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Time evolution of rain drop spectra over Cuddalore in coastal Tamilnadu

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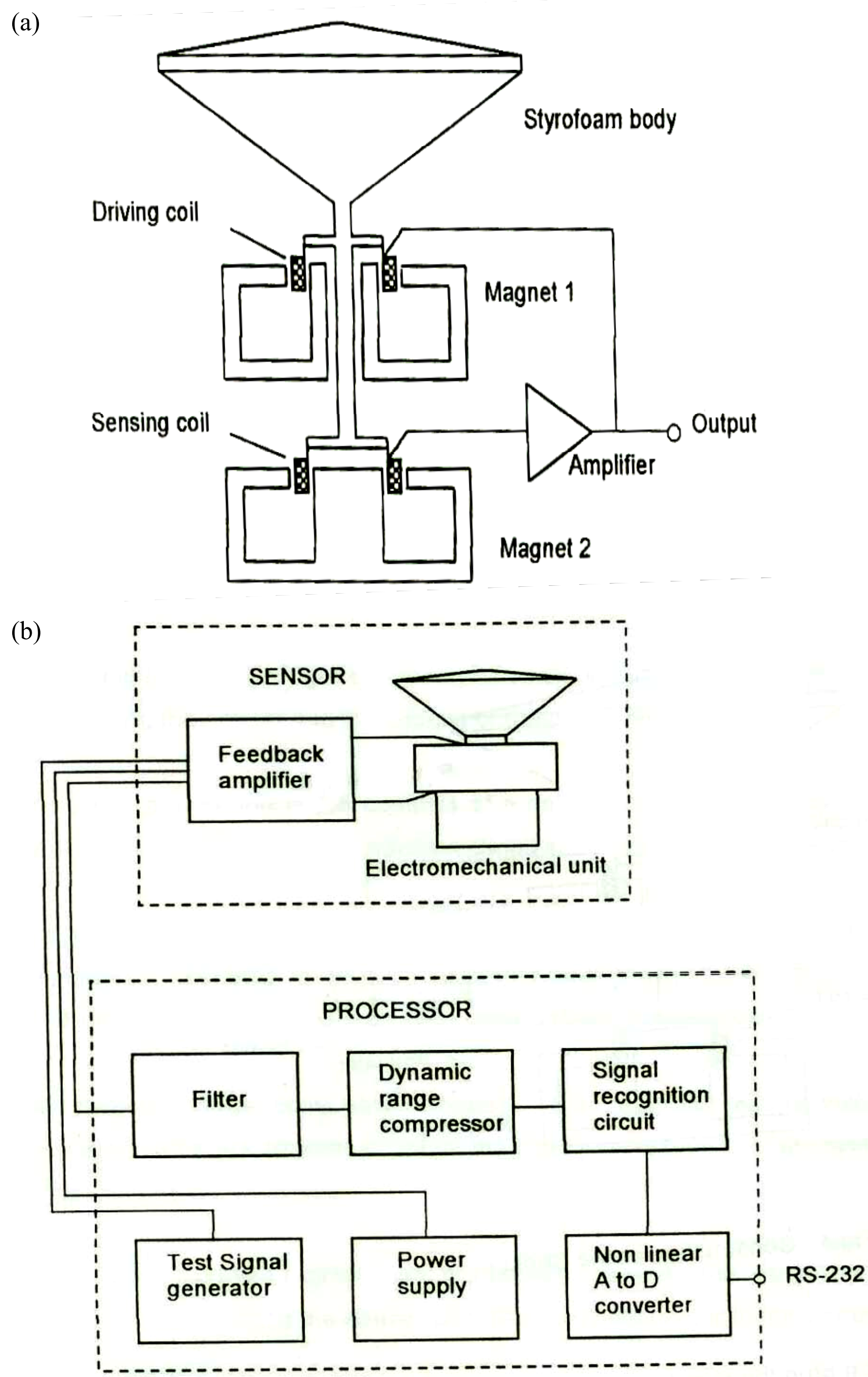
सार – अप्रैल 2002 के पहले सप्ताह में तमिलनाडु के तटीय क्षेत्र के मौसम केन्द्र, कड्डलूर में डिस्ड्रोमीटर लगाया गया। इस शोध पत्र में मई से अगस्त 2002 तक की अवधि में मानसून पूर्व ऋतु (मार्च से मई) और दक्षिण–पश्चिम मानसून ऋतु (जून से सितंबर) के अधिकांश भाग में वर्षा की बूँदों के आकार के वितरण (डी.एस.डी.) के परिणामों का विवेचन करने के अलावा डिस्ड्रोमीटर में उपलब्ध तकनीकी विशेषताओं और सुविधाओं के बारे में बताने का प्रयास किया गया है। 66 मि..मी. प्रति घंटे तक की वर्षा की गति के लिए डिस्ड्रोमीटर से मापी गई संचित वर्षा, सतही वर्षामापी से मापी गई मात्रा के बिल्कुल अनुकूल रही। दक्षिणी प्रायद्वीपीय भारत के तटीय केन्द्र कड्डलूर में वर्षा की बूँदों के आकार के संबंध में वर्षा के दौर के विरोधात्मक लक्षणों को बताया गया है यद्यपि वर्ष 2002 की अवधि में वर्षा की मात्रा बहुत कम थी। वर्षा की मोडल गति 10–40 मि.मी. प्रतिघंटा (11%) और उसके बाद 6 मि.मी. प्रति घंटा (84% आवृत्ति) तक कम रही। बूँदों की साँद्रता, विशेष रूप से बडी बूँदों की साँद्रता, वर्षा के प्रत्येक दौर में मई माह की तुलना में जून से अगस्त माह के दौरान अधिक रही। बूँदों के आकार की मॉडल श्रेणी का औसत व्यास 1.116 और 1.912 मि. मी. रहा। चरघातांकी और लॉग नार्मल दोनों तरह के वितरण डी.एस.डी. के अनुरूप रहे। इस अध्ययन में जिन दो ऋतुओं का अध्ययन किया गया है उनके लिए लॉग नार्मल वितरण प्रकार्य के संवेग जनक प्रकार्य (एम.जी.एफ.) के संवेग 3.67 (एम. $_{3.67}$) से व्युत्पन्न वर्षा की गति डिस्ड्रोमीटर से मापी गई वर्षा की गति के बिल्कुल अनुरूप रही। एक मिनट के अंतराल में, वर्षा की गति में विविधता, से स्पष्ट रूप से पता चलता है कि परिशुद्ध जेड–आर संबंध का उपयोग करने के बावजूद भी रेडार से प्राप्त संचित वर्षा की जानकारी गलत भी हो सकती है। इससे यह ज्ञात होता है कि वर्षा की गति का आकलन करने के लिए डी.एस.डी. और सूक्ष्म भौतिकीय प्रक्रियाओं, जिनके कारण बूँदों की साँद्रता में विविधता होती है, को अधिक बेहतर ढंग से समझने की आवश्यकता है। इसके अलावा संचित वर्षा का आकलन करने के लिए कम उँचाई पर स्थापित रेडार से लगातार जाँच करने की आवश्यकता के बारे में बताया गया है।

