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Analysis of shallow water ambient noise due to rain and derivation of rain parameters

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ABSTRACT

Ocean ambient noise time series data were measured in shallow waters off the East coast of India from 09/12/2011 to 20/01/2012 and off the West coast of India from 16/05/2012 to 03/07/2012 at around 30 m ocean depth using hydrophones placed at 15 m depth in the mid water column. The measurements of wind and rain were recorded by an anemometer and precipitation type rain gauge mounted on a buoy. The objective of this work is to analyse the ambient noise caused by rain and determining the rain parameters such as rain drop size, rain fall rate, terminal velocity, impact angle, etc. This is the first time such open sea measurements of noise have been made in Indian seas along with environmental parameters and influence of rain on ambient noise field is studied.

1. Introduction

The acquisition and analysis of ambient noise in coastal shallow waters is challenging because of the wave guide nature of the environment and the shipping activities. Since ambient noise from natural sources serve as the baseline of the sound level in the ocean, the study of these sounds is very important for any acoustic based ocean application. Wind and heavy rain fall are the main factors that cause higher noise level in the ambient sound of ocean. The primary noise productivity of the sound is the splashing of individual bubbles created by means of wave breaking and rain. The noise due to rain is caused by light, moderate and heavy rainfalls along with prevailing wind in the same band of frequencies. It is predominantly made up of sound radiated by two sizes of raindrops i.e.: small raindrops (0.8–1.1 mm diameter) and large raindrops (>2.2 mm diameter).

Rain noise varies due to many parameters such as frequency, rainfall rate, drop sizes, angle of impact, number of drops per unit area and rain drop-ocean surface impact and interaction. The technique that is available for acquiring the underwater rain noise is a hydrophone with data logger. There are lot of mechanisms by which rain can generate underwater sound – the striking of raindrops on the sea-surface [2], the sound of single bubbles produced by "small-size" raindrops [3] and the generation of splash products and associated bubbles caused by "large" raindrops [4]. This could be a challenging process when the addition of wind noise arises, which not only generates its own sound [5], but also affects the rain produced sound [6,7]. The splash of the rain drop depends on the drop size and splash produces acoustic signatures. If rain drop diameter is in the range 0.8 mm–1.2 mm consisting of small drops, it produces a loud sound. These small rain drops exist in all rain fall which include light rain called drizzling that has the frequency range of around 15 kHz and heavy rain called thunder storm, which falls in the frequency band of less than 10 kHz.

Time series ocean ambient noise measurements in shallow water of the East and West coast of India have been made for specific periods using autonomous noise measurement system developed by the National Institute of Ocean Technology, Chennai, India [1]. In India extensive studies have been carried out on wind/wave generated noise in different shallow water locations off the Indian coast, using these measurements (NIOT) [1]. Studies on noise due to rain have been initiated recently, using this autonomous system along with wind and rain sensors mounted on a moored buoy. The measurement site is at shallow waters off Goa coast and Visakhapatnam coast. The details of ship/vessels that crossed the site were obtained from the port office. Wind data was obtained from the wind sensor of a moored buoy deployed very close to the site. Marine species prevailing in the site have been identified by

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matching the data with species record from Central Marine Fisheries Research Institute (CMFRI) and Centre for Marine Living Resources & Ecology (CMLRE). Croakers have been identified off Goa and Terapon theraps have been identified off Visakhapatnam. They do not fall in the frequency band of rain noise.

In this work, heavy rain fall noise was acquired using 12 element vertical linear array of hydrophones (100 Hz to 10 kHz) in the autonomous system. The rain noise acquired by this vertical linear hydrophone array is completely due to heavy rain only.

At any given instant, the local pressure in the hydrophone at measurement site can be stated as the sum of all acoustic signature sources recorded on the hydrophone,

$$P_a = P_r + P_w + P_{ss} + P_{ml} + P_{st} + P_{other} \quad (1)$$

where r, w, ss, ml, and st are denotes rain, wind, sea state, marine life and ship traffic noise respectively [8].

The ambient noise at a particular location is produced by acoustic pressure of various sources such as wind, rain, marine species, shipping activities etc. From the frequency spectrum of the ambient noise, the sources can be distinguished by signal processing techniques. The receiving sensitivity of the hydrophone used is -170 dB relative to 1 VμPa^{-1}. The pre-amplifier system gain is fitted about 26 dB relative to 1 μPa^{2}Hz^{-1}.

In this work, noise data sets during rain events have been separated out from the time series and power spectral density has been carried out. Rainfall data from the rain sensor has been analysed in correlation with the noise data. The rainfall parameters such as rate of rainfall, drop size and terminal velocity have been derived. The results are compared with measured data sets. Also time series data of wind speed have been analysed along with wind noise spectrum. The rainfall events have been analysed in correlation with prevailing wind data. Finally rain noise and wind noise have been analysed for inter comparison of noise level.

