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# Source level of wind-generated ambient sound in the ocean[a)]

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**Abstract:** Inference of source levels for ambient ocean sound from local wind at the sea surface requires an assumption about the nature of the sound source. Depending upon the assumptions made about the nature of the sound source, whether monopole or dipole distributions, the estimated source levels from different research groups are different by several decibels over the frequency band 10–350 Hz. This paper revisits the research issues of source level of local wind-generated sound and shows that the differences in estimated source levels can be understood through a simple analysis of the source assumptions.


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## 1. Introduction

Ambient sound from local wind at the sea surface has been investigated in underwater acoustics for many decades, leading to an extensive literature of published work in several aspects of ambient noise and soundscape research.[1] The papers span research in understanding the physical sources of wind sound, in development of theoretical models for predicting the sound field, and in experimental measurements of ambient sound at sea that include recent analyses of long term data from moorings and cabled ocean observatories.[2–5] The focus here is on the latter two aspects, specifically on the assumptions made about the source of wind sound in model development and on the interpretation of ambient sound data. A survey of the many reports in the literature reveals that different authors used different approaches in defining the sound source for model development and in using the sound source assumption in analysis and interpretation of experimental data for estimating the source level of local wind sound. This has led to unintended confusion because, depending on the source assumptions, there are differences in the published estimates of source levels. This paper revisits the research issues of source level of local wind sound and shows that the differences can be understood through a simple analysis of the sound source assumptions.

Sound generated by local wind at the sea surface propagates at high angles in the ocean, and the sound intensity is strongly related to the wind speed. Models for predicting local wind-generated sound generally assume a distribution of monopole sound sources at or close beneath the sea surface or a distribution of dipoles at the sea surface. In each approach, the model requires an assumption of the monopole source depth.

It is well known that ambient sound in the ocean contains contributions from many different sound sources in addition to local winds. Moreover, the dominant component depends on frequency. Although sound generated by local wind is expected to dominate the soundscape at frequencies greater than ∼500 Hz, contributions from biological sources or even nearby ships cannot be ruled out. At frequencies between a few tens of hertz and a few hundred hertz, sound from distant ships is usually present in single hydrophone data and is generally the dominant component. Sound from baleen whales also contributes to ocean soundscapes below about 50 Hz. Measurement of local wind-generated sound is, thus, highly challenging and requires careful design of the measurement system to extract the wind component in the measured data.

Estimates of source levels of sound generated by local wind are not obtained directly but are inferred from measured data. Two approaches for deriving source levels have been described and used in the literature. One approach involves analysis of single sensor, omni-directional hydrophone data and a propagation model to account for sound propagation in the waveguide. Source levels are inferred by subtracting the calculated wave field from the propagation model

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from the experimental data. Using this approach, Kuperman and Ferla[6] reported wind sound source levels from hydrophone data from a shallow water site in the Mediterranean Sea for frequencies greater than ~400 Hz. At lower frequencies, the contributions from distant shipping could not be removed from the single hydrophone data. A similar approach using a calculated wavefield was used by Schmidt and Kuperman[7] to infer source levels at very low frequency from a bottom moored hydrophone.

A different approach involves measurements with a vertical line hydrophone array (VLA). This paper focuses on experiments that used VLAs to extract the local wind sound component from ambient ocean noise measurements. There is a distinct advantage in using a VLA, because the array response can be steered to map the vertical directionality of the acoustic field, giving the contribution to mean square sound pressure per unit frequency band per unit solid angle, henceforth abbreviated "differential power spectral density" and denoted $\left(\overline{p^2}\right)_{f,\Omega}$. The specific interest for sound generated by local wind is the vertically upward-looking direction, the upward endfire array beam, which captures the high-angle sound from sources directly above the array. With appropriate design of the array beamformer, sound leakage from lower-angle beams can be suppressed to ensure rejection of sound from interfering noise sources, such as baleen whale calls and distant ships and storms.

