CHAPTER IV

RAIN DROP SIZE DISTRIBUTION (DSD): CHARACTERISTICS & DEVELOPING AN EMPIRICAL MODEL TO DERIVE DSD WHEN RAIN RATE ALONE IS AVAILABLE
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CHARACTERISTICS
&
DEVELOPING AN EMPIRICAL MODEL TO DERIVE DSD WHEN RAIN RATE ALONE IS AVAILABLE

4.1. INTRODUCTION

Study of rain drop size distribution (DSD) is very useful in different areas like microwave communication, satellite meteorology, soil erosion and cloud physics. There is big interest in these areas for several reasons, including climatic change and increasing soil erosion due to expanding human activities. Accurate measurements of drop size distributions are important for many meteorological applications, including estimation of rainfall, cloud radiative transfer studies, and cloud model initialization and verification. For example, McGaughey et al. (1996), Viltard et al. (1998) and McKague et al. (1998) all demonstrated the large sensitivity of passive microwave algorithms to the prescribed drop size distribution of the precipitation originated from both convective and stratiform clouds. By tracking the rain DSD along their falling path is a direct way of even measuring rain evaporation (Li and Srivastava, 2001).

To overcome the time height ambiguity in radar measured reflectivity and surface rain rate, knowledge of hydrometeor size distribution within the precipitation layer is essential. The rain DSD is a critical factor in estimating rain rate using advanced dual-polarized weather radars (Vulpiani et al., 2006). A new neural-network algorithm to estimate the DSD from S-band dual-polarised radar measurement is presented in their paper. The corresponding rain rates are then computed assuming a commonly used raindrop diameter-speed relationship. Satellite measured rain parameters would be reliable and dependable if and only if the retrieval from the satellite primary data using the algorithm is accurate. Unfortunately, errors due to the seasonal dependence, back ground dependence etc. is very clear from the retrievals.
carrier out so far. Retrieval of the precipitation parameters from the active satellite measurements is found to be less accurate. The errors associated with the retrieval of rain rate from radar reflectivity factor can be eliminated, by knowing the target, which is the rain drop size distribution, from which the scattering of the electromagnetic radiation takes place. The same reflectivity may be obtained from different targets having different drop size distributions. Hence, there is a need to know the rain DSD in detail. The spatial, altitudinal and temporal variability of the Z-R relation is evident from the past measurements. Since the radar reflectivity factor is the 6th moment of rain DSD, the radar back scattered power is not only merely dependant on the rain rate, but also it depends purely on the number and size distribution of the rain drops. So the radar reflectivity factor should necessarily be derived from the rain DSD, for the derivation of an empirical relation for the altitudinal and spatial variation of Z-R equation and here lies the importance of the need of more rain DSD data and analyses. Since there is no one to one relation between this Z and R, a wide range of Z-R relations are mentioned in the literature (Battan, 1973). A common technique for radar estimation of rainfall is to develop relationships between the backscattered energy return to the radar (i.e., reflectivity, Z) and rainfall rate (R). Both Z and R are dependent on the drop size distribution. The Z–R technique has the advantage of producing rainfall estimates over large areas (50 000 km$^2$) in relatively short time (several minutes). Unfortunately, the existence of various range-dependent errors can produce significant biases in the scanning radar estimate of rainfall (e.g., Wilson and Brandes 1979; Zawadzki 1984; Austin 1987). Moreover, many previous observational studies have shown that natural variations of the drop size distribution in time and space can lead to different Z–R parameterizations, ultimately producing different estimates of rain rates (e.g., Battan 1973; Ulbrich 1983; Austin 1987; Huggel et al. 1996). Different Z-R relations should be used for each rain rate range, for better rain DSD derivation (Mali et al., 2003).

In the context of microwave communication, the performance of the microwave links at frequencies above 10 GHz is constrained by the excess attenuation...
due to precipitation, especially, rainfall. The lower atmosphere is absorptive, dispersive and inhomogeneous and therefore plays an important role in radio communication in the frequency range UHF to mm waves. The important parameters affecting the propagating wave are the shape of each rain drop and rain DSD. Rain attenuation increases with rain drop size and attains a maximum value at a particular drop size. Beyond this value of drop size, rain attenuation either remains constant or decreases (Verma and Jha, 1996b). Since the wavelengths of mm waves are of the same order as the rain drop sizes, the rate of attenuation is highly dependant on rain DSD (Verma and Jha, 1996a). In tropical climates, rain attenuation is severe due to higher rain rates (Jassel et al., 1994). “Sufficient data on propagation attenuation, rain rate and DSD are not available for tropical region and, in particular, for India where rainy season is characterised by the heavy monsoon rains. Due to the lack of rain DSD data in the tropics, the usage of available DSD data that are collected from the low rain rate regime like temperate regions, causes the attenuation prediction models are found to be very inadequate for tropics” they continued. These authors have developed a rain attenuation model based on the DSD data and compared with CCIR (International Radio consultative Committee) and other models. The usage of regional DSD data with its lognormal fit is very clear from their studies (and also Verma and Jha, 1996b) and the specific attenuation calculated using DSD with lognormal representation was more realistic compared to DSD with MP and gamma representations. So, these DSD measurements, their lognormal modelling and deep quantitative understanding have much relevance in the special scenario of attenuation of electromagnetic radiation with rain, especially with tropical heavy rainfall. Rain attenuation can be obtained directly through experiments or predicted from a knowledge of rain rate and DSD (Medhurst, 1965; Maciel and Assis, 1990; Ajai and Olsen, 1985). That is a model for the variation of DSD with rain rate is very essential. The difference in the experimental and theoretical attenuation results are due to the non-uniformity of DSD, which varies with the geographical locations (Medhurst, R.G., 1965). So, it will be helpful to understand more about the rain DSD for tropical climates, for improving the efficiency of
communication. Selection of frequency bands can be made on the basis of the DSD model derived for each location.

