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Evaluation of a new polarimetrically-tuned Z-R relation

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Abstract. A new polarimetrically-tuned Z-R estimator of the form $Z = aR^{1.5}$ is evaluated where the coefficient 'a' is continuously estimated based on polarimetric radar data of Z_{dr} and K_{dp}. Six storm events from the TRMM/LBA (Brazil) and TEFLUN-B (Florida) are analyzed using radar data from the NCAR/SPOL radar and a network of gages especially deployed for these two measurement campaigns. For storm total accumulation, the new 'pol-tuned' Z-R method gives a normalized bias of 6% and normalized standard error of about 20% (normalized bias is defined as $< R_{ZR} - R_g > / < R_g >$ here; normalized standard error is defined as $< |R_{ZR} - R_g| > / < R_g >$; R_g is the gage measurement of rain rate, and R_{ZR} is the rain rate estimation from the Z-R estimator; angle brackets denote average values). The method continuously 'tracks' the evolution of the drop size distribution and so no classification of rain types is necessary. In contrast, the use of conventional Z-R method (after stratiform-convective rain separation) results in a normalized bias of around 18% for storm-total accumulation and normalized standard error of 24%.

1 Introduction

The accurate estimation of the drop size distribution (dsd) and rainrate using radar is a long-standing research problem in radar meteorology. Broadly speaking, two separate approaches are available based on, (a) Doppler power spectrum at vertical incidence from vertically pointing profilers, and (b) dual-polarization data at low elevation angles. Both these techniques have their own advantages and disadvantages, but polarimetric radar can scan a large area and is thus suitable for continuous monitoring for hydrological applications whereas vertically pointing profilers are more suited for high resolution study of the vertical structure of rain.

This article addresses the use of polarimetric techniques for estimating the rainrate using information about the size, shape and orientation distribution of the raindrops (together with their fallspeed). In essence, the important polarimetric radar measureables are differential reflectivity (Z_{dr}) and specific differential phase (K_{dp}) in addition to the conventional radar reflectivity factor at horizontal polarization (Z_h). A thorough explanation of the polarimetric measureables is available in Bringi and Chandrasekar (2001). This article develops a polarimetrically-tuned Z-R relation of the form $Z = aR^{1.5}$ where the coefficient 'a' is continuously estimated based mainly on the polarimetric measureables Z_{dr} and K_{dp}. This is in contrast to directly developing a rainrate algorithm based on Z_{dr} and K_{dp}, e.g. of the form $R(Z_{dr}, K_{dp}) = aK_{dp}^b Z_{dr}^c$. The 'tuned' Z-R method appears to be more robust with respect to 'noisy' measurement fluctuations in Z_{dr} and K_{dp}, which occur at low rainrates or in stratiform rain events. However, it does depend on the system radar constant (or, radar system gain) whereas both Z_{dr} and K_{dp} are independent of the system gain (note that Z_{dr} will depend on the differential system gain between H and V polarizations, but this is easier to calibrate compared to the absolute system gain). It will be shown that the 'tuned' Z-R method offers all the advantages of radar polarimetry, but still keeps the form that most radar meteorologists are accustomed to. In addition, there is no need to separate stratiform and convective rain types before applying the 'tuned' Z-R method.

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2 Background

The methodology of deriving a 'polarimetrically-tuned' Z-R relation is based on the assumption of a gamma dsd of the form,

$$N(D) = N_w f(\mu) \left(\frac{D}{D_o} \right)^{\mu} \exp \Big[-(3.67 + \mu) D/D_o \Big] \quad (1)$$

where,

$$f(\mu) = \frac{6}{3.67^4} \cdot \frac{(3.67 + \mu)^{(4+\mu)}}{\Gamma(3.67 + \mu)} \quad (2)$$

