ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. (2016)
Published online in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl.692

RMetS
Royal Meteorological Society

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

Received: 28 June 2015
Revised: 26 May 2016
Accepted: 2 August 2016

Abstract

Effect of orography on tropical rain drop size distribution (DSD), which was not well known, is evidenced through the present study. DSD is the number of raindrops/unit volume/diameter interval, which tells about the underlying physics of rainfall process. Rain DSD was studied, using a Joss–Waldvogel disdrometer, at three coastal and a hill station in the Tropics. The variation in the characteristics of three physically significant parameters derived from the DSD with rain rate clearly unraveled the effect of orography on rain physics. The orographic rain appears to have larger drops compared with nonorographic rains when rain rate is high.

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

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; Huggel *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/s Distromet Ltd., Switzerland, was used for data collection. The outdoor unit of the disdrometer is a sensor with a sampling area of 50 cm^2 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 were studied using the Joss–Waldvogel type disdrometer installed at four tropical stations in the peninsular India, namely, Thiruvananthapuram, Kochi, Sriharikota (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, Marshal 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 Marshal 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,

$$N(D) = \frac{\exp(a_0)}{D} \exp\left\{-0.5\left[\frac{(\ln D - a_1)}{a_2}\right]^2\right\} \qquad (1)$$

where a_0, a_1 and a_2 are fit parameters, $N(D)$ is the number of rain drops m^{-3} mm^{-1} interval and D is the diameter of the drops.

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

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

where N_T is the total number of drops, D_g is the geometric mean diameter and σ 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 σ from the fit parameters using the following equations.

$$N_T = \exp(a) * \sqrt{2\pi}\ln(\sigma) \qquad (3)$$

$$D_g = \exp(b) \qquad (4)$$

$$\sigma = \exp(c) \qquad (5)$$

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 σ 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 nth root of the product of a set of n diameters. σ 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

