Listening to Raindrops

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Abstract: The sound of rain underwater is loud and distinctive. It can be used as a signal to detect and measure oceanic rainfall. These measurements are needed to support climatological studies of the distribution and intensity of global rainfall patterns. Individual raindrops produce sound underwater by their impacts onto the ocean surface and, more importantly, by sound radiation from any bubbles trapped underwater during their splashes. Because different raindrop sizes produce distinctive sounds, the underwater sound can be inverted to quantitatively measure drop size distribution in the rain. Acoustical Rain Gauges (ARGs) are being deployed on oceanic moorings to make long-term measurements of rainfall using this acoustical technique.

1. Why listen to raindrops?

Rain is one of the most important components of climate. Knowledge of its distribution and intensity is important not only to farmers and flood control planners, but also to meteorologists, oceanographers and climatologists. This is because the formation of a raindrop in the air is accompanied by latent heat release. This heat release is one of the primary sources of energy driving atmospheric circulation. Thus, understanding the global patterns of distribution and intensity of rainfall is needed to improve weather and climate forecasting. Furthermore layers of relatively fresh water due to rain at the ocean surface are now thought to significantly affect oceanic circulation[1], another component of global climate.

Unfortunately, rainfall is also very difficult to measure, especially over the ocean where few people live and where rain gauges commonly used on land don't work. But we all know that rain falling onto a tin roof makes a lot of noise, and so does rain falling onto water. In fact, rain falling onto water is one of the loudest sources of underwater sound. So maybe we can measure oceanic rain by listening to it from below the ocean surface.

2. How do raindrops make sound underwater?

There are actually two components to the sound generated by a raindrop splash. These are the splat (impact) of the drop onto the water surface and then the subsequent formation of a bubble underwater during the splash. The relative importance of these two components of sound depends on the raindrop size. Surprisingly, for most raindrops, it is the bubble that is, by far, the loudest sound source. Bubbles are one of the most important components of underwater sound[2]. They have two stages during their lifetimes: screaming infant bubbles and quiet adult bubbles. As a bubble is created, in general it is not in equilibrium with its environment. It radiates sound (screams) to reach equilibrium. The frequency of the sound is well defined[3]:

$$f_r = \frac{1}{2\pi a}\sqrt{\frac{3\gamma P_0}{\rho_0}}$$

and depends on bubble radius, a, local pressure, P_0, local water density, ρ_0, and a geophysical constant, $\gamma = 1.4$. The important observation is that the size of the bubble is inversely proportional to its resonance (ringing) frequency. Larger bubbles ring at lower frequencies. The sound radiated is often loud and narrowly tuned in frequency (a pure tone). But quickly, after just tens of milliseconds, a bubble in water becomes a quiet adult bubble and changes roles. It absorbs sound, and is especially efficient absorbing sound at its resonance frequency.

Naturally occurring raindrops range in size from about 300 microns diameter (a drizzle droplet) to over 5 mm diameter (often at the beginning of a heavy downpour). As the drop size changes, the shape of the splash changes and so does the subsequent sound production. Laboratory and field studies[4,5] have been used to identify five acoustic raindrop sizes (Table 1). For tiny drops (diameter < 0.8 mm), the splash is gentle, and no sound is detected. On the other hand, small raindrops (0.8 - 1.2 mm diameter) are remarkably loud. The impact component of their splash is still very quiet, but the geometry of the splash is such that a bubble is generated by every splash in a very predictable manner[6]. These bubbles are relatively uniform in size, and therefore frequency, and are very loud underwater. Small raindrops are present in almost all types of rainfall, including light drizzle, and are therefore responsible for the remarkably loud and unique underwater "sound of drizzle" heard between 13-25 kHz, the resonance frequency for these bubbles.

TABLE 1. Acoustic raindrop sizes. The raindrop sizes are identified by different physical

mechanisms associated with the drop splashes (4, 5).

