MAUSAM, **56**, 3 (July 2005), 643-658

551.577.23 (548.1)

Seasonal variability of raindrop size distribution over Cuddalore, a coastal station in Tamilnadu of southern peninsular India

R. SURESH and A. K. BHATNAGAR*

India Meteorological Department, Chennai - 600 001, India

**India Meteorological Department, New Delhi - 110 003, India*

(*Received 27 April 2004*)

सार – दक्षिणी प्रायद्वीपीय भारत के तमिलनाडु के उष्णकटिबंधीय तटीय क्षेत्र, कुड्डलूर (11.46°उ./79.46पू.) में मानसून से पूर्व (मार्च–मई), दक्षिण–पश्चिमी मानसून ऋतु (जून–सितंबर) और उत्तरी–पूर्वी मानसून (अक्तूबर – दिसंबर) के दौरान वर्षा होती है। यद्यपि मानूसन से पूर्व और दक्षिणी–पश्चिमी मानसून के दौरान अधिकतर वर्षा संवहनी होती है, तथापि उत्तरी–पूर्वी मानसून के दौरान अधिकतर वर्षा होती है। हालाँकि इन अवधियों में संवहनी और स्तरित दोनों ही प्रकार की वर्षा हो सकती है। इलेक्ट्रोमैकेनिकल डिस्ड्रोमीटर (जॉस–वाडवोगेल प्रकार के) से प्राप्त हुए आँकडों का उपयोग करते हुए कुड्डलूर में वर्षा ऋतु के दौरान वर्षा की बूँदों के आकार (डी. एस. डी.) में पाई गई विभिन्नताओं का अध्ययन किया गया है। स्तरित वर्षा में बूँदों का मॉडल आकार 2.0 मि.मी. से कम व्यास का होता है जबकि संवहनी वर्षा के दौरान अधिक व्यास (3 मि.मी. से भी अधिक) वाली बूँदों की काफी संभावना रहती है। मानसून से पूर्व की वर्षा के दौरान 3 मि.मी से बड़े आकार की बूँदों का औसत अधिकतम होता है जबकि उसके बाद आने वाली दक्षिणी–पश्चिमी मानसून वर्षा ऋतु में तीसरे पहर के दौरान मिश्रित और संवहनी धाराओं के कारण वर्षा की रफ्तार 10 मि.मी. प्रति घंटा होने पर बूँदों का आकार औसतन से अधिक हो जाता है। छोटे आकार की बूँदों (2 मि.मी. के व्यास से भी छोटे आकार की) का सांद्रण दक्षिणी–पश्चिमी मानसून की अपेक्षा उत्तरी पूर्वी मानसून के दौरान विशेष रूप से वर्षा की रफ्तार 8 मि.मी. प्रति घंटा से अधिक होने पर अधिक पाया जाता है क्योंकि उत्तरी–पूर्वी मानसून के दौरान या तो मंद अस्थिरता अथवा रात्रिकालीन स्थिरता वाली स्थितियों की प्रधानता के कारण उत्तरी–पूर्वी मानसून के दौरान सघन कण वास्तविक रूप से बड़ी बूँदों में बदल नहीं सकते हैं। संवहनी प्रकार के वर्षण की वर्षा स्तरित प्रकार के वर्षण से अधिक होती है। संवहनी स्थितियों के दौरान बूँदों के सांद्रण और वर्षा के बीच विपरीत संबंध का पता चला है जबकि स्तरित अवस्थाओं के दौरान उनके बीच रैखिक संबंध का पता चला है। लॉग प्रसामान्य बँटन उत्तरी–पूर्वी मानसून ऋतु के डी. एस. डी. (अधिकाँशतः स्तरित वर्षा) से अच्छा मेल खाता है। तथापि वर्ष 2003 के दौरान प्राप्त किए गए सीमित आँकडों के नमूनों के आधार पर (अधिकाँशत : संवहनी वर्षण) मानसून से पूर्व वर्षा और दक्षिणी–पश्चिमी मानसून ऋतु के दौरान की वर्षा की प्रति घंटा 10–50 मि.मी. की रफ्तार में कुछ विचलन पाया गया है।

ABSTRACT. Cuddalore (11.46° N / 79.46° E), a tropical coastal station in Tamilnadu of southern peninsular India receives precipitation from pre-monsoon (March – May), southwest monsoon (June – September) and northeast monsoon (October – December). While the precipitation during pre-monsoon (PM) and southwest monsoon (SWM) is mostly convective, that received during northeast monsoon (NEM) is mostly stratiform albeit a juxtaposition of both convective and stratiform is also feasible. The seasonal variability of raindrop size distribution (DSD) has been studied using the data obtained from electro-mechanical disdrometer (Joss-Waldvogel type) at Cuddalore. The modal drop size is less than 2.0 mm diameter in stratiform precipitation whereas drops of higher diameter (more than 3 mm) is quite probable in convective precipitation events. The mean concentration of rain drops of size more than 3 mm is highest during pre-monsoon followed by southwest monsoon in rain rates exceeding 10 mm h^{-1} due to rapid collision and coalescence taking place in afternoon mixing and convective currents. The concentration of smaller size drops (of size less than 2 mm dia) especially in rain rates exceeding 8 mm h^{-1} is more during NEM than the SWM because the condensed particles could not grow effectively into larger drops due to the prevalence of either weak instability or nocturnal stability conditions during NEM. Convective type precipitation has higher rain rates than the stratiform type. Inverse relationship between drop concentration and rain rate is seen during convective situations, while the relationship is linear during stratiform conditions. Lognormal distribution fits the DSD of northeast monsoon (mostly stratiform precipitation) extremely well. However, this fitting has some deviation in the rain rate 10-50 mm h^{-1} during pre-monsoon and southwest monsoon season (mostly convective precipitation) based on the limited data sample obtained during 2003.

Key words – Disdrometer, Drop size distribution, Log normal distribution, Exponential distribution, Rain rate, Radar reflectivity factor, Optical extinction.

1. Introduction

Describing the evolution of rain drop spectra and fitting the observations of the same through theoretical distributions and/or finding an analytical solution remains a challenging problem in cloud physics. The characteristics of the rain and the raindrop size distribution (DSD) and its moments are very important not

TABLE 1

Monthly rainfall and thunderstorm statistics of Cuddalore during October, 2002 – December, 2003 compared with climatology (1951-80)

Item	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					Climatological normal (1951-80)					
Rain (mm)	15.6	14.0	47.2	43.1	82.8	150.3	123.4	273.6	383.5	198.5
Rainy days	0.7	0.8	1.8	3.2	5.9	8.1	6.1	10.4	10.8	6.8
					Observation during October – December 2002					
Rain (mm)	-	-	-	-	-	-	-	188.5	297.5	130.4
Rainy days	-	-	-	-	-	-	-	14	13	2
Thunderstorm	-	-	-	-	-	-	-	10	2	1
					Observation during March – December 2003					
Rain (mm)	0.7	2.2	76.1	46.5	57.9	108.0	75.6	203.6	404.6	13.2
Rainy days	1	1	3	7	5	16	7	14	17	3
Thunderstorm	-	-	3	4	4	13	5	9	8	-

only for accurately estimating the rain rate but also due to their profound impact on the microwave propagation within the clouds besides the rain attenuation in different wave lengths. The most noteworthy contribution by Marshall and Palmer (1948) in fitting the DSD through an exponential distribution has been the pioneering study in rain drop size measurement and modeling. A two parameter exponential distribution was suggested by Srivastava (1978 and 1982). Other significant contribution in modeling DSD were made by Ulbrich (1983) by way of modified gamma distribution and log normal distribution by Feingold and Levin (1986). For a detailed discussion on the relative advantages and short comings of fitting DSD through various theoretical distributions, Atlas (1990), Sauvegeot (1991), Doviak and Zrnic (1993), Rinehart (1999) and Raghavan (2003) among others.

In the Indian context, the early work on DSDs using filter papers was carried out during late 1950s by Ramana Murty and Gupta (1959), Kelkar (1959) and Sivaramakrishnan (1961) over a few stations during southwest monsoon season (June – September) covering high altitude station (Poona in west coast), interior station (Delhi in north India) and Khandala (a port in west coast). A few studies have been conducted using the data received / obtained from optical rain gauge, Joss-Waldvogel disdrometer and the MST radar at Gadanki (13.5° N / 79.2° E, in Andhra Pradesh, about 130 km west-northwest of Chennai and about 190 km northwest of Cuddalore) to study the DSD during northeast and southwest monsoon season (Krishna Reddy and Toshiaki Kozu, 2003; Narayana Rao *et al*., 2001). However, no research work appears to have been carried out until 2002 on DSD over Tamilnadu which receives considerable rainfall from both northeast monsoon (NEM) during October - December and southwest monsoon (SWM) during June - September besides some convective rainfall during pre-monsoon (PM) during March - May. With the installation of a electromechanical type disdrometer devised by Joss and Waldvogel (1967; model RD 80 of M/s Disdromet Ltd., Switzerland) at Cuddalore (11.46° N/ 79.46° E, in Tamilnadu state) on 3rd April 2002, the DSD of a few rain spells during May, 2002 (covering pre-monsoon) and June – September, 2002 (covering southwest monsoon) was studied by Suresh *et al*. (2004) over this costal tropical station. In this paper, DSDs of PM, SWM and NEM rainfall have been critically analysed and the applicability of theoretical distributions to fit the DSDs have been discussed.