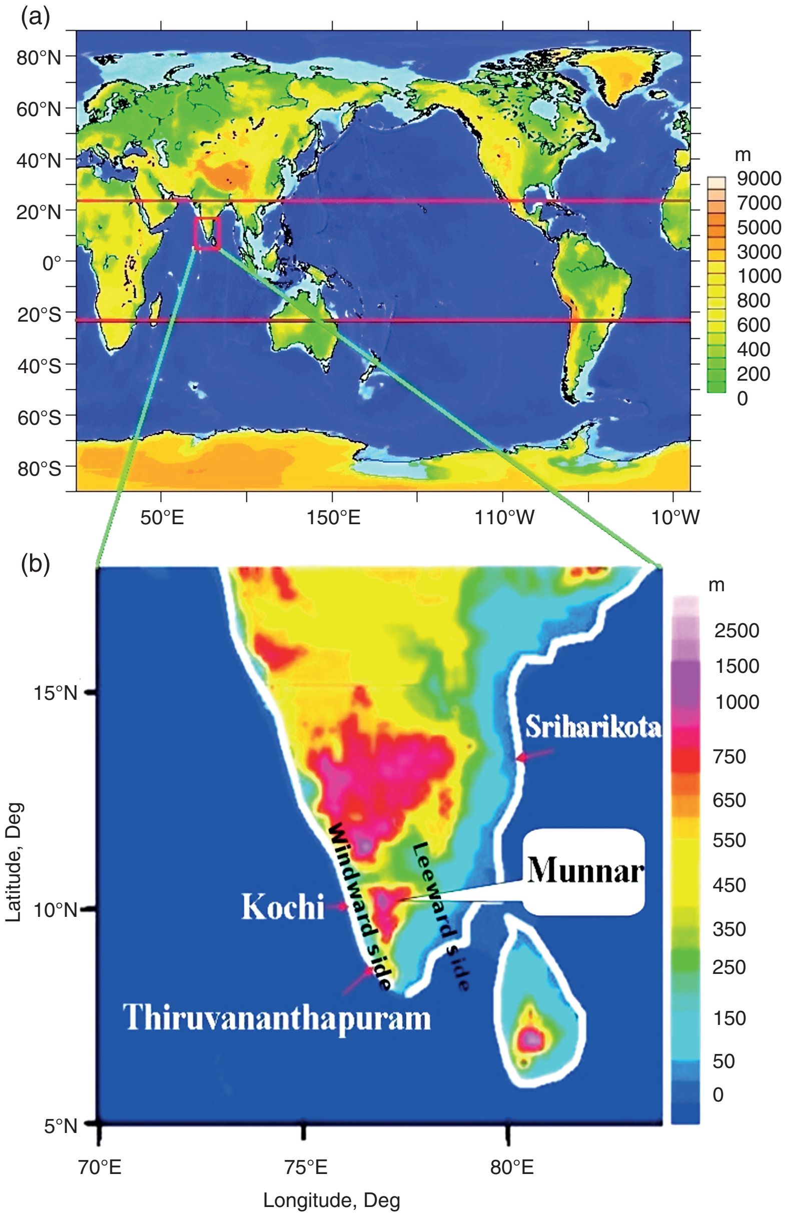

Figure 1. The geographical locations of the four stations shown in a physiographical map. The shaded portion in the panel (a) represents the tropical region. Windward and leeward sides (during the southwest monsoon season) are also shown in panel (b).

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 σ for each rain rate range were derived, and the variation of these parameters with rain rate

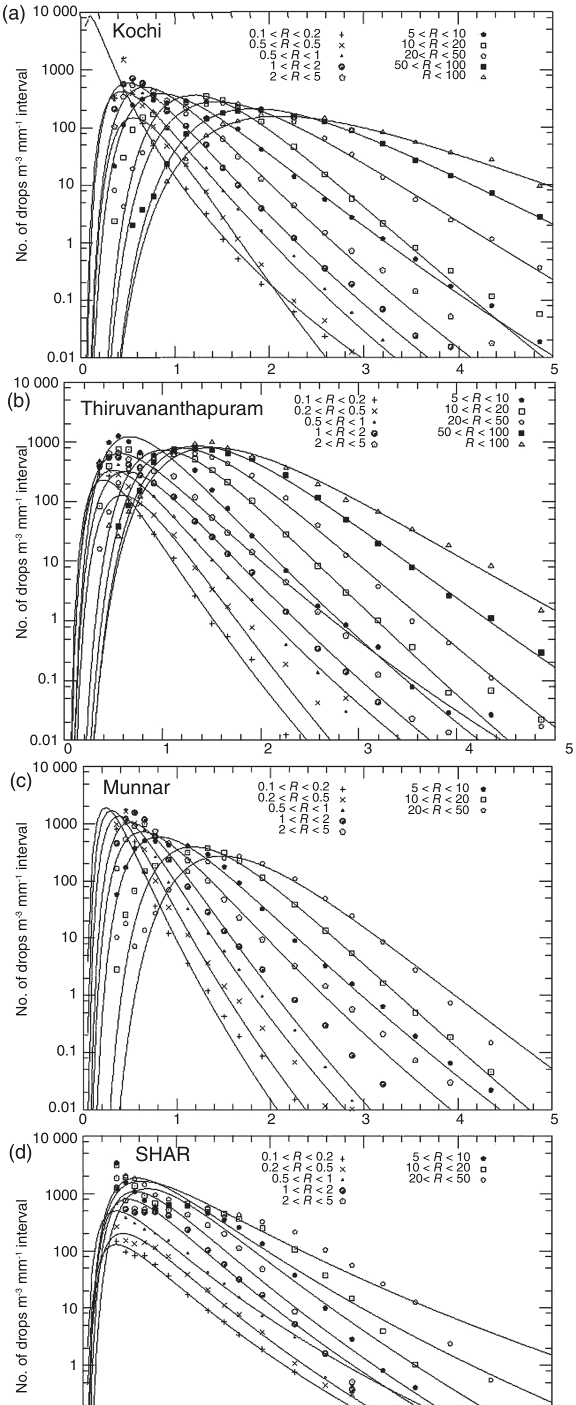

Figure 2. Rain DSD spectrum corresponding to the stations Kochi (July 2003; (a)) Thiruvananthapuram (July 2005; (b)), Munnar (July 2004; (c)) and SHAR (August 2003; (d)). The lognormal fit is also shown as solid lines along with the DSD data. *R* in the legend represents the rain rate.