Drop size	Diameter	Sound source	Frequency range	Splash character
tiny	<0.8 mm	silent		gentle
small	0.8-1.2 mm	loud bubble	13-25 kHz	gentle, with bubble every splash
medium	1.2-2.0 mm	weak impact	1-30 kHz	gentle, no bubbles
large	2.0-3.5 mm	impact loud bubbles	1-35 kHz 2-35 kHz	turbulent irregular bubble entrainment
very large	>3.5 mm	loud impact loud bubbles	1-50 kHz 1-50 kHz	turbulent irregular bubble entrainment penetrating jet

Interestingly, the splash of the next larger raindrop size, medium (1.2-2.0 mm diameter), does not trap bubbles underwater, and consequently medium raindrops are relatively quiet, much quieter than the small raindrops. The only acoustic signal from these drops is a weak impact sound spread over a wide frequency band. For large (2.0-3.5 mm diameter) and very large (> 3.5 mm) raindrops, the splash becomes energetic enough that a wide range of bubble sizes are trapped underwater during the splash, producing a loud sound that includes relatively low frequencies (1 - 10 kHz) from the larger bubbles. For very large raindrops, the splat of the impact is also very loud with the sound spread over a wide frequency range (1-50 kHz). Thus, each drop size produces sound underwater with unique spectral features that can be used to acoustically identify the present of that drop size within the rain.

An example of the underwater sound field generated by a heavy thunderstorm recorded in Miami, FL is shown in Figure 1. The variations in the sound field are associated with changes in the drop size distribution (Fig. 2). During the heavy convective downpour, with rainfall rates reaching 150 mm/hr, very large raindrops are present and the sound field is loud across the entire spectrum (1-50 kHz). At the end of the convective downpour, a long drizzle begins. This phase of the storm has few large drops. The sound generated by small drops dominates the sound field producing the distinctive 13-25 kHz peak in the sound field associated with drizzle. At the end of the event, a few large drops are again present and once again the sound field becomes elevated below 10 kHz. Because the sound signatures for each drop size are unique, it is possible to invert the underwater sound field to acoustically estimate the drop size distribution within the rain[5] (Fig. 2). Once an acoustic drop size distribution is obtained, a variety of interesting features associated with the rain can be calculated, for example, rainfall rate or median drop size.

The Underwater Sound of a Thunderstorm

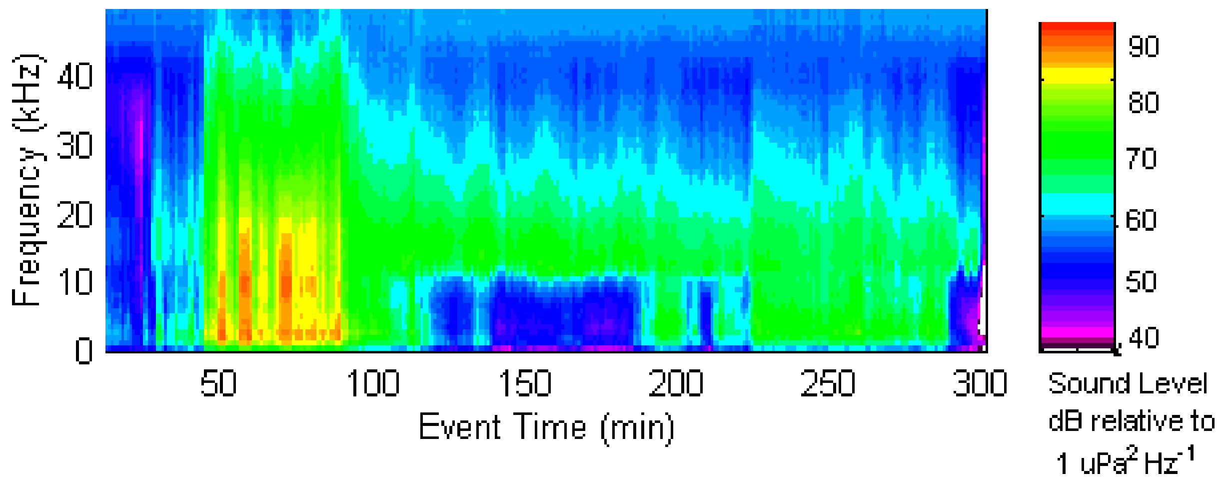

Figure 1. The underwater sound field during a thunderstorm. The changes in the sound are closely associatied with changes in the drop size distribution of the rain.

