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Rain drop size distribution characteristics of cyclonic and north east monsoon thunderstorm precipitating clouds observed over Kadapa (14.47°N, 78.82°E), Tropical semi-arid region of India

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सार – भारत के आन्ध्र प्रदेश राज्य के अर्धशुष्क भूभाग, कड़पा (14.47 डिग्री उ., 78.82 डिग्री पू.) में लगाए गए कण के आकार और वेग (पारवीवेल) वाले डिस्ड्रोमीटर स 'जल' चक्रवात से उत्पन्न वर्षण मेघों (07 नवम्बर 2010) तथा उत्तर पूर्व (एन. ई.) मानसून गर्ज वाले तूफान के वर्षण मेघों (16 नवम्बर 2010) के बूँद के आकार के वितरणों (आर. एस. डी.) को मापा गया है। प्रेक्षणात्मक परिणामों से हमें यह पता चला है कि चक्रवात की वजह से उत्पन्न वर्षण मेघों में संवहनी वर्षण प्रबल रहा। जबकि उत्तर पूर्व मानसून के मामले में गर्ज वाले तूफान वर्षण संवहनी मेघ के भाग स्तरी मेघों की तूलना में अधिक हैं। चक्रवात से उत्पन्न वर्षण, उत्तर पूर्व मानसून वर्षण की तुलना में स्तरी क्षेत्र (संवहनी क्षेत्र) में छोटी बूँदों (छोटी और मध्यम आकार की बूँदों) से संबंध है। स्तरी और संवहनी मेघ क्षेत्रों में उत्तर पूर्व मानसून वर्षण की तूलना में औसत द्रव्यमान भारित व्यास, चक्रवात से उत्पन्न वर्षण का Dm कम है। वर्षा की बूँदों के आकार का प्रेक्षण चक्रवातीय और उत्तर पूर्व मानसून गर्ज के साथ तूफानों के वर्षण मेघों में अलग तरह की भिन्नता देखी गई है।

ABSTRACT. Raindrop size distributions (RSD) of "JAL" Cyclone induced precipitating clouds (7 Nov. 2010) and North- East (NE) monsoon thunderstorm precipitating clouds (16 November 2010) were measured with a Particle Size and Velocity (PARSIVEL) disdrometer deployed at Kadapa (14.47°N; 78.82°E), a semiarid continental site in Andhra Pradesh state, India. From the observational results we find that stratiform precipitation is predominant than convective precipitation in cyclone induced precipitation clouds. Where as in the case of NE monsoon thunderstorm precipitation convective cloud fraction is more than stratiform clouds. The cyclone induced precipitation is associated with higher concentration of small drops (small and middrops) in stratiform region (convective region) than NE monsoon precipitation. The average mass weighted diameter, Dm of cyclone induced precipitation is less than the NE monsoon precipitation both in stratiform and convective cloud regions. The observed RSD are found distinctly vary from cyclonic and NE monsoon thunderstorm precipitating clouds.

Key words – "JAL" cyclone, Raindrop size Distribution, Disdrometer, Rain rate, Mean diameter.

1. Introduction

Rainfall is the most important variable in the tropics. In India, a long stretch of land situated to the south of tropic of cancer and east of the western ghats and the Cardamom hills experiences semiarid climate. It includes Karnataka, interior and western Tamil Nadu, Andhra Pradesh (except coastal region) and central Maharashtra. The problem of water shortage in arid zones of Andhra Pradesh is due to low annual rainfall and the unfavorable distribution of rainfall through the year. Kadapa (14.47°N; 78.82°E) experiences scanty rainfall and its annual average rainfall is much below the national average, therefore it experiences drought. The ground water level never reaches expected levels even in monsoon seasons due to scanty rainfall and poor seepage conditions. Under these conditions, only drought-resistant plant species alone survive resulting in the decrease of forest cover. In summer, the maximum temperature reaches ~46°C. These semi-arid conditions result in desertification. Many predict that total desertification is not far. Hence, it is very essential to study the lower atmosphere, more specially the precipitating clouds characteristics [*i.e.* Raindrop Size Distribution (RSD)], so as to take up the remedial measures.

There were a few studies on cyclones in determining the Raindrop Size Distribution (RSD) characteristics over the globe. From the airborne measurements, Merceret (1974) showed that the Marshall-Palmer form is also a good model for the spectra from tropical Hurricane Ginger and also applicable to surface raindrop distributions in extra tropical weather systems. Jorgensen and Willis (1982) represented a composite hurricane Z-R relationship of $Z=300R^{1.35}$ for both convective and stratiform rain regimes of the hurricane. RSD characteristics differences

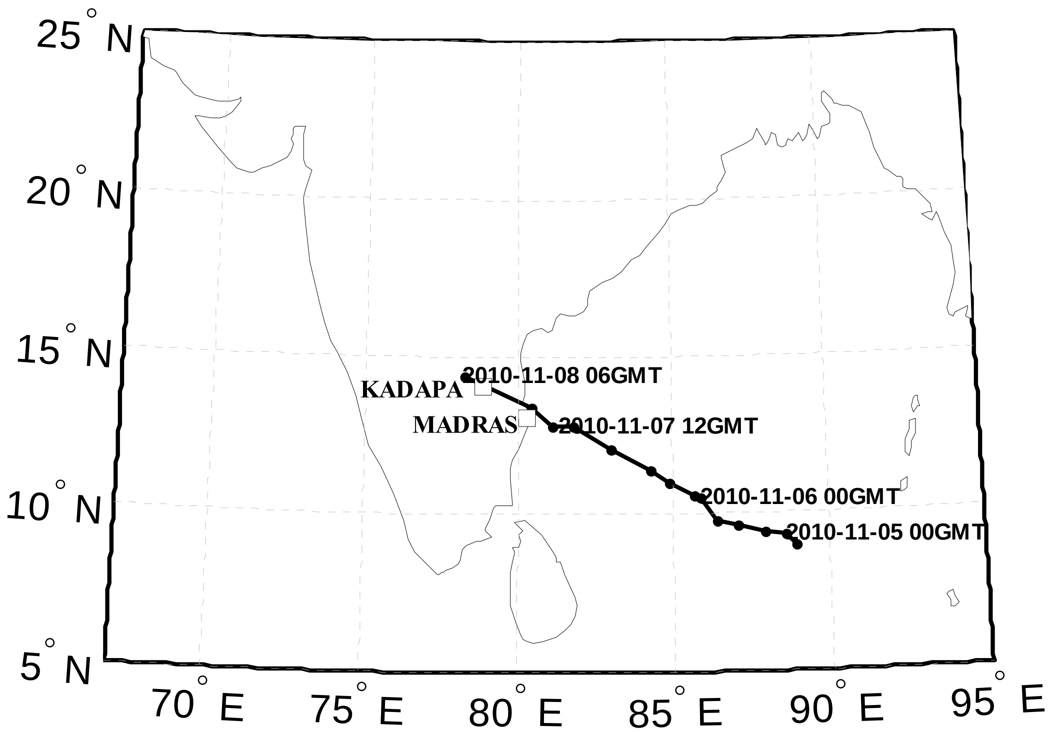
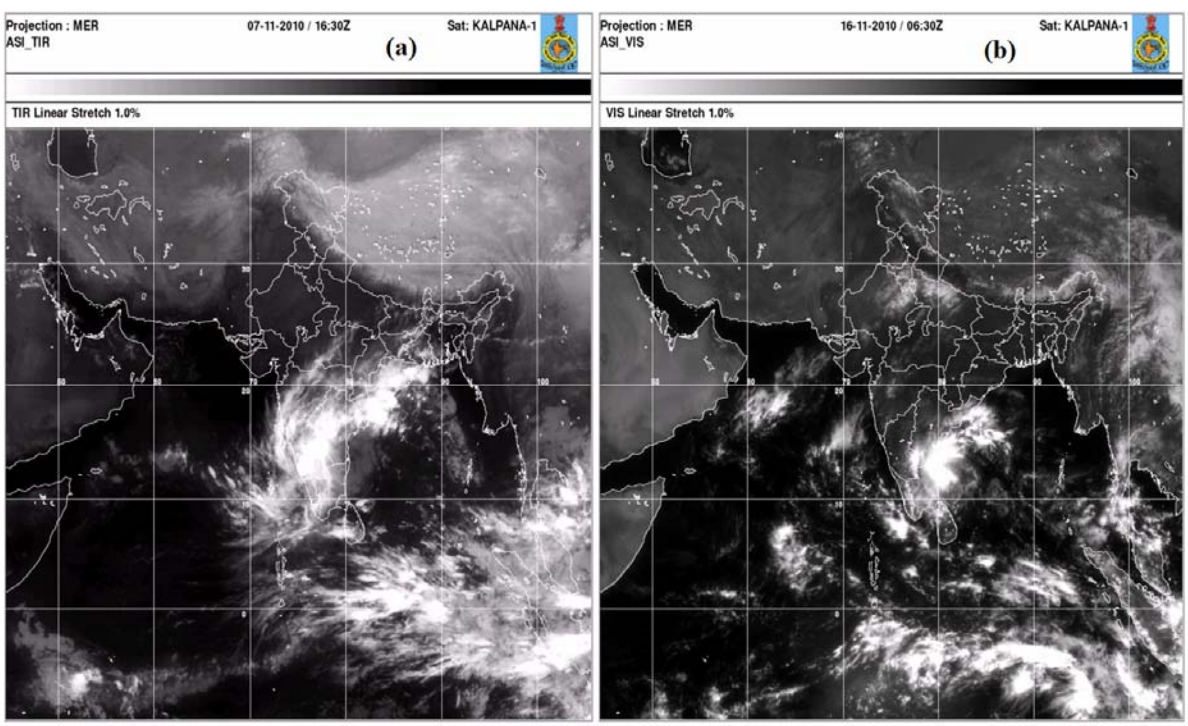


