Indian Journal of Radio & Space Physics
Vol 43, April 2014, pp 163-177

Diagnostic and statistical approach to the validation of Doppler radar rainfall around Chennai during 2006-2010

B Amudha[$,*], Y E A Raj, S B Thampi & RM A N Ramanathan

India Meteorological Department, Regional Meteorological Centre, Chennai 600 006, India

[$]E-mail: amudha2308@gmail.com

Received 5 April 2013; revised 15 January 2014; accepted 17 January 2014

Rainfall data obtained from the precipitation accumulation product of the Doppler Weather Radar at Chennai has been compared and validated with the rainfall recorded at 16 stations located within 100 km range of the radar. Statistical parameters, like correlation, mean error and mean absolute error have been calculated. When rainfall is indicated by both radar and observatory, a high degree of correlation, at 0.98, between the conditional means of radar and observatory rainfall in various ranges is observed along with consistency in underestimation of rain by radar. A regression equation has been constructed to correct the rainfall estimates from radar. Physics and radar engineering aspects, which contribute towards limitations in rainfall estimation, have been discussed.

Keywords: Doppler weather radar, Radar reflectivity factor, Rainfall, Rain rate, Correlation coefficient

PACS Nos: *92.60.jf*; 92.60. Wc; 84.40.Xb; 78.20. Ci

1 Introduction

A state-of-the-art modern remote sensing device, widely used for weather surveillance, is the digital Doppler Weather Radar (DWR). Meteorological radars are distinguished by the electromagnetic frequencies (like X, C or S bands) in which they operate and are deployed into the observational networks of the national weather services depending upon the specific requirement and type of weather phenomena to be monitored. Advancements in radar technology have been documented by pioneers, like Skolnik[1], David Atlas[2], Doviak & Zrnic[3] and Rinehart[4]. While conventional weather radars can look deeper into a weather system to provide information on intensity, rain rate, vertical extent, drop size distribution, etc.; the capability to probe internal motion of hydrometeors and hence to derive velocity and turbulence information has become available only after the advent of DWRs[5]. The base products from the DWR are reflectivity (*Z*), radial velocity (*V*) and spectrum width (*W*). Innumerable derived products obtained from these base products are utilised for real-time monitoring of weather events, like thunderstorms, squall lines and tropical cyclones, which are tracked when they are observed within the 400 km range of the radar. In view of this, DWR is a potential tool for nowcasting weather in general and rainfall in particular.

The quantum of rainfall (excess, normal or deficient as per meteorological parlance) realised over a region during a seasonal period is a crucial parameter, which exercises profound impact on climate and environment and also over a wide spectrum of areas, such as agriculture, water resource management, industrial development, commerce, etc., which are related to the sustenance of mankind. In view of the geographical diversity in terrain and orography, region-wise variabilities in the rainfall are inevitable on a global scale. Historically, rainfall measurements are known to have been taken by ancient Greeks as early as 500 BC, though many advanced techniques have evolved since 1600s. Rain gauge is the standard instrument used for recording of rainfall. In view of the importance of rainfall for sustenance of life on earth and its considerable amount of spatial variability, it has been the subject of interest and research especially amongst hydro-meteorologists.

In the Indian context, India Meteorological Department (IMD), which is the apex weather agency for India, maintains a network of 559 surface meteorological observatories where rainfall measurements are made using conventional manual rain gauges. In addition, around 3500 non-departmental rain gauge stations report daily rainfall and nearly 5000 rain gauge stations send monthly rainfall returns to IMD. The rainfall data, thus, collected are systematically archived by the National Data Centre, IMD, Pune. The rainfall pattern of stations in India in macro and micro scales has been studied and researched extensively[6-9]. IMD has brought out detailed atlases on seasonal Indian rainfall[10,11], which are referred by researchers, planners and various other users. Rainfall being highly spatially variable, the density of the network of rain gauges all over India, though adequate, was still considered less than the desired level. Further, in certain regions, these rain gauges were sparsely distributed. To increase the density and adopt modern technology on par with developed countries, IMD has augmented the surface observational network in the recent years by installing around 675 unmanned satellite-based Automatic Weather Stations (AWS) during 2007-2012, from which hourly meteorological data is received in near-real time basis. As on January 2014, over 1100 Automatic Rain Gauge (ARG) stations have also been commissioned. The modernisation initiative of IMD aims at installation of at least 2000 AWS and 4000 ARGs all over India in a phased manner in the next five years so as to ensure optimal representation in all districts. The rainfall data obtained from such a network is a discrete quantity representative of a small area around the station as rainfall is spatially a highly variable parameter.

Raghavan[12] has pointed out that rainfall recorded by a rain gauge is a point measurement and since rainfall is not a continuously variable function in space, measurement by a rain gauge is not truly representative of its surroundings. For all practical purposes, whatever be the increase in the number of rain gauges, the rainfall obtained from them would not be fully representing the areal coverage and spatial distribution of rainfall as that obtained from a digital DWR. The reason is that radar can observe precipitation over a wide area in a relatively short period of time. The areal average of rainfall derived from the DWR is most useful for varied applications. It is a well established fact that radar rainfall values are most reliable within the 100 km range of the radar. In a significant work on dual polarisation radars, Chandrasekar & Cifelli[13] have opined that the most important reason for using the radar to estimate precipitation is the fact that compared to a network of rain gauges, the radar (or a combination of radars) can sample a large area (>30,000 km^2 for a weather radar sampling out to 100 km) over a short period of time (<60 sec) as well as provide information on the movement and evolution of precipitating systems.

In the case of remote sensing devices, like the radar and the satellite, a major limitation is that precipitation is not obtained directly but is derived from certain parameters measured by them. The radar measures reflectivity integrated over the pulse volume, which is a function of the range and the beam width and is usually much larger than the volume sampled by a gauge. The sampled volume is at a height above ground level, which depends on the range. In operational hydrology, for flash flood forecasting, a network of rain gauges is used to estimate the areal average of rainfall over unit time to have accurate estimate of rainfall over catchment areas. The DWR is able to provide point values of rainfall estimates every minute over a wider area of places which have no rain gauges. Rinehart[4] has observed that there are some limitations in these estimates due to various physical and instrumental factors. However, inspite of such inherent errors, the conventional surface based rain gauge is the ‘ground-truth’ with which any other measurement of precipitation is to be compared as mentioned by Raghavan[12] and is used as a standard reference to quantify radar / satellite derived rainfall uncertainty.

Ideally, precipitation accumulation over an area for a specified period is desired as an areal measurement. However, due to inherent limitation of the conventional and mainstay measurement option available since long, viz. sparse network of rain gauges, one had to rely on point measurements hitherto and remain satisfied with linear interpolation between gauges for areal precipitation - accumulation figures. Radar measurement of precipitation scores high on this count because it gives a vivid picture of the spatial variations of precipitation compared to gauge based monotonic areal averages. At the same time, radar measurement of precipitation is subjected to many science and engineering constraints. Thus, it had become necessary to make use of a conventional and widely acceptable ground truth, i.e. gauge data to control the quality of radar based data towards keeping the deviations under check, removing outliers and reducing bias. As such, comparing radar based precipitation data with gauge based point precipitation data and adjusting the former to be closer to the latter is highly beneficial in obtaining a more reliable and useful precipitation dataset for water resource management. In the recent years, real time corrections / adjustments of the radar derived precipitation estimates are being done in several countries by adopting a multi-sensor approach which integrates data received online at the radar site from surface based telemetry networks of instruments like disdrometers, automated rain and intensity gauges.

Keeping in view the conceptual differences in rainfall measurements between radar and rain gauge, it is agreed by the meteorologists that one-to-one highly accurate match between the two types of measurements is unachievable and both are generally seen as complementary to each other with the advantages outweighing the limitations of both techniques. Radar data is available at near-real time and in order to have a reasonable judgment of the errors involved in the algorithms used to obtain digital rain estimates through radar, the standard used is still the conventional rain gauge. It is pertinent to note that Chandrasekar & Cifelli[13] have documented the accuracy levels of validation of radar rainfall using multi-sensor data fusion approach, which is currently acquiring prominence in the area of dual polarisation radars.

