Meteorological Sensors synergy for diagnosis of monsoon precipitating clouds over Kadapa, Semi-arid region of India

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Abstract— Long-term field experiment is an important approach to obtain microphysical information on monsoonal precipitating clouds in the semi-arid region, Kadapa (14.47°N; 78.82°E). A Micro Rain Radar (MRR), a PARSIVEL (PSD) Disdrometer have been deployed in the premises of Semi-arid-zonal Atmospheric Research Centre (SARC), Yogi Vemana University, Kadapa to study the characterization of tropical rainfall. Rain drop size distribution (DSD) and rain rate are obtained at the surface from the PSD data and at different heights from the MRR. And also, active radar observations from the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar provide high resolution satellite based rainfall estimates. To understand these measurements, it would be needed to compare with ground-based measurements and also be awared of the seasonal dependance of the satellite measurements. From 1 June 2009 to 31 July 2010, the monsoon experiment was carried out to understand performance of MRR and PSD with different monsoon DSD and vertical structure of precipitating clouds. The data from the disdrometer and that from micro rain radar corresponding to a height of 35 metre from the surface are taken here for comparison with the TRMM data. TRMM rain rate is available as 3 hourly data over a 0.25^o X 0.25^o grid. The correlation of the three hourly rainfall data between TRMM and PSDand TRMM and MRR have been found to be significant. For the southwest and the northeast monsoon periods, the correlation between the data from the TRMM and disdrometer is 0.9 and 0.8, respectively. The observational results indicate that MRR and PSD are reliable instruments for microphysical properties of monsoon precipitating clouds.

Index Terms— Monsoon; semi-arid region; Rain microstructure; Tropical rainfall; Radar Reflectivity, Rain drop size distribution

1 INTRODUCTION

Ground-based remote sensing and in-situ observations of atmospheric variables are collected in many sites worldwide for several applications, ranging from weather monitoring, meteorology, climatology, aviation support, etc.[1 - 4]. Ground-based remote sensing instruments based on different physical principles and working at different wavelengths of the electromagnetic spectrum are diversely sensitive to the different atmospheric properties[6,7]**.** Thus, instrumentations are able to observe diverse aspects of the atmosphere, such as chemical and physical composition, motion, thermodynamically properties (temperature, humidity, etc.) and rainfall. Each of these atmospheric parameters can be retrieved from ground-based observations with some degree of accuracy and certain advantages and limitations. However, instead of a single instrument, quite commonly a variety of ground-based instrumentation is deployed at the same site in order to cover more than one aspect of the atmosphere at the same time. While these instruments are typically used in standalone mode, their combination offers new possibilities to overcome intrinsic limitations. For example, a single instrument/technique may present limitations related to short range of application, poor spatial resolution, poor accuracy, ambiguous solution, simultaneous sensitivity to more than one parameter, or a combination of the above. In other words, each single instrument provides information about one or more parameters with the accuracy and the limitations associated with the used technology and technique, but sometimes part of these limitations may be overrun by the synergetic use of the other independent instrumentation operating at the same site [5-7].This research mainly focuses on monsoon precipitating clouds over Kadapa, a semi-arid zone of India. It is well known that rainfall plays a key role within the hydrological cycle. Its accurate and spatially revolved quantitative measurement is one of the main current challenges within the hydro-meteorological community [8]. Several techniques may be enumerated for this purpose: local direct instrumentation (such as rain gauges and disdrometers) and ground-based remote instrumentation [Micro Rain Radar (MRR)]. The synergy between all these instruments, with their advantages and drawbacks, is fundamental for a better comprehensive analysis of the rainfall features. For example, the measurement of hydrometeor size distributions from MRR can provide a powerful opportunity to directly investigate the microphysical properties of convective precipitating clouds and allow a comparison from retrievals performed by Disdrometer and MRR.

