The beginnings of operational marine weather observations using underwater ambient sound

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Abstract

It has been demonstrated that the underwater ambient sound field can be used to monitor precipitation, wind speed and ambient bubble populations in the oceanic environment. However, in order to provide climatologically useful data, and to establish scientific confidence in this technology, long term time series of acoustical data are needed. Acoustical Rain Gauges (ARGs) have been deployed on enhanced Tropical Atmosphere Ocean (TAO) moorings at 8°, 10° and 12°N, 95°W in the eastern tropical Pacific Ocean. The first three ARGs have been recovered and provide data from December 1999 to April 2000. The ARGs provide data on rainfall detection and accumulation. In the absence of precipitation, acoustic measurements of wind speed are obtained. Relatively little rainfall has been detected in the data collected so far. However these data show promising agreement between the ARGs and co-located R.M. Young rain gauges mounted on the moorings.

1. Introduction

Knowledge of the global distribution of precipitation is recognized as a particularly important issue for climatologists. The hydrological cycle of the upper ocean layer is an important part of mixing, both lateral and vertical [1]. The hydrological cycle in oceanic regions is particularly poorly sampled because of the difficulty of obtaining salinity and precipitation measurements. This lack of surface rainfall data is a recognized problem [2]. Surface instrumentation to measure rain, especially in oceanic regions, is limited. Data are needed to identify occurrence of rain, type of rainfall, and quantification of rainfall amounts. In turn, this information is needed to understand the local, regional and global heat and water budget which control the circulation of the atmosphere and upper ocean.

The ambient sound field offers a means to make these measurements as processes associated with precipitation are a principal source of underwater sound in the frequency band 500-50,000 Hz. In particular, rainfall is responsible for an unique underwater acoustic signal easily distinguished from other common sound sources (breaking waves, biology, etc.) and, furthermore, the sound levels produced by rain are much louder, by orders of magnitude, than these other sources. This allows detection and measurement of rainfall at sea. The sound field can also be used to identify rainfall type (heavy convective rain versus stratiform drizzle) [3], and to measure wind speed (± 1 m/s) [4] and ambient bubble populations (near-surface void fraction).

An ancillary advantage of using the ambient sound field to measure various air-sea exchange processes is that the measurement is remote from the ocean surface. This means that the instrument does not interfere with the processes being measured. And it also means that fouling, and the likelihood of vandalism and theft are reduced. Furthermore, the measurement can be made from a wide variety of platforms, including surface and sub-surface moorings, and drifters.

To take advantage of this acoustic signal, Acoustic Rain Gauges (ARGs) have been designed and built for autonomous deployment on ocean surface moorings. The Pacific Marine Environmental Laboratory (PMEL), National Atmospheric and Ocean Administration (NOAA) has established the Tropical Atmosphere Ocean (TAO) array of roughly 70 ATLAS (Autonomous Temperature Line Acquisition System) ocean surface moorings across the tropical Pacific Ocean to monitor environmental conditions [5]. Several of these surface mooring (in particular, moorings at 8°, 10° and 12°N, 95°W) have been augmented with ARGs. Long-term time series are now being collected to establish scientific confidence in the acoustic measurements of rainfall and wind speed. This paper reports comparisons of ARG measurements of rainfall and wind speed with surface instrumentation on these moorings.

2. Instrumentation

2.1 R.M. Young rain gauges

Precipitation measurements on Next Generation ATLAS moorings [6] are made using R.M. Young Model 50202 precipitation gauges, which have been modified by PMEL for integration into the ATLAS electronics. The sensors are mounted approximately at 3 m above mean sea level on the buoy tower. These sensors have a 100 cm^2 catchment cylinder mounted atop a funnel which leads water into a cylindrical measuring tube. Water height within the tube is determined by measuring capacitance. The measuring tube has a storage capacity of 500 ml, representing 50 mm of rainfall accumulation, after which it automatically drains via a siphon. Siphon events take about 30 seconds, and are typically identified by sharp declines in volume for 2 consecutive samples. In real-time processing, these events are ignored.

The R.M. Young gauge reports a water level within its collection chamber each minute, and calculates the difference to obtain a rainfall rate for that minute. Inspection of 1 minute rain data from recovered moorings of the TAO array [7] indicates that instrumental noise levels are generally low, a few tenth of mm hr^{-1}, relative to the signals of interest. The estimated instrumental error for 10-minute derived rainfall rates is 0.4 mm hr^{-1} [7]. Other sources of noise include undercatch of rainfall in high winds, excessive buoy motion, sea spray, and evaporation from the cylinder. These errors are extremely difficult to quantify.

