Orographic effect on tropical rain physics in the Asian monsoon region

R. Harikumar*
Ocean State Forecast Services, ESSO-Indian National Centre for Ocean Information Services (Ministry of Earth Sciences, Government of India), Hyderabad, India

*Correspondence to: R. Harikumar, Ocean State Forecast Services, ESSO-Indian National Centre for Ocean Information Services (Ministry of Earth Sciences, Government of India), "Ocean Valley", Pragathi Nagar (B.O.), Nizampet (S.O.), Hyderabad 500 090, India. E-mail: harikumar@incois.gov.in

1. Introduction

Understanding of rain drop size distribution (DSD) and its spatial variability is very essential and useful in the areas like cloud microphysics, microwave communication, satellite meteorology, soil erosion and landslide triggering studies (Feingold and Levin, 1986; Hugget et al., 1996; Verma and Jha, 1996; Ulbrich and Atlas, 1998; Testud et al., 2001; Liu et al., 2005; Kozu et al., 2006; Xie et al., 2006; Harikumar et al., 2008; Sasi Kumar et al., 2007). The rain DSD data at different orographies, especially in the Tropics, are very dearth. The studies on DSD spatial variability will also help us to model the tropical rain DSD more accurately and more region-specific. Since the global circulations are mainly driven by the tropical weather, the general understanding about every aspects of tropical precipitation processes itself is very essential (Verma and Jha, 1996; Liu et al., 2005; Xie et al., 2006; Rahman and Sengupta, 2007; Sasi Kumar et al., 2007). There is clear evidence from the Tropical Rainfall Measuring Mission (TRMM) satellite and Quick Scatterometer (QuikSCAT) observations that the regional distribution of monsoon rain is governed by topography, and thus such local orography enhances the rainfall, and narrow mountains anchor local rain and convection (Liu et al., 2005). Physics of tropical orographic precipitation in its purest form, unforced by weather disturbances or by the diurnal cycle of solar heating, has been studied at mountainous Dominica (15°N) in the trade wind belt by Smith et al. (2009, 2012). The mechanism of the local orographic-induced convection is postulated and simulated in numerical experiments by Xie et al. (2006). According to Grossman and Durran (1984), the Western Ghats, though not very high, play an important role in overall monsoon convection for India. Harikumar et al. (2007) has carried out a comparative study of DSD between the stations in the east and west coasts of India and unraveled the differences in the DSD, albeit they were minor. The present study on rain DSD, by comparing the DSD characteristics at coastal and high-altitude tropical stations, leads not only merely to a further evidence for orographic rainfall enhancement, but also to an unprecedented novel evidence and understanding about the effect of orography on tropical rain physics.

2. Experimental technique, data and data analysis

Joss–Waldvogel impact type disdrometer (RD-80), manufactured by M/å Distromet Ltd., Switzerland, was used for data collection. The outdoor unit of the disdrometer is a sensor with a sampling area of 50 cm² and the indoor unit consists of an analyzer ADA-90 (Figure S1, Supporting information). The rain DSD raw data from the disdrometer with a sampling period of 1 min are logged on to a computer connected to the processor. The disdrometer gives the number of drops in 20 different size classes ranging from 0.313 to >5.373 mm, integrated over 1-min intervals. A detailed explanation on the instrument and measurement techniques is given by Harikumar et al. (2009). The accumulated rainfall derived from the rain rate data from the disdrometer deployed at Thiruvananthapuram has been validated using a manual rain gauge deployed nearby. They have been found to agree reasonably well (Sasi Kumar et al., 2007). Rain DSD characteristics

Keywords: tropical rain physics; rain drop size distribution; orographic effect; lognormal distribution; disdrometer

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were studied using the Joss–Waldvogel type disdrometer installed at four tropical stations in the peninsular India, namely, Thiruvananthapuram, Kochi, Srikakulam (SHAR) and Munnar. The geographical locations, with topography, of the stations are shown in the physical map (Figure 1). Thiruvananthapuram is on the west coast, nearly at the tip of peninsular India. Kochi is an important commercial city in the Kerala state situated on the west coast on the shores of the state’s largest estuary. Munnar is a hill station about 130 km east of Kochi on the Western Ghats in South India (at about 1500 m amsl) and SHAR is an island on the east coast with a lake on the west side. Thiruvananthapuram, Kochi and SHAR experience rain rates \( R \) greater than 100 mm h\(^{-1} \) while the rain rate in Munnar is rarely close to 100 mm h\(^{-1} \) (Harikumar et al., 2009). The geographical characteristics of these stations and the durations for which the data have been collected are shown in the Table S1. The comparison between the disdrometer and TRMM data showed reasonable good agreement at all locations in the present study (Harikumar et al., 2008).

