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2pUWa8. Wind-dependence of low-frequency ambient noise in the deep-ocean sound channel

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In the low-frequency range (1-125 Hz), the deep-ocean ambient noise field is produced by seismic, marine life, ship traffic, and wind-dependent hydrodynamic noise mechanisms. This study focuses on the contribution of wind-related source mechanisms to the overall ambient noise field, as well as previous attempts to understand the physics of these mechanisms. The Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO) hydroacoustic monitoring system has produced nearly continuous recordings of the low-frequency deep-ocean ambient noise field at sites in the Pacific, Atlantic, and Indian Oceans, each spanning several years in length. Additionally, wind speed data have been recorded at the host island of each station by the National Oceanic and Atmospheric Administration (NOAA). Correlation techniques are used with these two datasets to determine the relationship between wind speed and the sound level in different frequency bands, and to determine the prominence of wind-related noise in the combined ambient noise spectrum. Results from the three sites are compared to each other to assess the uniformity of wind-generated noise over the world's ocean basins.

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INTRODUCTION

In the low-frequency range (1-115 Hz), ambient noise in the deep-ocean sound channel results from a combination of seismic activity, marine life, ship traffic, and wind-dependent hydrodynamic noise mechanisms. Without prior knowledge of source distributions, separating noise caused by different mechanisms is a difficult task. Since 1950, numerous investigators have proposed various theories on the production of low-frequency sound by surface wind. Longuet-Higgins proposed that the nonlinear effects of the interaction of two oppositely travelling surface gravity waves could produce non-attenuating sound waves of twice the frequency of the interacting surface waves. This theory has since been developed further by Hughes, who derived a theoretical spectrum for the noise generated by such interactions. Hughes’ model, which is intrinsically dependent on a sea surface height model, has been validated by several datasets within the 1-5 Hz frequency band. Above the 1-5 Hz frequency band, the most likely source of wind-dependent low-frequency ambient noise is the breaking of surface waves, which produce clouds of bubbles close to the sea surface. It has been hypothesized that these bubble clouds can produce low-frequency noise by amplifying turbulent pressure fluctuations near the surface, and through collective oscillations of the cloud itself. Though laboratory tests have confirmed that substantial noise is created by breaking waves, the importance of this source in the deep-ocean ambient noise field has not been definitively measured. At high frequency, ambient noise levels are known to be a function of sea state, which is strongly related to the surface wind speed.

A few investigators have attempted to determine the significance of these wind-related noise mechanisms in the low-frequency ambient noise field using various statistical methods. In 1975, Perrone and King attempted to use the autocorrelation coefficient function of a series of hourly noise measurements to discern between wind- and ship-related noise sources. Though it has not been used in many subsequent papers, this method can give rough estimates of wind-dependence, even without dependable local wind speed data. The more widely accepted method of determining wind-dependence is to calculate correlation coefficients between noise levels and wind speeds. This method, which has been used by several previous investigators, gives a more quantitative description of the wind dependence of ambient noise. This paper will employ both of these techniques with recent data, and compare the results with those seen by previous investigators.

The goal of this study is to determine the importance of wind-dependent noise sources in the low-frequency deep-ocean ambient noise field. Large sets of ambient noise data from the Comprehensive Nuclear-Test Ban Treaty Organization (CTBTO) hydroacoustic monitoring system are used in conjunction with wind speed data from the National Oceanic and Atmospheric Administration (NOAA) to identify the relationship between low-frequency ambient noise levels and surface wind speeds. These datasets are particularly advantageous because they span several years and multiple locations, reducing limitations experienced by previous investigators. This paper uses statistical correlation methods used by previous investigators in conjunction with improved datasets to quantify the dependence of low-frequency noise on surface wind speed.

DATA

The ambient noise data used in this study was recorded using three hydrophone stations from the CTBTO’s International Monitoring System (IMS), located at Diego Garcia, Ascension Island, and Wake Island. Each station is based at an island in a different ocean basin, as seen in the map in Figure 1. These stations were built for the purpose of detecting and locating unsanctioned nuclear testing, and have a very large detection range. Each station consists of a pair of triangular hydrophone arrays with a 2 km hydrophone spacing moored in the deep ocean sound channel, between 700 and 1400 meters below the ocean surface, depending on the location. The two arrays are located between 20 and 190 km away from the host island, on opposite sides of the island, to provide spatial discrimination, using the shadow zone created by the island. The signal from each hydrophone is amplified and digitized at a rate of 250 Hz and then transmitted via buried fiber optic cable to the surface station. Due to the 250 Hz digitization rate, the Nyquist frequency is 125 Hz, but to avoid the complications caused by the high frequency roll-off, only frequencies up to 115 Hz are considered. A generic schematic of stations used can be found in Figure 2, along with the station specifics found in Table 1.