2. Data

Description of the disdrometer, its validation and testing etc. have been mentioned in Suresh *et al*. (2004). The disdrometer data have been classified into 20 classes of rain drops. The characteristics of various classes of rain drops have been furnished in Appendix A. From the drop size and concentration, one can compute rain rate (*R*), liquid water content (LWC), radar reflectivity factor (*Z*), kinetic energy flux (KEF), moment generating functions etc. using the relationships mentioned in the Appendix B. For a detailed description of the disdrometer and formulas used for computation of the above, Joss *et al*. (1978). Disdrometer data collected at one minute interval at Cuddalore meteorological observatory during the period October 2002 to December 2003 have been used in this study. The disdrometer was kept ON during the said period to receive data when the conditions were conducive

TABLE 2

Mean concentration of rain drops (per minute) of various classes during pre-monsoon, southwest and northeast monsoon over Cuddalore during 2002-2003

Rain rate (mm/hr)	Diameter (mm) 0 -1	1 - 2	2 - 3	3 - 4	4 -5	> 5
(a) Pre-Monsoon, 2003						
0 - 2	30.0	3.3	0.1	0.0	0	0
2 – 4	179.8	85.0	4.2	0.1	0	0
4 – 6	232.7	116.1	11.9	0.2	0	0
6 - 8	257.5	107.8	27.0	3.0	0	0
8 – 10	0	0	0	0	0	0
10 – 20	148.0	180.0	46.0	12.2	1.0	0
20 – 40	199.4	278.2	126.8	21.6	2.4	2.9
40 – 60	180.3	288.3	178.3	59.6	3.8	0.2
> 60	170.5	398.0	232.5	101.0	5.5	0
(b) Southwest monsoon, 2003						
0 - 2	43.66	5.54	0.17	0.01	0.00	0.00
2 – 4	220.74	64.74	7.10	0.71	0.05	0.00
4 – 6	268.25	125.72	7.03	0.88	0.15	0.00
6 - 8	202.62	152.54	22.61	0.85	0.07	0.00
8 – 10	220.0	197.8	30.4	1.20	0.00	0.00
10 – 20	239.88	216.36	45.76	6.84	0.92	0.12
20 – 40	119.41	132.91	56.59	12.39	0.95	18.65
40 – 60	270.13	511.39	207.97	37.77	2.64	1.90
> 60	239.41	495.59	223.06	37.76	1.47	39.53

(c) Northeast monsoon, 2002 and 2003

Rain rate (mm/hr)	Year	Diameter (mm) 0 -1	1 - 2	2 - 3	3 - 4	4 -5	> 5
0 – 2	2002	108.46	5.42	0.23	0.00	0.00	0.00
	2003	125.91	9.33	0.46	0.02	0.00	0.00
2 – 4	2002	322.62	59.01	4.31	0.18	0.00	0.00
	2003	259.06	59.82	4.74	0.26	0.02	0.00
4 – 6	2002	404.52	111.53	8.16	0.31	0.00	0.00
	2003	290.32	111.29	10.76	0.66	0.04	0.00
6 - 8	2002	415.61	152.54	15.11	0.94	0.03	0.00
	2003	324.65	153.45	16.90	1.06	0.02	0.00
8 – 10	2002	396.37	207.73	20.67	1.17	0.03	0.00
	2003	320.34	199.21	22.83	2.00	0.12	0.04
10 – 20	2002	485.73	326.79	35.84	1.73	0.04	0.00
	2003	358.39	309.82	40.79	3.09	0.24	0.03
20 – 40	2002	329.97	461.90	125.91	10.03	0.40	0.03
	2003	328.74	446.00	117.56	10.90	0.84	0.38
40 – 60	2002	286.24	541.29	240.22	31.40	1.07	0.03
	2003	338.60	542.53	223.93	35.90	2.55	0.16
> 60	2002	257.20	642.23	352.31	71.43	2.57	0.06
	2003	327.09	669.09	325.75	69.98	4.14	0.23

for rain spells. A few tens of thousands of records of one minute duration were available during the study period. These records have been scrutinised to filter out 'noisy' data, data pertaining to no rain event and to retain those records which have atleast 0.01 mm h^{-1} rain rate and / or accumulated precipitation during a rain event with atleast 0.1 mm. With these restrictions, we identified 8211 records during NEM, 2002 and 232 / 1332 / 8308 records during PM / SWM / NEM, 2003 respectively. The 24 hours accumulation of rainfall recorded by Cuddalore observatory during the said period has been considered for inter-comparison with the disdrometer estimated rainfall. The three hourly auxiliary surface synoptic observations (specifically cloud observation) have been consulted for identifying the convective/stratiform precipitation.

3. Methodology

The climatological normal rainfall and the number of rainy days in each month of Cuddalore observatory [India Meteorological Department (IMD), 1999] have been compared with October 2002 – December 2003, barring January – February 2003 and the results are tabulated in Table 1. We adopted a simple criteria that a rain event was considered convective if either thunder was heard or lightning recorded or Cb cloud was recorded by the Meteorological Observatory, Cuddalore. Using the above criteria, it can be seen that while all the rain events during May 2003 were convective, about 74% were convective during SWM 2003 and 45% (50%) were only convective during NEM 2002 (NEM 2003). Cuddalore, being a coastal station in the east coast of the peninsular India, experience mostly convective type precipitation during PM and SWM while the precipitation during NEM is a juxtaposition of both stratiform and convective type depending on the weather situations. This can be verified from the climatological thunderstorm frequencies of October 2002 – December 2003 (IMD, 1999). The earlier findings by Prasad (1970), *viz*., the precipitation during PM and SWM over the east coastal peninsular India has diurnal variability with maximum precipitation during afternoon (at times extending upto early morning) while the maximum precipitation during NEM season is realised during night and early morning have been found to be valid for Cuddalore during the study period. The climatological average clouding at 0300 and 1200 UTC also supports the above findings (IMD, 1999).

3.1. *Concentration of rain drops*

The mean concentration of rain drops of various classes have been computed for each minute for PM 2003, SWM 2003 and NEM 2002 & 2003 by grouping the individual classes into the range 0 – 1, 1 – 2, 2 – 3, 3 – 4, 4 – 5 and > 5 mm diameter. Table 2 summarises the

TABLE 3

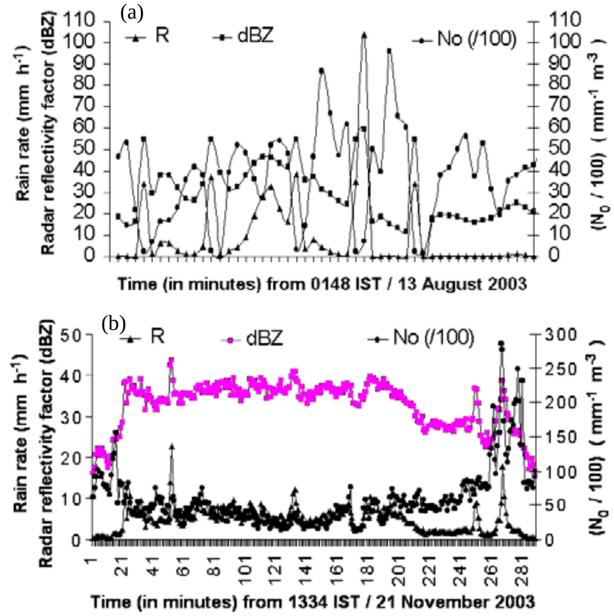
Mean value of maximum diameter of drops during 2002 – 2003 over Cuddalore

Rain rate (mm/hr)	PM 2002 *	SWM 2002 *	NEM 2002	PM 2003	SWM 2003	NEM 2003
0 – 2	1.54	1.39	1.186	1.171	1.294	1.090
2 – 4	2.47	2.84	2.361	2.459	2.402	2.408
4 – 6	2.34	2.54	2.501	2.644	2.675	2.677
6 – 8	3.06	2.37	2.774	3.143	2.942	2.842
8 – 10	2.58	2.99	2.894	3.544	3.022	2.987
10 – 20	3.41	3.36	2.947	4.171	3.668	3.114
20 – 40	3.61	3.98	3.552	4.248	4.895	3.619
40 – 60	--	5.03	4.067	4.583	4.273	4.189
> 60	--	4.35	4.366	4.604	4.639	4.467

* = Adopted from Suresh *et al.* (2004)

mean concentration of rain drops for various rain rate categories during the said period. Since all the three precipitation during PM were convective, the mean concentration of rain drops of size more than 3 mm in rain rates exceeding 10 mm h^{-1} was observed to be the highest of all the three seasons due to rapid collision and coalescence of drops. The concentration of smaller size drops (< 2 mm dia) especially in rain rates exceeding 8 mm h^{-1} is more during NEM than the SWM. This is so because during NEM, the precipitation is realised during late night or early morning during which period either weak instability and/or nocturnal stability conditions prevail based on the nearest upper air data from RS/RW observatory at Chennai (IMD, 1983; Suresh, 1998 and 2003) and hence the condensed particles could not grow effectively into larger drops by collection of cloud droplets. However, the concentration of larger drops (> 4 mm) is very high during SWM (wherein precipitation is realised mostly during afternoon or evening) since the drops grow in size with updrafts in view of the convective instability which normally prevails during summer afternoon. Since, both convective and stratiform precipitation are feasible in either season, the drop concentration in the range 2 – 4 mm are transitory in nature.

The mean value of maximum diameter of drops in each rain rate categories for all the three seasons have been worked out and presented in Table 3. For comparative purposes, the PM and SWM 2002 results (though both monsoons during 2002 received subdued rainfall and the number of rain spells were also relatively less) have been adopted from Suresh *et al.* (2004). From this Table also, it can be seen that the mean maximum drop size of different rain rate intensities during PM and SWM are higher than that of NEM.