However, due to lack of monsoon precipitation's time distribution which is one of the features (over Kadapa) of the semi-arid regions, so that there is a great degree of precipitations in the monsoons other than the required seasons and cannot be controlled [8] . The shortage precipitations and repetitive drought in the last two decades made the rural people to immigrate from villages to cities. Also, the cultivating and animal husbandry has been under losses. These immigrations tend to great problems in the cities' management. The shortage of the precipitations causes some problems in providing beverage water of cities and industries' water. Consequently, the study of precipitating clouds characteristics (in terms of vertical structure and rain drop size distributions) during South-west (SW) and North-east (NE) acquaintance of their condition in this period is more useful. Hence, Yogi Vemana University (YVU) is establishing theoretical, experimental and modeling activities of "Semi-arid-zonal Atmospheric Research Centre (SARC)" at YVU campus with the active support of Indian Space Research Organization (ISRO) to understand the monsoon, and also atmosphere processes/dynamics, more especially the precipitation thorough round the clock observations using remote and in-situ sensors [8].

For the present study, Automatic Weather Station and Tropical Rainfall Measuring Mission (TRMM) are utilized to understand performance of MRR and PSD for estimation of micro-physical parameters and vertical structure of the precipitating clouds during Southwest (SW) and Northeast (NE) Monsoon over Kadapa.

This paper is organized as follows. Section 2 presents an overview of the surrounding topography, and climte prevailing over experimental site. A brief description of instrumentation used for diagnosis of monsoon rainfall and data availability is depict in Section 3. Results concerning comparison of PSD virusus tipping rain gauge; PSD and MRR measurements and TRMM with MRR are presented in Section 4, while Section 5 summarizes important results of the paper.

2 Topography and Climate Over Kadapa

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. Andhra Pradesh is most disaster prone area in terms of drought, floods, cyclones and fire. It is the fifth largest state in India, in terms of both population and area. Spread over 2.75 lakh sq. km., it comprises 8.4 per cent of the country's total geographical area. . It has a long coastal line stretching approximately 1,030 km, and an equally long history of cyclones. It is battered by at least one cyclone per year. The coastal line districts are normally affected by cyclones and floods, whereas Rayalaseema, the western and northern part of Andhra Pradesh often experiences severe drought conditions. The ground water level is at 600-900 feet below the earth surface in many areas of Rayalaseema region, more especially in Kadapa and Anantapur districts.

The ground water level never reaches to expected levels even in monsoon seasons due to scanty rainfall and poor seepage conditions. Under these conditions, only drought prone plant species alone survive resulting in the decrease of forest cover. In summer, the maximum temperature reaches ~46^{o} C. These semi-arid conditions resulted in desertification. 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. The topography around Kadapa is shown in Figure 1. It is located in the south-central part of the state and 8 km south of the Penna River. Kadapa District is in the shape of an irregular parallelogram, divided in half by the range of the Eastern ghats. The district is surrounded on three sides by the Nallamala and Palakonda hills. It covers an area of 15,359 sq.kms. The two tracts thus formed possess different features. The first, a low-lying plain about 150 m above sea level constitutes the north, east and south-east of the city, while the other, which comprises the southern and south-western portion, forms a high table-land 760 m above sea-level.

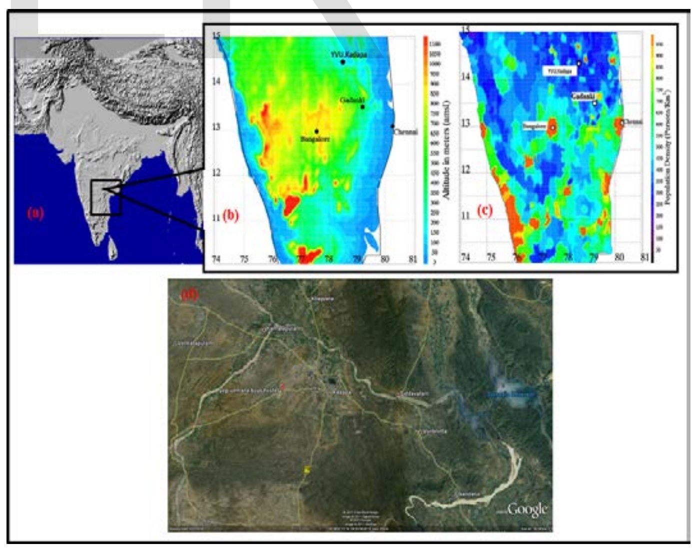

Fig. 1(a) Map showing the geographical location of the observation site along with the information on the topography and population density around the site.
(b) Perspective image of Yogi Vemana University Campus and surrounding Environment [downloaded from http://earth.google.com]