In conjunction with the ambient noise data, this study uses wind speed data reported by NOAA. This data was recorded by a weather station located at the airport on each island. At the Wake Island and Diego Garcia weather stations, wind speed and direction were reported every hour, on the hour. At Ascension Island, wind speed and
direction were recorded during each hour, but two-thirds of the observations were made fifty minutes after the top of the hour. For each of the three sites, missing points throughout the data series were filled in by linear interpolation.

![Map of the three CTBTO hydrophone stations used in this study](image1)

**FIGURE 1.** Map of the three CTBTO hydrophone stations used in this study

![Generic schematic of a CTBTO hydrophone station](image2)

**FIGURE 2.** Generic schematic of a CTBTO hydrophone station

<table>
<thead>
<tr>
<th>Station Code</th>
<th>Location</th>
<th>Station Type</th>
<th>Latitude, Longitude</th>
<th>Nominal Orientation</th>
<th>Data Period</th>
<th>Response Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA08</td>
<td>Diego Garcia</td>
<td>2-triad</td>
<td>7.3°S, 72.4°E</td>
<td>North-South</td>
<td>2002-2012 (10 years)</td>
<td>0.5-120 Hz</td>
</tr>
<tr>
<td>HA10</td>
<td>Ascension Is.</td>
<td>Hydrophone</td>
<td>14.4°W, 19.3°N</td>
<td>North-South</td>
<td>2004-2012 (8 years)</td>
<td>1-120 Hz</td>
</tr>
<tr>
<td>HA11</td>
<td>Wake Is.</td>
<td>Hydrophone</td>
<td>166.6°E</td>
<td>North-South</td>
<td>2007-2012 (5 years)</td>
<td>1-120 Hz</td>
</tr>
</tbody>
</table>
DATA PROCESSING

Since processing several years of continuous noise data is computationally cumbersome, strategic limits were placed on the amount of data that was actually processed. One hydrophone from each triangular array was selected for processing, for a total of six hydrophones, two from each island. Three months of data from each hydrophone, spanning from July 1 to September 30, 2010 was used. A three month data segment was selected because the first test, which depends on the autocorrelation coefficient function of the hourly noise levels, becomes unreliable when the data segment is too long. Throughout the segment of data, three minute samples were randomly selected from each hour, reducing the computational time by roughly a factor of twenty compared to processing the entire hour, while still maintaining the integrity of the data. Samples were selected randomly in an effort to reduce the chance of contamination by any hourly events occurring at the host island. Each three minute sample was then split into 11 30-second subsamples with a 50% overlap, which were then Hann-windowed and converted into frequency space by a fast Fourier transform. The 30-second subsample size results in a 1/30 Hz frequency resolution, which is more than adequate for our purposes, since the data will only be analyzed down to 1 Hz. The resulting 11 power spectral densities (PSDs) were then averaged together to form a single PSD which can be used to approximate the noise spectrum of the hour from which the sample was taken. Results presented in the remainder of this paper are derived from these hourly spectral estimates. The geometric mean of these hourly PSDs for each hydrophone can be seen in Figure 3. A geometric mean was used to prevent a relatively low number of high-power transient signals from skewing the results.

![Figure 1](image1.png)

**FIGURE 1.** Power spectral densities for the six CTBTO hydrophones between July 1 and September 30, 2010, determined by the calculating the geometric mean of three months of hourly spectral estimates.