We revisit the work of two research groups that reported estimates of source levels of sound generated by local wind for low frequencies (less than ~350 Hz). One is the report of Burgess and Kewley[8] (BK83) and the subsequent interpretation by Kewley *et al.*[9] These authors quoted estimates of source level based on a distribution of finite dipoles created by placing a sheet of monopoles beneath the sea surface. The other report is that of Chapman and Cornish[10] (CC93), who assumed a distribution of point dipoles at the sea surface in reporting their estimates. The primary objective here is to resolve the apparent differences in the reported source levels by clarifying whether these are properties of the distribution of individual monopoles or associated dipoles.

In the following, we first provide a brief review of the two experiments and then show a simple resolution of the difference in the reported source levels. The work demonstrates the importance of understanding the sound source assumptions in using the estimated source levels.

Underwater acoustical terminology follows ISO 18405 (Ref. 11) and ADEON (Ref. 12).

## 2. VLA measurements

### *2.1 Background assumptions*

The objectives of both research groups were similar, to investigate the effect of wind speed on source level of ambient sound generated by local winds at the sea surface. For a given wind speed condition at the sea surface, the areic surface-affected source spectral density level of local wind sound, $L_{A,\mathrm{dp}}$, [henceforth abbreviated dipole source level (DSL)] at frequency $f$ was assumed to be

$$L_{A,\mathrm{dp}}(f,\theta) = L_{A,\mathrm{mp}}(f) + 10\log_{10}D(kd_s,\theta)\ \mathrm{dB}, \quad (1)$$

where $L_{A,\mathrm{mp}}$ is the areic source spectral density level [henceforth abbreviated monopole source level (MSL)], $D(kd_s,\theta)$ is the source directivity function [defined by Eq. (1)], $d_s$ is the depth of the monopole beneath the sea surface, $k$ is the acoustic wavenumber, and $\theta$ is the vertical angle. The directivity term, $D(kd_s,\pi/2)$, accounts for the contribution of the direct and sea-surface reflected components of the radiated sound in the upward-looking endfire array beam.

Source levels for various wind speed conditions were derived from measured low frequency data in the following way. Measurements of the sound generated by local wind were first obtained from the spatially filtered VLA beam data. The only variable required is the sound speed in the water for applying the beamformer. The wind source level was then inferred from the vertical endfire beam data using a propagation model for the high-angle sound paths from the sea surface in the vicinity directly above the array.

Following an established practice for interpretation of high frequency measurements, the frequency dependence was assumed independent of the wind dependence.[13] For the low frequency wind dependence, a linear relation was assumed between the local wind sound and the logarithm of wind speed at the sea surface,[14,15]

$$L_{A,\mathrm{mp}}(f) = a(f) + 10\log_{10}\left(\frac{v}{v_0}\right)^{2n(f)}\ \mathrm{dB}, \quad (2)$$

where $L_{A,\mathrm{mp}}(f)$ is the MSL, $a(f)$ and $n(f)$ are regression constants, $v$ is the wind speed at a height of 10 m, and $v_0$ is 1 m/s. Both research groups noted a regime change in wind speed behavior at speeds of about 5 m/s, corresponding roughly to the onset of breaking waves at the sea surface. Equation (2) applies to wind speeds ~5 m/s $< v <$ ~20 m/s.