was studied to understand the characteristics of DSD. These are discussed below. Variation of σ is plotted against the mean rain rate. Typical graphs of σ from each station for the same months mentioned in the above section are shown in Figure S3. It is seen that, in general, σ was almost constant for all rain rate ranges (a small variation can be seen, but it is very small compared to the values of σ). 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' (ψ), 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 ψ has been derived as ψ/N_T, ψ/D_g or ψ/σ. If the fit is good, the value of ψ/N_T, ψ/D_g or ψ/σ should be close to zero. These values against the fit done for the variation of N_T, D_g and σ 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 $2\,\text{mm}\,\text{h}^{-1}$ (Figure 4(a) and (c)). At Thiruvananthapuram, the above-mentioned pattern of N_T variation was followed up to $3\,\text{mm}\,\text{h}^{-1}$, 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 any rain rate after $2\,\text{mm}\,\text{h}^{-1}$ at Kochi ($800\,\text{m}^{-3}\,\text{mm}^{-1}$ for $30\,\text{mm}\,\text{h}^{-1}$) and SHAR (e.g. $1100\,\text{m}^{-3}\,\text{mm}^{-1}$ for $30\,\text{mm}\,\text{h}^{-1}$) than that at Thiruvananthapuram (only $350\,\text{m}^{-3}\,\text{mm}^{-1}$ for $30\,\text{mm}\,\text{h}^{-1}$). Now, if we look in to D_g, at Thiruvananthapuram, it varies from 0.5 mm to up to a very high value of 2.5 mm. But, it reaches from 0.5 mm to up to a relatively smaller value at Kochi (only up to 1.6 mm) and SHAR (only up to 1 mm). Thus, for a rain event with a given rain rate, there are less number of drops and the drops are generally larger in size at Thiruvananthapuram than at Kochi and SHAR. In other words, rainfall, with high rain rates, at Kochi and SHAR is made up of more number of smaller drops compared to Thiruvananthapuram. The topographical difference and eventual orographic reason for such a difference at Thiruvananthapuram compared to other two stations in the plane, Kochi and SHAR, in the case of the variation of both N_T and D_g with rain rate are explained in the following section.

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		
		a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2
1	$0.1 < R < 0.2$	4.757	0.845	0.434	6.567	1.241	0.401	6.231	1.243	0.439	3.868	0.724	0.486
2	$0.2 < R < 0.5$	5.028	0.732	0.441	6.196	0.764	0.355	6.335	1.023	0.421	4.086	0.532	0.470
3	$0.5 < R < 1$	5.206	0.522	0.424	6.405	0.768	0.399	6.849	1.338	0.569	4.619	0.542	0.502
4	$1 < R < 2$	5.387	0.314	0.391	6.551	0.716	0.430	7.594	1.224	0.542	5.438	0.521	0.475
5	$2 < R < 5$	5.909	0.256	0.397	6.750	0.465	0.392	6.410	0.507	0.447	6.182	0.436	0.436
6	$5 < R < 10$	6.778	0.270	0.385	6.938	0.390	0.408	6.240	0.074	0.362	7.138	0.317	0.436
7	$10 < R < 20$	6.771	0.033	0.363	6.866	0.117	0.391	6.159	0.191	0.332	7.138	0.317	0.436
8	$20 < R < 50$	6.897	0.263	0.311	6.960	0.093	0.378	6.173	0.461	0.291	7.442	0.217	0.416
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	–	–	–	–	–	–

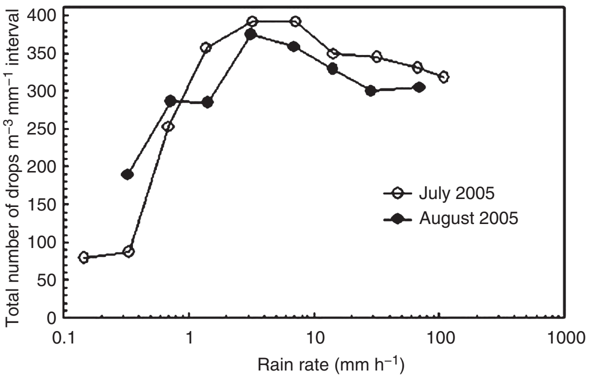

Figure 3. Variation of N_T with rain rate in July and August 2005 at Thiruvananthapuram.

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 Ghat 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^{-1}, N_T increases first (from 550 m^{-3} mm^{-1} for 0.1 mm h^{-1} to 700 m^{-3} mm^{-1} for 3 mm h^{-1}) and then decreases beyond with rain rate (and reaches up to even 350 m^{-3} mm^{-1} at ~50 mm h^{-1}), unlike all other coastal stations. D_g remains more or less constant (0.3 mm) up to 3 mm h^{-1} and then increases exponentially beyond with rain rate (0.3 mm for 3 mm h^{-1} to 1.6 mm for 30 mm h^{-1}). 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^{-1} 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.