ABSTRACT. A disdrometer has been installed at Meteorological Office, Cuddalore in Coastal Tamilnadu during first week of April 2002. This paper attempts to describe an overview of the technicalities and facilities available in this disdrometer besides describing the results of the rain drop size distribution(DSD) from May to August 2002 covering parts of pre-monsoon (March – May) and southwest monsoon (June – September) season. The rain accumulation as measured by the disdrometer matches perfectly with the surface rain gauge measured amount for the rain rate upto 66 mm/hr. The contrasting features of rain spells over Cuddalore, a coastal station in southern peninsular India are clearly brought out in terms of DSDs albeit the rain amount during these period in the year 2002 was very subdued. The modal rain rate was less than 6 mm/hr (84% frequency) followed by 10-40 mm/hr (11%). The concentration of drops, specifically the concentration of larger drops, per rain spell is higher during June - August than during May. The modal class of drop size has an average diameter of 1.116 and 1.912 mm. Both exponential and log-normal distribution seem to be fitting well with the DSD. The rain rate derived from the moment 3.67 ($m_{3.67}$) of the moment generating function (MGF) of the lognormal distribution function agrees reasonably well with the disdrometer measured rain rate for both the seasons considered. The variability of rain rate, in one minute interval, clearly reveals how the radar derived rainfall accumulation may go wrong even presuming that one uses a perfect $Z - R$ relationship. This suggests the need for understanding the DSD and the micro-physical processes that cause the variability of concentration of drops more precisely to estimate the rain rate and warns about the need for very frequent low elevation radar scans for estimating the rain accumulation.

Key words – Disdrometer, Drop size distribution, Rain rate, Radar reflectivity factor, Log-normal distribution, exponential distribution.

1. Introduction

The physics of rain formation mechanism depends on the rain drop size distribution (DSD). The characteristics of DSD which influence the rain rate depend on the dynamic and kinematic processes. The DSD and its moments are very important not only for the estimation of rain rate by radars but also for their impact



Figs. 1(a&b). Schematic diagram of (a) Sensor (b) Processor of the Disdrometer at Cuddalore

on the problems involved in the microwave propagation within the clouds and rain attenuation etc. Numerous theoretical and observational studies on DSDs reveal that they are not random but can be reproduced. Often exponential, log-normal and gamma distribution functions are applied to the shape of the DSD. Though the microphysical processes of collision/coalescence and breaking-up of rain drops contribute to the time evolution and thereby to the shape of DSD, atmospheric conditions leading to different rain rate, fall velocity and fall height do cause their impact to the shape of the DSD (Srivastava, 1982; List, 1988; Zev Levin *et al*., 1991; Hu and Srivastava, 1995). Observational fact revealed that the parameters of the DSDs are functions of rain rate (R) and since R varies both temporally and spatially, the observation on DSDs have to be made and data collected in such a way that the R remains nearly constant during the period of observation.

Rain drop size distribution over Poona (a leeward side, high altitude station over west coast of peninsular India) has been studied extensively by Kelkar through a series of papers (Kelkar, 1959 and 1968) and over New Delhi (an interior station of north India) by Srivastava and Kapoor (1961) using the well known filter paper technique and comparing the rain rate with radar reflectivity. Sivaramakrishnan (1961) summarises some of the earlier work done on drop size distribution especially over Indian sub-continent and describes a simple raindrop recorder. It has been accepted that a time resolution of one minute at the ground by a drop size measuring instrument would be sufficient to model the DSD (Joss *et al*., 1978; Feingold and Levin, 1986; Sauvageot and Lacaux, 1995). A maiden attempt has been made in this paper to analyse the data obtained from the latest micro processor and personal computer (PC) based disdrometer for the period May – August 2002 covering parts of pre-monsoon and southwest monsoon over this tropical coastal station. A brief introduction about Disdrometer has been given below.

1.1. *Disdrometer*

A disdrometer (Distromet Ltd., Switzerland make) has been installed at Meteorological Office, Cuddalore in Coastal Tamilnadu during the first week of April 2002 as part of INDO-US programme with the objective of validating rain rate estimation through Cyclone Detection Radar(CDR) at Karaikal which in turn will be used for the validation of the Tropical Rainfall Measuring Mission (TRMM) data and so also to the contemplated Global Precipitation Measurement (GPM) mission satellite programme. Observational studies are carried out to measure the DSD either from aircraft based or from ground based instrument. But the air borne measurements have poor spatial and temporal resolution besides the fact that the measurements at different altitudes pertain to different time periods whereas the ground based measurements have good time resolution albeit they do not show resolution with altitude. The ground based instrument that is most widely used to measure DSD throughout the world is the disdrometer (Distribution of raindrop size meter) devised by Joss and Waldvogel (1967). Disdrometer measures the size distribution of rain drops falling on the sensitive surface of the sensor automatically and continuously. From this the actual drop size distribution in a volume of air is calculated.

1.2. *Technical and scientific details of the disdrometer at Cuddalore*

The disdrometer (type RD 80 of Disdromet Ltd., Switzerland) was installed at Meteorological Office, Cuddalore (11.46° N / 79.46° E) on 3rd April 2002. The instrument consists of a sensor, a processor connected to a personal computer (PC). The sensor consists of styrofoam body, driving coil and magnet, sensing coil and magnet, and an amplifier in a common housing. When a water drop falls over the styrofoam surface, the two moving coils attached with it move downwards and a voltage is induced in the sensing coil. This voltage is amplified by an amplifier and is also applied to the driving coil so that a force counteracting the movement is produced which brings the system to its original position in a very little time. The amplitude of the pulse so produced by the electromechanical transducer is a function of the drop diameter. A conventional analysis yields the size distribution of the raindrops. Fig. 1(a) shows the typical schematic diagram of the sensor used in disdrometer.

The processor consists of a active band pass filter to chop off acoustic noise, a dynamic range compressor, a signal recognition circuit and a non-linear A/D converter. The noise filter is designed in such a way that the signal (from rain drops) to (acoustic) noise ratio is optimum. Since the acoustic noise from the surroundings affects the measurement of small drops, this filter circuitry has been incorporated which continuously sets a noise threshold so that noise is not counted as drop(s). However, there is an undesirable effect that signals from rain drops that are smaller than the acoustic threshold will also be filtered. The signal recognition circuit distinguishes the true signal from the acoustic noise. The amplitude response of the system to the desired level has been attained through the dynamic range compressor which consists of a voltage feedback amplifier. If the pulses from the rain drops exceed the acoustic noise oscillations, then the pulses are passed by a gate for analogue to digital (A/D) conversion. The A/D converter produces a 7-bit code at the output for every drop, hitting the sensitive surface of the sensor. The range of drop diameters that can be measured spans from 0.3 mm to 5.0 mm. Due to practical limits of the measuring principle drops smaller than 0.3 mm cannot be measured and normally drops larger than 5.0 mm are very rare because they often breaks up due to instability and collision between drops. The disdrometer RD-80 is

TABLE 1

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})
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 - 1.726	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	4.573 – 5.144	4.859	0.572	9.076
20	≥ 5.145	5.373	0.455	9.137

TABLE 2

Mean annual rainfall (mm) of Cuddalore during 1951-80 (Source : Climatological Tables, India Meteorological Department, New Delhi)

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Climatological Normal (1951-80)													
Rain (mm)	36.7	9.4	15.6	14.0	47.2	43.1	82.8	150.3	123.4	273.5	383.5	198.5	1378.1
Rainy days	2.1	0.8	0.7	0.8	1.8	3.2	5.9	8.1	6.1	10.4	10.8	6.8	6.8
Actual rainfall and rainy days during the year 2002													
Rain (mm)	55.6	158.8	0	42.9	14.1	108.4	25.0	25.7	--	--	--	--	--
Rainy days	6	3	0	3	3	3	5	9	--	--	--	--	--

capable of distinguishing 127 classes of drop diameter. To reduce the amount of data and to get statistically meaningful samples, the 127 classes of drop size data are combined more or less exponentially into 20 drop size classes distributed over the available range of drop diameters. Table 1 lists the different classes of drop size with their estimated fall velocity. The test signal generator checks the performance of the function of processor and checks the connectivity of the sensor. The sensor is connected to the processor by a cable of about 10m length.

