An Evaluation of the WOTAN Technique of Inferring Oceanic Winds from Underwater Ambient Sound

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ABSTRACT

The potential of the WOTAN technique to estimate oceanic winds from underwater ambient sound is thoroughly evaluated. Anemometer winds and sound spectrum levels at 11 frequencies in the range 3-25 kHz from the FASINEX Experiment are used to establish both the frequency and wind speed dependencies of ambient sound. These relationships are then tested using independent data from four other deployments, and found to hold in the deep ocean in the OCEAN STORMS but not in shallow coastal waters. The OCEAN STORMS ambient-sound wind speed estimates are within ±0.5 m s⁻¹ of anemometer values for wind speeds between 4 and 15 m s⁻¹. Causes of differences, including disequilibrium of the surface wave field, are discussed and it is argued that they are no larger than expected.

The procedure for processing ambient-sound data is developed. It includes temperature dependent calibrations, detection of shipping and precipitation contamination, and standardization of measurements to 1 m depth. The latter procedure allows data from different depths and sound speed profiles to be compared. The potential for using the technique on remote platforms is assessed. On-board processing and subsequent despiking and interpolation would result in a continuous wind record. For time scales of 12 hours or longer the results would be very similar to those obtained with an anemometer. Over shorter time scales there may be some important differences.

1. Introduction

The role the oceans play in climate has become an increasingly active field of research. At present, however, only a few of the important variables are being monitored on climate scales. The upper ocean is particularly challenging in this regard because of the numerous processes at work there, and the frequent sampling required by its rapid response to atmospheric forcing. An increased role of satellite-based measurements is predicted, but in situ measurements from platforms on or below the sea surface are required for some variables. In addition, satellites produce peculiar space–time sampling that may need to be augmented by in situ observations. Verification of remote measurements is complicated by the lack of independent observations.

Parameterization of the air–sea fluxes of momentum, sensible heat and moisture all involve the surface wind speed. However, accurate, frequent, and widespread wind measurements are not readily available. It is difficult to measure the wind from remote ocean surface buoys with an anemometer because the surface wave field generates platform motion and creates a generally destructive environment. Removal of ship velocity and flow distortion makes shipboard wind measurements difficult too (Large and Businger 1988). Another problem is that time-averaged winds at a point are not always as desirable as spatial averages for meteorology and oceanography.

An attractive alternative technique for estimating oceanic winds is to make use of the wind-generated high-frequency ambient sound at depth in the ocean. Inherent in this technique is spatial averaging of the wind signal. In addition the sensors can be positioned underneath surface buoys well below the hostile air–sea interface. Surface-drifting buoys are particularly well suited for covering large areas of the oceans.

Farmer and Vagle (1988b) established that a major part of the ambient sound is produced by breaking waves, and several studies have been carried out on the relationship between ambient sound and wind speed (Shaw et al. 1978; Evans et al. 1984; Lemon et al. 1984) showing good agreement between observed and ambient-sound-derived wind speeds. However, there are important differences in the various empirical relationships (Bourassa 1984). Clearly, a universal algorithm needs to be established before ambient sound can be used to estimate wind independently.

Other sound sources are also present in the ocean. The ever present shipping is a considerable source of

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noise, particularly in the 50–500 Hz band. For ships passing near by, however, the noise will contaminate the ambient sound signal even at 25 kHz. Precipitation is another sound source in the 10–20 kHz frequency range. Biological sound sources such as shrimps, whales, seals, etc. are in general not a problem because of the local and transient nature of the sound. The presence of large amounts of microbubbles in the upper parts of the ocean will also affect the measured ambient sound spectrum by absorbing and scattering the sound at acoustic frequencies above about 8 kHz (Farmer and Lemon 1984). Lower frequencies are mostly unaffected by bubbles. Measurements obtained with a hydrophone less than 20 m below the surface, however, will be influenced by selective trapping of the sound in the bubble layer, even at frequencies as low as 1 kHz (Farmer and Vagle 1989).

In this paper we report on a statistical analysis of the relationship between ambient sound and the wind as obtained in the Frontal Air–Sea Interaction Experiment (FASINEX). An algorithm relating the sound pressure variations to various wind variables is established and tested on other available ambient sound datasets. Consideration is then given to the contamination of the wind-induced ambient sound spectrum by precipitation, shipping, and bubbles. Finally, algorithms are evaluated for use on remote platforms.

2. The WOTAN system

A plane acoustic wave in the ocean has intensity \( I = (\rho c)^{-1} p^2 \), where \( p \) is the root mean square of the pressure fluctuations, \( \rho \) is the water density, and \( c \) is the sound speed. Since ambient sound in the ocean is broadband with a very large dynamic range, it is usually described by a sound pressure level (SSL), which is the intensity level in decibels (dB) as measured in a 1 Hz bandwidth centered at a frequency \( f \):

\[
SSL(f) = 10 \log \left( \frac{p^2(f)}{p_{ref}^2} \right)
\]

where \( p^2(f) \) is the variance of the pressure fluctuations in the 1 Hz bandwidth, and \( p_{ref} \) has the same dimensions as the reference level \( p_{ref} = 1 \mu Pa(\text{Hz})^{-1/2} \). Common logarithms are denoted as log, while \( \ln \) is reserved for natural logarithms.

The wind-generated ambient sound measured at any depth and geographical location is made up of the sound from a large number of individual sources at or just below the ocean surface. The sound propagation from each source will be affected by the directionality of the source, spreading losses, attenuation along the path, refraction effects caused by changes in the sound speed profile, and possible multipath propagation caused by reflections from the bottom. These factors are frequency dependent and the received SSL should be standardized before data from different locations are compared.

Most reported measurements of ambient sound directionality are consistent with the hypothesis of a dipole source formed by the actual source and its image on the sea surface (Anderson 1958). In a source field of dipoles with sound intensity \( I_0 \), each dipole will radiate \( I_0 \sin^2 \theta \) towards the receiver where \( \theta \) is the angle between the surface and the path to the receiver. The signal received from a source, a horizontal distance \( r \) from the point directly above a hydrophone at depth \( h \), will be

\[
I_r = (I_0 \sin^2 \theta) r^{-2} \exp(-\alpha l)
\]

where \( l \) is the path length from the source to the receiver including refraction effects, and \( \alpha \) is the frequency-dependent attenuation coefficient for bubble free water. Spreading and attenuation losses are accounted for in (2) by the \( l^{-2} \) and exponential terms, respectively. Integration of (2) gives the total intensity \( I_h \), which will be measured at a depth \( h \). The measured SSL at the depth \( h \) will be

\[
SSL(h, f) = 10 \log \left( \frac{\rho c I_h}{W(f)p_{ref}^2} \right)
\]

where \( W(f) \) is the effective bandwidth of the acoustic signal at the frequency \( f \). With a uniform distribution of sound sources the sound intensity at 1 m, \( I_1 \), is related to \( I_h \) through

\[
I_1 = I_h \left\{ \frac{\int_0^{\infty} \left[ \frac{r \sin^2 \theta \exp(-\alpha l)}{l^2} \right] dr}{\int_0^{\infty} \left[ \frac{r \sin^2 \theta_1 \exp(-\alpha l_1)}{l_1^2} \right] dr} \right\}^{-1}
\]

where \( \theta_1 \) is the angle between the surface and the path to a point at a depth of 1 m, and \( l_1 \) is the path length. The refraction and attenuation effects to 1 m are only about 0.01% for realistic sound speed profiles and can be neglected, so that the denominator inside the outside brackets of (4) becomes \( \frac{1}{2} \). The value of \( I_1 \) and its corresponding sound spectrum level, \( SSL_0(f) \), therefore, are both independent of measurement site, where

\[
SSL_0(f) = 10 \log \left( \frac{\rho c I_1}{W(f)p_{ref}^2} \right)
\]

\[
= SSL(h, f) + \beta(h, f)
\]

with

\[
\beta(h, f) = -10 \log \left[ 2 \int_0^{\infty} \left[ \frac{r \sin^2 \theta \exp(-\alpha l)}{l^2} \right] dr \right].
\]

The correction factor \( \beta \) has to be calculated for each acoustic frequency of interest from knowledge about the sound speed profile, which gives \( l \) as a function of \( r \) and \( h \) at the hydrophone site. As the hydrophone depth increases, the increase in area from which sound
will reach the hydrophone is largely offset by the increased spreading losses. With no refraction, the increase in $\beta$ with depth will be solely due to increased attenuation.