The objective of the present study is to validate the rainfall data obtained from the DWR at Chennai with rainfall data of 16 rain gauge stations (observatories) in Tamil Nadu located at their respective geo-coordinates within the 100 km range of the DWR for five year period (2006-2010) during pre-monsoon and post-monsoon seasons and understand the causative factors which induce differences between radar derived and observatory measured rainfall. A diagnostic study has been taken up by computing statistical parameters, such as correlation coefficient (CC), mean absolute error (MAE) and mean error (ME)[14]. A regression equation to correct the radar derived rainfall has been derived.

2 Past studies on validation of radar rainfall

Innumerable studies since 1940s have been undertaken worldwide for the validation of radar derived rainfall data. Historically, the Weather Radar Group at the Massachusetts Institute of Technology (MIT), under the leadership of Alan Bemis and based upon the work done by Austin & Williams[15], found large underestimates of the radar echoes from gauge measurements of rain. It was this difference that motivated Jones[16] in England to formulate the proper radar equation for meteorological scatterers[17]. According to Brandes[18], by combining the accuracy from rain gauges and the advantage of wider areal coverage from radar, one can reliably estimate the rain rate at a particular place. Doviak & Zrnic[19] observed that although radar techniques of obtaining rainfall over an area have practical limitations, DWRs have the advantage as these can survey vast areas and make millions of measurements in minutes. The factors introducing discrepancies between radar and rain gauge measurements have been listed by Zawadzki[20], classifying the errors into three categories, viz. random, systematic and range-dependent errors. The major factors which contribute towards errors between radar and gauge determined rainfall according to Koistinen & Puhakka[21] are: sampling difference between gauge and radar, collecting surface area, the reflectivity gradients in the pulse volume and the changing distribution of the precipitation particles in the radar pulse volume while falling to the ground. Radar calibration errors also induce certain discrepancies in rainfall measurement. According to Atlas[22], various instrumental configurations of DWRs require different approaches in understanding the significance of technical factors like attenuation, beam widening, cone of silence, anomalous propagation, increase in height with range of the sample volume, ground clutter, etc., which contribute towards the errors in the measurement of rainfall through radar and they cannot be ignored while undertaking validation studies.

After more than 60 years of research in radar meteorology, scientists are still exploring and suggesting various options for reliable and universally applicable methods to ensure close agreement between radar estimates and rain gauge obtained rainfall. Such studies are important in the context of adjusting the errors that creep in due to two fundamental aspects of rainfall estimation, namely: the physical science aspect and the engineering problem[15]. Numerous studies, which have compared radar and rain gauge data, have shown significant disagreement between the two sensors, viz. rain gauge and radar. Wilson & Brandes[18] and Joss & Waldvogel[23] have observed several sources of errors which affect the accuracy of the estimation of rainfall from radar. Austin[24] acknowledged the differences in sampling properties of radars and rain gauges due to spatial rainfall intensity gradients and the inadequate spatial sampling of rain gauges, which just record rainfall over a small cross section depending on its collector area whereas radar scans a much wider area above ground level. Kitchen & Blackall[25] focused on understanding the differences between point and areal rainfall and their relevance to radar gauge comparisons. They defined the so-called ‘representativeness error’ as a combination of two sources of errors; the spatial representativeness error associated with comparison between a point rainfall and an areal average; and the temporal representativeness error associated with the comparison between an accumulation and an integration of a set of instantaneous measurements. Collier *et al.*[26], Hildebrand *et al.*[27], Zawadzki *et al.*[28], Chandrasekar & Bringi[29] and Creutin *et al.*[30] have compared radar-derived rainfall with rainfall measured by conventional and automated telemetry rain gauges. Nevertheless, Raghavan & Sivaramakrishnan[31], Raghavan *et al.*[32], Suresh *et al.*[33], Sen *et al.*[34], Pradhan & Talukdar[35] have attempted such comparisons for specific Indian stations to correct the radar estimated rainfall.

3 Radar reflectivity factor

Before proceeding to the methodology of the present study using the DWR data, a conceptual understanding of the radar reflectivity factor would help in correlating the contributions of various physical parameters in obtaining rainfall estimates from radar. Representation of the reflectivity from the hydrometeors in clouds at a specific altitude on a spatial and temporal scale provides an areal view of the extent of precipitation and so the rainfall estimation from the reflectivity product of DWR is one of the quantitatively valuable inputs for the forecasters. Radar reflectivity factor (z) is the summation of the sixth power of the diameter of the individual hydrometeors / meteorological targets in one cubic metre of sample volume and has the units of mm^6 m^{-3}. Experimentally, ‘z’ can be related to the rainfall rate which is shown to be a function of the summation of third power of diameter of water drops in unit volume. Marshall & Palmer[36] studied the rain drop size distribution (DSD) and provided an exponential relationship for the number (N_D) of spherical droplets of diameter D(mm) as equal to $N_o\, e^{-\lambda D}$, where N_o = 8000 m^{-3} mm^{-1} (N_o is the value of N_D for D = 0); λ(mm) = 4.1 $R^{-0.21}$ mm^{-1}; and ‘R’, is rain rate measured as depth of water per unit time with units of mm h^{-1}. Then, given DSD from a sample volume of rain containing ‘i’ number of drops, ‘z’ defined as the sixth power of the drops of diameter (D_i in units of mm^6) summed over all the number of drops (N_i) in unit volume (units: m^{-3}) is given by $z = N_i\, D_i^6$. The term N_i is the number of drops of diameter D_i to $D_i + \delta D$, where δD is the diameter interval used in making the measurements. The most common mathematical relationship between rain rate and radar reflectivity factor given in Eq. (1) is empirical[37].

$$z = AR^b \qquad \ldots (1)$$

By plotting rain rate against reflectivity or by correlating both statistically, the relationship between these two can be established. Reflectivity factor (z) is converted into a new parameter called reflectivity (Z) in logarithmic units of dBZ because Z can have a tremendous range of magnitudes. Z in dBZ stands for decibels relative to a reflectivity of 1 mm^6 m^{-3} and so Z is defined as $Z = 10 \log_{10}[z/(1 \text{ mm}^6 \text{ m}^{-3})]$. Assuming a statistical DSD, Marshall & Palmer[36] used the empirical constant values of A = 200 and b = 1.6 for the *Z-R* relationship and fitted the values for rainfall of temperate latitudes and stratiform rain. Since then, it is the most widely used equation by radar meteorologists. In the words of Jameson & Kostinski[38], the common *Z-R* relationship is a statistical one and has no physical justification. However, many of the DWRs all over the world use A = 200 and b = 1.6 to derive the rainfall values. A fairly comprehensive list of research initiatives since 1970s providing several *Z-R* relationships to fit the DSD of rainfall in different parts of the world with various combinations of values of A and b has been given by Battan[39]. As the drop size distribution in nature varies widely from the assumed depending on the type of rain, season, geographic location, etc. so the values for A and b too vary.

4 Indian network of DWRs

In the Indian scenario, IMD is one of the few National Meteorological Services which embraced radar technology for meteorological purposes as early as in the late 1940s with the acquisition of war surplus radar equipments after the Second World War. Much of the experience with the new technology of analogue radars was gained between 1950s and 1970s. In the late 1980s and early 1990s, 24 X-band storm detection radars were inducted in other locations for thunderstorm monitoring. IMD had deployed a network of 10 S-band Cyclone Detection Radars during 1970s along the east and west coasts of India. Five of them were replaced with DWRs during 2001-02. The conventional S-band analogue radar at Chennai was replaced with a DWR in February 2002.

The frequency of operation is 2875 MHz and wavelength (λ) is 10 cm. Technical specifications and salient features of the DWR have been described by Bhatnagar *et al.*[5]. Radar products like reflectivity (*Z*), plan position indicator (PPI), volume velocity processing (VVP) and surface rainfall intensity (SRI) are uploaded on the web site (www.imd.gov.in) at every ten minutes interval on near real time basis. SRI provides instantaneous spatial rainfall distribution around the radar. Precipitation accumulation (PAC) at 0300 hrs UT is another derived product using SRI as the input data, which provides 24 hours rainfall accumulated in the 100 km range of the radar. Validation studies with rain gauge data of stations in the vicinity of DWR Chennai were first undertaken by Suresh *et al.*[33] considering the variations in DSD of rainfall during the period 1 March - 31 December 2003. A best fit regression equation was derived and new values of A = 267 and b = 1.345 in the *Z-R* relationship were used in the computational software of DWR Chennai for deriving the rainfall data. These values were used in DWR, Chennai for operational generation and archival of base and derived products. In order to validate longer periods of radar data with observatory (rain gauge) values, rainfall during the pre- and post-monsoon seasons for the period 2006-10 using DWR Chennai data was carried out by Amudha *et al.*[40,41]. A statistical diagnostic analysis was performed on the data set, the results of which indicated consistent underestimation of rainfall by radar. This paper studies the relationship between radar and observatory rainfall in a much more critical way and consolidates the results.