The entire data at each station were divided into ranges of different rain rate. The rain rate ranges used were from 0.1 to >100 mm h\(^{-1} \) with boundaries of 0.2, 0.5, 1, 2, 5, 10, 20, 50, and 100 mm h\(^{-1} \). The mean DSD for each rain rate range was computed. DSD corresponding to different rain rate ranges for the month of July 2005 at Thiruvananthapuram was selected as a sample and the dataset was fitted with all the three distribution functions, namely, Marshall Palmer, Gamma and lognormal. The correlation coefficient between the fitted data and the actual data was derived for each rain rate range. The variation of this correlation coefficient with rain rate is shown in Figure S2. A similar behavior is seen in the data from the other three stations also. From Figure S2, it is clear that the correlation between the DSD derived using the Marshall Palmer distribution function fit and the DSD data decreases as the rain rate increases. Even though the correlation coefficients of both the Gamma and lognormal distributions with the data are very similar for most of the rain rates, Gamma distribution shows a somewhat lower correlation at higher rain rates compared to the lognormal distribution. Hence, lognormal distribution was preferred to represent the DSD over this region.

Since the lognormal distribution is found to be the most suitable function to represent the DSD in this region, the DSD values were fitted with the lognormal distribution function of the form,

\[
N(D) = \frac{N_T}{2 \pi \ln \sigma D} \exp \left[ -\frac{\ln^2 (D/D_g)}{2 \ln^2 \sigma} \right] \tag{2}
\]

where \( N_T \) is the total number of drops, \( D_g \) is the geometric mean diameter and \( \sigma \) is the standard geometric deviation of the drop size.

The lognormal distribution function for the rain DSD proposed by Feingold and Levin (1986) has the form,

\[
N(D) = \frac{N_T}{\sqrt{2\pi} \ln \sigma D} \exp \left[ -\frac{\ln^2 (D/D_g)}{2 \ln^2 \sigma} \right] \tag{3}
\]

where \( N_T \) is the total number of drops, \( D_g \) is the geometric mean diameter and \( \sigma \) is the standard geometric deviation of the drop size.

If we compare the Equation (1) with Equation (2), we can derive the three physically significant parameters, namely, \( N_T, D_g \) and \( \sigma \) from the fit parameters using the following equations.

\[
N_T = \exp (a) \sqrt{2\pi} \ln (\sigma) \tag{3}
\]

\[
D_g = \exp (b) \tag{4}
\]

\[
\sigma = \exp (c) \tag{5}
\]

The parameters \( a, b \) and \( c \) are obtained, while the datasets are fitted with the lognormal distribution function (1) using the Marquardt–Levenberg algorithm with sufficient iterations. It is very easy to fit the datasets with lognormal distribution function using simple computer programs and to obtain fit parameters for huge long term data compared to the parameter estimate.

The distinct advantage of fitting the DSD with lognormal distribution function is that if the number of drops per unit volume per unit size category is distributed lognormally, then the higher moments of the distribution are also lognormally distributed. Apart from that, the parameters of the lognormal distribution have physical meaning. The physical meaning of the parameters, \( N_T, D_g \) and \( \sigma \) are given below. \( N_T \) is the total number of all rain drops of any size in a cubic meter volume. \( D_g \) is the geometric mean of the drop diameters (or median size diameter). It can be defined as the \( n \)th root of the product of a set of \( n \) diameters. \( \sigma \) represents the standard geometric deviation (standard deviation of the log of the drop diameters), which is the measure of the breadth of the spectrum. Ultimately, the standard geometric deviation describes how spread out are a set of numbers whose preferred average is the geometric mean. It is worth mentioning here that, unlike the usual arithmetic standard deviation, the geometric standard deviation is a multiplicative factor, and thus is dimensionless, rather than having the same dimension as the input values. Its connection to the lognormal distribution function is that, it is a measure of lognormal dispersion analogously to the geometric mean (Kirkwood, 1979). As the log transform of a lognormal distribution results in a normal distribution, we see that the geometric standard deviation is the exponentiated value of the standard deviation of the log-transformed values. As such, the geometric mean and the geometric standard deviation of a sample of data from a lognormally distributed population may be used to find the bounds of confidence.
Figure 1. The geographical locations of the four stations shown in a physiographical map. The shaded portion in the panel (a) represents the tropical region. Windward and leeward sides (during the southwest monsoon season) are also shown in panel (b).

intervals analogous to the way the arithmetic mean and standard deviation are used to bound confidence intervals for a normal distribution. Further details can be referred from the studies by Feingold and Levin (1986) and Harikumar et al. (2007).

