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Measurement of Oceanic Wind Speed Using Acoustic Ambient Sea Noise

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MEASUREMENT OF OCEANIC WIND SPEED
USING ACOUSTIC AMBIENT SEA NOISE

BY

SUSAN L. BOURASSA

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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MASTER OF SCIENCE THESIS

OF

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ABSTRACT

Knowledge of oceanic winds is vital to the understanding of air/sea interactions, but is difficult to obtain. This thesis investigates a technique for determining wind speeds from acoustic ambient noise data. The results show acoustic ambient noise in the ocean at 4.3, 8.0, and 14.5 kHz to be highly correlated with surface wind speed. Measurement of noise at the sea floor yields estimates of wind speed within ± 1 m/sec when compared with coincident surface observations.

Comparisons of ambient noise with coincident surface measured winds has confirmed the frequency dependence of the wind speed - noise relation reported by others (-20 dB/decade). For deployment with a low mean wind speed (4-6 m/sec), separate calibrations are required at 14.5 kHz for wind speeds above and below the speed characterizing white cap formation. The wind - noise calibration equations for the Atlantic and the equatorial Pacific agree with each other and with published results within the limits of experimental uncertainty. The effect of the different hydroographies of the two deployment sites seems to be negligible for deployments at similar depths. There is some evidence that a layer of bubbles at the surface will scatter and absorb high frequency noise sig-

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List of Symbols

Symbol	Definition
α	attenuation coefficient.
a, b, p	coefficients used in determining atmospheric drag coefficient under neutral conditions.
A, B	coefficients of NSL - noise count relation.
A', B', C'	coefficients used in determining the attenuation coefficient.
b'	sensitivity of the hydrophone in units of dB relative to 1 v/uPa .
BW	bandwidth (Hz) of the 3 frequency filters of WOTAN at 4.3, 8.0, 14.5 kHz.
c, d	coefficients of the $\log(\text{wind})$ - noise count relation.
C, D	coefficients of the $\log(\text{wind})$ - NSL relation.
C_D	atmospheric drag coefficient.
CNT	noise count recorded by WOTAN.
f_1, f_2	relaxation frequencies for boric acid and magnesium sulfate used in determining the attenuation coefficient.
GBW	bandwidth of the white noise generator used in the bench calibration of WOTAN.
k	von Karman constant ($k=0.41$).
m, n	coefficients of wind - noise count relation.
NSL	amount of noise pressure variance in a 1 Hz band in units of dB re 1 uPa^2 .
P_{BW}	noise pressure in a one Hertz band.
P_{rms}	rms noise pressure.
r, t	coefficients of noise count - noise voltage relation.

S atmospheric stability parameter.

T ratio of WOTAN's counting period in the ocean to the counting period during the bench calibration.

U(z) wind speed at height, z, above sea surface.

V_{rms} rms noise voltage.

WND wind speed in m/sec.

z_o aerodynamic roughness parameter.

z correction factor to scale 10 m winds to 3.5 m winds.

I. INTRODUCTION

A. Introduction

Reliable wind measurements over the open ocean have been difficult to obtain, but are necessary for the understanding of the complex interactions between the ocean and atmosphere. These interactions include the generation of surface waves, surface exchange processes, the deepening of the mixed layer, eddy motion (Phillips, 1966), and the wind-driven circulation (Swallow, 1980). The conventional methods of determining oceanic winds have included weather logs of ships, island weather stations, a limited number of moored instrumented platforms, and sea level atmospheric pressure charts. Each of the above methods has a weakness or disadvantage associated with it. Ships tend to avoid areas of high wind and stay in rather fixed lanes, thus their logs may be both fair-weather and geographically biased. Islands are not optimally located and their weather may be affected by locally induced convection. The moored platforms are expensive to install and maintain, are subject to sensor malfunction, and may break mooring lines and drift away. Geostrophic estimates of the wind speed can be determined from sea level pressure charts for most regions, but not for the tropics because of

the weak relationship between the wind and mass fields there. Satellite microwave scatterometry is promising but is not yet operational due to the untimely demise of SEASAT.

The idea of determining oceanic winds from acoustic ambient sea noise is relatively new (Shaw, et.al., 1975, Evans, et.al., 1984). The frequency range (2-20 Khz) and depths (3500-3800 m) chosen in this study, though, are unique; most of the other investigators, past and present (Cato, 1976; Crouch and Burt, 1972; Knudsen, Alford, and Emling, 1948; Perrone, 1969, 1970; Shooter and Gentry, 1981; Wilson, 1979, 1980), have studied the relation of wind speed on acoustic noise using data taken at lower frequencies and/or shallower depths than those chosen in this study.

This thesis was undertaken to quantitatively estimate the relationship between ambient noise and surface wind speed, and to compare that relationship for two oceanic environments. Two data sets are discussed in this thesis. The first data set of both ambient noise and surface wind is from a deployment in the equatorial Pacific (0° N 153° W) on NORPAX moorings from May to September, 1979. The second data set of ambient noise and surface wind is from a deployment off the New England shelf (39° N 70° W) from December, 1980 to August, 1981. Wind speeds are calculated from the ambient noise data using an empirical formula, and are then compared with in situ measurements of the surface wind speed.

As will be discussed in a later section, the equations

used to calculate wind speed from the ambient noise data are slightly different for the Pacific and the Atlantic deployments at 14.5 kHz. In order to determine the cause for this difference, the noise data were examined for differences due to season, geographic location, and water stratification. Raytracing techniques were used to trace the path of sound from the surface to the hydrophone depth. The temperature and salinity of the water column are used to calculate the sound speed profile, which is then used in the determination of the paths of the sound rays. This process will also determine the radius of the 'listening' area on the sea surface.

The remainder of this paper will be organized as follows. A brief review of historical literature will be followed by a section on the generation mechanism of ambient noise in the open ocean. The Methods section will discuss the instruments used, the laboratory calibration of the acoustic instruments, and will derive the equations used in calculating wind speed from ambient noise. Observation and Results are both divided into two sections - Pacific and Atlantic. The Discussion section will cover a comparison of the Pacific and the Atlantic results and will summarize my findings.

B. Historical Review

Underwater acoustics has been the subject of investigation since the early 1900's, but it was not until World War II that the technology was sufficient for major strides to be taken. Knudsen, Alford and Emling (1948) summarized the major advances in the study of underwater sound made during the war. Although the technology and data were limited, their results on the relationship between ambient noise and sea state and wind force are well-known and are still a good first approximation in the frequency range 500 Hz to 25 kHz (figure 1). They determined that in the absence of marine and man-made noise, the major contributor to ambient noise in open and deep water was water noise correlated with the agitation of the sea surface. The major emphasis of ambient noise studies during the war and thereafter was using the wind force or sea state to predict ambient noise levels so that SONAR operators would be able to determine background noise levels.

Since World War II, many advances have been made in instrumentation and recording technology, and the pre-WWII data base has been extended in terms of geographic coverage, frequency range and depth of observation. In 1962, Wenz reviewed the literature and drew the following conclusions. He suggested that the ambient noise spectrum is composed of

four overlapping component spectra: (a) a low frequency component (1-100 Hz), with a spectrum level slope of approximately -10 dB per octave and wind-dependence in shallow water, whose probable source is turbulent pressure fluctuations; (b) a mid-frequency component (10-1000 Hz), with a broad maximum between 10-200 Hz and a sharp negative spectral slope at frequencies above the maximum, the probable cause is oceanic traffic noise; (c) a high frequency, wind-dependent component (50 Hz to 20 kHz), primarily resulting from sea surface agitation, with a spectrum level slope of -6 dB per octave above 1 kHz; (d) a thermal noise component with a +6 dB per octave slope which becomes important at frequencies greater than 20 kHz and low wind speeds. Piggott (1964) determined that the noise spectrum level attributed to the wind-dependent source was proportional to the logarithm of the wind speed for shallow water noise data. Other investigators, (Crouch and Burt, 1972 and Perrone, 1969, 1970), have also shown this logarithmic relationship for deeper water. Shaw et.al., (1975) were the first to investigate the feasibility of determining wind speeds from ambient noise measurements. Up to this time, other investigators were still interested in determining noise levels from wind measurements.