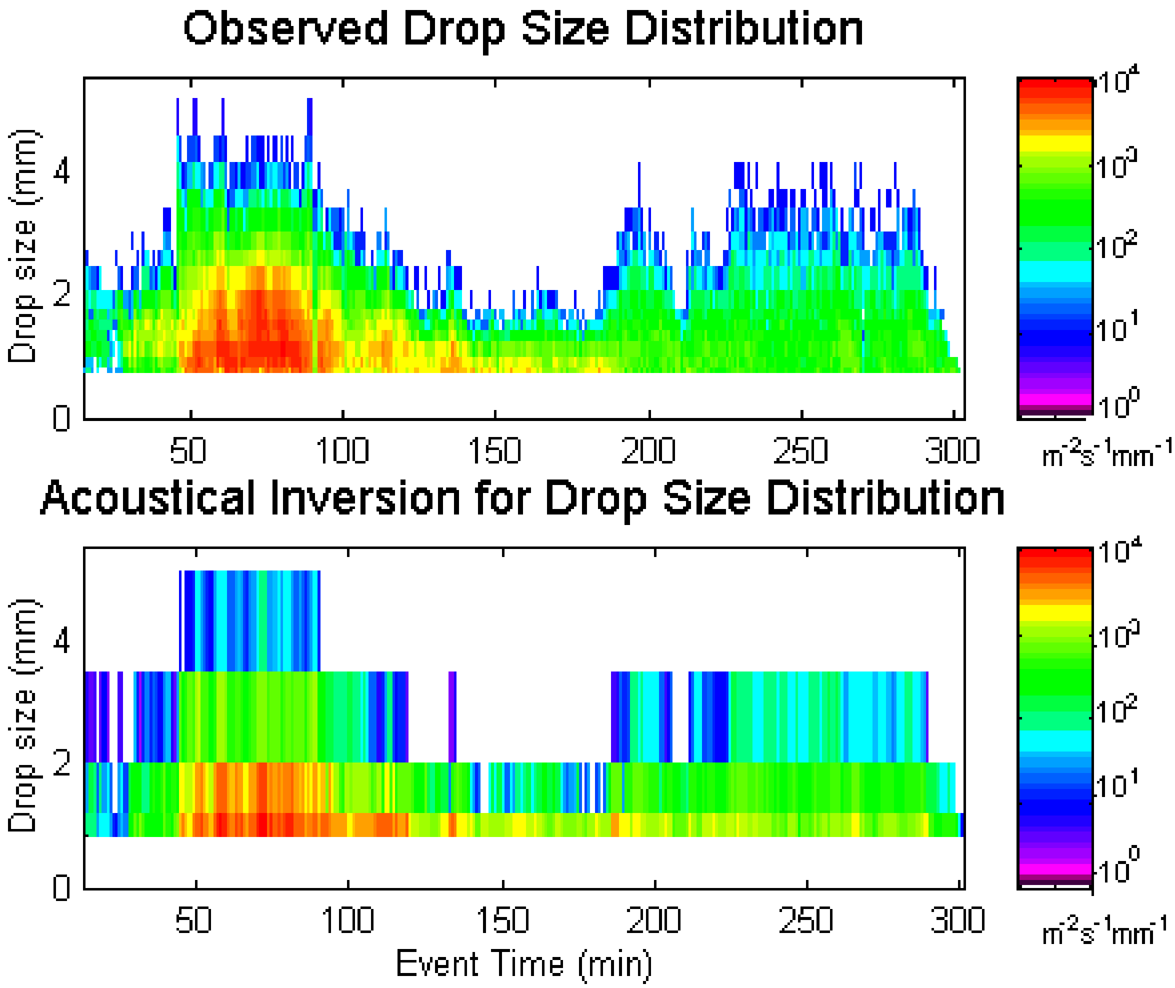

Figure 2. The observed drop size distribution in the thunderstorm and the acoustical inversion based on the unique sound signatures for each drop size. Very large raindrops are present during the heavy downpour. During the following drizzle, only small and medium raindrops are present and the sound of drizzle is heard between 13-25 kHz. Still later, a few large raindrops are present and the sound levels below 10 kHz become higher once again.

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3. Listening to the Ocean: Acoustic Rain Gauges

In order to measure rain at sea, Acoustic Rain Gauges (ARGs) have been designed and built at the Applied Physics Laboratory, University of Washington. The ARG consists of a hydrophone (underwater microphone), some electronic circuitry, a low-power sampling computer and a battery package designed to operate the ARG without servicing for up to a year. The ARG is attached to a mooring line, and can be placed at any depth, although practically the depth is limited by the crushing strength of the instrument case. Every few minutes the ARG "wakes up", evaluates and records the underwater sound field. Currently, the ARG design is autonomous from the surface float, and the recovery of data awaits recovery of the mooring. In the future, real-time transmission of the data will be needed to provide useful data for weather forecasting.

Figure 3. Dr. Jeffrey A. Nystuen holding an Acoustic Rain Gauge (ARG). This instrument is designed to be clamped onto an oceanic mooring and will record the underwater sound for one year.

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4. Detection and Measurement of Rain at Sea

When listening for rain in the ocean, the first step is to identify the sound as rain. There are lots of other sounds underwater, including the sounds of waves breaking, man-made sounds and biological sounds. Biological and man-made sounds are sometimes very loud and, if they contain frequency components which overlap the rain-generated sound, then they can prevent acoustical measurement of rain. These noises are usually intermittent or geographically localized. Some locations where persistent "noise" is present includes harbors (shipping and industrial activity) and snapping shrimp colonies. Snapping shrimp are from a family of shrimp species which make very loud "snaps" and that inhabit shallow tropical waters. Fortunately, the frequency content of most sounds is unique to their sources, and can be used to identify the sources, including rain, drizzle and whitecaps. Some examples of oceanic sound spectra are shown in Fig. 4.