2.2 Acoustic Rain Gauges (ARGs)

The Acoustic Rain Gauges (ARGs) consist of an ITC-8263 hydrophone, signal pre-amplifiers and a recording computer (Tattletale-8). The nominal sensitivity of these instruments is -160 dB relative to 1 V/μPa and the equivalent oceanic background noise level of the pre-amplifier system is about 28 dB relative to 1 $\mu Pa^2 Hz^{-1}$. Band-pass filters are present to reduce saturation from low frequency sound (high pass at 300 Hz) and aliasing from above 50 kHz (low pass at 40 kHz). The ITC-8263 hydrophone sensitivity also rolls off above its resonance frequency, about 40 kHz. A data collection sequence consists of four 1024 point time series collected at 100 kHz (10.24 ms each) separated by 5 seconds. Each time series is fast Fourier transformed (FFT) to obtain a 512-point (0-50 kHz) power spectrum. These four spectra were averaged together and spectrally compressed to 64 frequency bins, with frequency resolution of 200 Hz from 100-3000 Hz and 1 kHz from 3-50 kHz. These spectra are evaluated individually to detect the acoustic signature of rainfall and then are recorded internally.

The overall temporal sampling strategy is designed to allow the instrument to record data for up to one year and yet detect the relatively short rainfall events present in the tropics [8]. In order to achieve this, the ARG is designed to enter a low power mode "sleep mode" between each data sample. For these deployments, the ARGs "sleep" for 8 minutes and then sample the sound field. If "rain" is detected, the sampling rate changes to 1 minute (or 4 minutes if "drizzle" is detected) and stays at the higher sampling rate until rain is no longer detected. Some "noise" will trigger the high sampling mode and must be removed from the data.

A sound source at a free surface, the ocean surface, is an acoustic dipole, radiating sound energy downward in a $\cos^2\theta$ pattern where θ is the zenith angle. This allows the intensity of surface generated sound at some depth, h, below the surface to be given by:

$$I(h) = \int I_0 \cos^2\theta \quad atten(p)\, dA \tag{1}$$

where I_0 is the sound intensity at the surface and *atten(p)* describes the attenuation due to geometric spreading and absorption along the acoustic path, p. If the sound source is uniform at the surface and absorption and refraction are neglected, the measurement should be independent of depth. For any particular deployment, the attenuation along the acoustic path can be complicated, but have only resulted in minor corrections in other studies [4]. The ARGs have been deployed at 38 m depth on the mooring lines (wire cable). The depth was chosen to be above the thermocline, lessening the effects of acoustic refraction, and to maximize sampling area, so that the buoy itself does not occupy a significant portion of the effective listening area. Equation (1) can be used to estimate the effective sampling area at the surface. Neglecting refraction and absorption, 90% of the signal is arriving from a sampling area equal to:

$$\text{sampling area} \equiv \pi(3h)^2 \tag{2}$$

where h is the depth of the ARG. The integrating area of the hydrophone is important for two reasons. First, rainfall is inhomogeneous on all scales, but rainfall measurements are needed on large temporal or spatial scales. An instrument with a large inherent sampling area should produce a better "mean" rainfall statistic. Second, the large spatial sampling allows the short temporal sampling periods being used for each data sample to include many individual raindrop splashes.

3. Acoustical Measurements of Rain and Wind

3.1 Acoustical Rainfall Rate Measurements

Two types of acoustic rainfall rate algorithms are available. Because different raindrop sizes have distinctive acoustic signatures underwater [9], the underwater sound can be decomposed into components associated with each drop size. This allows an acoustic measure of the drop size distribution in the rain [10]. Once a drop size distribution is obtained, then rainfall rate can be calculated. While the sound field can be "inverted" to measure drop size distribution, the algorithm used here is a simpler empirical algorithm relating the sound level at 5 kHz (SPL_5) to the rainfall rate R [11]:

$$\log_{10}(R) = (SPL_5 - 50)/17 \tag{3}$$

3.2 Acoustical Wind Speed Measurements

An algorithm for the acoustic quantification of wind speed is available [4]. After sound records containing noise, including precipitation, are removed, the sound level is empirically related to 10-m height wind speed by

$$U_{10} = {(10^{SL_8/20} + 104.3)}\Big/{53.91} \tag{4}$$

where SL_8 is the sound level at 8 kHz and U_{10} is the estimated wind speed at 10 m. This relationship was empirically developed using 8 kHz data from the North Atlantic Ocean. This algorithm has a mathematical limit of roughly 2 m/s. There is a physical limit to the acoustical wind speed measurement. For very low wind speeds, no breaking of waves or wavelets occurs and thus there is no mechanism for wind to generate underwater sound [12].