### *2.2 BK83 measurements*

BK83 (Refs. 8 and 9) reports estimates of wind source levels from experiments at deep water sites in the Tasman Sea east of Australia and in the South Fiji Basin. Shipping density in these areas of the South Pacific was significantly lower than at sites in the Northern Hemisphere, so the contribution from distant ships was expected to be very low. The VLA consisted of 31 hydrophones spaced to provide 11-element arrays to span the frequency band 30–800 Hz. The array was suspended at ∼300 m near the axis of the deep sound channel. Local wind source levels, presented as MSL, were derived from analysis of data in the upward-looking and downward-looking endfire array beams. The estimated values for several wind speeds from ∼2.5 to 20 m/s are plotted vs frequency in Fig. 1. The values shown in the figure are those from the analysis of Kewley *et al.*,[9] assuming a monopole depth of one-quarter wavelength. For the higher wind speeds (>10 m/s), the frequency dependence is very weak, essentially flat over the band 30–600 Hz. However, at lower wind speeds, the frequency dependence is flat at frequencies greater than 100 Hz but rises weakly at lower frequencies. This behavior may indicate the presence of interfering noise sources that affect measurements at lower wind speeds and frequencies.[8]

Also, shown in Fig. 1 are the MSL estimates for frequencies greater than 400 Hz derived by Kewley *et al.*[9] for the shallow water Mediterranean ambient sound data of Kuperman and Ferla. These values are based on the definition of source level proposed by Schmidt and Kuperman[7] and use $d_s = 1/4$ wavelength for the monopole source depth. The revised estimates decrease with frequency above about 600 Hz but register well with the lower frequency monopole estimates from BK83 for the same wind speeds.

### 2.3 CC93 measurements

CC93 (Ref. 10) reported estimates of local wind source levels from a series of experiments carried out at several deep water sites in the Northeast Pacific from 1977 to 1986. VLAs consisting of 10 or 16 elements were deployed at ∼330 m in the deep sound channel and used separately to span the frequency band 10–350 Hz. Data were recorded only in "silent periods" when power on the research ship monitoring the array was shut down for about half an hour, and the recording system operated on batteries. A simple propagation model based on ray theory was used to describe the differential power spectral density generated by local winds, $\left(\overline{p^2}\right)_{f,\Omega}$, in the upward-looking endfire beam,

$$\left(\overline{p^2}\right)_{f,\Omega} = S_{A,\mathrm{mp}} D(kd_s, \pi/2)/(1 - V(\theta_b))\sin\theta_s, \tag{3}$$

where $S_{A,\mathrm{mp}}$ is the areic source factor spectral density, $D(kd_s, \pi/2)$ is the source directivity in the upward-looking endfire beam, $V(\theta_b)$ is the ocean bottom plane wave reflection coefficient at grazing angle $\theta_b$, and $\theta_s$ is the ray angle at the sea surface. For the upward-looking endfire beam, $\sin\theta_s \approx 1$, and $\theta_b \approx \pi/2$.[10] The model accounts for the direct path from sound sources above the array and the contributions from high-angle sea surface and bottom reflected paths. The ocean bottom reflection coefficients were obtained from independent experimental measurements of the bottom loss at each site.

The estimates of CC93 (Ref. 10) are local wind source levels, reported as DSLs, the product of the MSL and the radiation distribution. Estimated values for frequencies spanning 13–300 Hz are shown in Fig. 2 for several wind speeds. The values represent averages over independent measurements at the same wind speeds, and standard deviations are about 1 dB. For high wind speeds (>10 m/s), the estimates indicate roughly flat behavior over the frequency band between 100 and 300 Hz and are weakly increasing with frequency lower than 100 Hz. At lower wind speeds, there is a minimum around 100 Hz. The reason for this behavior is not understood. Compared to the values reported by BK83 (Refs. 8 and 9) the estimates for the same wind speeds appear to be ∼5–6 dB greater. Overall, the low frequency dependence is consistent with the behavior of wind sound level vs frequency derived by Cato.[16] Cato's curves of wind noise vs frequency include information from recent experimental work up to about 2008. They show the same relatively flat relationship below