C. Mechanism of Sound Generation

Despite over sixty years of study, the mechanism by which the wind-dependent noise (frequency range 2-20 kHz) is produced is still poorly understood. White caps and spray will create noise when they exist, however the ambient noise levels also increase steadily at the lower wind speeds where white caps are absent. Figure 2 is a diagram showing some of the sources of deep water ambient noise (Urlick's figure 7.1, 1983). Several mechanisms have been put forth, but it is not known whether ambient noise is generated predominantly by one of these mechanisms or by some combination of them. Marsh (1962) suggested that wave motion at the surface would set up pressure waves at depth in the fluid which would be received by a hydrophone as noise. The wave motion, height, and period would all be functions of the prevailing wind field. Kuo (1968) investigated the possibility of noise generation by capillary patches ("cat's paws") on the sea surface, where the noise is related to pressure fluctuations due to the capillary waves, this time under forced conditions. Wenz (1962) and others (Franz, 1959; Thorpe and Humphries, 1980) have investigated the excitation of small bubbles near the surface as the generation mechanism for ambient noise. There would be both free and forced oscillations of bubbles in the ocean, particularly in the surface agitation due to wind

action. Franz (1949) has studied air bubbles formed when air is entrained in water following the impact of a water droplet on the surface of the water. He found the sound energy radiated by these bubbles has a gradual decline of -6 to -8 dB per octave toward higher frequencies (greater than 1 kHz). This bubble noise slope agrees with the ambient noise spectrum slope above 1 kHz (-6 dB/octave) given by Wenz and Knudsen. These bubbles radiate efficiently at their natural frequencies and the noise from the bubbles could be observed at a considerable distance. Natural frequency of the bubble is inversely proportional to its size. A bubble of radius 0.33 cm would oscillate at about 1000 Hz; a bubble of radius 0.066 cm would oscillate with a frequency of 5 kHz (Wenz, 1962). Thorpe and Humphries have studied the relationship between acoustically detected sub-surface bubble clouds and white caps or breaking waves in a lake environment. They concluded there is some causal relationship between subsurface bubble clouds and breaking waves, but they could not determine that relationship from their data. Cavitation noise also shows the -6 dB per octave slope at frequencies greater than 1 kHz. It also produces a broad-band maximum similar to the noise spectrum in the frequency range 0.1 to 1.0 kHz (see figure 1) (Wenz, 1962, Urick, 1983).

Burger and Blanchard (1983) have shown an increase in bubble surface life with decreasing humidity and increasing wind speed at the surface. These factors increase evapor-

ation, creating a salinity gradient along the bubble cap which produces a surface tension gradient. The effect of the increased surface tension is to pull water up to the bubble cap, resisting the thinning of the cap by gravity flow, and thus causing a longer surface life. With longer lifetimes, bubbles would have more oscillations before bursting and would thus create more noise than bubbles with shorter lifetimes. Another effect of longer bubble lifetimes would be to increase the bubble population which would again increase the amount of noise. Franz has also investigated the effect of water droplets from spray and precipitation on underwater sound levels and has determined that rainfall will add noise at all frequencies. He has also shown the spectrum of rainfall noise is nearly white, whereas Knudsen's spectrum of wind generated noise has a slope of -6 dB per octave (-20 dB per decade). Figure 3 (from Shaw, et.al., 1975) shows the Franz curves for three rainfall rates with the Knudsen curves for three wind speeds superimposed. Because of the different spectral slopes of the wind-dependent noise and the rain-dependent noise, the measurement of ambient noise levels at more than one frequency allows, in principle, for the calculation of both wind speed and rainfall rate. More importantly, measuring noise levels at different frequencies enables one to isolate wind events versus non-wind events.

Nystuen (1983) has investigated the sound produced by spray and water droplets falling on a water surface. He has

found a large broad-band peak centered between 15 and 20 kHz in the rainfall spectrum. Because of this broad peak, the rainfall noise spectrum between 4 and 15 kHz is blue, instead of white as Franz showed. The reason for this apparent discrepancy may be due to the size of the rain drops studied. Franz studied mainly large rain drops. Nystuen has found that large rain drops, greater than 2 mm, increase the ambient noise spectral level at all frequencies. This is similar to Franz' results. For small rain drops, less than 1.5 mm, Nystuen has found that the ambient noise levels only increase at the higher frequencies, near 14-15 kHz; the noise levels did not increase at frequencies near 4.5 kHz. Thus small raindrops would give rise to a blue spectral slope between 4 and 15 kHz, and large rain drops would give rise to a white spectral slope in the same frequency range.

II. METHODS

A. Equipment

Two instruments, named WOTAN (Weather Observations Through Ambient Noise), were built to record acoustic ambient noise while moored on the seafloor (Evans and Watts, 1981). They operate at 4.3, 8.0, and 14.5 kHz, spanning nearly two octaves. Figure 4 is a photograph of the electronics and hydrophone and figure 5 is a block diagram of the major components. Each instrument consists of an aluminum pressure case, a sensitive omnidirectional hydrophone, a low noise, low power amplifier, $\pm 7.5\%$ band-pass frequency filters, logarithmic peak detector circuit and digitizer developed by W. Hill of Sea Data Corporation. The log peak detector responds to the envelope of the noise signal. (A true RMS detector would have been better, but the log peak detector was all that was commercially available at the time). It is quite sensitive to short period spikes in the input signal, which could give an artificially high output. Considerable effort was devoted to eliminate low level pickup problems in the detector itself. Probability density analyses (Urlick, 1983) indicate oceanic ambient noise is nearly Gaussian, so that

the bench calibration method using Gaussian white noise gives the correct relationship between detector input and output. Another weakness associated with log detectors in general occurs when the NSL values change significantly during the averaging period. In this case the average of $\log(\overline{V^2})^{0.5}$ does not equal the log of the average of $(\overline{V^2})^{0.5}$. This weakness does not affect these measurements significantly because WOTAN's NSL records are shown to have very little variance at periods as short as the averaging period (4.25 min.), in agreement with Byshev and Ivanov (1969). The system responds linearly through 66 dB of dynamic range. Data are averaged for a selected measurement period (2-60 min.) and are recorded on a high density digital tape recording system for periods up to one year. All functions are controlled by a crystal clock and are powered by lithium batteries.

B. Instrument Calibration

The underlying assumption in the bench calibration of the WOTAN instrument is that if a white noise generator circuit with the proper impedances is placed in series with the hydrophone, then the rest of the system will accept the noise generator signal as originating from the hydrophone and data can be collected as a function of a known input (figure 6).

One feature of the calibration is that the input test signal is allowed to travel through the entire instrument signal path before being recorded. This allows for checks on the operation of the entire system in subsequent calibrations. The noise generator circuit consists of a General Radio white noise generator (bandwidth = $\pi/2 * 20000$ Hz), an attenuator and two resistors serving as a voltage divider. A measured voltage from the noise generator is input to the system and the digital output is recorded on a bit box.

The setup for determining the bandwidth of the filters is similar to that of the calibration except the white noise generator is replaced by an audio oscillator and the input voltage is attenuated to the millivolt range to prevent saturation of the electronics. In this procedure, a known frequency is the input and digital counts are recorded as the output.

Figures 7 and 8 are plots of the calibration data of counts versus voltage for the two instruments, S/N 001 and S/N 002, respectively. The curves roll off at high signal levels due to saturation of the electronics; the curves roll off at low signal levels due to the threshold level of the self-noise of the instrument. The data in the linear region are fitted by linear regression to the expression:

$$CNT = r * 20 \log \left(\frac{V_{rms}}{1 \text{ v}} \right)_{gen} + t \quad (1)$$

where CNT are the output and V is the input voltage and r and t are regression coefficients. Table 1 tabulates the coefficients, r and t , at each frequency for the two instruments, including the uncertainty at the 95% confidence level in each term. The WOTAN instruments have been calibrated four times since their first deployment, and the four calibrations have yielded the same coefficients for equation 1 within experimental uncertainty.

The relationship between the digital counts and the noise spectral levels, NSL, (defined as the amount of noise pressure variance in a 1 Hertz band, in units of dB relative to 1 micropascal²), can be determined empirically.

By definition:

$$NSL = 10\text{Log} \frac{P_{rms}^2}{\text{Hz}} \frac{P_{ref}^2}{\text{Hz}} \quad (2)$$

where $P_{ref} = 1 \mu\text{Pa}$.

This rms pressure can be expressed in terms of the filter bandwidths as:

$$NSL = 20\text{Log}(\overline{P_{BW}^2})^{0.5} - 10\text{Log}(BW) \quad (3)$$

The noise pressure received at the hydrophone is converted to a voltage; they are related by the following expression for the frequency band of interest.

$$20\text{Log}(V_{\text{rms}})_{\text{BW}} = 20\text{Log}(\overline{P^2})_{\text{BW}}^{0.5} + b' \quad (4)$$

where b' is a measure of the hydrophone sensitivity, provided by the manufacturer in units of dB re 1V/ μPa .

Combining equations 3 and 4 will give NSL in terms of noise voltage.

$$\text{NSL} = 20\text{Log}(V_{\text{rms}})_{\text{BW}} - 10\text{Log}(\text{BW}) - b' \quad (5)$$

In order to relate NSL to the digital counts, we need the relationship between the V_{rms} noise voltage (transducer input) and the input test voltage. As before, V_{rms} can be expressed in terms of the filter bandwidth.

$$20\text{Log}(V_{\text{rms}}) = 20\text{Log} \frac{V_{\text{rms}}}{\sqrt{\text{Hz}}} + 10\text{Log}(\text{BW}) \quad (6)$$

The voltage from the noise generator is given by

$$20\text{Log}(V_{\text{rms}})_{\text{gen}} = 20\text{Log} \frac{V_{\text{rms}}}{\sqrt{\text{Hz}}} + 10\text{Log}(\text{GBW}) \quad (7)$$

where GBW is the bandwidth of the white noise generator.

