Rainfall at Sea: Using the Underwater Sounds of Raindrops as a Rain Gauge for Weather and Climate

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Rain on Land, Rain at Sea

Were you out walking when it starts to rain, you might take shelter in a shed with a tin roof. By listening to the sound of the raindrops plunking on the roof, you could tell that it is raining, how much it is raining, the size of the raindrops, and when the rain has stopped.

Listening to raindrops over the ocean surface using a hydrophone is analogous to listening to the rain under a tin roof. Raindrops hitting the sea surface generate loud sounds underwater. The ocean conducts sound very efficiently so that the sounds from the sea surface propagate down with little loss of energy; the sound environment of the ocean is much like a large echo chamber. The nature of the sound is unlike the plunking on a tin roof, however. Rain over the ocean sounds like the hiss of white noise underwater (Discovery of Sound in the Sea: Rainfall; see bit.ly/3KoN55m), with frequencies that extend well above the threshold of human hearing. In this article, we describe how those sounds convey considerable information about the nature of rainfall at sea.

Rain is, of course, intermittent in both time and location and has a wide variety of characteristics, ranging from light drizzle to heavy tropical downpours. On land, it is relatively easy to measure: a simple cup placed in the open for an interval of time can be used to determine the rate of rainfall. At sea, however, rain is difficult to measure because the ever-present sea spray can be confused for rain and a rain gauge can be violently disturbed by the confounding effects of waves. These difficulties, together with the obvious underwater sounds from rain, have led to the development of an acoustic rain gauge. Deploying an instrument at sea still faces the perennial problem of requiring some platform to put it on, however.

It might appear that the measurement of rain through acoustics would be challenging because there are many contributors to noise in the ocean. The sound environment can be complicated, and all ocean ambient sound is time, frequency, and location dependent. But rain is one of the major natural sources of underwater sound, and when rain is present on the ocean, its sound usually dominates all other sound sources. The dominant sound of rainfall, which occurs in the acoustic frequency range from 1 to 50 kHz, can be used to infer rain rate, accumulation, and the size of the drops themselves.

Why Listen to Rain?

Knowing the distribution of rain is necessary for weather forecasts in day-to-day life and is an essential variable for climate studies. Still, the accurate measurement of rain is an important challenge for climate science. Although it is essential to know the rainfall accurately, the quality of data from the rain gauges on at-sea moorings is poor. Satellite-based remote sensing can also measure the rainfall over the ocean, these measurements provide large-scale coverage of rainfall parameters such as rain rate and accumulation. However, satellite data cannot be used to determine the local variability and details such as drop size distribution.

Because of the great value of having data on the rainfall over the expanses of the oceans, novel methods had to be developed to get accurate measures. Through developments described in this article, acoustic rain gauges have been designed for practical, cost-effective deployment on many observation platforms.

Over the past quarter century, the oceanographic community has been developing the Global Ocean Observing

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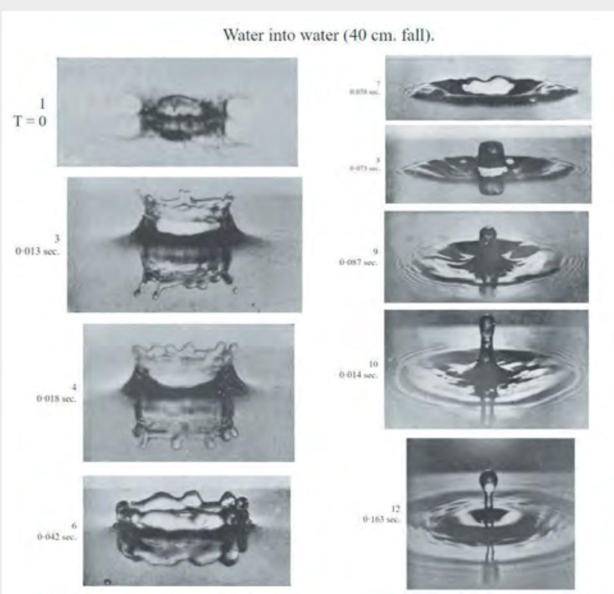
System (GOOS; see goosocean.org). Recognizing the importance of oceanographic information for society on the one hand (tsunamis, El Niño events, climate) and the difficulty and expense of obtaining oceanic data on the other, the GOOS comprises a variety of shared, sustainable platforms, from autonomous floats to long-term moorings to scientific cabling systems across the sea floor and terminating on shore. The availability of these platforms means that the acoustic rain gauges have the potential to become ubiquitously deployed rain gauges for global ocean coverage. In addition, the measurement of ocean sound is recognized as an essential ocean variable for GOOS, and the hydrophones of the rain gauges can be employed to measure sound generally.