Rain DSD spectra for each station are shown in Figure 2. The lognormal distribution function fitted for each rain rate range is also shown. The corresponding fit parameters are given in Table 1. At a particular station, the rain DSD, and hence, the variation of all the three derived parameters with rain rate have shown a similar trend in different months. As a typical example, the variation of $N_T$ with rain rate for two different months (July and August) at the same station, Thiruvananthapuram is shown in Figure 3 to convince the fact that the behavior of the variation of any derived rain parameters with rain rate in different months at a particular station is similar. In this manner, at any station, any parameter during different months behaves similar, which suggests that there is no remarkable intermonth variability at a station, but there is interstation variability. Hence, though the entire available data (total of 45 months, 1-min resolution data) from all the stations were used for the analyses, the indicative months shown in all the figures in this manuscript are July 2003 for Kochi, July 2005 for Thiruvananthapuram, July 2004 for Munnar and August 2003 for SHAR (since any July data were not available for SHAR, August data were used), as a typical sample for each station.

3. Results and discussion

$N_T$, $D_g$, and $\sigma$ for each rain rate range were derived, and the variation of these parameters with rain rate
was studied to understand the characteristics of DSD. These are discussed below. Variation of $\sigma$ is plotted against the mean rain rate. Typical graphs of $\sigma$ from each station for the same months mentioned in the above section are shown in Figure S3. It is seen that, in general, $\sigma$ was almost constant for all rain rate ranges (a small variation can be seen, but it is very small compared to the values of $\sigma$). It indicates that, the width of the DSD spectrum (whose preferred average is the geometric mean) is almost the same irrespective of the rain rate, and the case is similar for all the stations.

Since the coastal stations and high-altitude station behave very differently with special reference to the variations of $N_T$ and $D_g$ with rain rate, they are treated separately in the following sections.

3.1. Coastal stations

The variation of $N_T$ and $D_g$ with the rain rate was fitted with the expression $N_T/D_g = aR^b$, as suggested by Verma and Jha (1996), and is shown in Figure 4. The fitted equations are also shown in Figure 4. The standard deviation of the fit ‘Stdfit’ ($\psi$), i.e. the root of the sum of the squared residuals (difference between fitted value and measured value) divided by the number of degrees of freedom (number of data points less the number of fit parameters) is derived. This is the well-known root-mean-square error. To understand the goodness-of-fit, a normalized $\psi$ or $\psi/N_T$, $\psi/D_g$ or $\psi/\sigma$ should be close to zero. These values against the fit done for the variation of $N_T$, $D_g$ and $\sigma$ with rain rate are given in Table S2. All values, except that for $N_T$ at Thiruvananthapuram (0.15), are so close to 0 indicating a good fit.

It is found that, at Kochi and SHAR, $N_T$ generally has an exponential increase after a rain rate of 2 mm h$^{-1}$ (Figure 4(a) and (c)). At Thiruvananthapuram, the above-mentioned pattern of $N_T$ variation was followed up to 3 mm h$^{-1}$, but then it remains more or less constant or starts decreasing beyond (Figure 4(e)). $D_g$ increases monotonically with rain rate at all the three coastal stations (Figure 4(b), (d) and (f)). The interpretation of the magnitude variation of $N_T$ and $D_g$ with rain rate is discussed below. First, let us consider the magnitudes of $N_T$. It always has a higher value for $\psi/D_g$ and $\psi/\sigma$, if the fit is good, the value of $\psi/N_T$, $\psi/D_g$ or $\psi/\sigma$ should be close to zero. These values against the fit done for the variation of $N_T$, $D_g$ and $\sigma$ with rain rate are given in Table S2. All values, except that for $N_T$ at Thiruvananthapuram (0.15), are so close to 0 indicating a good fit.