2. Experimental instrumentation and setup

A long mooring experiment for time series acquisition of underwater ambient noise off the East coast and West coast of India was conducted during 09/12/2011 to 20/01/2012 and during 16/05/2012 to 03/07/2012 respectively (Fig. 1). NIOT has indigenously developed an autonomous ambient noise sub surface system consisting of a 12 element vertical linear array of omni-directional hydrophones, with associated data acquisition modules and battery pack in an enclosure, along with subsea floats and surface marker buoy in the mooring line. As a mandatory working procedure of NIOT, the sensors are calibrated at the Underwater Acoustic Test Facility of NIOT which is the only NABL accredited laboratory in India. The sensor is calibrated against a standard sensor, before taking to field. The system has capability of sampling 12 channels simultaneously, with the sampling rate of 50 kHz per channel at duration of 30 s every 3 h. Precipitation measurements at the site are acquired with the help of R.M. Young model 50202 self-siphoning rain gauge, which is mounted at a height of 3 m above the sea surface on the buoy. This rain gauge has a 100 cm^2 catchment cylinder mounted on top of a fill tube. The measuring tube has a maximum capacity of 500 ml which is equivalent to 50 mm of rainfall accumulation, after which it automatically drains through a siphon. Siphon events take about 30 s, and are typically identified by sharp declines in volume for two consecutive samples. In post processing, data that are associated with siphon events are ignored and removed. Fig. 2a shows the rain fall event that was recorded during 27 December 2011 to 01 January 2012 in the East coast of India.

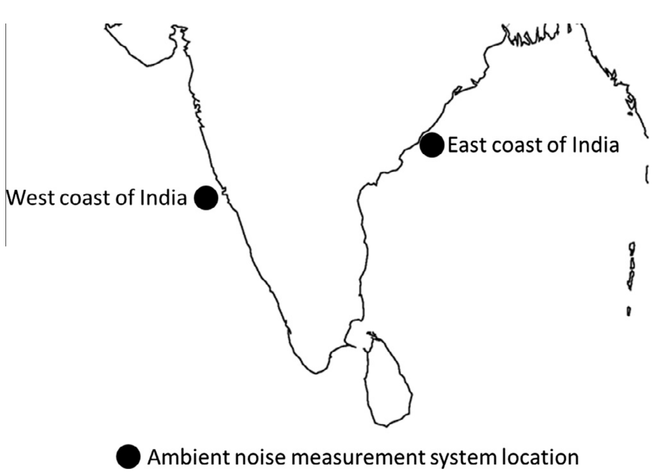

Fig. 1. The deployed locations of autonomous ambient noise sub surface system off East coast and West coast of India.

3. Results and discussion

3.1. Detecting and estimating heavy rain

When the number of heavy rain fall drops increases, it dominates the noise levels that are produced by the small rain drops [10]. The autonomous ambient noise sub surface system with a buoy mounted wind sensor and precipitation type rain gauge was deployed at ocean depth of around 30 m in the West coast of India during 16/05/2012 to 06/07/2012. On retrieving the data sets, it was observed that the overall rain fall was found to be about 3700 mm (3.7 m) of water during 04/06/2012 to 04/07/2012. Fig. 3a shows the rain fall events that were recorded in the buoy mounted precipitation type rain gauge. The rain noise data sets pertaining to heavy rain fall were taken for analysis that is encircled in Fig. 3a. It is clearly observed that (Fig. 3a) very heavy rain fall was observed on 18/06/2012 with about 510 mm of water. Fig. 3b shows the time series of wind speed that was recorded in the buoy mounted anemometer. The maximum wind speed was observed about 9.6 m/s on 17/06/2012. Fig. 3c–f shows the noise level as a function of frequency for the wind speeds at 3.2 m/s, 2.74 m/s, 2.2 m/s, 1.3 m/s with heavy raining condition and no raining condition in the same location and the correlation is shown in the respective figures. It is clearly observed that the heavy rain fall produces more noise. Wind speed induces the surface wave breaking noise only beyond 2 m/s, as in the case of Fig. 3f, it is proven that the noise field is due to the rain since the wind speed is about 1.3 m/s. The acoustic noise level of large and very large drops produce an approximately straight fit line in the frequency spectrum range less than 5 kHz. This is because all the rain drops that impinge on the sea surface are almost same in size. It is noted that the noise level is fairly high though the wind speed is equal.

The frequency spectra that were generated by the rain noise in the range 2 to 7 kHz is above that of wind speed. The frequency spectrum is mainly produced by the rain drops of size in the range between ~2.2 mm to 4.6 mm in diameter, and the number of drops during heavy rain fall is associated with the rain fall rate and hence can be used for quantifying the rain fall rate. Noise spectrum level at different frequencies for varying precipitations and noise spectrum level at the Beaufort scale of 2 for different precipitations are shown in Fig. 4a and b respectively. In Fig. 4b the peak at 2.7 kHz is found to be due to biological source. The result shows that the noise spectrum level increases with precipitation and the correlation between the noise level and precipitation is very good in the frequency range 2 to 5 kHz. In the band 0.5 to 2 kHz, the noise is dominated by wind only. It is seen that the correlation coefficient (r) is low for the low frequency range and increases thereafter, but in the case of wind it is completely vice versa [11] (see Table 1).