Combining equations 6 and 7, yield the relationship between noise voltage and the test voltage.

$$20\text{Log}(V_{\text{rms}})_{\text{BW}} = 20\text{Log}(V_{\text{rms}})_{\text{gen}} + 10\text{Log}(\text{BW}) - 10\text{Log}(\text{GBW}) \quad (8)$$

Combining equations 5 and 8 will give the relationship

between NSL and the test voltage.

$$NSL = 20\text{Log}(V_{\text{rms}})_{\text{gen}} + 10\text{Log}(BW) - 10\text{Log}(GBW) - 10\text{Log}(BW) - b' \quad (9)$$

Combining terms yields

$$NSL = 20\text{Log}(V_{\text{rms}})_{\text{gen}} - 10\text{Log}(GBW) - b' \quad (10)$$

Equation 1 is the relationship between the input test voltage and the output digital counts for the laboratory calibration. The relationship between the test voltage and the counts from an ocean deployment includes a factor for the different counting periods for deployment (255.1996 sec) and calibration (15.1996 sec).

$$CNT_{\text{oc}} = T[r*20\text{Log}(V_{\text{rms}})_{\text{gen}} + t] \quad (11)$$

$$\text{where } T = \frac{255.1996}{15.1996}$$

Rearranging terms yields

$$20\text{Log}(V_{\text{rms}})_{\text{gen}} = \frac{CNT_{\text{oc}}}{T*r} - \frac{t}{r} \quad (12)$$

Combining equations 10 and 12

$$NSL = \frac{CNT_{\text{oc}}}{T*r} - \frac{t}{r} - b' - 10\text{Log}(GBW) \quad (13)$$

or

$$NSL = \frac{CNT_{OC}}{A} + B \quad (14)$$

where $A = T \cdot r$ and $B = -\frac{1}{r} - b' - 10 \log(GBW)$

The coefficients A and B are tabulated in Table 2. A detailed example of the propagation of errors for equations 13 and 15 may be found in the appendix.

The bandwidth of the 14.5, 8.0 and 4.3 kHz filters in WOTAN were determined by inputting known frequencies and recording the output counts. Equation 1 was used to calculate voltages from the counts. The voltages are normalized by the highest voltage (usually at the center frequency), and this value is then squared and plotted against frequency. Sample bandwidth plots are shown in figures 9 and 10. The center frequency may be determined by finding the midpoint between the -3 dB points of the normalized voltage squared versus frequency curve. The bandwidth, in Hertz, is determined by integrating that same curve. See Table 2 for the bandwidths of each filter of the two instruments.

C. Data Processing Techniques

The noise data recorded by WOTAN is stored on a high density digital cassette tape. Upon recovery of the instru-

ment, the data on the cassette tape is transferred to a 9-track tape using the HP-2116 computer. The data is then run through a bitsorting program on the Prime computer to convert the data to integers.

The raw acoustic data is checked for continuity in time, and compared with the coincident wind speed data. As was mentioned in the introduction, Piggott and others have shown the ambient noise in the ocean is empirically related to the common logarithm of the wind speed by an expression of the form:

$$20\text{Log}(\text{WND}) = C*\text{NSL} + D \quad (15)$$

The coefficients, C and D, are determined by performing a linear regression (log of the wind speed versus NSL's) on a small subset of the data. To give equal weighting to the different wind speeds throughout the observed range, seven pairs of uncorrelated observations (wind and noise) are selected in each 1 m/s class interval for the regression subset. The maximum number of uncorrelated observation available at the lowest wind interval (1-2 m/sec) and the higher wind intervals (9-10 m/sec, Pac. and 15-20 m/sec, Atl.) was seven. Therefore seven observations were chosen for each 1 m/sec interval. Once the coefficients have been calculated, wind speeds for the entire acoustic data set can be determined by equation 15. Table 3 contains the coeffi-

cients of equation 15 for both the Atlantic and Pacific deployments.

The WOTAN instrument records all ambient noise impinging on the transducer, thus bursts of noise from sources other than the wind action at the surface are also recorded. These spikes in the data are removed with a despiking program which replaces data outside a specified window. The program replaces bad points with values interpolated from a running average. The width of the window was chosen by determining the spikiness of the measured wind data.

For final presentation, a smoothing program was run on all of the data, both measured winds and calculated winds. The data were smoothed or averaged over 6 hours.

III. OBSERVATIONS

A. PACIFIC

Both WOTAN instruments, S/N 001 AND S/N 002, were deployed in the equatorial Pacific at 3800 m depth and each mooring had surface instruments (VAWR) measuring wind speed, direction, atmospheric pressure, and air and sea temperature. The sensors on the VAWR were located 3.5 m above the sea surface. The VAWR's were deployed and maintained by Dr. David Halpern of the Pacific Marine Environmental Laboratory in Seattle (Halpern, 1978). Mooring 1, WOTAN S/N 001, was at $0^{\circ} 41' \text{ S } 153^{\circ} \text{ W}$; and mooring 2, WOTAN S/N 002, was at $0^{\circ} 0.3' \text{ N } 152^{\circ} \text{ W}$. The two sites are separated by about 135 km along a line approximately NE/SW.

The sampling period of the WOTAN instruments was 256 seconds, while the sampling period of the VAWR instruments was 30 minutes. Both WOTAN data sets were subsampled to the half-hour time interval. Two subsampling schemes were used: (1) data points were averaged over the thirty minute period and (2) single data points coinciding with the time of the wind data were selected. There were no apparent differences in the regression, nor in the wind speeds calculated from

noise data subsampled by these two methods, (probably due to the lack of high frequency variance), so the second method was chosen. The data from mooring 1 starts at 0300 Z April 30, 1979 and ends at 1630 Z October 6, 1979, 7708 observations before subsampling. The second WOTAN instrument developed problems with its tape recording system and only has two months of good data from 0300 Z June 3, 1979 to 1900 Z July 31, 1979, 2817 observations. The observed wind speeds in the Pacific ranged from 0-10 m/s.

B. ATLANTIC

One instrument, S/N 001, was deployed in the North Atlantic at $39^{\circ} 0.15' N$ $69^{\circ} 59.93' W$ in 3500 m of water. Coincident wind speed data was available from three weather service buoys maintained by the National Data Buoy Office. The sensors on the weather service buoys were 10 m above the sea surface. These buoys measure wind speed, direction, atmospheric pressure, air and sea surface temperature, and wave height, direction and period. Buoy 4 was about 20 km south of the WOTAN mooring; Buoys 3 and 5 were about 200 km and 300 km NE of the WOTAN mooring respectively. Only the data from Buoy 4, closest to WOTAN, was used in the processing. As before, the WOTAN recorded data every 256 seconds; the surface instrument data, the Buoy 4 data, was recorded

every hour. The WOTAN data was subsampled to a one hour time interval. The WOTAN data set started at 1000 Z December 6, 1980 and ended at 0600 Z August 8, 1981. The buoy data started at the same time, but it ended at 1900 Z May 16, 1981 when the instrument platform broke its mooring lines and drifted away. The observed wind speed range for this deployment was 0-20 m/sec.

IV. RESULTS

A. PACIFIC

1. Regression Results

Using the technique described earlier under Methods, the common logarithm of the measured wind speed was regressed against the noise levels from WOTAN, using a small coincident subset of the data. Using the regression coefficients and equation 15, wind speeds were calculated for the entire noise data set. Unless noted otherwise, the WOTAN data presented in this section is 14.5 kHz data. The scatterplot of measured winds versus calculated winds for S/N 001, has definite curvature, instead of the expected straight line (figure 11). The curvature in the scatterplot indicates the WOTAN winds are underestimated at the higher wind speeds. The data appear to be better fit by two straight lines intersecting at 5.5 m/sec; this is the speed at which white caps become prevalent. It would seem that some mechanism, possibly associated with white caps, causes a decrease in the noise levels at 14.5 kHz. If this mechanism is associated with white caps, perhaps the entrained bubbles scatter the high fre-

quency sound. This decrease in noise levels is in contrast with Perrone's (1969) observation of an increase in noise levels at similar wind speeds. As a refinement on the above procedure, separate fits were calculated for wind speeds above and below 5.5 m/sec for S/N 001. The plot of wind speeds calculated by the two equation procedure versus the measured winds now yields a straight line with a slope of about unity (figure 12). The calculated winds for the second WOTAN instrument were plotted against the winds measured at that mooring in fig. 13. There seems to be a slope change also, although it is not quite as striking as in figure 11. One reason for this is because the second deployment only covers the months of June and July, whereas the first deployment includes data from May to the beginning of October. The winds were less energetic in June and July, often not exceeding 9 m/sec and so there would be less dynamic range in these winds compared to the higher wind range in the other months.