To simplify later analysis we define a dimensionless sound pressure variance at a depth of 1 m in a 1 Hz band, $p_0^2(f)$, such that:

$$SSL_0(f) = 10 \log(p_0^2(f)).$$  \hspace{1cm} (7)

The Sea Data model 661 WOTAN (Weather Observations Through Ambient Noise) is a sensitive listening device that measures SSL at frequencies in the audio range and records them internally on a cassette tape. The instrument is no longer built. In its present configuration the instrument can be operated at depths up to 1000 m, measuring the ambient sound over the frequency range: 3.0–25.0 kHz. The instrument consists of an ITC 1001 hydrophone mounted on top of an aluminum pressure casing containing electronics, a cassette recorder, and a battery. The voltage fluctuations from the hydrophone are passed through a linear pre-amplifier and then fed to 11 analog bandpass filter channels with equivalent bandwidths of approximately 16% of the respective center frequencies. In older instruments the pre-amplifiers were logarithmic (Hill 1984). For a white noise input the output of the channel $i$ filter is proportional to $p_i^2$ at the center frequency $f_i$, $i = 1, \ldots, 11$ of the filter. The square root of the mean of this output is converted to DC, which controls an oscillator (VCO), such that the number of pulses sensed by a counter and stored on cassette tape is proportional to $p_i(f)$ (Waddell and Farmer 1988). These digital data are used to compute, from (1), the in situ SSL$(f)$ at the 11 channel frequencies.

The center frequencies of the channels were chosen to cover the acoustic frequency bands dominated by wind and precipitation. A second consideration was to include the frequency bands used by previous investigators (4.3, 8.0, 14.5, and 25.0 kHz) for comparison purposes. A fifth channel, 3.0 kHz, was added to cover the lower frequency range of the wind-produced sound spectrum. The remaining six channels were positioned at intervals between 3.0 and 25.0 kHz, with a higher concentration in the precipitation generated spectral range as shown in Fig. 1. The final choice of the channel center frequencies was: 3.0, 4.3, 5.3, 6.5, 8.0, 10.8, 12.5, 14.5, 16.8, 19.5, and 25.0 kHz.

In order to obtain reliable absolute SSL or ambient sound pressure measurements from the WOTAN instrument, careful calibrations were necessary. The calibrations for the hydrophone (ITC 1001) were supplied by the hydrophone manufacturer and are traceable to a standard reference. The common pre-amplifier was calibrated for gain versus frequency; the measurements show a flat response, within ±0.1 dB, for 2–30 kHz. The frequency response of each bandpass filter was measured, and its equivalent bandwidth was calculated. Finally, the effective gains of the RMS to DC converters and the VCOs were obtained by writing the results of known input signals to tape. As much as 0.4 dB temperature sensitivity in measured SSL over the range 5 to 22°C has been found. Therefore, independent calibrations were performed following each deployment in a laboratory at about the same temperature as the ocean at the instrument depth. This procedure is adequate when instruments are placed below large temperature changes such as found in the seasonal thermocline.

The position of the hydrophone below the ocean surface provides a method for adjusting the surface area that contributes to the measured SSL. As discussed in Farmer and Vagle (1988b), in the absence of refraction effects one can parameterize this averaging area by defining a depth and frequency dependent listening radius $r_L$ as:

$$r_L = \frac{1}{2} h \left\{ \frac{E_1(ah) - E_3(ah)}{E_3(ah)} \right\}^{1/2} \hspace{1cm} (8)$$

where $E_1$ and $E_3$ are the exponential integral functions of first and third order (Abramowitz and Stegun 1964). The area defined by $\pi r_L^2$ represents the ocean surface area from which 70% of the received sound signal originates. Figure 2 shows $r_L$ as a function of depth for 3.0 and 25 kHz. The effective listening area will be increased or decreased relative to (8) depending on whether the sound speed profile is, respectively, downward or upward refractive.

3. FASINEX

The Frontal Air–Sea Interaction Experiment (FASINEX) was designed to investigate the air–sea interaction processes associated with the oceanic fronts of the subtropical convergence zone of the western North
Atlantic Ocean. In October 1984, two long-term subsurface moorings were deployed along 70°W at 25.5°N and at 28.0°N to span the frontal region. In January 1986, an oceanic front was located about 500 km southwest of Bermuda, near 70°W, 27°N and a 40 km × 40 km array of eight moorings was deployed across it. Five of these moorings had meteorologically instrumented surface buoys as described by Weller et al. (1990). A month of intensive oceanographic and meteorological observations from two research vessels, and from up to six aircraft began about 10 February. A multitude of measurements were taken from these platforms, including the two datasets used in our study.

An 11-channel WOTAN instrument was attached at 150 m depth to the FASINEX mooring at 26°53′N, 69°43′W. At this depth the effective listening area (πr_L^2), varies from 0.28 km² and 3 kHz to 0.13 km² at 25 kHz. The instrument was in operation from 27 January to 12 May, and sampled the sound field during 20.125 s intervals, 16 times an hour. The duty cycle was chosen so that data tape and battery power would finish at the same time. (Hereafter, times will be referenced as 1986 year days in UTC.) Of the 40 208 records on the tape, 39 937 were free of parity or other errors and were available for analysis. However, the counts written from the 14.5 and 16.8 kHz channels inexplicably drop to zero in about 10% of these records. These intermittent failures tend to occur at low wind speeds, so there appears to have been a threshold problem with these channels. Consequently, these channels were not used for quantitative analysis. However, for qualitative purposes about 36% of the 14.5 kHz data and 31% of the 16.8 kHz data were determined to be useful by comparison with data from neighboring frequency channels.

Meteorological data for comparison with the WOTAN data were available from meteorological sensors on the surface buoy directly above the WOTAN instrument. These instruments and their performance are discussed by Weller et al. (1990). One set of wind data was obtained by a cup and vane system referred to as a Vector Averaging Wind Recorder (VAWR), and another from a propeller-vane anemometer that was part of an independent Meteorological Recorder (MR). Each system determined the wind speed over a short interval by counting the number of revolutions of the cup or propeller. The vane’s orientation relative to the buoy was sampled along with the heading of a flux-gate compass. Each instrument thus measured a wind vector, the components of which were averaged over 7.5 minutes (VAWR), or 15 minutes (MR), and recorded as eastwards, \( U_e \) and northwards, \( U_v \) components. Hourly wind values at the measurement height of \( z = 3.6 \text{ m} \) were computed by averaging \( U = (U_e^2 + U_v^2)^{1/2} \) over eight (VAWR) and four (MR) sequential records. From hourly averages of sea surface temperature, air temperature, and relative humidity a bulk stability parameter \( \tau = z/L \), where \( L \) is the Monin-Obukhov length, and a drag coefficient, \( C_D = C_D(z, \tau) \), were found using the method of Large and Pond (1981).

In the following, five hourly wind variables \( U_m \), will be related to the WOTAN SSL values; namely

\[
U3 = U (3.6 \text{ m})
\]

\[
U10 = U (10 \text{ m}) = U3 \left[ \frac{1 + C_D^{1/2}}{\kappa} \left( \ln \left( \frac{10 \text{ m}}{z} \right) \right) + \psi_m \left( \frac{z}{L} \right) \right]
\]

\[
U_{N10} = U3 \left[ \frac{1 + C_D^{1/2}}{\kappa} \left( \ln \left( \frac{10 \text{ m}}{z} \right) + \psi_m \left( \frac{z}{L} \right) \right) \right]
\]

\[
u^* = C_D^{1/2} U3
\]

\[
\tau = \rho_u u^* \frac{2}{\kappa}
\]

where \( \rho_u \) is air density, \( \kappa \) is von Karman’s constant (0.4), and the empirical functions \( \psi_m \) are given in Large and Pond (1981). Use of \( U3 \) facilitates comparisons with previous studies where the wind speed at a buoy anemometer height was used. A standard meteorological measurement height is 10 m, hence the use of U10, and its equivalent neutral value \( U_{N10} \). The latter accounts for stability variations. Ideally, direct measurements of the friction velocity, \( u^* \), and the wind stress magnitude, \( \tau \), should also be used, because turbulence variables may be better related to the ambient sound than a mean wind speed. Some evidence of this behavior is discussed in section 5. Since direct stress measurements are not available bulk parameterizations (9) are used for \( u^* \) and \( \tau \). This bulk \( u^* \) differs from \( U3 \) in that it includes the wind speed and stability dependence of \( C_D^{1/2} \), and \( \tau \) is proportional to both \( C_D \) and \( U^2 \) and will vary with a little with air density. The drag coefficient computed from bulk formulae may occasionally differ from its local hourly value by as much as a factor of
two, so averages over a day or more are needed in order to reduce the associated uncertainty in values of \( u^* \) and \( \tau \). Once the relationships with the WOTAN signals have been established, corresponding wind variables will be derived solely from the WOTAN SSL data, and compared with the buoy measurements.