Figs. 1(a&b). Variability of rain rate (*R*), radar reflectivity factor (dBZ) and concentration of rain drops (N_o) from (a) 0148 hrs (IST) / 13 August 2003 and (b) 1334 hrs (IST) / 21 November 2003 over Cuddalore

3.2. *Seasonal variability of rain rate*

The minute to minute variability of rain rate over a period of time is a well known problem in precipitation processes. Plots of rain rate (*R*), radar reflectivity factor (*Z*) estimated from the rain drops and the number concentration of various drop size (N_o, unit: m^{-3} mm^{-1}) for a 50 minutes duration from 0148 hrs (IST) on 13 August 2003 and for more than 280 minutes duration from 1334 hrs (IST) on 21 November 2003 have been shown in Fig. 1. The above sample have been selected to indicate the convective and stratiform type precipitation events. On 13 August Cuddalore observatory recorded 'thunder heard' at 0015 hrs (IST) though there was no rain upto 0117 hrs (IST). It is quite interesting to note that convective clouds were observed even during late night (instead of the preferred afternoon timings) on 13 August 2003 [Fig. 1(a)]. Fig. 1(b) is representative of a stratiform type precipitation during northeast monsoon.

On 13th August, the rain event over Cuddalore started only at 0118 hrs (IST) (an hour after hearing the thunder) and the rain rate from 0118 to 0147 hrs (IST) was varying between 1 and 5 mm h^{-1} with two spikes of 17 and 35 mm h^{-1} at 0132 and 0139 hrs (IST) respectively. However, the rain rate as high as 104 mm h^{-1} was observed at 0222 hrs (IST). In the stratiform precipitation, the rain rate was more or less uniform (less than 10 mm h^{-1}) in the long period of just over 280 minutes duration but for an occasional maximum of

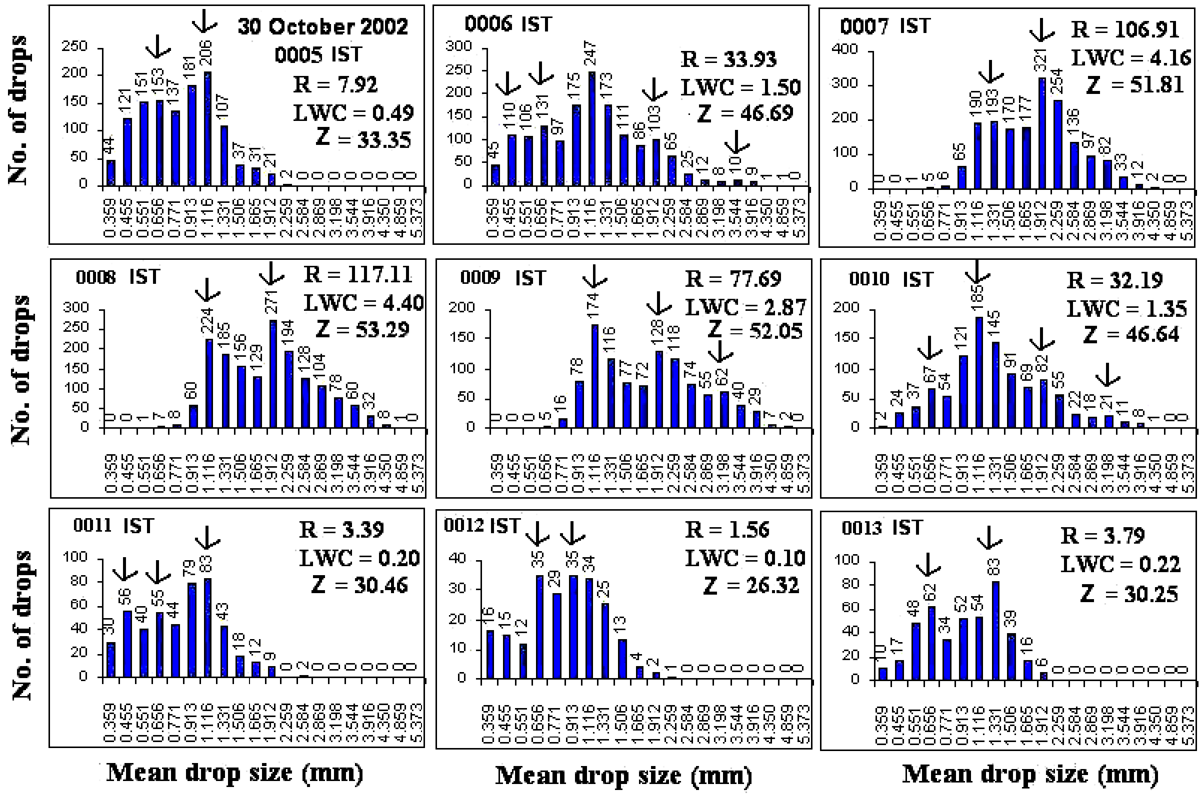


Fig. 2. Time series of concentration of rain drops of various sizes on a stratiform precipitation situation from 0005 to 0013 hrs (IST)/October 30, 2002. *R* is the rain rate (mm h^{-1}), LWC is the liquid water content (g m^{-3}) and *Z* is the radar reflectivity factor (dBZ). Modal classes have been marked with a downward arrow above the bars

just above 20 mm h^{-1}. As one normally expects, the minute to minute variability in *R* was very high during convective type precipitation than that from the stratiform type. From these two figures, one can observe that the convective type precipitation has higher rain rates while the stratiform type has lesser rain rates.

Though there exists a one to one relation between *Z* and *R*, as expected, an inverse relationship between N_o and *R* (so also with *Z*) can be clearly seen in convective situation [Fig. 1(a)]. As the value of N_o is very high, N_o / 100 has been plotted here for ease of readability. On a careful analysis, we could see that the higher values of *R* and *Z* have been resulted from the higher concentration of larger size drops (due to 'collision and coalescence' and 'collection efficiency') more specifically the drop size D_{18} to D_{20} while the low values of *R* and *Z* have resulted from the lower drop size classes (from D_1 to D_{10}). This is in accordance with the definition of convective type of precipitation, *viz*., 'the precipitation particles forming in an active updraft of a Cb cloud, growing primarily by the collection of cloud droplets (*i.e*., by coalescence and/or riming) and falling out' (Glickmann, 2000). Such an inverse relationship between N_o and *R* could not be seen in the case of stratiform precipitation, but the phase of both these curves are almost in the same direction indicating that a direct one-to-one relationship between them could be probable. The very high concentration of smaller rain drops (drop classes of less than D_9) during NEM could be the contributory cause for the maximum N_o. This indirectly confirms that the collision and coalescence mechanism was not quite active during NEM stratiform precipitation conditions. The surface meteorological observation of 21st November confirmed that neither towering Cu clouds nor lightning/thunder were observed during the entire day.

It is worth mentioning here that the rain accumulation from 0118 to 0300 hrs (IST) on 13th August by the conventional ordinary rain gauge and self recording rain gauges were 10.8 mm whereas that estimated from Disdrometer (integrating the minute to minute rain rate estimation by the Disdrometer) was 11.13 mm. In the stratiform type precipitation on 21st November, the

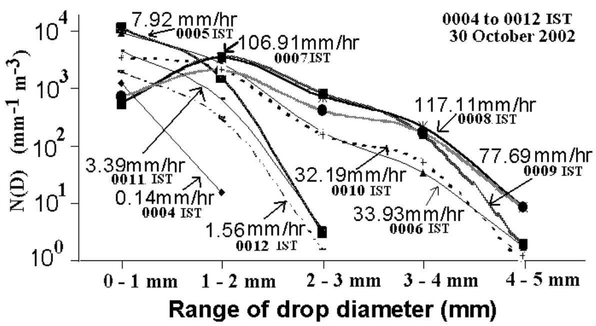


Fig. 3. Time evolution of a typical rain drop spectra of stratiform precipitation during northeast monsoon (from 0004 to 0012 hrs (IST) / 30 October 2002)

accumulated precipitation as estimated from Disdrometer data was 29.48 mm as against ordinary rain gauge value of 35.8 mm. The difference in this case is due to the fact that the Disdrometer records were available only from 1300 hrs (IST) and the Disdrometer could not record data from 0300 to 1300 hrs (IST) due to power failure during which period about 5 mm rainfall had realised. Nonetheless, it is evident that the accumulated rain from the Disdrometer estimation of rain rate compares reasonably well the measured rainfall. Similar comparisons were made earlier by Suresh *et al*. (2004) which also certifies the usability of Disdrometer for rain rate studies over Cuddalore.

3.3. *Modes of drop size distributions*

3.3.1. *Stratiform precipitation*

The concentration of rain drops of different classes on a stratiform precipitation have been shown in Fig. 2 for the period 0005 to 0013 hrs (IST) of 30 October 2002 (date and time selected at random) to identify modal rain drop class(es), if any, of the DSD. The mean diameter of each class has been furnished in the abscissa. We adapted the following criteria adopted by Sauvageot and Koffi (2000) to identify the modes. *i.e.*, if n_i is the number of drops in class i of DSD (where i = 1,2,3,..,,20 represents the different rain drop classes defined in Appendix A), then n_i is the mode of class i provided $(n_i - n_{i-1}) \geq 1$ and $(n_i - n_{i+1}) \geq 1$. The plot reveals that the DSD is multi-modal. Rain drop classes D_4 (mean diameter 0.656 mm) and class D_7 (1.116 mm) have the highest occurrences of 6 minutes in this 9 minutes interval followed by D_{11} (1.912 mm) class with a frequency of 5. This is in conformity with Sauvageot and Koffi (2000) that the modal class of the drop size of this tropical stratiform precipitation is less 2 mm.