The time series of the Pacific wind speed data are plotted in figure 14 for both moorings. The curve on the bottom is the VAWR wind from mooring 1 and just above it are the wind speeds calculated from WOTAN from that mooring. The WOTAN wind speeds have been offset by 3 m/sec for ease in comparing them. The top two short time series are from mooring 2 with the WOTAN wind speeds on the top. Both of these curves have been offset by additional multiples of 3 m/sec. The agreement between WOTAN and VAWR winds is quite apparent,

as well as the agreement among moorings separated by 135 km. The only major disagreement between all four data sets occurs during the month of June. The VAWR instrument on mooring 1 recorded wind speeds that were several m/sec lower than the other three instruments (the two WOTAN's and the other VAWR). Since the two WOTAN data sets and the VAWR data from mooring 2 agree, it is reasoned that the VAWR instrument from mooring 1 was not working properly. It is not known what caused it to work improperly, nor why it was only affected in June, although fouling and subsequent clearing of the anemometer would be consistent with this observation.

Using equation 14, the noise spectral levels (NSL) can be calculated from the recorded counts. Figure 15 displays NSL at 8.0 and 4.3 kHz plotted against NSL at 14.5 kHz. By plotting the data in this manner, the parametric dependence on the wind speed is removed; in order to demonstrate the parallelism of the Knudsen curves. The difference in the intercepts of the NSL lines divided by the differences of the logarithms of the frequencies is the slope of the Knudsen curves. The results of this type of calculation for the difference between 14.5 and 4.3 kHz and between 8.0 and 4.3 kHz are -18.94 dB/decade and -18.75 dB/decade respectively. These values agree with Knudsen's -20 dB/decade slope to within the uncertainty in calculating NSL's.

2. Spectral Analysis

A spectral analysis was performed on the two wind data sets - the calculated winds and the directly measured winds. In figure 16, the spectral density of the wind variance is plotted against frequency. The solid line is the VAWR data and the dashed line is the WOTAN data. The spectra obviously track very closely. Figure 17 is a plot of the coherence between the two data sets. They are coherent at the 95% significance level with no significant phase difference for frequencies less than approximately 0.1 cycles per hour (cph). The decrease in coherence at higher frequencies may arise because the root mean square wind speed falls below the nominal VAWR accuracy, so the signal-to-noise ratio becomes poor. However, the correspondence between the two wind data sets still holds during times with energetic high frequency fluctuations. Figure 18 illustrates this with seven days of data with a 30 min. sampling period.

B. ATLANTIC

1. Regression Results

Because the surface wind data was recorded at different heights above sea level in the Pacific and the Atlantic, one data set had to be corrected to the sensor height of the other data set. Since the Pacific data were analyzed first, I chose to scale the Atlantic Buoy winds from 10 m to 3.5 m sensor height, using the procedure outlined by Kondo (1975) which assumes a logarithmic boundary layer above the earth. His equation requires a roughness parameter which is a function of the atmospheric drag coefficient. This drag coefficient depends on atmospheric stability and wind speed. The atmosphere is stable if the air temperature is warmer than the sea surface temperature. It is neutral if the air and sea surface temperatures are about the same; and the atmosphere is unstable if the sea surface is warmer than the air. The atmosphere is usually unstable in the winter and stable in the summer. The drag coefficient was determined using monthly means of the sea - air temperature difference and wind speed. Monthly means are used in order to average the daily changes in the sea - air temperature difference and to obtain seasonal trends. I also calculated drag coefficients for a number of hourly observations at wind speeds lower than

the monthly means. Although the drag coefficients are lower at the lower wind speeds, the corrected wind speeds from the procedure using monthly means are not significantly different from corrected wind speeds using hourly wind and temperature data. The equation for the drag coefficient under neutral conditions is given by:

$$C_D(10m) = [a + b*U^p]*10^{-3} \quad (17)$$

where a,b,p are numerical constants (see table 4).

U is the monthly mean wind speed.

Kondo defines a stability parameter, S

$$S = \frac{S_o |S_o|}{|S_o| + 0.01} \quad (18)$$

$$\text{where } S_o = \frac{(SST - AT)}{U^2} \quad (19)$$

Equation 19 holds for data taken at 10m above the sea surface. For stable conditions, $SST < AT$ and $S < 0$, the drag coefficient is given by:

$$C_{DD} = [0.1 + 0.03*S + 0.9*\exp(4.8*S)]*C_D \quad (20)$$

where C_D is the drag coefficient under neutral conditions (eq. 17).

For unstable conditions, $SST > AT$ and $S > 0$, the drag coefficient is given by:

$$C_{DD} = [1.0 + 0.47*S^{0.5}] * C_D \quad (21)$$

where C_D is the drag coefficient for neutral conditions.

Next the aerodynamic roughness parameter, z_o , is determined from the logarithmic profile.

$$z_o = \exp\{\ln(10m) - k[C_D(10m)]^{0.5}\} \quad (22)$$

where k is the von Karman constant ($k = 0.41$) and C_D is the calculated drag coefficient dependent upon atmospheric stability.

To scale wind speeds to a new height, z :

$$U(z) = \frac{\ln \frac{z}{z_o}}{\ln \frac{10}{z_o}} * U(10m) \quad (23)$$

or

$$U(z) = Z * U(10m) \quad (24)$$

where Z is the ratio of the logarithm of the height to roughness parameter for the new height over the old height. Table 5 summarizes the drag coefficient, z_o , and the correction factor, Z , to $U(10m)$ for each month of available Buoy data. As you can see by this table, the winter months, December - March, had unstable atmospheric conditions and April and May had neutral to stable conditions.

Using equation 23, the Buoy winds were scaled to a 3.5m

sensor height. As before, a small subset of ambient noise data and the corrected Buoy wind data was chosen with an equal number of observations in 1 m/sec intervals. A linear regression was performed and the data were fitted to equation 15. The coefficients, C and D, may be found in Table 3. A scatter plot of the measured winds (Buoy) versus the winds calculated from WOTAN (14.5 kHz) is shown in figure 19. There is the expected linear relationship. There does not seem to be any slope change at 5.5 m/sec as was seen in the Pacific. The large number of observations at wind speeds greater than 5.5 m/sec may dominate the regression so that the mechanism which caused the change in slope in the Pacific data is accounted for and only one equation is needed. To test this idea, I plotted buoy winds versus WOTAN winds (14.5 kHz) for the wind range 1-10 m/sec (fig. 20). With the reduced number of high wind observations there is a change in slope similar to that seen in the Pacific.

The apparent increase in scatter at higher wind speeds in figure 19, is due to non-wind events recorded by WOTAN. During wind events, there should be a constant difference in NSL values between the different frequencies. According to the Knudsen curves, the difference in NSL from 4.3 to 14.5 kHz should be about 8-9 dB; and between 4.3 and 8.0 kHz should be about 6 dB. In order to differentiate between wind events and non-wind events, one can look at the difference in NSL values at two frequencies. For example, if the differ-

ence in $NSL(4.3\text{kHz})$ minus $NSL(14.5\text{kHz})$ is less than the constant value, 8 dB, then rain-like noise is present. If the difference is greater than the expected constant value, then ship-like noise is present. Figure 21 presents a scatterplot of Buoy wind versus WOTAN wind (14.5 kHz) with rain- and ship-like events removed. As you can see, most of the scatter is accounted for. A time series of the data is presented in figure 22. The bottom curve is the Buoy winds and the upper curve is the WOTAN winds at 4.3 kHz. The good agreement between the WOTAN derived winds and the directly measured Buoy winds is evident.

The NSL values at 8.0 and 4.3 kHz are plotted against the NSL values at 14.5 kHz in figure 23. The curves are parallel except at high values of NSL. At high NSL's ($NSL(14.5\text{ kHz}) > 40\text{ dB}$), the plot of 14.5 kHz versus 4.3 kHz curves below a straight line with slope 1, indicating that the $NSL(14.5\text{kHz})$ values are not increasing as rapidly as expected. Lemon and Farmer (1984) have recently investigated a similar phenomenon. They have found that a layer of bubbles at the sea surface will scatter and absorb sound at high frequency and high wind, changing its spectral slope. They also have observed the NSL's at 14.5 kHz to decrease with increasing wind speed at speeds greater than 12 m/sec, due to the scattering and sound absorbing effect of the layer of bubbles. They found only the 14.5 kHz signal to be affected and not the 8.0 and 4.3 kHz signals.