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especially in terms of southwest monsoon season. Here, the behavior of DSD of rainfall at windward side of the Western Ghats during peninsular by Harikumar (2012) shows the enhancement (June–August 2002–2003, averaged) over the Indian satellite detection (TRMM satellite data) of rainfall on behalf of the Royal Meteorological Society. 0.3 mm) up to 3 mm/h. \(< R < 100\) is a coastal station. But the aerial distance to the it is a hill station situated on the Indian Western Ghats compared to all other stations is that, topographically, it is a high-altitude station on the Western Ghats. Western Ghats influence the cloud formation mechanism in such a way that the offshore convection is formed as a result of interaction of low-level flow with the Western Ghat mountains (Grossman and Durran, 1984) (at least in the southwest monsoon season, when south westerlies are prevailed, and its eventual precipitation happens). Smith et al. (2009) described that the orographic enhancement in rainfall is caused primarily by repetitive convective triggering over the windward slope of the mountains. The triggering is caused by terrain forced lifting of the conditionally unstable wind cloud layer. Ambient humidity fluctuations associated with open-ocean convection may play a key role. The convection transports moisture upward and causes frequent brief showers on the hilltops. Being the rainfall process in the hill slopes is a terrain forced lifting convective one, which is remarkably different from that happens in the plains, it shall hence affect also the physics of the rainfall process.

If we clearly observe, Thiruvananthapuram shows a saturation in the \(N_T\) beyond a rain rate of 3 mm/h as explained in the earlier section. The reason for the possible similarity, in DSD characteristics (especially, in terms of \(N_T\)) at Munnar and Thiruvananthapuram (but Munnar does not have such a similarity with Kochi and SHAR) is probably attributed to the cloud formation mechanism, pointed out above, which is existed for Munnar as well as for Thiruvananthapuram also, to some extent, but not for Kochi and SHAR. Being Munnar is a high-altitude station on the Western Ghats, and at the same time the aerial distance to the foot hills of the Western Ghats from the Thiruvananthapuram station is only around 20 km, though Thiruvananthapuram is a coastal station. But the aerial distance to the foot hills of the Western Ghats from the Kochi station is around 100 km. Since the offshore convection is formed, when the low-level flow interacts with Western

3.2. High-altitude station

The DSD characteristics at Munnar are very different from other stations, and it has significance in the present study. The only difference Munnar possesses compared to all other stations is that, topographically, it is a hill station situated on the Indian Western Ghats at a distance of around 130 km straight east from Kochi. The rainfall enhancement due to orography in the windward side (windward and leeward sides are marked in the Figure 1) of Western Ghats is a well-known fact (Muralidharan et al., 1985). Study of the satellite detection (TRMM satellite data) of rainfall (June–August 2002–2003, averaged) over the Indian peninsula by Harikumar (2012) shows the enhancement of rainfall at windward side of the Western Ghats during southwest monsoon season. Here, the behavior of DSD (especially in terms of \(N_T\)) at Munnar is very different compared to other three coastal stations (however, a minor similarity exists in the behavior of \(N_T\) at Munnar with Thiruvananthapuram, and its reason is explained in the coming paragraph). Up to a rain rate of around 3 mm/h, \(N_T\) increases first (from 550 m\(^{-3}\) mm\(^{-1}\) for 0.1 mm/h to 700 m\(^{-3}\) mm\(^{-1}\) for 3 mm/h) and then decreases beyond with rain rate (and reaches up to even 350 m\(^{-3}\) mm\(^{-1}\) at \(\sim 50\) mm/h), unlike all other coastal stations. \(D_g\) remains more or less constant (0.3 mm) up to 3 mm/h and then increases exponentially beyond with rain rate (0.3 mm for 3 mm/h to 1.6 mm for 30 mm/h). This difference in the behavior of the variation of \(N_T\) as well \(D_g\) with rain rate at Munnar compared to the coastal stations suggests that rainfall \(> 3\) mm/h at Munnar consists of less number of bigger drops than coastal stations in the plane. As mentioned earlier, Munnar is a high-altitude station (at about 1500 m amsl) situated in the Indian western Ghats. Western Ghats influence the cloud formation mechanism in such a way that the offshore convection is formed as a result of interaction of low-level flow with the Western Ghat mountains (Grossman and Durran, 1984) (at least in the southwest monsoon season, when south westerlies are prevailed, and its eventual precipitation happens). Smith et al. (2009) described that the orographic enhancement in rainfall is caused primarily by repetitive convective triggering over the windward slope of the mountains. The triggering is caused by terrain forced lifting of the conditionally unstable wind cloud layer. Ambient humidity fluctuations associated with open-ocean convection may play a key role. The convection transports moisture upward and causes frequent brief showers on the hilltops. Being the rainfall process in the hill slopes is a terrain forced lifting convective one, which is remarkably different from that happens in the plains, it shall hence affect also the physics of the rainfall process.