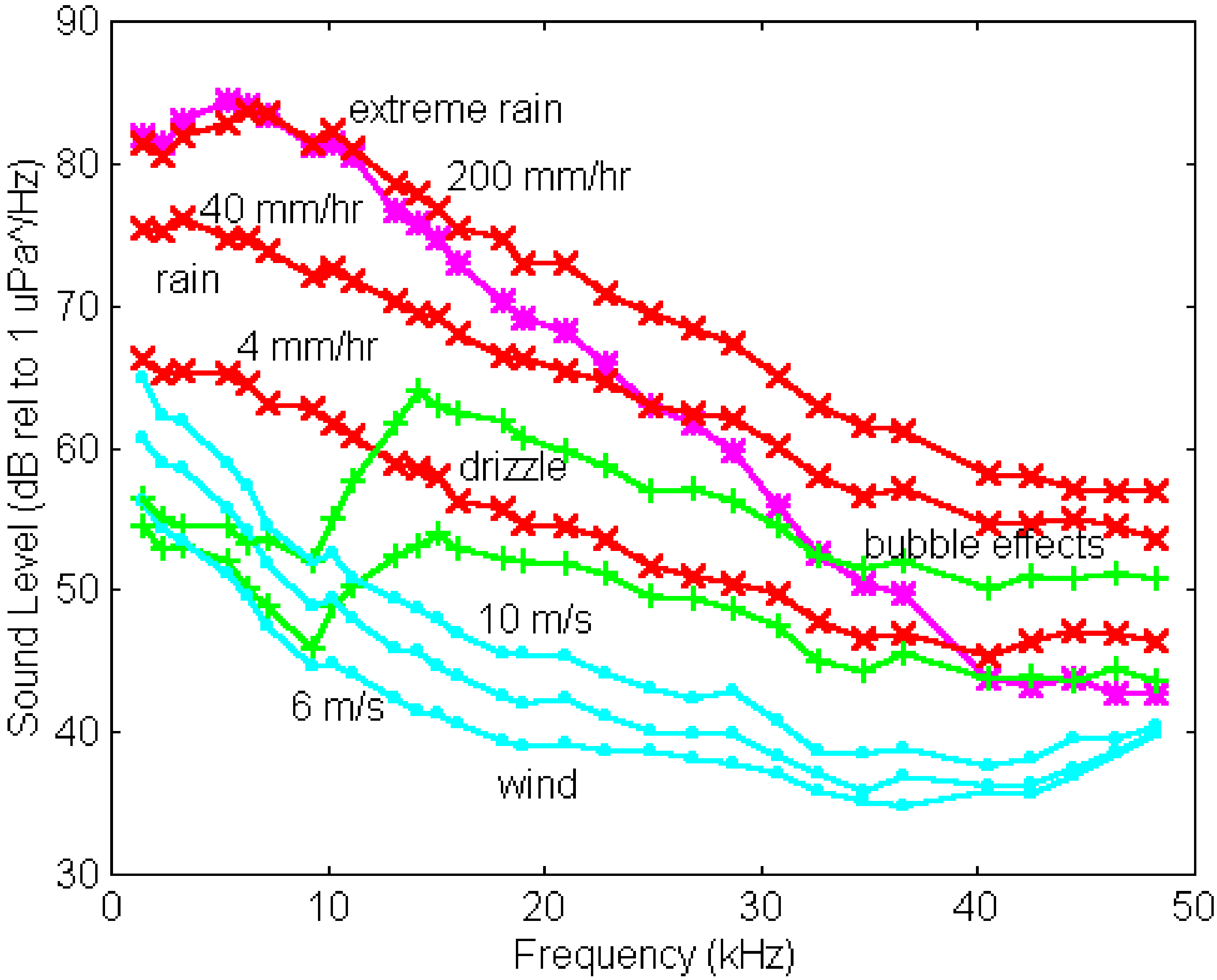

Figure 4. Examples of underwater sound spectra recorded from an oceanic mooring in the South China Sea. The sound spectra from wind-only conditions (cyan) show an uniform shape and a sound level which is

proportional to wind speed. The sound of drizzle (green) shows the characteristic peak associated with the sound generation mechanism of the small raindrops. The sound of heavy rain (red) is louder and includes lower frequencies. The sound of extreme rain includes sound generated by very large raindrops and is very loud. It also shows the effect of "quiet adult bubbles". Two spectra from extreme rain (200 mm/hr) are shown. The first (red) shows extremely high sound levels at all frequencies. The second (magenta) shows relatively lower sound levels above 10 kHz. This spectrum was recorded five minutes after the first, and yet the rainfall rate was still the same. A layer of bubbles had been injected into the sea surface. New "rain sound" has to pass through the bubble layer to reach the ARG sensor, and is partially absorbed by the bubbles. Since smaller bubbles (higher resonance frequency) are less buoyant than larger bubbles, they stay in the water longer and thus, this bubble effect is most noticable at higher frequencies.