Fig. 1. The track of "JAL" cyclone, observational site location (Kadapa) and Chennai IMD, Doppler radar location are denoted by square boxes



Figs. 2(a&b). Kalpana satellite image of cyclonic day (7 November 2010) and NE monsoon precipitation day (16 November 2010) in prior to and during the passage of remnants of Hurricane Helene formed over Atlantic Ocean during 2000 presented by Ulbrich and Lee (2002) using JWD disdrometer. Maeso *et al*., (2005) studied the RSD characteristics during the passage of tropical storm Jeanne formed during 2004 with two-dimensional video disdrometer. Tokay *et al*., (2008) observed high concentrations of small and/or midsize drops in the presence or absence of large drops with maximum drop diameter rarely exceeded 4 mm.

In India, tropical cyclones mostly form over Bay of Bengal during north-east monsoon (October to December) period causes damage to the life and economy of Andhra Pradesh, Tamil Nadu, and parts of Kerala state. Studies on precipitation (drop size distribution studies) in terms of their statistical characteristics (Sen and Singh, 1999, Kirankumar *et al*., 2008), monsoon variability (difference in south west and north east monsoon) (Reddy and Kozu 2003, Narayana Rao *et al*., 2009), spatial, seasonal and diurnal variation (Kozu *et al*., 2006, Radhakrishna & Narayana Rao, 2009), Radar Reflectivity factor (Z)- Rain Rate (R) relations (Narayana Rao *et al*., 2001, Sen *et al*., 2009), its variation between eastern and western coasts (Harikumar *et al*., 2007) were carried out. A few studies are carried out on tropical cyclone RSD characteristics (Radhakrishna & Narayana Rao 2009). As the characteristics of RSD in tropical cyclones are important for representation of microphysical process in mesoscale models and also microphysical characteristics vary from one cyclone to other cyclone, it is essential to study the microphysical characteristics of individual cyclones.

Usually, the coastline districts of Andhra Pradesh state are affected by cyclones and floods, whereas for the first time over Kadapa a semiarid region of India which is in the interior of Andhra Pradesh too was affected by precipitation during passage of "JAL" cyclone from east coast to west coast. The tropical cyclone "JAL" (India Meteorological Department designation: BOB 05) is the fifth named cyclonic storm and the fourth severe cyclonic storm of the year 2010 developed from a low pressure area in the South China Sea in the form of tropical depression on 28th October 2010 and formed in the Bay of Bengal during 4th November 2010 to 7th November 2010. The complete track of "JAL" cyclone and measurement site, Kadapa is indicated as square box in Fig. 1. The precipitation induced due to "JAL″ cyclone and NE monsoon thunderstorm clouds over Kadapa is observed with the help of Kalpana satellite IR cloud cover images [Figs. 2(a&b)] and also from the Chennai Doppler Weather Radar, Maximum radar reflectivity and Plane Position Indicator images of Doppler velocity (Fig.3). For the first time in India, this paper examines the PARSIVEL Disdrometer measurements collected over semiarid region of Kadapa during "JAL" cyclone passage and NE monsoon thunderstorm precipitating clouds, with main focus on characteristic comparison of the spectral shapes of RSD from cyclone induced precipitation and north eastern monsoon precipitation. The paper is organized as follows: section 2 describes the Instrumentation. Section 3 presents RSD analyses of cyclone induced precipitating clouds and NE monsoon precipitating cloud. Section 4 examines the measurement of raindrop fall velocities. Section 5 details variation of meteorological parameter for cyclonic and NE monsoon precipitation and the major findings are summarized in section 6.