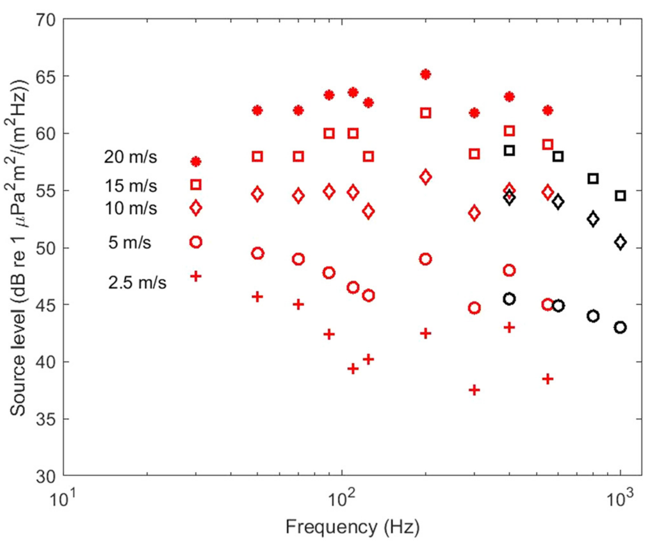


Fig. 1. MSLs vs frequency and wind speed. Red, BK83; black, Kuperman and Ferla. Plus (+), 2.6 m/s; circles, 5 m/s; diamonds, 10 m/s; squares, 15 m/s; asterisks, 20 m/s.

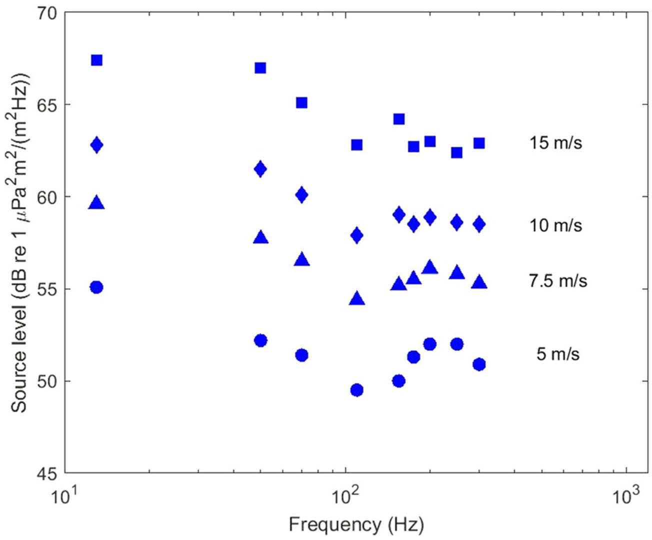


Fig. 2. CC93 DSLs vs frequency and wind speed. Circles, 5 m/s; triangles, 7.5 m/s; diamonds, 10 m/s; squares, 15 m/s.

350 Hz, with a minimum around 100 Hz for low wind speeds. At frequencies lower than ∼100 Hz, the sound level increases weakly for all wind speeds.

### 3. Comparison of monopole and DSLs

The differences between the reported values can be resolved easily by analysis of the source level assumptions. For a monopole at depth $d_s$ beneath the sea surface, the monopole source directivity $S_{A,\mathrm{mp}}$ is related to the dipole source directivity $S_{A,\mathrm{dp}}$ according to

$$S_{A,\mathrm{mp}}/S_{A,\mathrm{dp}} = D\left(kd_s, \frac{\pi}{2}\right) = 1/4\sin^2 kd_s, \tag{4}$$

where $k$ is the acoustic wavenumber. To evaluate this expression, it is convenient to average over frequency (or depth), such that

$$S_{A,\mathrm{mp}}/S_{A,\mathrm{dp}} = 1/\overline{4\sin^2 kd_s}, \tag{5}$$

where the overbar represents an average over a specified frequency band. For areic sound sources like wind (or rain), it is common to consider a sheet of monopoles placed a quarter-wavelength from the sea surface.[1] In this condition ($kd_s = \pi/2$), the source depth can be expressed in terms of the centre frequency $f_c$ of a selected frequency band,

$$d_s = \frac{c}{4f_c}, \tag{6}$$

and for the band $f_2 - f_1$, Eq. (5) can then be evaluated without approximation to give[17]

$$\frac{S_{A,\mathrm{mp}}}{2S_{A,\mathrm{dp}}} = \left(1 - \frac{\sin\frac{\pi f_2}{f_c} - \sin\frac{\pi f_1}{f_c}}{\frac{\pi f_2}{f_c} - \frac{\pi f_1}{f_c}}\right)^{-1}. \tag{7}$$