The observation site, Yogi Vemana University Campus (14^{0} 28' N 78^{0} 42' E, 150 m above mean sea level), is about 15 km from

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Kadapa city in the southern part of India. There are hills in the northern and southern sides of the observation site about 15 km distance and the average height of the hills is about 750 m, with a maximum height of about 1100 m. A major road passes near the observation site, with a usage of a few hundreds of vehicles each day. The population of YVU campus is about 1000 people only, while that of Kadapa is about 0.5 million. There are major cement industries nearby at Kamalapuram and Yarraguntla. The observation site is about 300 and 200 km from the two nearby major cities, Chennai to the southeast, and Bangalore to the south-west respectively [*Figure 1 (a)*].

The meteorological/climatic conditions over Indian subcontinent have been defined by India Meteorological Department (IMD). According to it, the seasons over India are divided into winter (January and February), pre-monsoon/summer (March, April, and May), monsoon/South-West (SW) monsoon (June, July, August, and September), and post-monsoon/North-East (NE) monsoon (October, November, and December). The SW and NE monsoon are also known as summer-monsoon and winter-monsoon respectively. The normal onset of the SW monsoon is around the first week of June, and withdrawal during the middle of September. After onset of SW monsoon, it takes around a week time to observe it at the observational site. Post-monsoon season is a period of rains in the southern part of India, and is called locally the NE monsoon, because of the northeasterly winds that prevail in this period. Normal onset of NE monsoon is around middle of October. The winter and the summer seasons are relatively dry in most parts of the country. India experiences two monsoons namely SW and NE monsoon. They account for the majority of the annual total rainfall. The two monsoons are different in the sense that, in summer, warm equatorial maritime air predominates over a major portion of the country. In winter, the air masses recede south and are replaced by cool tropical continental air.

3 Instrumentation And Data

Three different devices , as shown in Fig. 2 [a Parsivel (optical) disdrometer, a rainfall tipping gauge, and a Micro Rain Radar (MRR)] have been used in this study for calibration and reliability of measured precipitation characteristics.

The Disdrometer and MRR are located 5 m apart in an open ground and can be said to be exposed to the same rain conditions. The instruments are operated based on different physical principle, thus providing independent measurement of the same rain event. MRR measures the backscattered signal from the rain drops to calculate different microphysical parameters at different heights whereas Disdrometer measures the momentum of the rain drops at ground. Thus Disdrometer depends on mechanical principle whereas MRR depends on electromagnetic interaction. Details of the instruments are provided in the following subsection.

The detailed information of the PARSIVEL disdrometer given by Loffler-Mang and Joss [9] and in brief by Baljai and Reddy [10]. It measures hydrometeors with a size ranging from 0.2 - 5 mm for fluid precipitation and 0.2 to 25 mm for solid precipitation and with a particle velocity ranges from 0.2 to 20 m/s. Micro Rain Radar (MRR) collocated with PARSIVEL disdrotmer is utilized to separated precipitating cloud fractions into stratiform and convective. MRR is capable of providing vertical structure of Precipitation and vertical structure of RSD profiles. MRR is a low cost vertical profiling radar used to determine the enhanced radar reflectivity at zero degree isotherm (Bright Band)[11,12]. Instrumentations and methodology of MRR can be found in Löffler-Mang, and Kunz[13] research work.