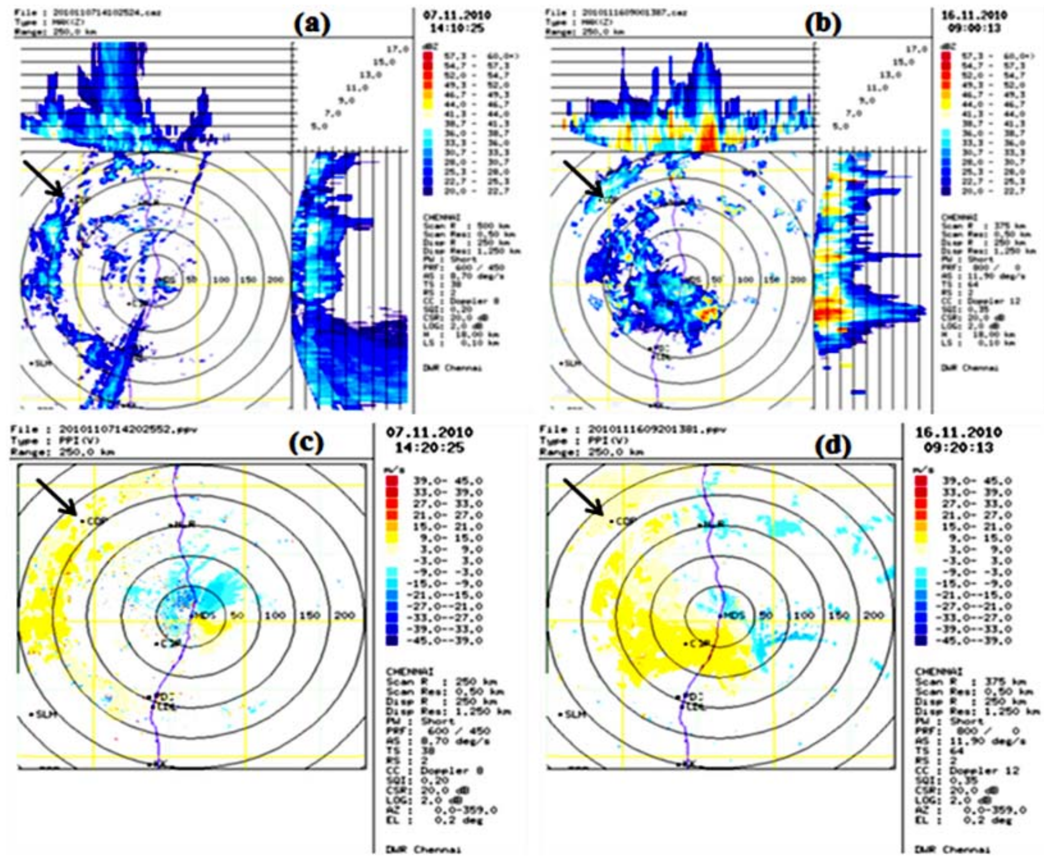
2. Data and methodology

2.1. *Instrumentation*

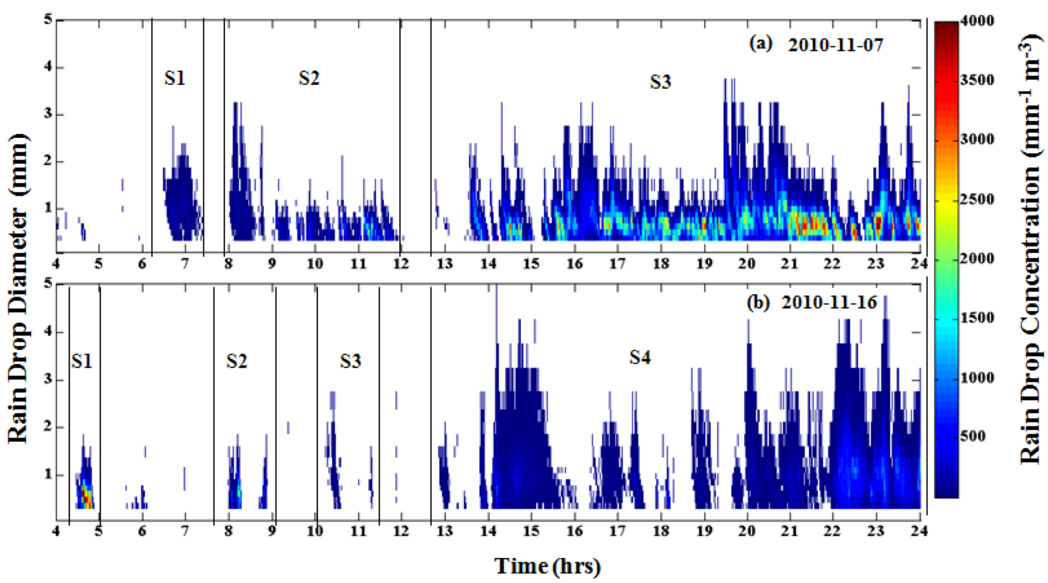
For the present study data obtained from a ground-based optical disdrometer called PARSIVEL disdrometer and Automatic Weather Station (AWS) installed at Yogi Vemana University (14^{o} 47' N, 78^{o} 82' E) in Kadapa district during the land fall of "*JAL"* cyclone and NE monsoon precipitation day is utilized. The Kadapa is about 220 km from Chennai (13.08^{o} N, 80.27^{o} E) and are shown with square boxes in Fig. 1. The PARSIVEL disdrometer was designed to count and measure simultaneously the fall speed and size of precipitation particles. The core element of the instrument is an optical sensor that produces a horizontal sheet of light (180-mm long, 30-mm wide, 1-mm high, wave length of 650 nm and output voltage of 3 mW). The particle diameter from the PARSIVEL disdrometer can be measured from the maximum reduction of the voltage. PARSIVEL detect 8 different precipitation types (drizzle, mixed drizzle/rain, rain, mixed rain/snow, snow, snow grains, ice pellets and hail) according to the WMO, SYNOP, METAR and NWS weather codes. It measures precipitation particles sizes up to 25 mm (0.2 to 5 mm for liquid precipitation and 0.2 to 25 mm for solid precipitation) and uses 32 size bins of different widths, ranging from 0.125 to 3 mm. The velocity is also subdivided into 32 bins with different widths, ranging from 0.1 to 3.2 m/s. The lowest two size bins are not used at all, because of their low signal-to-noise ratios. The measurement of this instrument is done by assuming the hydrometeors as oblate spheroids with a pre-assumed relationship between drop axis ratio (A_r - defined as the ratio of height to width) and drop diameter (D_{eq}).

$$A_r = 1.075 - 0.075\ D_{eq} \quad (1)$$

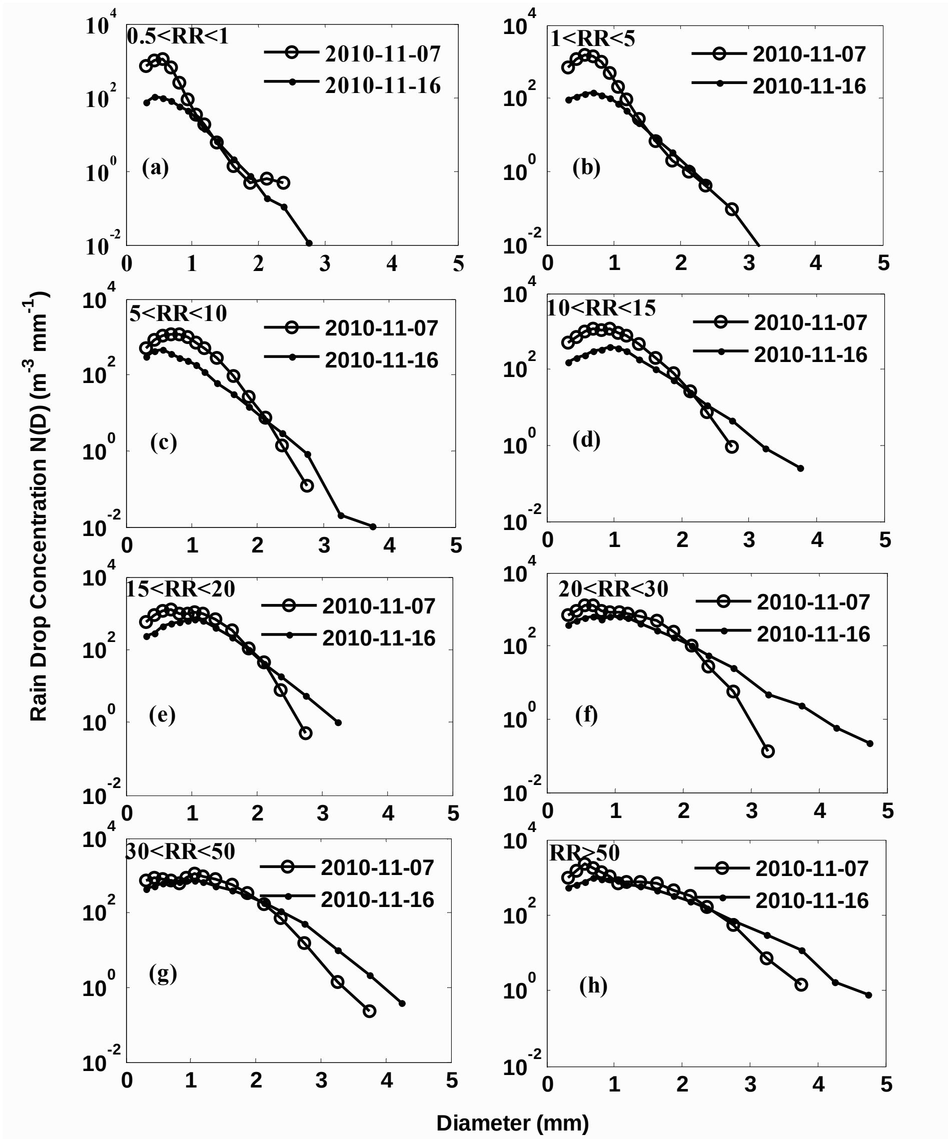
In the range from 1 to 5 mm, all raindrops are assumed to be horizontally oriented oblate spheroids with axial ratio (A_r) linearly varying from 1 to 0.7 and for