If the analysis is carried out in decidecade bands such that $f_1 = 10^{-1/20} f_c$ and $f_2 = 10^{+1/20} f_c$, the ratio of source directivities becomes

$$\frac{S_{A,\mathrm{mp}}}{S_{A,\mathrm{dp}}} \approx 0.2528. \tag{8}$$

Consequently, DSL exceeds MSL by 5.97 dB, and the MSL estimates reported by BK83 require the addition of ∼6 dB for direct comparison with the DSL estimates reported by CC93.

Figure 3 shows the comparison between the DSLs of CC93 and the BK83 estimates adjusted as DSLs assuming a decidecade frequency average as in Eq. (8). The adjusted monopole estimates of BK83 are in much closer agreement with the dipole estimates of CC93. However, the BK83 values are consistently slightly higher, and this is strongly evident for

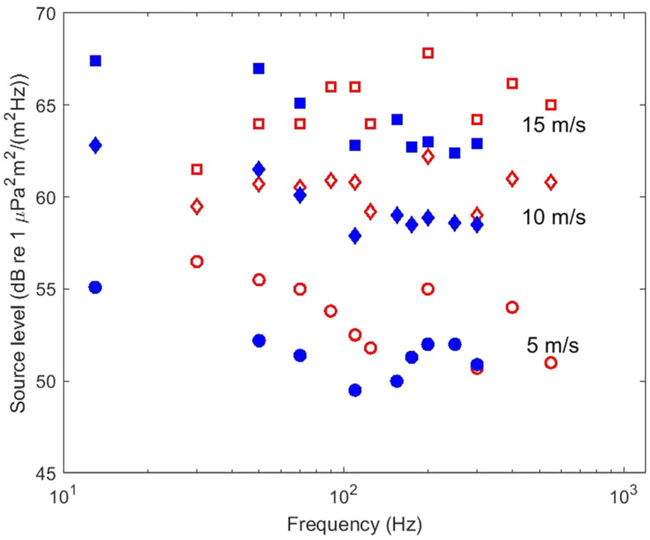


Fig. 3. Comparison of DSLs. Monopole BK83 estimates shown in red are increased by 6 dB, and dipole CC93 estimates are shown in blue. Circles, 5 m/s; diamonds, 10 m/s; squares, 15 m/s.

the lowest wind speed of 5 m/s. A plausible explanation for this discrepancy is the presence of other unaccounted for noise sources in the BK83 data.

### 4. Conclusions and discussion

Estimates of source levels of sound generated by local wind based on ambient sound data obtained with VLAs have previously been reported from experiments at deep water sites in the Southern[8,9] and Northern Hemispheres.[10] Although the reported frequency dependence of wind sound is similar over the low frequency band, there are offsets of ∼4–6 dB in the estimated source levels for wind speeds from 5 to 15 m/s. The analysis in this paper shows that the differences in the published values are due largely to the assumptions about the wind sound source used in interpreting the VLA data—whether dipole or monopole distributions. When the source directionality is properly accounted for, the reported estimates are in much closer agreement over the low frequency band ∼50–350 Hz. The VLA estimates provide benchmark wind source level measures for use in on-going research.

What has not been established is the angle dependence of the radiated sound. A $\sin^2\theta_s$ dependence for the surface-affected source factor is widely assumed, consistent with a dipole model, but has not been confirmed by measurements. The angle dependence could be measured by steering the VLA increasingly away from endfire.

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### Author Declarations

*Conflict of Interest*

The authors have no conflicts of interest to disclose.

### Data availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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