A number of recent studies have examined the applicability of separate \( Z-R \) relations for rain that originate from convective and stratiform clouds. Short et al. (1990) and Tokay and Short (1996) have shown, using Disdrometer data from Darwin, Australia, and the tropical western Pacific, that the DSD undergoes abrupt shifts between convective and stratiform precipitation and that rainfall rates derived are improved when two \( Z-R \) relations are used instead of one. However, Steiner and Houze (1997) showed that the use of two \( Z-R \) relations instead of one did not significantly improve monthly rain totals using radar data at Darwin, Australia. Also, Yuter and Houze (1997) have argued that convective and stratiform DSDs in the tropical western Pacific are not statistically distinct. Clearly, more research on the variability of the DSD in different precipitation regimes is required. The profiler retrievals for the MCS were partitioned into a three-tier classification scheme (i.e., convective, mixed convective–stratiform and stratiform) following a modified version of Williams et al. (1995) in order to isolate the microphysical characteristics in different precipitation types.

Kenji et al. (1999) has made measurements of rain DSD and kinetic energy of the rainfall at T-sukuba for 2 years and Ishigaki for 1 year, and compared the energy-rain rate equations. Their main finding on regional characteristics of Ishigaki was that, there were large sized raindrops below 30 mm/h rain rate and the distribution of raindrop size wide from 1 mm to 5 mm in diameter. But in Tsukuba the distribution of raindrop size concentrated between 1 mm to 2 mm. The impact of rain on soil that causes soil erosion at these different locations will be different because of the difference in DSD. So, the understanding about rain DSD will help us to take precautions in determining the agriculture field structure.

The gamma parameters have been derived on the ground with the Disdrometer and aloft with VHF and UHF radar measurements made at Gadanki in the southwest monsoon season by Narayana Rao et al. (2006). This is to study the \( \mu-\lambda \).
(shape parameter-slope parameter) relation (parameter derived from the gamma fit to the rain DSD) with respect to this climatic regime and also as a function of height. This relation is different at Gadanki compared to other places like Florida and Oklahoma and also this relation is found to be varying with height. An experimental study of small scale variability of DSD has been carried out at Wallops Island, Virginia by Tokey and P.G. Bashor (2007). They also recognised the sampling issues of the Disdrometer and thus itself presented the findings for 1-, 3-, 6-, 10- and 15-minute averaged disdrometric measurements. Using the Disdrometer measurements at different climatic regions, constraints on the gamma distribution has been developed to retrieve DSD from the dual-frequency radars by Munchak and Tokey (2008). DSD data obtained from Disdrometer could be used for the simulation of algorithms to derive back the DSD (Tokey and Dickens, 2000).

The natural conclusion by Haddad et al. (2003) is that, in spite of the dual-frequency radar that GPM will carry, the careful a-priori modeling of the DSD, at scales commensurate with the GPM radars’ resolution, will be crucial to the success of the GPM core retrieval algorithm. This enforces the fact that DSD should be modeled for its variation with rain rate very region specific.

According to Weischet (1969), the tropical area characteristically has a rainfall maximum between 1000 metres and 1500 metres. Still, there is possibility of many local or regional complications to occur (Barry, 1981). The rainfall characteristics over mountains are determined by several factors such as latitude, altitude and orography. A convective pattern of vertical precipitation distribution is widely found in the tropics. According to Rao (1958), the monsoon currents become convectively unstable when it is lifted by the mountains during travel along a short distance. The amounts of orographic precipitation depends on the air mass characteristics and synoptic-scale pressure pattern, local vertical motion due to the terrain, microphysical processes in the cloud and the evaporation of the falling rain drops (Sawyer, 1956).
Orographic effect of the western ghats on the monsoon rainfall has been studied for the southwest and northeast monsoon using normal rainfall data of 50 years (1901 to 1950). The precipitation is dependant on altitude over the western slope which is on the windward side with respect to the southwest monsoon, whereas it is independent of altitude over the eastern slope which is on the leeward side. The situation exactly reverses during the northeast monsoon rainfall. The study of Muralidharan et al. (1985) reveal that the amount of precipitation on the western slope of the western ghats above an altitude of about 600 metres increases with the altitude to a maximum at a height of about 1300 meters; and further up it decreases. Almost in a similar manner on the eastern slope of the Ghats above an altitude of about 370 metres the rainfall increases to a maximum about 1800 metres above mean sea level, and thereafter decreases continuously. Their rainfall profiles more or less agree with the results obtained from the global survey carried out by Lauer (1975) and also by Lauscher (1976) for other tropical mountains.

With the development of instruments that can give drop size data continuously and at relatively low costs, DSD measurements are becoming more common. However, there haven’t been many measurements in India. Some of them are Jassal et al. (1994), Verma and Jha (1996a and 1996b), Reddy and Kozu (2003), Sasi Kumar et al. (2003), Mali et al. (2003), Krishna Reddy et al. (2005), Soma Sen Roy et al. (2005), Rao et al. (2006) and Harikumar et al. (2007; 2009). We present here the characterization of rain DSD and derivation of a rain DSD model for 4 different locations in southern India, viz. Thiruvananthapuram and Kochi, which are west coast stations; Munnar, a high altitude station in the Western Ghats and Sriharikota (SHAR), a station on the east coast, (Details of these stations are explained in the Chapter II) using a Joss-Waldvogel Disdrometer (JWD; Joss and Waldvogel, 1967). Some preliminary results from Thiruvananthapuram were presented in an earlier paper by Sasi Kumar et al. (2003) and the comparison of rain DSD between the stations in the eastern (SHAR) and western (Thiruvananthapuram and Kochi) coasts of India has also been presented by Harikumar et al. (2007).
Chapter IV: DSD-Characteristics and Empirical Model