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**Table 1.** Fit parameters of the lognormal distribution function fitted to rain DSD at all stations.

| Sl. no. | Rain rate range | Kochi | Thiruvananthapuram | Munnar | SHAR |
|--------|----------------|-------|-------------------|--------|------|
|        | \(0.1 < R < 0.2\) | \(a_0\) | \(a_1\) | \(a_2\) | \(a_0\) | \(a_1\) | \(a_2\) | \(a_0\) | \(a_1\) | \(a_2\) |
| 1      |                 | 4.757 | 0.845 | 0.434 | 6.567 | 1.241 | 0.401 | 6.231 | 1.243 | 0.439 |
| 2      | \(0.2 < R < 0.5\) | 5.028 | 0.732 | 0.441 | 6.196 | 0.764 | 0.355 | 6.335 | 1.023 | 0.421 |
| 3      | \(0.5 < R < 1\) | 5.206 | 0.522 | 0.424 | 6.405 | 0.768 | 0.399 | 6.849 | 1.338 | 0.569 |
| 4      | \(1 < R < 2\) | 5.387 | 0.314 | 0.391 | 6.551 | 0.716 | 0.430 | 7.594 | 1.224 | 0.542 |
| 5      | \(2 < R < 5\) | 5.909 | 0.256 | 0.397 | 6.750 | 0.465 | 0.392 | 6.410 | 0.507 | 0.447 |
| 6      | \(5 < R < 10\) | 6.778 | 0.270 | 0.385 | 6.938 | 0.390 | 0.408 | 6.240 | 0.074 | 0.362 |
| 7      | \(10 < R < 20\) | 6.771 | 0.033 | 0.363 | 6.866 | 0.117 | 0.391 | 6.159 | 0.191 | 0.332 |
| 8      | \(20 < R < 50\) | 6.897 | 0.263 | 0.311 | 6.960 | 0.093 | 0.378 | 6.173 | 0.461 | 0.291 |
| 9      | \(50 < R < 100\) | 7.103 | 0.394 | 0.320 | 6.989 | 0.301 | 0.364 | –– –– –– | –– –– –– |
| 10     | \(R > 100\) | 7.164 | 0.528 | 0.337 | 7.600 | 0.584 | 0.290 | –– –– –– | –– –– –– |

**Figure 3.** Variation of \(N_T\) with rain rate in July and August 2005 at Thiruvananthapuram.
Ghats, the measure of interaction of low-level flow shall be a function of the aerial distance from the shore to the Western Ghat. So in this way, we should expect at least a minor similarity in the DSD characteristics at Munnar and at Thiruvananthapuram, but not between Munnar and other coastal stations Kochi and SHAR (SHAR is anyway situated in the east coast, and not in the windward side of the western Ghats). The effect of orography on tropical rain physics is very clear from these major differences in the rain DSD between Munnar, a high-altitude station (1500 m asl), and all other coastal stations (though a very small similarity exists otherwise between Munnar and Thiruvananthapuram, and the possible reason for that is explained above already).

Another depending factor for the spatial variation of rain DSD could be the difference in anthropogenic aerosol distribution at these locations. The difference in the DSD behavior shown at Munnar and SHAR (both stations are far from the west coast) at least during southwest monsoon period (June–September; when westerlies are prevailing) suggests the nontribution of the influence of the anthropogenic aerosol distribution on rain DSD. If it would have been the case, DSD at Munnar and SHAR should have behaved similarly, since the precipitating clouds at both of these stations, should have been originated from the Arabian Sea, and are traversed and crossed through the Indian subcontinent during the southwest monsoon period. But the characteristics in terms of rain DSD are

Figure 4. Variation of $N_T$ (a, c, e and g) and $D_g$ (b, d, f and h) (with fits of the form $Y = aR^b$ are shown as legend) with rain rate at stations (a, b) Kochi, (c, d) SHAR, (e, f) Thiruvananthapuram and (g, h) Munnar.
very different at Munnar and SHAR during southwest monsoon period. One more evidence for this postulate is that, if the anthropogenic aerosol would have been attributed to the cause for the difference in DSD characteristics, Kochi and Thiruvananthapuram also should have behaved similarly, since both are west coast stations and are also similar in the possible presence of anthropogenic aerosols. But they also show minor differences. Moreover, instead of showing a similarity to another west coastal station Kochi, Thiruvananthapuram shows a similar behavior to Munnar because of the similarity in orographic reasons explained above. All these interpretations and results suggest that the effect of orography may be the dominating factor for the spatial variability of rain DSD. However, there are no datasets on aerosol distribution available during these periods in these stations to have a meticulous analysis with special reference to aerosols, and there lies the importance of the self evident detailed analyses and interpretations made above.