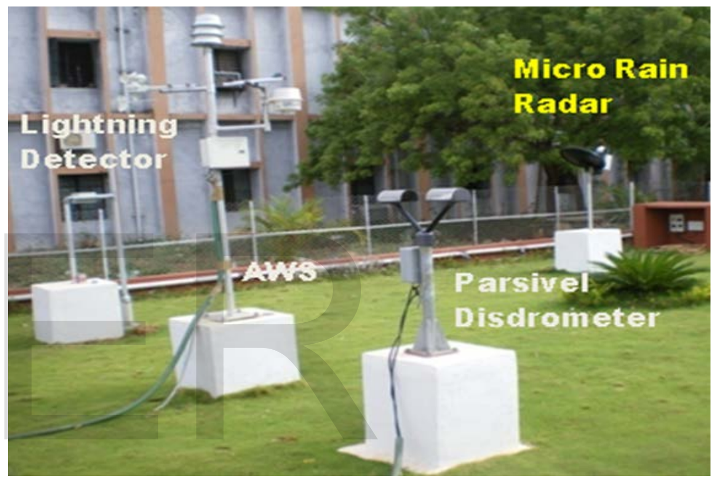

Fig.2 : Instrumentation used: in the foreground, optical disdrometer Automatic Weather Station with a tipping rainfall gauge and Lightning Detector and in the background the Micro Rain Radar (MRR).

Methodology

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

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

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, Di (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 fall velocity V_j

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

$$M_n = \int_{D_{min}}^{D_{max}} D^n \, N(D) dD \quad (2)$$

Where n stands for the n^{th} moment of the size distribution. The one minutes RSD are fitted with gamma function suggested by Ulbrich [14] and is given as

$$N(D) = N_o D^{\mu} \exp(-\Lambda D) \quad (3)$$

where D (mm) is the drop diameter, N(D) (mm^{-1} m^{-3}) is the number of drops per unit volume per unit size interval, N_0 (mm^{-1} m^{-3}) is the number concentration parameter, μ is the shape parameter, and Λ (mm^{-1}) is the slope parameter. The mass-weighted mean diameter D_m (mm), shape parameter μ and slope parameter Λ (mm^{-1}) are evaluated from the 3^{rd}, 4^{th} and 6^{th} moments of the size distribution.

$$D_m = \frac{M_4}{M_3} \quad (4)$$

The normalized intercept parameter N_w (mm^{-1} m^{-3}) defined by Bringi et al. [15]

$$N_w = \frac{4^4}{\pi \rho_w} \left(\frac{10^3 W}{D_m^4} \right) \quad (5)$$

Where ρ_w (1.0 g/m^3) represents the density of water and W (g/m^3) represents the liquid water content for the corresponding size distribution.

The disdrometer used for this study is the Laser Disdrometer, which fully characterizes surface precipitation. The device uses laser measurement techniques to include all types of precipitation. It measures the quantity, intensity, particle size, and fall speed. The system calculates the intensity, liquid water content, precipitation range (the diameter and speed of the drops), the meteorological visibility in the rain, and the radar reflectivity. A heating system with controlled temperature makes it possible to take reliable measurements throughout the whole year, and the technology also takes into account the influence of external sources of light.Fluctuations in temperature and contamination of the optics are compensated automatically.

The weather station has a tipping bucket rain gauge.The volume of precipitation stored in each box before tipping is 0.1 mm. The system records the time when the tipping mechanism is activated. To determine the amount of water precipitated the number of times the bucket dumps is counted. The following criterion was used to identify the precipitation events during 2009 and 2010: each dump separated by more than 20 minutes from the previous one was considered as a new rainfall event.

At the experimental, MRR, PSD and Tipping Rain Gauge are collocated with a spatial distance of about 3-m to check the performance and reliability of MRR and PSD , and in a variety of rainfall regimes during SW and NE monsoon. For comparison study data collected from April 2009 to March 2011 are utilized.

These three instruments provide three series of data on precipitation. Although they all reflect similar rainfall characteristics, they do so on the basis of different parameters, so the data may differ. These differences are referred to in Section 4, where the three instruments are compared. Precipitation events from 2009 and 2010 were used as the database for this study. The first step was to identify the events with the data from the rainfall gauge, using the criterion that all of the dumps that were less than 20 minutes apart were considered as forming part of the same event.The events were then tabulated and, after applying basic statistical tests, were summarized in a graph that shows the amount of rainfall recorded on a monthly basis throughout the whole year (Fig.3).

4 Sensors Synergy: Intercomparision Study

Monsoon precipitating clouds are not easy to detect and measure with a single meteorological sensor never enough to depict the whole picture. There are no ground-based instruments which can do it all. Different sensors have to be combined in a clever, synergistic way. The combination of instruments should give better accuracy of the individual sensors. In this section, Micro Rain Radar , Laser disdrometer, Automatic Weather Stations and Tropical Rainfall Measuring Mission (TRMM) are utilized to evaluate performance of MRR and PSD for reliable estimation of microphysical parameters.

