Variability of raindrop size distribution and its impact on polarimetric rain rate estimators

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Four years of raindrop size distribution (DSD) by Joss-Waldvogel (JW) Disdrometer measurements made at Gadanki (13.5°N, 79.2°E) have been used to derive relations for rainfall estimation from polarimetric radar variables. The polarimetric variables are estimated in X-band (at 9.368 GHz, the chosen frequency for the radar being developed at Gadanki) from the observed DSD measurements and scattering amplitudes derived using T-matrix scattering simulations. Three rainfall estimators, namely $R-Z$, $R-K_{DP}$ and $R-(Z_H, Z_{DR})$, are derived for both stratiform and convective types of rain. Also, following the earlier reports, which highlighted the large variability of DSD between the seasons, the above relations are derived for three seasons (pre-monsoon, southwest monsoon and northeast monsoon). The scatter plots of $R$ and $Z$ show large scatter around the regression fits, even after separating the data into different seasons and types of rain, indicating the large and complex variability of DSD. Among all the relations, $R-Z$ relation depends heavily on the DSD with its coefficients vary significantly between the seasons and types of rain. The other two relations show weak dependency on DSD, however, the coefficients are found to be distinctly different from those reported elsewhere. Both qualitative and quantitative evaluation analyses on a case study reveal that $R-(Z_H, Z_{DR})$ relation provides better $R$ among the three relations.

Keywords: Raindrop size distribution (DSD), Rainfall estimation, Polarimetric variables, Scattering coefficient

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1 Introduction

One of the most difficult parameters to quantify and parameterize in meteorology is precipitation. Traditionally, the rain gauges have been used to obtain the surface rainfall information. Although high resolution rain gauges are now available with a time resolution of a minute to few minutes, their spatial density is still too low to yield high resolution rainfall maps for the whole country, like India. On the other hand, weather radars have many advantages over rain gauges because of their extended areal coverage and providing high resolution measurements$^{1,2}$. In case of single polarization radar, the backscattered echo power from hydrometeors [in terms of radar reflectivity factor ($Z$, in dBZ)] is the only parameter available for the estimation of rain rate ($R$ in mm h$^{-1}$). They employ either a fixed established $Z-R$ relation(s) or a varying relation in accordance with a gauge. The reflectivity based measurements are prone to several errors: radar calibration issues, evolution of rainfall from the measurement height to the surface, shape of the hydrometeor and the highly variable and ambiguous $Z-R$ relation$^{2,3}$.

On the other hand, the polarimetric radars, typically transmit with horizontal and vertical polarizations, overcome many of the problems noted above and are becoming popular because of their ability in improving quantitative precipitation estimates (QPE), discriminating hail from rain, retrieving raindrop size distribution (DSD) and identifying precipitation types and meteorological and non-meteorological targets$^4$. Different types of dual polarized weather radars, ranging from huge S- and C-band radars to small and cost-efficient X-band radars, are operational worldwide. Polarimetric radars provide several additional parameters, besides the basic radar parameters of reflectivity factor, radial velocity and spectral width, like differential reflectivity$^5$ ($Z_{DR}$), specific differential phase$^6$ ($K_{DP}$) which is the range derivative of differential propagation phase ($\phi_{DP}$). Recent research has demonstrated that polarimetric radars operating in X-band have several advantages, like improved sensitivity to weak targets (compared to S- and C-band radars), smaller in size, cost reduction, and easy deployment even in mountainous regions$^{7-10}$. For
example, the $K_{DP}$ estimated from scattering simulations at X-band is larger by about 1.5 and 3 times than at C and S bands, respectively for the same $R$ (Ref. 11). This means, $K_{DP}$-based rainfall estimates become meaningful even at small $R$, as low as ~3 mm h$^{-1}$ (Ref. 12). On the flip side, the X-Band radars suffer with severe attenuation and therefore, the Z- and $Z_{DR}$-based rainfall estimations will have large biases. The strong attenuation in heavy rain also reduces the radar range coverage. The attenuation can be corrected using the phase measurement, $\phi_{DP}$, which is immune to the attenuation and helps for the correction of power based measurements $Z_H$ and $Z_{DR}$ (Ref. 13). Further, phase-based measurements, like $K_{DP}$ can also be used, either independently or in combination with other polarimetric parameters, to measure the rainfall more accurately.