5 Data

Rainfall data from the DWR, Chennai and conventional observatories are the main source for this validation study. Values of the daily cumulative rainfall of the past 24 hours for the pre-monsoon (March, April and May) and post-monsoon (October, November and December) seasons for the five year period (2006-2010) are extracted from the PAC product of DWR Chennai for 16 stations in Tamil Nadu (TN), which are located within 100 km range of the radar. The stations are spatially spread out as shown in Fig. 1. Though six conventional rain gauge stations of Nellore and Chittoor districts in the state of Andhra Pradesh are located in the northwest (NW) sector of the DWR Chennai, these stations were not considered due to lack of continuous data for the period of the study, and the analysis has been confined to stations of TN only for which data was available without break.

The daily rainfall data from the conventional rain gauges of these 16 stations, namely Chennai Nungambakkam (NBK), Meenambakkam (MBK), Tiruvallur (TVL), Ponneri (PNR), Poondi (PND), Red Hills (RDH), Tirutanni (TTN), Sriperumbudur (SPP), Chengalpattu (CGP), Kanchipuram (KCP), Tambaram (TBM), Sholingur (SLG), Arakonam (ARK), Vandavasi (VDV), Cheyyur (CYR) and Madurantagam (MDG) were collected from the database of the Weekly Weather Reports of IMD, Chennai.

6 Methodology for retrieval of data from DWR

When the radar transmits the electromagnetic waves at a particular frequency, the pulses hit the targets and the reflected signals are received as echoes and processed by the receiver. Three base products, viz. *Z, V* and *W* form the inputs for generation of numerous derived products. Using *Z*, SRI product algorithm converts it into rain rate and generates an image of spatial distribution of rain rate over a specified surface layer above ground, for all visible points around the radar. SRI product images are, in general, obtained at every 6 to 10 minutes interval. Extent of visibility for a given surface layer is dependent on a few scan parameters. For a given surface layer (SL), the farthest visible range of SRI product (R_{max}) is decided by the lowest elevation angle of scan (El_{low}) and the closest visible range (R_{min}) is limited by the highest elevation angle of scan

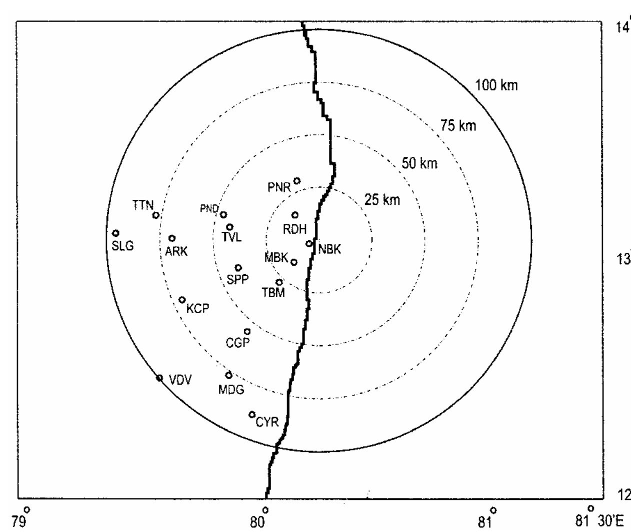

Fig. 1 — Locations of 16 stations in Tamil Nadu in the 100 km range of DWR Chennai

(El_{high}). Typical values for SL, El_{low}, El_{high}, R_{max}, R_{min} are 1 km, 0.5°, 9°, 100 km and 5 km, respectively. Spatial resolution of rain rate field in the image is decided by the size of the image specified at the time of product definition. For this study, the spatial resolution is selected as 500 m in both directions. The display shows colour coded rainfall amount in mm for the defined time period. The values of A=267 and b=1.345, respectively are used at DWR Chennai for generation of SRI product for all seasons and types of rain.

PAC is a second level rainfall product which uses the SRI product data as input and PAC algorithm computes the accumulated rain for a specified period by integration of discrete SRI values and generates spatial distribution of accumulated rain over the layer and spatial resolution corresponding to the SRI product. In this study, PAC product for 24 hours period ending at 0300 hrs UT with 500 m × 500 m spatial resolution is generated and used.

Temporal representativeness error (TRE) associated with the PAC product increases with inter-sampling period. One major difference between rain gauge and radar measurement is that a rain gauge accumulates the rain continuously while radar samples the instantaneous rain rate over an appropriate space above the gauge at frequent intervals. In between two samples, radar algorithm assumes that the rain rate changes linearly through the slope of line joining the two sampled values. So, TRE is the error due to the deviation of actual temporal variation of rain over the gauge to the assumed variation along the linear slope joining the two sampled values. TRE is minimised by keeping the sampling frequency high. The data set of 2006-2010 used in this study had different sampling frequencies for SRI product ranging from 4 to 6 samples per hour (viz. between 15 and 6 minutes). Errors are most likely to be induced in the rainfall estimates obtained by the SRI scan due to such variations in inter-sampling period during the occurrence of rainfall spells, which can be very heavy, heavy, slight, intermittent or no rain. Moreover, the best combination of factors involved in scan strategy is finalised for every DWR after various permutations and combinations based on the experience of monitoring the weather over a particular location and comparing the actual representation of the realised weather by the DWR. Since DWR at Chennai is the first digital radar to be operationalised by IMD in February 2002, various experimental sampling periods during 2002-2006 ranging from 15 minutes to 10 minutes and elevation scans were tried and tested to suitably conclude the best and adopt them for operational purposes while monitoring mesoscale thunderstorm activities and synoptic scale systems, like cyclonic storms. During the period of study 2006-2010, based on the trials at Chennai, the scan strategy was almost standardised for other subsequently installed DWRs of IMD like Kolkata, Machilipatnam and Visakhapatnam on par with the global practices. The inter-sampling period was brought down for all radars to around 10 minutes. PAC product is derived from the accumulation of such 10 minutes SRIs of a 24 hours period and so there is definitely an error component due to such variations in inter-sampling time which is called the TRE.

In general, radar measured parameters (both data as well as image) are stored as one byte data with 255 possible levels. As the study for a number of years has to accommodate cases with no rain as well as exceptionally heavy rain, a data resolution of 1 mm is selected while generating daily PAC products. Rain less than 1 mm is shown as no rain and rain in excess of 255 mm is set to be reported in the highest group of 255 and more. Number of pixels per image is given by the expression $(2*R_{max}$ / Spatial resolution$)^2$. With 100 km as R_{max} and 500 m as spatial resolution, the image size works out to be 400*400. From such a set of PAC data, point rainfall values corresponding to the geo-locations of the 16 stations in the 100 km range are picked by running a custom transformation script.

Detailed methodology of the algorithm and processing steps utilised in Next Generation Weather Radars (NEXRAD) of United States of America (USA) are provided by Fulton ***et al.***[42]. The algorithm adopted by the Rainbow software of the Gematronix make DWR at Chennai is not exactly the same but similar to it. As elucidated above, the PAC product, used in this study, contains in it a series of sixteen thousand 8-bit data representing 24-hour precipitation accumulation values over some contiguous area around the radar. Take a square area of 100 km×100 km with the radar location at the centre. The first byte of data represents the precipitation accumulation over a tiny square of size 500 m × 500 m at the left bottom corner of the big square. Subsequent bytes of data represent such tiny squares progressing initially towards right till reaching the right bottom of the big square, then folding back to the left, climbing one step up and progressing further like that till the last byte representing the right top corner of the big square is reached. The geometry is pictorially depicted in Fig. 2. Taking the geo-coordinates of the radar and the rain gauge as input, the custom script computes the pixel number corresponding to the rain gauge. Then the script crawls through the data set and picks the data corresponding to the gauge location from the product file. Thus, the precipitation accumulation for each gauge location is obtained.