We would have preferred to use the MR anemometer data exclusively for WOTAN evaluation, because of the more desirable operating characteristics of propeller-vane anemometers relative to cup-vane systems. At low wind speeds they are more nearly linear and are less dependent on calibrations, because they turn a fixed number of revolutions per meter of air passage. They also have a much better cosine response to off axis wind components, and overspeeding is not significant (Zhang 1988). The overspeeding of cups is a well-known problem (e.g., Coppen 1982). Weller et al. (1990) compared VAWR and MR winds from the FASINEX surface buoy above the WOTAN. They found larger differences than could be attributed to overspeeding of this moderately fast response, cup anemometer. On average, VAWR winds were 9% higher, but during low winds they were often more than 1.5 times the MR winds speeds. Pond (1968) shows that buoy motion should not affect the measurement of the mean wind this much. Extensive wind tunnel testing indicates that calibration uncertainties are much smaller at 1% to 2%. When similar cup and propeller anemometers were later used on the same buoy with identical, well tested WAVR processing, the cup speeds were on average only 5% higher. Therefore, it appears likely that the MR processing, being used for the first time in the field during FASINEX, may have reduced the wind speed measured by its propellers. Part of the problem may have been too infrequent (15 seconds) sampling of the compass.

In the following analysis is presented that utilizes the VAWR cup data, as recommended by R. Weller (personal communication, 1989). No correction for overspeeding is applied, because the appropriate factor has not yet been determined. How such a factor could be applied to the results at a later time is discussed in section 5. No data are used from periods when the wind speed was below 2 m s\(^{-1}\), because the very large VAWR to MR wind speed differences could be due to either or both wind measurement systems. A similar analysis using the MR data has also been performed and the results are quoted where appropriate.

In order to test algorithms developed from the FASINEX data, WOTAN data from three other deployments were used. The Queen Charlotte Sound (QCS) data were recorded in August 1982 at two sites (QCS\(_1\) and QCS\(_2\)) on the continental shelf off British Columbia (Lemon et al. 1984). The WOTAN instruments had wide bandpass filters (>22% equivalent bandwidth) at 4.3, 8.0, 14.5, and 25.0 kHz. They were mounted on the sea floor below surface anemometers at 265 and 287 m depth, respectively.

A second dataset was collected during the winter 1985–1986 Canadian Atlantic Storms Project (CASP) (Dobson 1987) by a WOTAN instrument deployed at the site of an anemometer station recording averaged wind components. This CASP instrument was mounted at a depth of 93 m in 100 m deep water. Twenty days of data were used starting 11 December 1985. The CASP instrument also had channels at 4.3, 8.0, 14.5, and 25.0 kHz, all of them narrowband except that at 4.3 kHz. In both of the above experiments the buoy mounted anemometers were at approximately 3 m height, so \( U3 \) is the corresponding wind parameter from (9).

Ocean Storms is the third deployment. It took place during the autumn and winter of 1986–1987 about 200 km off the coast of Washington State at a latitude of 47°N. The FASINEX WOTAN in an unchanged configuration was mounted at 150 m on a subsurface mooring. Wind speeds were obtained at a height of 5 m from a surface meteorological buoy moored approximately 6 km north of the WOTAN mooring.

Characteristic sound speed profiles calculated from CTD data obtained during FASINEX, Ocean Storms, and CASP are shown in Fig. 3. The sound speed profiles from Queen Charlotte Sound were similar to the Ocean Storms profiles. The corresponding \( \beta \) values calculated using (6) are listed in Table 1. For comparison the corrections have also been calculated for FASINEX when refraction effects have been neglected. The FASINEX sound speed profile is slightly downward refractive. Therefore, a slightly larger value of \( \beta \) needs to be added to the in situ SSL measurements to give the surface value in (5).

4. Empirical relationships

The well-behaved frequency dependence of wind generated sound above about 1 kHz (Knudsen et al. 1948; Piggott 1964; Crouch and Burt 1972) implies that the wind and frequency dependencies of the ambient sound are separable:

\[ p_0^2(f) = g(U)f^q, \quad f < f_c(U) \]

or

\[ SSL_0(f) = Q \log f + G(U) \] (10)

where \( G(U) = 10 \log g(U) \) and \( Q = 10 \delta \) is the slope of the logarithmic spectrum of the wind-generated sound and needs to be determined. The observations of Farmer and Lemon (1984) at high wind speeds, up to 25 m s\(^{-1}\), indicate that (10) fails at frequencies above a critical frequency, \( f_c(U) \), which itself is a function of the wind.

The difference is SSL at two frequencies \( f_1 \) and \( f_2 \) where (10) holds is

\[ \Delta SSL(f_2 - f_1) = SSL(f_2) - SSL(f_1) = Q \log(f_2/f_1). \] (11)
peak at $\approx 14$ kHz caused by the ringing of bubbles entrained in the water by the drop impact process (Pumphrey et al. 1989) and by the drop impacts themselves (Nystuen 1986). Distant shipping sound is greatly attenuated at WOTAN frequencies, but may redden the spectrum at low wind speeds, as could the sound from distant storms. The signature of nearby ships is discussed by Lemon, et al. (1984). Low frequencies dominate, enhancing the redness of the spectrum. Therefore, measurements of SSL at several frequencies make it possible to exclude records contaminated by such extraneous sound from the quiet dataset whenever the spectral slope is irregular or differs markedly from the (frequency)$^{-1.9}$ dependence ($Q = -19.0$) found in section 4a.

Before the ambient sound dataset was used to obtain empirical relationships the data records contaminated by precipitation and shipping noise were flagged and not used. A precipitation flag was set whenever

$$\Delta \text{SSL}(19.5 \pm 3.0) > (Q + 2) \log(19.5/3.0)$$

$$= -13.82 \text{dB}, \quad (13)$$

or

$$\Delta \text{SSL}(12.5 \pm 3.0) > -10.54 \text{dB}, \quad (14)$$

or

$$\Delta \text{SSL}(8.0 \pm 3.0) > (Q + 3) \log(8.0/3.0)$$

$$= -6.82 \text{dB} \quad (15)$$

were satisfied. A total of 36,956 records or 93% remained unflagged. A shipping flag was set if either of the following two conditions was found:

$$\Delta \text{SSL}(6.5 \pm 3.0) < (Q - 3) \log(6.5/3.0)$$

$$= -7.39 \text{dB}, \quad \Delta \text{SSL}(8.0 \pm 3.0) < -9.37 \text{dB}. \quad (16)$$

The second criterion was not applied at very high wind

We wish to explore the relationships between ambient acoustic sound, SSL, and the five FASINEX wind variables. The first requirement is a quiet dataset where the only identifiable source of sound is the wind. The wind sound spectrum (10) is red, $Q < 0$, and fortunately other major sources of sound produce a different spectral dependency. Rainfall (see Fig. 1) has been found to produce an acoustic spectrum with a spectral

$$\log f_c = 1.9 - 0.07 \times U, \quad (12)$$

for $U$ in m s$^{-1}$ and $f_c$ in kHz. The maximum wind speed encountered during FASINEX was about 15 m s$^{-1}$; where (10) holds only for frequencies below about 7 kHz, according to (12). The FASINEX results, including (12), should not be extrapolated much beyond 15 m s$^{-1}$ until data at higher wind speeds become available.

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speeds \((\text{SSL}(3.0) > 65 \text{ dB})\), because of possible bubble attenuation at 8.0 kHz. Spectral slopes steeper than \((Q - 3) \text{ dB/decade}\) were thus flagged in 7360 records. In 502 records both precipitation and shipping flags were set. At this point the number of unflagged records was 30,098, or 75% of the original total. The data from all WOTAN channels were standardized to the 1 m level from a depth of \(h = 150 \text{ m}\) according to \((5)\). Table 1 shows the necessary frequency dependent corrections.

Hourly SSL\(_0\) values were generated for each WOTAN frequency by averaging only those records with neither precipitation nor shipping flags set. Time averages are computed by averaging the dimensionless pressure variance, \(p_t^2\), and transforming the result back to SSL\(_0\) in dB. An hourly value is thus,

\[
\text{SSL}_0(f) = 10 \log(\langle \log^{-1}(\text{SSL}_0(f)/10) \rangle) \tag{17}
\]

where \(\langle \cdot \rangle\) represents an average of the unflagged records in an hour. In about half the number of available hours there were no flagged records and 10\% of the available hours had all records flagged. About 75\% of the hours had more than 10 unflagged—out of 16—records. Each hourly value was then checked for excessive scatter due to entrantageous sound sources. The scatter due to wind speed variability was removed by differencing the 12.5 and 3.0 kHz channels and computing a mean difference \(\Delta \text{SSL}(12.5-3.0)\) and standard deviation using only the unflagged records of each hour. A scatter flag was set at any hour where the above standard deviation exceeded 1.0 dB.