A Bit of History

The nature of splashes of droplets hitting a water surface is a surprisingly complicated subject that has long attracted scientific interest. More than a century ago, photographs were used to describe the detailed process by which droplets strike the water surface. In that process, a drop will often create a small, temporary crater, splashes, or waves on the water surface. More importantly about rain-producing sound, a raindrop will often also form a cavity or entrain a small bubble of air when it enters the water. The phenomenon of a drop striking a water surface is controlled by surface tension or the attractive forces of liquid molecules along the water surface. The book by Worthington (1908), *A Study of Splashes*, has beautiful images of droplet splashes (**Figure 1**).

Figure 1. *A series of photos shows the impact process of a droplet falling into the water at different times starting at time (T) = 0. After the initial impact (1), a crater is formed and the crown-shape ring rises (3 and 4) and falls (6 and 7). Then a central column emerges (8 to 10), with ripples propagating outward (12). Adapted from Worthington (1908). Available at bit.ly/3Cq4aZS.*



Medwin and colleagues (1992) used an abandoned vertical utilities shaft with an anechoic tank at the bottom to build a unique facility for raindrop sound research. Rainfall could be simulated because the shaft was a 26-m-tall air chamber that allowed falling water drops to reach terminal velocity. Using this shaft, distinctive underwater sounds of different drop sizes and their drop splashes could be examined. They could also identify the different acoustical characteristics of the drop sizes (Medwin et al., 1992). Concurrent field studies developed the use of underwater sound to detect and quantify rainfall (Nystuen, 1986). From this work, passive acoustic instruments were developed to use the oceanic ambient sound field to measure rain rate, drop size distribution, and other properties (Nystuen, 2001). Such instruments are called "passive" because they do not require deploying an "active" acoustic source.

Extracting the Rain Signal from Noise

Ocean ambient sound originates from two basic sources: the activities of humans (anthropogenic sound: shipping, pile driving, construction) and nature (rain, wind, wave breaking, fish, marine mammals, earthquakes). Different sources of ocean ambient sound contribute to the overall sound level in different frequency ranges; here, we need only concern ourselves with the sound from the wind or rain.

Oceanic ambient sound is measured by a hydrophone mounted on a suitable platform that provides power for data sampling, recording, storage, and transmittal. At any given time, the local acoustic pressure fluctuations (in micropascals [μPa]) measured by a hydrophone result from the total contributions of the myriad sounds of the ambient environment.

For a given frequency, the contributions to the pressure fluctuation from different sources cannot be distinguished. But if sources have unique frequency spectra (sound pressure level frequency), then the times when only those sources are

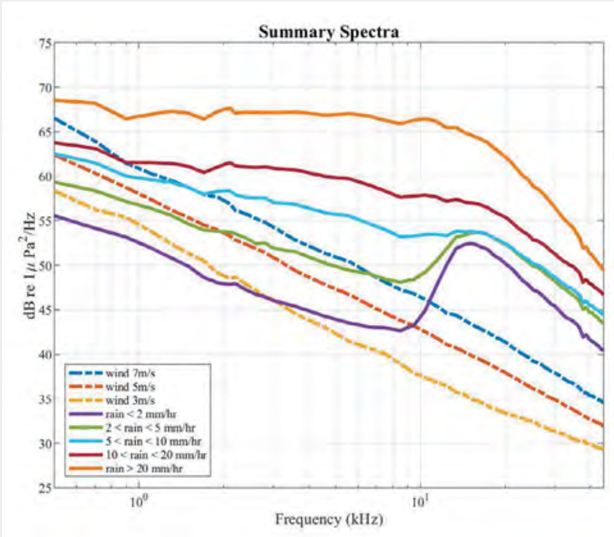


Figure 2. *The spectra of ambient sound during times of only rain or only wind. The data were collected from 14 open ocean locations over 90 months (Ma and Nystuen, 2005a), © American Meteorological Society, used with permission.*

present can be identified. For example, the noise generated by the wind is the major persistent noise component over the frequency range from 1 to 50 kHz, characterized by a simple spectrum that decreases with increasing frequency by about 16 dB per decade. When rain is present, however, the sound it generates usually dominates all other sources in that frequency range. When measuring rain, the dominant sound source is a signal that can be used to determine the properties of the rain. For example, the sound spectra of ambient sounds from wind only, rain only, and combined rain and wind are distinctly different (**Figure 2**) (Ma and Nystuen, 2005a). Importantly, the separate spectra of wind and rain in a combined spectrum can be distinguished by considering spectral slopes and relative spectral levels across different frequency bands.