4. Conclusion

The variation of the three physically significant parameters, derived from the lognormal fit to the rain DSD data, with rain rate shows the differences in the DSD characteristics between coastal stations and high-altitude station. The standard geometric deviation $(\sigma)$ did not show any significant dependence on rain rate. The variation of $N_T$ and $D_m$ with rain rate at Kochi and SHAR are similar, even though their magnitude and slopes are different. Rainfall at Kochi and SHAR is made up of more number of smaller drops compared to Thiruvananthapuram, while the rain rates are $>2 \text{ mm h}^{-1}$. Variation of $N_T$ with rain rate at Munnar and Thiruvananthapuram showed a common behavior different from that at Kochi and SHAR. As explained earlier, Munnar is a high-altitude (at about 1500 m amsl) station on the Western Ghats, and at the same time, the aerial distance to the foot hills of the Western Ghats from the Thiruvananthapuram station is only around 20 km, though Thiruvananthapuram is a coastal station. But the aerial distance to the foot hills of the Western Ghats from the Kochi station is around 100 km. In such a way, in the scenario of the effect of the Western Ghats in the rainfall process, Munnar and Thiruvananthapuram shall have a common and similar effect, unlike that is having at Kochi.

The major difference in the DSD characteristics between a high-altitude station, Munnar and the coastal stations in the plain, namely Kochi and SHAR, and a minor similarity between Munnar and Thiruvananthapuram (which is a coastal station, but the aerial distance from the coast to the foothills of Western Ghats is only $\sim$20 Km) reenforces the fact that the effect of orography is the dominating factor for the spatial variability in the rain DSD.

It is very clear from the present study that a heavy rainfall at Munnar consists of less number of bigger drops than coastal stations in the plane Kochi and SHAR, and even than Thiruvananthapuram. That means, the orography is seen to affect the drop size and thus orographic rain appears to have larger drops when rain rate is high. This situation is very crucial because larger drops could cause more soil erosion that may lead to the triggering of land slide. Therefore the present study of orographic effect on rain physics would also be useful and throw more light on landslide triggering mechanisms.

Acknowledgements

The present study was financially supported by the Space Applications Centre–Indian Space Research Organisation, Ahmedabad (Department of Space), Government of India under its Megha-Tropiques Utilisation Programme (MTUP). The author, who was an Investigator of that project, is indebted to such a support. The Director of ESSO-Indian National Centre for Ocean Information Services (INCOIS) is thanked for support. The Director of National Centre for Earth Science Studies is also thanked. The author is so grateful to Dr S. Sampath (late; was Scientist at National Centre for Earth Science Studies), and also to Dr V. Sasikumar (Retired Scientist, NCESS) for fruitful discussion they had earlier. I thank M/s Tata Tea Ltd., Munnar, and SHAR for extending facilities for making measurements at their premises. I also thank Sri T.K. Krishnachandran Nair (retired) and Sri M. Mohammed Ismail of ASD, NCESS, and Dr P.V.S.S.K. Vinayak and Shri K.P. Bhaskaran of Regional Camp Office, NCESS, Kochi, for their help in installing the instrument and collecting the data. I thank the three anonymous reviewers for their suggestions and comments that led to remarkable improvements of this manuscript. There is no conflict of interest exists in connection with this manuscript. This is INCOIS contribution 263.

Supporting information

The following supporting information is available:

Figure S1. The disdrometer processor and sensor.

Figure S2. Variation of the correlation coefficient for the correlation analysis between the DSD derived from each functional fit and the DSD data to which the fit has applied with rain rate.

Figure S3. The variation of $\sigma$ with rain rate at all stations.

Table S1. Data availability

Table S2. Normalised stdfit (root-mean-square error) for the fit of the variation $N_T$, $D_m$, and $\sigma$ with rain rate at all stations.

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