Underwater noise due to rain, hail, and snow

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The spectra of underwater noise generated by rain, hail, and snow have been measured in a lake at a depth of 35 m, for a variety of atmospheric conditions. Rain noise spectra, for light winds (< 1.2 m s⁻¹), have a sharp peak at 13.5 kHz with a steep falloff (~60 dB/oct) on the low-frequency side and a more gradual falloff (9 dB/oct) on the high-frequency side. A quasi-flat spectral regime exists in the frequency interval 2–10 kHz. Wind, for speeds increasing above 1.2 m s⁻¹, progressively rounds the peak. The spectral level at 15 kHz (i.e., near the peak) shows a linear dependence on the log of the rain rate with wind speed as a parameter. Correlation of the rain noise spectra with raindrop-size distributions suggests that low frequencies are generated by the larger drops, although this aspect of the problem needs further work. Hail noise spectra have rounded maxima appearing between 2 and 5 kHz with an approximately 10-dB falloff on each side. The spectrum of underwater sound generated by gently falling snow shows a linear increase in level, averaging 5 dB/oct, when plotted against the log of frequency.

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INTRODUCTION

The sources of underwater noise in the ocean are many: wind, surf, and biological organisms constitute a few of the better known ones.¹

The objective of the work reported here was to determine the underwater noise signature of rainfall, i.e., to determine the spectral characteristics of underwater acoustic noise generated by rain, for a variety of rainfall rates and ambient conditions. In the course of pursuing this objective, hail and snowfalls occurred and the opportunity was taken to measure the underwater noise signature of these precipitation forms. The hail signature, which is quite different from that of rain, can be used to help explain the noise generating mechanisms of both precipitation forms. The characteristics of noise generated by gently falling snow are totally different from those of the rain and hail and are possibly associated with the melting process rather than the kinetic energy of the falling snow which appeared negligible. To avoid the dominance of wind-generated noise, light wind situations were emphasized in the analysis. A large lake was chosen as the experimental site in order to simplify logistics and avoid contamination from ship noise.

The characteristics of underwater noise in the sea and its relationship to wind speed or sea state was first investigated by Knudsen² and Knudsen et al.³ Many other studies of the ambient noise followed, and those have been reviewed by Wenz⁴ and Urick.¹ In the 1970s, oceanographers and meteorologists began to consider the inverse problem of inferring wind speed from underwater noise measurements. Shaw et al.⁵ demonstrated a method of measuring wind speeds over the oceans by monitoring underwater acoustic noise at a single frequency of 5 kHz. Later, WOTAN⁶ (Weather Observation Through Ambient Noise) systems were developed to measure ambient noise at three frequencies, 4.3, 8.0, and 14.5 kHz, with a ± 7.5% bandwidth, and, hence, to infer wind speed. Kerman⁷ has reviewed the controversy among workers regarding the noise level dependence on wind speed and has contributed new data. Lemon et al.⁸ showed that WOTAN systems placed on the continental shelf were able to infer wind speeds that were highly correlated with buoy-mounted anemometer measurements. They also showed that departures of the spectral slope from that of the wind-induced sound spectrum allowed unambiguous determination of the presence or absence of rain, as first suggested by Shaw et al. Quantitative comparisons, using Franz's⁹ quasi-empirical relationship with observations at nearby lighthouse weather stations, showed agreement within a factor of approximately two. These results remain the first and, so far, the only quantitative acoustic rainfall measurements obtained at sea.

Previous measurements of rain noise spectra have been obtained by Heindsmann,¹⁰ Bom,¹¹ and Wylie.¹² Franz has considered the theory of sound generation mechanisms and compared it with observations of underwater sound generated in a tank by water drops. A preliminary summary of the work described here has been reported elsewhere by Scrimger.¹³ Recently, Nystuen¹⁴ has described observations
of ambient sound due to rainfall on a lake which showed a peak at 15 kHz; a numerical model of sound generated by the impact of water drops was able to reproduce the essential characteristics of the observed spectra.