Effective Listening Area

The underwater noise caused by wind and rain comes from the ocean surface. The sound intensity at a particular depth below the surface is a summation of all the contributions of sound created at the surface. The rainfall rate can therefore be obtained from a measurement of sound at depth because that sound is composed of all the sounds from the surface. In such a measurement, the sound sources are assumed to be uniformly distributed over the surface. If the absorption and refraction of sound are neglected (in practice, just minor corrections), the rainfall measurement is independent of depth.

Although the summation of surface sounds is theoretically over the entire ocean sea surface, as a practical matter, the effective listening surface area has a radius only three times the hydrophone depth; sounds from beyond that radius make only minor contributions. Thus, an instrument located at a 100-m depth samples an area with a radius of 300 m or roughly 0.28 km^2. Importantly, the measurement is inherently integrating over area, producing a spatially averaged rainfall statistic. In addition, because the total sampling period of a single measurement is about 1 min, the sound from many individual raindrop splashes is quickly accumulated, providing a robust measurement (Nystuen, 2001).

Types of Rain Sounds: It's All About the Bubbles

Raindrops hitting the ocean surface generate acoustic signals in two ways: the impact on the surface and the tiny bubble entrained by the drop and pulled below the surface. Surprisingly, the bubble is the loudest sound source for most raindrops, not the impact. When a bubble is created, the pressure inside is not in equilibrium with the surrounding water. During the impact process, a bubble is pushed and compressed. The pressure of the trapped air increases as the bubble shrinks by these forces and it becomes higher than that of the water. After shrinking, the bubble then expands, decreasing its pressure. In this way, a bubble oscillates between high and low pressure, a rapid process reaching an equilibrium at a high frequency and creating a unique sound at the bubble's resonant frequency. The bubble is "ringing," much like a bell rings. The sound radiates energy so the fate of the bubble is to lose its energy and reach equilibrium with the surrounding water.

The next thing to keep in mind is that the resonance (ringing) frequency of a bubble depends on its radius and the local pressure and water density. The resonance frequency is inversely proportional to the size of the bubble, so the smaller the bubble, the higher the resonance frequency (the higher the pitch of the sound). This quite accurate relationship was defined nearly 90 years ago by Minnaert (1933).

Of particular importance in the context of a gauge for ocean rain, bubble size is determined by drop size. If

Table 1. *Acoustic raindrop sizes and corresponding types of bubbles generated*

Drop Size	Diameter	Sound	Frequency Range, kHz	Bubbles Generated	Splash Character
Tiny	<0.8 mm	Silent		No	Gentle
Small	0.8-1.2 mm	Loud bubble	13-25	Type I	Gentle Bubbles every splash
Medium	1.2-2.0 mm	Weak impact	1-30	No	Gentle No bubbles
Large	2.0-3.5 mm	Impact Loud bubbles	1-35 2-35	Type II, III	Turbulent Irregular bubble entrainment
Very large	>3.5 mm	Loud impact Loud bubbles	1-50 1-50	Type II, III	Turbulent Irregular bubble entrainment Penetrating jet

Raindrop sizes are identified by different physical mechanisms associated with the drop splashes. Table from Ma and Nystuen (2005b).

rain were to consist of drops all the same size, those drops would all form bubbles of identical size, and the spectrum of the sound from such a hypothetical rainfall would have a peak at the resonance frequency of the bubbles. Conversely, if the frequencies of the spectral peaks in the sound of rain can be determined, the associated raindrop sizes can also be determined. Three types of bubbles generated from raindrops and their sound characteristics have been identified (**Table 1**).

Type I bubbles are generated from small raindrops. The impact component of the small raindrops is very quiet, and each such raindrop predictably generates a small type I bubble (Pumphrey et al., 1989). The frequency range of these bubbles is a high resonant frequency that Medwin (1990) called a "screaming infant."