It may be seen from the Fig. 2 that the liquid water content (LWC) has increased from 1.50 g m^{-3} at 0006 hrs (IST) to 4.40 g m^{-3} at 0008 hrs (IST) and then dropped to 1.35 g m^{-3} at 0010 hrs (IST) during which period R has increased from 33.93 mm h^{-1} to 117.11 mm h^{-1} and dropped to 32.19 mm h^{-1} respectively. The time evolution of rain drop spectra has been depicted in Fig. 3. It may also be noted that rapid collection efficiency has increased the rain rate of 7.92 mm h^{-1} at 0005 hrs (IST) to 33.93 mm h^{-1} at 0006 hrs (IST) and thereafter to 106.91 and 117.11 mm h^{-1} at 0007 and 0008 hrs (IST) respectively. The increase in size of the rain drops beyond 3 mm has increased both LWC and rain rate. The break up of drops after 0010 hrs (IST) may explain the reduction in LWC as well as the rain rate.

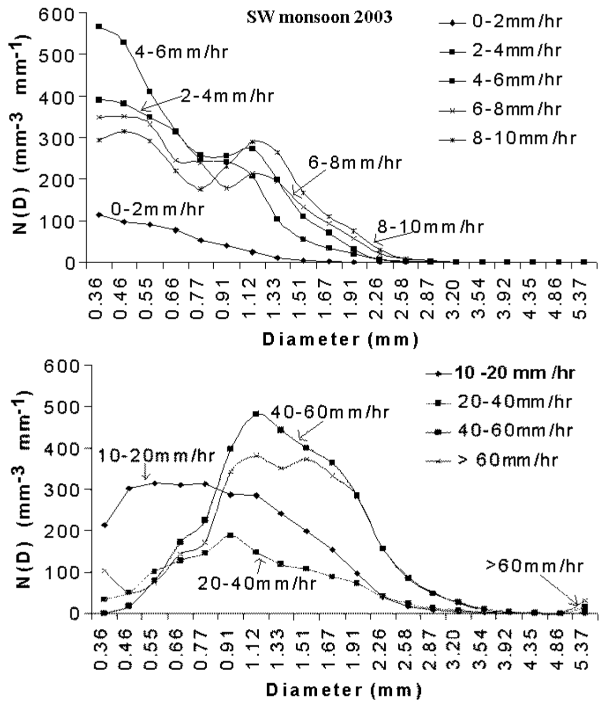
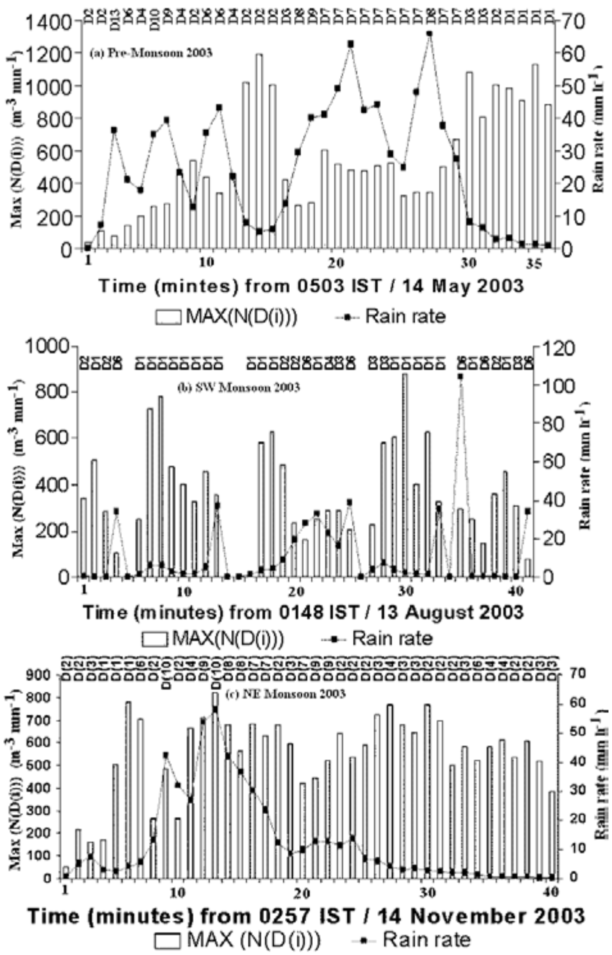


Fig. 4. Mean concentration of various classes of rain drops during southwest monsoon, 2003

3.3.2. *Convective precipitation*

In the convective precipitation situations, the modal class of the rain drops were invariably noticed in the higher drop sizes (exceeding 2 mm). Fig. 4 shows the mean drop concentration of various rain drop classes for the convective rain rates for the SWM 2003. Two mean modal classes (0.359 and 1.116 mm) have been seen in the low rain rate categories (R < 10 mm h^{-1}) and the concentration of smaller drops is very high similar to the stratiform type precipitation events. Also it may be noted that the concentration of drops of size exceeding 3 mm are nearly absent in this category. However, in regard to high rain rate categories (R > 10 mm h^{-1}), the mean modal class is between 0.913 and 1.506 mm and the concentration of higher drop size (> 2 mm diameter) is very high.



Figs. 5(a-c). Plot of maximum of $N[D(i)]$ *vis-à-vis* rain rate over a few rain spells during (a) pre-monsoon, (b) southwest and (c) northeast monsoon season, 2003 over Cuddalore

3.3.3. *Juxtaposition of convective and stratiform precipitation*

In some situations, both convective and stratiform precipitation could be possible over a period of rain events. $N[D(i)]$ has been computed for each rain drop class (i = 1,2,3,..n) using the formula furnished in appendix B and the maximum of $N[D(i)]$ has been worked out for each minute. Fig. 5 shows the plot of max $N[D(i)]$ *vis-à-vis* rain rate on a few days representing PM, SWM and NEM season. The bar indicates the max $N[D(i)]$ and line graph indicates rain rate at that minute. The modal drop class (Di) for each rain rate has been placed atop the bar.

On 14 May 2003, there was no rain prior to 0503 hrs (IST) though the thunderstorm was recorded by Cuddalore observatory at 0500 hrs (IST). The modal rain drop class was D_7 (1.116 mm dia) and D_{13} (2.584 mm dia) was the highest rain drop class having max $N[D(i)]$ on this rain spell. The rain event on 13 August 2003 has been considered as a mixture of both convective and stratiform type precipitation since the size of the modal rain drop class vary between D_1 (0.313 mm dia) and D_6 (0.913 mm) only. Though thunder was heard at 0015 hrs (IST), the rain spell started only after an hour or so and that too of smaller intensity suggesting that enough convection had not taken place when the rain event was observed over Cuddalore. The very small size of the modal rain drop class between 0148 and 0219 hrs (IST) also suggest that the collision and coalescence efficiency during this period could not be convective but could be stratiform. The rainfall on 14 November 2003 during NEM 2003 has D_2 as the modal class (0.405 mm dia) and the highest modal drop class was D_{10} (1.665 mm dia). Thunder was heard at 0300 hrs (IST). Though there were contribution by drops of higher sizes D_{12} to D_{20}, the modal drop size class was less than 2 mm only which supports the earlier finding by Sauvageot and Koffi (2000) that the modal class of tropical rain lies between 1 and 2 mm only.

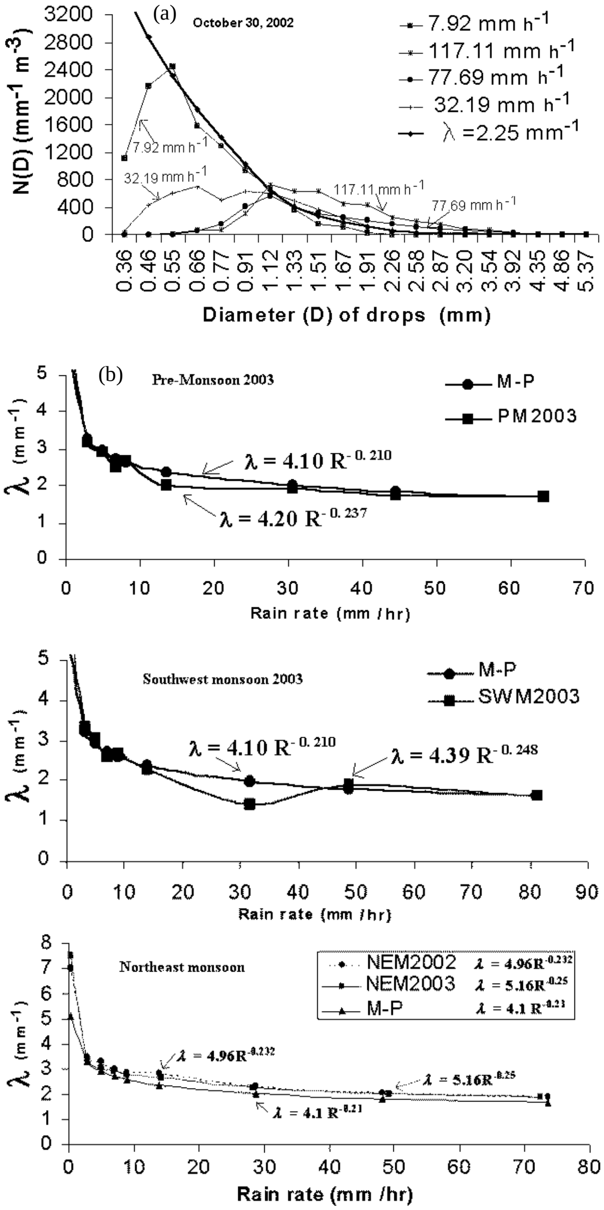
4. Theoretical distributions

The competing effects of collection, collision and coalescence processes can be approximated through an exponential relationship using a simple parameterization, *viz*.,

$$N(D) = N_o\, e^{-\lambda D} \tag{1}$$

where N_o is a parameter indicating the concentration of drops with diameter o and slope λ. Relationship between $N(D)$ and R, LWC, radar reflectivity factor (z), slope (λ) and kinetic energy flux (KEF) have been established by Gunn and Kinzer (1949), Joss and Waldvogel (1967) and Joss *et al.* (1978). The above relationships have been shown in Appendix B.