I. MEASUREMENT SITE AND EQUIPMENT

The site chosen for the experimental work was McKenzie Bay, an approximately 2-km-square, 83-m-deep arm at the southeastern end of Cowichan Lake, a body of fresh water on Vancouver Island, British Columbia, Canada (48°48'15"N, 124°10'12"W), as shown in Fig. 1. The hydrophone was mounted 0.7 m from the lake floor, 300 m from shore, on a gently shelving bank where the depth was 35 m. The water temperature profile was isothermal (within 0.1 °C) throughout the experiment. The distrometer, anemometer, and rain gauges were located within 30 m of the shore on a flat area so as to represent as closely as possible overwater conditions.

The wind speed and direction were measured with a type 45B anemometer supplied by the Atmospheric Environment Service (AES) and a Gill (model 12102) anemometer, both mounted on a 7-m tower. Rainfall rate was measured continuously with an AES tipping-bucket rain gauge used in conjunction with a standard rain gauge for total rain amount. The drop-size distribution was determined with a Joss-Valdégel, RD 69 distrometer.

The hydrophone (ITC 8084A) was omnidirectional over the frequency range 100 Hz to 50 kHz in at least the upward-looking hemisphere. The frequency response of the hydrophone and post amplifiers was within ± 1 dB over the frequency range 100 Hz to 50 kHz. The ambient noise level was monitored continuously in the frequency band 15–20 kHz to select periods for data analysis. Two-min samples of the ambient noise were recorded on analog magnetic tape for selected periods of precipitation. Simultaneous observations of rain rate using both a tipping-bucket rain gauge and a distrometer were obtained. Generally, a minimum of six contiguous 30-s samples of distrometer data was gathered for each tape-recorded noise sample. An HP 3580 spectrum analyzer with 300-Hz spectral resolution was used to produce the spectra. The recording system is illustrated in Fig. 2.

II. EXAMPLES OF RAIN-INDUCED NOISE SPECTRA

Figure 3 shows a reproduction of spectra of rain noise recorded directly from the analyzer, as well as a spectrum of
TIPPING BUCKET RAINGAUGE
DISTROMETER
ANEMOMETER
POST-AMPLIFIER
HYDROPHONE- PREAMPLIFIER
ANALOG TAPE RECORDER
OSCILLOSCOPE
SPECTRUM ANALYZER
BANDPASS FILTER
DC-LOG AMPLIFIER
STRIP CHART RECORDER

FIG. 2. Block diagram of the recording system. The rain and wind gauges had chart readouts and the distrometer output was processed by a microcomputer. However, the pulsed electrical outputs from these instruments were also tape-recorded.

The background noise obtained shortly before the spectral observations. These “raw” data illustrate the well-defined peak at approximately 13.5 kHz, as well as some contamination in the data in the form of radio interference spikes near 24.8, 37, and 48 kHz. These spikes remained in identical locations on the spectrum throughout the experiment. Moreover, they occur in a slowly varying part of the rain noise spectra. A few days into the observation period, the peak amplitudes diminished so that, generally, only the spike at 24.8 kHz pierced the spectra, and this was readily removed from all spectra hereinafter reported. Figure 3 also shows two calibrations: a noise-level calibration, a, corresponding to an acoustic spectral level of 69.5 dB re: 1 μPa²Hz⁻¹ and a frequency calibration, f. The noise-level calibration signal was obtained from a white noise voltage generator and could encompass both the frequency range and the total dynamic range of the acoustic amplifying system by attenuating the input signal with a conventional balanced attenuator. The higher level pair of spectra, b and c, was taken consecutively at 21.44 and 21.46 h PST on 21 March 1985 and corresponds to a rain rate of 1.2 mm/h and a wind speed of 1 m s⁻¹; these illustrate the reproducibility of the data. The lower level curve, d, corresponds to a lower rain rate of 0.25 mm/h and a slightly higher wind speed of 1.2 m s⁻¹. It is to be noted that the upper curves exhibit a very sharp cutoff on the low-frequency side of 13.5 kHz, whereas the cutoff for the lower curve, for slightly windier conditions, is not as sharp.