The relations to estimate the rainfall from polarimetric radars are derived empirically from DSD measurements and/or through simulations$^{4,6}$. The DSD, however, depends on the physics of the precipitation at the measurement location, therefore, varies from one region to the other and also between the seasons and rain regimes even at the same location$^{14}$. Therefore, region, season and system (e.g. convection, stratiform, etc.) specific relations are needed to obtain improved QPE. The main aim of this paper is, therefore, to obtain valid coefficients (for India in general and southeast India in particular) for relations containing polarimetric parameters and $R$ corresponding to different seasons and different types of rain, using four years of disdrometric measurements at Gadanki. In this regard, it is important to remember that DSD exhibits strong seasonal variability at Gadanki$^{15,16}$. It is imperative to understand the implication of this seasonal variation (in DSD) on polarimetric measurements and also on rain rate relations. Also, earlier studies have shown that the use of two or three variables reduces the retrieved rain rate uncertainty due to DSD and drop shape variability$^{17,18}$. Therefore, coefficients for relations connecting multiple polarimetric parameters have been derived. It is then possible to see how different/similar are the relations (obtained in the present study) in comparison with those seen in other regions.

2 Data and Computational methodology

The Joss-Waldvogel disdrometer (JWD) (Ref. 19) measurements made at Gadanki for four years (during 2006-2009) have been used for the present study. The JWD is an impact type disdrometer which converts the vertical momentum of the raindrop impacting the sensor into the drop size. Though it identifies 127 drop sizes, it finally groups them into 20 raindrop classes (ranging from 0.3 to 5.3 mm) to obtain a statistically stable rain DSD. The JWD underestimates small drops during heavy rain due to the increase in the background noise level. The drop count in each channel of the disdrometer is, therefore, corrected for the dead time of the instrument$^{20}$. To avoid sampling problems, data having fewer than 10 drops per minute (sampling interval) and $R < 0.1$ mm h$^{-1}$ have been excluded from the present analysis. The $R$ and other rainfall integral parameters [$Z$, mass weighted mean diameter ($D_m$) and liquid water content (LWC)] are estimated directly from the disdrometric DSD and the polarimetric parameters were computed using the T- matrix scattering simulations$^{21,22}$ at X-band (9.368 GHz) frequency.

The rainfall rate $R$ (mm h$^{-1}$), for the DSD discussed above, is estimated using the following integral:

$$R = 0.6\pi \int_{D_{mn}}^{D_{mx}} D^3 v N(D) dD$$

…(1)

where, $v(D)$, is the drop terminal fall velocity in ms$^{-1}$; $D$, the drop diameter in mm; and $N(D)$, the number concentration in mm$^{-1}$ m$^3$. The horizontal ($Z_H$) and vertical ($Z_V$) reflectivity is given as$^4$:

$$Z_{HV} = \frac{4\lambda^4}{\pi^4} \left| K_w \right|^2 \int_{D_{mn}}^{D_{mx}} |S_{HH,VV}(D)|^2 N(D) dD$$

…(2)

where, $S_{HH}$ and $S_{VV}$, are backward scattering amplitudes at horizontal and vertical polarizations, respectively; and $K_w$, the dielectric factor of water. Here, the dielectric factor is estimated for 9.368 GHz (frequency of the polarimetric radar being developed at NARL) and at a temperature of 20$^\circ$C. The shape of the raindrops was approximated to be an oblate spheroid for bigger drops. The axial ratio of the spheroid, being a function of the equivolumetric sphere diameter, was calculated with the model$^{23}$.