7 Analysis

All the days of the pre- and post-monsoon seasons during the five year period 2006-2010 for 16 stations depicted in Fig. 1 and located in the 100 km range of DWR Chennai have been included for extracting the rainfall days in the 16 stations. The total number of samples including NIL rainfall days of 16 stations during the six months [(2 × (31+30+31)) = 184 days] of pre- and post-monsoon seasons for the period 2006-2010 is n = 14720 (184 × 5 × 16). Out of the n=14720 samples, when both observatory and radar reported rain, it has been taken as '*yes-yes*' category, which is equal to 2055 pairs. The analysis has been limited only to these 2055 pairs of rainfall as the objective is to validate the data and assess the range of deviations involved when rainfall is reported both by radar and observatory for these 16 stations. Obviously, there are instances coming under other possibilities, viz. (a) radar reports rain but observatory has not recorded rain (*yes-no*); (b) radar has not reported rain but observatory records rain (*no-yes);* and (c) neither radar nor observatory reports rain (*no-no)* but have not been considered as there are quite a number of reasons attributed to instrumental and physical biases for the (a) and (b) categories, which need separate discussions and are beyond the scope of the objective of this study and is planned to be dealt separately. In the case of (c), since rainfall is not reported by radar and observatory, such cases have not been dealt with here.

For the comparison and validation of rainfall estimates from radar and observatory recorded rain gauge rainfall, in view of the initial conditions decided for processing the radar PAC product as mentioned above, only the rainfall values of 1 mm and above have been taken though the observatories report rainfall less than 1 mm also. So occasions of rain less than 1 mm have been taken as dry days. Radar and observatory rainfall are taken as 'x' and 'y', respectively in the forthcoming discussions. The number of samples 'N'=2055. The scatter plot of all the 2055 pairs of '*yes-yes'* is shown in Fig. 3. The correlation coefficient (CC) computed between 'x' and 'y', is 0.80, which explains 64.4% of the variation. Equation (2) represents the bias / mean error (ME), i.e. the average of the difference (x-y) between the rainfall reported by radar (x) and observatory (y), which is -6.8 mm indicating underestimation by radar.

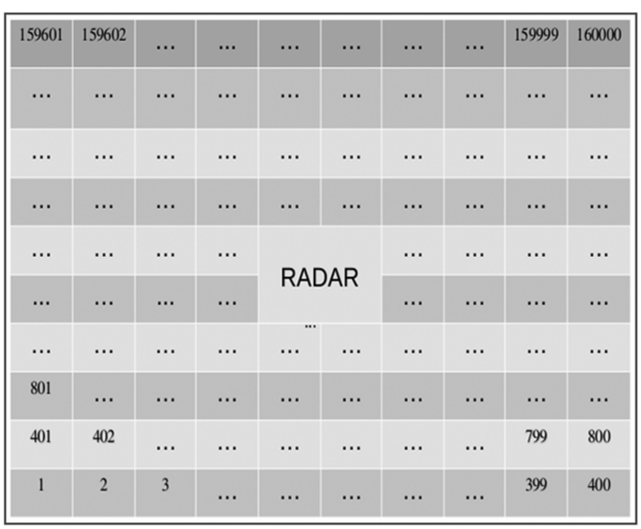

Fig. 2 — Data sequence and image geometry of PAC product

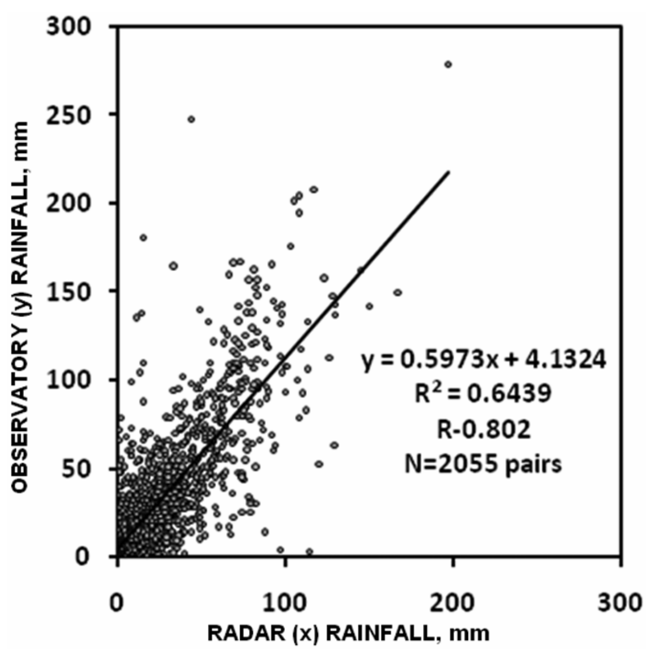

Fig. 3 — Scatter plot of the 2055 pairs of '*yes-yes'* rainfall during 2006-2010

$$\text{Bias or Mean Error(ME)} = \frac{1}{N}\sum_{i=1}^{N}(x-y) \quad \ldots (2)$$

$$\text{Mean Absolute Error(MAE)} = \frac{1}{N}\sum_{i=1}^{N}|x-y| \quad \ldots (3)$$

$$\text{Root Mean Square Error(RMSE)} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x-y)^2} \quad \ldots (4)$$

MAE is calculated as per Eq. (3) by averaging the absolute values of the errors and so it is always positive, whereas ME takes into account both the positive and negative errors/bias values. MAE for the 2055 samples is 12.2 mm and RMSE according to Eq. (4) is 20.5 mm.

In order to probe the underestimation of DWR derived rainfall a bit further, an in-depth analysis is conducted. Since radar rainfall is available at every 500 m resolution, it is possible to obtain estimates of rainfall at locations where observatories are not present by constructing a regression equation from this data set. Table 1 is a contingency table for 'x' and 'y' rainfall classified under the common ranges (categories) applying which the PAC imagery of DWR is normally generated and displayed. As such, by changing the categories into say, 1-10 mm, 10-20 mm, etc., the frequencies get distributed in different class intervals only. Frequencies of occurrences of rainfall in the higher ranges were very less and hence, such instances have been combined under a single category, viz. 93.4-300 mm. Table 1 gives a spread of the frequencies of rainfall occurrences. For example, out of the 2055 pairs of rainfall reported by both radar and observatory, if one takes the first category, viz. 1-7.6 mm of radar rainfall, observatory reported rainfall in the same range in 457 instances; while 88 were in the category 7.6-14.2 mm, 26 in 14.2-20.8 mm and so on. Thus, it gives an overview of the variability and frequency distribution (FD) of rainfall in each of the categories (Column 1 of Table 1) in which rainfall occurred in observatory, given the range in which radar reported rainfall. In addition, the mode and median of the FD in each category is evident. As stated by Zawadski[20], point-derived rainfall data and that estimated by radar are not exactly same all the time. In a large data set of rainfall reported by both radar and observatory, the mean calculated independently for both data sets would be unduly influenced by extreme rainfall values in the samples. To avoid this, the values are divided among various ranges of rainfall as given in the first column of Table 2, which are commonly used to display the PAC product. The mean, thus, computed for the total number of samples (counts) in each of these ranges is known as conditional mean,

Table 1 — Contingency Table depicting variation of actual observatory rainfall given the radar rainfall (mm)