2. Installation, testing and facilities available in the disdrometer RD-80 at Cuddalore

The site chosen within the Cuddalore meteorological observatory meets the conditions stipulated by the World Meteorological Organisation for the establishment of surface rain gauges. The sensor of the disdrometer is exposed to free atmosphere without any obstacle and possible effect of wind induced turbulence has been taken care off by placing the sensor with its top level even with the level of the surroundings. Due care has been taken to ensure that there is no object in the vicinity of the sensor which can either resonate with rain drop or splash the rain drops into the sensor. Since the noise from thunderstorm and rain falling over metallic sheets may provoke rising of the noise threshold and the movement of vehicles cause the earth vibrations, the transducer has been set up away from the buildings and noise sources, in the middle of a grassy area with rubber beading cushioning to avoid earth vibrations. Thus it has been ensured that the disdrometer did not record any data when vehicles pass on the road about 40 m away from the observatory site. On 4 April, 2002 the functioning of the disdrometer was tested by creating a rain like situation by sprinkling water in the vicinity of the sensor and observing the recording by the processor. The values obtained were quite encouraging and in conformity with the results available in the literature. Based on the experience since 1980s, there could be two possible errors in measuring the small drop size through the disdrometer, *viz*., (*i*) the acoustic noise (which has been eliminated now by actuating a noise filter) and (*ii*) ringing of styrofoam cone when hit by rain drops. The second type of error cannot be avoided by any outdoor precautionary measure but can be reduced by using the theoretical and practical information about the DSD and by knowing the dead time of the instrument after every drop pulse (Appendix of Sauvageot and Lacaux, 1995). The correction formula for drops in each of the twenty channels has been introduced in the disdrometer installed at Cuddalore to avoid the error due to dead-time of the instrument after the sampling area is hit by the drops. Thus the disdrometer installed at Cuddalore averts the possible errors in measuring the smaller diameters.

The sampling area of styrofoam cone is 0.005 m^2. The disdrometer collects data at one minute interval. The data is archived in a PC regularly. The PC is connected to a dial up modem for the purpose of accessing data from the outside world. For ease of comparison of the total rainfall, both manual and self recording rain gauge (SRRG) data are available in this observatory. The disdrometer became operational from 4 April, 2002 and data have been archived systematically since then. The competing effects of collision and coalescence processes can be approximated through an exponential DSD using a simple parameterisation, *viz*.,

$$N(\mathrm{D}) = N_{\mathrm{o}}\, e^{-\Lambda \mathrm{D}} \qquad (1)$$

where N_{o} is a parameter indicating the (number) concentration of drops with diameter o and Λ is its slope. Relationship between N(D) and rain rate (R) , liquid water content in a given volume (LWC), radar reflectivity factor (Z) exist and the disdrometer provide these data for every one minute DSD based on the formulations devised originally by Gunn and Kinzer (1949), Joss and Waldvogel (1967) and Joss *et al*. (1978). In addition, the slope Λ, and kinetic energy flux (KEF) are also available from the disdrometer software programme output. The formulas used have been given in the Appendix.

TABLE 3

Comparison of disdrometer derived rainfall amount with the self recording rain gauge (SRRG) data at Cuddalore, May-August 2002

Date	Disdrometer measured rainfall (mm)	SRRG measured rainfall (mm)
3 May, 2002	4.705	4.5
4 May, 2002	4.193	4.2
4 Jun, 2002	0.603	0.5
18 Jun, 2002	3.082	3.1
19 Jun, 2002	0.651	0.7
11 Jul, 2002	10.71	11.8
8 Aug, 2002	6.534	6.5
16 Aug, 2002	6.220	6.3

3. Data used and validation

The normal rainfall of Cuddalore and the amount of rainfall received during the year 2002 have been furnished in Table 2. Though Cuddalore receives maximum rainfall during October-December (northeast monsoon season), it receives an average rainfall of about 47.0 mm during May (a month in pre-monsoon season) and 43.0, 83.0 and 150.0 mm during June, July and August respectively (part of southwest monsoon season). However the current year's rainfalls during both seasons are very subtle and subdued (roughly about 30%, 30% and 17% of the normal during May, July and August respectively). During the month of June 2002, on two spells of rainfall of 28.0 mm and 78.8 mm, the disdrometer could not record data due to prolonged power failure. Despite the above limitations, the 21014 DSD data records (each of one minute duration with 20 channel information) archived by the disdrometer during May – August 2002 have been used in this paper, as a pioneer study to understand the DSD in both the seasons over a tropical coastal station with this disdrometer data. However, the effective data records for the analysis of fitting statistical distributions were restricted to those period at which the surface rain gauge located at the very same observatory recorded atleast 0.25 mm of rainfall (coinciding with the definition of a rainy day) regardless of the individual rain rates. The number of such records was 2832.

As part of validation, the disdrometer derived rain accumulation has been compared with the SRRG chart

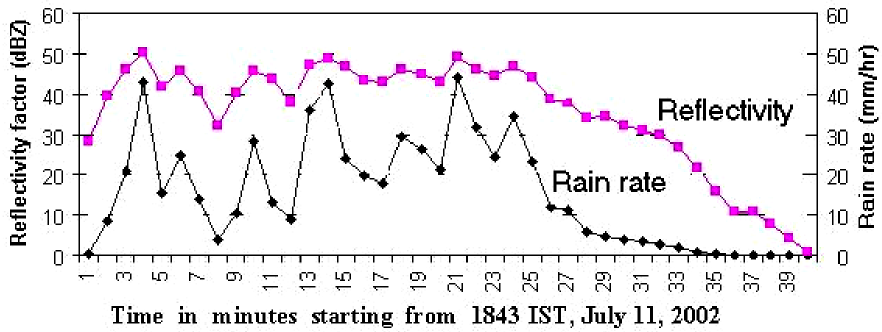


Fig. 2. Temporal variability of radar reflectivity factor and rain rate as estimated by disdrometer at Cuddalore