Three different distribution functions are commonly used by different authors to describe rain drop size spectra, namely, the Marshall and Palmer (1948) type of exponential distribution, the gamma distribution (Ulbrich, 1983) and the lognormal distribution (Feingold and Levin, 1986). It is generally agreed that the exponential distribution is valid only for data averaged over long periods of time (Joss and Gori, 1978), or over large volumes of space. However, the negative exponential is not appropriate for use in tropical regions and gamma model distribution too must be modified (Awang and Din, 2004). Thus, lognormal raindrop size distribution models are suitable and thus used it to estimate rain attenuation and compared to rain attenuation measurements from microwave links installed at Wireless Communication Centre (WCC), Universiti Teknologi Malaysia, UTM Skudai, Johor by these authors. Raindrop spectra often tend to have a monomodal distribution, which can be modelled by the gamma distribution function. This has the advantage that it tends to the exponential function as one of the parameters tends to zero. In the cases of the exponential and gamma distributions, however, the parameters have no physical significance.

The lognormal distribution was explored by Feingold and Levin (1986) and was found to be as good as, if not better than, the gamma distribution in terms of fitting with observations. While the former showed better fit with the observed raindrop size distribution, the computed rain rate was marginally better when the gamma function was used. However, the lognormal distribution has the advantage that the parameters have physical significance (Feingold and Levin, 1986). The variations in these parameters with rain rate or with time would, therefore, have implications on the physical processes that lead to the formation of rain drops and the processes that take place as the drops fall from the cloud to the ground.

Testud et al. (2001) developed a concept of normalization of DSD as normalizing raindrop spectra is an appropriate way to identify the shape of the distribution. The concept of normalization of DSD is based upon two reference
variables, the liquid water content LWC and the mean volume diameter $D_m$. This normalization procedure helps in clearly defining the stratiform and convective rain types and hence a better insight into the cloud microphysics. The major point of this approach is that this normalisation is totally free of any assumption about the shape of the DSD. This new normalization has been successfully applied to the airborne microphysical data of the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) collected by the National Center for Atmospheric Research Electra aircraft. The classification of the TOGA COARE raindrop spectra into stratiform and convective have been done to impress on the usefulness of this approach.

In the present study, we have tried to understand the characteristics of DSD rather than use the DSD to distinguish the type of rainfall. Therefore, the approach of Testud et al. (2001) is not adapted here. However, the liquid water content (LWC) is varying linearly with rain rate at all the stations. So, the study of the variation of all the parameters with rain rate indirectly implies its variation with LWC too.

4.2. CHARACTERISTICS OF RAIN DROP SIZE DISTRIBUTION (DSD)

4.2.1. Data and Data Analysis

The data covers a period of roughly 34 months in which there was rainfall. This includes 22 months in the SW monsoon season, 8 months in the pre-monsoon season and 4 months in the NE monsoon season. Data for four months are from the high altitude station Munnar and for three months from the east coast station SHAR. The remaining data are from two stations on the west coast as explained in the Chapter I. One method for obtaining drop size distribution (DSD) functions requires previous normalization of both measured drop diameters and concentrations. This normalization, proposed by Sekhon and Srivastava (1971, 1978), and later by Willis (1984), was meant to comprise the entire dataset, thus achieving a universal distribution function independent of observation site or rain type. An alternative method is based on previous grouping of rain registers in different rain-rate classes to obtain mean size distributions. These distributions can then be fitted to theoretical
models whose parameters will depend on the rain rate, usually through a power law. (Cerro et al., 1999). We followed the second method to analyse and thus parameterize our DSD data.

4.2.2. Representing the Rain DSD – Best Fitting Distribution

The data obtained in each minute were corrected for dead time errors and the rain DSD was computed. The rain rate for each minute was then computed from the corrected data, and the entire data for each month were sorted in ascending order of rain rate. The data were then divided into different ranges of rain rate, as explained below. The values for each range were then averaged and the average DSD was computed for each range of rain rate. The mean rain rate for each range was also determined. The next step would be to find out the most suitable distribution that represents the rain DSD.

Three well known distribution functions have been used by different authors to represent the DSD.

Marshal Palmer (MP) distribution (Marshal and Palmer, 1948) of the form

\[ N(D) = N_0 \exp(-\lambda D) \]  \hspace{1cm} (4.1)

where \( N_0 \) is the Intercept parameter (signifies the number density in the first channel of the Joss Waldvogel Disdrometer) and \( \lambda \) is the Slope parameter,

a Gamma (\( \Gamma \)) distribution (Ulbrich, 1983) of the form

\[ N(D) = N_0 D^\mu \exp(-\lambda D) \]  \hspace{1cm} (4.2)

where \( N_0 \) is the Intercept parameter, \( \lambda \) is the Slope parameter and \( \mu \) is the Shape parameter, and a lognormal distribution (LN) (Feingold and Levin, 1986) of the form

\[ N(D) = \frac{N_T}{\sqrt{2\pi} \ln \sigma D} \exp \left[ -\frac{\ln^2 (D/D_g)}{2 \ln^2 \sigma} \right] \]  \hspace{1cm} (4.3)

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.
By substituting
\[ \frac{N_r}{\sqrt{2\pi \ln \sigma}} = A \] (4.4)
\[ \ln D_g = B \quad \text{and} \]
\[ \ln \sigma = C \] (4.5) (4.6)
and simplification, finally the equation (4.4) takes the form
\[ N(D) = \frac{\exp(A)}{D} \exp \left\{ -0.5 \left[ \frac{(\ln D - B)^2}{C} \right] \right\} \] (4.7)
where \( D \) is the drop diameter, \( N(D) \) is the number of drops per cubic meter per unit diameter interval, and \( A, B \) and \( C \) are fit parameters.