Figure 23 is replotted in figure 24 for NSL's at wind speeds less than 12 m/sec. This figure does not show any decrease in the 14.5 kHz signal at high NSL. Instead the curves are linear and parallel. The spectral slope of these curves is determined by taking the difference in NSL at two frequencies divided by the difference in the log of those frequencies; this should be equal to Knudsen's -6 dB/octave or -20 dB/decade for wind events. For the difference between 4.3 and 14.5 kHz and 4.3 and 8.0 kHz, the spectral slope is -21.9 dB and -22.3 dB/decade respectively. Both of these values are within experimental error of Knudsen's -20 dB/decade.

Figure 23 was also replotted for NSL values at 14.5 and 4.3 kHz for wind speeds greater than 12 m/sec (figure 25). This figure shows the roll-off of the 14.5 kHz NSL values at high NSL. There also appears to be a large number of events where the NSL's at 14.5 kHz did not decrease, but increased in the expected linear fashion. There is some evidence that some process which decreased the 14.5 kHz noise signal such as the layer of bubbles does exist and does change the 14.5 kHz signal, but this bubble layer may not exist at all times at high wind. Because of the behavior of the 14.5 kHz signal at higher wind speeds, the data presented in the following section will be the 4.3 kHz signal from WOTAN.

2. Spectral Analysis

A spectral analysis was performed on the two wind data sets - the winds calculated from WOTAN and the directly measured Buoy winds. The spectral density of the wind variance is plotted against frequency in figure 26. The heavy line is the Buoy data and the light line is the WOTAN data. The spectra track very closely. The coherence between the two data sets is plotted in figure 27. The coherence remains good until a period of about 10 hours. The data were high pass filtered (10 hours) to check the correspondence at the higher frequencies. A time series of the filtered data is presented in figure 28; the lower plot is the Buoy data and the 4.3 kHz WOTAN data is above it. The $\pm$ values presented in this plot are the variation of the instantaneous wind speed from a 10 hour averaged wind speed. There is little energy at the higher frequencies with most of the variability at wind speeds less than about 2 m/sec. For occurrences at wind speeds greater than 2 m/sec, there is a strong visual correspondence between both the upward and downward spikes. This is also supported by statistics. Table 6 summarizes the results of linear regression on the data performed in the following manner. The Buoy winds were regressed against the 4.3 kHz WOTAN winds. First, I used all the high frequency data except that data with values between -1.0 and +1.0 m/sec since 1 m/sec is the nominal accuracy of the surface wind

recorders. The regression coefficients using data chosen in this manner are the first entry in Table 6. I next increased the range of omitted values; I used all the data except those with values between -1.5 and $+1.5$ m/sec in the regression. These results are found on the second row in Table 6. The remaining entries had successively larger limits as listed in the table. For the case where only data greater than 2.5 m/sec and less than -2.5 m/sec were used, the regression slope was 0.9 , the intercept was -0.2 , and the correlation coefficient, R , was 0.96 . The other correlation coefficients are also high. Thus these events are well correlated as long as the signal is strong enough. The decrease in coherence at high frequency is thus a statistical artifact due to low overall variance in the data, rather than indicating some other physical process. Figure 29 is a 7 day time series of the Buoy wind and the 4.3 kHz WOTAN wind showing good correlation.

V. DISCUSSION

Comparisons of the Atlantic and Pacific results with two published results are shown in figures 30 and 31 for 14.5 and 4.3 kHz respectively. In each figure, the curve marked P is the Pacific wind - noise relation; and the line marked A is the Atlantic wind - noise relation (the vertical error bars are the ± 1 m/sec uncertainty in the wind; the horizontal error bar is the ± 1.7 dB uncertainty in determining NSL). The line marked S is the wind - noise relation published by Shaw et.al. (1975) scaled to 14.5 and 4.3 kHz. The line marked W is the wind noise relation published by Wenz (1962) scaled to 14.5 and 4.3 kHz. In figure 30 at 14.5 kHz, the Pacific curve reflects the two regression equations - one for high winds and the other for low wind speeds. When the VAWR winds were plotted against the WOTAN winds at 4.3 kHz, there did not seem to be any significant change in slope. This was also true for the Atlantic data (see figure 32a and 32b). Thus in figure 31, the Pacific curve represents the original one equation regression at 4.3 kHz. In figure 30, all four curves agree well at low wind speeds, but the Pacific curve will yield lower wind speeds than the other three at constant NSL at wind speeds greater than about 4-5 m/sec. Vice versa,

for a given wind speed, the Pacific has a higher NSL value than the Atlantic.

In figure 31 (4.3 kHz), the Atlantic and Pacific curves agree very well, and both do not agree as well with Wenz or Shaw. Because Wenz did not give any uncertainties for his results, I cannot say whether the error bars would overlap or not. Shaw gives an uncertainty of ± 2.5 m/sec, so it does agree with the WOTAN results except at high winds. One reason why the curves do not agree is because different methods and instruments were used. Shaw's ambient noise measurements were made using a modified inverted echo sounder at 5 kHz. Wenz's work was a compilation of data collected by the Navy using different equipment at different frequencies. In his paper, Wenz (1962) notes that data measured in the same area, with the same system, at the same wind speeds, often has considerable variability in the observed noise levels when measured in different seasons (on the order of 5-10 dB). At this time, Wenz and other investigators were still using wind speed data to predict ambient noise levels. Given this variability is not surprising that published results may not agree well with each other or with the WOTAN results at all frequencies.

One purpose of the Atlantic experiment, in addition to making measurements in a region with a higher range of winds, was to test the reproducibility of the Pacific wind - noise relations for a different ocean regime. By figures 30 and

31, it would seem that the wind - noise relations for the Atlantic and Pacific are comparable. In order to quantify this agreement, I investigated the effects of geographic location, season, and depth on the noise levels received by the hydrophones. This information will also be valuable for comparisons with future ambient noise investigations. I first investigated the effect of the local hydrography on the propagation of sound to the hydrophone. I next tried to determine if there was any relationship between NSL and sea surface temperature, since sea surface temperature was variable in the Atlantic and fairly constant in the Pacific.

By using historical temperature, salinity and pressure data, I calculated the sound speed profile for the Atlantic and the Pacific deployment sites. Using the sound speed profile, I traced the path of sound rays from the hydrophone to the surface for a variety of hydrophone depths. In doing so, I chose to ignore surface and bottom reflections because I wanted to trace the direct paths only. Due to attenuation and other transmission losses, the reflected paths would not contribute to the total noise level received by WOTAN at the deep deployment depths. Figure 33 is a sound speed profile for the equatorial Pacific in April; the ray diagram associated with this sound speed profile is plotted in figure 34. Rays leaving the hydrophone at shallow angles are refracted back into the ocean before they reach the surface because of the sharp negative gradient near the surface in the sound

speed profile. Once a critical angle is reached, the rays are able to reach the surface. In this case, all rays leaving the hydrophone at angles greater than or equal to about 10.0° will reach the surface. The first ray to reach the surface describes the 'listening' area of the WOTAN instrument. Here, the first ray hits the surface at a distance of 19.86 km from a point directly above the WOTAN instrument. All sound generated at the surface within a radius of 19.86 km should reach the hydrophone. All sound generated at the surface at distances greater than 19.86 km will not be received by WOTAN.

Figures 35 and 36 are a sound speed profile and ray diagram for the Northwest Atlantic in April. The sound speed profile in the Atlantic is different than that in the Pacific and so is its ray diagram. As before, rays leaving the hydrophone at shallow angles are refracted downward by the negative sound speed gradient between 50 - 100 m depth. After the critical angle is reached, 5.0° in this case, the rays are no longer as strongly refracted and are able to reach the surface. For this sound speed profile, the first ray to reach the surface hits it at a distance of 35.90 km from a point directly above the WOTAN instrument. Thus, for this case, the WOTAN receives noise from a circular area of radius 35.90 km.

Because of the different water properties (temperature and salinity) in the Atlantic and the Pacific, the ray dia-

grams cannot be compared directly. Sound is attenuated in the ocean and the attenuation is a function of temperature, salinity and pressure. In order to compare the Atlantic and the Pacific, I determined the intensity of sound reaching the hydrophone in a manner similar to that presented by Bradner and Howard (1978). The sound intensity received at the hydrophone can be considered to be the sum of contributions from horizontal annular regions of radius x , centered on the sea surface above WOTAN. The equation used assumes a uniform layer of dipole sources at the surface, all with a unit source strength. Measurements by other investigators have been consistent with the hypothesis of a dipole sound source at the surface formed by the actual source and its image in the sea surface (Urlick, 1983). Therefore the downward radiation pattern of a dipole, $\cos^2\theta$, was used. The intensity is therefore:

$$I = \int_{x=0}^{x_m} \frac{(2\pi x) * 10^{-\alpha R} \cos^2\theta}{R^2} dx \quad (25)$$

where θ is the ray direction with respect to the vertical, R is the straight line distance (km) from the hydrophone to the mid-point of the annulus and α is the attenuation coefficient calculated using Fisher and Simmons (1977) formulation.

$$\alpha = \left[\frac{Af_1 F^2}{f_1^2 + F^2} + \frac{Bf_2 F^2}{f_2^2 + F^2} + CF^2 \right] \quad (\text{units of dB/m}) \quad (26)$$

This attenuation coefficient includes the absorption effects

by chemical relaxation. The coefficients A' , B' , C' , f_1 , f_2 are dependent upon temperature ($^{\circ}\text{C}$) and pressure (atm.). f_1 and f_2 are the relaxation frequencies for boric acid and magnesium sulfate respectively. F in the above equation is the frequency of interest, 4.3, 8.0, or 14.5 kHz. The coefficients in equation 26 were determined using the formula given by Fisher and Simmons (1977) with depth averaged values for temperature and pressure. The range of integration used was out to x_m , the refractive limit on noise received at the hydrophone.