Brown and Whittlesey (1992) extended the parameterization of collisional break-up proposed by Low and List (1982) by fitting the DSD of the form $N(D,R) = R\ \psi(D)$ where $\psi(D)$ is a generic function independent of R. If this fitting is valid, then the ratio $\int_{D_{\min}}^{D_1} N(D)\mathrm{d}D \;/\; \int_{D_1}^{D_{\max}} N(D)\mathrm{d}D$ would be a constant for an arbitrary value of D_1. But our computation of this ratio during the study period (Figures not shown) revealed that this ratio is no longer a constant but strongly dependent upon R for arbitrary value of $1 < D_1 < 2$ mm. Similar results have been



Figs. 6(a&b). (a) Variability of $N(D)$ with D during northeast monsoon 2002 over Cuddalore and (b) Variability of rain rate *vis-à-vis* slope of the exponential distribution for pre-monsoon, southwest monsoon and northeast monsoon season over Cuddalore during 2003

arrived at by Sauvageot and Lacaux (1995) with D_1 = 1.7 mm. Hence, this type of DSD is not considered in this study.

4.1. *Exponential distribution*

Marshall and Palmer (1948), hereafter referred to as M – P relationship, used filter paper technique to fit the DSD into an exponential distribution of form (1) and obtained a relation with N_o = 8000 mm^{-1} m^{-3} between the slope λ and rainrate R as

$$\lambda = 4.1\, R^{-0.21} \qquad (2)$$

Since then a number of relationships between λ and R have been obtained throughout the world and the fitting of this form has been adjudged as mixed success (Atlas, 1990; Doviak and Zrnic, 1993; Rinehart, 1999). As λ goes on decreasing with R and for $D < D_c$, where D_c is the threshold diameter varying with R, there is no stationary shape in that area of DSD (Willis and Tattleman, 1989). Sauvageot and Lacaux (1995) give a plausible reason for this as 'the depletion of small drops by coalescence is not totally compensated for by the production of breakup'. The λ of DSD for $D > D_c$ is normally constant and does not appear to vary much with R. Fig 6(a) shows the variation of $N(D)$ with D for different rain rates on 30 October 2002. We infer that for R < 10 mm h^{-1}, $D_c \approx$ 0.66 mm; for 10 < R < 100 mm h^{-1} , $D_c \approx$ 1.0 mm and for R > 100 mm h^{-1}, $D_c \approx$ 2.0 mm. The Disdrometer derived λ and R data have been fitted to have the relationship of the form (2) for the mean values of different rain rate categories for PM, SWM and NEM 2003 and shown in Fig. 6(b). All the three seasonal distributions fit well with the M-P relation except in 10-30 mm h^{-1} rain rate category. PM has slight deviation between 10 and 30 mm h^{-1} and in respect of SWM the deviation is more between 10 and 40 mm h^{-1}. Beyond 30 mm h^{-1} (specifically beyond 50 mm/hr) R *versus* λ follows M-P relationship in both PM and SWM. However the agreement is very good in NE monsoon (wherein stratiform precipitation is more) even in the low rain rates (less than 10 mm h^{-1}) and a fixed bias from the M–P relationship is seen in both NEM 2002 and 2003.

TABLE 4

The concentration of rain drops, slope of the exponential distribution, radar reflectivity factor and liquid water content as a function of rain rate over Cuddalore during different seasons

Parameter	NEM 2002	PM 2003	SWM 2003	NEM 2003
Slope λ	4.96 $R^{-0.232}$ CC = -0.99	4.202 $R^{-0.237}$ CC = -0.99	4.394 $R^{-0.25}$ CC = -0.96	5.16 $R^{-0.25}$ CC = -0.98
Concentration N_o	22429.0 $R^{-0.126}$ CC = -0.41	3730.2 $R^{0.157}$ CC = 0.73	5128.0 $R^{0.111}$ CC = 0.39	8136.6 $R^{0.113}$ CC = 0.94
N_o / λ	3328.0 $R^{0.211}$ CC = 0.71	1496.7 $R^{0.21}$ CC = 0.87	1495.4 $R^{0.21}$ CC = 0.87	2131.4 $R^{0.266}$ CC = 0.99
Radar reflectivity factor (z)	106.8 $R^{1.78}$ CC = 0.95	96.7 $R^{1.83}$ CC = 0.99	97.2 $R^{1.83}$ CC = 0.99	54.3 $R^{1.89}$ CC = 0.93
Liquid water content (LWC)	0.066 $R^{0.88}$ CC = 0.99	0.0573 $R^{0.90}$ CC = 0.99	0.0863 $R^{0.89}$ CC = 0.79	0.06 $R^{0.895}$ CC = 0.99

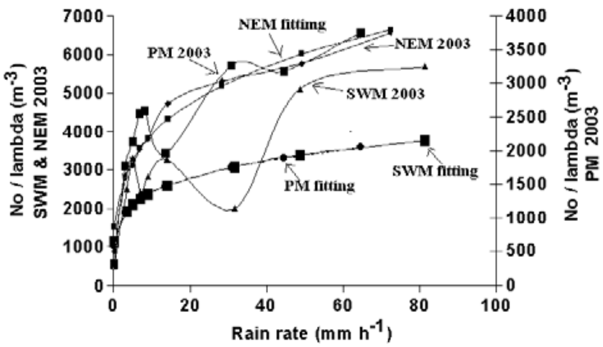


Fig. 7. Plots of N_o / λ *vis-à-vis* R (observed and fittings) during pre-monsoon, southwest and northeast monsoon season, 2003

N_o has wide variability with R and its correlation coefficient (CC) is opposite in sign even between NEM 2002 and NEM 2003. In order to find as to whether exponential relationship exists between N_o and R, we computed N_o/λ for each rain rate category and a exponential curve fitting was made for each season. Table 4 summarises the relationships between R and λ, N_o, N_o / λ, z and LWC for PM 2003, SWM 2003 and NEM 2002 and 2003. The correlation coefficients (CC) have also been furnished for each fitting. The fittings are rather very tight with R (CC close to unity) but for the fitting between N_o and R during NEM 2002. Fig. 7 depicts the variability of N_o/λ with R. The exponential fitting appears to fit well during NEM 2003 since the variability between observed and theoretical (N_o/λ) is very less. The fitting is somewhat reasonable in PM 2003 but it deviates markedly from the observation during SWM 2003 in higher rain rates exceeding 10 mm h^{-1}. The SWM 2003 ($N_o / \lambda = 1495.4\ R^{0.21}$) and PM2003 ($N_o / \lambda = 1496.7\ R^{0.21}$) has more or less the same fitting where as for NEM 2003 the fitting $N_o / \lambda = 2131.4\ R^{0.266}$ differs significantly even from its previous year's fitting, *viz*., NEM 2002 ($N_o / \lambda = 3328\ R^{0.211}$).

Sauvageot and Lacaux (1995) opined that the ratio N_o / λ is the zeroth moment of the exponential distribution (1) and is equal to the total number of drops of the distribution. It is interesting to note that in the rain rate exceeding 10 mm h^{-1}, the SWM 2003 does not follow the exponential distribution presumably because of the intense collision and coalescence process during strong afternoon convective currents. However, a minimum deviation from the fitting is only observed during PM 2003 wherein also the convective currents play a vital role in the precipitation mechanism. Since the sample during PM 2003 is very small and rain intensity was very less during this season, a definite conclusion is plausible only after studying more rain events with higher rain intensity in the ensuing years.

4.2. *Lognormal distribution*

It has been observed by many researchers that high concentration of small drops (diameters less than 0.595mm) of drop size classes D_1 to D_3 are associated with low rain rates of less than 20 mm h^{-1} and the concentration of theses small drops is very low in comparison to the other classes for rain rates exceeding 20 mm h^{-1} (Fig. 5). Three parameter gamma distribution (Ulbrich, 1983) and lognormal distribution (Feingold and Levin, 1986) have been considered by the researchers in order to quantify the shape of the distribution, precisely to accommodate the small drop quantities for higher rain rates. In the gamma distribution, the deviations from the exponential are expressed in terms of the curvature parameter μ. However the relative dependence of one of the parameter (N_o) with the other (μ) causes serious inconvenience in using the modified gamma distribution (Feingold and Levin, 1986 and Chandrasekar and Bringi, 1987). Moreover, since the exponential distribution is a limiting case of gamma distribution (μ = 0) and the fitting through exponential distribution has some errors in the rain rate 20-50 mm h^{-1}, we confined our attempt to fit the DSD to lognormal distribution function only in this paper because of its simplicity, ease of geometrical interpretation besides the fact that its moment generating function can by written in the form of multiplication of three terms concerning only with one parameter (in our case the R). Sauvageot and Lacaux (1995) gives a good account of the lognormal distribution as applicable to DSD.