DSD corresponding to different rain rate ranges for the month of June 2005 at Thiruvananthapuram was selected as a sample and the data set was fitted with all the three distribution functions mentioned above. 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 4.1. A similar behaviour is seen in the data from the other three stations also.

From figure 4.1, 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. According to Munchak and Tokey (2008), even though good relations between the gamma parameters are seen, the relations do not necessarily hold at all rain rates and for all precipitation events. Taking into consideration this result also, lognormal distribution was preferred to represent the DSD over this region.
Figure 4.1. 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.

4.2.3. Drop Size Distribution Spectrum-General features

Figure 4.2 shows typical rain DSD spectrums with fitted lognormal curves for all the stations. The curves fit the data reasonably well in all the data ranges. The distribution is narrow when the rain rate is low and becomes significantly wider with increasing rain rate, indicating the increasing presence of larger drops. The initial increasing trend of number of drops with drop diameter is not very clearly seen at the low diameter end for low rain rates, though a tendency for that may be made out. We are not in a position to determine whether the number of drops actually increase with drop diameter in this region since we have data only from 0.313 mm onwards. However, this can be clearly seen in the case of DSDs corresponding to large rain rates. Therefore, it may be reasonable to assume that this trend extends to the low rain rates also. Though, there is a possibility of under estimation in the number of smaller drops in heavy rains due to instrument’s electronic design for self-noise control as
explained earlier in the Chapter II. But there is no way as on today to eliminate this error completely. In the present case, the sensor is mounted such that acoustic noise and wind effects are reduced to a minimum.
Figure 4.2. Rain DSD spectrum corresponding to the stations Kochi (July 2003; top panel) Thiruvananthapuram (July 2005; second panel), Munnar (July 2004; third panel) and SHAR (August 2003; bottom panel). The lognormal fit is shown as solid lines along with the DSD data. R in the legend represents the rain rate.
Behaviour of rain DSD at different locations is very clear from visual observations of these spectra (figure 4.2). At Thiruvananthapuram, an increase is seen in the drop diameter at which the distribution peaks with rain rate. The amplitude of this peak decreases as the rain rate increases. At Kochi, the behaviour is very similar to that of Thiruvananthapuram but the amplitude is found to be constant for all the rain rates. At Munnar, the characteristics are similar to Thiruvananthapuram, but the amplitude of the peak decreases very drastically as rain rate increases. But at SHAR, there is no shift in the peak and the amplitude increases as rain rate increases.

From the fitted lognormal distribution, the three physically meaningful parameters $N_T$, $D_g$ and $\sigma$ were evaluated to study the characteristics of DSD in our region.

### 4.2.4. Evaluation of $N_T$, $D_g$ and $\sigma$

Feingold and Levin (1986) computed the fit parameters by using the observed total number concentration, $N_T$, and the number of drops in each size class to calculate the geometric mean diameter, $D_g$, and standard geometric deviation, $\sigma$, of the truncated distribution. They then used these values in the equation 4.3, to obtain the expression for number of rain drops per cubic metre per unit diameter interval ($N(D)$), where $D_g$ and $\sigma$ are in millimetres. A different method has been followed here. Instead of computing the fit parameters, the DSD for each range was fitted with a lognormal distribution function. The functional fits were made using gnuplot, a graphing software that uses the Marquardt-Levenberg algorithm for non-linear curve fitting. It is very easy to fit the data sets with lognormal distribution function using simple computer programs and to obtain fit parameters for huge long term data compared to the parameter estimate. Since the number of drops varies from 0 to thousands or tens of thousands, we took the natural logarithm of both sides of the equation before fitting so that all the points get equal weightage. Thus, the actual equation used for fitting was

\[
\ln(N(D)) = A - \ln(D) - \frac{(0.5(\ln(D) - B)/C)^2}{1}
\]  

(4.8)
where D is the drop diameter, \( N_{(D)} \) is the number of drops per cubic metre per unit diameter interval and A, B, C are the fit parameters. Comparing this with Eqn. 3, we can, thus, derive the values of \( N_T \), \( D_g \) and \( \sigma \) from A, B and C using the equations 4.4, 4.5 and 4.6 respectively.

Table IV.I shows the rain rate ranges into which the data were divided and the mean rain rate obtained in each range for a typical month in each station. The rain rate ranges were chosen such that the width of the range increases in a roughly exponential manner. The reason is that the data showed, in general, that the rainfall duration was high at the low rain rate end and decreased in a roughly exponential manner with increasing rain rate so that there was data for a longer duration for lower rain rate. A detailed analysis of the distribution of rain rate is given in our paper (Sasi Kumar et al. 2007). There we show that rainfall is below 5 mm/h, 70 to 90% of the time in most of the months, and sometimes even higher.