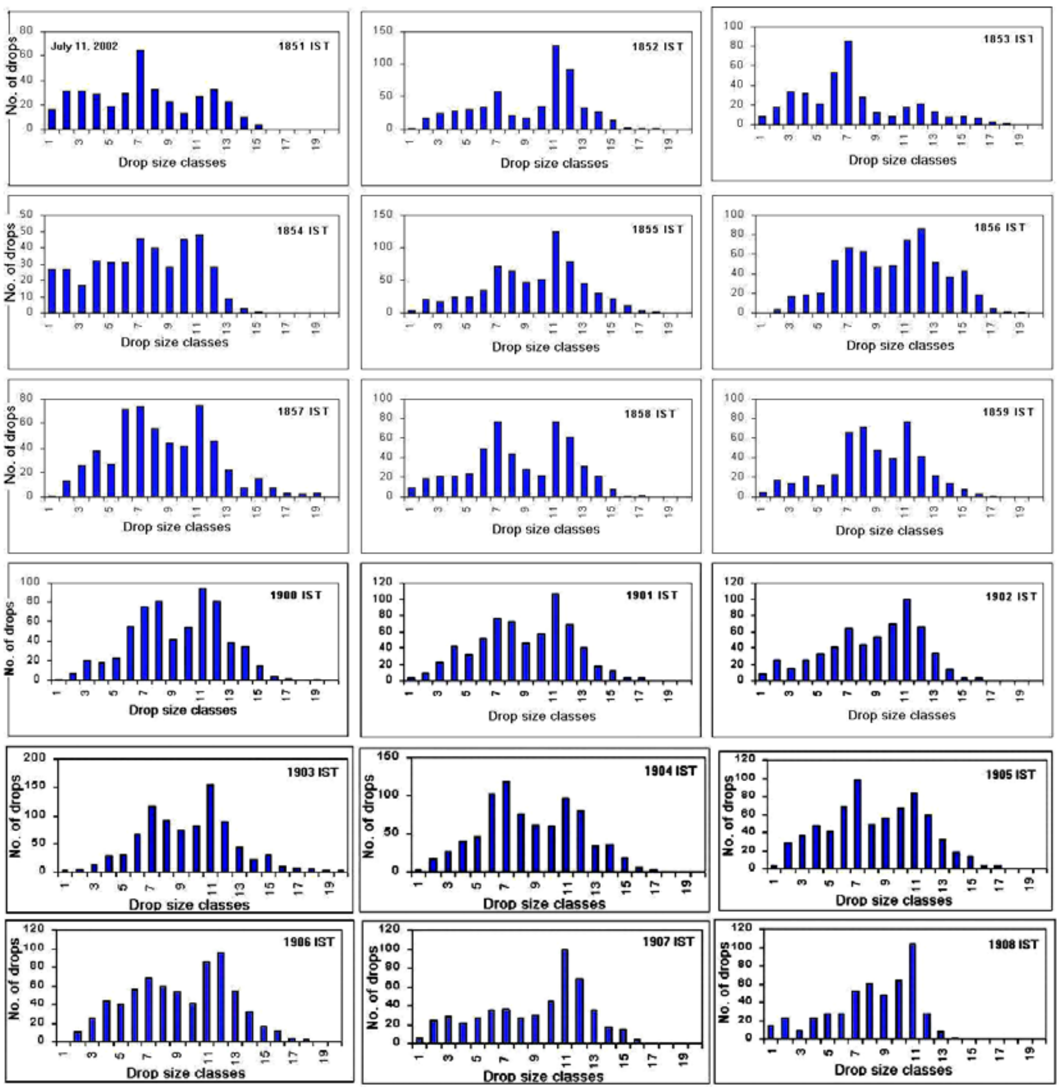


Fig. 3. Time series of concentration of drops of various sizes over time (1843 to 1908 IST /11 July 2002)

interpolated rainfall amount and the results have been unbelievably matching well. The results have been tabulated in Table 3. Though the disdrometer measured accumulated rain has been tallying very well with the SRRG in spells which had rainfall accumulation upto 12mm and rain rate upto 66 mm/hr, the validation of

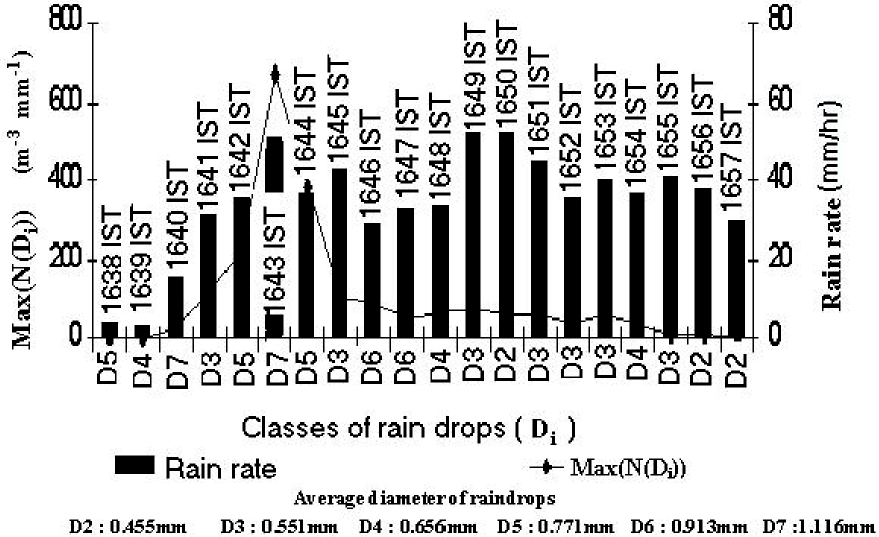


Fig. 4. Plot of rain rate and Max [N (D$_i$)] from 1638 to 1657 IST/16 August 2002

heavy rainfall incidences (of more than 65.0 mm in 24 hours) is yet to be carried out during the ensuing northeast monsoon season (October – December) since with the data available with us we missed such an incidence during June 2002 due to technical difficulties. As the instrument has been working well with the spells mentioned above, the 2832 data records have been subjected to further statistical analysis as discussed in the following sections.

4. Mode(s) of drop size distributions

A typical plot of radar reflectivity factor (Z) and rain rate (R) as estimated by the disdrometer at Cuddalore based on the observation from 1843 IST of 11 July, 2002 has been shown in Fig. 2. The fluctuation in rain rate as well as in reflectivity suggests the variability of rain drops, presumably due to collision and coalescence, at every minute. This is quite understandable for the meteorologists since the intensity of rain varies very frequently in tropics. In order to ascertain as to whether the DSD has any modal value, the concentration of rain drops of different classes have been plotted for the period 1851 to 1908 IST in Fig. 3. We adapted the following criteria to identify the modes. (*i.e.*) Let n_i be the number of drops in class i (where i =1,2,3.., 20 as defined in Table 1) of the DSD, then n_i is the mode of class i if $(n_i - n_{i-1}) \geq 1$ and $(n_i - n_{i+1}) \geq 1$. For a detailed discussion on this criteria, Sauvageot and Koffi (2000). The plot reveals that the DSD is multi-modal. The modes are mostly seen at classes 7 and 11 which correspond to the average drop diameter of 1.116 mm and 1.912 mm respectively. This is in conformity with the results obtained by many researchers and the latest being by Sauvageot and Koffi (2000) in their analysis with the data from Ivory coast and Niger-Congo in West Africa. In addition to the modes of classes whose diameters are less than 2.0 mm, low amplitude modes are rarely seen at classes 12, 15 and 16 (*i.e.*, having average diameter of 2.259 mm, 3.198 and 3.544 mm respectively).

The maximum of N(D$_i$) where (i = 1,2,3,..,19,20) has been plotted against time in Fig. 4. The maximum N(D$_i$) concentration of drop size classes reveals that the class D$_7$ (0.999 – 1.231mm with average diameter of 1.116 mm) is associated with peak rain rate of 66.58mm/hr at 1643 IST on 16 August, 2002. In some other cases, the maximum concentration in association with peak rain rate was seen from the class D$_{11}$ with an average diameter of 1.912mm. It has been attributed by Sheppard (1990) and Mc Farquhar and List (1993) that small irregularities of the transfer function of the electronic circuits could bias the DSD between some classes of fixed size and a similar counting bias could affect the relative maxima of the other classes of DSD also. The maxima obtained due to counting bias has been termed as 'instrumental modes' and attempts made to remove such modes did not yield any satisfactory result so far (Sauvageot and Koffi, 2000). One such attempt they made was to find out the real mode of the DSD by removing the DSDs whose diameter is less than 2.0 mm. But with this attempt, even the main mode of the DSD also got suppressed. However it has been documented by them that the tropics have modes less than 2.0 mm albeit there are deficit in small drops. Hence we proceeded with the analysis of the DSD with a caution