4.2.1. *Fitting DSD through log-normal distribution*

The lognormal distribution function can be written as

$$N(D) = [N_T / \{(2\pi)^{0.5}\ \mathrm{Ln}(\sigma) D\}] * \exp[-\mathrm{Ln}^2 (D / D_g) / \{2\mathrm{Ln}^2 (\sigma)\}] \quad (3)$$

where σ is the standard geometrical deviation of drop diameter D, D_g is the mean geometrical diameter and N_T is the total number of drops. These three parameters can be obtained from the following relations.

$$N_T = \int_0^\infty N(D)\, \mathrm{d}D \quad (4)$$

$$\mathrm{Ln}(D_g) = \overline{\mathrm{Ln}(D)} \quad (5)$$

$$\mathrm{Ln}^2(\sigma) = \overline{\{\mathrm{Ln}(D) - \mathrm{Ln}(D_g)\}^2} \quad (6)$$

TABLE 5

Mean values of the three parameters of log normal distribution and rain rate. The length of one minute interval data record used to compute the mean values has also be given in the 'frequency' column

Rain rate (*R*) (mm h^{-1})	Season	Mean *R* (mm h^{-1})	D_g	σ	N_T	Frequency
0-2	NEM 2002	0.346	1.022	1.754	170.71	5712
	NEM 2003	0.277	0.909	1.841	93.88	7631
	PM 2003	0.176	0.999	1.778	43.43	177
	SWM 2003	0.276	1.126	1.735	59.65	1074
2-4	NEM 2002	2.848	2.288	1.293	449.23	783
	NEM 2003	3.997	2.234	1.224	573.90	710
	PM 2003	3.010	2.403	1.231	278.69	10
	SWM 2003	3.321	2.324	1.283	302.34	62
4-6	NEM 2002	4.933	2.439	1.255	552.36	401
	NEM 2003	4.994	2.607	1.258	409.40	381
	PM 2003	4.965	2.621	1.140	349.85	9
	SWM 2003	4.964	2.569	1.318	398.60	40
6-8	NEM 2002	6.964	2.698	1.267	571.78	285
	NEM 2003	6.870	2.773	1.248	470.90	220
	PM 2003	6.871	3.084	1.219	392.17	4
	SWM 2003	7.036	2.854	1.273	337.30	13
8-10	NEM 2002	8.902	2.837	1.220	569.60	183
	NEM 2003	8.932	2.907	1.257	490.91	134
	PM 2003	8.108	3.544	1.000	673.95	1
	SWM 2003	8.969	2.997	1.135	373.24	5
10-20	NEM 2002	13.860	2.890	1.229	761.27	365
	NEM 2003	14.132	3.305	1.200	593.21	303
	PM 2003	13.611	4.136	1.140	292.87	6
	SWM 2003	14.054	3.565	1.268	426.62	24
	NEM 2002	28.730	3.499	1.186	655.95	257
20-40	NEM 2003	28.282	3.563	1.191	652.42	227
	PM 2003	30.596	4.187	1.188	420.19	13
	SWM 2003	31.641	4.847	1.155	232.21	66
40-60	NEM 2002	48.090	4.031	1.142	698.24	118
	NEM 2003	49.140	4.149	1.147	748.61	98
	PM 2003	44.439	4.548	1.134	433.92	10
	SWM 2003	48.824	4.241	1.130	649.12	31
> 60	NEM 2002	73.511	4.344	1.104	783.58	35
	NEM 2003	72.384	4.430	1.138	589.03	44
	PM 2003	64.558	4.597	1.057	521.35	2
	SWM 2003	81.220	4.591	1.157	604.63	18

The three parameters N_T, σ and D_g have been computed and their mean values for various rain rates for different seasons have been furnished in Table 5. In some rain rate categories, the length of Disdrometer data (frequency) is very low and hence definite conclusions about the mean values of these parameters from those poor sample could not be drawn. Nevertheless, with the available data, we have fitted analytic functions between these parameters and *R*. The fittings have been shown in Fig. 8.

From Table 5 and Fig. 8, one can see that N_T, the total number of drops, increases as a function of *R* with its derivative decreasing [*i.e.*,$N_T = f(R^n)$ where $0 < n < 1$]. For a given *R*, N_T is the highest for NEM in comparison to SWM and PM. This is so because that the precipitation from NEM is mostly stratiform and hence the number of smaller drops is maximum. The value of N_T is the least for almost all *R* during PM, albeit we have very little sample data during PM, presumably because of collection efficiency and concentration of larger drops due to convectional currents prevailing during this period. Oscillation from its perfect monotonic increase relationship could be seen between 10 and 50 mm h^{-1} rain rate categories during SWM. During NEM, we observed that D_g was increasing with R^n where $0 < n < 1$ and the increase in almost monotonic. However, such a smooth increase could not be seen in PM and SWM. σ, the standard geometrical deviation of *D*, does not vary significantly with *R*. This is in agreement with some of the earlier results using log normal distribution over tropical coastal Africa (Sauvageot and Lacaux, 1995). The mean maximum value of D_g for any *R* was observed mostly in PM which again reconfirms that the intense collision and coalescence process in convective currents accelerate the growth of larger rain drops and thereby the concentration of higher drops was more during this season. The NEM fitting is rather smooth than the other two. In general, the log normal distribution fits well for NEM for all rain rates and this fitting does not support the rain rate between 10 and 50 mm h^{-1} in respect of PM and SWM based on the limited and subdued rain spells during these seasons in 2003.

4.2.2. *Moment generating functions of log-normal distribution*

As discussed in section 4.2.1., the parameters N_T , D_g have been expressed by power functions of *R* and σ has been fitted linearly with *R* in view of its lesser variability with *R*. The relationships between these parameters have been presented in Table 6. According to Sauvageot and Lacaux (1995), the moment generating function (MGF) of lognormal distribution can be written as

$$m_n = N_T\, D_g^{\,n}\, \exp[(n^2/2)\, \mathrm{Ln}^2(\sigma)] \qquad (7)$$

The exponential in the MGF, *viz*., $H_n = \exp[(n^2/2)\, \mathrm{Ln}^2(\sigma)]$, has been found to vary as a power of *R*. The advantage of this relationship is that for a choice of *n*, one can get the estimates of optical extinction (n = 2), liquid water content (n = 3), rain rate (n = 3.67) and radar reflectivity factor (n = 6). These relationships have been furnished in Table 6. The correlation coefficients are very tight (≈ 1) and the sign and order are matching well with the already documented results of Chandrasekar and Bringi (1987) and Sauvageot and Lacuax (1995; 2002, personal communication). Since the exponential of MGF is expressed as power of $R\left(H_n \propto R^{b_n}\right)$, it is convenient to express the MGF in the form

$$m_n = N_T(R) * D_g^n(R) * H_n(R) = a_n\, R^{b_n} \qquad (8)$$

where a_n and b_n are coefficients to be worked out so that moments can be expressed in terms of *R* with a simple power relation for different values of *n*. For a detailed discussion on the relationship between *R* and fall velocity, mean drop diameter, LWC, radar reflectivity factor etc., Doviak and Zrnic (1993) and Atlas and Ulbrich (1977).

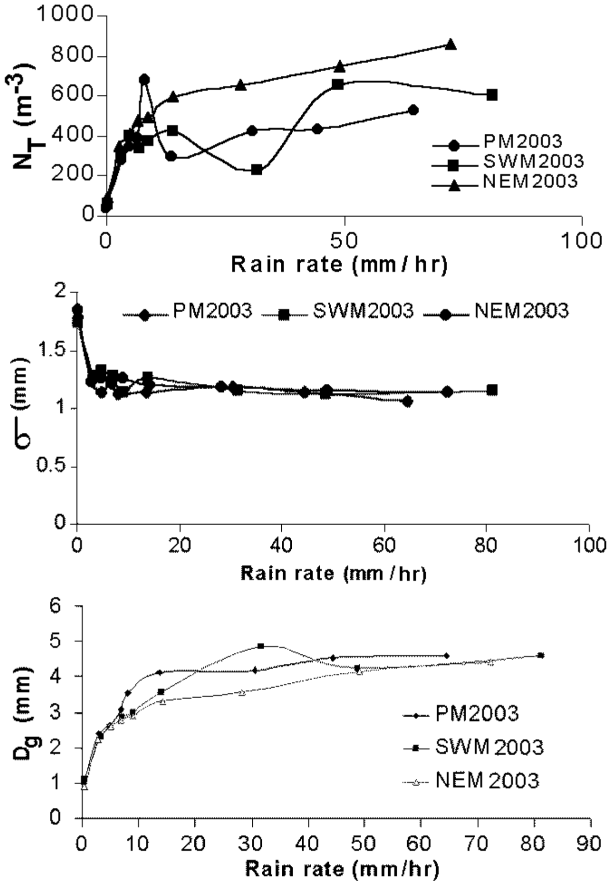


Fig. 8. Parameters of log normal distribution as functions of rain rate for pre-monsoon, southwest monsoon and northeast monsoon season, 2003 over Cuddalore

Since the integral rainfall parameters of interest such as rain rate, radar reflectivity factor, I_n, are proportional to the MGF, I_n can be expressed as

$$I_n = C_n * m_n = C_n * a_n * R^{b_n} \qquad (9)$$

where C_n is a coefficient to be estimated. The rain rate (*R*) is proportional $I_{3.67}$, if the terminal velocity of the drops in still air is $V(D) = 3.78\, D^{0.67}$ with *D* in mm and $V(D)$ in ms^{-1} (Atlas and Ulbrich, 1977). Hence, one can expect that $C_{3.67} * a_{3.67} \approx 1$ and $b_{3.67} \approx 1$ if our assumptions are correct. In order to verify this, we have estimated the coefficients C_n, a_n and b_n for all the seasons and the results have been presented in Table 7. While the coefficients $C_{3.67} * a_{3.67} = 1.005$ and $b_{3.67} = 1.007$ are very close to unity in respect of NEM 2003, these coefficients

TABLE 6

Analytical functions / relationships between parameters of log normal distribution and rain rate