The hours with 10 or more unflagged records and where the scatter flag was not set, were merged with corresponding hourly means of the five wind variables. These hours with \(U_3 > 2.0 \text{ m s}^{-1}\) were chosen as the quiet dataset. Of the 2,513 hours spanned by the FASINET WOTAN dataset 1,847, or 73\%, are included.

\[a. \text{ Frequency dependency}\]

The quiet dataset was sorted by wind speed \((U_{s10})\) into five 2 m s\(^{-1}\) wide bins starting at 2 m s\(^{-1}\), and a 12–16 m s\(^{-1}\) bin. An average SSL\(_0\) \((17)\) and a standard deviation were calculated for each bin and each frequency channel, with the average weighted by the number of unflagged records in each hour. Figure 4 shows the results for the 8–10 m s\(^{-1}\) bin. The slope of a linear regression with \(\log f\) as the independent variable gives \(Q\), and the 1 kHz value is \(G(U_{s10})\). Some results for all the bins are shown in Table 2. Since \((10)\) holds only for frequencies below \(f_c\) \((12)\), the higher frequency channels were not used for the higher wind speed bins. In addition, the 5.3, 14.5, 16.8, and 25.0 kHz channels were always excluded from the final regressions. It is suspected that unknown acoustic sources contaminated the 5.3 kHz channel, hence the high positive residuals at all wind speeds. Perhaps a little leakage is responsible for the regular positive residuals at 4.3 and 6.5 kHz. These however, are not large enough to exclude the channels. The unreliability of even the qualitative subset of the 14.5 and 16.8 kHz data at low wind speed is clearly shown by some high positive residuals in Table 2. However, Fig. 4 shows how well these independent data fit the regressions at the higher wind speeds. The 25.0 kHz channel has a very high residual at all wind speeds, and so was never used. Similar behavior was observed with a broadband drifting instrument in the vicinity, so it is neither an instrument problem, nor an effect of mooring motion.

The weighted average of the slope from the six wind speed bin regressions gives \(Q = -19.0 \text{ dB/decade}\). There is close agreement with the values of \(-18.94\) and \(-18.75 \text{ dB/decade}\) reported by Bourassa (1984) from measurements at 3800 m depth in the equatorial Pacific. There is somewhat poorer agreement with Bourassa's deep Atlantic results of \(-21.9\) and \(-22.3 \text{ dB/decade}\), and with the \(-17.0 \pm 2.0 \text{ dB/decade}\) result of Lemon et al. (1984). Nonetheless, the agreement with these results and with Knudsen's (1948) frequency\(^2\) dependency \((Q = -20.0 \text{ dB/decade})\) is within experimental uncertainty, especially considering that they were obtained at different depths, did not account for absorption, and utilized winds from different anemometers. It is likely that the slopes would be less steep if all the sound levels were standardized to the 1 m level.

There appears to be a slight tendency for the slope in Table 2 to steepen at the higher wind speeds, but this effect is not significant, because of the smaller frequency range. However, it could be due to bubble scattering and absorption despite the frequency restriction.
Table 2. Summary of the SSL(\(f_f\)) versus \(\log f\) regression analysis for the six FASINEX wind speed bins.

<table>
<thead>
<tr>
<th>(U_{N10}) (m s(^{-1}))</th>
<th>Hours</th>
<th>(G(U))</th>
<th>(Q)</th>
<th>3.0</th>
<th>4.3</th>
<th>5.3*</th>
<th>6.5</th>
<th>8.0</th>
<th>10.8</th>
<th>12.5</th>
<th>14.5*</th>
<th>16.8*</th>
<th>19.5</th>
<th>25.0*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-4</td>
<td>39</td>
<td>58.1</td>
<td>-19.7</td>
<td>-46</td>
<td>.59</td>
<td>3.34</td>
<td>.19</td>
<td>-08</td>
<td>-31</td>
<td>0.00</td>
<td>.06</td>
<td>3.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-6</td>
<td>300</td>
<td>-18.8</td>
<td>0.09</td>
<td>3.08</td>
<td>.04</td>
<td>-21</td>
<td>-24</td>
<td>-05</td>
<td>2.83</td>
<td>1.73</td>
<td>.24</td>
<td>3.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-8</td>
<td>635</td>
<td>-18.6</td>
<td>0.09</td>
<td>2.62</td>
<td>.24</td>
<td>-23</td>
<td>-21</td>
<td>-03</td>
<td>1.08</td>
<td>.52</td>
<td>.19</td>
<td>3.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-10</td>
<td>508</td>
<td>68.7</td>
<td>-19.0</td>
<td>-12</td>
<td>2.8</td>
<td>1.96</td>
<td>.11</td>
<td>-20</td>
<td>-19</td>
<td>0.00</td>
<td>-01</td>
<td>1.3</td>
<td>3.80</td>
<td></td>
</tr>
<tr>
<td>10-12</td>
<td>177</td>
<td>71.1</td>
<td>-19.6</td>
<td>-20</td>
<td>2.5</td>
<td>1.89</td>
<td>1.18</td>
<td>-16</td>
<td>-15</td>
<td>.09</td>
<td>0.00</td>
<td>-43</td>
<td>.17</td>
<td>3.80</td>
</tr>
<tr>
<td>12-16</td>
<td>94</td>
<td>74.2</td>
<td>-20.0</td>
<td>-15</td>
<td>.19</td>
<td>1.54</td>
<td>.14</td>
<td>-18</td>
<td>-57(^t)</td>
<td>-41(^t)</td>
<td>.61</td>
<td>-93(^t)</td>
<td>2.31</td>
<td></td>
</tr>
</tbody>
</table>

Weighted average: -19.0 -12.28 2.08 .11 -21 -22 -03 .12 3.70

\(^*\) Channels never included in regression analysis; see text.
\(^t\) Values excluded in regression analyses because \(f > f_f\).

The results given in Table 2 indicate that over the decade of frequencies spanned by the WOTAN and over the wind speed range of 2–16 m s\(^{-1}\), the power law relationship given in (10) with values of \(q = -1.9\) and \(Q = -19.0\) dB/decade is a good model of the frequency dependence of \(p_0^2\) and SSL_0.

b. Wind dependencies

The well-behaved frequency dependence of the SSL allows reliable frequency channels to be shifted to a common reference frequency, \(f_f\):

\[
\text{SSL}_0 = \langle \text{SSL}_0(f_f) \rangle = 10 \log p_0^2 - 19.0 \log(f_f/f_f)\]

where \(\langle \quad \rangle\) indicates averaging over the reliable channels. The reference frequency was chosen to be 8.0 kHz because it lies approximately in the middle of our frequency range, and earlier WOTAN instruments (Evans et al. 1984; Lemon et al. 1984) had channels at this frequency. The mean SSL_0 and a standard deviation, \(p_0\) and \(p_0^2\), were calculated for each hour of the quiet dataset. The maximum standard deviation was only 1.3 dB.

In the past it has been common to relate pressure variance to the wind parameters in (9) as a power law (Bourassa 1984; Evans et al. 1984):

\[
g(U) = cU^b \]

\[
G(U) = B \log U + C\]

where \(B = 10b\) and \(C = 10 \log c\). Using this model, (10) becomes

\[
\text{SSL}_0 = B \log U + (C - 17.2 \text{ dB})\]

where \(Q \log f_f = -17.2 \text{ dB}\). Linear regressions were performed with \(\log U\) as the independent variable and the resulting coefficients are given in Table 3. In fifteen records the WOTAN SSL_0 values inserted into a first-pass linear regression gave a \(V_{N10}\) value more than 2 m s\(^{-1}\) greater than the observed \(V_{N10}\) and these data were removed because of possible spikes in the buoys winds. The effect on the linear regressions was negligible, because so few data were affected. The results for \(U_{N10}\), \(u^*\), and \(\tau\) are plotted in Fig. 5 as dashed lines.

In previous studies, 20 logU3 has been linearly regressed against the in situ SSL, so an exact comparison is not possible. The best that can be done is to convert \(B\) to a slope of 0.74 and \((C - 17.2 \text{ dB})\) to an offset of -20.0, corresponding to 20 logU3 versus SSL_0 (8.0 kHz). These values fall between the 0.659 ± 0.014 slope and 18.5 ± 0.7 offset found by Lemon et al. (1984) and the 0.838 slope and -26.6 offset of Evans and Watts (1981). Bourassa’s (1984) one equation regression results from the Pacific ranged from 0.65 to 0.87 in slope, and from -17.6 to -26.9 in offset.