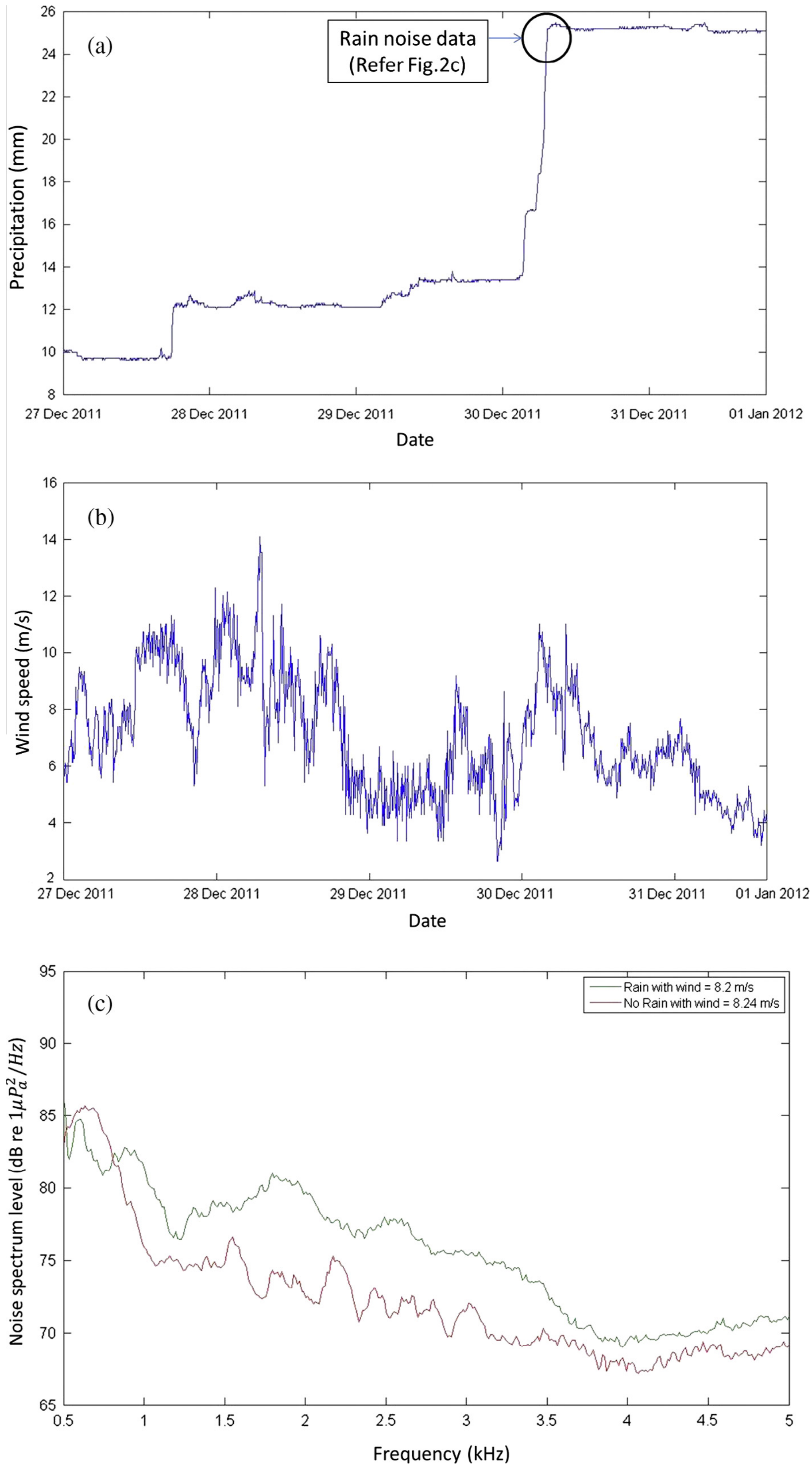

Fig. 2. (a) The rain fall event observed from 27 December 2011 to 01 January 2012 in the East coast of India, (b) wind speed recorded from 27 December 2011 to 01 January 2012 in the East coast of India and (c) correlation of rain and wind noise spectrum with nearly same wind speed around 8.2 m/s in the East coast of India.