Observatory (y) rainfall range, mm	Radar (x) rainfall range, mm															
	1.0-7.6	7.6-14.2	14.2-20.8	20.8-27.4	27.4-34.0	34.0-40.6	40.6-47.2	47.2-53.8	53.8-60.4	60.4-67.0	67.0-73.6	73.6-80.2	80.2-86.8	86.8-93.4	93.4-300.0	Total
1.0-7.6	457	88	26	12	3	3	0	0	0	0	0	0	0	0	2	591
7.6-14.2	205	120	44	16	11	7	1	2	0	0	1	0	0	1	0	408
14.2-20.8	86	76	32	35	13	5	2	3	1	1	0	0	0	0	0	254
20.8-27.4	27	46	30	19	19	6	3	6	1	0	1	2	0	0	0	160
27.4-34.0	13	21	19	22	22	12	7	1	1	0	0	2	1	0	0	121
34.0-40.6	7	12	14	17	10	14	9	4	0	1	1	1	0	0	0	90
40.6-47.2	9	7	5	7	11	13	10	4	3	3	0	4	0	0	0	76
47.2-53.8	5	2	7	10	8	5	3	4	3	1	1	0	1	0	1	51
53.8-60.4	2	7	6	1	6	4	10	3	8	3	1	1	0	1	0	53
60.4-67.0	1	3	1	5	3	4	3	2	4	2	2	3	1	0	2	36
67.0-73.6	2	1	3	1	0	4	6	5	6	4	1	1	0	2	0	36
73.6-80.2	1	0	0	0	2	1	4	4	1	5	1	4	1	0	1	25
80.2-86.8	0	0	0	0	0	3	1	3	2	3	0	4	0	0	1	17
86.8-93.4	0	0	1	0	0	1	1	3	4	3	2	1	1	1	2	20
93.4-300.0	0	4	2	0	2	2	3	4	6	12	20	15	11	10	26	117
	815	387	190	145	110	84	63	48	40	38	31	38	16	15	35	2055

Table 2 — Conditional means of actual observatory rainfall (y) and radar rainfall (x) computed for various ranges of radar rainfall

Range of radar rainfall, mm	Counts, n	Mean of radar rainfall (x)	Mean of observatory rainfall (y)	Absolute error (y~x), mm	% error (y~x)/x, mm
1.0-7.6	815	3.48	9.54	6.06	174.1
7.6-14.2	387	10.70	17.44	6.74	63.0
14.2-20.8	190	17.16	23.81	6.65	38.8
20.8-27.4	145	23.42	26.61	3.19	13.6
27.4-34.0	110	30.32	33.74	3.42	11.3
34.0-40.6	84	36.82	40.95	4.13	11.2
40.6-47.2	63	44.41	53.06	8.65	19.5
47.2-53.8	48	50.25	56.35	6.10	12.1
53.8-60.4	40	56.90	69.06	12.16	21.4
60.4-67.0	38	63.26	80.33	17.07	27.0
67.0-73.6	31	70.23	95.33	25.10	35.7
73.6-80.2	38	76.66	83.34	6.68	8.7
80.2-86.8	16	82.88	105.70	22.79	27.5
86.8-93.4	15	89.73	104.40	14.65	16.3
93.4-300.0	35	115.60	125.70	10.02	8.7

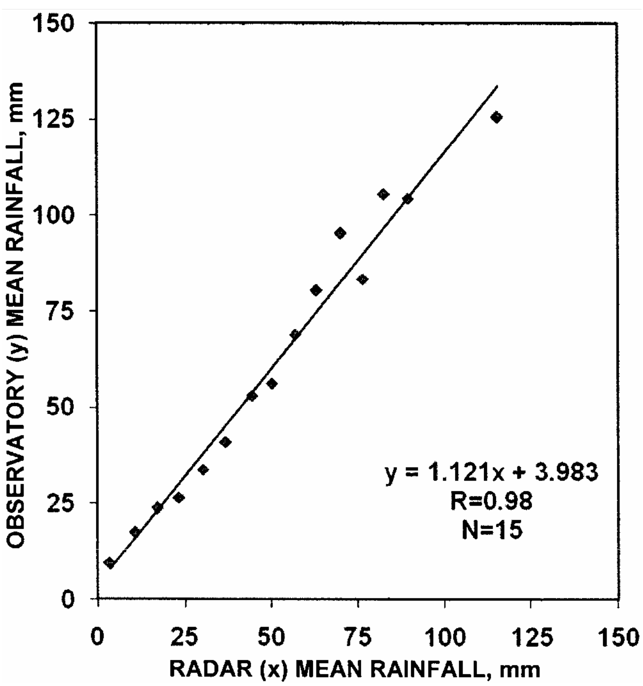

Fig. 4 — Correlation between conditional means of rainfall (mm) of radar and observatory

which is more reliable to understand the extent of linear relationship / correlation between radar and observatory rainfall. Conditional means of 'y' given 'x' have, thus, been computed (Table 2) for each of the 15 categories and the high degree of correlation of 0.98 is depicted in Fig. 4. The regression equation obtained from the conditional means is given by $y = 1.121x + 3.983$, which can be used to estimate 'y' for given 'x'.

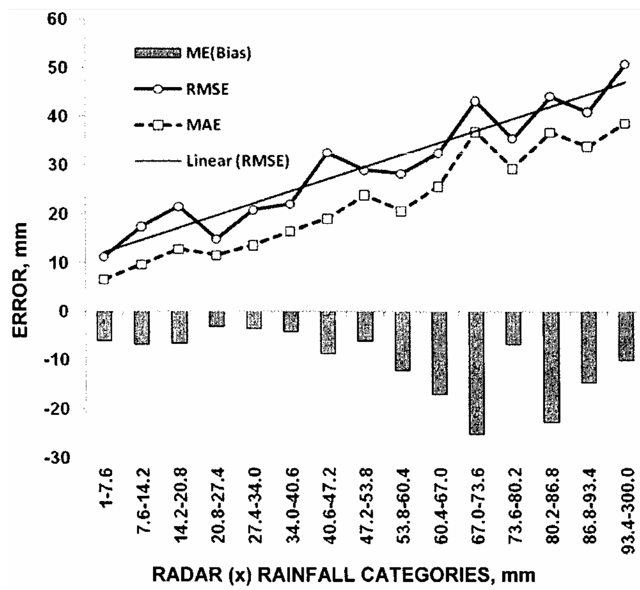

Fig. 5 — Mean error (ME), root mean square error (RMSE) and mean absolute error (MAE) between radar and observatory rainfall in different categories

For the same categories, ME, MAE and RMSE have been calculated and graphically represented in Fig. 5, which indicates the underestimation by radar in all the categories in varied degrees. A sense of direction of the error (x-y) in rainfall measured is provided by ME. MAE and RMSE are used together to diagnose the variation in the errors in a set of data. The greater the difference between them, the greater is the variance in the individual errors in the sample. If RMSE=MAE, then all the errors are of the same magnitude. MAE is most useful in understanding the

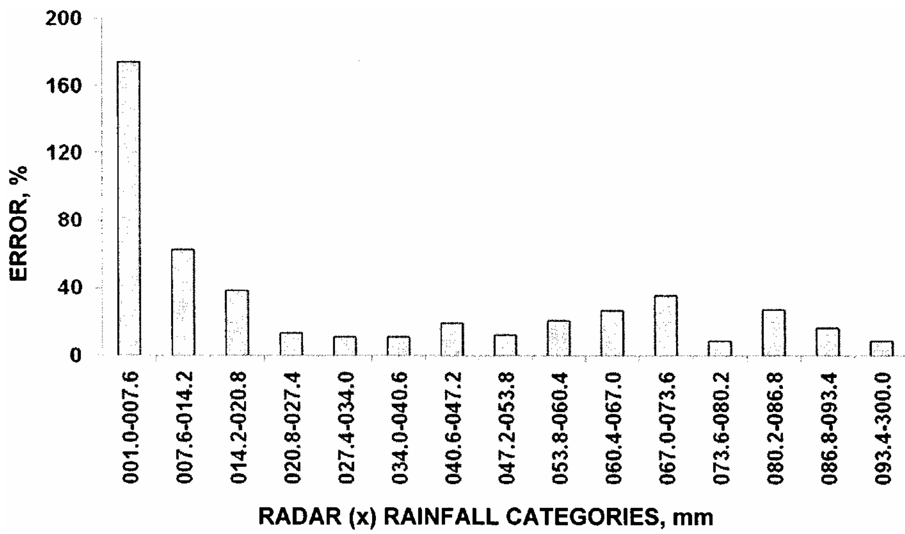

Fig. 6 — Percentage of error when compared with radar mean rainfall in each range

error pattern when large errors are particularly undesirable as RMSE is disproportionately influenced by large errors than MAE. In the case of discrete variables like rainfall of individual stations, MAE measures the average magnitude of the errors in a set of samples without considering their direction as evident from Fig. 5. Here, RMSE is observed to be always greater than MAE and an overall increasing trend in errors is observed in the higher ranges of rainfall measurement. Percentage of error when compared with radar mean rainfall in each category is presented in Fig. 6. In addition to the above category-wise analysis of the rainfall, station-wise correlation and error analysis have also been performed, which are depicted in Fig. 7 and Fig. 8, respectively. CC ranges 0.66-0.90 for each of the 16 stations. A consistently negative trend in ME is observed station-wise as well.