Two hundred measurements of precipitation spectra and associated environmental conditions were made. It became apparent in the course of the analysis that those spectra obtained under calm conditions, generally with wind speeds below 1.2 m s⁻¹, exhibited the sharp cutoff at 13.5 kHz, while those recorded under windier conditions had a more rounded peak and less steep falloff. Accordingly, these two spectral types are presented separately below.

III. RAIN NOISE SPECTRA—LOW WIND SPEED

The three examples of rain noise spectra in Fig. 4, obtained when the wind speed was less than 1.2 m s⁻¹, show...
FIG. 4. Rain noise spectra, observed in low wind speeds (<1.2 m s⁻¹), corresponding to rain rates of 1.2 mm/h (O—O), 1.2 mm/h (+ + +), and 0.4 mm/h (∆—∆). The straight line is the Knudsen curve for Sea State ½. Spectral level is expressed in dB relative to 1 μPa² Hz⁻¹.

the well-developed peaks and linear falloffs of about 9 dB/ oct on the high-frequency side of the peaks, a slope of 60 dB/ oct on the low-frequency side, and an approximately flat regime, between 2 and 10 kHz, the latter being in good agreement with Bom’s observations. These curves, at very low wind speeds, remain virtually unchanged in form while they rise or fall in level as the rain rate increases or diminishes. The light straight line is the classic Knudsen curve for Sea State ½ (wind speed 0.5 to 1.5 m s⁻¹) and is included for reference.

IV. RAIN NOISE SPECTRA—MEDIUM WIND SPEED

The effect of wind blowing across the surface is to smear the peak found in the spectra observed under calm conditions. When the wind speed is higher than about 1.2 m s⁻¹, as illustrated in Fig. 5, there are four identifiable components in the spectra, three in common with the low wind spectra, viz.: (i) the linear falloff in level above 20 kHz; (ii) the steep falloff on the low-frequency side of the peak; (iii) the quasi-flat regime between 2 and 10 kHz; and a fourth— the now broad peak between 10 and 20 kHz. The three samples of rain noise spectra shown in Fig. 5 are accompanied by the classic Knudsen curve for Sea State ½ for reference. The progressive broadening of the spectral peak is illustrated in Fig. 6 which shows the frequencies of the “1-dB-down” points from the peak of rain noise spectra for a range of wind speeds.

V. SOUND LEVEL DEPENDENCE ON RAIN RATE

As seen from Figs. 4 and 5, the rain noise spectrum depends on both rain rate and wind speed. To demonstrate the relationship between noise spectral level and rain rate, it is evidently desirable to use a spectral level in that part of the spectrum most sensitive to rain, i.e., close to the peak. However, this part of the spectrum is strongly influenced by wind. On the other hand, choice of a frequency far removed from the peak will result in minimal sensitivity to both wind and rain. Accordingly, the spectral level at 15 kHz was chosen as a best compromise, and this is plotted against rain rate for various wind speed ranges in Fig. 7. Considerable scatter is evident in these data. This scatter is due to several factors. First is the uncertainty in the rain rate measurements due to the limitations of the tipping-bucket rain gauge. For low rain rates, the sensitivity of the gauge is very poor. A second factor is that the rain noise spectrum may depend on raindrop-size distribution as well as total rate. Other factors are the effect of the wind speed and possibly other noise sources.

The plots suggest a linear relationship between sound spectrum level and the log of the rain rate of the 4-dB increase for each doubling of the rain rate which agrees with measured values of Lokken and Bom. The plots suggest a linear relationship between sound spectrum level and the log of the rain rate of the 4-dB increase for each doubling of the rain rate which agrees with measured values of Lokken and Bom. The plots suggest a linear relationship between sound spectrum level and the log of the rain rate of the 4-dB increase for each doubling of the rain rate which agrees with measured values of Lokken and Bom. The plots suggest a linear relationship between sound spectrum level and the log of the rain rate of the 4-dB increase for each doubling of the rain rate which agrees with measured values of Lokken and Bom. The plots suggest a linear relationship between sound spectrum level and the log of the rain rate of the 4-dB increase for each doubling of the rain rate which agrees with measured values of Lokken and Bom. The plots suggest a linear relationship between sound spectrum level and the log of the rain rate of the 4-dB increase for each doubling of the rain rate which agrees with measured values of Lokken and Bom.
FIG. 7. Dependence of sound spectral level at 15 kHz on rain rate for four wind speed intervals. Spectrum level expressed in dB relative to 1 $\mu$Pa Hz$^{-1}$.