TABLE 4

Mean values of maximum drop diameter (D_{max}), rain rate(*R*), liquid water content(LWC), radar reflectivity factor(*Z*), kinetic energy flux (KEF) for different rain rates for pre-monsoon and southwest monsoon seasons over Cuddalore during 2002

Category of rain rate *R* (mm hr^{-1})	Period	D_{max} (mm)	*R* (mm hr^{-1})	LWC (g m^{-3})	*Z* (dBZ)	KEF ($Jm^{-2}hr^{-1}$)
≤ 2.0	May	1.54	0.680	0.046	16.93	7.44
	June – August	1.39	0.497	0.029	10.70	7.03
2.0 – 4.0	May	2.47	3.10	0.170	31.07	53.84
	June – August	2.84	2.56	0.127	31.96	48.19
4.0 – 6.0	May	2.34	4.74	0.251	32.93	74.86
	June – August	2.54	5.44	0.286	33.73	86.88
6.0 – 8.0	May	3.06	7.58	0.397	35.27	127.00
	June – August	2.37	7.17	0.380	34.52	109.75
8.0 - 10.0	May	2.58	9.74	0.487	36.66	165.92
	June – August	2.99	8.98	0.416	37.99	183.70
10.0 – 20.0	May	3.41	11.36	0.534	39.65	237.66
	June – August	3.36	14.51	0.656	40.35	310.10
20.0 – 40.0	May	3.61	29.06	1.267	43.76	644.93
	June – August	3.98	27.21	1.126	44.85	677.82
40.0 – 60.0	May	---	---	--	---	---
	June – August	5.03	43.32	1.630	49.31	1285.04
> 60.0	May	---	---	---	---	---
	June – August	4.35	66.58	2.630	49.63	1784.49

that the modes seen at lower drop classes could be taken as it is but their amplitude could have been little biased by the electronic circuit.

The distribution appears to be a juxtaposition of normal and multimodal albeit the skewness keeps on meandering from time to time. But as compared to modal value (frequency of drops in the modal class) of rain drops of diameter around 2.0 mm, the modal value of drops having diameter more than 3.0 mm is quite low. The possible cause for such a low modal values of drops more than 3.0 mm could perhaps be that the smaller drops carried up by the updrafts might have followed a complex trajectory before falling out to the ground without undergoing the dynamical processes such as collision and coalescence since the precipitation occurred from a stratiform cloud (*i.e.*) under non-quiescent condition). However for arriving at a solid conclusion about the modal values of the drops of size exceeding 3.0 mm, we may have to wait for and analyse the DSD data from the ensuing northeast monsoon season (October – December) wherein convective precipitation resulting from meso scale and synoptic scale systems of height extending beyond 14 km is quite probable. In view of the facts that

TABLE 5

Average concentration of drops of various diameters per rain spell (as measured by disdrometer in 20 classes furnished in Table 1) during May and June-August, 2002 over Cuddalore

Period	Diameter of the drops (mm)					
	0.0-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	>5.0
May	13345.0	4776.0	983.0	67.0	5.0	0.0
June-August	14617.0	5357.4	1193.6	158.8	9.6	0.4

(*i*) as high as 85 cm rainfall (62% of annual rainfall) is realised in this season (Table 2) over Cuddalore and (*ii*) the variability of precipitable water vapour, atmospheric stability conditions and the structure of the planetary boundary layer during the northeast monsoon season over the peninsular coastal area as established by Suresh and Raj (2001) and Suresh *et al*. (2002) using Tiros Operational Vertical Sounder (TOVS) data received from National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite passes over peninsular India, analyses of DSD data of the period October-December may perhaps reveal some important / additional results.

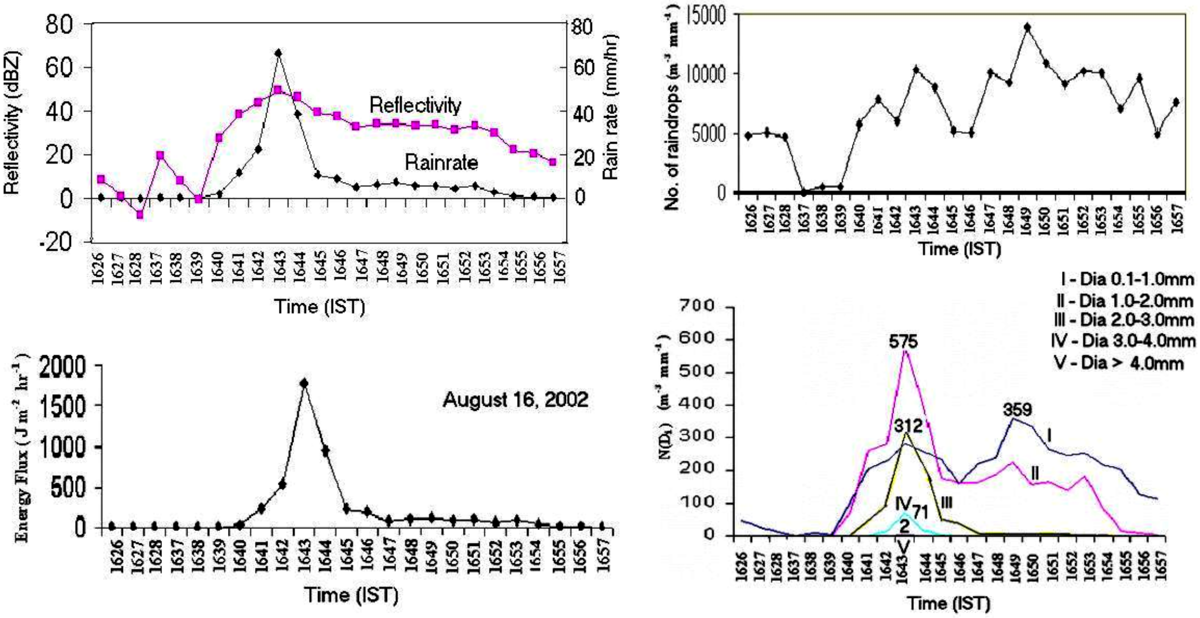


Fig. 5. Time variability of *Z*, *R* and KEF with N_o. Note that there was no rain during the period 1629-1636 IST, 16 August 2002

5. Variability of drop size distribution

The DSD data have been analysed in two groups, *viz*., May and June - August to examine the variability of DSDs over time. Further the rain rates have been classified into different categories to assess not only the parameters of the exponential distribution [as mentioned in equation (1)] but also to see the variability of the other derivable meteorological variables of interest such as *Z*, LWC etc. The results are summarised in Table 4. In about 84% of the cases, the rain rate was less than 6 mm/hr, higher rate of 10-40 mm/hr occurred in 11% of the cases and the balance 5% of the cases accounted for the remaining categories of rain rates.

An inference that can be drawn from Table 4 is that the KEF is relatively higher during June – August than during May, for the rain rates exceeding 4.0 mm/hr (except in 6-8 mm/hr rain rate), presumably due to the contribution by the high concentration of droplets of moderately larger diameters advected from the southwest monsoon current from the west coast and/or due to sea breeze convergence. Average number of drops of various ranges of diameters (*i.e*., for the 20 classes given in Table 1) have been worked per rain spell for the month of May and for the period June-August and tabulated in Table 5. Since KEF depends both on diameter of the droplets and their fall velocities and as it is well known that the fall velocity is higher for larger drops (see the values in Table 1 and Gunn and Kinzer, 1949), the reason for relatively higher KEF during June - August could be attributed to the high concentration of droplets and precisely the larger drops.