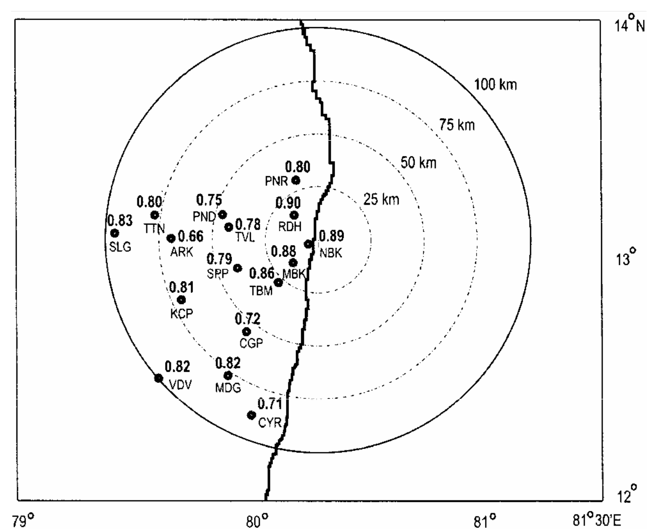

Fig. 7 — Station-wise correlation between radar and observatory rainfall

8 Results and Discussion

8.1 Statistical interpretation

The regression equation obtained from the conditional means is given by $y = 1.121x + 3.983$, which indicates that the radar rainfall is underestimated in all the ranges. Existence of a systematic bias in the rainfall measured by DWR Chennai utilising the factors A and b currently in use in Eq. (1) leads to underestimation of rainfall in a location. It is, thus, evident that radar rainfall (x) should be corrected to obtain a more accurate estimate of rainfall at a particular location (y). The regression equation can be used to obtain reliable estimates of rainfall from radar for places where there is no rain gauge data and will be valid for situations when radar rainfall is 1 mm and above. Correction factor of 3.98 mm as per the regression equation is required to be added to estimate the rainfall in places where there are no rain gauges within the 100 km range of the DWR Chennai. Since, the radar derived rainfall (x) greater than 1 mm alone has been considered in this analysis, the option of y value for $x=0$ mm in the regression equation does not arise. It is also evident from the conditional mean values of almost all the 15 categories that radar rainfall is an underestimation in all of them during the five year period of study.

The category-wise errors in conditional means of the rainfall in various ranges are depicted in Table 2. The percentage of error in each of the ranges as seen from Fig. 6 is highest in the light rainfall category 1-7.6 mm and minimum in the range 93.4-300 mm in contrast to the results obtained when errors in category-wise reporting of rainfall were analysed as in Fig. 5. This feature can be explained in terms of radar attributed errors. Ground clutter produces spurious echoes by distortion of the antenna beam. As a consequence, reflectivity values are registered by the radar giving a false impression that rainfall has occurred in a place introducing errors in measurement. The standard deviations for radar and observatory rainfall and the coefficient of variation (CV) (not presented here) indicated a high degree of variability. The effectiveness in recording rainfall by rain gauges in the lower ranges is prominent whereas such a sensitivity for radar-derived values in the lower ranges appears to be absent, which is misleading since the radar sensitivity in rainfall detection is 0.1 mm per 0.5 dBZ and hence, needs careful interpretation by accounting for the rainfall processing parameters and methodology used in the algorithms.

Figure 7 depicts the station-wise spatial variability of the CCs between x and y, which range from 0.66 to 0.90, the lowest being of ARK located around 70 km west of the DWR and highest is for RDH which is around 18 km NW of the DWR. Station-wise analysis of ME for the 16 stations during 2006-2010 ranges from -1 to -13 mm and indicates a consistent pattern of underestimation by radar. MAE ranges from 8.7 to 16.4 mm. The RMSE is in the range 12.6-26.5 mm (Fig. 8) for all the 16 stations. The weighted ME as given by Eq. (5) considering the 2055 pairs of '*yes-yes*' rainfall values of 16 stations is -6.8 mm, which shows an overall underestimation by radar. Similarly, the weighted MAE for the same data set is 12.2 mm.

$$\text{Weighted Mean Error} = \frac{1}{N}\sum_{i=1}^{i=16} a_1(x_i = y_i) \qquad \dots (5)$$

where, a_i, corresponds to the rainfall counts pertaining to ith station with $(x_i - y_i)$ being its corresponding error. The sum of all a_i of 16 stations is N=2055.

8.2 Interpretation based on radar processing

The fundamental contributions from the radar instrumentation to the errors in rainfall estimation have to be kept in mind while interpreting the results of the validation study. Radar measures the rainfall at around 1 km above ground level. Inherent limitations in radar technology, for example spreading of the radar beam with distance, beam blockage, various elevation angles of the scanning antenna, cone of silence, etc. also contribute to the underestimation of rainfall. Mason & Andrews[43] pointed out that DSD

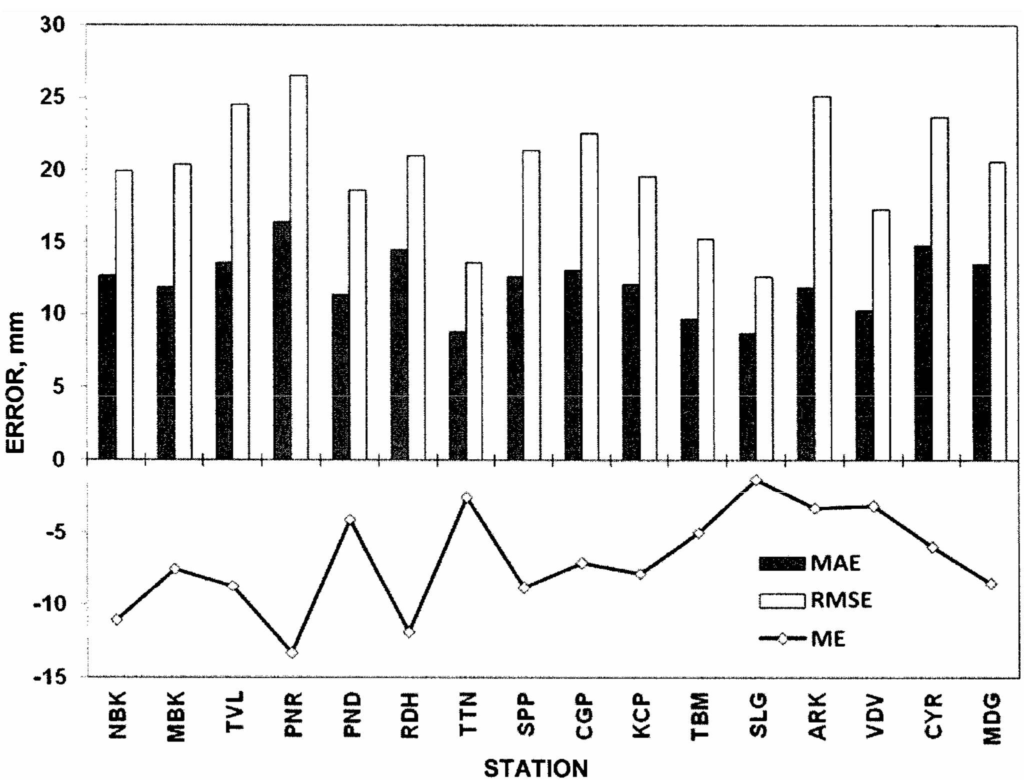

Fig. 8 — Station-wise error analysis for the period 2006-2010

varies with type of precipitation and may vary spatially and temporally even within a single precipitating system and induce limitations in measurement of radar rain with high resolution in the lower ranges. The radar rainfall processing range of 1-255 mm was selected to accommodate the maximum rainfall value of 255 mm in a day. Radar is capable of providing data at a resolution of 0.1 mm per 0.5 dBZ. Radar accommodates reflectivity from rain drops of the order of -31.5 dBZ to 95 dBZ for the said rainfall range of 1-255 mm. A change in reflectivity (from 25 to 25.5 dBZ) of 0.5 dBZ corresponds to a rain rate of 0.1 mm h^{-1} in the lower ranges of reflectivity and when reflectivity tends to increase, say, for example from 50 to 50.5 dBZ, the rain rate becomes 7.3 mm h^{-1}. Hence, in reality, the accuracy of DWR in reporting rainfall in the lower ranges is better than that in higher ranges and the reason for the apparent error in conditional mean between radar and observatory rainfall in the lower range of 1 to 7.6 mm in the data is clearly an artefact of the processing methodology followed obviously to accommodate all ranges of rainfall in a day, which explains the differences in the results. Similarly, for the higher range (93-300 mm), the variability in rain rate is high for every 0.5 dBZ and the contribution from higher rainfall rate has led to a value of the conditional mean which is less than that of the lower range.