cy interval 2.4-4.8 kHz. Also, using Franz's quasi-empirical relationship between rain noise spectral level and rain rate, these workers attributed the variation in rain rate principally to changes in drop-size distribution rather than changes in the number of drops falling per second. This relationship is roughly the same for all wind speed intervals. Furthermore, as indicated by the cursor drawn at 1 mm/h rain rate, the spectral level at 15 kHz decreases with increasing wind speed, which is to be expected because of the progressive eroding of the 13.5-kHz spectral peak with increasing wind speed.

VI. CORRELATION OF RAIN NOISE CHARACTERISTICS WITH RAINDROP-SIZE SPECTRA

In most cases, when rain noise samples were recorded, a distrometer was used to measure the distribution of raindrop sizes. Initial inspection of the rain noise spectra in conjunction with the drop-size distributions in the rainfall suggested that the larger drops might be responsible for increasing the spectral level, relative to the remainder of the spectrum, in the frequency regime below the 13.5-kHz peak. This possibility is difficult to pursue because the low-frequency end of a given rain noise spectrum can, in many cases, be dominated by the contribution to the noise by the wind. With this in mind, only spectra obtained in low wind speeds ($< 1.2$ m s$^{-1}$) were examined. In low wind speeds, only the rain noise spectra with sharp peaks at 13.5 kHz are generated. However, several rain noise spectra observed at the borderline wind speed of 1.2 m s$^{-1}$ were found having the rounded peak so that it was possible to examine both types of spectra for the influence of the drop-size distributions in the rainfall on the spectral shape.

Figure 8 shows two sharply peaked rain noise spectra obtained at wind speeds of 0.9 m s$^{-1}$. The straight line at the bottom of the graph corresponds to the Knudsen curve for 0.9 m s$^{-1}$. While the lower rain noise spectrum is probably limited by wind noise up to a frequency of 7 kHz, the upper curve is well above the wind noise level.

FIG. 8. Examples of two rain noise spectra produced by rain of different drop-size distributions. The lowest level (straight-line) spectrum corresponds to a Knudsen curve for a wind speed of 0.9 m s$^{-1}$, the wind speed of both cases. The distrometer rates were 0.4 mm/h for a and 0.3 mm/h for b.

FIG. 9. Distrometer drop counts versus bin number. Each histogram is for a 30-s-long sample. Samples consecutive in time are plotted vertically so that each vertically arranged group corresponds to the time interval (90 s) needed to acquire each of the spectra shown in Fig. 8.
Table I. Drop-size (diameter) intervals corresponding to distrometer bin numbers.

<table>
<thead>
<tr>
<th>Bin number</th>
<th>Size interval (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3–0.4</td>
</tr>
<tr>
<td>2</td>
<td>0.4–0.5</td>
</tr>
<tr>
<td>3</td>
<td>0.5–0.6</td>
</tr>
<tr>
<td>4</td>
<td>0.6–0.7</td>
</tr>
<tr>
<td>5</td>
<td>0.7–0.8</td>
</tr>
<tr>
<td>6</td>
<td>0.8–1.0</td>
</tr>
<tr>
<td>7</td>
<td>1.0–1.2</td>
</tr>
<tr>
<td>8</td>
<td>1.2–1.4</td>
</tr>
<tr>
<td>9</td>
<td>1.4–1.6</td>
</tr>
<tr>
<td>10</td>
<td>1.6–1.8</td>
</tr>
<tr>
<td>11</td>
<td>1.8–2.1</td>
</tr>
<tr>
<td>12</td>
<td>2.1–2.4</td>
</tr>
<tr>
<td>13</td>
<td>2.4–2.7</td>
</tr>
<tr>
<td>14</td>
<td>2.7–3.0</td>
</tr>
<tr>
<td>15</td>
<td>3.0–3.3</td>
</tr>
</tbody>
</table>