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<tr>
<td>1</td>
<td>0.1 &lt; R &lt; 0.2</td>
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<td>148</td>
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<tr>
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<td>329</td>
<td>1.479</td>
<td>152</td>
</tr>
<tr>
<td>5</td>
<td>2 &lt; R &lt; 5</td>
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<td>404</td>
<td>3.172</td>
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<td>5 &lt; R &lt; 10</td>
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<td>124</td>
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<tr>
<td>7</td>
<td>10 &lt; R &lt; 20</td>
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<td>147</td>
<td>14.517</td>
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<tr>
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<td>20 &lt; R &lt; 50</td>
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<td>31.016</td>
<td>75</td>
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<tr>
<td>9</td>
<td>50 &lt; R &lt; 100</td>
<td>67.277</td>
<td>41</td>
<td>65.754</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>R &gt; 100</td>
<td>109.27</td>
<td>3</td>
<td>113.26</td>
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Table IV.I. Mean rain rate obtained in each range for one month in each station. (R=rain rate. n=Number of minutes for which rain was measured).
The significance of taking the entire data for a month for the analysis, rather than taking each rainfall episode separately is discussed here. This was done for the following reasons: This region has mainly three seasons, as far as rainfall is concerned. These are the South-West (SW) monsoon (June–September), North-East (NE) monsoon (October–December) and Pre-monsoon (January–May). Rainfall during the SW monsoon is mostly from stratiform clouds, and during the other two seasons is from cumuliform clouds, mostly thunderstorms. Therefore, it is expected that the rainfall during a season is mostly from similar type of clouds. One important difference is there in the characteristics of rainfall between the stations in the west coast and those in the east coast, which is relevant to this study. Ie, during the SW monsoon period, rainfall over west coast is oceanic while rainfall at east coast is continental because the wind is mostly southwesterly or westerly. We took each month separately because it gave better time resolution compared to taking an entire season as a whole. This also helped to a certain extent to see whether there are changes within a season. It is found by Kozhu et al. (2006) that the DSDs are affected even by diurnal convective cycles and seasonal variations in precipitation characteristics. Further, we were trying to identify how DSD is influenced by rain rate, rather than to understand, for example, how DSD varied during the course of a rainfall event. The analysis procedure was selected to enable this.

In a previous paper (Sasi Kumar et al. 2003), it was stated that the distribution measured at Thiruvananthapuram in April (pre-monsoon) appears to be different from that in June (SW monsoon) for low rain rates. At that time, they had divided rainfall periods into five rain rate ranges and tried to fit the gamma function to the distribution. The low rain rate ranges in June showed a behaviour that was closer to the Marshall-Palmer type of distribution than to gamma. However, after analysing a much greater volume of data, and in greater detail than earlier, we find that the lognormal distribution is more appropriate and fits most of the data. The deviation from lognormal is limited to about a tenth of the data we have obtained so far.

R. Harikumar
4.2.5. Variation of $N_T$, $D_g$ and $\sigma$ with rain rate

$N_T$, $D_g$ and $\sigma$ for each rain rate range in each month was derived to study the variation of these parameters with rain rate to study the characteristics of DSD. These are discussed here.

Variation of $\sigma$ with rain rate

Variation of $\sigma$ is plotted against the mean rain rate. Typical graphs of $\sigma$ for one month from each station are shown in Figure 4.3. It is seen that in general $\sigma$ was almost constant for all rain rate ranges (Harikumar et al., 2007). A small variation can be seen, but it is very small compared to the values of $\sigma$.

![Figure 4.3. The variation of $\sigma$ with rain rate in August at Sriharikota and in July in the other stations.](image)

Variation of $N_T$ and $D_g$ with rain rate

The typical Variation of $N_T$, $D_g$ (with fit of the form $Y=aX^b$) and $N_T D_g^3$ (a measure of LWC) (with fit of the form $Y=mX+c$) with rain rate at all the stations are shown in the figure 4.4.
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Figure 4.4. Variation of $N_T$ (left panel), $D_g$ (middle) (with fit of the form $Y=aX^b$) and $N_TD_g^3$ (right) (with fit of the form $Y=mX+c$) with rain rate at stations Thiruvananthapuram (top panel), Kochi (2nd panel), Munnar (3rd panel) and SHAR (bottom panel). For all the stations except SHAR, the data shown here is for the month of July and for SHAR, it is for August.

The variation of these parameters with rain rate at all the stations have been included together in the figure 4.5. Comparison of the variation of these parameters with rain rate between all the stations is explained in detail below. Since Kochi and SHAR behaved same they have been treated together and since Munnar and Thiruvananthapuram behave same they are being treated separately.
Figure 4.5. Comparisons of the Variation of $N_T$ (top panel) and $D_g$ (bottom panel) with rain rate at all the stations.
Kochi and SHAR

We see that $N_T$ generally tends to increase exponentially with rain rate; but the rate of increase is different for these two stations (figure 4.5). The graph also shows fitted curves of the form $Y=aX^b$, where $a$ and $b$ are constants. It may be noted that the total number of drops is more or less the same at both the stations up to about 3mm/h. Above that the total number of drops increase faster with rain rate at SHAR compared to that at Kochi. This results in $N_T$ being higher for large rain rates at SHAR. As a consequence, there should be more number of larger drops in Kochi during high rain rates. In other words, the mean drop size should be higher in Kochi during heavy rainfall, as we shall see below.

As in the case of $N_T$, we have fitted the Dg data with curves of the form $Y=aX^b$ and the fitted equations are also shown in the figure. The periods for which the data are taken are the same as in the case of $N_T$. The variation is very similar to that of $N_T$. We see that the values of Dg are more or less same up to around a rain rate of 3 mm/h. Above this rain rate, the rate of increase of Dg is high for Kochi and less for SHAR. Thus, a faster increase in the number of drops at SHAR is compensated by a slow rise in drop size.