The $Z_{DR}$ is given as the ratio of the horizontal over the vertical reflectivity$^5$:

$$Z_{DR} = \frac{Z_{HH}}{Z_{VV}}$$

…(3)

The specific differential phase$^6$ is given by:

$$K_{DP} = \frac{180\lambda}{\pi} \int_{D_{mn}}^{D_{mx}} \text{RE}[F_{HH}(D) - F_{VV}(D)] N(D) dD$$

…(4)
where, $F_{HH}$ and $F_{VV}$, are forward scattering amplitudes at horizontal and vertical polarizations, respectively; and $\lambda$, the wavelength. All the above mentioned parameters are dependent on drop size, shape and dielectric constant. Rain drops tend to become oblate as they grow in size, causing $Z_{DR}$ to increase. The specific differential phase is the derived parameter ($\phi_{DP}$ differential phase shift) It is also an indicator of the drop oblateness and tends to increase as the radar waves propagate through the rain.

The scattering coefficients are computed using T-matrix scattering simulations based on a Gamma distribution model for the DSD and a linear drop axis ratio model. The polarimetric variables ($Z_H$, $Z_V$, $Z_{DR}$ and $K_{DP}$) are estimated [using Eqs (2 - 4)] for a variety of rain DSD measurements made over four years at Gadanki.

Earlier studies have noted significant seasonal variations in DSD even at the same $R$ [Refs (16,27)]. It means that the rain rate relations also vary with the season. The data, therefore, are segregated into three seasons: (a) pre-monsoon (PMON: March – May); (b) southwest monsoon (SWM: June-September); and (c) northeast monsoon (NEM: October-December) and the rainfall relations are obtained for all seasons separately. These relations are compared and contrasted among themselves and also with other existing relations (elsewhere). Since the DSD varies between different types of rain, the disdrometer data are separated based on the type of rain (stratiform and convection). The separation from convective to stratiform rain is based on the rain rate threshold. If the rain rate of the $i$th and its 10 neighbouring samples (5 each on either side, i.e. $i$-5 to $i$+5) is less than 10 mm h$^{-1}$, then all those samples are considered as associated with the stratiform rain, else convection. This classification technique includes samples with $R < 10$ mm h$^{-1}$ in convection, if they are neighbouring the convective cells.

3 Disdrometer observations

The temporal evolution of the DSD, rainfall integral parameters and polarimetric variables and the identification of different types of rain are illustrated here with a typical example. Figure 1 shows the temporal variation of DSD (a typical case, where the intense convection is followed by stratiform rain) during a rain event on 27-28 July 2007. The stratiform and convective types of rain are identified from the time series of estimated $R$ and are denoted by black and red squares, respectively on the figure. As expected, DSD is broad during convective rain, whereas it is narrow during the stratiform rain. The DSD in the leading and trailing edges of the convection is found to be different. The leading edge of the convection contains drops as large as 4-5 mm, whereas at the trailing edge drops never exceeded 4 mm. This variability in DSD between different types of rain and also within the same type of rain (leading and trailing edges of convection) is the main cause for the variations in rain rate relations.

The rainfall integral parameters are estimated from the DSD, obtained from the disdrometer, using the standard formulae (Fig. 2). Although all the rainfall integral parameters show the distinction between the convective and stratiform rains, the $R$ and $LWC$ show the distinction much more clearly than the other two parameters. The convective rain is characterized by large $R$, $LWC$ and $Z$ and moderate to large $D_m$ (2-3 mm). The $R$ and $LWC$ values are nearly one order
of magnitude smaller during the stratiform rain than that of convective rain, whereas the $D_m$ values are generally smaller, but nearly equals at times to those observed during the convection.

The polarimetric variables simulated from the observed disdrometer DSD and T-matrix formulation are shown in Fig. 3. The $Z_H$ and $Z_V$ are found to be large during convection decrease steadily and then increase again during the stratiform rain, a typical variation described by several researchers\(^{15,29}\).

The $Z_{DR}$ values vary between 0.5 and ~3 for most part of the rain event with relatively larger values during the convection than in stratiform rain. The $K_{DP}$ shows clear distinction between the stratiform and convective types of rain. From Figs (2 and 3), one can notice good correspondence between reflectivity values ($Z_H$, $Z_V$ and $Z_{DR}$) and $D_m$. The specific differential phase, on the other hand, has weak dependence on the drop size (and $D_m$) but depends heavily on the rain rate.