6. Variability of radar reflectivity, rain rate, kinetic energy flux with concentration of drops in a unit volume

A typical plot of variability of *Z*, *R*, KEF, N_o and $N(D_i)$ [which is the number concentration of drops of specific category range of diameter per unit volume as mentioned in appendix and its computation is discussed in section 7] with time on 16 August, 2002 has been displayed in Fig. 5. It may be noted that there was no rain from 1629 to 1636 IST. Maximum *Z* and maximum KEF were observed not at the time when N_o was at its peak (1649 IST) instead they were maximum when $N(D_i)$ was at its peak (1643 IST) for the drop size classes (II, III, IV and V as mentioned in the figure) exceeding 1.0 mm diameter. The maximum N_o at 1649 IST corresponding to the smaller rain drops of less than 1.0 mm diameter (category I in the figure) resulted in low *Z* and KEF. But the 2 drops of size exceeding 4.0 mm (category V), 71 drops of size 3.0 – 4.0 mm (category IV), 312 drops of 2.0 – 3.0 mm (category III) and 575 drops of 1.0 - 2.0 mm diameter (category II) have contributed to maximum *Z* and KEF at 1643 IST in view of their larger size and high fall velocities.

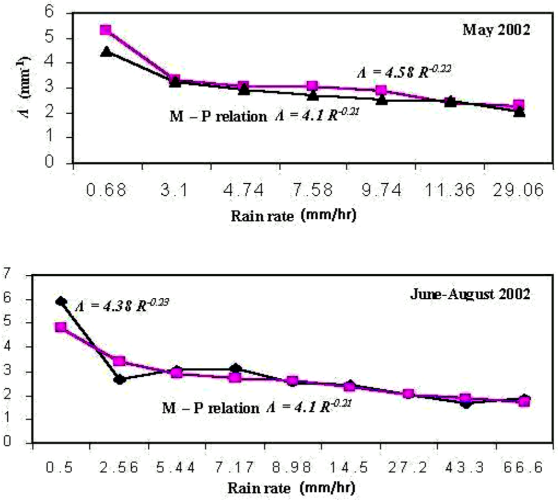


Fig. 6. Variability of Λ *vis-à-vis* *R* for pre-monsoon and southwest monsoon during 2002 at Cuddalore

7. Fitting of statistical distributions

7.1. *Exponential distribution*

Marshall and Palmer (1948) used filter paper technique to fit the DSD into an exponential distribution of the form (1) where N_0 =8000 mm^{-1} m^{-3} and the relation between the slope and rain rate (R)

$$\Lambda = 4.1\ R^{-0.21} \tag{2}$$

was proposed by them. Attempts have been made by several authors by fitting the DSD into this sort of exponential distribution throughout the world and contrasting and inconclusive results have been obtained [Atlas (1990); Doviak and Zrnic (1993); Rinehart (1997)]. The disdrometer derived Λ and R data have been fitted to have the relationship of the type(2)for May(Λ=4.58 $R^{-0.22}$) representing pre-monsoon and June-August(Λ=4.38 $R^{-0.23}$) representing southwest monsoon season and a plot for the mean values for the different rain rate categories considered in this paper has been depicted in Fig. 6. It can be seen that the exponential fit as propounded by Marshall and Palmer agrees well for both the season. The correlation coefficient between Λ and R is –0.97 for May and –0.94 for June - August. The decreasing of Λ with increasing R has been well documented in all the research papers mentioned in this paper. However it is seen in both the seasons, but for small variations in the order of magnitude of R, that the sharp decrease of Λ has been noticed from 0.1 to 4mm/hr rain rate thereafter the Λ remains more or less constant upto 15 mm/hr and again decreases but of course very slowly. This supports the earlier findings of continuous decrease of Λ with R for high rain rates exceeding 20mm/hr by Willis and Tattleman (1989).

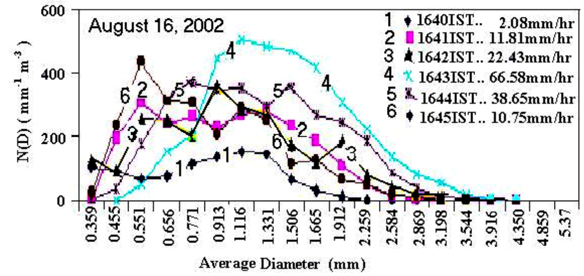


Fig. 7. Time evolution of drop size distribution for the different classes of rain drop diameters for the different rain rate categories on 16 August 2002

The mean values of N_o (*i.e.* the number of concentration of drops with diameter$_o$) has also been worked and tabulated in Table 6. N_o / Λ which is the zeroth moment of (1) has been calculated and it is plotted (not shown in this paper) against the mean rain rate for the categories considered in Table 4 of this study to ascertain as to whether any relationship exists between these two parameters. But it is seen that the curve is quite variable unlike the more or less exponential graph obtained for Ivory coast and Niger-Congo regions in South Africa by Sauvageot and Lacaux (1995). As such it is concluded that N_o / Λ does not have a straight forward relationship with the rain rate whereas Λ when considered alone has good relationship with R over Cuddalore, on the east coast of Bay of Bengal. This is quite logical since the value of N_o is quite high in low rain rates but its value randomly decreases and increases for higher values of R where as Λ decreases with increasing R in a systematic way. To summarise, by and large, the exponential distribution function fits the DSD well. However, the concentration of small drops of size less than 0.5 mm diameter in the low rain rate category affects the perfect fitting by the exponential distribution function to the DSD.

7.1.1. *Possible errors in estimation of rain accumulation from radar reflectivity data*

The number density of drops per unit volume [N(D$_i$)] have been worked out for all the twenty drop size classes from the disdrometer measured drops in each class i where (i = 1,2,3,..,20) based on the formula given in the appendix. A typical plot of [N(D$_i$)] *versus* R has been displayed as Fig. 7. It can be seen that the maximum rain rate (66.58 mm/h, labelled 4) had more number of rain drops of diameter more than 1mm and the concentration

TABLE 6

Mean values of parameters of exponential and lognormal drop size distribution for different rain rates and seasons over Cuddalore during 2002

Category of R (mm h^{-1})	Period	N_o (mm^{-1}m^{-3})	Λ (mm^{-1})	N_T (mm^{-1}m^{-3})	D_g (mm)	σ	H_2	H_3	$H_{3.67}$	H_6
≤2.0	PM	7508.4	5.28	165.7	1.42	1.54	1.45	2.30	3.49	28.2
	SWM	3329.2	5.91	85.3	1.21	1.73	1.81	3.82	7.43	212.7
2.0 – 4.0	PM	10311.7	3.31	329.7	2.33	1.38	1.23	1.58	1.98	6.23
	SWM	2541.4	2.66	187.1	2.81	1.17	1.05	1.12	1.18	1.56
4.0 – 6.0	PM	7439.9	3.08	370.7	2.34	1.06	1.01	1.01	1.02	1.06
	SWM	8153.1	3.04	377.2	2.52	1.11	1.03	1.06	1.09	1.25
6.0 – 8.0	PM	16284.5	3.08	576.8	3.03	1.17	1.05	1.12	1.18	1.57
	SWM	11722.4	3.13	458.3	2.36	1.07	1.01	1.02	1.03	1.07
8.0 - 10.0	PM	10765.1	2.89	506.9	2.59	1.02	1.00	1.00	1.00	1.00
	SWM	6594.6	2.54	337.2	2.93	1.22	1.09	1.20	1.32	2.10
10.0 – 20.0	PM	8491.9	2.42	543.1	3.36	1.19	1.06	1.14	1.22	1.71
	SWM	7930.4	2.42	456.5	3.30	1.21	1.08	1.18	1.28	1.95
20.0 – 40.0	PM	11385.3	2.27	562.8	3.62	1.02	1.00	1.00	1.00	1.00
	SWM	6730.2	2.04	493.2	3.95	1.13	1.03	1.07	1.11	1.32
40.0 – 60.0	PM	---	---	--	---	---	---	---	---	---
	SWM	3849.2	1.64	428.3	5.02	1.05	1.00	1.01	1.02	1.04
> 60.0	PM	---	---	---	---	---	---	---	---	---
	SWM	10320.8	1.87	751.1	4.35	1.02	1.00	1.00	1.00	1.00