Most of the time, it is not raining and no man-made or biological noises are present. When this is true, the sound is from the whitecaps generated by wind and can be used to quantitatively measure wind speed[7] as the number of whitecaps is proportional to wind speed. The shape of the sound spectrum generated by breaking waves is controlled by the distribution of bubble sizes generated by the breaking wave[8]. An interesting feature of the wind-generated signal is an apparent limit to the loudness of the sound at higher frequencies. This is due to quiet adult bubbles absorbing the higher frequency sound levels[9]. Because of their smaller size, bubbles which absorb high frequency sound stay in the water longer and can form effective layers of sound absorbing bubbles.

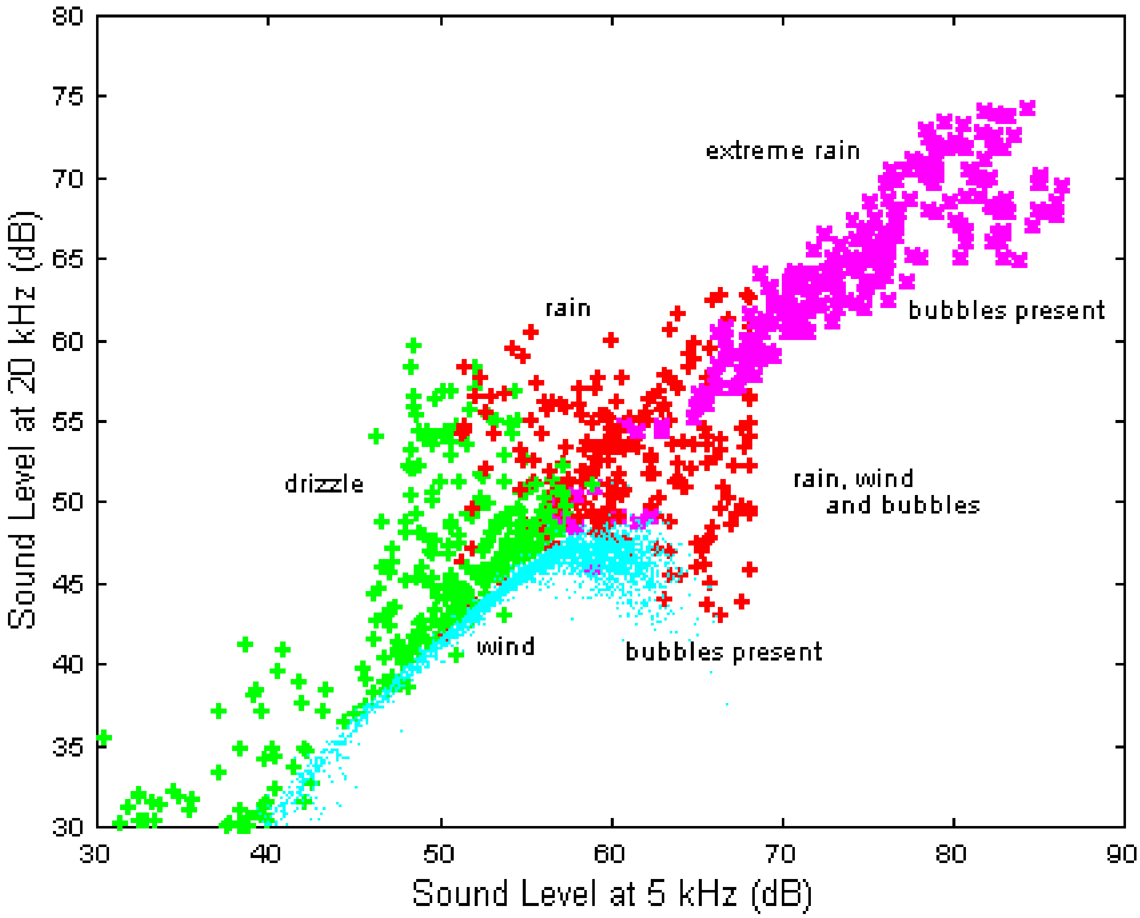

Figure 5. Acoustic weather classification uses features of the underwater sound spectrum to identify the sound source: wind (cyan), drizzle (green), rain (red), extreme rain (magenta) and to detect ambient bubbles.