Table 7 tabulates the intensity of sound reaching the hydrophone in the Atlantic and Pacific for April at a number of hydrophone depths. Tabulated is the intensity and intensity levels without ($\alpha=0$) and with attenuation effects. The reference intensity used in the calculation of the intensity levels was $6.76 \times 10^{-19} \text{ W/m}^2$ which is approximately equal to 1 μPa . As can be seen in the table, the intensity level, disregarding attenuation, at the hydrophones only differs from 188.77 dB to 189.63 dB between the different depths used and between the different oceans.

At the deployment depths, 3500 m in the Atlantic and 3800 m in the Pacific, and allowing for attenuation effects, the computed intensity level in the Pacific is slightly higher than in the Atlantic at 14.5 kHz but it is never higher by more than 0.36 dB. In effect, although WOTAN listens to a larger surface area in the Atlantic, the greater absorption

of sound in the Atlantic decreases the amount of sound reaching the hydrophone. Because attenuation effects are the strongest for the rays on the outside edge of the listening area, sound from this area may not reach the hydrophone. Thus, I calculated an effective listening radius, ie. the radii in which 90% and 99% of the total intensity reaching the hydrophone was generated. The effective radius is frequency dependent because of the attenuation. These radii are also tabulated in Table 7 for each of the depths used (99% only calculated for the two deployment depths). The effective listening areas at 90% intensity for the two oceans are quite similar.

I repeated this procedure using water property data taken in the fall. The fall and spring hydrographies give rise to the most different sound speed profiles of the four seasons. Figures 37 and 38 are the sound speed profile and ray diagram for the Pacific and figures 39 and 40 are the sound speed profile and ray diagram for the Atlantic. The radius of the 'listening' area on the surface in the Pacific in the fall is a little less than in the spring - 16.91 km. In the Atlantic, because of the sharp thermocline and thus sharp negative sound speed gradient, the radius of the listening area dropped considerably in the fall to 18.81 km. Table 8 tabulates the intensity and intensity levels reaching the hydrophone in the Pacific and the Atlantic for a number of hydrophone depths using the fall water stratification. As

was the case in the spring, the difference between the Atlantic and Pacific intensity levels at the deployment depths is small, never more than 0.42 dB.

In summary, the investigation on hydrographic effects show the received noise intensity at the deployment depths in the Atlantic and equatorial Pacific are quite similar. Comparisons of Tables 7 and 8 show geographically, the difference in the received sound intensity for the deployment depths in the Pacific and the Atlantic is largest at 14.5 kHz, about 0.4 dB ($P > A$) for both spring and fall and it is smaller at the other two frequencies (eg. at 4.3 kHz, $P - A = 0.14$ dB, in the spring and $P - A = -0.22$ dB, in the fall). By itself, a change of 0.4 dB in NSL corresponds to about a 2% change in computed wind speed; a 0.2 dB NSL change gives rise to a 1% wind speed change. The change in noise level between the two seasons in the Atlantic showed about a 0.2 dB decrease in NSL from spring to fall at 14.5 kHz and about a 0.2-0.25 dB increase at 8.0 and 4.3 kHz when going from spring to fall; this corresponds to a 1% change in computed wind speed. In the Pacific, noise levels were slightly higher in the spring from 0.12 dB (14.5 kHz) to 0.03 dB (4.3 kHz). These NSL changes are relatively small considering the large hydrographic differences between the equatorial Pacific and northwest Atlantic. These fractions of a dB changes are not significant when compared to the almost 2 dB absolute uncertainty in determining NSL's, but are systematic.

The study on the effect of hydrophone depth did have significant changes in noise levels due to the greater attenuation at the deeper hydrophones. For example, the 100 m hydrophones were computed to have (Tables 7 and 8) noise levels about 8, 4, and 2 dB higher than the 3500 m hydrophones at 14.5, 8.0, and 4.3 kHz respectively. For the comparison of the 1000 m hydrophones to those at 3500 m, noise levels differed by approximately 6, 3, and 2 dB for 14.5, 8.0, and 4.3 kHz. A NSL change of 8 dB corresponds to about a 40% change in wind speed; 4 dB corresponds to a 20% wind speed change, hence it would be necessary to adjust the wind-noise relations presented in this paper when comparing with results taken at significantly different depths. The changes in NSL are lowest at 4.3 kHz for all of the effects studied.

I next investigated the possibility of a relationship between NSL and sea surface temperature (SST). Since the sea surface temperature was quite constant (25-26 °C) in the equatorial Pacific from May to October and was quite variable in the Atlantic (3-18 °C) from December to August, it was hypothesized that the slight difference in the wind-noise relations may be due to some relation between NSL and SST. In order to test for a relationship between NSL and SST, I first looked at scatterplots of NSL versus SST at constant wind speed in the Atlantic. Figure 41 shows two of these plots; the upper plot was for a wind speed of 8.30 m/sec and the lower plot is at wind speed equal to 12.45 m/sec. In

each plot, the lower curve is the NSL at 14.5 kHz and the upper curve is NSL at 4.3 kHz. These plots cover the period December to May. There does not seem to be any relationship between NSL and SST at either frequency. Similar results were found at both lower and higher wind speeds.

It is an established fact that SST increases and the mean wind speed decreases in non-tropical regions in the summer. I next tried to determine if there was a seasonal dependence of NSL on sea surface temperature. Since I do not have any summer data from Buoy 4 which was closest to WOTAN, I used the wind and SST data from Buoy 3, 200 km northeast of WOTAN. The hypothesis was that if NSL and SST are somehow related, then as the sea surface warms in the summer, the noise levels reaching the hydrophone may then be changed from the expected value for a given wind speed. This would subsequently change the calculated wind speed from its expected value. In figures 42 and 43, sea surface temperature, Buoy 3 wind speed and WOTAN wind speed (14.5 kHz and 4.3 kHz respectively) are plotted against time. The data presented here have been averaged over a two week period. The wind sensors on Buoy 3 were 5 m above the sea surface. Because of this and due to the 200 km distance between them, the Buoy 3 winds and the WOTAN winds cannot be compared directly. So I scaled the WOTAN winds to the Buoy 3 winds by multiplying the WOTAN winds by the ratio of the Buoy wind to WOTAN wind at the first data point February 8, 1981. The WOTAN winds in these

figures have been scaled in this manner. As can be seen from both figures, there is no apparent difference between the winds measured by the Buoy and the winds calculated from WOTAN as the sea surface temperature increases.

It is evident by the previous sections that geographical and seasonal differences in the deployment sites (Atlantic and equatorial Pacific) will not cause any significant discrepancies when comparing wind speeds calculated using either set of equations. Because the hydrophone is the only part of the WOTAN instrument that is not tested by the bench calibration, and any loss in transducer sensitivity due to aging of the ceramics could not be discovered, the WOTAN transducers were returned to the manufacturer for recalibration. After the recalibration, it was discovered that the sensitivity of the transducer had decreased by 1.8 dB at 14.5 kHz and by about 0.9 dB at 4.3 kHz. The hydrophone sensitivity is an additive factor in the equations (see eq. 14) and so any change in this value changes the offset and not the slope in the final equations.

In figure 30 (14.5 kHz), at a wind speed of 8 m/sec, the Atlantic and Pacific wind - noise relation differed by 3.4 dB. If we subtract 1.8 dB for the decrease in transducer sensitivity and 0.4 dB for the difference due to hydrographic effects (see Tables 7 and 8), then the net difference between these two wind - noise relations at 14.5 kHz and 8 m/sec is 1.2 dB and is within the uncertainty in determining NSL's.

the ceramics and not due to some physical effect in the two oceans.

Future work on this topic should include an investigation into the effects of the surface bubble layer, ie. when it exists or not. It would also be interesting to know whether this bubble layer is a source or scatterer of ambient noise, or whether it is both. This investigation may be of great importance to the new generation of WOTAN instruments which are attached about 100 m below surface drifters. Because of the short distance to the surface, attenuation will be less of a factor than for the deep deployments. Other work of interest would be to try to determine a method for determining rainfall rates from a comparison of ambient noise at two frequencies using Franz' curves and Nystuen's results.

