution of sound sources. In this context, the 12-Hz wind signal and the 17-Hz whale vocalizations will play a role.

ACKNOWLEDGMENTS

We appreciate the help of the many people who contributed to the collection of these data, including S. Leach, D. Reddaway, and S. Weslander, APL-UW; K. Metzger, University of Michigan; C. Miller, Naval Post-graduate School; J. Peeples, RPI; and the staff at the Whidbey Island Naval Facility. Helpful discussions with C. Clark, K. Fristrup, A. Frankel, and D. Mellinger of Cornell University and J. Calambokidis of Cascadia Research are gratefully acknowledged. C. Clark, B. Dushaw, and three anonymous reviewers provided helpful comments that lead to improvements of this manuscript. This work is supported by the Acoustic Thermometry of Ocean Climate program sponsored by the Strategic Environmental Research and Development Program (SERDP) through the Advanced Research Projects Agency, and by the Ocean Acoustics Program of the Office of Naval Research.

APPENDIX

Consider a very simplified ocean (no convergence zones, etc.), where the intensity per unit surface area is I0 and a signal is attenuated by two possible mechanisms: loss due to spreading (spherical or cylindrical) and loss due to absorption. Although representing the surface sources as dipoles is more realistic and is necessary for a hydrophone near the surface,16 for simplicity we will ignore the ray angle from the source to the hydrophone and consider the surface sources to be monopoles. If we represent the loss mechanism as spherical spreading out to some transition radius rT and as cylindrical spreading for greater radii, the expression I, for the intensity received at the hydrophone is

\[ I_r = I_0 \int_{0}^{2\pi} \int_{d}^{\infty} \frac{\exp(-\alpha s)}{2s} ds \ d\theta \]

where \( \alpha = (r_T^2 + d^2)^{-1/2} \), s is the slant range \( (s^2 = r^2 + d^2) \), and \( \alpha \) is the chemical absorption at the frequency \( f \) of interest.

The solution is then

\[ I_r(R,f) = 2 \pi I_0 \left[ \ln(\alpha s) + \sum_{k=1}^{\infty} \left( \frac{-\alpha s}{k \cdot k!} \right)^{1/2} \right]_{d}^{\infty} \]

\[ + \frac{a}{2} \left[ \frac{\exp(-\alpha s)}{\alpha^{1/2}} \right]_{(r_T^2 + d^2)^{1/2}} \]

As the first term is a constant, the second term shows that \( I_r(R,f) \) has a limit as \( R \to \infty \). Thus it is possible to define an effective listen radius \( R_e \) such that \( I_r(R_e,f) = 0.95 I_0(\infty,f) \).


27 Christopher Clark, personal communication (1997).
33 Christopher Clark, personal communication (1998).