DATA ANALYSIS

The goal of this study is to determine the dependence of the low frequency ambient noise spectrum on surface wind speeds. To achieve this goal, this study employs two distinct correlative approaches, which have both been previously used in low frequency ambient noise studies. Since results obtained using data from the north and south arrays are sufficiently similar, only the results from the northern arrays will be presented in this paper.
Autocorrelation Coefficient Function

The first test was initially developed by Perrone and King\textsuperscript{7,8}, and involves computing the autocorrelation coefficient function of the time series of the hourly spectral estimates within each available frequency band. For the purposes of this paper, the autocorrelation coefficient function is defined as follows\textsuperscript{16}:

$$\begin{align}
R(\tau) &= \frac{\sum_{i=1}^{n} (x_i - \bar{x})(x_{i+\tau} - \bar{x}) \sum_{j=1}^{n} (x_j - \bar{x})^2}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{j=1}^{n} (x_j - \bar{x})^2}} \\
&= \frac{\sum_{i=1}^{n} (x_i - \bar{x})(x_{i+\tau} - \bar{x}) \sum_{j=1}^{n} (x_j - \bar{x})^2}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{j=1}^{n} (x_j - \bar{x})^2}} \times \frac{\sum_{j=1}^{n} (x_j - \bar{x})^2}{\sum_{j=1}^{n} (x_j - \bar{x})^2},
\end{align}$$

where $x$ is the hourly string of data, and $\tau$ is the time lag in hours between the two segments of $x$. It should be noted that this expression is identical to the Pearson product-moment correlation coefficient calculated from two segments of the same time series, spaced a time lag $\tau$ apart. The possible values of the autocorrelation coefficient function range from 1 to -1, with a value of 1 implying a perfect positive-slope linear correlation, -1 implying a perfect negative-slope linear correlation, and 0 implying no linear correlation between the two segments.

The goal of this first test is to identify similarities in the characteristics of the autocorrelation coefficient function of a possible forcing function (i.e. wind speed) and the autocorrelation coefficient function of the noise level in different frequency bands. Since wind speed is a nonstationary process, it is expected that its autocorrelation coefficient function will slowly drop towards zero as the time lag increases. In contrast, the autocorrelation coefficient function of a stationary white noise signal will very quickly drop to zero\textsuperscript{17}. In theory, if the noise level within a specific frequency band is the result of the local wind speed, the autocorrelation coefficient function of that time series of noise levels drop down to zero at a similar rate as that of the wind speed. Physically, such a similarity implies that the two processes change at a similar rate, suggesting a causal relationship between the two.

For this test, the autocorrelation coefficient functions were computed for the time series of spectral density levels in each frequency band as well as for the local wind speeds. Figure 4 shows a few examples of the autocorrelation coefficient functions calculated using data from Wake Island. The 1 Hz band was selected because it is within the microseism peak, whereas the 50 Hz band was selected because it is likely not significantly influenced by wind. Note the similarities in initial decay time between the functions calculated from wind speed and the 1 Hz data. These are the similarities which this test hopes to exploit.

To quantify the similarities between the calculated autocorrelation curves, the threshold crossing time, defined as the first lag time associated with an autocorrelation coefficient of less than 0.3, was determined for each frequency band time series and wind speed time series. These characteristic threshold crossings for the noise level time series are summarized in Figure 5. From the three wind speed time series, the average threshold crossing time was calculated to be about 28 hours, which can be seen as a dashed line in Figure 5. This lag time does fluctuate significantly, depending on location, time, and length of the data segment, so it should only be used as an approximate reference value. Because wind speed is a nonstationary process, the threshold crossing time is generally above 20 hours, which significantly longer than the 4 hour threshold crossing time seen in frequency bands with predominantly stationary noise sources, allowing for discrimination between the two types of sources. When the threshold crossing time for a frequency band is greater than 28 hours, it is likely that the noise in that band is predominantly caused by surface wind. As the threshold crossing time decreases below 28 hours, the contribution of wind related sources to the noise field declines, until other sources dominate in the frequency range where the threshold crossing time is close to zero. It is important to note, however, that a high threshold crossing time can only be used to identify frequency bands whose autocorrelation coefficient functions might show a decay rate similar to that of the wind speed data, because a high threshold crossing time could also be seen if the autocorrelation coefficient function drops quickly to a steady value near 0.3.

Though the three curves in Figure 5 were calculated using data from hydrophones which were thousands of miles apart from each other, there are some interesting trends shared by all three sites. Below 2 Hz, each curve has an obvious peak threshold crossing time. Below about 1.6 Hz, all three datasets have a threshold crossing time of greater than 28 hours, suggesting that at all three sites, wind is the dominant source of ambient noise below 1.6 Hz. Looking closer, the autocorrelation coefficient functions in this frequency range display the slow decay characteristic of nonstationary processes, so wind dependence is confirmed. Above 3 Hz, all three curves are generally constant, with a few exceptions, with a threshold crossing time between 1 and 5 hours, which implies that the ambient noise field above 3 Hz is predominantly caused by sources other than wind. The two sharp peaks around 7.5 Hz and 20 Hz do not appear to be present at all locations. Upon further investigation, the autocorrelation coefficient functions in these regions quickly fall to a steady value, as expected for a stationary process, and, in the case of Wake Island, oscillate with a period of 24 hours about this steady value. This oscillating behavior may be
caused by a narrow-band signal with an oscillating power, but since it shows the quick decay characteristic of a stationary process, noise in this region is likely not related to wind speed. Perrone ran a similar test on 9 days of ambient noise measurements, and found a similar wind-dependence up to 4 Hz.