Table 3. Regression coefficients for linear and quadratic fits between SSL_0 and the logarithm of the wind variables.

<table>
<thead>
<tr>
<th>(\log U/3)</th>
<th>(A_0)</th>
<th>(A_1)</th>
<th>(A_2)</th>
<th>(C - 17.2 \text{ dB})</th>
<th>(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.80</td>
<td>40.03</td>
<td>-7.99</td>
<td>26.76</td>
<td>27.25</td>
<td></td>
</tr>
<tr>
<td>21.69</td>
<td>38.70</td>
<td>-7.38</td>
<td>26.62</td>
<td>26.46</td>
<td></td>
</tr>
<tr>
<td>15.68</td>
<td>49.33</td>
<td>-12.24</td>
<td>24.43</td>
<td>28.39</td>
<td></td>
</tr>
<tr>
<td>59.98</td>
<td>8.10</td>
<td>-16.14</td>
<td>65.51</td>
<td>27.46</td>
<td></td>
</tr>
<tr>
<td>59.67</td>
<td>4.68</td>
<td>-4.04</td>
<td>64.50</td>
<td>13.76</td>
<td></td>
</tr>
</tbody>
</table>

Although the model (20) gives a high correlation coefficient of 0.95 for all wind variables, and leads to results consistent with previous studies, it is not entirely satisfactory. The linear regressions systematically overestimate SSL_0 at the higher values of the wind variables (Fig. 5). This feature is most pronounced for \(u^*\) and \(\tau\), because of the wind speed dependency of \(C_D\). Bourassa (1984) noted a similar tendency and chose to fit one linear segment to data below 5.5 m s\(^{-1}\) and another to higher winds. Since (20) does not appear to hold over a wide range of wind speeds, the large range in reported slopes and offsets may be due in part to the wind speed range of the datasets.
It seems preferable to fit curves rather than linear segments to the data, because there is no reason to expect abrupt changes in slope at any particular wind speed. Curvilinear regressions were therefore performed with \( \log U \) as the independent variable to obtain the coefficients of

\[
SSL_0 = A_0 + A_1 \log U + A_2 (\log U)^2
\]

for each wind variable \( U \). The results are given in Table 3. In no case was a cubic term, \( A_3 (\log U)^3 \), statistically significant. As is evident in Fig. 5, the solid lines (21) provide a better fit over a wider range of wind speeds than do the dashed lines (20). The correlation coefficients are all only slightly higher (0.96) because there are few data at high wind speeds. In the parallel analysis using MR data the nonlinearity was significant only for \( \eta^* \) and \( \tau \).

Although (21) is a statistical improvement over (20) it does not reduce to a simple expression such as a power law (19) that might be derived from a physical model. More physically realizable power series expansion models, therefore, will now be investigated, namely

\[
p_0 = \sum_{i=0}^{\infty} a_i U^i,
\]

\[
p_0^2 = \sum_{i=0}^{\infty} a_i U^i
\]

where the \( a_i \) depend on which wind variable and model is used. Curvilinear regressions were performed with the \( U \) as the independent variables. The quadratic terms of (22) for \( U_3 \), \( U_{10} \) and \( U_{N,10} \), and of (23) for \( \tau \) are not statistically significant. The linear fit of \( p_0 \) to \( \eta^* \) differs from the quadratic by at most 10% over the range of values of the FASINEX dataset. Figure 6 shows both the linear and quadratic fits to the data for \( U_3, 10 \), \( \eta^* \), and \( \tau \). The linear fits are very good, especially considering the imperfect wind data. It is, therefore, a good approximation to relate pressure fluctuations linearly to wind variables:

\[
p_0 = (b + sU), \quad \text{for } U_3, U_{10}, U_{N,10}, \eta^* \quad (24)
\]

\[
p_0^2 = (b + sU), \quad \text{for } \tau \quad (25)
\]

where the \( b \) and \( s \) are linear regression coefficients given in Table 4. They differ somewhat from the values of \( a_0 \) and \( a_1 \) derived from (22) and (23). The minimum \( SSL_0 \) value of the quiet dataset is \( SSL_0 = 34 \text{ dB} \), corresponding to \( p_0 \) and \( p_0^2 \) values of about 51 and 2600, respectively, and the linear relationships appear to hold to these limits.

Extrapolation of (24) and (25) leads to no sound \((p_0 = p_0^2 = 0)\) at finite values of the wind variables (e.g., \( U_3 = 1.9 \text{ m s}^{-1}\)). This feature may be real, in that the surface processes (e.g., breaking waves) that generate the sound may not be active in lower winds. In this case the ambient sound could not be used to
estimate these lower winds. Another possibility is that the pressure to wind relationships become very non-linear at low signal levels. A possible complication is that FASINEX wind records represent vector time averages, whereas the ambient sound should depend on a scalar spatially averaged wind. Typically vector and scalar averages differ by only about \( \frac{1}{2} \% \), but in very light winds with highly variable wind direction the scalar average could be much larger than a vector average.

5. A WOTAN wind algorithm

An algorithm is needed to estimate, from a WOTAN measurement of SSL at frequency \( f < f_c \) (12) at depth \( h \), the five wind variables \( V \) corresponding to the buoy measurements \( U \) given by (9). Assuming that a local sound speed profile is available, a value of \( \beta(f) \) can be estimated from (6), and SSL, \( p_0 \), and \( p_0^2 \) from (5) and (7):

\[
\mathrm{SSL}_0 = \mathrm{SSL}(f) + Q \log(f_0/f) + \beta(f)
\]

\[
p_0 = 10^{(\mathrm{SSL}_0/20)}.
\]

(26)

Although the quiet dataset is well described by the quadratic fits (21), (22), and (23), we chose not to use them for the following reasons. A simple physical model is less likely to predict a quadratic dependency, than a linear one such as (24). There are cases where the quadratic equations do not have real roots, so inversion is not always possible. The regression coefficients depend strongly on the wind speed range of the dataset. Instead, the linear relations (24) and (25) are used to give

\[
V = \begin{cases} 
(p_0 - b) s^{-1}, & \text{for } U3, U10, U_N10 \\
(p_0^2 - b) s^{-1}, & \text{for } \tau
\end{cases}
\]

(27)

where \( f_0 = 8.0 \) kHz is the reference frequency at which the coefficients \( b \) and \( s \) were determined (Table 4).

The values of \( V \) corresponding to \( p_0 = 0 \) are the lowest wind values that can be calculated from (27). For most purposes measurements of lower winds are not important because such winds contribute little to the wind stress and heat fluxes, and hourly scalar averages are rarely so small. Therefore, no attempt is made here to extend (27) to accommodate this range of winds. The quadratic fits (21) could be patched to (27) so that any nonzero \( p_0 \) measurement would give finite values of \( V \). It seems prudent, however, to wait until much better low-wind anemometer measurements become available before exploring the small value wind to ambient sound relationships.

Comparisons of WOTAN estimates and buoy observations are very good, and three examples are shown in Fig. 7. The five comparisons of \( V \) from the WOTAN and \( U \) from the VAWR all give a correlation coefficient of about 0.97. The slope and offset of the linear regressions are 1.00 and 0.00 respectively, in all five cases. The standard deviation of the \( V \) is only about 3% larger.
than that of the corresponding $U$. The root-mean-square differences are 0.56 m s$^{-1}$, 0.63 m s$^{-1}$, 0.59 m s$^{-1}$, 0.021 m s$^{-1}$, and 0.015 Pa for $U3$, $U10$, $U_{10}$, $u^*$, and $\tau$, respectively. In all cases the degree of scatter is independent of wind speed. These results demonstrate that the algorithm (27) produces very good wind estimates from the SSL0 values of the quiet dataset. There are no systematic biases, and minimal scatter. Since the key wind dependencies are linear, extrapolation to higher wind speeds is less dangerous than would be the case for higher order relationships.

Plots of the observed differences between estimated and observed wind speeds, estimated from the lowest acoustic frequency (3.0 kHz) (see Fig. 8), suggest that the scatter occurs during periods with changing winds. This could explain why, in Fig. 7, the scatter is independent of wind speed and not normally distributed. The results in Fig. 8 show that the ambient sound algorithm underestimates the wind speed when the wind is increasing and overestimates the wind speed at periods with decreasing winds. Even though no apparent correlation was found between the differences and changes in wind direction it has been suggested (Farmer and Vagle 1988a) that such changes will introduce more wave breaking and, therefore, more ambient sound. Our results indicate variability in the ambient sound field when the surface wave field is out of equilibrium. During periods when the wind is increasing, the ambient sound level lags that predicted for the stationary case, with the opposite occurring for decreasing winds. It is clear that knowledge of the age of the wavefield and the physics of wavebreaking and sound generation mechanisms is needed if even better wind estimates from ambient sound are required, especially if the variability at timescales shorter than 12 hours is important. This may not be true, however, in the case of bulk derived wind stress estimates such as (9), because smaller than average drag coefficients have been reported during increasing winds (Large and Pond 1981). Therefore, the sound levels could be following variations in wind stress, which may have a similar dependency on wave breaking.