Figure 9 shows the drop-size distributions (plotted vertically), in three contiguous 30-s intervals, in the rainfall which generated the two rain noise spectra of Fig. 8. The drop-size intervals corresponding to bin numbers are given in Table I. For case a, the distribution of drop sizes was over bins 2–9 (i.e., diameters 0.4–1.6 mm). For case b, the drop sizes were small, ranging only over bins 1–6 (i.e., diameters 0.3–1.0 mm). The rain rates for the two events were virtually the same since a smaller number of the large drops fell on one occasion compared with the large number of smaller drops on the other. However, the rain noise spectrum, a, associated with the larger drops, shows an almost 10-dB enhancement at its low-frequency end.

Figure 10 shows three rain noise spectra taken in a wind of 1.4 m s⁻¹ and a straight line spectrum corresponding to the Knudsen curve for 1.5 m s⁻¹. Spectra labeled c, d, and e correspond to rain rates of 3.2 mm/h, 0.6 mm/h, and 0.4 mm/h, respectively. These rain noise spectra have started to show the rounding of the peak due to the wind and the lowest level spectrum is likely being limited by wind noise. Above 12 kHz, the spectral levels conform reasonably well with the distrometer-measured rain-rate ratios expressed in dB, viz., 0.4 mm/h (0 dB), 0.6 mm/h (2 dB), and 3.2 mm/h (9 dB). The spectral levels in the frequency regime below 10 kHz may be more due to drop size. Figure 11 shows raindrop-size distributions that correspond to the rainfall which produced...
TABLE II. Characteristics of the various hail noise spectra (as shown in Fig. 12).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Vertical displacement (dB)</th>
<th>+ ve slope dB/oct</th>
<th>- ve slope dB/oct</th>
<th>Peak level (dB)</th>
<th>Frequency of peak (kHz)</th>
<th>Wind speed (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>0</td>
<td>12.5</td>
<td>-9.5</td>
<td>87.5</td>
<td>2.9</td>
<td>1.8</td>
</tr>
<tr>
<td>+</td>
<td>-5</td>
<td>10</td>
<td>-9.5</td>
<td>86.5</td>
<td>3.9</td>
<td>2.7</td>
</tr>
<tr>
<td>△</td>
<td>-10</td>
<td>10.5</td>
<td>-8.5</td>
<td>85.5</td>
<td>2.9</td>
<td>2.7</td>
</tr>
<tr>
<td>●</td>
<td>-15</td>
<td>9</td>
<td>-8.0</td>
<td>79.5</td>
<td>5.0</td>
<td>1.4</td>
</tr>
<tr>
<td>×</td>
<td>-20</td>
<td>10.5</td>
<td>-10.5</td>
<td>76.0</td>
<td>2.3</td>
<td>3.4</td>
</tr>
</tbody>
</table>

The spectra shown in Fig. 10. The labels c, d, and e on the sets of drop-size spectra correspond to the noise spectra labels. The drop-size distributions show it was mainly small drops that produced the lowest level spectrum, e. For case d, the drop counts were relatively low with an increased rainfall rate due to the larger drop sizes. These larger drops could account for the roughly 7-dB higher level seen in the low-frequency (< 10 kHz) end of the midlevel rain noise spectrum, d. Finally, for case c, the rainfall was composed of a large number of drops covering a size range similar to d. The increased number of these large drops may well be responsible for the further heightening in level observed at the low-frequency (< 10 kHz) end of the highest level rain spectrum, c, of Fig. 10.

A priori, these observations show reasonable accord with the theoretical work of Nystuen. However, it should be stressed that, while these spectra indicate that the low frequencies (< 10 kHz) in the rain noise spectra are due to the presence of large drops in the rainfall, there are cases to be found in the data set where this dependence is not apparent. The correlation between the acoustic-noise and raindrop-size spectra is a complex one and considerably more study will be needed before the relationship between the two spectra is fully understood.