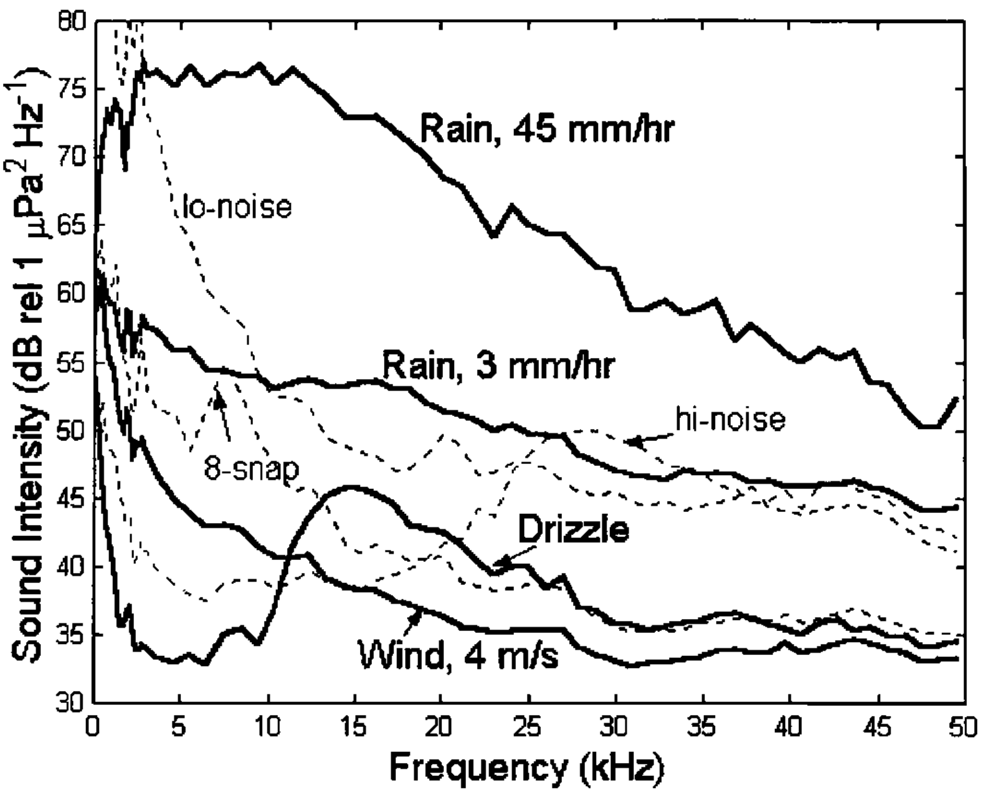

Figure 1. Examples of the underwater sound spectra from geophysical sources (rain, wind and drizzle) and some distinctive noises (lo-noise, hi-noise and 8-snap) recorded at the ATLAS mooring at 10°N, 95°W.

3.3 Extracting the Signal from Background Noise

The desired geophysical signal is usually persistent and, in the case of rain, very loud. However, in the ocean, there are other underwater sounds which can interfere with acoustical weather measurements. Some examples of the geophysical signals (wind, rain and drizzle) are shown in Figure 1, along with some distinctive noises (lo-noise, 8-snap and hi-noise) that were detected at these surface moorings. The exact sources of the noise spectra are unknown, but occurred regularly enough that they are likely to be associated with specific sources. Throughout the record at 8°N and 10°N, intermittent "snaps" were present (8-snap). This noise may be biological in origin. At 10°N, loud low frequency noise (lo-noise) was present during 10 days of February and during April. This may be flow/splash noise associated with strong currents on the mooring. In all cases, sound spectra not consistent with known geophysical signals (wind, rain and drizzle) are assumed to be "noise" and were removed from the data record. This was done objectively using features of the spectra, i.e. levels, slopes and peaks, and also subjectively by examining all events that triggered the high sampling mode of the ARGs.