Figs. 3(a-d). Chennai Doppler Weather Radar PPI of Radar reflectivity (dBZ) and Doppler velocity covering Kadapa (indicated by arrow at CDP) for cyclonic (7 November 2010) and NE monsoon precipitation day (16 November 2010)



Figs. 4 (a&b). Time series of rain drop size distributions for cyclonic day (7 November 2010) and NE monsoon precipitation day (16 November 2010)



Figs. 5(a-h). Raindrop concentration *Vs* drop diameter at different rain rates cyclonic day (7 November 2010) and NE monsoon precipitation day (16 November 2010)

particles with diameters above 5 mm, the axial ratio (A_r) is kept constant value of 0.7. Complete details of measurement technique, along with the assumptions made in determining the size and velocity of hydrometeors can be found in Loffler-Mang and Joss (2000) and Tapidor *et al.*, (2010).

2.2. *Methodology*

The rain drop concentration $N(D)$ (mm^{-1} m^{-3}) at an instant of time from the PARSIVEL disdrometer counts is obtained from the following equation,

$$N(D_i) = \sum_{j=1}^{32} \frac{n_{ij}}{A.\Delta t.V_j.\Delta D_j} \quad (2)$$

where n_{ij} is the number of drops reckoned in the size bin i and velocity bin j, A (m^2) and Δt (s) are the sampling area and time, D_i (mm) is the drop diameter for the size bin i and ΔD_i is the corresponding diameter interval (mm), V_j (m/s) is the fall speed for the velocity bin j. From the rain drop concentration $N(D)$, drop diameter (D) and

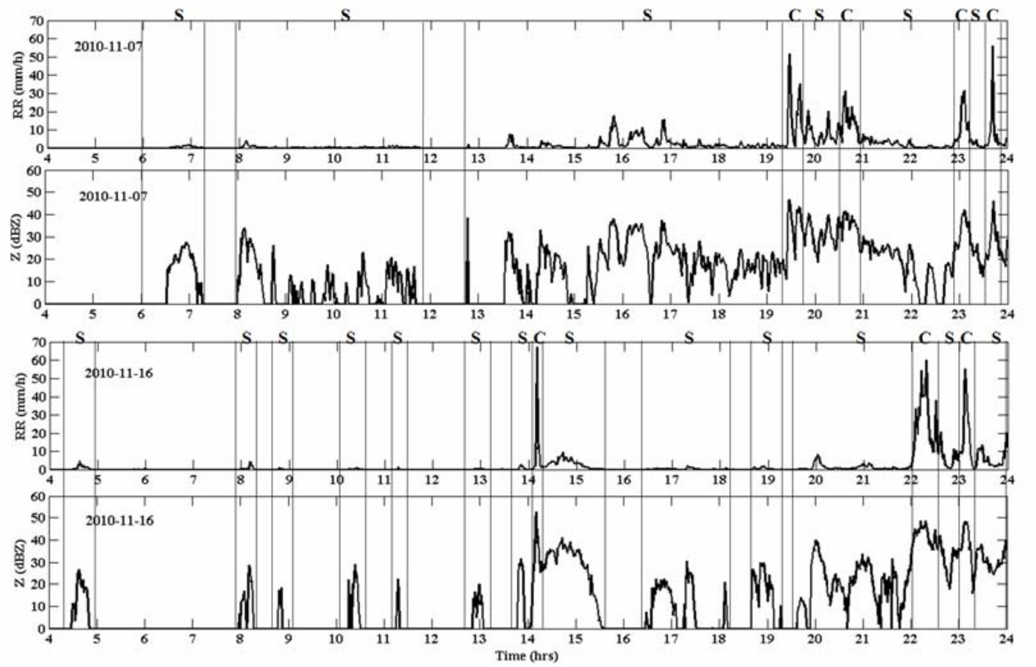
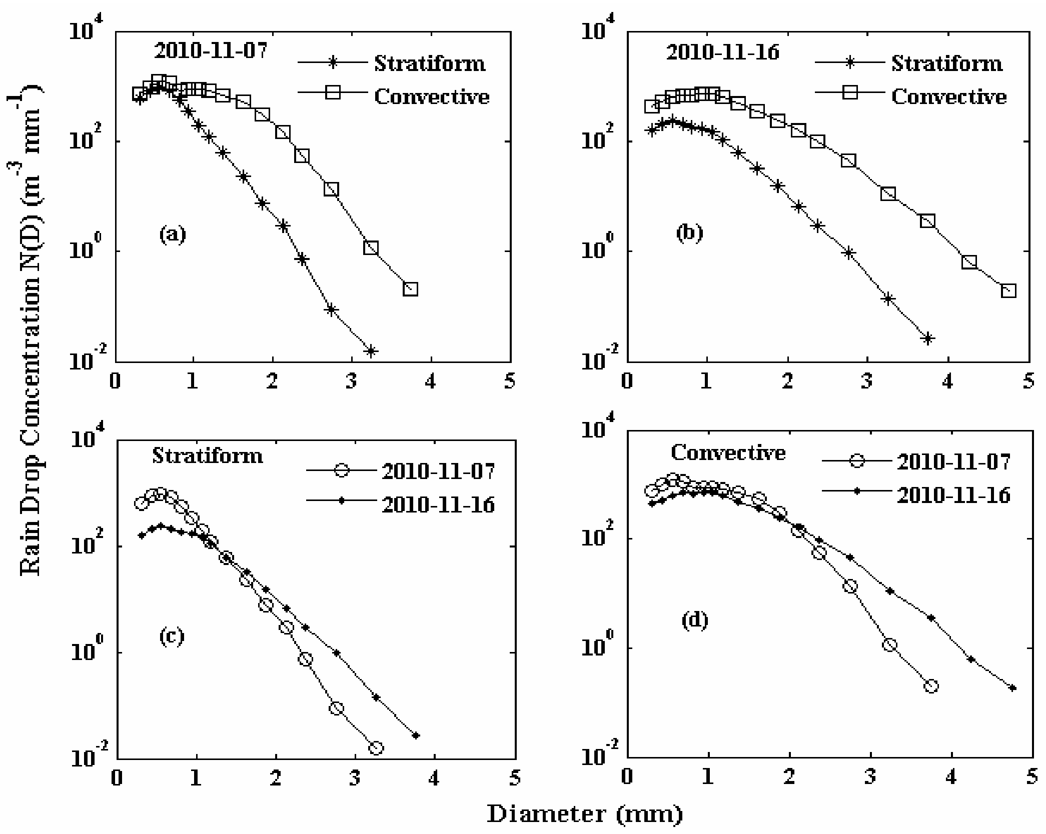


Fig. 6. Classification of Convective (C) and stratiform (S) region of cyclonic (7th November 2010) and NE monsoon precipitation (16 November 2010) days