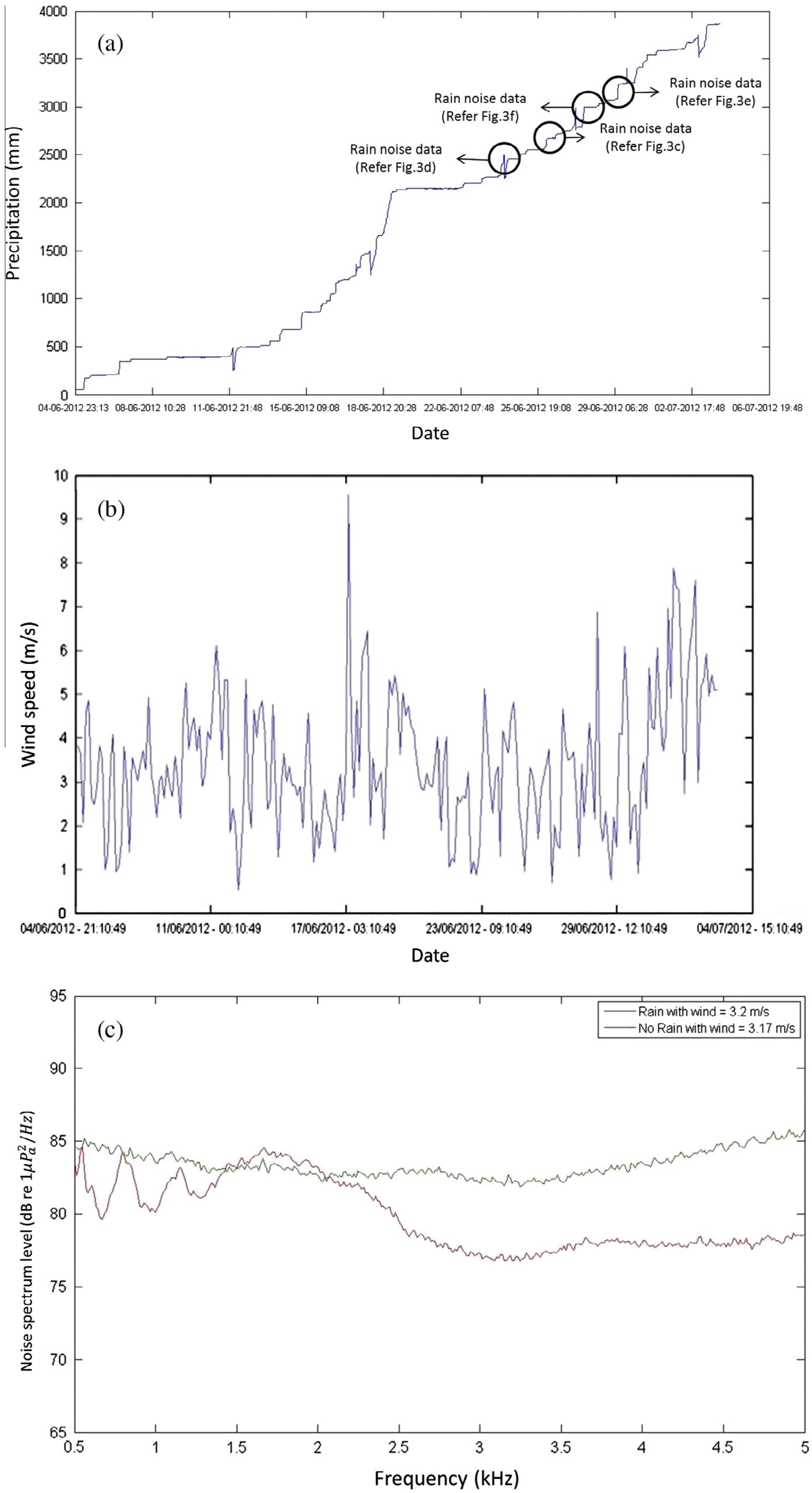

Fig. 3. (a) Rain fall event observed from 04 June 2012 to 04 July 2012 in the West coast of India, (b) Wind speed recorded from 04 June 2012 to 04 July 2012 in the West coast of India, (c) correlation of rain and wind noise spectrum with nearly same wind speed around 3.2 m/s in the West coast of India, (d) correlation of rain and wind noise spectrum with nearly same wind speed around 2.7 m/s in the West coast of India, (e) correlation of rain and wind noise spectrum with nearly same wind speed around 2.2 m/s in the West coast of India and (f) correlation of rain and wind noise spectrum with nearly same wind speed around 1.3 m/s in the West coast of India.