If higher acoustic frequencies are used for wind estimation, bubble effects will also have to be considered (see section 6). We now have a dataset in which the wavefield was observed so that effects of the wavefield age on the ambient sound can be investigated further.

a. Tests with independent data

Are the relationships (27) between the ambient sound and wind variables universal? This question is examined using the four datasets from different locations described in section 3. Only the 4.3 kHz channels were used and values for SSL0 were obtained using the $\beta$ values listed in Table 1. The data were averaged over 60 minutes for QCS and CASP and over two hours (to reduce the number of points) for Ocean Storms. The FASINEX derived algorithm (27) was applied to these averages to produce wind speed estimates, which are plotted against locally measured wind speeds in Fig. 9.

Least squares fits were derived from the data. Although a unit slope fits well in the 6–12 m s$^{-1}$ wind speed range for all four cases, there remain serious discrepancies. In QCS1 and QCS2 the ambient sound underestimates the anemometer wind speeds by 2.6 $\pm$ 1.0 m s$^{-1}$ and 2.0 $\pm$ 0.6 m s$^{-1}$, respectively. At the higher wind speeds the unit slope relationship is lost. For CASP the ambient sound estimates are 2.9 m s$^{-1}$ above the anemometer winds, and there is very significant scatter. Here the departure from unit slope is most obvious at wind speeds below 6 m s$^{-1}$. Figure 5 indicates that a 2 m s$^{-1}$ change in wind speed from 5 to 7 m s$^{-1}$ corresponds to about a 4 dB change in SSL0, which is much larger than the uncertainty in the SSL0 measurements.

The OCEAN STORMS data, in contrast, show excellent agreement. These, like the FASINEX data were collected in the deep ocean and Fig. 9 supports the applicability of the algorithm (27) for oceanic wind

### Table 4. Regression coefficients for linear and quadratic fits between pressure fluctuations $p_b$ and $p_b^2$ and the wind variables.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Response</th>
<th>Quadratic</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a_0$</td>
<td>$a_1$</td>
</tr>
<tr>
<td>$U3$ (m s$^{-1}$)</td>
<td>$p_b$</td>
<td>-38.77</td>
<td>42.95</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}p_b^2$</td>
<td>6.81</td>
<td>-2.89</td>
</tr>
<tr>
<td>$U10$ (m s$^{-1}$)</td>
<td>$p_b$</td>
<td>-35.72</td>
<td>40.76</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}p_b^2$</td>
<td>5.85</td>
<td>-2.32</td>
</tr>
<tr>
<td>$U_{10}$ (m s$^{-1}$)</td>
<td>$p_b$</td>
<td>-63.16</td>
<td>43.35</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}p_b^2$</td>
<td>6.29</td>
<td>-2.51</td>
</tr>
<tr>
<td>$u^*$ (m s$^{-1}$)</td>
<td>$p_b$</td>
<td>-109.9</td>
<td>1698.8</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}p_b^2$</td>
<td>-684</td>
<td>-11.34</td>
</tr>
<tr>
<td>$\tau$ (Pa)</td>
<td>$p_b$</td>
<td>77.99</td>
<td>3012.7</td>
</tr>
<tr>
<td></td>
<td>$10^{-4}p_b^2$</td>
<td>-1.672</td>
<td>136.22</td>
</tr>
</tbody>
</table>
measurements. In the range of the FASINEX calibration a linear regression gives 0.0 m s\(^{-1}\) offset and a near unity slope of 0.99. Thus the FASINEX cups at 3.6 m height give the same wind speed as the Ocean Storms propellers at 5.0 m. Since wind speeds at 5.0 m should be about 3% higher than winds at 3.6 m, use of the WOTAN as an intermediate standard indicates that the FASINEX cups overspeed by only 3% relative to the Ocean Storms propellers.

The reasons for the observed discrepancies in Queen Charlotte Sound and CASP are not fully understood. The WOTAN instruments in both deployments were bottom mounted in shallow water and possible effects due to the bottom are hard to establish. Farmer and Lemon (1984) concluded that the contributions of bottom reflected sound will be very small for the layered sediments found in Queen Charlotte Sound. However, Ingenito and Wolf (1989) found substantially lower SSL values in deep water than in shallow depths (often greater than 10 dB) under the same wind speed and sea-state conditions for frequencies greater than 2 kHz. Zakarauskas et al. (1989) observed ambient sound levels on the Scotian shelf, where the CASP instrument was deployed, which were approximately 5 dB above the corresponding deep water SSL in the 30–900 Hz frequency range. These results agree with similar measurements of Wenz (1962). Zakarauskas et al. (1989) also reported a very high shipping density and excellent propagation conditions in the same area. Large temporal variations in the spectral slope measured in CASP and the large scatter, tend to confirm the presence of shipping and other industrial noise. The low frequency results reported by Zakarauskas et al. and Wenz cannot be directly applied to the high frequency results reported in this study, but rather give an indication of possible reasons for the departures from unit slopes and the bias in Fig. 9. The QCS WOTAN instruments were not calibrated in the same way as the later instruments used in CASP, FASINEX, and Ocean Storms and this can be a source of error. It is also worth noting the difference between QCS\(_1\) and QCS\(_2\) in Fig. 9 for two instruments less than 100 km apart, indicating possible disagreements within the anemometer calibrations. It is also known that limitations in fetch will influence the wave field and in turn affect the sound produced by wave breaking. The QCS and CASP datasets were obtained during fetch limited conditions for certain wind directions.

6. Anomalies

WOTAN data affected by source of noise other than the wind must be identified before applying an algorithm such as (27) to obtain wind estimates. The criterion need not be as stringent as used to generate the quiet dataset, because the purpose is not to establish universal empirical relationships. The FASINEX dataset was used to check if a flagging operation leads to
sensible results. A shipping flag was set according to only one criterion, namely (16), when $\Delta S S L (8.0-3.0)$ fell below $-9.37$ dB. Of 4063 flagged data points, 89% were coincident with wind speeds less than 4 m s$^{-1}$. At these lower wind speeds the wind generated SSL is much reduced, resulting in ships being detected at a

![Graphs showing wind speed estimates from different datasets with regression lines](image)

**Fig. 9.** Wind speed estimates from (27) and 4.3 kHz channels on independent WOTAN ambient sound datasets: Queen Charlotte Sound (QCS1 and QCS2), CASP, and Ocean Storms. The data are hourly averages except for Ocean Storms where two hour averages were used.
larger range. It is also possible that in winds below 2 m s\(^{-1}\) the slope of the wind generated sound spectrum changes as a result of changes in the sound producing mechanisms.

The characteristic shape of the ambient sound spectrum produced by precipitation makes it possible to distinguish this sound source. In the absence of wind it may also be possible to obtain the rainfall rate and drop size distribution from measurements of the ambient sound (Scrimger et al. 1987, 1989; Nystuen and Farmer 1987a, 1987b). Our present understanding, however, is insufficient to allow determination of rainfall rates and drop size distributions in the presence of both wind and rain. This is partly due to lack of reliable independent measurements of rainfall rates at sea. Also, there may be a wind speed limit above which the background wind generated sound masks the spectral signature of precipitation. Since the surface buoy had no instrument for measurements of rainfall, it is not our intention here to investigate the possibility of measuring the rainfall rate but rather to check our ability to flag and measure the frequency of these periods. An increase in the high frequency part of the sound spectrum above about 12.5 kHz is an indication of precipitation (Nystuen and Farmer 1989). The spectral slopes between 3.0 and 8.0 kHz and between 3.0 and 19.5 kHz are both used as measures of precipitation:

\[
\Delta SSL(19.5-3.0) > (Q + 3) \log(19.5/3) = -13.25 \text{ dB} \quad (28)
\]

or

\[
\Delta SSL(8.0-3.0) > (Q + 3) \log(8/3) = -6.82 \text{ dB}. \quad (29)
\]

Equation 25 was added to give an indication of precipitation at higher wind speeds when the 19.5 kHz channel will be masked by the presence of bubbles. As an independent measure of periods with rain, we made use of the relative humidity, insolation, and air-temperature records from the surface buoy, and a 24 hour time series of these quantities and of \(\Delta SSL(19.5-3.0)\) are plotted in Fig. 10. At approximately 0100 UTC year day 82 the relative humidity rose to above 90%, the wind speed dropped by 4 m s\(^{-1}\), and the air-temperature dropped by more than two degrees. There was, therefore, a high probability of rainfall until 0800 UTC when the wind speed and air-temperature rapidly increased, and the relative humidity dropped. Spectra averaged over 8 points, or 30 minutes, were spline fitted for all channels except the 5.3 and 25.0 kHz from 0:00 to 9:30 UTC year day 82 and are shown in Fig. 11. The spectra indicate that it started raining between 0130 and 0200 UTC. The spectral slope at this time suggests light rain followed by the characteristic spectrum of heavier rain at 0530 UTC. It appears to have stopped raining sometime between 0730 and 0830 UTC.