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4.1 Intercomparision of Rain rate obtained from PSD, and Tipping bucket rain guage.

The data from the disdrometer are compared with observations using Tipping rain gauge. The PSD was originally designed for the purpose of calculating radar reflectivity factor and rainfall rate. The PSD is a reliable instrument that can be operated continuously and unattended.

The rainrates calculated from disdrometer were compared with the values measured by a tipping bucket rain gauge as integral part of Automatic Weather Station (AWS) at the same site. The disdrometer and AWS are spatially separated about 3-m in the Yogi Vemana University Meteorological Observatory. For the present study, three months (September to November 2012) precipitation data was collected from disdrometer and AWS have been utilized to understand the accuracy of the PARSIVEL disdrometer in measuring the observed rainrates. The 5-minutes averaged rainrates calculated from the RSD measured by the disdrometer were compared to the values measured by a rain gauge at the same site.

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Table 1: Two-year (from August 2009 to July 2010) statistical comparison of rain rate obtained from PSD and Tipping Rain Gauge.

Sl. No.	Year Season	Number of Observations (min.)	Intercept	Slope	Standard error of estimate (Percentage of Mean) (SEE)
1.	2009-SW	1843	0.18	1.05	17%
2.	2009-NE	2855	0.13	1.13	20%
3.	2010-SW	2343	0.16	1.08	24%
4.	2010-NE	2754	0.11	0.88	29%

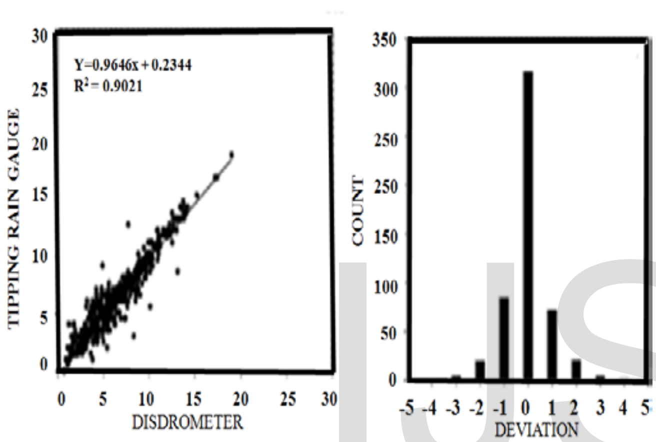

Fig.3: Comparison of rainrate (RR, mm/hr) measured with PARSIVEL Disdrometer and Tipping Bucket Rain gauge

Figure 3 demonstrates the regression relation [figure.3 left panel figure] and deviation [figure. 3 right panel figure] between the two sources of measurement. The least square fitting of the two measurements is close to 0.95. The observational results are in fairly good agreement and acceptable in view of the differences in the measurement technique.

4.2 Comparision of PARSIVEL Disdrometer with Micro Micro Rain Radar

An important property characterizing rainfall is raindrop size distribution (RSD), defined as the concentration of number of raindrops as a function of diameter. Accurate knowledge of RSD is a key factor for understanding precipitation processes and developing and validating precipitation remote sensing retrieval techniques [15]. The characteristics of RSD at ground (such as the shape) result from several different precipitation formation processes (such as coalescence, break-up and drop-sorting).

Information on raindrop size distribution (RSD) at near surface and aloft is of interest in different areas like radar meteorology and cloud physics [16]. There is much interest in these areas for several reasons, including climatic change due to human activities. With the development of PSD and MRR instruments that can give drop size data continuously and at relatively low costs, DSD measurements are becoming more common.