Type II bubbles are generated by large and very large raindrops. A large raindrop creates a large, primary, type II bubble that occurs about 50 ms after the drop impact (Medwin et al., 1992).

Type III bubbles are also generated by large and very large raindrops. Large drops form an impact crater in the surface so large that tiny droplets are ejected into the air (Nystuen and Medwin, 1995). The reentry splashes of these tiny droplets produce secondary bubbles. These secondary, type III bubbles are delayed, occurring more than 100 ms after the initial drop impact. Because of the wide range in bubble size formed by the droplets, the frequency range of these bubbles is wide.

Drizzle (light rain) has a unique signal because it consists of small 1-mm raindrops and no large raindrops. Heavier rainfall, containing both large and small drops, produces very loud sound levels across a wide frequency range (Nystuen et al., 1993). Breaking waves also produce sound from bubbles. The distributions of bubble sizes produced by breaking waves and raindrops are quite different, however, so that the sound source, whether wind, waves, rain, or drizzle, can be distinguished by the distinctive spectral characteristics of the recorded sound.

The Effect of Wind on the Sounds of Rainfall

The presence of wind during rain can affect the sound signals created by the drops, depending on wind speed and drop size. Wind causes the rain to slant as it approaches to the sea surface, and it affects the splash of the interaction at the surface. The effect has been studied in laboratory experiments that assessed the chances that an individual drop blown by wind will produce a bubble, creating a measurable sound. Those chances decrease linearly from 100% for normal incidence (rain falling straight down) to 10% for oblique incidence (rain falling at a 20° angle from the vertical) (Nystuen, 1993). The wind naturally has a

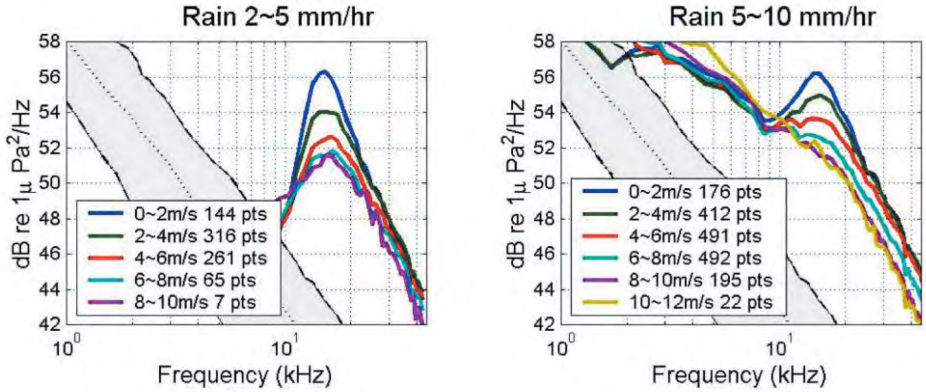


Figure 3. *The average sound spectra for rainfall rates of 2-5 (**left**) and 5-10 (**right**) mm/h are decomposed into various wind speeds. **Gray area**, wind-only spectra; **dashed-dotted** (left), **dotted** (center), and **dashed** (right) black lines, average spectra for wind speeds at 2-4, 4-6, and 6-8 m/s, respectively; **numbers in box**, number of data points in each category (Ma and Nystuen, 2005b). Increasing wind speed causes decreasing sound levels in a predicable way.*

greater effect on smaller raindrops, so the sound signal from drizzle is highly sensitive to wind speed. The wind appears to suppress the bubble creation mechanism of small raindrops, with the rain-generated sound at around 15 kHz inversely proportional to the wind speed (**Figure 3**). For larger raindrops that generate sound in the 2- to 8-kHz frequency band, the sound level is relatively insensitive to the wind speed. The bubble-trapping mechanism for large drops appears to be insensitive to the angle of impact (Ma and Nystuen, 2005b). To develop corrections for wind speed in acoustic rain gauges, rainfall spectra have been classified for various wind speeds using coincidental acoustic and wind speed data obtained during rain events.

Acoustic Rain Gauges

The need for better measurements of rainfall rates at sea and the ability to make such measurements by recording ambient-noise spectra led to the development of acoustic rain gauges (ARGs), later renamed Passive Aquatic Listeners (PALs) by Nystuen et al. (2015) (**Figure 4**). Nystuen received the Medwin prize from the Acoustical Society of America (ASA) for this work in 2003 (Ma and Leopold, 2021). The PAL was a self-contained, low-power acoustic recorder that could estimate and store acoustic spectra every minute over year-long periods. The PAL data-collection sequence consisted of first obtaining four 10- to 24-ms time series sampled at 100 kHz at 5-s intervals, from which power spectra were computed (0-50 kHz). These spectra were averaged and compressed to 64 frequency bins, forming the 1 rain measurement.