An interesting observation at Kochi is that $N_T$ was rather low in the three months of May, June and July 2004. Thus, for instance, for a rain rate of 3 mm/h, $N_T$ was 366 in July 2003. But it came down to 138 in July 2004. $D_g$, on the other hand, increased from 0.774 in July 2003 to 1.101 mm in July 2004. Figure 4.6 shows the graphs for $N_T$ and $D_g$ for Kochi for July 2003 and July 2004 which makes the difference clear. i.e., during 2003 at Kochi, the geometric mean sizes of the drops are always smaller compared to that during 2004 for any particular rain rate. The presence of comparatively smaller drops in the convective clouds was explained by Tokay and Short (1996) is as given below. The time required for the growth of precipitation particles in convective clouds is much less than that in the stratiform clouds. Therefore, the precipitation particles originate and grow not far from the cloud base. With the existence of strong updrafts, it is possible that the precipitation particles in convective
clouds are carried upward and continue to grow until they become heavy enough to overcome the updraft and begin to fall relative to the ground. In convective clouds, growth by accretion of liquid water is the dominant mechanism followed by collisions, coalescence and breakup of raindrops.

![Image](image1.png)

**Figure 4.6. Comparison of variation of \(N_T\) (left panel) and \(D_g\) (right panel) with rain rate in July 2003 and July 2004 at Kochi. The fitted equations are also shown.**

This indicates the possibility of rainfall being predominantly from convective clouds in 2003. To confirm the prevalence of convection in 2003 compared to 2004, we checked the Outgoing Longwave Radiation (OLR) data. The OLR data is downloaded for a maximum possible spatial resolution of 2.5° lat X 2.5° lon grid corresponding to Kochi (7.5°N to 10°N, 75°E to 77.5°E) from the NOAA website (Liebmann and Smith, 1996). The high convection in the year 2003 compared to 2004 is clear from the low OLR value (OLR~ 199.827 W/m²) during July 2003 compared to July 2004 (OLR~ 209.542 W/m²) at Kochi.

**Munnar and Thiruvananthapuram**

During the four months in which we measured DSD in Munnar, we find that \(N_T\) varies very differently. We see that \(N_T\) initially increases with rain rate up to about 3 mm/h, indicating that the increase in rain rate is primarily due to increase in the number of drops, as in other stations. This is supported by the fact that the increase in
D_g is small over this range. Beyond 3 mm/h, we see that N_T decreases rapidly and D_g increases rapidly. At Thiruvananthapuram, the variation up to about 3 mm/h more or less follows an increasing pattern, but then N_T remains more or less constant or starts decreasing, though slightly. This kind of behaviour is found in most of the months at Thiruvananthapuram, though the rain rate at which the change in profile occurs is different for different months. D_g increases correspondingly to compensate for N_T remaining steady or decreasing. Table IV. II shows this clearly. It also shows how N_T and D_g for the same rain rate is different for different stations.

<table>
<thead>
<tr>
<th>R</th>
<th>N_T</th>
<th>D_g</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>Tvm</td>
<td>Kochi</td>
<td>Shk</td>
</tr>
<tr>
<td>0.3</td>
<td>68.5</td>
<td>168.9</td>
<td>140.9</td>
</tr>
<tr>
<td>3.2</td>
<td>300.7</td>
<td>366.4</td>
<td>367.6</td>
</tr>
<tr>
<td>30</td>
<td>343.9</td>
<td>770.8</td>
<td>1077</td>
</tr>
<tr>
<td>110</td>
<td>317.8</td>
<td>1090.7</td>
<td>--</td>
</tr>
</tbody>
</table>

Table IV. II. N_T, D_g and σ for same rain rate at different stations (Tvm = Thiruvananthapuram, Mnr = Munnar, Shk = Sriharikota).

To understand the differences in the magnitudes of these parameters at each station, the values of N_T and D_g are plotted together for a rain rate of 30 mm/h for all the stations are shown in figure 4.7. It is apparent from the figure that as total number of drops increases mean diameter decreases. The N_T (D_g) is lowest (most) for Thiruvananthapuram, is less (more) for Munnar, is more (less) for Kochi and most (lowest) for SHAR.
Chapter IV: DSD-Characteristics and Empirical Model

The comparison of the variation of these two parameters between a station at west coast (Kochi) and at a high altitude station (Munnar) lying in the same latitude during southwest monsoon period gave an insight to the orographic effect on rain DSD apart from the known orographical rainfall enhancement (Muralidharan et al., 1985). Recently, study of the satellite detection (TRMM satellite data) of rainfall (June-August 2002-2003, averaged) over the Indian peninsula by Harikumar et al. (2009a) shows the rainfall enhancement at windward side of the Western Ghats during southwest monsoon season. It is very clear from figure 4.5 that a heavy rainfall at Munnar consists of less number of bigger drops, while Kochi rain consists of more number of smaller drops at a particular rain rate. That means, the orography is seen to affect the drop size and thus orographic rain seems 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 study of orographic effect on rainfall, especially on rain DSD would be useful and throw light on landslide triggering mechanisms.

Figure 4.7. Station-wise variation of $N_T$-$D_g$ pairs corresponding to a rain rate of 30 mm/h.

R. Harikumar
Variation of $N_TD_g^3$ with rain rate

As mentioned earlier, we find that both $N_T$ and $D_g$ vary in a similar fashion with rain rate. We also find that when one of these parameters increases slowly with rain rate, the other parameter seems to compensate and increase more rapidly, and vice versa. This is natural since a certain quantity of water has to be provided by the drops to create particular rain rate. We plotted the function $N_TD_g^3$ against rain rate $R$ and found that there existed a linear relationship between $R$ and $N_TD_g^3$. In figure 4.4, the graphs for a month at each station are also shown. It is interesting to note that the regression coefficient is around 0.999 most of the time, even for Munnar where the variation of $N_T$ and $D_g$ with $R$ is irregular, as mentioned above. The regression coefficient is, however, lower (0.91) for SHAR. Here, the points are away from the line and follow a kind of arc. This is possibly because DSD curves fitted badly with the lognormal distribution function, as mentioned earlier. The regression lines were not forced to go through the origin and hence the equations give a finite y-intercept. The values are, however, small and can be ignored.