Figs. 7(a-d). Raindrop concentration *Vs* drop diameter of convective and stratiform precipitation of cyclonic (7 November 2010) and NE monsoon precipitation (16 November 2010) days fall velocity V_j the the radar reflectivity factor Z (mm^6 m^{-3}) and rain rate R (mm/h) are derived by

$$Z = \sum_{j=1}^{32} N(D_j) D_j^6 \Delta D_j \quad (3)$$

$$R = \frac{6\pi}{10^4} \sum_{i=1}^{32} \sum_{j=1}^{32} V_j N(D_j) D_j^3 \Delta D_j \quad (4)$$

the n^{th} order moment of the drop size distributions is expressed as

$$M_n = \int_{D_{min}}^{D_{max}} D^n N(D) dD \quad (5)$$

Where n =3 for 3rd moment , 4 for 4th moment and 6 for 6th moment of the size distribution. The mass-weighted mean diameter D_m (mm), shape parameter μ and slope parameter Λ (mm^{-1}) are obtained from the 3rd, 4th and 6th moments of the size distribution as

$$D_m = \frac{M_4}{M_3} \quad (6)$$

The slope parameter - Λ (mm^{-1}) is given by

$$A = \frac{(\mu + 4) M_3}{M_4} \quad (7)$$

Where μ is the shape parameter without dimensions and is given by

$$\mu = \frac{(11G - 8) + \sqrt{G(G + 8)}}{2(1 - G)} \quad (8)$$

Where G is

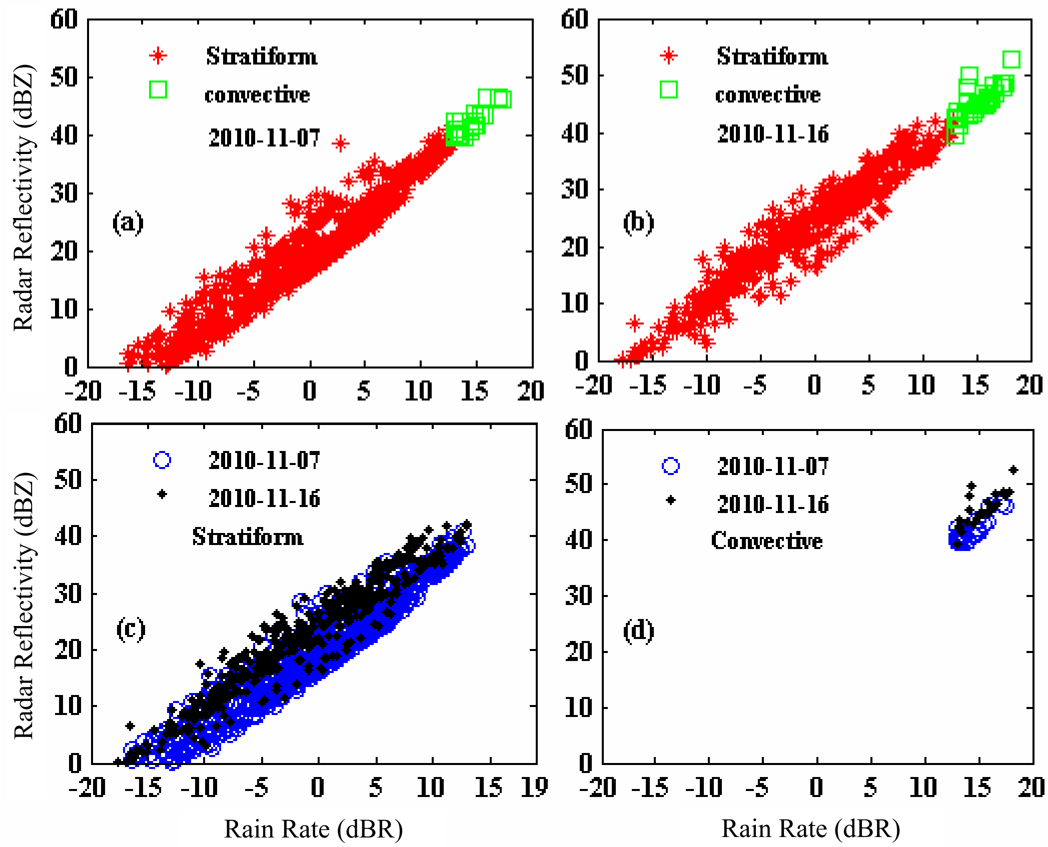
$$G = \frac{M_4^3}{M_3^2 M_6} \quad (9)$$

3. RSD analyses of cyclonic and NE monsoon precipitating clouds

3.1. *Comparison of raindrop concentration for cyclonic and NE monsoon precipitation*

The time series of the RSD during the passage of "JAL" cyclone on 7th November 2010 revealed three different segments that were separated by rain intermittence of half an hour to an hour with total rain accumulation of 41.0 mm occurred for a total period of 8 hours 49 minutes [Fig. 4(a)]. We considered raindrops with below 1 mm diameter as small drops, above 3 mm as large drops and those in between the diameter range 1- 3 mm as midsize drops. The first segment occurred for 42 minutes in between 06:33 & 07:15 hrs (IST). The highest reflectivity of 27.6 dBZ, and maximum rain intensity, 1.8 mm/h with a maximum drop concentration of 218.8 m^{-3} mm^{-1} and rainfall accumulation of 0.5 mm is observed during this event. The concentration of small drops is more compared to midsize and large drops during this segment. The second segment lasted over 2 hours 41 minutes from 08:01 to 11:46 hrs (IST) with rain gaps ranging from one minute to seventeen minutes with maximum rain rate 3.4 mm/h, reflectivity 34.1 dBZ with a maximum concentration of 2249.1 m^{-3} mm^{-1} and rainfall of 0.9 mm. The concentration of the second segment is in between first and third segment. In this segment relatively low concentrations (1000-1500 m^{-3} mm^{-1}) of small drops are observed. The third and the most intense regime of the cyclonic precipitation had 5 hours 26 minutes of continuous rainfall from 12:34 to 24:00 hrs (IST). In this segment maximum rain rate of 55.6 mm/h and radar reflectivity of 46.5 dBZ and drop concentration of 4305.3 m^{-3} mm^{-1} with a rain accumulation of 39.6 mm is observed. At the end of the third portion from 21:00 hrs (IST) large concentrations of small drops were present, while an appreciable number of medium drops also present. Interestingly, higher reflectivity and rain rate values are observed during this third segment of the cyclonic precipitation between 21:00 to 23:00 hrs (IST). Relatively high concentrations of midsize and large drops are responsible for the heavy rain and high reflectivity. The parameters values of these three segments (S1, S2 & S3) are given in the Table 1.

The time series of the RSD of NE monsoon thunderstorm precipitation occurred on 16th November 2010 revealed four different segments that were separated by rain intermittence of one hour twenty two minutes to three hours six minutes with total rain accumulation of 36.3 mm occurred for a period of 8 hours 39 minutes [Fig. 4(b)]. The first segment occurred for 23 minutes between 04:29 to 04:51 hrs (IST). The maximum reflectivity of 26.5 dBZ, and maximum rain intensity, 4.3 mm/h with a maximum drop concentration of 5105.0 m^{-3} mm^{-1} and rainfall accumulation of 0.5 mm is observed during this event. The concentration of small drops is more compared to midsize drops during this segment. The second segment occurred for 24 minutes between 07:59 & 08:52 hrs (IST) with a rain gap of 29 minutes. In this segment maximum reflectivity of 28.6 dBZ, maximum rain intensity of 4.2 mm/h, maximum drop concentration



Figs. 8 (a-d). Radar reflectivity (dBZ) and rain rate (dBR) relations for convective and stratiform regions of cyclonic and NE monsoon precipitation days.