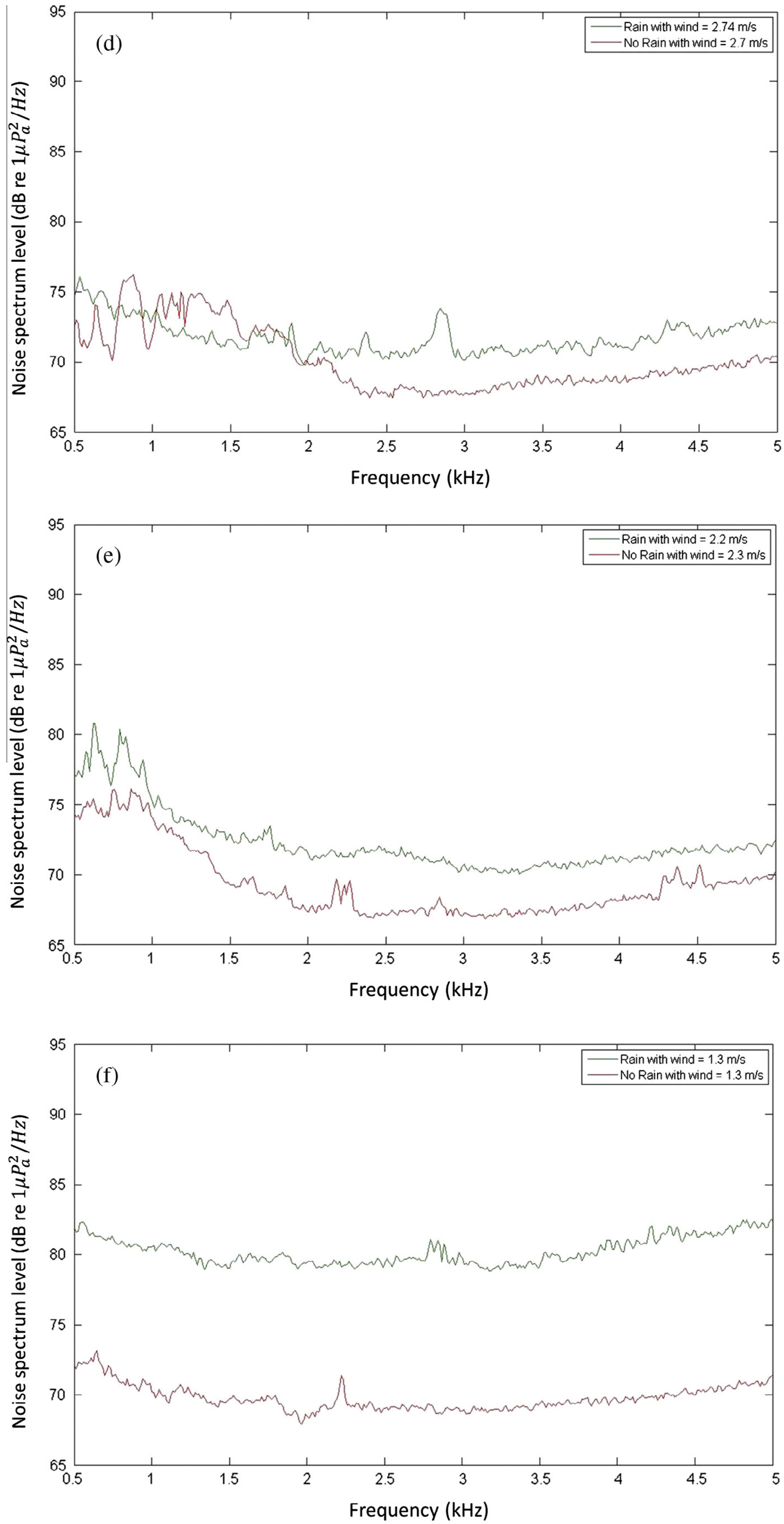

Fig. 3 (*continued*)