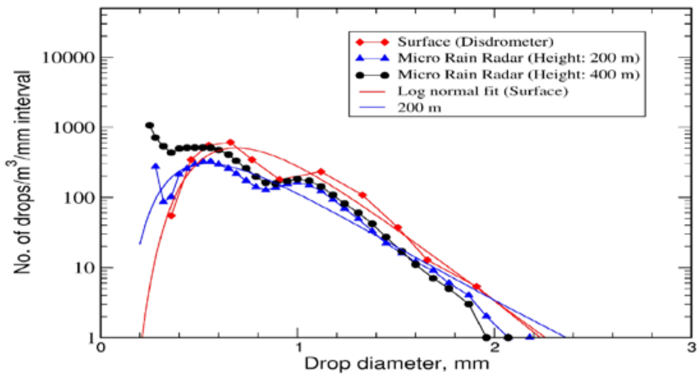

Fig..4: Comparison between PSD and MRR DSD from 01 to 31 July 2010.

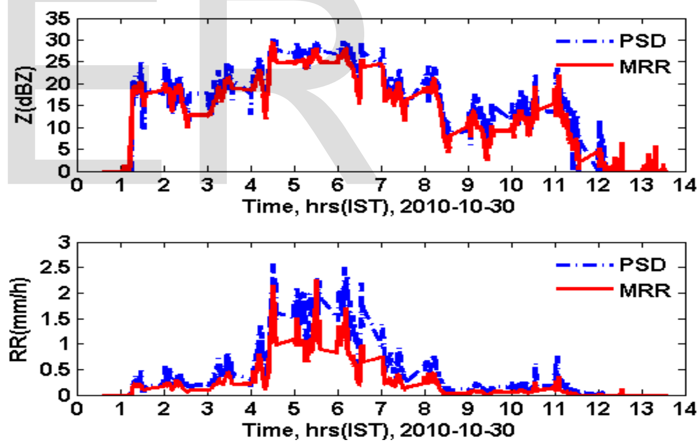

Fig.5: Time series comparison of radar reflectivity (Z, dBZ) and rainrate (RR,mm/h) obtained from Parsivel disdrometer (PSD) and Micro Rain Radar (MRR).

The reliability of the MRR data has been assessed by comparing the data obtained from the MRR with that from a co-located PARSIVEL (LASER) disdrometer. Monsoon precipitation (3369 minutes) data from 01 to 31 July 2010 were used to evaluate the precision of the Micro Rain Radar. The compared quantities were: 1- minute- averages of the first six moments of the Rain drop size distribution viz., rain rate, Radar Reflectivity and the accumulated precipitation. However, Figure 4 shows comparison of Rain drop concentration obtained from MRR and PSD during the passage of different precipitating cloud systems. From the observational results, it is found that rain rates are fairly in agreement between PSD and MRR., MRR measured higher accumulation during lower rain rates - due to lower PSD sensitivity-and heavy rain, partly caused by splashing losses [17]. Small drops are subject to turbulence, which masks the true terminal velocity leading to measurement error, whilst large drops are often under sampled by the MRR. Further errors are attributed to wetting losses, wind effects, drop splashing and dirt, condensation on instrument, evaporation and on-site turbulence. MRR also suffer detectable wind induced error when measuring ran rate, since However, the MRR's drop concentrations (at its lowest level) shows good agreement with that of Disdrometer.

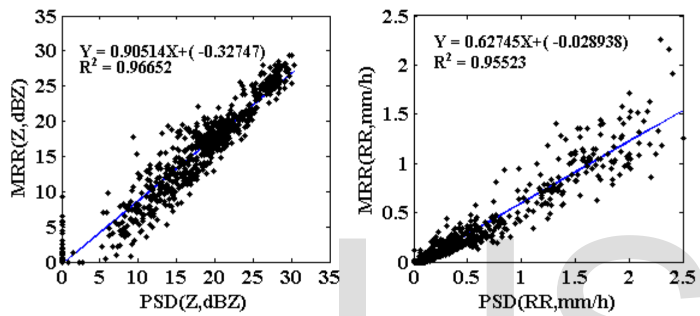

Fig. 6: Scatter plots comparison of radar reflectivity (Z, dBZ and rainrate (RR,mm/h) obtained from Parsivel disdrometer (PSD) and Micro Rain Radar (MRR).