TABLE 1

Maximum values of rain rate (RR- mm/h), radar reflectivity(Z-dBZ) and rain drop concentration [N(D) - m^{-3} mm^{-1}] of cyclonic day (7th November 2010) and NE monsoon thunderstorm precipitation day (16th November 2010) in different segments (S1-S4)

Parameters	Cyclonic Day			NE Monsoon Precipitation Day			
	S1	S2	S3	S1	S2	S3	S4
Duration (minutes)	42	161	326	23	24	15	457
RR_{max} (mm/h)	1.8	3.4	55.6	4.3	4.2	1.2	67.2
Z_{max} (dBZ)	27.6	34.1	46.5	26.5	28.6	29.2	52.8
$N(D)_{max}$ (m^{-3} mm^{-1})	218.8	2249.1	4305.3	5105.0	2223.3	483.8	1706.1
Rainfall (mm)	0.5	0.9	39.6	0.5	0.3	0.1	35.4
Total rainfall (mm)		41.0				36.3	

of 2223.3 m^{-3} mm^{-1} with rainfall accumulation of 0.3 mm observed. The third segment occurred for 15 minutes between 10:16 & 11:18 hrs (IST) with a rain gaps ranges from one minute to 43 minutes. In this segment maximum reflectivity of 29.2 dBZ, maximum rain intensity of 1.2 mm/h with a maximum drop concentration of 483.8 m^{-3} mm^{-1} and rainfall accumulation of 0.1 mm were observed. The fourth segment occurred for 7 hrs 37 minutes between 12:52 & 24:00 hrs (IST) with a rain gaps ranges from one minute to 51 minutes. In this segment maximum reflectivity of 52.8 dBZ, maximum rain intensity of 67.2 mm/h with a maximum drop concentration of 1706.1 m^{-3}

mm^{-1} and rainfall accumulation of 35.4 mm were observed. The parameter values of above four segments (S1, S2, S3 & S4) are given in Table.1.

3.2. *Variation of RSD with rain rate*

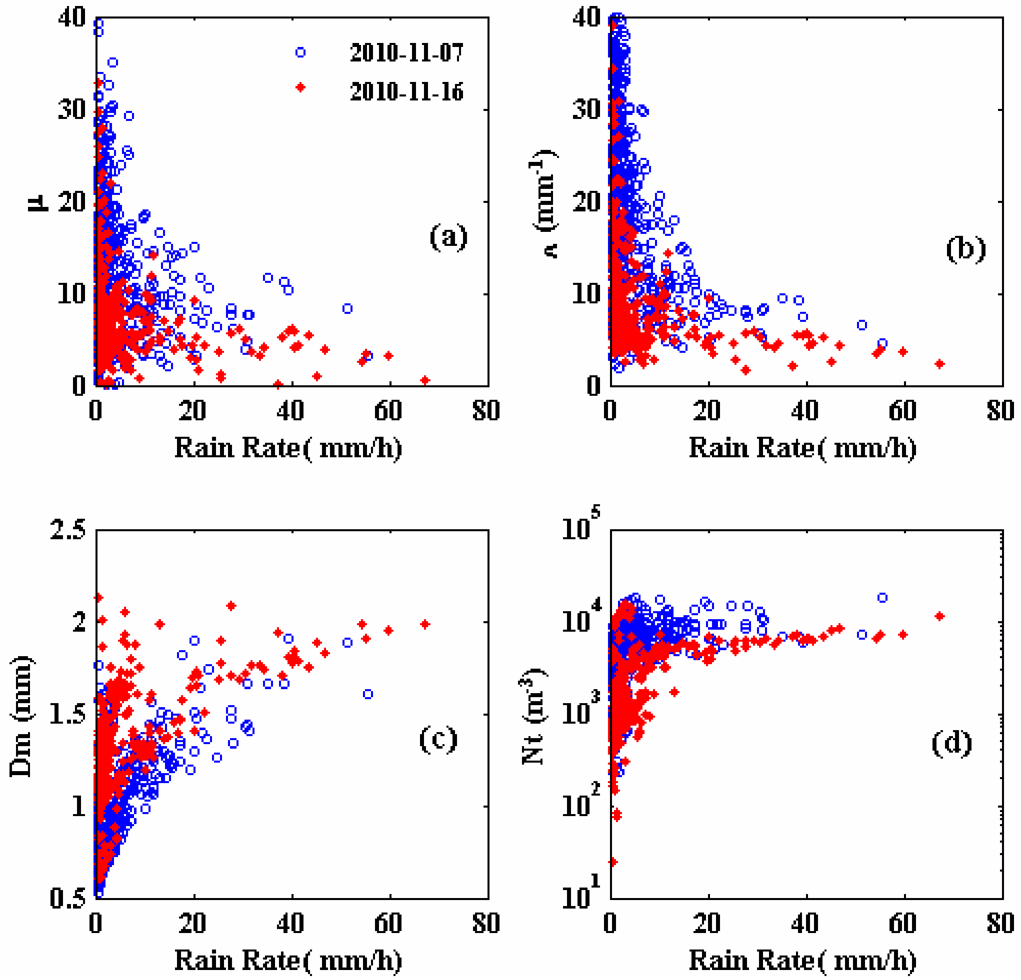
The RSD of cyclonic (7th November 2010) and NE monsoon (16th November 2010) precipitation at different rain rate ranges are depicted in Figs. 5(a-h). We have classified the rain rates (RR) of cyclonic and NE monsoon precipitation into 8 categories (0.5<RR<1, 1<RR<5, 5<RR<10, 10<RR<15, 15<RR<20, 20<RR<30, 30<RR<50, RR>50) and the RSD in each category is averaged to get the mean RSD of each rain rate range. In the rain rate range 0.5 to 1.0 mm/h, 104 minutes of cyclonic precipitation and 57 minutes of NE monsoon precipitation is observed [Fig. 5(a)]. In this rain rate range small drops have high concentration in the cyclonic than NE monsoon precipitation where as midsize drops have same concentration for both precipitations. For the rain rate range 1 to 5 mm/h, 289 minutes of cyclonic and 152 minutes of NE monsoon precipitation is observed [Fig. 5(b)]. In this rain rate range high concentration of small drops and same concentration of midsize drops is observed for cyclonic and NE monsoon precipitation but there were no large drops in this rain rate range for both the precipitations. In the rain rate range 5-10 mm/h, 60 minutes of cyclonic and 45 minutes of NE monsoon precipitation is shown [Fig. 5(c)]. In this rain rate range small and midsize drops below 2mm diameter of cyclonic precipitation is having higher concentration than NE monsoon precipitation but it is reversed for midsize drops above 2mm diameter. In the rain rate range 10-15 mm/h, 31 minutes of cyclonic and 20 minutes of NE monsoon precipitation is observed [Fig. 5(d)]. In the rain rate range 15-20 mm/h, 12 minutes of cyclonic and 7 minutes of NE monsoon precipitation is observed [Fig. 5(e)]. In both the rain rate ranges (10-15 and 15-20 mm/h) small and midsize drops up to 2.5 mm diameter are having high concentration in cyclonic than NE monsoon precipitation and this pattern is reversed in midsize drops above 2.5 mm diameter. In the rain rate range 20-30 mm/h, 13 minutes of cyclonic and 11 minutes of NE monsoon precipitation is observed [Fig. 5(f)]. In the rain rate range 30-50 mm/h, 07 minutes of cyclonic and 14 minutes of NE monsoon precipitation is observed [Fig. 5(g)]. In these rain rate ranges (20-30 mm/h and 30-50 mm/h) small and midsize size drops up top 2.0 mm diameter are having same concentration for both cyclonic and NE monsoon precipitation. Midsize drops above 2.0 mm are having less concentration for cyclonic precipitation than NE monsoon precipitation. For above 50 mm/h rain rate range, 2 minutes of cyclonic and 04 minutes of NE monsoon precipitation is observed [Fig. 5(h)]. In this rain rate range small and midsize drops are having same concentration for both cyclonic and NE monsoon precipitation where as for large drops have less concentration in cyclonic compared to NE monsoon precipitation. In cyclonic precipitation below 20mm/h rain rate range, the concentration of small drops is greater compared to midsize drops and there were no large drops.