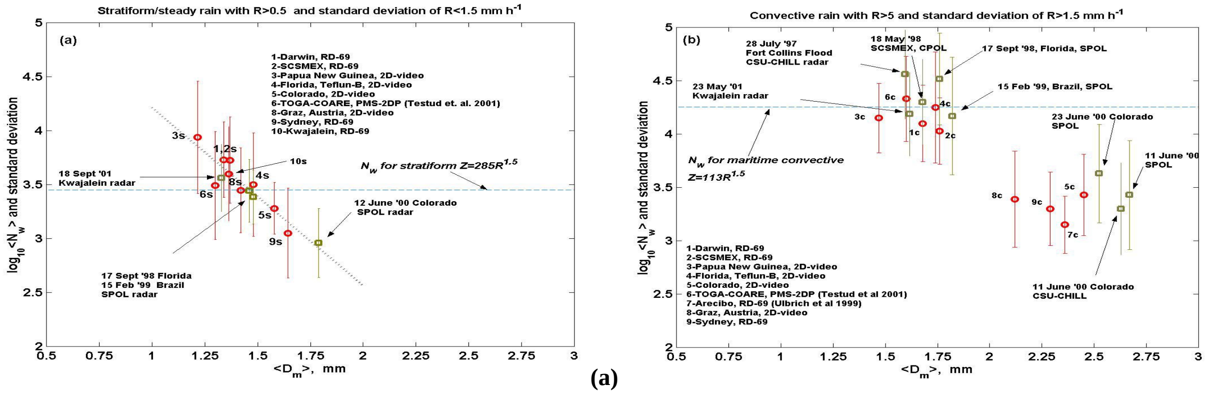

Fig. 1. The average value of $\log_{10}(N_w)$ (with $\pm 1\sigma$ standard deviation bars) versus average D_m from disdrometer data and radar retrievals as indicated for **(a)** stratiform rain, and **(b)** convective rain. Also, the dashed horizontal lines at constant $\log_{10}(N_w)$ are the N_w's used for stratiform and convective fixed Z-R relations. Note that the unit of N_w in this figure is mm^{-1} m^{-3}.

and,

$$N_w = \frac{3.67^4}{\pi \rho_w}\left[\frac{W}{D_o^4}\right] \tag{3}$$

The above form is the so-called normalized gamma form (Willis, 1984; Testud et al., 2001); note that W in Eq. (3) is the water content and ρ_w is the water density. Assuming Rayleigh scattering and a power law form for the terminal fallspeed of drops, $V(D) = 3.78D^{0.67}$ (Atlas and Ulbrich 1977), then it is easy to show that the reflectivity factor Z is related to rain rate R as,

$$Z = \frac{a'(\mu)}{\sqrt{N_w}} R^{1.5} \tag{4}$$

where $a'(\mu)$ depends on μ only and other constants. Testud et al. (2001) further generalized (4) to be applicable to any general dsd, not necessarily of the gamma form. They also show that the sensitivity to μ is only around 15%, much less than the sensitivity to the range of N_w in different rain types.

In several recent articles it has been shown that D_o, N_w and μ can be retrieved from polarimetric radar measurement of Z_h, Z_{dr} and K_{dp} (Gorgucci et al., 2001; Bringi et al., 2002). A major development has been methods to account for drop oscillations and drop canting in an "effective" manner, and to extend the retrieval methodology to cases where Z_{dr} and K_{dp} tend to be "noisy" because of measurement fluctuations, especially in light rainfall events. The retrieval algorithm is fully explained in Gorgucci et al. (2001) and Bringi et al. (2002) and will not be repeated herein because of space limitations. Analysis of 2D-video disdrometer dsd data shows that D_o and $\log_{10}(N_w)$ can be retrieved to an accuracy of around 5–6% (in the absence of any measurement fluctuation error). Figure 1a and b show disdrometer and radar-based plots of $\log_{10} < N_w >$ versus $< D_m >$ for different climatic regimes (D_m is the mass-weighted mean diameter which is close to D_o; angle brackets denote average values). Note how the stratiform rain type falls on a straight line. Note also the grouping of the convective rain type into a maritime cluster and a continental cluster. The dashed horizontal lines depict the fixed Z-R for stratiform and convective rain types used later to compare against the 'pol-tuned' Z-R.

3 Radar data processing

Polarimetric radar data used in this study are from the NCAR SPOL radar during the TRMM/LBA and TEFLUN-B programs (locations are Brazil and Florida, respectively). Evaluation of the 'tuned' Z-R algorithm is based on individual gage comparisons; the gage locations for TRMM/LBA and TEFLUN-B are shown in Figs. 2a and b. The radar data stream consists of Z_h, Z_{dr} and ϕ_{dp} (differential propagation phase) available every 150 m in range. The ϕ_{dp} data are filtered in range using the iterative method of Hubbert and Bringi (1995). The filtered ϕ_{dp} range profiles are used to estimate K_{dp}. The Z_h data are corrected for rain attenuation using Testud et al. (2000) adapted for S-band, while Z_{dr} is corrected for differential attenuation using a self-consistent, constraint-based algorithm described by Bringi et al. (2001). These attenuation-corrections are significant only when the total ϕ_{dp} exceeds around 50°. In addition, gaseous attenuation is estimated from Doviak and Zrnic (1993). The Z_{dr} calibration is based on examining the values in the region of storms where Z_{dr} should be 0 dB because of low density and isotropic orientation (this method was used to 'fine tune' the Z_{dr} calibration based on vertical pointing data in light rain, which was only available on certain days during the experiment). Such 'fine-tuning' showed that the nominal NCAR/SPOL calibrated Z_{dr} values had to be adjusted lower by 0.15 dB for both TRMM/LBA and TEFLUN-B experiments. The system gain (or, radar constant) was 'fine tuned' using reconstruction of ϕ_{dp} range profiles (derived by integrating $K_{dp} = f(Z_h, Z_{dr})$ and comparing with the measured ϕ_{dp} range profiles. An upper/lower bound method was used resulting in a reflectivity adjustment of 1.25 dB for