If we clearly observe, Thiruvananthapuram shows a saturation in the N_T beyond a rain rate of 3 mm h^{-1} 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

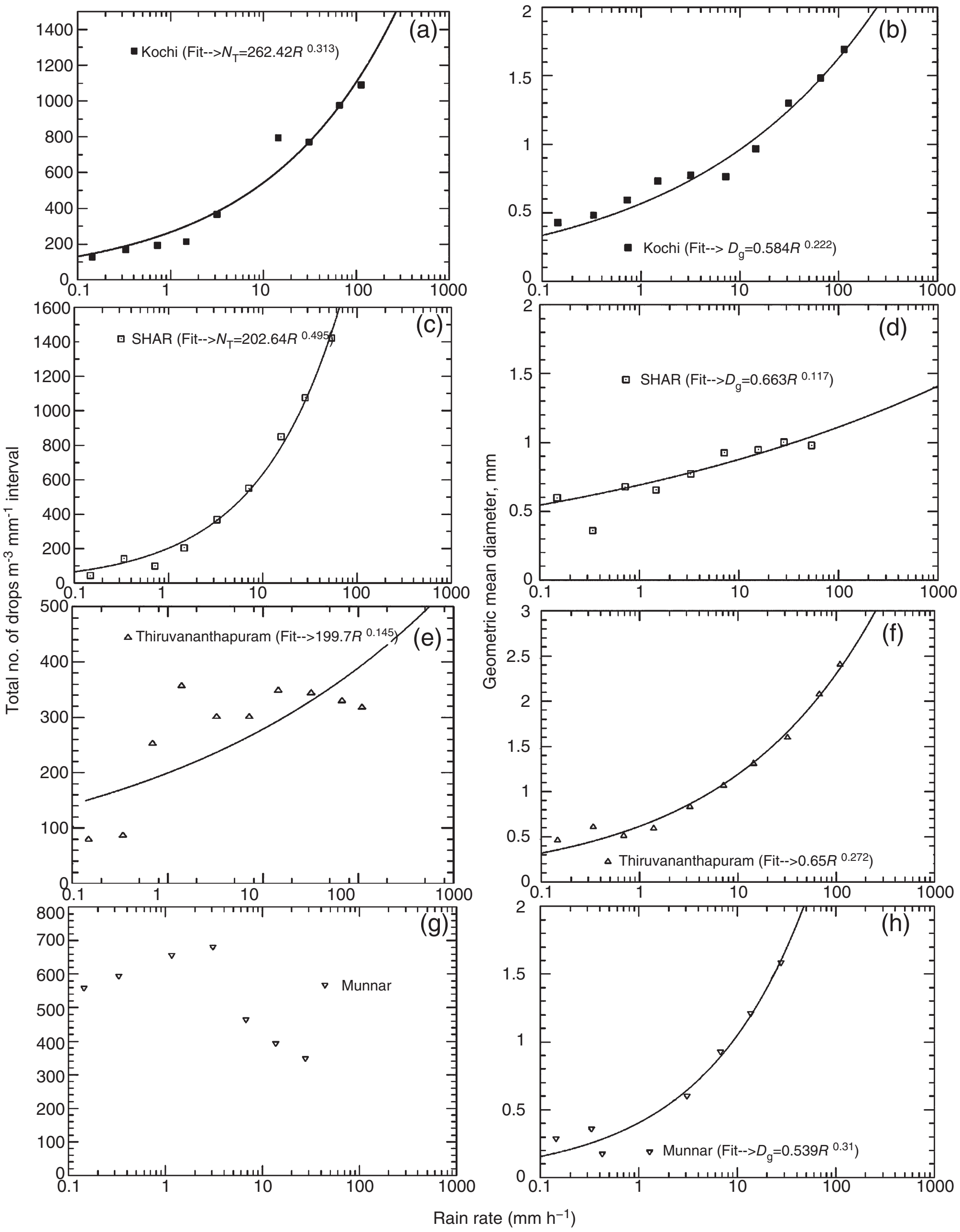

Figure 4. Variation of N_T (a, c, e and g) and D_g (b, d, f and h) (with fits of the form $Y = aR^b$ are shown as legend) with rain rate at stations (a, b) Kochi, (c, d) SHAR, (e, f) Thiruvananthapuram and (g, h) Munnar.