Using Figure 4, the differences between wind-only and rain-generated spectra often appear to be subtle. However, by presenting the data in a different manner (Fig. 5), acoustic identification of different weather conditions becomes apparent. The sound of rain and drizzle contains relatively more high frequency sound than the sound from wind-only conditions. Furthermore, it is much louder. Even drizzle, under low wind speed conditions, has sound levels which can be orders of magnitude louder than wind-only conditions. The characteristic sound of drizzle, the 13-25 kHz peak, is sensitive to wind and has not been detected when the local wind speed is over 8-10 m/s. On the other hand, the sound from heavy rain is very robust and can be detected even in very high wind speed conditions (over 20 m/s) [10]. Extreme rain (over 100 mm/hr) is even louder, and can generate an ambient bubble layer which will distort the recorded sound spectrum (Fig. 4).

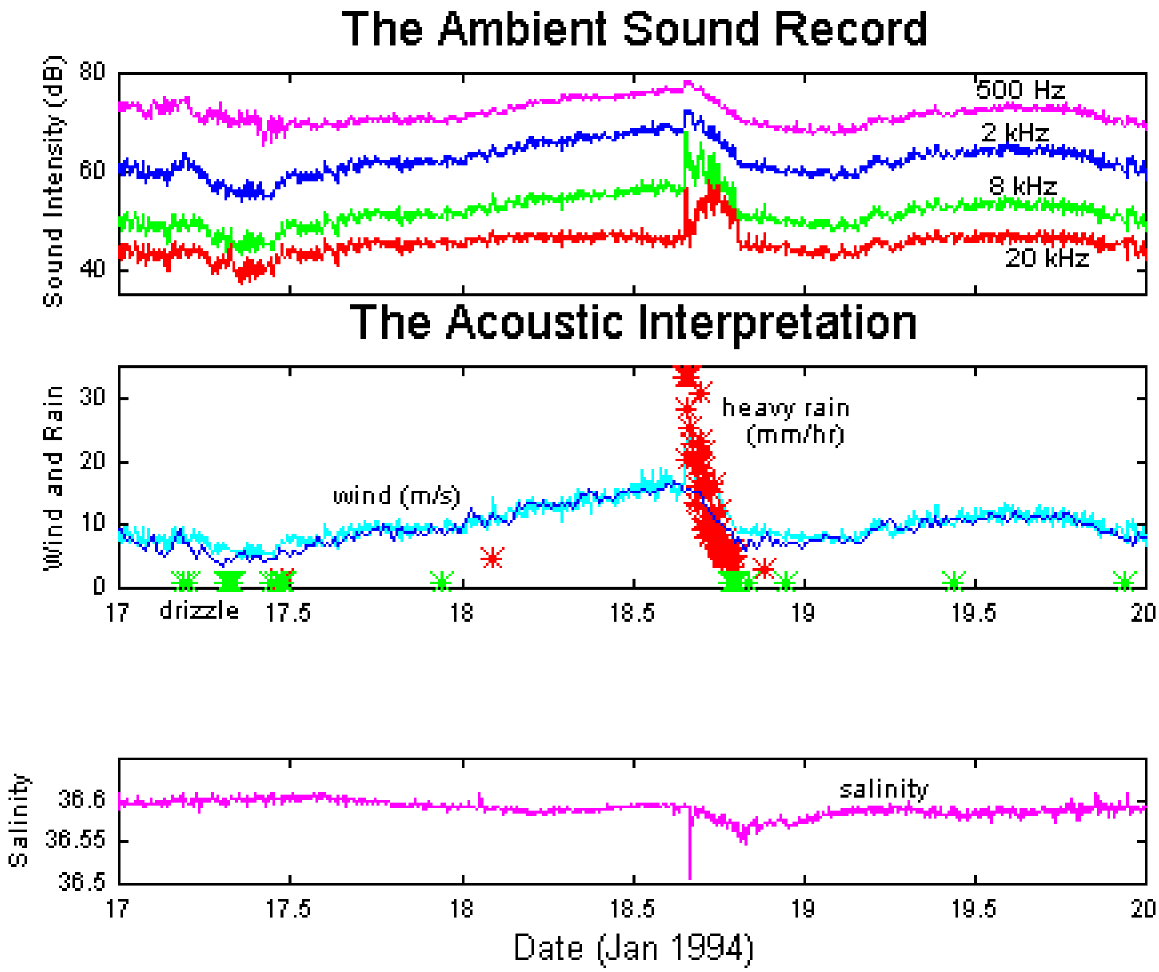

Figure 6. A temporal history of the sound field over three days at four different frequencies from the North Atlantic Ocean (ASREX Experiment, sponsored by Office of Naval Research). The lowest frequency (500 Hz) is not affected by precipitation, while the highest frequency (20 kHz) is affected by rain, drizzle and ambient bubbles. The acoustic interpretation of the sound record measures wind speed (cyan), rainfall rate (red) and detects drizzle (green). Comparison data for wind speed (blue) and near-surface salinity (magenta) from a nearby surface mooring are also shown.

An example of the acoustic interpretation of the underwater sound field is shown in Fig. 6. During this three day period a strong atmospheric front passed over the location of an ARG. When it was not raining, the acoustic estimate of wind speed matched a nearby mechanical anemometer to within ± 1 m/s (very good agreement). Because rain is so loud underwater, acoustical wind speed measurements are only possible when is not raining. During the peak of the storm, heavy rain was detected. This acoustic observation was "confirmed" by near-surface (1-m depth) salinity measurements. Similar records of acoustic measurement of rainfall have been obtained from ARGs on drifting buoys[11] and from an oceanic mooring in the South China Sea[12].

5. Conclusions