3.3. *Variation of RSD with convective and stratiform precipitation*

The JAL cyclone induced precipitation (7th November 2010) and NE monsoon thunderstorm precipitation (16th November 2010) are classified into convective and stratiform regions with the rain rate threshold values of 20 mm/h. Precipitation segments with rain rate below 20 mm/h are considered as stratiform and above as convective type (Fig. 6). Cyclone induced precipitation day (7th November 2010) is having convective precipitation for a period as 22 minutes and 783 minutes of stratiform precipitation. The NE monsoon precipitation day is associated with 499 minutes of stratiform precipitation and 29 minutes of convective periods. In cyclone induced precipitation day raindrops below 1 mm diameter are having same concentration in both convective and stratiform region [Fig.7(a)] and above 1mm diameter the drop concentration is high for convective precipitation than stratiform precipitation. In NE monsoon precipitation day convective precipitation is having high concentration than stratiform precipitation [Fig.7(b)]. In the stratiform region the cyclone induced precipitation is having high drop concentration up to ~1.4 mm diameter than NE monsoon precipitation and a reverse pattern is observed above 1.4 mm diameter [Fig. 7(c)]. In convective region, rain drops above 2mm cyclone induced precipitation is having low drop concentration than NE monsoon and for the raindrops below 2mm diameter the cyclone induced precipitation is associated with slightly higher concentration than NE monsoon. [Fig. 7(d)]. The $Z= A*R^b$ relations of stratiform and convective regions of cyclone induced precipitation and NE monsoon precipitation days are obtained from scatter plots of radar reflectivity (dBZ) and rain rate (dBR) [Figs. 8(a-d)]. The coefficient 'A' and exponent 'b' of stratiform, convective regions of cyclonic and NE monsoon thunderstorm precipitation days are shown in Table. 2. From the Z-R scatter plots of stratiform and convective regions it is clear that the cyclone induced precipitation is having raindrops of size less than or equal to that of NE monsoon thunderstorm precipitation rain drops.

3.4. *Variation of mean drop diameter (D_m), shape(μ) and slop(Λ) parameters*

The variation of shape(μ) and slope parameter Λ (mm^{-1}), mean diameter *Dm* (mm) and total drop



Figs. 9(a-d). The scatter plot of (a) μ (b) Λ (mm^{-1}) (c) *Dm* (mm) and (d) the total concentration of raindrops N_t (m^{-3}) *Vs* rainfall rate (mm/h) of cyclone induced precipitation and NE monsoon precipitation days

TABLE 2

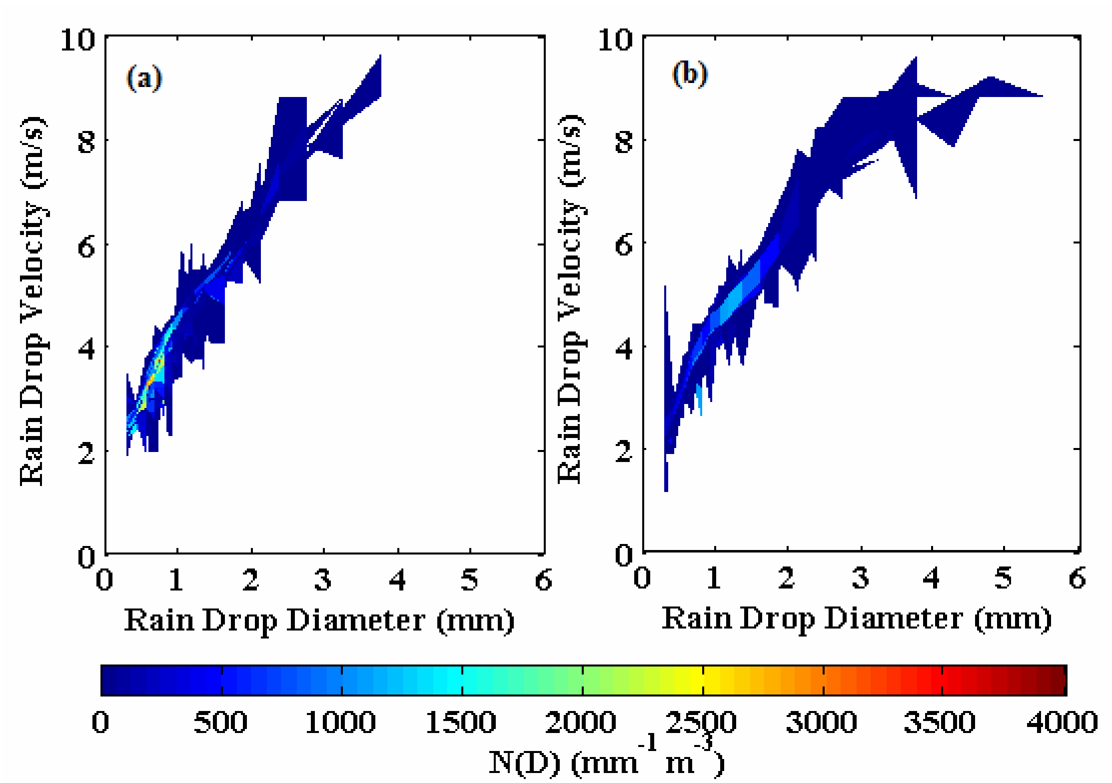
Z = A*R^b values of stratiform and convective regions of cyclonic and NE monsoon thunderstorm precipitation

Day	Stratiform			Convective		
	A	**B**	**R^2**	**A**	**B**	**R^2**
7 November 2010	96.04	1.33	0.9521	122.65	1.46	0.8688
16 November 2010	263.10	1.35	0.9608	238.35	1.42	0.7552

TABLE 3

Mean values of μ (dimensionless), Λ (mm^{-1}), *Dm* (mm) and N_t (m^{-3}) in the stratiform and convective regions of cyclone precipitation and NE monsoon thunderstorm precipitation

Day	Stratiform				Convective			
	μ	Λ	*Dm*	*Nt*	μ	Λ	*Dm*	*Nt*
7 November 2010	13.8	21.4	1	6326.9	7.8	7.6	1.6	9235.4
16 November 2010	7.9	10.1	1.3	2400.1	3.7	4.4	1.8	6394.5