Fig. 2 — Temporal variation of disdrometer-derived: (a) $R$, (b) $Z$, (c) $D_m$ and (d) LWC for the rain event during 27-28 July 2007

Fig. 3 — Temporal variation of polarimetric variables for the rain event during 27-28 July 2007: (a) horizontal reflectivity factor ($Z_H$), (b) vertical reflectivity factor ($Z_V$), (c) differential reflectivity ($Z_{DR}$), and (d) specific differential phase ($K_{DP}$) [polarimetric radar variables are simulated at 9.368 GHz frequency using the disdrometer measured DSDs and a drop shape model\(^{23}\)]
It is clear from the above figures that there is a distinct difference in DSD and associated parameters between the stratiform and connective rain.

4 Relation between $R$ and polarimetric variables

Although several rain rate estimators from polarimetric variables are available in the literature, here only three commonly used rain rate estimators are discussed:

(i) The $Z$-$R$ relation is the most commonly used relation to convert $Z$ into $R$ by the radar meteorology community. The variability of this relation over various scales (from one region to another, between different rain types, etc.) is widely documented.

(ii) $R$-($Z_H, Z_{DR}$) relation: As $Z_{DR}$ is the ratio of power measurements, it is used along with the $Z_H$ for the estimation of $R$. It is one of the multi-parameter models for the estimation of rainfall rate.

(iii) $R$-($K_{DP}$) relation: The main advantage of this relation lies in the fact that $K_{DP}$ is immune to radar calibration errors and beam blockage issues.

The general form of the rain rate relations discussed above is represented as a power law as:

$$Z = a_1 R^{b_1} \quad \text{...(5)}$$

Based on scattering simulations with varying drop shape assumptions, authors have proposed schemes that use a power-law combination of two to three polarimetric variables to reduce both DSD and shape dependency as:

$$R = a_2 Z_H^{b_2} Z_{DR}^{c_2} \quad \text{...(6)}$$

$$R = a_3 K_{DP}^{b_3} \quad \text{...(7)}$$

Each of the integrals given in Eqs (1), (2) and (4) are computed using the observed DSD data (rather than simulated DSD) and the scattering amplitudes from T-matrix scattering simulations. Least square regression analysis is performed to obtain the coefficients for the above relations.

4.1 $Z$-$R$ relation

Earlier studies have shown that the coefficients (both prefactor and exponent) of the $Z$-$R$ relation depend on the functional form ($Z = a R^b$ or $R = a Z^b$) and regression method (direct regression or regression after taking the logarithm to the equation) employed.

In the present study, the conventional $Z$-$R$ relation of the form $Z = a R^b$ is modified to a more appropriate form as $R = \left( \frac{1}{n} \right)^{\frac{1}{n}}$ by considering $R$ as dependent variable. The linear least square analysis is performed after taking logarithm to the above relation. Figure 4 shows the scatter plot between the $Z$ and $R$ for different types of rain during different seasons. The regression fits to the data corresponding to the stratiform, convection and total rain are also shown in the figure. The coefficients ($a_i$ and $b_i$), obtained from the regression analysis, for the above categories are tabulated (Table 1). The plots clearly show large scatter around the fits and this large scatter in the $Z$ - $R$ plot is mainly due to variations in the DSD.

Fig. 4 — Scatter plots of $Z$ and $R$ for: (a) pre-monsoon, (b) southwest monsoon and (c) northeast monsoon seasons, respectively [square and star denotes the data of stratiform and convective types of rain, respectively; regression fits for stratiform (blue line), convection (red line) and total data (black line)]
Given that $Z$ and $R$ depend on $D$ differently, any variation in DSD results into a different $Z$ and $R$, causing the scatter. Inspite of segregating the data (based on seasons and type of rain), the scatter persists, highlighting the large variability in the DSD. This scatter sets the theoretical limit on radar rain estimation.