![Figure 10](image)

**Fig. 10.** Difference in sound spectrum level between 19.5 and 3.0 kHz showing changes in slope associated with precipitation as suggested by increasing relative humidity, decreasing air temperature, and falling wind speed.

In order to obtain a measure of the efficacy of (28) and (29) at detecting periods with rain, WOTAN records flagged as precipitation data points at which one or both inequalities were satisfied were correlated with the changes in relative humidity, air-temperature, and insolation. Of the 2298 flagged records, 1511 satisfied (28), 1550 satisfied (29), and 763 satisfied both. From the buoy records, it was found that 680 points (45\%) satisfied (28) at periods with high likelihood of rain, 366 (24\%) satisfied (29), and 300 (40\%) satisfied both. Of the total number of flagged points, 1346, or 58\%, correspond to periods of increased relative humidity and decreased insolation (when available) and air-temperature. It is impossible to discard the other 42\% of the flagged data points without more accurate measurements of precipitation. However, 75\% of these data points were flagged during periods with wind speed less than 2 m s\(^{-1}\). At these lower wind speeds there is little wave breaking and the \(-19.0 \text{ dB/decade} \) slope cannot be expected to dominate the acoustic spectrum (see section 4b). We found that for wind speeds above 12 m s\(^{-1}\), (29) gave the best agreement between rainfall periods estimated from the WOTAN records and the rain periods as suggested by the meteorological datasets. For wind speeds below 12 m s\(^{-1}\) (28) gave the best agreement. This agrees well with the results obtained by Farmer and Lemon (1984), who found that above 10–12 m s\(^{-1}\) the higher acoustic frequencies will be attenuated by the presence of large numbers of microbubbles.
FIG. 11. Sound spectra $SSL_0(f)$ averaged over eight points, or 30 minutes, from 0000 to 0930 (UTC) on year day 82. Dashed lines indicate a slope of $-19$ dB/decade.

When the anomalies due to precipitation, shipping noise, and low wind speed have been removed from the ambient sound time series, the remaining variations in spectral slope are mostly caused by masking of the sound by microbubbles. In Figure 12 the spectral slope as well as the wind speed have been plotted against time for a six week period. The spectral slopes have been averaged over 30 minutes and data points satisfying (16), (28), or (29) have been removed. The low frequency modulations in the spectral slopes correspond directly to changes in wind speed. The higher frequency sound is absorbed in the bubble layer and the spectrum becomes steeper. This effect is clearly seen at the times marked A and B in Fig. 12, where the wind speed increases above 11 m s$^{-1}$. The attenuation of the sound even affects the 8.0 kHz signal and puts restrictions on algorithms that make use of changes in the spectral slope to determine precipitation and shipping noise. For the wind speed range 4–11 m s$^{-1}$, the acoustical spectral slope varies as much as $\pm 2$ dB/decade.

7. Evaluation of an operational system

The analysis of the quiet dataset in section 4 established an empirical relationship between $SSL$ and both frequency and wind. The OCEAN STORMS results indicate that this relationship holds in deep ocean regimes. However, these analyses do not provide an evaluation of how well a WOTAN may perform as part of an operational wind measurement system. For that purpose we now use the FASINEX WOTAN dataset to simulate what might be transmitted from such a system in a remote environment. A continuous-wind

FIG. 12. Spectral slope averaged over 30 minutes for year days 55 to 97 showing the effect of bubbles in modulating the spectral slope during periods with high winds: (A) and (B).
time series is constructed, which is then compared to the FASINEX buoy winds. The FASINEX dataset is utilized here to assess how serious WOTAN problems are in both the time and frequency domains. Examples of potential problems are data gaps due to detected extraneous sound, errors due to undetected extraneous sound, uncertain WOTAN estimates at low wind speeds, and the inherent scatter expected from such an indirect measure of the wind.

Suppose a WOTAN system is to be used on a remote platform, such as a free-drifting ocean surface buoy. The number of channels is to be minimized for economy, and for reduced power consumption. We assume that there are data transmission restrictions, so that only one wind value can be received from the platform each hour. On-board processing is needed to check each record for precipitation and shipping sound, and for computing hourly wind values. This processing is to be minimal, because the platform presumably has other tasks to perform. A second stage of processing the received hourly values does not have these restrictions. We simulate remote operation by utilizing only three channels of the FASINEX dataset. A low-frequency channel is needed to indicate shipping sound and to measure high wind speeds; we take the 3.0 kHz channel. A high-frequency channel is needed to indicate precipitation. The spectral peak is at 14 kHz, so the 14.5 kHz channel would have been the optimal choice. However, due to the unreliability of the 14.5 and 16.8 kHz channels we used the 19.5 kHz channel to indicate precipitation. We also take a midfrequency channel to measure low and moderate wind speeds, because these frequencies are less subject to shipping sound contamination than is 3.0 kHz. We use the 8.0 kHz channel, which also allows the slopes of different sections of the sound spectrum to be checked for precipitation and shipping noise.

The simulated on-board processing of these three channels proceeds as follows: for each of the 3.75 minute records taken over an hour, a precipitation flag is set if either (28) or (29) are satisfied, and a shipping flag is set if (16) is satisfied. Hourly averages of SSL, \( \rho_0 \), and \( \rho_0^2 \) at 8.0 kHz are computed from the unflagged records (18), with a null value assigned whenever all 16 records in an hour are flagged. The desired wind variable is computed using the algorithm developed in section 5. A warning flag is set whenever the algorithm produces a \( U_N \) value greater than 14.2 m s\(^{-1}\); such that 8.0 kHz is greater than \( f_c \) given by (12). In these cases, hourly averages at 3.0 kHz are computed and used by the algorithm to give the desired wind parameter. A single wind magnitude is thus produced each hour for transmission. An algorithm still remains to be developed to utilize the high-frequency channel for precipitation estimates. However, the number of precipitation flags set per hour could serve as a measure of precipitation frequency. An additional sensor system would be needed to provide a wind direction for the

hour so that the vector wind velocity and stress could be estimated.

In practice, the sound speed profile and estimates of \( \beta(f) \) may not be available on board. A wind variable computed from (27) will then be an inexact estimate, \( V' \), which will need to be corrected subsequently once the profile is known. The correction is

\[
V = (V' + bs^{-1})10^{(\beta(f)/m)} - bs^{-1},
\]

where \( m = 10 \) for \( V = \tau \) and \( m = 20 \) otherwise. We note that the sound speed profile could be provided by a relatively sparse thermistor array down to the depth of the hydrophone.

In this simulation WOTAN wind estimates could be computed from 93% of the 2513 hours. In 41 cases the warning flag was set for 8.0 kHz channel, so the 3.0 kHz channel was utilized. In 11 of these cases the algorithm indicated too high a wind for the 3.0 kHz, because of spikes in the data.

The processing of the received hourly wind estimates requires first that spikes be removed, and second that these spikes and missing (null valued) data be replaced with interpolated values so that a continuous time series can be constructed. First, the wind time series was converted back to a time series of \( \rho_0 \) values. For each value the slope between it and the preceding accepted value, \( S_1 \), and the slope to the next available value (excluding null values), \( S_2 \), were calculated. A reference slope \( S_0 = 50 \text{ h}^{-1} \) was chosen, and any point was regarded as a spike if \( S_1 > S_0 \) and \( S_2 < -S_0 \). The procedure reflects the fact that spikes due to excess noise were expected. Big jumps were also regarded as spikes if \( S_1 > 2S_0 \) or \( S_2 < -2S_0 \). There were 105 spikes removed. Linear interpolation was used to replace these spikes and to fill in the 169 null values. The resulting \( \rho_0 \) time series was then converted back to wind.