Further, in order to understand the nuances of the radar technique in estimating rainfall, station-wise analysis was done with the PAC product of DWR of a few days in the cases of moderate to heavy precipitation on 29 October 2007 and light but widespread rain on two days, viz. 26 October 2008 and 7 November 2010 (Fig. 9). In the lower ranges of light to moderate rainfall, when the distance of the station from the centre of the radar increases, radar rainfall was more than the gauge rainfall in the case of few stations like CYR, VVS, SLG, MDG, TTN, ARK, PND and CGP. However, when the rainfall was in the heavy and higher ranges, radar rainfall showed an underestimation.

Raghavan[12] has indicated that Z will be underestimated at larger ranges as the sample volume is not representative of the lower portion of the precipitating cloud and that the minimum detectable Z increases with range resulting in error in spatial distribution of precipitation in the higher range. Samples considered in this study are from pre- and

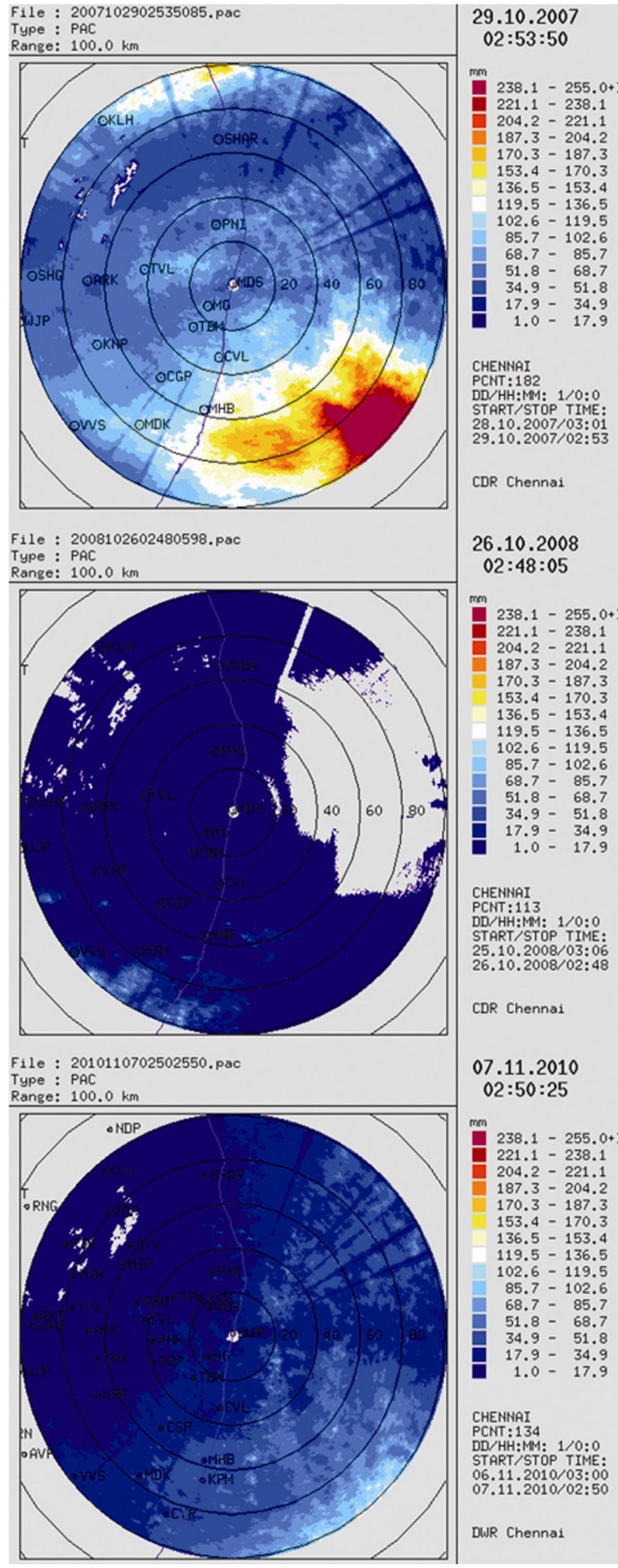

Fig. 9 — PAC imageries of 29 October 2007, 26 October 2008 and 7 November 2010

post-monsoon seasons and so rainfall could be either from stratiform or convective clouds. Perhaps due to this reason, consistent over/under estimation of rainfall with decrease/increase, respectively in range from the centre of the radar could not be established for the stations considered. This is also because of the dependence of radar reflectivity factor on the sixth power of the DSD where rainfall rate is related to drop size (D) differently. Wide variation exists in the natural DSD inside different types of rain events (stratiform, convective, winter, summer, orographic, maritime, tropical cyclones, etc.) occurring in and around a coastal city like Chennai which cause all these differences. Since measurements of DSD around DWR Chennai are not available, re-deriving A and b has not been attempted.

9 Conclusions

The following conclusions have emerged from this study:

(i) Validation results indicate a high degree of correlation (CC=0.80) between radar and observatory rainfall. The dependability of radar estimated rainfall for operational weather forecasting is clear.

(ii) The weighted ME considering the 2055 pairs of '*yes-yes*' rainfall values of 16 stations is -6.8 mm, which shows an overall underestimation by radar. Consistent underestimation of rainfall by radar in lower and higher ranges as well is evident.

(iii) A correction factor of 3.98 mm according to the regression equation (y = 1.121x + 3.983) could be added with the radar rainfall to obtain the rainfall realised in a location where rain gauge is non-existent.

(iv) Though there is an optimum areal coverage of reporting rainfall by radar, there is a significant spatial variation station-wise, in the degree of CC, which varies from 0.66 to 0.90.

(v) A generalised conclusion that CC decreases with increase in the distance of the station from the DWR could not be made from the station-wise analysis.

(vi) There are various error contributors due to the different types of DSD in the case of rainfall due to normal convective activity, stratiform clouds, orography or that due to passage of cyclonic storms.

(vii) The processing of the data could be done for sub-classifications of the whole range of 1-255 mm to capture more accurately the variability in both higher and lower ranges instead of processing the rainfall data for a highly dispersed and wide range of 1-255 mm.

(viii) It should be borne in mind that heavy intensity rainfall occurs in short durations due to convective activity during the pre- and post-monsoon seasons and under the influence of tropical cyclone associated rainfall. Just a single type of rain bearing cloud pattern is normally not observed in a maritime tropical city like Chennai.

(ix) A one-to-one ideal match between radar and observatory derived rainfall is limited by the technical differences in inherent design aspects of both the types of rainfall measurement.

(x) Based on empirical validation of a year's rainfall data of Chennai and its contiguous areas, a single value of A=267 and b=1.345 was considered as the best fit values for DWR Chennai. It may perhaps be suitable to address the issue of differentially varying A and b for the Z-R relation for each of the four seasons after substantiating / validating with actual data to get better correctness in radar-derived rainfall data during all seasons.

(xi) By suitable modification of A and b in the Marshall-Palmer relationship being used and utilising appropriate scan strategies for different rain drop size distributions expected, better accuracy could be ensured. Pending such developments the regression equation y = 1.121x + 3.983 could provide better estimates of actual rain given DWR rain.

Acknowledgement

The valuable help of Shri V Aravindan, DWR Chennai in retrieval of the data is gratefully acknowledged. The authors express their thanks to Dr L S Rathore, Director General of Meteorology, India Meteorological Department for permission to publish this paper in the Indian Journal of Radio and Space Physics. The suggestions of the referees in improving the quality of the manuscript are also acknowledged.