The PAL recorded spectra at 1-min intervals during rainfall events and 8-min intervals otherwise. When rain or drizzle signals were detected, determined by obtaining

Figure 4. *Jeffrey Nystuen and a self-contained Passive Aquatic Listener designed for deployment on a mooring in 2001.*

rain-type spectra with a minimum threshold in sound pressure level, the spectral data began to be saved at 1-min intervals. Assumed rain spectra were then collected at 1-min time intervals until no rain was detected. After a rain event stopped, a longer sampling time interval of 8-min was used, and the stored spectra were labeled as wind spectra. This sampling scheme made it possible to record acoustic spectra over the long term using the computer-embedded system technology available around 1990 when the PAL was developed. The acoustic rain measurement proved to be a success, and measurements that were equal to or better than other automatic rain gauges. Other rain gauges employed a variety of methods, including weighing, capacitance, tipping bucket, optical, or disdrometer methods (Nystuen et al., 2000).

Rain Detection and Quantification

The spectra data collected by the PALs need to be processed after data recovery to obtain a refined, precise detection and characterization of rain events while eliminating false alarms or events not related to rain. A series of tests were devised to eliminate spectra inconsistent with natural ambient sound and to identify spectra consistent with known types of rain.

The screening process removed two types of noise. The first was associated with "bangs" when one of the four spectra was much louder than the other three. Such events might occur when a wave slaps on the hull of the surface buoy. The second test, like that used to detect wind noise, used the shape of the recorded spectrum to eliminate sound spectra that were not consistent with known rainfall signals.

Another set of criteria was developed to use the unique spectral and temporal characteristics of the different types of rainfall to detect the presence of precipitation (drizzle or rain). The acoustic data were divided into spectra with drizzle or rain detection and wind detection, based on characteristics consistent with rain or wind spectra. Once a rainfall signal was detected, the spectral amplitude was used to estimate the instantaneous rainfall rate, which can be quantified using a simple relationship to sound intensity. Measurements of rainfall accumulation obtained this way agree well with satellite and buoy rain gauge measurements on seasonal timescales (**Figure 5**).

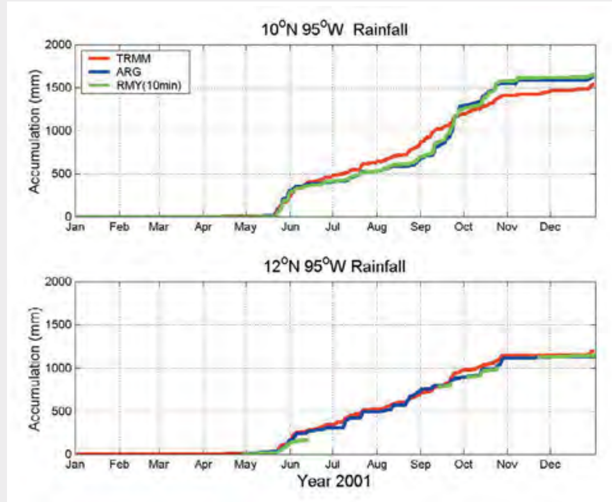


Figure 5. *Rainfall accumulation measurements at two locations from acoustic rain gauge (ARG), R. M. Young company surface rain gauges (RMY), and satellite estimates from the Tropical Rainfall Measuring Mission (TRMM) of precipitation at two deep ocean moorings in the equatorial Pacific. Fouling and other problems caused some loss of data for the RMY rain gauge at 12°N. The accumulation data for RMY are offset to match the ARG accumulation after periods of nonperformance. Adapted from Ma and Nystuen (2005a), © American Meteorological Society, used with permission.*

Inversion for Drop Size Distribution

A rain event's drop size distribution (DSD) characterizes rainfall by describing the number of drops per unit volume per drop size bin. From the DSD, useful properties such as liquid water content, optical cross-section, rainfall rate, or radar reflectivity can be calculated (Nystuen and Amitai, 2003). Furthermore, different rainfall types such as stratiform (a heavy downpour) or convective (a persistent light rain) can be identified by the DSD (Atlas et al., 1999).