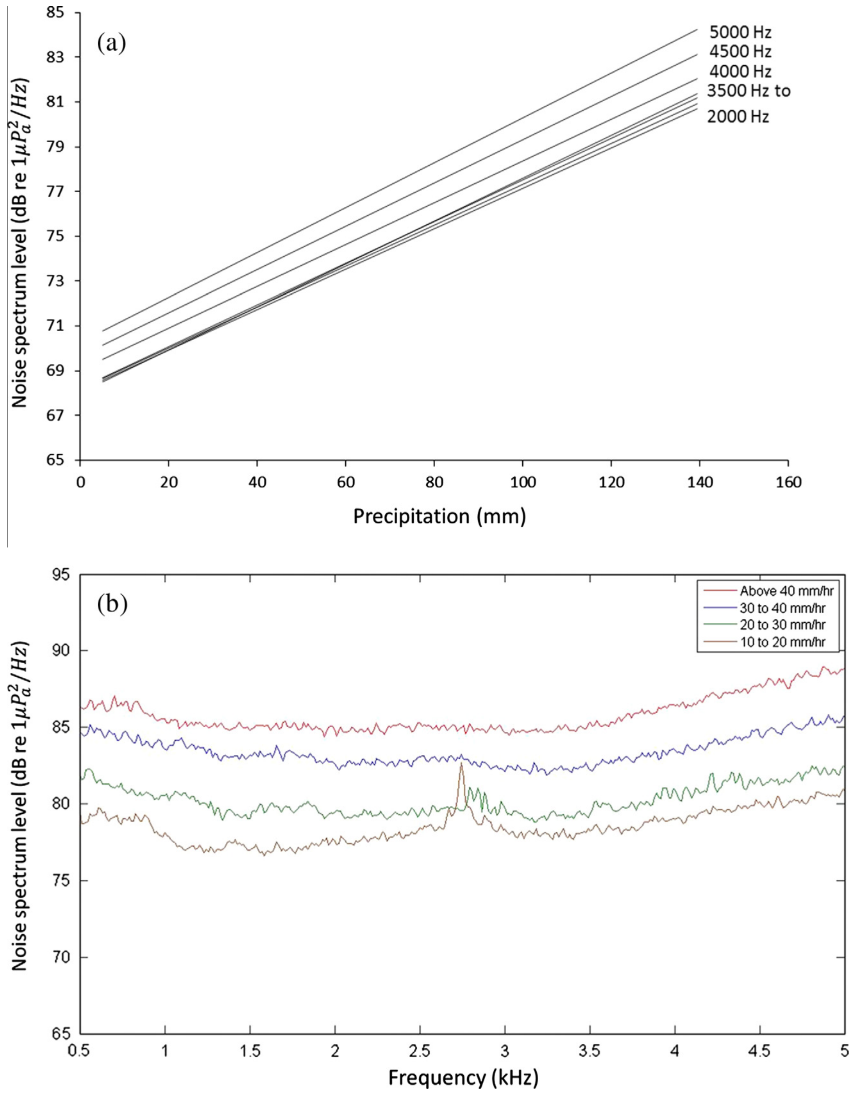

Fig. 4. (a) Noise spectrum levels at different frequencies for varying precipitations and (b) noise spectrum levels at different precipitations for varying frequencies at the Beaufort scale of 2.

3.2. Analysis of wind noise spectrum along with rain

The main noise source in the shallow waters is wind and the frequency of wind noise is broad band in nature. Power spectral density of noise is computed using Welch's averaged modified periodogram method. Data is split into smaller segments, windowed with a Hamming window and Fast Fourier Transform is performed with 50% overlaps, which are averaged. The spectrum is calculated with a FFT 2048 points. The Lambrecht combined small wind sensor (1453) is mounted on the buoy at a height of 3 m from the sea surface and the data is recorded for 10 min and averaged.

A rain fall event was observed with 11.6 mm of precipitation during Dec 31 2011 at 06:23 am to Dec 31 2011 at 10:43 am. This was a heavy rain fall recorded since it is more than 10 mm. Simultaneously, acoustic signatures of these rain falls, which lie at the frequency band less than 10 kHz were acquired by the autonomous ambient noise sub surface system. For analysis purpose, data set having rain fall event and data set having no rain fall event with nearly same wind speed were taken. Fig. 2b shows time series of wind speed which was recorded in a moored buoy during 27 December 2011 to 01 January 2012. Fig. 2c shows the noise spectrum for the wind speed at 8.2 m/s with heavy rain condition along with no rain condition in the same location and the study of correlation is also shown in the same figure. While the wind is strong it can produce loud sound [9] but when it is associated with heavy rain it produces more sound in the band 2–5 kHz. The rain drops in large size having diameter greater than 2.2 mm produce noise in this band as illustrated in Fig. 2c. The acoustic signal of heavy rain dominates the wind, and so quantitative measures of heavy rain can be achieved in a wide range of windy conditions.

Table 1
Results of linear regression of noise level with precipitation. *F* is the frequency (Hz), *r* is the correlation coefficient between noise level and precipitation at different frequencies.

F	*r*
2000	0.69
2500	0.72
3000	0.72
3500	0.74
4000	0.75
4500	0.75
5000	0.76

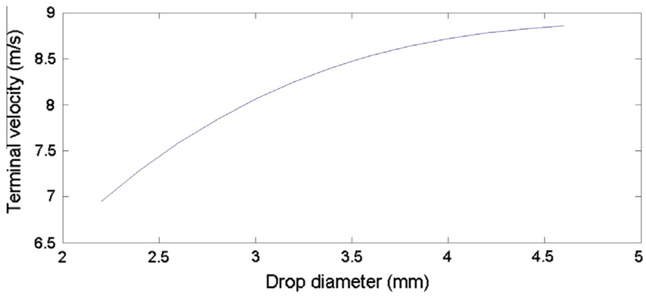

Fig. 5. Terminal velocity of the rain drops as a function of diameter for the range from 2.2 mm to 4.6 mm.

3.3. Terminal velocity, rainfall rate and noise level of the rain drops

At Normal Temperature and Pressure (NTP) atmospheric conditions, the terminal velocity of the rain drops having diameter "*D*" falling to the earth depends on rain fall rate. The factors that cause terminal velocity (V_T) are wind speed and wind direction. V_T is a function of "*D*" and was found from "*D*" by a polynomial fit to some standard data [13,14]. For rain drops having diameter 2.2 to 4.6 mm and assuming there is no vertical wind [15], the expression that relates V_T and "*D*" is (Fig. 5) [12],

$$V_T(D) = 0.0561D^3 - 0.921D^2 + 5.03D - 0.254 \tag{2}$$

Franz [16] and Medwin et al. [17] research works revealed that the rain drops having diameter >2.2 mm attains maximum terminal velocity and incident on the sea surface normally that produces both impact sound and strongly radiating bubbles.