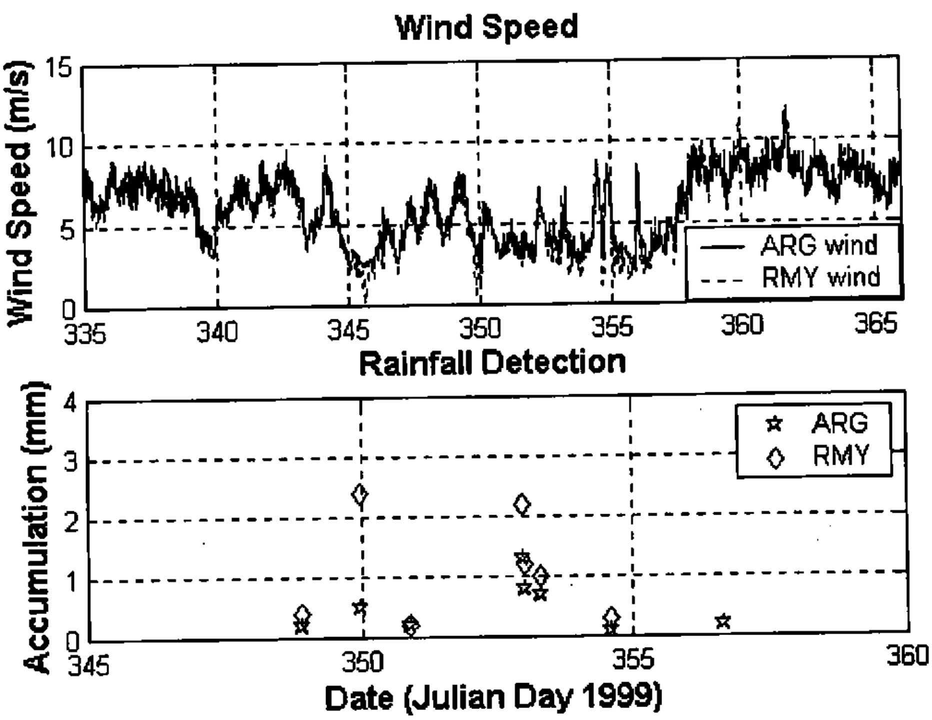

Figure 2. Wind speed measurements and rainfall detection from the ATLAS mooring at 8°N, 95°W during December 1999. The top panel shows a comparison of ARG and anemometer wind speed measurements. The bottom panel shows rainfall detection and accumulation for the rain events detected during the month. The accumulation totals for one event, shown in more detail in Figure 4, are off scale.

4. Results

4.1 Data from the ATLAS mooring at 8°N, 95°W

Figure 2 shows an example of the comparison of acoustical and surface measurements for wind speed and rainfall detection. The buoy winds have been corrected to equivalent 10 m height using the COARE V2.5b bulk flux algorithms [13] and then smoothed with a 30-minute binomial filter. The mean absolute difference between the ARG measurement and the anemometer is 0.5 ± 0.4 m/s (Figure 3). The bias is less than 0.1 m/s. Note that the acoustic wind speed algorithm does not allow values less than 2.2 m/s. Similar agreement is observed for the other months.

Figure 2 also shows rainfall detection by both instruments. Unfortunately very little rainfall was recorded during the deployment period (December 1999-April 2000). Several rainfall events were detected during December 1999, but only one of these would be considered heavy rainfall. Temporal co-detection of these events by both instruments was excellent. Only one light event detected acoustically was not recorded by the R.M. Young rain gauge. This shows the sensitivity of the sound field to detect rain, even very light rain. A detailed examination of the rainfall record for the event on Day 353 (Figure 4) shows some features of the acoustic rainfall measurement. Each of the sub-events within this rain are detected by both instruments. The temporal resolution of the acoustic measurement is much higher than the R.M. Young rain gauge, allowing a more detailed examination of the temporal structure of the rain events. The ARG rainfall rate is also an instantaneous value, while the RMY rainfall rate is for a fixed interval, in this case 10-minutes.