Because of the different sound-generating mechanisms present for different raindrop sizes, categories of DSD can be defined acoustically based on the mean acoustic energy per drop for different raindrop sizes. The DSD is computed from the acoustic data via an inversion using standard techniques. The approach is based on using an empirically determined transfer function that relates simultaneous acoustic field measurements and DSD measurements.

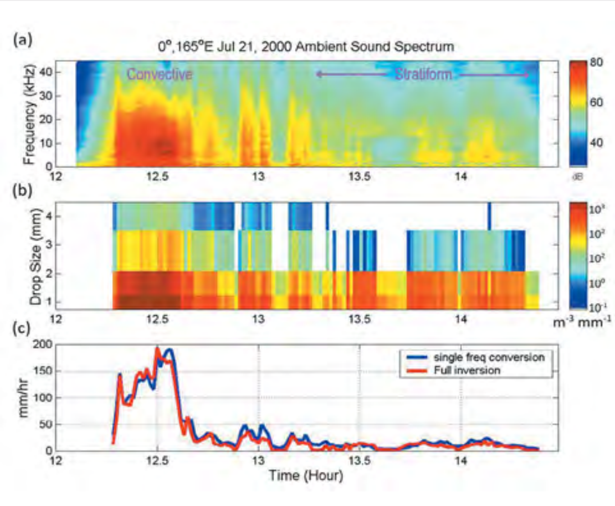


Figure 6. *The ambient ocean sound from 0, 165°E.* ***a:*** *Convective rain produces strong sound signals from 1 to 35 kHz. The stratiform rain (drizzle) has a peak signal at 15 kHz.* ***b:*** *Drop size distribution (DSD) using acoustic inversion.* ***c:*** *Rainfall rate is derived using the single-frequency conversion and full-inversion methods.*

Nystuen (2001) first computed an acoustic inversion for the DSD based on field data collected in a shallow brackish pond in Florida. Applying the same inversion algorithm to open ocean data required a frequency-independent adjustment of the transfer function (accounting for shallow-water reverberation in the pond and a lower initial acoustic pressure of large bubbles in saltwater compared with freshwater). When new methods to measure the DSD directly in the open ocean are developed, a new transfer function can be calculated.

The DSD rainfall estimates based on the sound-intensity relationship and inversion diverge as rain changes from convective to stratiform. The simple relationship between sound intensity and rain rate implicitly assumes a DSD shape typical of convective rainfall. Stratiform rainfall has relatively fewer small- and medium-sized raindrops, and thus the sound-intensity relationship overestimates stratiform rainfall rates. Using the DSD inversion method improves the agreement between acoustic DSD estimates and surface rain gauges. The result suggests that the full DSD acoustic inversion for rainfall rate should be used when mixed stratiform/convection rainfall events are being measured acoustically (**Figure 6**).

More Platforms for Collecting Passive Acoustic Data

Over the last two decades, advanced observation platforms entered service to survey the global ocean, all of which could be considered components of GOOS. The need to remotely sense the air-sea interface from underwater led to the addition of hydrophones to collect ocean ambient-noise data. Besides the moorings that have hosted PALs, various autonomous platforms have been developed for acoustic rain and wind measurements, including Argo floats (Yang et al., 2015), seagliders (Ma et al., 2018), and cabled seafloor observing systems. These platforms provide near-real-time acoustic spectra data and some also record raw acoustic time series, which offers opportunities to extract useful ocean information using passive acoustic methods.

Seagliders are underwater autonomous vehicles about 2 m in length that use internal changes in buoyancy to "drive" the vehicle to cycle up and down in the water column. The seaglider has small, fixed wings that cause it to move horizontally as it moves up and down. As a result, a seaglider glides horizontally while zigzagging up and down, usually between the surface and 1,000 m in depth. At the surface, the seaglider uses satellite communications to send its data back to shore.

In an experiment in the tropical Pacific (Lindstrom et al., 2017), ambient-noise data were acquired using a hydrophone system on the seagliders. The acoustic data were processed and averaged into 7 frequency bins from 1 to 55 kHz and transmitted to shore. Using the rule-based detection method, various rain and wind conditions were distinguished and classified using ambient-noise spectra shapes. Rain noise was still detected acoustically to 1,000 m, the maximum depth of the seaglider (**Figure 7**).