Parameter	NEM 2002	PM 2003	SWM 2003	NEM 2003
N_T	$302.03\ R^{0.26}$ CC = 0.91	$141.7\ R^{0.38}$ CC = 0.85	$146.37\ R^{0.35}$ CC = 0.84	$210.8\ R^{0.367}$ CC = 0.93
D_g	$1.535\ R^{0.256}$ CC = 0.98	$1.757\ R^{0.266}$ CC = 0.58	$1.677\ R^{0.26}$ CC = 0.98	$1.48\ R^{0.279}$ CC = 0.98
σ	$1.366 - 0.0048\ R$ CC = - 0.54	$1.288 - 0.0041\ R$ CC = - 0.41	$1.348 - 0.0035\ R$ CC = - 0.51	$1.368 - 0.0043\ R$ CC = -0.49
z	$106.84\ R^{1.776}$ CC = 0.95	$96.72\ R^{1.83}$ CC = 0.99	$97.19\ R^{1.827}$ CC = 0.99	$54.3\ R^{1.887}$ CC = 0.98
H_2	$1.43\ R^{-0.99}$ CC = - 0.86	$1.37\ R^{-0.099}$ CC = - 0.846	$1.41\ R^{-0.93}$ CC = - 0.87	$1.50\ R^{-0.116}$ CC = - 0.86
H_3	$2.29\ R^{-0.24}$ CC = - 0.88	$1.188\ R^{-0.031}$ CC = - 0.49	$2.178\ R^{-0.21}$ CC = - 0.87	$2.50\ R^{-0.26}$ CC = - 0.86
$H_{3.67}$	$3.36\ R^{-0.34}$ CC = - 0.86	$1.24\ R^{-0.014}$ CC = - 0.08	$3.32\ R^{-0.315}$ CC = - 0.87	$1.59\ R^{-0.081}$ CC = - 0.91
H_6	$4.39\ R^{-0.297}$ CC = - 0.98	$1.82\ R^{-0.041}$ CC = - 0.09	$22.73\ R^{-0.84}$ CC = - 0.87	$3.49\ R^{-0.216}$ CC = - 0.90
I_2	$5.3\ R^{0.51}$ CC = 0.99	$4.26\ R^{0.578}$ CC = 0.98	$4.22\ R^{0.586}$ CC = 0.96	$2.03\ R^{0.821}$ CC = 0.99
I_3	$3.13\ R^{0.67}$ CC = 0.99	$2.11\ R^{0.78}$ CC = 0.98	$2.24\ R^{0.776}$ CC = 0.98	$1.27\ R^{0.95}$ CC = 0.99
$I_{3.67}$	$2.23\ R^{0.77}$ CC = 0.99	$1.43\ R^{0.91}$ CC = 0.97	$1.21\ R^{0.665}$ CC = 0.96	$1.005\ R^{1.007}$ CC = 0.95
I_6	$0.80\ R^{1.05}$ CC = 0.99	$0.324\ R^{1.33}$ CC = 0.96	$0.345\ R^{1.24}$ CC = 0.96	$0.798\ R^{0.997}$ CC = 0.96

TABLE 7

Relationship between moment generating function of log normal distribution with rain rate($m_{3.67}$), radar reflectivity factor (m_6), liquid water content(m_3) and optical extinction (m_2)

Seasons	Moment of the log normal distribution (m_n)	Coefficients of moment generating function of log normal distribution			
		a_n	b_n	C_n	$C_n * a_n$
Pre-monsoon 2003	m_2	1064.9	0.578	0.0040	4.26
	m_3	2344.7	0.779	0.0009	2.110
	$m_{3.67}$	4091.9	0.908	0.0003	1.426
	m_6	33262.4	1.33	0.0000097	0.324
Southwest monsoon 2003	m_2	1025.3	0.587	0.00412	4.22
	m_3	2318.7	0.776	0.00097	2.24
	$m_{3.67}$	3416.2	0.665	0.00035	1.21
	m_6	44705.2	1.24	$7.7 * 10^{-6}$	0.345
Northeast monsoon 2003	m_2	637.5	0.821	0.00318	2.027
	m_3	1578.2	0.952	0.000804	1.269
	$m_{3.67}$	3249.2	1.007	0.000311	1.005
	m_6	81432.7	0.997	$9.81 * 10^{-6}$	0.798

depart far from unity during SWM and PM 2003 suggesting that the estimation of rain rate from MGF of log-normal distribution appears to be quite valid for NEM rather than the other two monsoons. One probable reason for this could be that the total number of drops used for estimation during NEM is very much higher than the other two monsoons and in view of large sample the fittings are close to the theoretical considerations. Rainrate has been estimated using $m_{3.67}$ and compared with the Disdrometer recorded value during NEM 2003 using χ^2 test and found

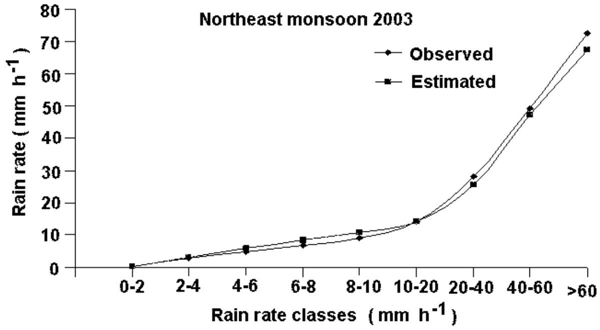


Fig. 9. Comparison of mean values of rain rate estimated from $m_{3.67}$ with that measured through Disdrometer at Cuddalore during northeast monsoon 2003

TABLE 8

***Z – R* relationship during northeast monsoon season, 2002 over Cuddalore**

Rain rate (mm h^{-1})	Data records used	*Z – R* relationship
0 – 2	2400	194.9 $R^{1.23}$
2 – 4	783	251.1 $R^{1.31}$
4 – 6	401	212.0 $R^{1.37}$
6 – 8	285	65.9 $R^{2.01}$
8 – 10	183	689.3 $R^{0.86}$
10 – 20	365	157.6 $R^{1.46}$
20 – 40	257	55.8 $R^{1.80}$
40 – 60	118	76.7 $R^{1.69}$
> 60	35	134.5 $R^{1.54}$
Overall	4827	106.8 $R^{1.78}$

that the fit is significant at 99.9% level of significance. A plot of mean values of rain rate observed and estimated from $m_{3.67}$ during NEM 2003 has been shown in Fig. 9. Though the estimation through $m_{3.67}$ is promising and certifying the worthiness of log-normal distribution during northeast monsoon season, the fitting through log normal needs to be checked in the ensuing years not only for NEM but also during pre-monsoon and southwest monsoon seasons based on large volume of Disdrometer data before arriving at a meaningful conclusion on the usability of this distribution.

4.2.3. *Variability of relationship between z and R*

One primary reason for the failure of any theoretical distribution to fit the DSD is perhaps due to the highly variable nature of the relationship between *z* and *R*. The inter- and intra- seasonal variability of rain rates have been well documented in literature and thousands of *z – R* relationships are available thro' the world. We have subjected the NEM 2002 data (since this season had fairly a large number of one minute Disdrometer data record of all the seasons considered in this study), to work out the *z – R* relationship and observed that there is a wide variation in both exponent and mantissa of the Marshall – Palmer (M - P) *z – R* relationship (Table 8). Further classification on stratiform and convective precipitation has been made and the *z – R* relationship was re-worked out. But the variability of the M – P exponential coefficients between rain rates still remained albeit of different orders of magnitude. This re-confirms that the microphysical mechanism that causes the variability of DSD and thereby variability in *R* at a time scale smaller than a minute is yet to be fully understood. However, when the *z – R* relationship is considered for the entire rain spell (by using a single relationship for all the rain rates of an individual rain spell), the estimation appears to give a satisfactory result of bias less than 15%. Hence it is concluded that the overall relationship developed by pooling a large number of data helps to mask the variability between the instantaneous rain rates. In this connection it is not out of place to mention the remarks made by Zawadzki (1984) that the DSD introduces one, but not the most severe, of the many errors in estimating *R* remains true even today.

5. Conclusions

The following conclusions have been arrived at from this study.

(*i*) The mean concentration of rain drops of size more than 3 mm during pre-monsoon in rain rates exceeding 10 mm h^{-1} was observed to be the highest of all the three seasons due to rapid collision and coalescence of drops. The concentration of smaller size drops (< 2 mm dia) especially in rain rates exceeding 8 mm h^{-1} is more during NEM than the SWM because the condensed particles could not grow effectively into larger drops by collection of cloud droplets due to the prevalence of either weak instability or nocturnal stability conditions during NEM. However, the concentration of larger drops of more than 4 mm during SWM (wherein precipitation is realised mostly during afternoon or evening) is very high since the drops grow in size with updrafts in view of the convective instability which normally prevails during summer afternoon.

(*ii*) Convective type precipitation has higher rain rates while the stratiform type has lesser rain rates.

(*iii*) An inverse relationship between N_o and *R* (so also with *Z*) is seen during convective situations whence drop size is more and concentration is less due to collision and coalescence process. In stratiform precipitation, there appears to be direct relationship between these two parameters since the concentration is more with lesser drop sizes.

(*iv*) The modal class of the drop size of the stratiform precipitation is less 2 mm.

(*v*) Exponential distribution of DSD fits well during stratiform precipitation. However in regard to convective precipitation, a deviation from exponential fit could be seen in 10 – 20 mm h^{-1} rain rate.

(*vi*) Lognormal distribution fits extremely well during northeast monsoon. However this fitting during pre-monsoon and southwest monsoon appears to have some deviation in rain rates between 10 and 50 mm h^{-1}. Further analysis needs to be done with larger data sample during the ensuing years.