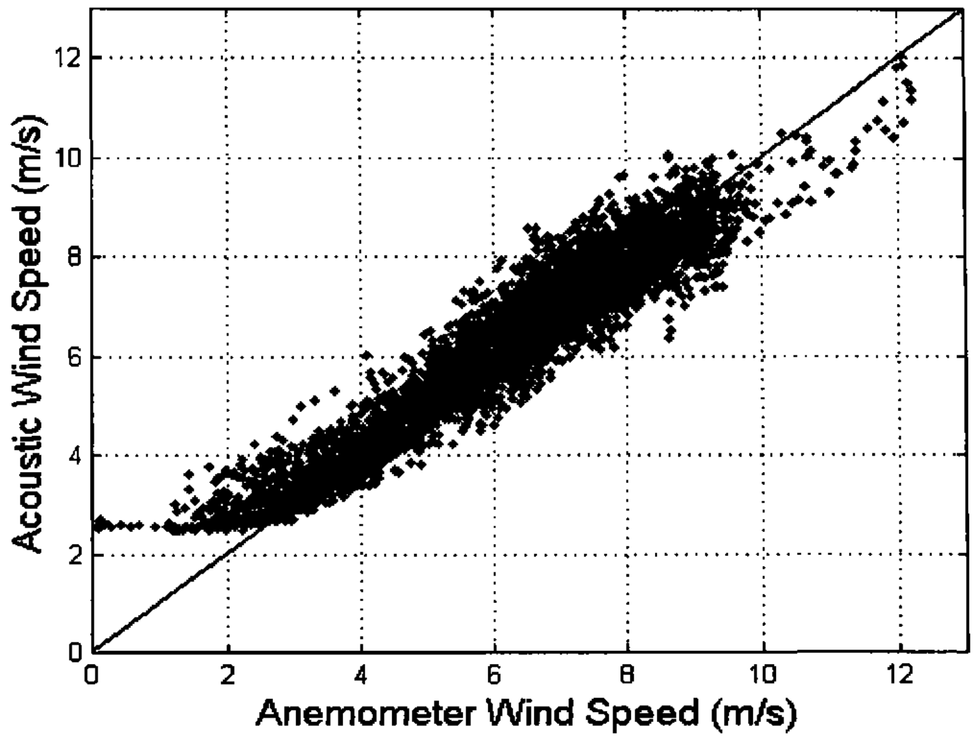

Figure 3. A comparison of wind speed measurements from the ATLAS mooring anemometer and the ARG for December 1999 at 8°N, 95°W. Other months and moorings show similar agreement.

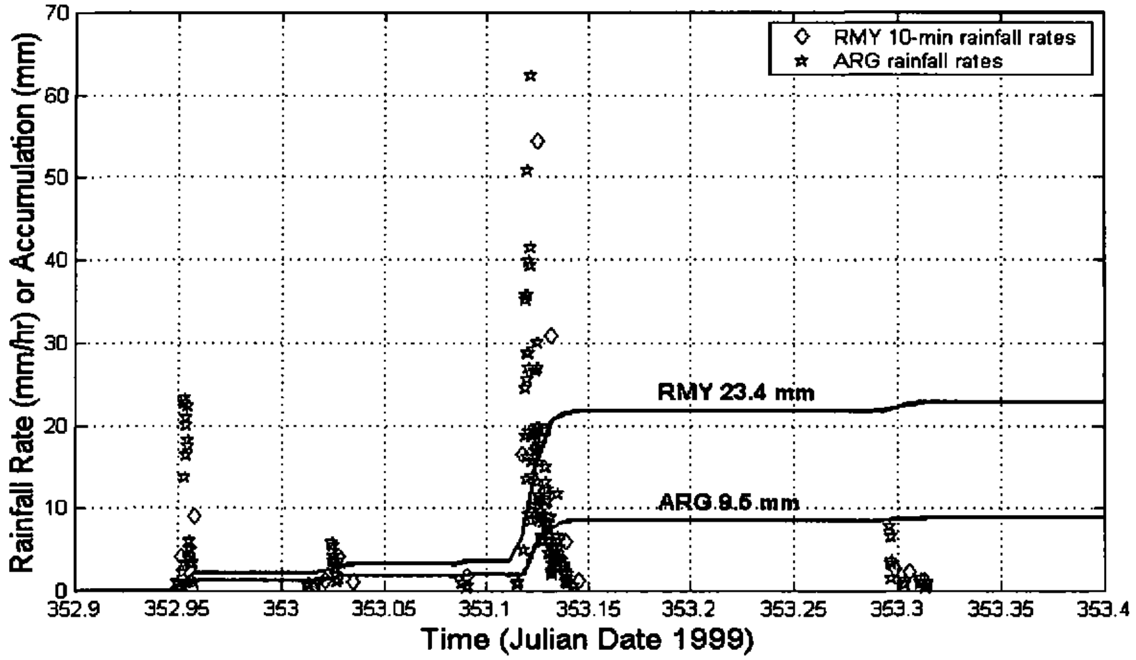

Figure 4. Details of the rain event on Julian Day 353 (Dec 19, 1999) at 8°N, 95°W. The ARG rainfall rate is instantaneous, while the RMY rainfall rate is for a 10-minute interval. Accumulation totals allow direct comparison.