The sound of rain underwater is a loud and distinctive signal which can be used to detect and measure rain at sea. Individual raindrops make sound underwater by two distinct mechanisms: the impact of the raindrop onto the ocean surface and sound radiation from any bubbles trapped underwater during the splash. For most raindrops, the sound radiation by bubbles is, by far, the louder sound source. Because the geometry of their splashes regularly trap a bubble of uniform size, small raindrops (0.8-1.2 mm diameter) are unexpectedly loud underwater. These drops are responsible for the remarkably loud "sound of drizzle" heard between 13-25 kHz. Medium raindrops (1.2-2.0 mm diameter) are relatively quiet, while large (2.0-3.5 mm diameter) and very large (> 3.5 mm) raindrops have energetic splashes which can trap larger bubbles. These bubbles radiate sound at frequencies as low as 1 kHz. Because the different raindrop sizes produce sound with distinctive features, the sound field can be "inverted" to measure the raindrop size distribution within the rain. This is a good measure of rainfall rate, or other interesting features of rainfall.

Although there are sometimes man-made or biological noises which are loud and could potentially interfere with the acoustical measurement of rain, these noises are generally intermittent or geographically localized. When rain is present, the sound from rain dominates the underwater sound field. There are two features of rain and drizzle generated sound that allow detection of rain at sea. These are the relative level (very loud) and the relatively higher sound levels at higher frequency (over 10 kHz) when compared to wind. By monitoring for these distinctive spectral features, it is possible to detect and then quantify rainfall at sea.

New ARGs are currently being deployed on several of the moorings that form the Tropical Atmosphere Ocean (TAO) deep ocean mooring array deployed by NOAA in the tropical Pacific Ocean[13]. Data from these ARGs should become available for scientists beginning in the year 2000. By learning to listen to the ocean we can make important rainfall observations which will help meteorologists, oceanographers and climatologists to better understand the distribution and intensity of this important component of climate.

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