It is evident from the Fig. 4 and Table 1 that the $Z$-$R$ relationship varies widely between the seasons and also with the type of rain, in tune with the DSD variations reported by earlier studies\textsuperscript{15,16}. These studies have shown large variation in DSD between the seasons\textsuperscript{15,16} and attributed these differences to differences in prevailing cloud systems and microphysical and dynamical processes occurring during the drop descent to the ground\textsuperscript{27}. They noted more small drops and fewer big drops in NEM than in SWM for the same $R$. More small drops in NEM increases $R$ more than $Z$, decreasing (increasing) the slope (exponent) and also the intercept on logZ - log$R$ plot, as seen in Fig. 4 (and Table 1). The observed significant seasonal differences in DSD and the $Z$-$R$ relations at Gadanki are not seen at other locations within the Asian monsoon system. For example, Kozu et al.\textsuperscript{52} have not seen any significant difference in the $Z$-$R$ relationships among different monsoon seasons at Singapore and Kototabang.

It is clear from Table 1 that the $Z$-$R$ relationship for the stratiform rain is very different from that of the convective rain in all seasons. The $Z$-$R$ relationship for convective rain has a lower (larger) intercept (slope) than for the stratiform rain. Further, coefficients of the $Z$-$R$ relationship for total data (combined relation) are nearly equal to that for the stratiform rain. It is mainly due to the predominance of stratiform rain (60-70\% in terms of occurrence) in the total data.

4.2 $R$ -$ (Z_H, Z_{DR})$ relation

Polarimetric radars provide more than one parameter, facilitating the use of multi-parameter rainfall estimation. Here, relations for $R$ are derived by combining $Z_H$ and $Z_{DR}$ using regression analysis. The derived coefficients for different seasons and types of rain are given in Table 2. It can be seen that not much variation is seen in the prefactor ($a_2$) between different types of rain. However, it varies slightly between the seasons. The other coefficients also do not show much difference between the seasons and types of rain. Nevertheless, these relations differ very much from those reported elsewhere (Table 3). It is evident from Tables (2 and 3) that none of the coefficients are equal at Gadanki and other regions, indicating the dependence of these relations on local meteorological conditions (which in turn affects the DSD and the above relation).

<p>| Table 1 — Coefficients of $Z$-$R$ relation [$Z=a_1R^b_1$] for convective, stratiform and all types (combined) of rain during pre-monsoon (PMON), southwest monsoon (SWM) and northeast monsoon (NEM) seasons |</p>
<table>
<thead>
<tr>
<th>Season</th>
<th>Combined relation</th>
<th>For convective rain</th>
<th>For stratiform rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>a&lt;sub&gt;1&lt;/sub&gt;</td>
<td>b&lt;sub&gt;1&lt;/sub&gt;</td>
<td>a&lt;sub&gt;1&lt;/sub&gt;</td>
<td>b&lt;sub&gt;1&lt;/sub&gt;</td>
</tr>
<tr>
<td>PMON</td>
<td>468.09</td>
<td>1.39</td>
<td>318.31</td>
</tr>
<tr>
<td>SWM</td>
<td>349.89</td>
<td>1.34</td>
<td>264.13</td>
</tr>
<tr>
<td>NEM</td>
<td>297.50</td>
<td>1.37</td>
<td>166.88</td>
</tr>
</tbody>
</table>

<p>| Table 2 — Coefficients of $R$ -$ (Z_H, Z_{DR})$ relation [$R=a_2Z_H^c_2Z_{DR}^c_2$] for convective, stratiform and all types (combined) of rain during pre-monsoon (PMON), southwest monsoon (SWM) and northeast monsoon (NEM) seasons |</p>
<table>
<thead>
<tr>
<th>Rain type</th>
<th>Season</th>
<th>Combined relation</th>
<th>For convective rain</th>
<th>For stratiform rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>a&lt;sub&gt;2&lt;/sub&gt;</td>
<td>b&lt;sub&gt;2&lt;/sub&gt;</td>
<td>c&lt;sub&gt;2&lt;/sub&gt;</td>
<td>a&lt;sub&gt;2&lt;/sub&gt;</td>
<td>b&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>PMON</td>
<td>4.23×10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>0.983</td>
<td>-6.85</td>
<td>4.21×10&lt;sup&gt;-2&lt;/sup&gt;</td>
</tr>
<tr>
<td>SWM</td>
<td>3.72×10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>0.975</td>
<td>-6.86</td>
<td>3.73×10&lt;sup&gt;-2&lt;/sup&gt;</td>
</tr>
<tr>
<td>NEM</td>
<td>4.33×10&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>0.985</td>
<td>-6.62</td>
<td>4.32×10&lt;sup&gt;-2&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
R and K_{DP} on D is nearly same (~4th power), whereas the dependencies of R and Z on D are different (3.67th for R and 6th power for Z). Therefore, any variation in DSD changes R and K_{DP} in a similar fashion, while it is not the case with R and Z. This feature can be seen clearly in Figs (1-3).