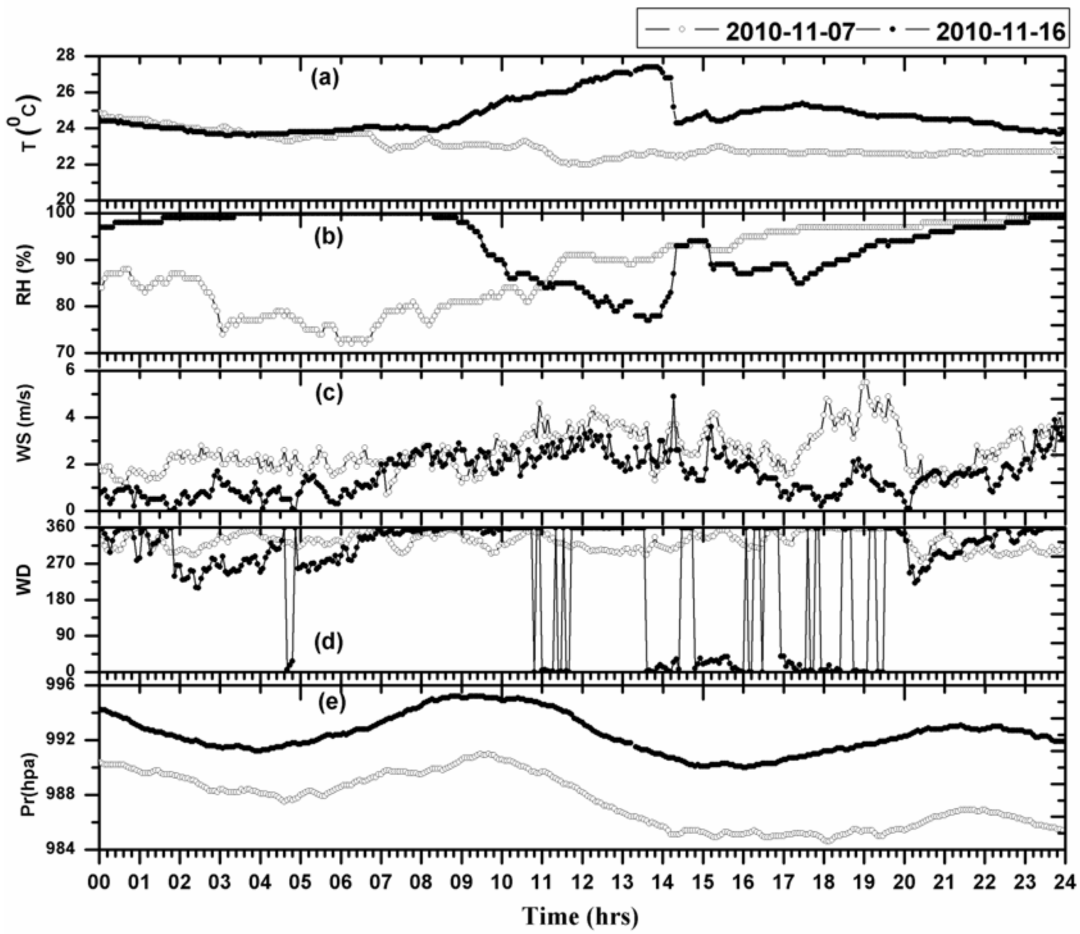


Figs. 10 (a&b). Raindrop concentration [$N(D)$] as a function of the raindrop diameter and raindrop fall velocity for the (a) cyclonic precipitating day (7 November 2010) and (b) NE monsoon precipitating day (16 November 2010)

concentration N_t (m^{-3}) with rain rate of cyclone induced precipitation and NE monsoon thunderstorm precipitation are shown in Figs. 9(a-d). From the Fig. 9 it is clear that the range of variability of μ, Λ, *Dm* and N_t is more for cyclone induced precipitation than NE monsoon precipitation in the rain rate less than 20 mm/h. This variation decreases with increase in rain rate and becomes more uniform above 20 mm/h. The shape (μ) and slope parameter Λ (mm^{-1}) decreased with the increase in rain rate and this decrease is more sharp in NE monsoon precipitation than cyclone induced precipitation. The *Dm* increased with increase in rain rate but this increase is more steep in NE monsoon precipitation than the cyclone induced precipitation. In the cyclone induced precipitation the average *Dm* values is 1 mm for the rain rate below 20 mm/h and 1.6 mm for above 20 mm/h and for NE monsoon precipitation this values is 1.3 mm and 1.8 mm below and above 20 mm/h rain rate. In cyclone induced precipitation and NE monsoon precipitation day N_t is increased upto rain rate range of 20 mm/h. The shape (μ) and slope parameter Λ (mm^{-1}) , mean diameter *Dm* (mm) and total drop concentration N_t (m^{-3}) values of stratiform and convective regions of cyclone induced precipitation and NE monsoon precipitation are given in Table 3. From the values of D_m and N_t it is clear that in the cyclone induced precipitation the convective region is mainly composed of small to mid size drops rather than large drops where as the stratiform region is composed of only small drops.

4. Drop size and fall velocity relation

Raindrop fall velocity is useful for the measurement of rain integral parameters like radar reflectivity, liquid water content and rain rate. Fall velocity plays an important role in rain related studies in numerical simulation and remote sensing (Pruppacher and Klett 1998; Cotton and Anthes 1989). Figs. 10 (a&b) show the observed drop concentration as a function of drop diameter and the fall velocity for the cyclonic and NE monsoon precipitation. For the cyclone induced precipitation small drops have high concentration with fall velocities less than 4 m/s, where as for NE monsoon precipitation midsize drop have high concentration with fall velocity ranging 4-6 m/s. There is a larger spread in the drop fall velocities of mid and large drops in the NE monsoon precipitation compared to cyclonic precipitation.



Figs.11(a-e). Time series of meteorological parameters (Temperature, Relative humidity, Wind speed, Wind direction, Pressure) obtained from AWS for cyclonic (7th November 2010) and NE monsoon precipitation (16th November 2010) days

5. Variation of meteorological parameters

Figs. 11(a-e) details the diurnal variation of meteorological parameters like temperature, relative humidity, wind speed, wind direction and pressure. It is clear from Fig. 11(a) that a sudden fall of temperature by an amount of 4° C from 13:54 hrs (IST) to 14:34 hrs (IST) is observe for NE monsoon precipitation where as in cyclonic precipitation there is no significant fall and diurnal pattern of temperature. Throughout the cyclonic day temperature varies from 24.9 to 21.7° C. A gradual increase of relative humidity from 06:00 hrs (IST) is observed on 7th November 2010 [Fig. 11(b)]. There is not much variation of wind speed in both cyclonic and NE monsoon day precipitations [Fig. 11(c)]. But there is a significant difference in the wind direction between cyclonic and NE monsoon precipitation days [Fig. 11(d)]. From the Fig. 11(d) it is clear that for cyclonic day the winds are moving from north west to south east where as for NE monsoon precipitation day there is no significant observation of wind direction. The diurnal pattern [Fig. 11(e)] of pressure remains the same for both cyclonic and NE monsoon precipitation but pressure is lowered by an average value of 4.9 hPa in cyclonic precipitation compared to NE monsoon precipitation.

6. Results

For the first time Raindrop Size Distributions (RSD) of cyclone (7th November 2010) induced precipitation and North-East monsoon thunderstorm precipitation (16th November 2010) was studied at a site located in a region of semiarid, temperate, plateau climate. In the cyclonic induced precipitation the concentration of small drops is high compared to midsize and large drops where as in NE monsoon precipitation the concentration of all the drops (small, mid and large) is almost same. The maximum raindrop diameter does not exceeds 4 mm even at higher rain rates in cyclone induced precipitation but for NE monsoon precipitation raindrop diameter exceeds 4 mm at higher rain rates. From the RSD characteristics it is clear that, both cyclonic and NE monsoon precipitation contains more small and mid drops up to 3 mm diameter at lower rain rates (< 5 mm/h). The cyclonic precipitation is associated with lower rain rates (< 5 mm/h) is having longer duration than NE monsoon precipitation. At the lower rain rate range (<5 mm/h) the small raindrops have high concentration in cyclonic than NE monsoon precipitation and midsize drops have same concentration in both cyclonic and NE monsoon precipitation days. Above 20 mm/h rain rates small and mid drops up to 2.0 mm diameter are having same concentration both in cyclonic and NE monsoon precipitation. The cyclone induced precipitation is associated with more stratiform events than convective events compared to that of NE monsoon precipitation. In cyclone induced precipitation raindrops below 1.5 mm diameter in stratiform region and 2 mm in convective regions are having higher concentration than NE monsoon precipitation. Which imply that cyclone induced precipitation is predominated by small and mid drops. The stratiform region of cyclone induced precipitation is having high concentration of small drops (<1 mm). Where as in the convective region of cyclone induced precipitation the small and mid drops (<2 mm) are having slightly higher concentration in cyclone induced precipitation than NE monsoon precipitation. From stratiform and convective regions of the Z-R scatter plots it is clear that the cyclone induced precipitation is having raindrops of size less than or equal to that of NE monsoon precipitation rain drops. In both stratiform and convection regions the mean values of total drop concentration N_t (mm^{-3}), shape parameter (μ), slope parameter Λ (mm^{-1}) are found to be larger and mass weighted diameter Dm as smaller in cyclone induced precipitation than NE monsoon precipitation. A large spread in fall velocities of mid and large drops is observed for NE monsoon precipitation than cyclone induced precipitation. A significant difference in the wind direction between cyclonic and NE monsoon precipitation days is observed and the pressured values is lowered by an average value of 4.9 hPa in cyclonic precipitation compared to NE monsoon precipitation.

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