4.2.6. Discussion

Lognormal distribution is found to be a very good representation for rain DSD for the entire rain rates. The parameters $N_T$ and $D_g$ vary with rain rate in such a manner that an increase or decrease in one parameter is compensated by an opposite change in the other. At Kochi and SHAR, $N_T$ and $D_g$ increases exponentially with rain rate. In Munnar, and in Thiruvananthapuram to some extent, we find that these parameters vary in a manner that is very different from that at the other two stations. $N_T$ increases first up to a rain rate of around 3 mm/h and then decreases beyond as rain rate increases. At Thiruvananthapuram, for some months a constant value is also seen for $N_T$ instead of decreasing beyond 3 mm/h. $D_g$ increases very gradually up to around 3 mm/h and then increases very sharply beyond around 3 mm/h. For a particular rain rate The $N_T(D_g)$ is lowest (most) for Thiruvananthapuram, is less (more) for Munnar, is more (less) for Kochi and most (lowest) for SHAR.
The difference in the behavior of these parameters at Munnar and SHAR in the southwest monsoon season, when the wind is westerly or south-westerly suggests that the effect of CCN may not be the possible reason for the DSD spatial variability. The more or less similar behavior shown by Munnar and Thiruvananthapuram and that shown by Kochi and SHAR as explained above also suggests that, effect of orography on rainfall is a possible reason for the spatial variability of the rain DSD within the tropical areas. However, more detailed studies would be needed to confirm this.

\( N_t D_g^3 \) varies linearly with rain rate, with an exception at SHAR. This also points out the need to have more data at east coast stations.

4.3. EMPIRICAL MODEL FOR THE VARIATION OF RAIN DROP SIZE DISTRIBUTION WITH RAIN RATE

4.3.1. Derivation of the empirical model

An empirical model for DSD in this region was derived using the data. All the available data, except that for a few months, was used for this purpose. The data for the few months that was not used was kept aside for validating the derived model. The data thus kept aside was for the months of May, June and October 2005 at Thiruvananthapuram, May and July 2004 (up to 8\(^{th}\)) at Kochi, July 2004 (from 9\(^{th}\) onwards) at Munnar and August 2003 at Sriharikota. The method of deriving the empirical model is given below.

DSD data for each of the three monsoon periods was sorted according to rain rate, viz. southwest monsoon (June, July, August & September), northeast monsoon (October, November & December) and pre-monsoon (January to May). Then this data was grouped into the different rain rate ranges specified earlier. The mean DSD and the mean rain rate for each range for each season was then determined. This mean DSD corresponding to each rain rate range was fitted with the lognormal distribution function (Equation 4.7). The functional fits were made using gnuplot, a graphing software that uses the Marquardt-Levenberg algorithm for non-linear curve fitting as
mentioned earlier. A typical set of rain drop size distribution spectra along with lognormal fits for each station is shown in Figure 4.2.

The values of the lognormal fit parameters A, B and C for the fit corresponding to each rain rate range were obtained from the curve-fitting process. The variation of these parameters with rain rate was then studied. The variation of these three parameters with rain rate has the same form in all the monsoon seasons at all the stations. This variation of the fit parameter A could be fitted with an expression of the form

$$A = A_0 + A_1 R + A_2 \ln R$$

(4.9)

where $A_0$, $A_1$ and $A_2$ are the fit parameters and $R$ is the rain rate. The fit parameter B also could be represented by a similar relation.

$$B = B_0 + B_1 R + B_2 \ln R$$

(4.10)

where $B_0$, $B_1$ and $B_2$ are fit parameters and $R$ is the rain rate. The parameter C was found to be almost a constant for all stations and all seasons.

Variation of these three parameters with rain rate during the southwest monsoon season at Thiruvananthapuram is shown in Figure 4.8.

Incorporating the expressions for A and B into the original lognormal distribution (Equation 4.7), we get a rain DSD equation in which number of rain drops is a function of both drop diameter and rain rate. Thus the empirical model can be written in the form

$$N(D, R) = \frac{\exp(A_0 + A_1 R + A_2 \ln R)}{D} \exp\left\{-0.5 \left[\frac{(\ln D - (B_0 + B_1 R + B_2 \ln R))^2}{C}\right]\right\}$$

(4.11)
Figure 4.8. Variation of the fit parameters $A$, $B$ and $C$ with rain rate during southwest monsoon season at Thiruvananthapuram.
The same analysis was done for all the four stations. The values of all the seven fit parameters in the above expression corresponding to each season for all the stations are shown in Table IV.III. By incorporating these values in the basic empirical model, the DSD corresponding to each season at each station can be derived.

<table>
<thead>
<tr>
<th>Station</th>
<th>Season</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A₀</td>
</tr>
<tr>
<td>Thiruvananthapuram</td>
<td>PRE</td>
<td>4.930</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>5.318</td>
</tr>
<tr>
<td></td>
<td>NE</td>
<td>4.968</td>
</tr>
<tr>
<td>Kochi</td>
<td>PRE</td>
<td>4.850</td>
</tr>
<tr>
<td></td>
<td>SW</td>
<td>5.080</td>
</tr>
<tr>
<td>SHAR ASO*</td>
<td></td>
<td>5.268</td>
</tr>
<tr>
<td>Munna r</td>
<td>SW</td>
<td>5.960</td>
</tr>
</tbody>
</table>

The values of most of the parameters are rather close to each other, except a few. With more data, it should be possible to reduce the scatter and improve the empirical model for DSD.