The population of 2.2 to 4.6 mm drops was highly associated with rainfall rate and can be used to quantify rainfall. The work done by Ma Barry and Nystuen [18] reveals that the sound level at 5 kHz is proportional to the rainfall rate and relative invariant to the wind speed [19,20]. The expression that relates rainfall rate and sound pressure level is,

$$\mathrm{SPL}_{5\mathrm{kHz}} = 15.4X \log(R) + 42.4 \tag{3}$$

where $\mathrm{SPL}_{5\mathrm{kHz}}$ is the sound pressure level at 5 kHz in dB re 1 $\mu\mathrm{Pa}^2\mathrm{Hz}^{-1}$ and *R* is the rainfall rate in mm/hr. The above equation (Eq. (3)) is usable for the rainfall rates in the range 2 to 200 mm/hr in the frequency band 1 to 10 kHz [21]. Using Eq. (3), data was simulated and it was compared with the real time ocean ambient noise data pertaining to the respective rainfall rates (Fig. 6). It has been clearly observed from Fig. 6 that high correlation between the experimental and theoretical values of ocean ambient noise data was found.

3.4. Isolating the rain noise

The sound spectra having only wind and the sound spectra with rain are collective in nature. The resultant combination of these

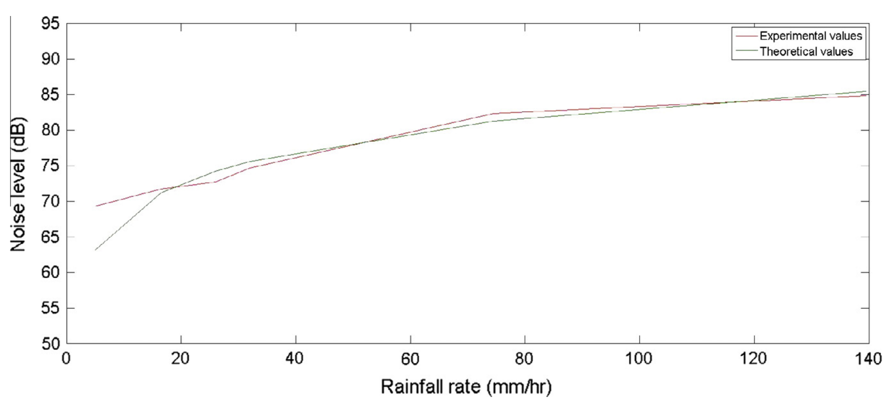

Fig. 6. Comparison between theoretical and experimental values of ocean ambient noise data as a function of rainfall rate.

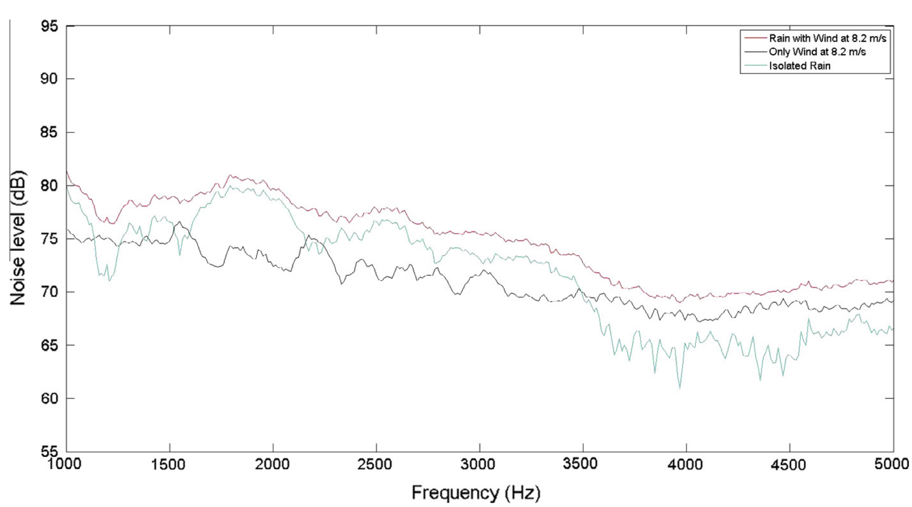

Fig. 7. Isolated rain-only noise from the noise having both wind and rain noise.