The coefficients a_3 and b_3 obtained from the regression fits to the data in Fig. 5 are given in Table 4. Clearly, the difference in coefficient values is smaller between the seasons than between different types of rain. Also, the R-K_{DP} relation for convective rain is nearly similar to that for the total rain. The coefficients of R-K_{DP} relation for stratiform rain are slightly different, but are within the reported values elsewhere (Table 5).

From the above analysis, it can be seen that the impact of changes in DSD (caused by different types of rain or by varying meteorological conditions in different seasons) is highest on the Z-R relation. The other two relations (R-(Z_{ib}, Z_{DR}) and R-K_{DP}) although not completely immune to the changes in DSD, but their variation is not much between the seasons and types of rain. Earlier studies have shown that the R-K_{DP} relations are more sensitive to the assumed drop aspect ratio (shape) model than to the details of DSD^{11}.

Now, the performance of the three R estimators is evaluated qualitatively and quantitatively by comparing the R obtained by the estimators with the disdrometer derived R (R_{dis}). For the evaluation, the case study discussed above is considered. It facilitates the examination of how the different radar relations derived for the whole data set compare to an individual event in the convective and stratiform rain. Figure 6 shows the comparison of R obtained with the above three rain estimators and the disdrometer. To show the variations in the stratiform rain clearly, the R during the stratiform rain is multiplied by 10. The periods of stratiform rain are shown on the top of the figure. It is evident from the figure that all estimators nearly follow the R_{dis} and its variations, nevertheless, R obtained by Z show large departures from R_{dis} in both stratiform and convective rain regimes.

To evaluate the differences quantitatively, two types of error metrics are considered: (i) total amount of rain; and (ii) normalized root mean square error (RMSE) (or percentage RMSE or PRMSE), defined as^{10,11}:

\[ \text{RMSE} = \frac{\sqrt{\frac{(R_{est} - R_{dis})^2}{R_{dis}^2}}} \]

where, < > means the average; and R_{est} is R obtained from estimators. The above two metrics are estimated separately for the convective and stratiform rain and

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Table 3 — R-(Z_{ib}, Z_{DR}) relations [R = a(Z_{ib})^2 Z_{DR}^c] reported elsewhere for different types of rain

<table>
<thead>
<tr>
<th>Type</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>3.99 \times 10^{-3}</td>
<td>1.07</td>
<td>-5.97</td>
<td>Bringi &amp; Chandrasekar^{3}</td>
</tr>
<tr>
<td>Convective rain</td>
<td>1.01 \times 10^{-2}</td>
<td>0.91</td>
<td>-4.92</td>
<td>Maki et al.^{11}</td>
</tr>
<tr>
<td>Stratiform rain</td>
<td>1.49 \times 10^{-2}</td>
<td>0.83</td>
<td>-4.89</td>
<td>Maki et al.^{11}</td>
</tr>
</tbody>
</table>

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Fig. 5 — Scatter plots of R and K_{DP} for: (a) pre-monsoon, (b) southwest monsoon and (c) northeast monsoon seasons, respectively [square and star denotes the data of stratiform and convective types of rain, respectively; regression fits for stratiform (blue line), convection (red line) and total data (black line)]
are tabulated (Table 6). It is evident from the table that the R-Z relation underestimates the convective rain amount by ~10 mm (13%), whereas the convective rain amount, obtained by the other two relations, agree well with that obtained by the disdrometer. The PRMSE of R-Z in convection (30%) is nearly a factor of 2 higher than that of the other two relations. While the agreement between R-Z and \(R_{dis}\) is very good for the stratiform rain amount, but the PRMSE is quite large (49%). The \(R-(Z_H, Z_{DR})\) relation provides small PRMSE in both convective and stratiform rain and their rain amounts are somewhat closer to that obtained by the disdrometer, indicating that this is the best rain estimator among the three relations derived in the present study. The \(R-K_{DP}\) relation seems to be the next best rain estimator.