**FIGURE 2.** Autocorrelation coefficient function calculated from noise data received at the Wake Island north hydrophone #1 between July 1 and September 30, 2010, in two frequency bands, and from wind speed data from the Wake Island airport during the same time period.

**FIGURE 3:** Shortest lag time required for the autocorrelation coefficient function of individual frequency bands to fall below 0.3. The three curves were calculated using the hourly spectral estimates of the ambient noise from the northern hydrophone array at each of the three CTBTO stations between July 1 and September 30, 2010. The constant dashed line is the average lag time required for the autocorrelation coefficient function of the wind speed time series to fall below 0.3.
Correlation Coefficients

The second test consisted of computing the Pearson correlation coefficient between individual frequency band time series of noise data and the wind data time series. For this paper, the Pearson correlation coefficient, for a specified time lag \( \tau \), is defined as following:

\[
\rho(\tau, f) = \frac{\sum_{i=1}^{n} (y_i - \bar{y})(y_{i+\tau} - \bar{y}) (x(f_i) - \bar{x}(f)) (x(f_{i+\tau}) - \bar{x}(f))}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2 \sum_{i=1}^{n} (x(f_i) - \bar{x}(f))^2}},
\]

where \( x(f) \) is the time series of logarithmic noise spectral densities for the 1/30 Hz frequency band starting at frequency \( f \), \( y \) is the time series of local wind speeds, measured at the host island, and \( \tau \) is the time lag of the noise segment relative to the wind data segment. To account for the fact that the wind speed was not measured directly above the hydrophone station, and that surface gravity waves do take time to develop, correlation coefficients were calculated for a \( \tau \) between -20 and 20 hours, with a positive lag implying that wind comes before noise. In theory, this test should be more effective at determining the wind dependence of ambient noise than the previous test, with the constraint that it requires sufficient knowledge of the local wind speed.

Figure 6 shows the maximum correlation coefficients between the logarithmic noise level and the local wind speed for the northern arrays at the three CTBTO hydrophone stations. Like the previous test, all three curves, though calculated using data from three different oceans, produced very similar results. Above 3 Hz, the maximum correlation coefficient for all three datasets is between 0.2 and -0.2. Such a low correlation coefficient implies that less than 4% of the variation in the noise level directly depends on the variations in wind speed. All three curves approach a maximum between 1 and 2 Hz, suggesting that between 1 and 115 Hz, wind speed has the most noticeable effect on noise level between 1 and 2 Hz. Previous investigators have made similar calculations, and have likewise found that the strongest correlation between noise level and wind speed is close to the 1 Hz frequency band.

CONCLUSIONS

The primary goal of this study was to determine the wind dependence of low-frequency ambient noise in the deep ocean sound channel, using two different statistical tests. The first test relied on the autocorrelation coefficient function, which gave a more categorical and inexact result, but has the advantage that complete local wind data is
not necessary, because it relies on the fact that nonstationary processes, such as wind speed and wind-dependent noise, have autocorrelation correlation functions which decay noticeably slower than those of stationary processes. The second test relied on the correlation coefficients between the time series of spectral densities in specific frequency bands and the local surface wind speed. This test produced much more quantitative results, which confirmed the findings of the first test. Qualitatively, both tests showed that the strongest wind dependence is found between 1 and 2 Hz, regardless of the location of the data source. It is well known that microseisms, which are caused by the nonlinear interactions of surface wind waves, create noise within the 1 to 2 Hz range, so it is safe to assume that microseisms are the mechanism by which wind energy couples into the low frequency noise field. Above 3 Hz, neither test revealed any strong relationship between wind and noise level. Though there are physical methods by which surface wind could cause deep ocean noise at such frequencies, it appears that any contribution from such mechanisms is masked by other noise sources.

REFERENCES