Table 1.

Coefficients of $CNT = r * 20 \log \frac{V_{rms}}{1 \text{ v}} + t$

S/N 001

	<u>r</u>	<u>Δ_r</u>	<u>t</u>	<u>Δ_t</u>
14.5 kHz	16.65	0.92	1382.54	31.82
8.0 kHz	15.97	0.64	1359.47	21.91
4.3 kHz	15.39	0.44	1301.16	12.55

S/N 002

	<u>r</u>	<u>Δ_r</u>	<u>t</u>	<u>Δ_t</u>
14.5 kHz	15.44	0.84	1325.71	23.21
8.0 kHz	15.13	0.65	1302.58	18.08
4.3 kHz	15.20	0.46	1281.44	12.92

Note: all uncertainties presented in these Tables are uncertainties at the 95% confidence level.

Table 2.

Coefficients of $NSL = \frac{CNT}{A} + B$

S/N 001

	<u>A</u>	<u>Δ_A</u>	<u>B</u>	<u>Δ_B</u>	<u>BW(Hz)</u>	<u>10LogBW</u>
14.5 kHz	279.50	15.49	-6.54	4.98	2253.7	33.53
8.0 kHz	268.13	10.66	-8.51	3.65	1408.8	31.49
4.3 kHz	258.36	6.11	-9.24	2.16	754.8	28.78

S/N 002

14.5 kHz	259.29	14.02	-11.13	4.88	4319.2	36.35
8.0 kHz	254.05	10.94	-11.57	3.99	2291.4	33.60
4.3 kHz	255.22	7.81	-9.18	2.72	1205.3	30.81

Table 3.

Coefficients of $20\text{Log}(\text{WND}) = C \cdot \text{NSL} + D$

Pacific

S/N 001 - two equation regression

		<u>C</u>	<u>Δ_C</u>	<u>D</u>	<u>Δ_D</u>	<u>R^2</u>
14.5 kHz	High	0.87	0.04	-24.90	2.67	0.91
	Low	0.60	0.03	-13.13	2.27	0.78
8.0 kHz	High	0.84	0.04	-26.40	3.22	0.88
	Low	0.52	0.04	-12.61	1.74	0.69
4.3 kHz	High	0.83	0.03	-30.13	1.90	0.91
	Low	0.48	0.02	-12.52	2.29	0.66

S/N 001 - one equation regression

14.5 kHz	0.66	0.04	-15.55	2.31	0.90
8.0 kHz	0.65	0.04	-17.59	2.66	0.90
4.3 kHz	0.84	0.04	-31.24	2.31	0.90

S/N 002

14.5 kHz	0.88	0.05	-24.28	3.63	0.82
8.0 kHz	0.87	0.05	-26.89	3.24	0.82
4.3 kHz	0.91	0.04	-35.54	2.31	0.82

Atlantic

S/N 001

14.5 kHz	1.11	0.03	-32.67	2.94	0.87
8.0 kHz	1.09	0.02	-39.48	3.53	0.87
4.3 kHz	1.05	0.02	-42.09	3.21	0.87

Table 4.

Coefficients of $C_D = [a + b*U^p]*10^{-3}$

<u>U(10m)</u> <u>m/sec</u>	<u>a</u>	<u>b</u>	<u>p</u>
0.3-2.2	0	1.08	-0.15
2.2-5.0	0.771	0.0858	1
5.0-8.0	0.867	0.0667	1
8.0-25.0	1.2	0.025	1
25.0-50.0	0	0.073	1

Table 5.

Summary of Drag Coefficient Results

	<u>Dec.</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>
Stability	unstbl	unstbl	unstbl	unstbl	neutr1	neutr1
<SST-AT>	8.56	7.62	3.50	8.02	-0.35	-0.39
<U(10m)>	9.78	9.24	9.44	11.56	8.75	7.85
S	0.0850	0.0803	0.0313	0.0600	-0.0046	-0.0063
$10^3 C_D$ (neutral)	1.44	1.43	1.44	1.49	1.42	1.39
$10^3 C_{DD}$ (for given stability)	1.64	1.62	1.56	1.65	1.42	1.39
$10^4 z_o$	3.96	3.97	3.05	4.11	1.81	1.58
Z	0.896	0.897	0.899	0.896	0.904	0.905

Table 6.

Regression Results - High Pass Filtered Wind Data - Atlantic

$$\text{Buoy Wind} = m * \text{WOTAN Wind} + b$$

Range of data omitted (m/sec)	Slope <u>m</u>	Intercept <u>b</u>	Correlation <u>R</u>
-1.0 to 1.0	0.64	-0.19	0.68
-1.5 to 1.5	0.73	-0.23	0.76
-2.0 to 2.0	0.76	-0.23	0.82
-2.5 to 2.5	0.90	-0.22	0.96
-3.0 to 3.0	0.82	-0.65	0.96
-3.5 to 3.5	0.75	-0.97	0.91

Table 8.

Raytracing and Intensity Results - October

Hydrophone Depth	Atlantic			Pacific			
	100m	1000m	3500m	100m	1000m	3500m	3800m
Intensity W/m^2	6.06	5.27	5.13	6.04	5.07	4.98	4.89
IL dB re 1 μPa	189.52	188.92	188.80	189.51	188.75	188.67	188.60
Intensity - attenuation (W/m^2)							
14.5 kHz	5.30	2.84	0.68	5.30	2.94	0.86	0.75
8.0 kHz	5.78	4.16	2.31	5.79	4.11	2.46	2.32
4.3 kHz	5.98	4.75	3.65	5.96	4.60	3.61	3.47
IL dB re 1 μPa (attenuation accounted for)							
14.5 kHz	188.95	186.23	180.06	188.94	186.38	181.05	180.48
8.0 kHz	189.33	187.90	185.34	189.33	187.84	185.61	185.34
4.3 kHz	189.47	188.47	187.33	189.46	188.33	187.27	187.11
Max Range km	2.59	6.02	18.81	2.43	5.12	16.69	16.91
Range at 90% Intensity (km)							
14.5 kHz	0.54	2.88	5.88	0.54	2.63	6.38	6.63
8.0 kHz	0.66	3.38	8.88	0.64	3.13	8.88	9.38
4.3 kHz	0.71	3.63	9.88	0.67	3.38	10.38	10.63
Range at 99% Intensity (km)							
14.5 kHz			10.63				11.63
8.0 kHz			15.88				15.13
4.3 kHz			17.38				15.63

DEEP-OCEAN AMBIENT-NOISE SPECTRA

Figure 1. Knudsen curves showing noise spectral level vs the log of the frequency. Each curve corresponds to a different wind force as given in the legend.

From Urick (1985)

Figure 2. Diagram showing the sources and directionality of ambient noise in the open ocean. Urick's fig 7.1

Figure 3. Knudsen - Franz curves relating NSL to the log of the frequency along lines of constant wind speed (dashed lines) and showing the 'white' rainfall noise.

Figure 4. Photograph of WOTAN.

Figure 5. Block diagram of the electronics of WOTAN.

Figure 6. Diagram of the white noise replacement circuit for the bench calibration of WOTAN.

Figure 7. Bench calibration data for S/N 001 - noise counts vs log of the test voltage.

Figure 8. Bench calibration data for S/N 002 - noise counts vs log of the test voltage.

Figure 9. Bandwidth calibration data at 8.0 kHz for S/N 001. Normalized voltage vs log of the frequency. The center frequency and -3 dB points are marked.

Figure 10. Bandwidth calibration data at 8.0 kHz for S/N 002. Normalized voltage vs log of the frequency. The center frequency and -3 dB points are marked.

Figure 11. Scatterplot of VAWR winds vs WOTAN winds (14.5 kHz) based on the single regression equation. Data is from mooring 1, 0° 41' S 153° W and shows the change in slope at 5.5 m/sec.

Figure 12. Scatterplot of VAWR winds vs WOTAN winds (14.5 kHz) from mooring 1. WOTAN winds were calculated using two equations: one for low wind speeds (<5.5 m/sec) and the other for high wind speeds.

Figure 13. Scatterplot of VAWR winds vs WOTAN winds (14.5 kHz) for mooring 2, 0° N 152° W.

Figure 14. Comparison of wind measured by VAWR with those measured by WOTAN in the equatorial Pacific. The bottom two lines are data from mooring 1 of which the bottom line is the VAWR data. The WOTAN data above it has been offset by 3 m/sec. The top two lines are from mooring 2. The top line is the WOTAN data. Both of these two lines have been offset by multiples of 3 m/sec.

Figure 15. NSL at 8.0 and 4.3 kHz plotted against NSL at 14.5 kHz for the WOTAN at mooring 1. The value of the constant difference between the curves implies a -20 dB/decade slope to the NSL vs frequency curves at all observed wind speeds.