References

1 Skolnik M I, *Radar handbook* (McGraw Hill, New York), 1970, pp 24.1–24.40.

2 David Atlas, Ed, *Radar in meteorology* (Am Meteorol Soc, Boston), 1990.

3 Doviak R J & Zrnic D S, *Doppler radar and weather observations,* 2nd ed (Academic Press, London), 1992.
4 Rinehart R E, *Radar for meteorologists*, Part III, 2^{nd} ed. (University of North Dakota, USA), 1991.
5 Bhatnagar A K, Rajesh Rao P, Kalyanasundaram S, Thampi S B, Suresh R & Gupta J P, Doppler Weather Radar – A detecting tool and measuring instrument in meteorology, *Curr Sci (India)*, 85 (2003) 256.
6 Sinha K L, An analysis of the space distribution of rainfall in India and Pakistan, *Indian J Meteorol Geophys,* 3 (1952) pp 1-16.
7 Sikka D R & Gadgil S, Large scale rainfall over India during the summer monsoon and its relation to the lower and upper troposphere, *Indian J Meteorol Hydrol Geophys,* 29 (1978) pp 219-231.
8 Krishnamurthy V & Shukla J, Intra seasonal and inter annual variability of rainfall over India, *J Clim (USA),* 13 (2000) pp 4366-4377.
9 Khole M & De U S, A study on northeast monsoon rainfall over India, *Mausam (India),* 54 (2003) pp 419-426.
10 *100 years (1901-2000) monthly rainfall data series for districts, states, meteorological subdivisions and all India* (Hydrometeorology Division, India Meteorological Department, Pune), 2012.
11 *Rainfall Atlas of India, 1951-2000* (Hydrometeorology Division, India Meteorological Department, Pune), 2012.
12 Raghavan S, *Radar meteorology* (Kluwer Academic Publishers, Netherlands), 2003, pp 262-264.
13 Chandrasekar V & Robert Cifelli, Concepts and principles of rainfall estimation from radar: Multi sensor environment and data fusion, *Indian J Radio Space Phys,* 41 (2012), pp 389-402.
14 Wilks S Daniel, *Statistical methods in the atmospheric sciences-An introduction* (Academic Press, New York), 1995.
15 Austin P M & Williams E L, *Comparison of radar signal intensity with precipitation rate* (Weather Radar Research Tech Rep 14) (Dept of Meteorology, Massachusetts Institute of Technology, USA), 1951, 43.
16 Jones J Richard Probert, The radar equation in meteorology, *Q J R Meteorol Soc (UK),* 88 (1962) pp 485-495.
17 Hitschfeld W, The invention of radar meteorology, *Bull Am Meteorol Soc (USA),* 67 (1986) pp 33-37.
18 Wilson J W & Brandes E A, Radar measurement of rainfall-A summary, *Bull Am Meteorol Soc (USA),* 60 (1979) 104.
19 Doviak R J & Zrnic D S, *Doppler radar and weather observations* (Academic Press, London), 1984, 179.
20 Zawadzki I, Factors affecting the precision of radar measurements of rain*, Preprints of 22nd Conference on Radar Meteorology, Zurich, Switzerland* (Am Meteorol Soc, Boston)*,* 1984, pp 251-256.
21 Jarmo Koistinen & Timo Puhakka, Can we calibrate radar with rain gauges? *Geophysica (Finland)*, 22 (1-2) (1986) pp 119-129.
22 Atlas D, Radar calibration-some simple approaches, *Bull Am Meteorol Soc (USA),* (2002) pp 1313-1316.
23 Joss J & Waldovogel A, Precipitation measurement and hydrology, in *Radar in meteorology, Battan Memorial and 40th Anniversary Conference on Radar Meteorology*, Ed: Atlas D (Am Meteorol Soc, Boston), 1990, pp 577-606, 2977.
24 Austin P M, Relation between measured radar reflectivity and surface rainfall, *Mon Weather Rev (USA),* 115 (1987) pp 1053-1070.
25 Kitchen M & Blackall R M, Representativeness errors in comparisons between radar and gauge measurement of rainfall, *J Hydrol (USA),* 134 (1992) pp 13-33.
26 Collier C G, Harrold T W & Nicholass C A, A comparison of areal rainfall as measured by a rain gauge-calibrated radar system and rain gauge networks of various densities, in *Preprints, 16th Conference on Radar Meteorology* (Am Meteorol Soc, Boston), 1975, pp 467-472.
27 Hildebrand P H, Towery N & Snell M R, Measurement of convective mean rainfall over small areas using high density rain gauges and radar, *J Appl Meteorol (USA),* 18 (1979) pp 1316-1326.
28 Zawadzki I, Desrochers C, Torlaschi E & Bellon A, A radar-rain gauge comparison, in *Preprints, 23rd Conference on Radar Meteorology* (Am Meteorol Soc, Boston), 1986, pp 121-124.
29 Chandrasekar V & Bringi V N, Simulation of radar reflectivity and surface measurements of rainfall, *J Atmos Ocean Technol (USA),* 4 (1987) pp 464-478.
30 Creutin J D, Delrieu G & Lebel, Rain measurement by rain gauge – radar combination: A geostatistical approach, *J Atmos Ocean Technol (USA),* 5 (1988) pp 102-115.
31 Raghavan S & Sivaramakrishnan T R, Radar estimation of precipitation around Madras, *Mausam (India),* 33 (1982) pp 21-28.
32 Raghavan S, Sivaramakrishnan T R, Rengarajan S & Premkumar S W, A radar reflectivity-rainfall rate relationship for the southwest monsoon season for the Madras area, *Masuam (India),* 38 (1987) pp 335-340.
33 Suresh R, Ravichandran P K, Gupta J P, Thampi S B, Kalyanasundaram S & Rajesh Rao P, On optimum rain rate estimation from a pulsed Doppler Weather Radar at Chennai, *Mausam (India),* 56 (2005) pp 433-446.
34 Sen Jaiswal R, Uma S & Santhakumaran A, Study of Z-R relationship over Gadanki for different rainfall rates, *Indian J Radio Space Phys,* 38 (2009) pp 159-164.
35 Pradhan D & Talukdar I, Evaluation of constants ‘A’ and ‘b’ of Z-R relation for Kolkata (India) and surroundings using DWR and SRRG data during pre-monsoon period, in *Book of Abstracts, National Seminar on Doppler Radar and Weather Surveillance, DRaWS-2011, 17-18 November 2011* (India Meteorological Department, Hyderabad, India), 2011, pp 28-37.
36 Marshall J S & Palmer W McK, The distribution of raindrops with size, *J Meteorol (USA),* 5 (1948) pp 165-166.
37 Skolnik M I, *Introduction to radar systems*, 3rd ed. (Tata McGraw Hill, New Delhi), 2001, p 444.
38 Jameson A R & Kostinski A B, Reconsideration of the physical and empirical origins of Z-R relations in Radar Meteorology, *Q J R Meteorol Soc (UK)*, 127 (2001) pp 517-538.
39 Battan L J, *Radar observation of the atmosphere* (University of Chicago Press, Chicago), 1973, 324.
40 Amudha B, Raj Y E A, Thampi S B, Prasad A & Aravindan V, Validation of PAC product of Doppler Weather Radar at Chennai with conventional rain gauge data, *Book of Extended Abstracts, National Seminar on Doppler Radar and Weather Surveillance, DRaWS-2010, 18-19 March 2010* (India Meteorological Department, Chennai), pp 74-81.

41 Amudha B, Raj Y E A, Thampi S B & Ramanathan RM A N, Diagnostic verification of radar derived spatial variability in rainfall around Chennai during 2006-10, *Book of Abstracts, National Seminar on Doppler Radar and Weather Surveillance, DRaWS-2011, 17-18 November 2011* (India Meteorological Department, Hyderabad), pp 57-65.

42 Fulton R A, Jay P Breidenbach, Dong-Jun Seo, Dennis A Miller & Timothy O' Bannon, The WSR-88D rainfall algorithm, *Weather Forecast (USA),* 13 (June 1998) pp 378-395.

43 Mason B J & Andrews J B, Drop size distribution for various types of rain, *Q J R Meteorol Soc (UK),* 86 (1960) pp 346-353.