Note : PM : Pre-Monsoon (May); SWM : Southwest Monsoon (June – August); $H_n = \exp[(n^2/2)\,\mathrm{Ln}^2(\sigma)]$ is the exponent term of moment generating function of the lognormal distribution function as defined in equation (7)

of larger rain drops decreases progressively with the decreasing rain rate. More over, the time evolution of growth of rain drops to maximum (labelled from 1 to 4) and the gradual decay of the drop concentration (labelled from 4 to 6) indicating the variability of rain intensity on the time scale. This gives an idea as to how the radar derived rain accumulation often goes wrong since the radar estimate of the precipitation accumulation pre-supposes that the rain intensity corresponding to a particular time of observation prevails till similar areal observation during the next scan strategy (*i.e.*, after completing the current scan strategy in 5 to 10 minutes time). For example, if the current scan strategy had commenced at 1643 IST and measured the reflectivity factor (Z) corresponding to the maximum rain rate of 66.58 mm/hr and took ten minutes to complete a full volume scan, then the next scan probes this area only at 1653 IST. During this interval, the average rain intensity might have been say 20 mm/hr or reduced to a low average rain rate of say 6 mm/hr or even lower.

For calculation of the rain accumulation, in the absence of observation from 1644 to 1652 IST, one normally assumes that rain rate of 66.58 mm/hr might have prevailed for the entire ten minutes and calculation made accordingly. This may lead to an error or over-estimation of about 6 to 8 mm in the ten minutes span considered. In case the time lags between two successive scans are more than ten minutes, then the error could be potentially dangerous. Hence it is absolutely inevitable to understand the dynamics, kinematics and micro-physical processes that cause the growth and decay of the DSD to have meaningful estimation of rain rates from the radar. As such the disdrometer measured raindrops distribution has to be critically analysed and a suitable statistical distribution fit has to be devised for its use in hydrological models.

7.2. *Lognormal distribution*

The concentration of small drops of classes 1 to 3 (diameters less than 0.595 mm) are very low in comparison to the other classes for rain rates exceeding 20 mm/hr (computation not shown, but can be visualised from the Figs. 5 and 7). In order to quantify the shape of the distribution, precisely to accommodate the small drop quantities for higher rates, the three parameter gamma distribution (Ulbrich, 1983) and lognormal distribution have been considered by the researchers (Feingold and Levin, 1986). Since it has been documented by Feingold and Levin (1986) and Chandrasekar and Bringi (1987) that the relative dependence of one of the parameter (N_o) with the other (μ) causes serious inconvenience in using the modified gamma distribution, in this paper we confined our attempt to fit the DSD to lognormal distribution function only because of its simplicity, 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. The lognormal distribution function can be written as

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

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.

$$N_T \;=\; \int N(\mathrm{D})\,\mathrm{dD} \quad \text{(between the limits 0 to } \infty) \quad (4)$$

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

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

The three parameters N_T , σ and D_g have been computed and the results summarised in Table 6. Though N_T is increasing with R with its derivative decreasing (*i.e.*, N_T = f (R^n) where $0 < n < 1$), little oscillation from its perfect monotonic increase relationship could be seen especially with June-August DSD data. A linear fit has also been made and shown in Fig. 8 for comparison. In a similar way, D_g and so also the σ do have good relationship with R. According to Sauvageot and Lacaux

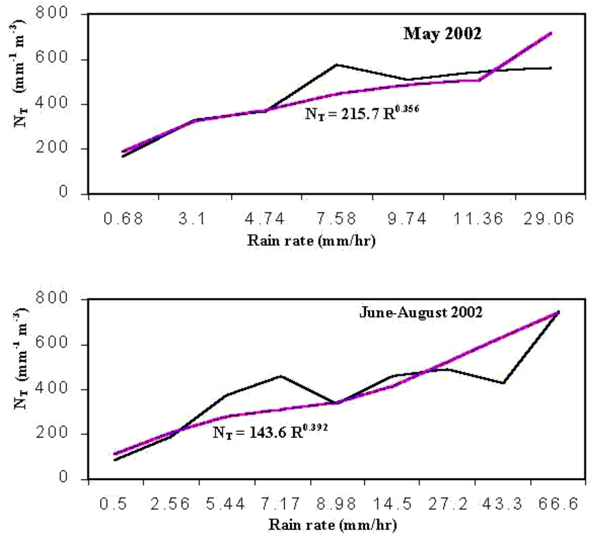


Fig. 8. Plot of N_T (mm^{-1} m^{-3}) with rain rate R (mm/hr)

(1995), the moment generating function of lognormal distribution can be written as

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

The exponential in the moment generating function (H_n = exp[(n^2/2) Ln^2 (σ)]) were also tried for their plausible relationship with R for the known values of n, *viz*., n = 2 for optical extinction, n = 3 for liquid water content, n = 3.67 for rain rate and n = 6 for the radar reflectivity. The relationship between all the parameters of lognormal distribution have been summarised in Table 7. The correlation coefficients (CC) are mostly tight (close to one) since they were obtained from the averaged values of individual parameters for rain rate categories considered in our study (7 categories for May and 9 categories for June-August). Also this sort of high CC between variables, independent of sample size, has been well documented by Chandrasekar and Bringi (1987). The sign and magnitude of CC are perfectly matching with the results obtained from another coastal station in the tropics (Suavageot, 2002, personal communication) which is also shown in Table 7. Hence it is convenient to express the moment generating function (7) in the form

$$\mathrm{m_n} = N_T(R) * \mathrm{D_g}^n(R) * \mathrm{H_n}(R) = \mathrm{a_n} R^{\mathrm{bn}} \quad (8)$$

where a_n and b_n are coefficients to be worked out so that the moments can be expressed in terms of R with a simple power relation for different values of n. For a similar discussion of relationship between R and fall velocity, mean drop diameter, liquid water content,

TABLE 7

Fitting of various parameters of exponential and lognormal distribution function with rain rate over Cuddalore compared with an equatorial African coastal station [@ adapted from Sauvageot and Lacaux (1995)]