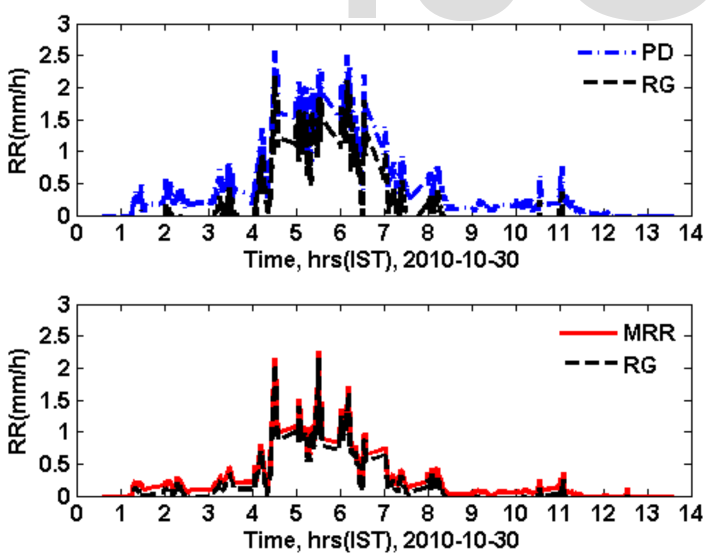

Fig. 7: *Time series comparison of rainrate (RR,mm/h) between Parsivel Disdrometer (PSD) versus Rain Gauge (RG) and Micro Rain Radar (MRR) versus Rain Gauge(RG).*

The instruments (MRR, PSD & RG) used in the present study are compared with each other for their validation. Time series of radar reflectivity (Z) and rainrate (RR) of Parsivel disdrometer (PSD) and 450-m observations of Micro Rain Radar (MRR) are given in *figure 5* and their corresponding scatter plots given in *figure 6* showed a good agreement between PD and MRR. Similar comparison is done between PD, Rain Gauge(RG) and MRR, Rain Guage(RG). The time series of RR obtained from PSD, RG and MRR, RG are shown in *figure 7.* Their corresponding scatter plots given in *figure 8* also showed good agreement among the three instruments

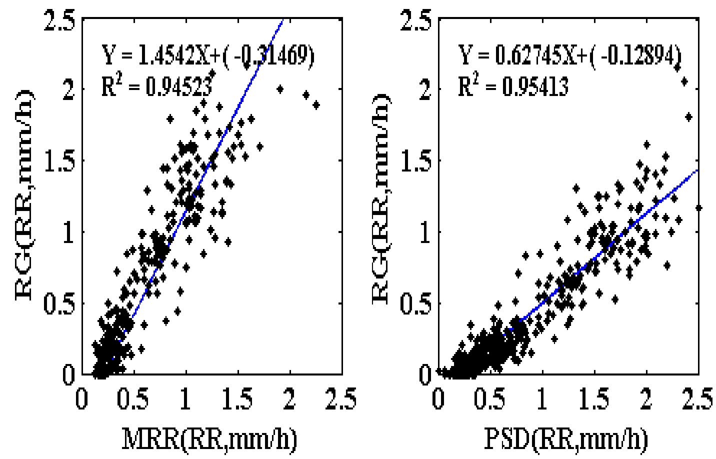

Fig.8: Scatter plots comparison of rainrate (RR,mm/h) between Parsivel Disdrometer (PD) versus Rain Gauge (RG) and Micro Rain Radar (MRR) versus Rain Gauge(RG).

Table 2: Two-year (from August 2009 to July 2010) statistical comparison of rain rate obtained from PSD and MRR**.**

Sl. No.	Year Season	Number of Observations (min.)	Intercept	Slope	Standard error of estimate (Percentage of Mean) (SEE)
1.	2009-SW	1143	0.18	1.15	19%
2.	2009-NE	1855	-0.49	1.23	22%
3.	2010-SW	1343	0.90	1.11	29%
4.	2010-NE	1754	0.11	0.87	31%

Rain accumulations and rain rate measurements from different instruments has been compared to understand the reliability of the data. Since this paper mainly depends on the rain DSD data and its integral parameters, it is essential to have a comparison between the DSD obtained from Disdrometer and MRR. Such a comparison carried for a rain event on 12th June 2010, that lasts for hardly five minutes (02:00 to 02:05 hrs) is shown in Figure.8. The average rain rate of this event was 3.34 mm/h. The decreasing trend as diameter decreases below a diameter of 0.6 mm is shown by both the instruments. The minimum available altitude at which DSD is given by the MRR is 200 m. The DSD data obtained from the Disdrometer and also that given by MRR for a height of 200 m follows a gamma distribution function. The decreasing trend as diameter decreases below a diameter of 0.6 mm is shown by both the instruments. The tailing end of the DSD spectrum also showed good agreement.