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 amsl), 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 nonattribution 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 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 (σ) did not show any significant dependence on rain rate. The variation of N_T and D_g 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 $>2\,\mathrm{mm\,h^{-1}}$. 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 ~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 σ 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_g, and σ with rain rate at all stations.

References

Feingold G, Levin Z. 1986. The lognormal fit to raindrop spectra from frontal convective clouds in Israel. *Journal of Climate and Applied Meteorology* **25**: 1346–1363.

Grossman RL, Durran DR. 1984. Interaction of low-level flow with the Western Ghat mountains and offshore convection in the summer monsoon. *Monthly Weather Review* **112**: 652–672.

Harikumar R. 2012. *Tropical rain Drop Size Distribution and Integral Rain Parameters: A Study Using Ground-Based and Satellite Measurements*. Lambert Academic Publishing: Saarbrücken. ISBN: 978-3-8484-1267-9.

Harikumar R, Sasi Kumar V, Sampath S, Vinayak PVSSK. 2007. Comparison of drop size distribution between stations in eastern and western coasts of India. *Journal of Indian Geophysical Union* **11**(2): 111–116.

Harikumar R, Hamza V, Sampath S, Mohan Kumar G, Gairola RM. 2008. Comparison of TRMM precipitation data with Micro Rain Radar and Disdrometer data during different Monsoon seasons. In Proceedings of the 37th COSPAR Scientific Assembly, Montreal, Canada; 2535 pp.

Harikumar R, Sampath S, Sasi KV. 2009. An empirical model for the variation of rain drop size distribution with rain rate at a few locations in Southern India. *Advances in Space Research* **43**: 837–844.

Huggel A, Schmid W, Waldvogel A. 1996. Raindrop size distributions and the radar bright band. *Journal of Applied Meteorology* **35**: 1688–1701.

Kirkwood TBL. 1979. Geometric means and measures of dispersion. *Biometrics* **35**: 908–909.

Kozu T, Reddy KK, Mori S, Thurai M, Ong TJ, Rao DN, Shimomai T. 2006. Seasonal and diurnal variations of raindrop size distribution in Asian monsoon region. *Journal of the Meteorological Society of Japan* **84A**: 195–209.

Liu WT, Xie X, Tang W. 2005. Monsoon, orography, and human influence on Asian rainfall. In Proceedings of the First International Symposium on Cloud-Prone & Rainy Areas Remote Sensing. Chinese University of Hong Kong: Hong Kong.

Muralidharan V, Kuriyan PP, Sampath S. 1985. A brief study of the orographic effect of Western Ghats on monsoon rainfall. *Geographical Review of India* **47**: 32–37.

Rahman H, Sengupta D. 2007. Preliminary comparison of daily rainfall from satellite and Indian gauge data. Technical Report No. 2007AS1. Indian Institute of Science: Bangalore; 26 pp.

Sasi Kumar V, Sampath S, Vinayak PVSSK, Harikumar R. 2007. Rainfall intensity distribution at a few places in Kerala. *Journal of Earth System Science* **116**(5): 451–463.

Smith RB, Schafer P, Kirshbaum DJ, Regina E. 2009. Orographic precipitation in the tropics: experiments in dominica. *Journal of the Atmospheric Sciences* **66**: 1698–1716, doi: 10.1175/2008JAS2920.1.

Smith RB, Justin RM, Alison DN, Trude S, Daniel JK, Robert W, Neil L, Philippe P, Arlington J, Jeffrey F. 2012. Orographic precipitation in the tropics: the dominica experiment. *Bulletin of the American Meteorological Society* **93**: 1567–1579, doi: 10.1175/BAMS-D-11-00194.1.

Testud J, Oury S, Amayenc P. 2001. The concept of ‘normalized‘ distribution to describe raindrop spectra: a tool for hydrometeor remote sensing. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **25**(10–12): 897–902, doi: 10.1016/S1464-1909(00)00122-2.

Ulbrich CW, Atlas D. 1998. Rainfall microphysics and radar properties: analysis methods for drop size spectra. *Journal of Applied Meteorology* **37**: 912–923.

Verma A, Jha K. 1996. Raindrop size distribution model for Indian climate. *Indian Journal of Radio & Space Physics* **25**(1): 15–21.

Xie SP, Xu H, Saji NH, Wang Y, Liu WT. 2006. Role of narrow mountains in large-scale organization of Asian monsoon convection. *Journal of Climate* **19**: 3420–3429.