	May 2002	June-August 2002	Equatorial African coastal station@
Exponential distribution	$\Lambda = 4.58\ R^{-0.22}$	$\Lambda = 4.38\ R^{-0.23}$	$\Lambda = 4.58\ R^{-0.22}$
function	CC = - 0.97	CC = - 0.94	CC = - 0.92
	$Z = 129.3\ R^{1.74}$	$Z = 97.7\ R^{1.76}$	$Z = 400.0\ R^{1.17}$
	CC = 0.86	CC = 0.98	
	$\mathrm{LWC} = 0.064\ R^{0.88}$	$\mathrm{LWC} = 0.057\ R^{0.91}$	$\mathrm{LWC} = 0.061\ R^{0.87}$
	CC = 0.99	CC = 0.99	
Lognormal distribution	$N_T = 215.7\ R^{0.356}$	$N_T = 143.6\ R^{0.392}$	$N_T = 670.0\ R^{0.74}$
Function	CC = 0.93	CC = 0.92	CC = 0.98
	$D_g = 1.64\ R^{0.25}$	$D_g = 1.66\ R^{0.26}$	$D_g = 0.97\ R^{0.13}$
	CC = 0.96	CC = 0.94	CC = 0.97
	$\sigma = 1.319–1.32\times10^{-2}\,R$	$\sigma = 1.29–5.16\times10^{-3}\,R$	$\sigma = 1.36–4.0\times10^{-4}\,R$
	CC = - 0.62	CC = - 0.54	CC = - 0.35
	$H_2 = 1.32\ R^{-0.11}$	$H_2 = 1.36\ R^{-0.96}$	$H_2 = 1.23\ R^{-0.014}$
	CC = - 0.89	CC = - 0.77	CC = - 0.78
	$H_3 = 1.89\ R^{-0.23}$	$H_3 = 2.03\ R^{-0.22}$	$H_3 = 1.60\ R^{-0.031}$
	CC = - 0.89	CC = - 0.76	CC = - 0.78
	$H_{3.67} = 2.59\ R^{-0.35}$	$H_{3.67} = 2.87\ R^{-0.32}$	$H_{3.67} = 2.01\ R^{-0.046}$
	CC = - 0.89	CC = - 0.77	CC = - 0.78
	$H_6 = 7.81\ R^{-0.86}$	$H_6 = 1.83\ R^{-0.11}$	$H_6 = 6.0\ R^{-0.12}$
	CC = - 0.86	CC = - 0.44	CC = - 0.78

reflectivity etc., Doviak and Zrnic (1993) and Ulbrich (1983) and Atlas and Ulbrich (1977).

If the terminal velocity as suggested by Atlas and Ulbrich (1977), *viz*., $V(\mathrm{D}) = 3.78\ \mathrm{D}^{0.67}$, where D is in mm and V(D) is in m/s, is considered then it can be shown that R is proportional to $m_{3.67}$. (*i.e.*) The rain rate is proportional to $m_{3.67}$. The other rain parameters of interest such as reflectivity factor and liquid water content and optical attenuation factor, *viz*., optical extinction can also be expressed as a function of m_n for suitable *n*. (*i.e.*)

$$I_n = \mathrm{K_n m_n} = \mathrm{K_n a_n} R^{\mathrm{b_n}} \tag{9}$$

where K_n is a constant and I_n can be either *R*, *Z* etc. If $R = I_{3.67}$, then one would expect $K_n\ a_n \approx b_n \approx 1$. To verify this, we considered the $m_{3.67}$ and obtained the coefficients of the fittings. As we do not have sufficient independent data set, the fitting has been verified with the development data itself and the results are presented in Table 8. Since the optical extinction is concerned about the optical propagation and it does not affect the microwave propagation, the same is not considered in this paper for further analysis.

It is seen from Table 8 that only the $K_{3.67}$ $a_{3.67}$ and $b_{3.67}$ are close to 1 in both the seasons as one normally should expects. The rain rate derived from the moment generating function ($m_{3.67}$) agrees reasonably well with the disdrometer measured rain rate for both the seasons considered. However, both the (m_3 and m_6) derived rain rates were in disagreement with the disdrometer measured values by, and a large margin. Since the fitting with m_6 was quite unsatisfactory, we even removed the low rain rates (0-4mm/hr for May and 0-2mm/hr for June-August) presuming that the contribution from the small droplets might have contaminated our fittings but even after this no appreciable improvement could be seen in other rain rates. In view of two proportionalities (one for the m_6 with Z and the other which is the well known problem for the

TABLE 8

Relationship of moment generating function of lognormal distribution with rain rate and reflectivity factor. The mean values of rain rates for specified categories mentioned in Table 4 measured by the disdrometer are furnished

Rain rate (mm/hr)	Disdrometer estimated *R*	*R* estimated from			Disdrometer estimated *R*	*R* estimated from		
		m_3	$m_{3.67}$	m_6		m_3	$m_{3.67}$	m_6
		May 2002			**June – August 2002**			
	Kn a_n :	1.38	1.12	0.27	Kn a_n :	1.59	0.90	0.08
	b_n :	0.93	1.03	1.78	b_n :	0.92	1.03	1.78
0 – 2	0.68	0.98	0.84	-	0.50	0.84	0.44	-
2 – 4	3.10	3.74	3.43	-	2.56	3.76	2.37	0.42
4 – 6	4.74	5.43	5.10	2.57	5.44	7.51	5.15	1.60
6 – 8	7.58	8.21	7.89	5.09	7.17	9.68	6.84	2.62
8 – 10	9.74	10.24	9.96	7.32	8.98	11.90	8.63	3.92
10 – 20	11.36	11.72	11.50	9.16	14.51	18.47	14.15	9.21
20 – 40	29.06	26.80	27.54	35.74	27.21	32.88	27.04	28.21
40 – 60	-	-	-	-	43.33	50.38	43.67	64.59
>60	-	-	-	-	66.58	74.71	67.97	138.74

Note : m_3 , $m_{3.67}$, m_6 are the moments of lognormal distribution function that are proportional to liquid water content, rain rate and reflectivity factor respectively.

meteorologists that the relationship proportionality between *Z* and *R*) involved in estimating the *R* from m_6 and so also in the case of *R* from m_3 , it is afraid that the fitting is not yielding the desired outcome due to the complicated proportionality relationships. However in the case of *R* estimated through $m_{3.67}$ since only one proportionality has been involved, the fitting seems to be quite alright for estimating the *R*. However, this aspect will be further verified during the ensuing rainy period with totally independent data.

8. Conclusions

(*i*) The slope of the exponential distribution function (Λ) decreases sharply from 0 to 4 mm/hr rain rate and remains almost constant for the rain rates 4 -15 mm/hr and thereafter decreases very slowly. This agrees with the earlier finding by Willis and Tattleman (1989).

(*ii*) Exponential distribution function fits well the DSD for both the seasons. However, the concentration of a large number of smaller drops of size less than 0.5 mm diameter causes the some imperfection in the fitting.

(*iii*) The rain rate derived from the moment generating function ($m_{3.67}$) of the lognormal distribution function agrees reasonably well with the disdrometer measured rain rate of May - August, 2002 considered in the study. However, the (m_6) derived rain rates were in disagreement with the disdrometer measured values by, and a large margin, presumably due to error involved in two parameterisation proportionalities (comparing m_6 -first with *Z*, and then comparing with *R*).

(*iv*) The variability of rain rate, in one minute interval, clearly reveals how the radar derived rainfall accumulation may go wrong even presuming that one uses a perfect *Z* – *R* relationship. This suggests the need for understanding the DSD and the micro-physical processes that cause the variability of concentration of drops more precisely to estimate the rain rate besides giving information about the need for a very frequent low elevation radar scan for estimating the rain accumulation.

(*v*) Even after averting, to the maximum possible extent, the errors due to acoustic noise and due to dead-time of the instrument after the sampling area is hit by drops, the modal class of drop size has an average diameter of 1.116 and 1.912 mm. This confirms the earlier findings that the tropics have modal drop diameters of less than 2.0 mm.

(*vi*) The modal rain rate was less than 6mm/hr (84% frequency) followed by 10-40 mm/hr (11%) and the rest of rain rate accounted only 5% of the rain events analysed.

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Appendix

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 D_i (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 lognormal distribution function of order n

Formulae used

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

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

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

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

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

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

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

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