Rain rates obtained from the Disdrometer were compared With MRR estimated rain rates during different seasons. The results of a linear least-squares fit for each season are given in *table 2*. The standard error of estimate (SEE) is expressed as a percentage of the average rain rate from Disdrometer for all seasons. During SW monsoon rain rate showed the smallest value of the linear fit about 17% and NE monsoon the largest of 29%. Overall, the disdrometer and MRR performed well with inter-correlations of order 0.85 and bias less than 15%. However, both instruments showed some limitations under different rainfall situations. In particular, under extremely heavy rainfall rates, the bias between the disdrometer and the Micro rain radar was low. Under light rainfall rates the optical gauge was more sensitive than the disdrometer and the bias is high. This may be due to the background noise levels. It has been suggested that variations in the drop size distribution are responsible for the disagreement between the MRR and disdrometer. Though there exist small variations in the estimation of rainfall from both the systems, they are fairly in good agreement. The present results are very much encouraging in view of the fact that the disdrometer data can be used for the investigation of seasonal variation of DSD.

4.3 Comparision of PSD, MRR and TRMM 3BV6-42 data

Experimental field campaigns of rain precipitation usually require the coexistence of several ground and satellite based observations in order to guarantee a more complete analysis of the collected case studies at the various spatial and temporal scales of interest.

The 3-hourly rain rate derived from Disdrometer and MRR are compared with the TRMM satellite 3B42-V6 data (as shown in Figure 9). It is apparent from the figure that the data from Disdrometer and MRR agree well. Since the TRMM data is an area averaged data, the difference from former 2 instrument's data could be clearly made out. In order to compare with the Ordinary rain gauge data, the daily accumulations are derived from all other three sensors. Agreement between all the four sensors is very clear from such a comparison.

The data collected from ground-based instruments at Kadapa have been compared and their acceptability for studies has been brought out. The rain rate, rainfall and DSD data obtained from PSD, MRR and Ordinary Rain Gauge instruments are found to be agreeing very well within the limits of experimental error.

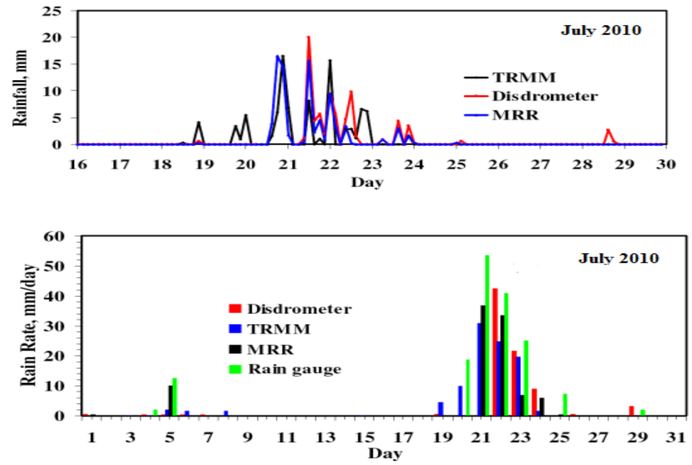

Fig. 9: Comparison of July 3-hourly (top panel) and daily (bottom panel) rainfall obtained from TRMM, Disdrometer, MRR and Rain Gauge.

5 Summary And Conclusion

Simultaneous observations of PSD and MRR and their application in rainfall estimation are evaluated. Comparison of Rain integral parameters during different monsoons PSD and MRR shows a fairly good agreement. Comparison of rain rate and radar reflectivity obtained from PSD and MRR in different precipitation events in different seasons show reasonably good agreement between the two instruments. However, systematicdifference of 1-2 dB is observed. This difference could be due to natural variation of DSD and bias of the radar reflectivity measurements. The comparison of rainfall rate shows much more difference, but the tendency, in general, is similar to the radar reflectivity.

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