Acknowledgements

Facilities extended by the Deputy Director General of Meteorology, Regional Meteorological Centre, Chennai to conduct this study are gratefully acknowledged. The authors acknowledge the enthusiastic support extended by the personnel working at Meteorological Observatory, specifically to Shri S. Rajamani, for the operation of the Disdrometer and supply of data for this study. The first author (RS) acknowledges the help extended by Dr. Henry Sauvageot of France and also for his keen interest shown on this study and comments.

References

Atlas, D., 1990, ed: Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference, *American Meteorological Society*, Boston, ISBN 0-933876-86-6, p806.

Atlas, D. and Ulbrich, C. W., 1977, "Path and area-integrated rainfall measurements by microwave attenuation in the 1 – 3 cm band", *J. Appl. Meteor.*, **16**, 1322-1331.

Brown, P. S. and Whittlesey, S. N., 1992, "Multiple equilibrium solutions in Bleck-type models of drop coalescence and break up", *J. Atmos. Sci*., **49**, 2319-2324.

Chandrasekar, V. and Bringi., V. N., 1987, "Simulation of radar reflectivity and surface measurements of rainfall", *J. Atmos. Oceanic Technol*., **4**, 464-478.

Doviak, R. J. and Zrnic, D. S., 1993, "Doppler radar and weather observations", Academic Press Inc., San Diego, ISBN 0-12-221422-6, p562.

Feingold, G. and Levin, Z., 1986, "The log normal fit to raindrop spectra from frontal convective clouds in Israel", *J. Climate Appl. Meteor.*, **25**, 1346-1363.

Glickmann, T. S., 2000, ed. Glossary of Meteorology, *Amer. Met. Soc*., Boston, p855.

Gunn, R. and Kinzer, G. D., 1949, "The terminal velocity of fall droplets in stagnant air", *J. Meteor*., **6**, 243-248.

India Meteorological Department (IMD), 1983, "Frequencies of stable layers in the planetary boundary layer over India", Part I and II, IMD, New Delhi.

India Meteorological Department, 1999, "Climatological Tables of Observatories in India", 1951-80, 5th ed., IMD, New Delhi.

Joss, J. and Waldvogel, A., 1967, "Ein Specctrograph fur Nieder-schlagstropfen mit automatisher Auswertung", *Pure Appl. Geo. Phys*., **68**, 240-246.

Joss, J., Waldvogel, A. and Gori, G., 1978, "Shapes of raindrop size distributions", *J. Appl. Meteor.*, **17**, 1054-1061.

Kelkar, V. N., 1959, "Size distribution of raindrops – Part I", *Indian J. Met. Geophys.*, **10**, 1, p125.

Krishna Reddy, K. and Toshiaki Kozu, 2003, "Measurements of raindrop size distribution over Gadanki during south-west and north-east monsoon", *Indian J. Radio & Space Phys*., **32**, 286-295.

Low, T. B. and List, R., 1982, "Collision, coalescence and breakup of raindrops. Part II: Parameterization of fragment size distributions", *J. Atmos. Sci.*, **39**, 1607-1618.

Marshall, J. S. and Palmer, W.M.K., 1948, "The distribution of rain drops with size", *J. Meteor*., **5**, 165-166.

Narayana Rao, T., Narayana Rao, D., Mohan, K. and Raghavan, S., 2001, "Classification of tropical precipitating systems and associated Z – R relationships", *J. Geophys. Res.*, **106**, D16, 699-711.

Prasad, B., 1970, "Diurnal variation of rainfall in India", *Indian J. Met. Geophys*., **21**, 3, 443-450.

Raghavan, S., 2003, "Radar Meteorology", Kluwer Academic Publishers, Netherlands, ISBN 1-4020-1604-2, p549.

Ramana Murty, B. V. and Gupta, S. C., 1959, "Precipitation characteristics based on rain drop size measurements at Delhi and Khandala during southwest monsoon", *J. Sci. Ind. Res.*, **18A**., 352-371.

Rinehart, R. E., 1999, "Radar for Meteorologists, Rinehart Publications", P.O. Box 6124, Grand Forks, ND58206-6 124, USA, ISBN 0-9658002-0-2, p428.

Sauvageot, H., 1991, "Radar Meteorology", Artech House, London, p315.

Sauvageot, H. and Lacaux, J. P., 1995, "The shape of averaged drop size distributions", *J. Atmos. Sci.*, **52**, 1070-1083.

Sauvageot, H. and Koffi, M., 2000, "Multimodal raindrop size distributions", *J. Atmos. Sci.*, **57**, 2480-2492.

Sivaramakrishnan, M. V., 1961, "Studies of raindrop size characteristics in different types rain using a simple raindrop recorder", *Indian J. Met. Geophys.*, **12**, 2, 189-216.

Srivastava, R. C., 1978, "Parameterization of raindrop size distributions", *J. Atmos. Sci.*, **35**, 108-117.

Srivastava, R. C., 1982, "A simple model of particle coalescence and breakup", *J. Atmos. Sci.*, **39**, 1317-1322.

Suresh, R., 1998, "On some aspects of boundary layer over Madras airport", *Mausam*, **49**, 4, 528-530.

Suresh, R., 2003, "Air pollution- Physics and meteorological aspects", *Environment Science & Engineering*, **1**, 3, 47-55.

Suresh, R., Gupta, J. P., Rajesh Rao, P. and Bhatnagar, A. K., 2004, "Time evolution of rain drop spetra over Cuddalore in Coastal Tamilnadu", *Mausam*, **55**, 3, 441-456.

Ulbrich., C. W., 1983, "Natural variations in the analytical form of the rain drop size distribution", *J. Climate Appl. Met.*, **22**, 1764-1775.

Willis, P. T. and Tattleman, P., 1989, "Drop-size distribution associated with intense rainfall", *J. Appl. Meteor.*, **28**, 3-15.

Zawadzki, I., 1984, "Factors affecting the precision of radar measurements of rain", Pre-prints of 22nd Radar Meteorology Conf., Zurich, *Amer. Met. Soc.*, 251-256.

Appendix A

Characteristics of drop size classes

Drop size class D_i	Range of diameter (mm)	Average diameter of D_i (mm)	Class interval $\Delta(D_i)$ (mm)	Fall velocity of D_i (m s^{-1}) *i.e.*, $V(D_i)$
1	0.313 - 0.404	0.359	0.092	1.435
2	0.405 - 0.504	0.455	0.100	1.862
3	0.505 - 0.595	0.551	0.091	2.267
4	0.596 - 0.714	0.656	0.119	2.692
5	0.715 - 0.826	0.771	0.112	3.154
6	0.827 - 0.998	0.913	0.172	3.717
7	0.999 - 1.231	1.116	0.233	4.382
8	1.232 - 1.428	1.331	0.197	4.986
9	1.429 - 1.581	1.506	0.153	5.423
10	1.582 - 1.747	1.665	0.166	5.793
11	1.748 - 2.076	1.912	0.329	6.315
12	2.077 - 2.440	2.259	0.364	7.009
13	2.441 - 2.726	2.584	0.286	7.546
14	2.727 - 3.010	2.869	0.284	7.903
15	3.011 - 3.384	3.198	0.374	8.258
16	3.385 - 3.703	3.544	0.319	8.556
17	3.704 - 4.126	3.916	0.423	8.784
18	4.127 - 4.573	4.350	0.446	8.965
19	4.574 - 5.144	4.859	0.572	9.076
20	≥ 5.145	5.373	0.455	9.137

Appendix B

Symbols

R	:	Rain rate (mm/h);
Z	:	Radar reflectivity factor (dBZ);
D_{max}	:	Largest drop size recorded (mm);
W	:	Liquid water content ($mm^3\ m^{-3}$)
N_o	:	Number concentration of drops with diameter o ($m^{-3}\ mm^{-1}$)
Λ	:	slope (mm^{-1});
LWC = W	:	Liquid Water Content ($g\ m^{-3}$)
KEF	:	Kinetic energy flux ($J\ m^{-2}\ hr^{-1}$)
D_i	:	Mean diameter of drops in i^{th} class (mm); ΔD_i : Class interval (mm)
$V(D_i)$	:	Fall velocity of a drop with diameter Di ($m\ s^{-1}$)
F	:	Collection area of the styrofoam = 0.005 m^2
$N(D_i)$	:	Frequency of drops with diameter D in class i per unit volume ($m^{-3}\ mm^{-1}$)
n_i	:	Frequency of drops in i^{th} class during time interval t where t = 60 second
m_n	:	Moment generating function of log normal distribution function of order n

$$R = (\pi/6) * (3.6/10^3) * (1/F * t) * \Sigma(n_i * D_i^3) \quad \text{where } (i = 1,2,\ldots, 19,20).$$

$$LWC = W = (\pi/6) * [1/(F * t)] * \Sigma [(n_i * D_i^{\,3}) / V(D_i)] \quad \text{where } (i = 1,2,\ldots, 19,20).$$

$$Z = 10 \log \{1/(F * t) * \Sigma [(n_i * D_i^{\,6}) / V(D_i)]\} \quad \text{where } (i = 1,2,\ldots, 19,20).$$

$$KEF = (\pi * 3600) / (12 * F * t * 10^6) * \Sigma [(n_i * D_i^{\,3} * V(D_i)^2]$$

$$N_o = (1/\pi) * W * (6\,!/\pi)^{4/3} * (W/Z)^{4/3}$$

$$\Lambda = [W * 6\,!/(Z * \pi)]^{1/3}$$

$$N(D_i) = n_i / [F * t * V(D_i) * \Delta D_i]$$

$$m_n = N_T\ D_g^{\,n}\ \exp[(n^2/2)\ \mathrm{Ln}^2(\sigma)]$$

.