4.3.2. Validating the empirical model

In order to validate the empirical model derived, the model derived DSD values were compared with actual measurements. These actual measurements have not been used in deriving the model. Figures 4.9 to 4.15 show such comparisons for the stations Thiruvananthapuram, Kochi, Munnar and SHAR respectively for a few rain rates. The figures show a qualitative comparison. To evaluate the statistical significance of this comparison for all the rain rates, correlation between the model derived values and the actual measurements have been obtained.
Chapter IV: DSD-Characteristics and Empirical Model

Thiruvananthapuram

Pre monsoon

Figure 4.9. Comparison of the model with the observed DSD for the month of May 2005 at Thiruvananthapuram.
Southwest monsoon

Figure 4.10. Comparison of the model with the observed DSD for the month of June 2005 at Thiruvananthapuram.

R. Harikumar
Northeast monsoon

Figure 4.11. Comparison of the model with the observed DSD for the month of October 2005 at Thiruvananthapuram.
Kochi

Pre monsoon

Figure 4.12. Comparison of the model with the observed DSD for the month of May 2004 at Kochi.
Southwest monsoon

Figure 4.13. Comparison of the model with the observed DSD for the month of July 2004 at Kochi.
Munnar (Southwest Monsoon)

Figure 4.14. Comparison of the model with the observed DSD for the month of July 2004 at Munnar.
SHAR (August, September and October)

Figure 4.15. Comparison of the model with the observed DSD for the month of August 2003 at SHAR.

Figure 4.16 shows the correlation of the DSD derived from the empirical model with actual DSD data for all the rain rates for all the four stations. For all the stations, except SHAR and Kochi SW, the correlation coefficient is greater than 0.9. For SHAR, beyond 1 mm/h, correlation coefficient decreases as rain rate increases and reaches a minimum value of around 0.75. At Kochi during southwest monsoon season, correlation coefficient of 0.85 is shown for a rain rate of around 7 mm/h. The lowest correlation coefficient being 0.75 indicates that the empirical model represents the
DSD measurements well. This model can be improved further with more data available from these stations.

4.4. SUMMARY AND CONCLUSION

Rain DSD was observed using a JW type Disdrometer at four places, three of them coastal and one at an altitude of about 1500 m. The DSD data were divided into periods of different ranges of rain rate and fitted with the lognormal distribution function. The function fitted the data well, except in a few rare cases. The total number of drops, $N_T$, the geometric mean diameter, $D_{g}$, and the standard geometric deviation, $\sigma$
was derived from the fitted function. \( \sigma \) was found to be more or less constant for all rain rates. The other two parameters showed an exponential increase with rain rate, \( R \). At two sites, namely, Munnar and Thiruvananthapuram, \( N_T \) was found to behave differently from the other two. At Munnar, \( N_T \) increased initially and decreased beyond around \( R = 3 \text{ mm/h} \). At Thiruvananthapuram, \( N_T \) increased with rain rate up to some value of \( R \) that was different for different months. But above this value of \( R \), \( N_T \) remained more or less constant or decreased slightly. An interesting observation at Kochi is that \( N_T \) was rather low in the three months of May, June and July 2004 compared to that at 2003. Thus, for instance, for a rain rate of 3 mm/h, \( N_T \) was 366 in July 2003. But it came down to 138 in July 2004. \( D_\delta \), on the other hand, increased from 0.774 in July 2003 to 1.101 mm in July 2004. This indicates the possibility of rainfall being predominantly from convective clouds in 2003 at Kochi. The high convection in the year 2003 compared to 2004 is evidenced from the low NOAA-OLR value (OLR~199.827 W/m\(^2\)) during July 2003 compared to July 2004 (OLR~209.542 W/m\(^2\)) at Kochi.

It was found that, in spite of the different kinds of behaviour observed in \( N_T \), the function \( N_T D_\delta^3 \) increased linearly with rain rate. For SHAR, however, the variation was not strictly linear. The very different behaviour of \( N_T \) at Munnar could be attributed to the orographic effect. The situation in Thiruvananthapuram and Munnar is similar with respect to DSD. Since Thiruvananthapuram is closer to the Western Ghat mountains compared to Kochi, it is probable to expect an influence of the mountains on the rain DSD at this site. Grossman and Durran (1984) indicate that the influence of the Western Ghats could extend from 50 to 200 km to the windward side. Thiruvananthapuram is less than 50 km westward of the mountain. Thus we could expect the influence of mountain to be felt at Thiruvananthapuram also.

Since the rain DSD in this region could be best represented with the lognormal distribution function for all the rain rates, a lognormal empirical model has been derived for all the seasons for all the stations from where the data is available. The values of the lognormal distribution parameters are very close to each other in all

\( R. \text{ Harikumar} \)
the cases. The correlation between the DSD values derived using the empirical model and the actually measured DSD has been found to be generally good. The correlation coefficient between the DSD derived using the empirical model and the DSD data used for validation is greater than 0.9 for all the seasons for the stations with a few exceptions. For SHAR, as rain rate increases beyond 1 mm/h, the correlation coefficient decreases and reaches a value of around 0.75. For southwest monsoon season at Kochi, the correlation coefficient shows a low value of 0.85 for a rain rate of around 7 mm/h. This derived empirical model can give an average DSD for particular values of rain rate. With more data sets when available could be used to update the model to represent the DSD even better.

Fitting the lognormal distribution function to measured DSD thus seems to give some insight into differences and similarities in the behaviour of rain rate and clouds at different places. It is expected that this could lead to a better understanding of clouds in this region, especially monsoon clouds.