To test the validity of the seaglider data, simultaneous rain measurements were obtained from a buoy rain gauge and satellite rain rate products. The comparison showed small discrepancies between different measurement methods due to differing spatial and temporal sampling schemes. Although it was difficult to compare rainfall rates and rain events, the seasonal accumulations were in agreement. The instantaneous acoustic method has advantages (higher temporal resolution and larger effective surface-sampling area) compared with conventional rain gauges.

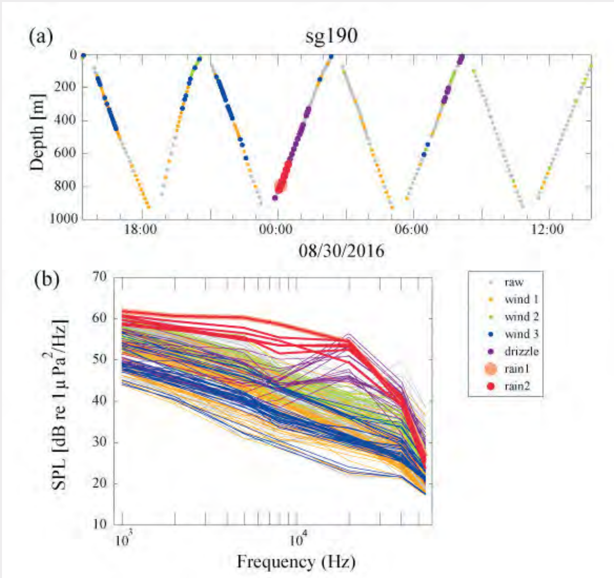


Figure 7. ***a:*** *Seaglider (SG-190) profiles during a field experiment at 10°N, 125°W.* ***b:*** *Acoustic spectra of wind and rain were identified using rule-based algorithms.* ***Color dots*** *in* ***a*** *correspond to* ***color spectra*** *in* ***b*** *and indicate the detection of wind and rain according to various detection rules (wind 1-3, rain 1-2, and drizzle). SPL, sound pressure level; raw, no rain or wind.*

The challenges for the acoustic method are that it is passive, it relies on correct amplitude calibration, and other sources of ambient sound can affect acoustic data quality.

The Future

To a large extent, the development of the Ocean Observing System has resolved the perennial problem of available platforms to hang a rain gauge on at sea. In addition, a cabled observing system across the seafloor provides a constant stream of real-time data from passive acoustic sensors located both on the seafloor and in the water column. These systems, which are cabled to shore, allow real-time data access from the comfort of one's home. Rainfall signals can be extracted from the acoustic data stream from a cabled hydrophone system (Schwock and Abadi, 2021). These observations, employed for scientific studies or monitoring beyond the rain measurements, align with the concept of multipurpose acoustic systems suggested by Howe et al. (2019). The adoption of general-purpose acoustic receivers can serve the scientific community interested in passive acoustic monitoring.

Ocean sound as an essential ocean variable (Miksis-Olds et al., 2018) is gaining more visibility and traction in the global ocean-observing community. For instance, the MERMAID program (Nolet et al., 2019; Simons et al., 2021), a project of the *United Nations Decade of Ocean Science for Sustainable Development 2021–2030*, developed floats for hydroacoustic monitoring of earthquakes. Float capabilities are now being extended to general purpose use, including rain and wind measurements and marine mammal detections.

The original PAL was developed to provide a consistent, reliable, and self-contained long-term recorder. It stored spectra and very short sound bites (seconds) only to ease the computational burden of data processing. The lack of complete time series, however, limits the ability to distinguish transient noises either from platform self-generated noises or unidentified sources. A 1-month acoustic time series, sampled at 120 kHz, requires several terabytes of data storage, which is now readily available. Such large datasets are helpful to dissect the transient sounds that may harbor new discoveries. Some of the advanced autonomous platforms of Ocean Observing Systems can transmit processed data in near-real time, but they are limited by onboard power storage and data bandwidth. It is an art to balance all the factors to decide when, what, and how to process and transmit useful ocean environmental data. The challenge of vast datasets may be addressed with machine-learning applications that may reduce dimensionality and cluster and classify acoustic source data (Bianco et al., 2019), perhaps allowing Nystuen's vision (hearing) to reach its full potential.

We hope to develop next-generation instruments for new passive acoustic rain measurements specifically and for high-frequency sound monitoring generally, exploiting all the recent advances. Such instruments would be designed to be deployed on any of the several platforms available from operational Ocean Observing Systems.

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