Accumulation totals allow direct comparison. Using the acoustic rainfall rate algorithm (Equation 3) the acoustic accumulations are just 41% of the rainfall accumulations from the R.M. Young rain gauge for these data. This suggests that the acoustic rainfall rate algorithm will need to be modified, however more data are required before proposing a modified algorithm. For the entire deployment, the ARG rainfall total was 44% of the R.M. Young rain gauge accumulation.

4.2 Data from the ATLAS mooring at 10°N, 95°W

Results similar to the data from 8°N, 95°W were obtained from the mooring at 10°N, 95°W. Once again, only a few rain events occurred in December 1999, along with some very small events in February and March 2000. Co-detection of the events in December was excellent. Again, the acoustic rainfall accumulation was low relative to the R.M. Young gauge (40%). Wind speed comparisons were similar to Figure 3. One difference was very high levels of low frequency noise in the sound field (lo-noise in Figure 1) during 10 days of February and during April. Ocean current measurements from this mooring show local currents of increasing from tens of cm s^{-1} to over 1 m s^{-1} in February (The current meter broke shortly after the currents reached this speed.) and there was physical evidence of damage to the mounting cage for the ARG, also suggesting high currents. On the surface, bird guano fouled the R.M. Young gauge.

4.3 Data from the ATLAS mooring at 12°N, 95°W

This mooring was attacked by pirates on March 9, 2000 (acoustically detected). The surface instrument tower was stolen. The sub-surface instruments survived the attack. This is a surprisingly big problem for remote ocean moorings. On several occasions the surface float has been left intact, allowing recovery of sub-surface instrumentation. This problem highlights one of the advantages of the acoustic measurements. They are covert and away from the ocean surface, reducing the likelihood of vandalism or theft. Obviously no comparison is available between the ARG data and the surface instruments (stolen), but the acoustic record can be evaluated. Wind speed was measured, but only two rain events occurred during the deployment (in April).

Table 1 summarizes the rainfall comparisons for all three moorings. While the co-detection of rain events was high, several light rain events were not co-detected by both instruments. Overall, 19 of the 24 events (80%) detected by the R.M. Young gauge were also detected by the ARG and 20 of the 22 events detected by the ARG were also detected by the R.M. Young gauge (91%). The total rain accumulation for the ARGs was 26 mm which was 42% of the 62 mm collected by the R.M. Young rain gauges.

		DEC 99	JAN 00	FEB 00	MAR 00	APR 00
8°N	ARG	6 events (11 mm)	2 events (1 mm)	no rain	no rain	no data (electrical failure)
	RMY	6 events (26 mm)	2 events (1 mm)	no rain	no rain	no rain
10°N	ARG	5 events (10 mm)	no rain	4 events (2 mm)	2 events (2 mm)	no data (mooring noise)
	RMY	5 events (28 mm)	no rain	4 events (6 mm)	4 events (1 mm)	no data (bird guano)
12°N	ARG	no rain	no rain	no rain	no rain	2 events (11 mm)
	RMY	no data	no data	no data	no data	no data
			(pirates steal surface instruments on March 9th)			

Table 1. A summary of the rain event detections and accumulation totals from the ARG and R.M. Young (RMY) rain gauge for these three mooring deployments.

5. Conclusions

The first deployments of ARGs on ocean surface moorings show the promise of passive acoustical measurements of important air-sea processes, in particular, for rainfall detection and measurement. Unfortunately, very little rainfall was recorded at these three surface moorings during these deployments. When it did rain, the rain events were detected by both the R.M. Young rain gauges and the ARGs. The acoustic algorithm used to quantify rainfall rate measured 42% of the total rainfall accumulation relative the R.M. Young rain gauges. The algorithm can be adjusted, but more data need to be collected before a new algorithm is proposed. These data are being collected. The acoustic wind speed measurement shows excellent agreement with the ATLAS mooring anemometers, with a bias of less than 0.1 m/s and an absolute mean difference of 0.5 ± 0.4 m/s for wind speeds from 2-12 m/s (30-minute smoothed wind speed data).

Although the acoustical signal from rain is loud and distinctive, allowing rainfall detection even when other noises are present, the surface moorings are a noisier environment than expected (Figure 1). Nevertheless, long-term measurements from surface moorings, where comparison instrumentation is available, are needed to provide confidence in this technique for measurement of rainfall and wind speed. Other measurement platforms, including Lagrangian drifters and sub-surface moorings, may ultimately prove to be better platforms from which to apply this acoustic technology.

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