Given that the polarimetric radars provide several rainfall estimators raises a legitimate doubt as to which relation is more suitable for R estimation. Each relation has its own advantages and disadvantages. For instance, the \(Z-R\) relation provides R with fine space-time scales, but suffers with calibration and
attenuation (at higher frequencies) issues. On the other hand, \( K_{DP} \), which is immune to calibration, attenuation and beam blockage issues, provide better \( R \) but suffers with poor spatial resolution. Also, \( K_{DP} \) may not be useful for quantifying light rain, particularly if one uses radars operating at longer wavelengths (for example, S-band radars). Recently, several approaches are being suggested synthesizing different rainfall estimators\(^{33-35} \). The former suggested that adjusting the \( Z-R \) relationship for mean field bias taking the \( K_{DP} \)-based estimate as reference is the best way to obtain unbiased radar-rainfall estimates at fine space-time scales. Instead of following decision tree logic, which most of the studies generally follow, Pepler et al.\(^{35} \) proposed weighted combinations of estimators based on their error characteristics at various \( R \). This approach avoids discontinuities in \( R \) at various threshold values chosen for polarimetric variables.

5 Conclusions

The present study aims to understand the impact of variability of DSD on polarimetric rainfall estimators. Three different rain rate estimators from polarimetric variables \([R-Z, R-(Z_{TH}, Z_{DR}) \text{ and } R-K_{DP}]\) are derived for stratiform and convective types of rain during different monsoon seasons. Polarimetric variables are estimated in X-band frequency using four years of disdrometric measurements and T-matrix scattering simulations. The coefficients for the above relationships are derived by fitting multiple regression equations on the values of \( R \) and three polarimetric radar variables. The scatter around the regression is found to be larger in \( Z \) vs \( R \) plot than in \( R \) vs \( K_{DP} \) plot, mainly because the polarimetric variables depend differently on \( D \). Inspite of segregating the data into different types of rain and seasons, the scatter persists in the \( Z-R \) plot, highlighting the large variability in the DSD even in the same type of rain. The impact of this variability in DSD is higher on the \( Z-R \) relation than on other two rain rate relations. The \( R-K_{DP} \) relation is not much different between the seasons, but has shown some difference between different types of rain. The \( R-(Z_{TH}, Z_{DR}) \) relation also shows a weak dependence on the DSD variation (the coefficients for seasonal and different types of rain are nearly equal), confirming earlier reports that multi-parameter equations generally reduce the dependence on DSD. Nevertheless, these relations are found to be different from those reported elsewhere [compare Tables (2 and 3) and Tables (4 and 5)] indicating that these relations vary based on local meteorological conditions and therefore, appropriate relations need to be derived for the region of interest. The evaluation of the three rain estimators is done by comparing them with \( R_{dis} \). The analysis reveals that the \( R-(Z_{TH}, Z_{DR}) \) relation provides better rainfall estimates than other relations. The \( R-Z \) relation shows large error in both rain amount (particularly in convective rain) and PRMSE.

This study assumes special significance because the National Atmospheric Research Laboratory (NARL), Gadanki in collaboration with ISRO Telemetry Tracking & Command Network (ISTRAC), Bangalore is developing an X-band polarimetric radar, which is nearing completion. Appropriate rain rate relations are, therefore, required to convert these polarimetric variables into rain rate. The rain rate relations derived in the present study are, therefore, not only useful for basic understanding of the microphysics of rain but also has some operational value, as they can be used in the rain rate algorithms of the radar, which is being built at NARL. This polarimetric radar in conjunction with a network of rain gauges, disdrometers and wind profilers, which are already in operation, at Gadanki will form an ideal setup for the validation of satellite rainfall and also for improving satellite retrieval algorithms.

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