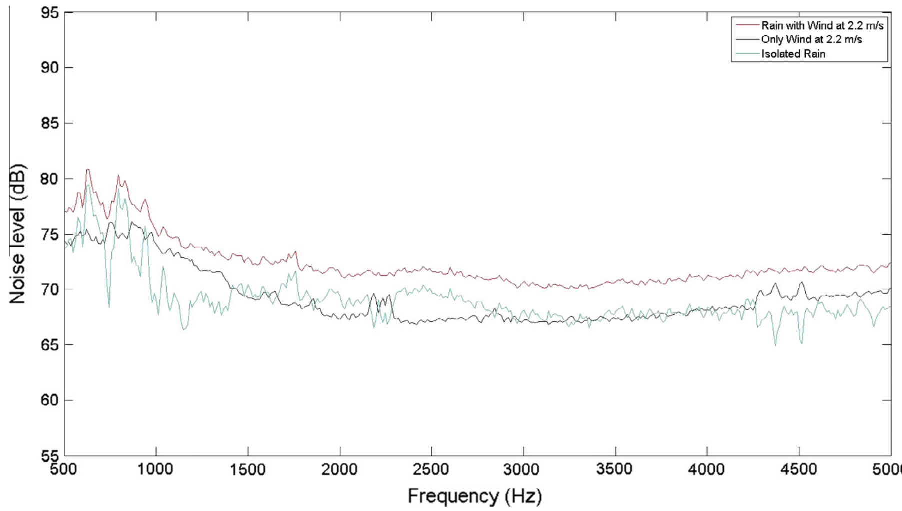

Fig. 8. Isolated rain-only noise from the noise having both wind and rain noise.

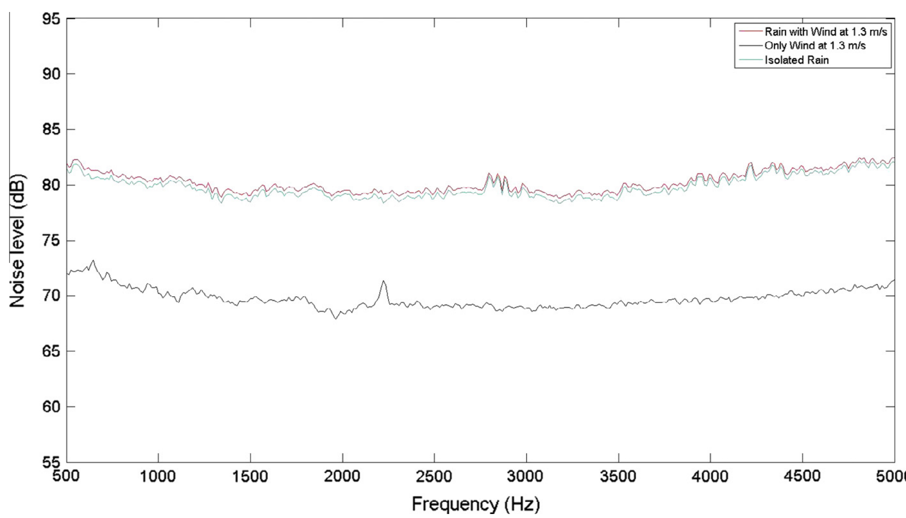

Fig. 9. Isolated rain-only noise from the noise having both wind and rain noise.

sound spectra can be determined by using power summation method [10],

$$SPL_{WR} = 10\log_{10}\left(10^{\frac{SPL_W}{10}} + 10^{\frac{SPL_R}{10}}\right) \tag{4}$$

where SPL_{WR} is the sound pressure level for the sound spectra having both wind and rain noise. SPL_W is the sound pressure level for the sound spectra having only wind noise. SPL_R is the sound pressure level for the sound spectra for only rain noise.

Using logarithmic identities and re-arranging the above Eq(4), it is formatted as,

$$SPL_R = 10\log_{10}\left(10^{\frac{SPL_{WR}}{10}} - 10^{\frac{SPL_W}{10}}\right) \tag{5}$$

The isolation of noise due to rain only, from the noise having both wind and rain is carried out by using the above Eq. (5) for the wind speeds 8.2 m/s, 2.2 m/s and 1.3 m/s shown in Figs. 7–9 respectively. The figures clearly show that rain is the dominating source of noise, when wind and rain are present. The wind speed below 2 m/s does not contribute to ambient noise. Hence the sound produced is very low and the same is illustrated in Fig. 9.

4. Conclusions

This work has been carried out for the first time in Indian seas. The frequency spectra that are generated by the rain noise were used to detect the rain fall rate. The observation that the frequency of the signal remains constant while the amplitude is a function of the drop size and its terminal velocity is beneficial in extracting the rainfall parameters. This study reveals that by continuous monitoring of ambient noise along with wind and rain parameters, the effect of these parameters on noise field is understood and the rain fall rate, terminal velocity and drop size can be determined. A correlation study of ocean ambient noise levels with high rain fall and with no rain fall at shallow waters of East coast and West coast of India has been carried out. A comparative study between theory and observed values of ocean ambient noise has been made and rainfall rates pertaining to the sound levels have been identified.

The examination of the effect of wind speed on the acoustic signatures of rain is carried out and correlated. It is understood that heavy rain noise is the predominant factor when both rain and wind are present.

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