The constructed WOTAN time series and the hourly averaged buoy data have been compared for all five wind variables in both the time and frequency domains. The \( \tau \) time series from \( U \) (buoy) (solid line) and \( V \) (WOTAN) (dotted line) are shown in Fig. 13. There are days of persistent \( V < U \) (day 72), and of persistent \( V > U \) (days 75–76). Interpolation over long periods can miss periods of peak winds (day 28). At low winds there is a tendency for \( V > U \) (e.g., day 65). The buoy data are not perfect and there is a spike in \( U \) at day 56.6. Not all the \( V \) spikes have been removed (day 60). To see how these effects diminish as the averaging period increases we have compared \( U \) and \( V \) averaged over 1, 3, 6, 12, 24, 168, 314, and 628 hours. Table 5 gives the results for \( U_N \) and \( \tau \). A linear regression gives

\[
V = \alpha + \gamma U,
\]

and a correlation coefficient \( r^2 \) for each averaging period. Also computed are the root mean square of the difference \( (U - V) \) and the ratio of the standard deviations, \( \sigma_u/\sigma_v \).
For the shorter averaging intervals there is a positive offset, $\alpha > 0$, and $\gamma < 1.0$, because of the low wind speed tendency for $V$ to exceed $U$. The interpolations smooth $V$, and give $\sigma_v < \sigma_u$, despite any remaining spikes in $V$. The correlation coefficients are always greater than 0.96. After averaging over 24 hours the standard deviations become nearly equal, and the rms values are reduced to about 0.4 m s$^{-1}$ in $U_{N10}$ and 0.01 Pa in $\tau$. Scatterplots of the 12 hour averages, Fig. 14, show only a small bias at low winds. For the most part spikes in $V$ and in $U$ appear to have averaged out. As the averaging gets longer (1 week to 1 month) the amount of data and its range become small, so that regression lines can easily depart from a 1:1 line at

<table>
<thead>
<tr>
<th>Averaging interval</th>
<th>1 h</th>
<th>3 h</th>
<th>6 h</th>
<th>12 h</th>
<th>1 d</th>
<th>1 week</th>
<th>~2 weeks</th>
<th>~1 month</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>2513</td>
<td>837</td>
<td>418</td>
<td>209</td>
<td>104</td>
<td>14</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

$\sigma_V/\sigma_U$  
$\alpha$  
$\gamma$  
$r^2$  
rms

<table>
<thead>
<tr>
<th>$U_{N10}$ (m s$^{-1}$)</th>
</tr>
</thead>
</table>
| 0.93  
| 0.94  
| 0.94  
| 0.95  
| 0.95  
| 0.97  
| 1.04  
| 1.11  
| 1.09  |

<table>
<thead>
<tr>
<th>$\tau$ (Pa)</th>
</tr>
</thead>
</table>
| 0.89  
| 0.90  
| 0.90  
| 0.90  
| 0.93  
| 0.96  
| 0.96  
| 0.98  |

10$^3$$\alpha$  
$\gamma$  
rms
reduced high-frequency variance in the WOTAN is expected as a result of the interpolations and of the inability of the WOTAN technique to track low wind speeds. This behavior may be partially real with the WOTAN spectrum being a better measure of a spatially averaged wind. The enhanced WOTAN low-frequency variance may be due to the low-frequency variations in the wind to sound level relationships discussed in section 6. The agreement in the variances of 24 h averages, as shown in Table 5, is thus fortuitous in that the two tendencies are just canceling one another.

Figure 15 also shows that the two wind time series are highly coherent at frequencies below about 0.05 cph. The coherence begins to drop at a frequency corresponding to a period between 12 and 24 h. The phase relationship between the two time series varies between ±5 degrees at all frequencies, with a slight tendency for the WOTAN to lag. Note that at three hour periods the coherence squared is less than 0.4 and the spectra differ by more than a factor of 2. Thus, WOTAN wind estimates may not be adequate when variability at time scales as small as three hours is important. However, the WOTAN estimates become much better at following 12 h and longer wind variations.

extreme winds even though they agree well within the small cluster of data. This agreement is shown by the small rms values.

Figure 15 compares the buoy and WOTAN $U_{10}$ estimates in the frequency domain. The power spectra from all five wind parameters show similar features. A peak at about $10^{-2}$ cph (4 d period) is captured by both the buoy and the WOTAN. The WOTAN values (dashed line) tend to fall below those of the buoy (solid line) at higher frequencies, and above at lower frequencies. Over the whole spectrum the WOTAN variance is less, but as more averaging excludes the high frequencies the WOTAN variance becomes larger relative to the buoy variance; as seen in Table 5. Again,
8. Conclusions

The observations and analysis described above have shown that ambient sound measurements at depth in the ocean can give reliable estimates of averaged wind parameters provided sufficient care is taken. The ambient sound was converted to a non-dimensional sound spectrum level at a depth of 1 m in order to account for variable instrument depths and acoustic refraction from site to site. High frequency data at high wind speeds were not used, because of potential attenuation by near surface bubbles. Multiple frequency channels were used to flag periods of suspected precipitation and shipping, both of which generate extraneous noise. Careful calibrations of the entire system were performed at the temperature of the instrument during deployment.

The analysis and establishment of empirical relations were complicated by the uncertain performance of the FASINEX anemometers. The FASINEX propeller data of the MR was not reliable, so the VAWR cup anemometer data was used, even though overspeeding by an unknown factor g was expected. The WOTAN wind algorithm (27) developed using the FASINEX VAWR data holds for independent data from the Ocean Storms experiment with \( g = 1.03 \) for \( U_3, U_{10}, U_{30.10} \), and \( u^* \) and \( g = 1.06 \) for \( \tau \). These corrections affect neither the form of (27), nor the offsets \( b \), but the linear regression slopes of Table 4 should be increased from \( s \) to \( gs \), thereby reducing the WOTAN wind estimates appropriately.

The algorithm (27) does not hold in shallow waters or close to shore, presumably because of changes in the ambient sound field due to environmental factors such as industrial noise, bottom effects and effects of wind direction on the fetch. Inadequate performance of the anemometers, or the acoustic instrumentation may also have contributed to this result.

At high wind speeds the effects of microbubbles on the higher frequencies become important. However, for the wind speeds observed in the experiments discussed here (≤16 m s\(^{-1}\)) the lowest frequencies (<8 kHz) were minimally influenced by the bubbles. At the highest wind speeds observed in OCEAN STORMS the results shown in Fig. 9 suggest a departure from a linear relationship. However, due to the limited amount of data further studies are needed to check the relationship at wind speeds above 16 m s\(^{-1}\).

The results indicate that the wind speed and frequency dependencies of the acoustic spectrum are separable. The latter is found to vary as \( f^{-1.9} \), though this appeared to approach \( f^{-2} \) at higher wind speeds. An overall \( f^{-2} \) dependency is not ruled out because other sources of sound besides the wind were likely present. The mean square pressure fluctuations were linearly related to the wind stress and the root mean square pressure fluctuations were linearly related to the wind speed and friction velocity.

The finding of Farmer and Vagle (1988b) that most of the high frequency ambient sound is generated by breaking waves suggests that the state of the surface wave field should be more important than these results indicate. However, the analysis in section 6 shows that the ±0.5 m s\(^{-1}\) limit in the wind speed estimates can be reduced by including the state of the ocean surface. The influence of changing wave conditions and the resulting lag between the wind speed and the ambient sound field suggests that averages greater than at least three hours are needed to obtain reliable wind estimates from the ambient sound.

The evaluation of an operational system suggests that the ambient sound to wind relationships and contamination are sufficiently well understood to allow routine wind estimates from a remote system. The errors due to problems such as a lack of understanding of the underlying physics of sound generation, undetected extraneous sound, data gaps, and low wind speeds do not appear to be serious. A simple three channel system should suffice, and internal processing could reduce the data flow to one data word per hour. Subsequently despiking and interpolation could produce a continuous wind record. When averaged in 12 hour blocks the wind estimates from such a system would be indistinguishable from those from an anemometer. Over shorter time periods there are noticeable differences and the coherence decreases.

The WOTAN wind estimates could not be compared to direct measurements of a spatially averaged wind. The use of time-averaged buoy winds may explain some of the low wind-speed behavior, and the loss of high-frequency coherence and variance. For some purposes, such as initializing atmospheric models and forcing ocean numerical models, the use of spatial averages is more appropriate, so the WOTAN estimates could be superior to anemometer winds. This would be especially true if the ambient sound was actually more closely related to the turbulent wind, \( u^* \) and \( \tau \), than to the mean wind. These same issues arise in regard to scatterometer estimates of oceanic winds, which are spatial averages that may be more closely related to the turbulent wind.

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