VII. UNDERWATER NOISE DUE TO HAIL

Of the two dozen or more hail spectra that were recorded, all but about six were marred by either the nonstationarity of the sample (which took about 100 s to obtain), or by being mixed with rain. Five examples of hail spectra are shown in Fig. 12. These plots were displaced vertically to avoid overcrowding (see Table II). These hail noise spectra were all recorded within a 10-h period during which time the wind speed varied between 1.3 and 3.4 m s⁻¹. In contrast with the rain noise spectra, the frequencies at which the peaks in hail noise spectra occurred varied between 2.3 and 5 kHz, and the peak widths exhibited no correlation with wind speed.

VIII. UNDERWATER NOISE DUE TO SNOW

During the observation period, several heavy snowfalls occurred over a 2-day interval. The underwater noise spectra produced by three of these snowfalls are shown in Fig. 13. As can be seen the spectra all have, essentially, the same form. Evidently, the rates of snowfall were different on the three occasions that the spectra were obtained, producing spectra successively spaced by 2 or 3 dB. No independent quantitative data were obtained about the snowfall rate. Conditions were generally calm with wind speeds less than 0.5 m s⁻¹, the air temperature was -1 °C, and the snowflakes were large, gently falling, and limiting visibility to about 20 m.

IX. UNDERWATER NOISE DUE TO WIND

During periods free of precipitation, wind noise spectra were recorded whenever wind of significant speeds pre-
vailed. Such data, in the context of precipitation measurement, are of more than academic interest because they provide a check on the proper functioning of the acoustic measurement equipment and provide some insight into the acoustic environment at the site.

Figure 14 shows a set of wind noise spectra which covers the range of wind speeds encountered in the course of the experiment. Also plotted are the Knudsen curves for Sea States 0, 0.5, 2, and 4 and their associated range of wind speeds. By and large, good agreement is evident between the observed wind noise spectra and the Knudsen curves, except for the observed wind noise curve corresponding to a wind speed of 6.7 m s\(^{-1}\), which appears to be about 3 dB higher than warranted by the wind speed measured.

X. SUMMARY AND CONCLUSIONS

The spectral characteristics of underwater noise generated by rain, hail, and snow have been measured at a depth of 35 m in a freshwater lake, using a bottom-mounted hydrophone. Rain rates were limited to 10 mm/h. For light winds (<1.2 m s\(^{-1}\)), rain noise spectra have a sharp peak at 13.5 kHz with a 9-dB/oct falloff on the high-frequency side of the peak and a steep, \(~60\text{-dB/oct falloff on the low-frequency side. A quasi-}\)

A-i-flat spectral regime, with a positive slope of 0–4 dB/oct, exists in the frequency interval 2–10 kHz. For wind speeds above about 1.2 m s\(^{-1}\), the spectral peak is rounded. The spectral level at 15 kHz shows a logarithmic dependence on rain rate, increasing 4 dB for each doubling of rain rate. Comparison of rain-induced underwater noise spectra and simultaneous measurements of raindrop-size spectra suggests that the low-frequency part of the spectrum may be more responsive to the larger drops. However, at this stage, these hypotheses are somewhat tenuous and more study is required.

The spectra of noise produced by hail have a broad peak in the 2- to 5-kHz region.

Snow induced noise has a spectral level of between 36 and 40 dB (re: 1 \(\mu\text{Pa}^2\text{Hz}^{-1}\)) at 35 kHz and a positive 5-dB/oct spectral slope and is essentially ultrasonic.

Because of the peaked nature of the rain noise spectra reported above, it is difficult to make comparisons with data of other workers. Franz’s empirically derived noise spectra show very broad maxima in the region of 3 kHz and suggest a relatively low sensitivity to the amount of “rainfall” falling. On the other hand, Bom’s spectra, which were obtained in a narrow low-frequency spectral band (300–9600 Hz), correspond well in shape, over the same spectral range, with the above reported spectra but show considerably greater sensitivity to the rainfall rate. Nystuen’s data, in some cases, indicate a peak near 15 kHz.

Because of the obvious differences in the chemistry and biology of sea and lake waters, it is important that the above measurements be repeated in the ocean if an oceanic application is foreseen. Also, note will have to be taken of such environmental factors as the temperature profile and bottom reflectivity, since these can influence measured rain-generated sound levels and, hence, the inversion algorithm relating rain rate to observed sound level.

ACKNOWLEDGMENTS

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