Figure 16. A log-log plot of the spectral density of the wind variance vs frequency in cycles per hour for VAWR (solid line) and WOTAN (dashed line) wind data from mooring 1.

Figure 17. The coherence between the VAWR and the WOTAN winds. The large tick mark on the y-axis is the level of statistical significance at the 95% level.

Figure 19. Scatterplot of Buoy winds vs WOTAN winds (14.5 kHz) from the Atlantic mooring 39° N 70° W.

Figure 20. Scatterplot of Buoy winds vs WOTAN winds (14.5 kHz) for the wind range 1-10 m/sec showing the change in slope at 5.5 m/sec.

Figure 21. Scatterplot of Buoy winds vs WOTAN winds(14.5 kHz) at all wind speeds with non-wind events removed.

Figure 22. A comparison of winds measured by the Buoy with those measured by WOTAN in the NW Atlantic. The bottom plot is the Buoy winds and the upper plot is the WOTAN winds.

Figure 23. NSL at 8.0 and 4.3 kHz plotted against NSL at 14.5 kHz for the Atlantic deployment showing the roll-off of the 14.5 vs 4.3 kHz curve at high NSL.

Figure 24. NSL at 8.0 and 4.3 kHz vs NSL at 14.5 kHz for wind speeds less than 12 m/sec. The value of the constant difference implies a -20 dB/decade slope to the NSL vs frequency curves.

Figure 25. NSL at 4.3 kHz vs NSL at 14.5 kHz for wind speeds greater than 12 m/sec showing the roll-off at high NSL's.

Figure 26. A log-log plot of the spectral density of the wind variance vs frequency in cycles per hour for the Buoy data (heavy line) and the WOTAN data (light line).

Figure 27. The coherence between the Buoy and the WOTAN wind. The large tick mark on the y-axis is the level of statistical significance at the 95% level.

Figure 28. A time series of the high-pass filtered Buoy and WOTAN wind data.

Figure 29. A detailed example of the agreement between winds measured by the Buoy and by WOTAN (4.3 kHz). The WOTAN winds are offset by 6 m/sec.

Figure 30. A comparison of the Atlantic and Pacific results at 14.5 kHz with the published results of Wenz (1962) and Shaw (1975), both scaled to 14.5 kHz. The line marked A is the Atlantic results, P = Pacific, W = Wenz, and S = Shaw.

Figure 31. A comparison of the Atlantic and Pacific results at 4.3 kHz with the published results of Wenz and Shaw scaled to 4.3 kHz. A = Atlantic, P = Pacific, W = Wenz, and S = Shaw.

Figure 32a. Scatterplot of VAWR wind vs WOTAN wind (4.3 kHz) for the Pacific deployment at mooring 1 showing no apparent change in slope. (upper plot).

Figure 32b. Scatterplot of Buoy wind vs WOTAN wind (4.3 kHz) for the Atlantic deployment showing no apparent change in slope. (lower plot).

Figure 33. Sound speed profile for the equatorial Pacific in April.

Figure 34.. Ray diagram for Pacific in April.

Figure 35. Sound speed profile for the NW Atlantic in April.

Figure 36. Ray diagram for Atlantic in April.

Figure 37. Sound speed profile for the equatorial Pacific in October.

Figure 38. Ray diagram for Pacific in October.

Figure 39. Sound speed profile for the NW Atlantic in October.

Figure 40.. Ray diagram for: Atlantic in October.

Figure 41. Scatterplots of NSL vs SST at constant wind speed. The upper plot is at wind = 8.30 m/sec and the lower plot is at wind = 12.45 m/sec. In each plot the upper curve is for NSL at 4.3 kHz and the lower curve is for NSL at 14.5 kHz.

Figure 42. Comparison of the sea surface temperature, Buoy 3 winds and WOTAN winds (14.5 kHz). Data presented here have been averaged over a two week period.

Figure 43. Comparison of SST, Buoy 3 winds and WOTAN winds at 4.3 kHz. Data presented here been averaged over a two week period.

APPENDIX

This appendix includes the propagation of errors in the two most important equations, eq. 13 and eq. 15. Detailed examples are presented for S/N 001 at 14.5 kHz with the results for the other frequencies. All uncertainties listed here and in the Tables are uncertainties at the 95% confidence level.

$$\text{Equation 13} \quad \text{NSL} = \frac{\text{CNT}_{\text{OC}}}{A} + B$$

$$\text{where } A = T \cdot r \text{ and } B = -\frac{t}{r} - b' - 10\text{Log}(\text{GBW})$$

From equation 1:

$$\begin{array}{lll} r = 16.647 & \sigma_r^2 = 0.08406 & \sigma = 0.290 \\ t = 1382.545 & \sigma_t^2 = 100.029 & \sigma = 10.001 \end{array}$$

$$\begin{aligned} A = T \cdot r \quad \sigma_A^2 &= T^2 \sigma_r^2 + r^2 \sigma_T^2 = (16.789889)^2 (0.08406) + 0 \\ \sigma_A^2 &= 23.696 \quad \sigma_A = 4.868 \end{aligned}$$

at 95% confidence level uncertainty = $\sigma \cdot t$, where t is the value of the Student t -test (Bendat and Piersol, 1971).

$$\Delta_{\text{CL}} = 4.868 \cdot 3.1182 = 15.490$$

$$A = 279.501 \pm 15.490 \quad \text{at the 95\% CL.}$$

$$B = -t/r - b' - 10\text{Log}(\text{GBW})$$

$$\sigma_{t/r}^2 = \frac{\sigma_t^2}{r^2} = \frac{t^2}{r^4} \sigma_r^2 = \frac{100.029}{(16.647)^2} + \frac{(1382.545)^2}{(16.647)^2} (0.08406)$$

$$\sigma_{t/r}^2 = 2.453$$

The variance in the transducer sensitivity and the white noise generator is about ± 1 dB for each.

$$\sigma_{t/r}^2 = 2.453 \quad \sigma_{t/r} = 1.566$$

$$B = -t/r - b' - 10\text{Log}(\text{GBW})$$

$$\sigma_B^2 = \sigma_{t/r}^2 - \sigma_b^2 + \sigma_{\text{GBW}}^2 = 2.453 - 1 + 1$$

σ_b^2 is subtracted because b' is a negative quantity and would be subtracted from the other terms.

$$\sigma_B^2 = 2.45 \quad \sigma_B = 1.56 \quad \text{at } 95\% \text{ CL} \quad \Delta = 4.98$$

$$B = -6.54 \pm 4.98$$

$$\text{For equation 13} \quad \text{NSL} = \frac{\text{CNT}_{\text{OC}}}{A} + B$$

S/N 001

14.5 kHz	A = 279.50 $\pm$ 15.49;	B = -6.54 $\pm$ 4.98
8.0 kHz	A = 268.13 $\pm$ 10.66;	B = -8.51 $\pm$ 3.65
4.3 kHz	A = 258.36 $\pm$ 6.11;	B = -9.24 $\pm$ 2.16

S/N 002

14.5 kHz $A = 259.29 \pm 14.02$; $B = -11.13 \pm 4.88$
 8.0 kHz $A = 254.05 \pm 10.94$; $B = -11.57 \pm 3.99$
 4.3 kHz $A = 255.22 \pm 7.81$; $B = -9.18 \pm 2.72$

For equation 15 $20\text{Log}(\text{WND}) = C*\text{NSL} + D$

Atlantic S/N 001 14.5 kHz

$$C = 20Ac \quad D = 20(d - ABc)$$

$c = 0.0001985 \quad \sigma^2 = 1.0549 \times 10^{-12} \quad \sigma = 1.027 \times 10^{-6}$
 $d = -1.996 \quad \sigma^2 = 0.000224 \quad \sigma = 0.01496$
 $A = 279.501 \quad \sigma^2 = 23.696 \quad \sigma = 4.868$
 $B = -6.535 \quad \sigma^2 = 2.453 \quad \sigma = 1.566$

Small letters c and d are from the regression of log(wind) versus noise counts.

$$C = 20Ac \quad \sigma_{Ac}^2 = A^2 \sigma_c^2 + c^2 \sigma_A^2$$

$$\sigma_{Ac}^2 = (279.501)^2 (1.0549 \times 10^{-12}) + (0.0001985)^2 (23.696)$$

$$\sigma_{Ac}^2 = 1.0161 \times 10^{-6}$$

$$\sigma_C^2 = (20)^2 \sigma_{Ac}^2 = 0.00406 \quad \sigma_C = 0.0202$$

at the 95% CL $\Delta = 0.0336$

$$C = 1.11 \pm 0.03$$

Pacific S/N 002

14.5 kHz	C = 0.88 ± 0.05;	D = -24.28 ± 3.63
8.0 kHz	C = 0.87 ± 0.05;	D = -26.89 ± 3.24
4.3 kHz	C = 0.91 ± 0.04;	D = -35.54 ± 3.01

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