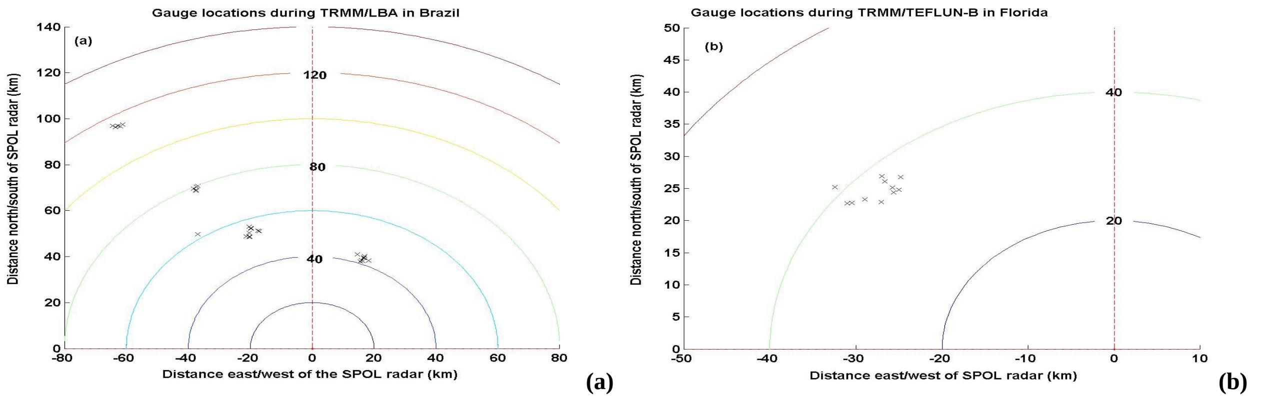

Fig. 2. Gauge locations relative to the SPOL radar as the origin, **(a)** TRMM/LBA configuration in Brazil, and **(b)** TRMM/TEFLUN-B configuration in Florida.

TRMM/LBA (nominal NCAR/SPOL reflectivity values were increased by 1.25 dB) and zero adjustment for TEFLUN-B. Our TRMM/LBA adjustment is in excellent agreement with other independent measures (Anagnostou et al., 2001). Such accurate calibration and inclusion of rain and gas attenuation corrections are necessary for proper evaluation of polarimetric rainfall algorithms.

For comparison against gages, a small polar 'box' is constructed around each gage location (nominally 1 km in range and 1.5° in azimuth angle) and it is assumed that each 'point' gage rain rate estimate represents this polar area. Data from radar beams that intersect this polar area are used to estimate an average μ and N_w for the area (equations are given in the Appendix of Bringi et al., 2002); then (4) is applied to find the average rain rate over the area. We refer to the 'pol-tuned' Z-R relation as $Z = \hat{a}R^{1.5}$ where $\hat{a}$ is the multiplicative coefficient obtained as $\hat{a} = a'(\langle\mu\rangle)/\sqrt{\langle N_w\rangle}$ (angle brackets represent areal averages). The hypothesis here is that over short time intervals, the dsd shape parameter μ and the generalized 'intercept' parameter N_w are stationary over the small polar area. However, because of the nonlinearities involved, such a procedure can give a small bias in the retrieval of the average rain rate but we have estimated this bias (from the data itself) to be less than around 10%. We have also determined (from the data itself) that the assumption of a 'stationary' N_w over small areas is quite reasonable for the events analyzed herein (in general agreement with Testud et al., 2001).

4 Results

Radar/gage datasets were analyzed for 3 storm days during TRMM/LBA (15, 18 and 27 February 1999) and 3 storm days during TEFLUN-B (21 August and 9, 17 September 1998). The gage data consisted of a time-series of 1 min rain rates. The radar scanning strategy was variable, but generally the sampling interval was around 1–2 minutes except for events of 18 and 27 February 1999. In all cases, only data from low elevation angles were used (0.5 - about 1°). Non-meteorological echoes were removed by using the radial standard deviation of ϕ_{dp} over 10 consecutive gates, the mean ρ_{hv} and the SNR as the data 'quality' indicators. The use of polarimetric data to identify non-meteorological echoes and to generally improve data quality as compared with a conventional Doppler radar cannot be overemphasized.

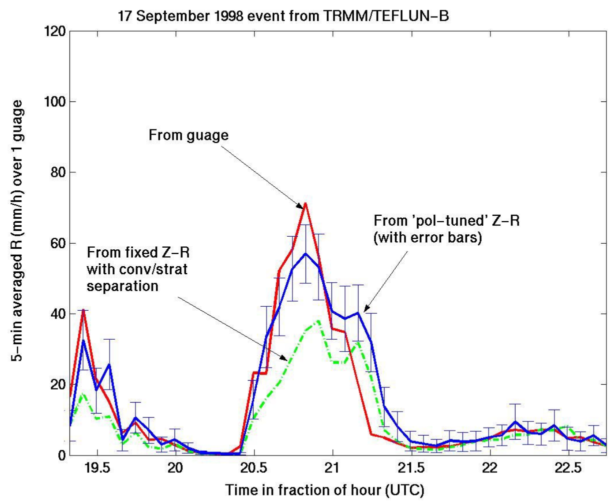

Fig. 3. Time-series of 5 min-averaged rain rates for one event over a particular gauge location. The standard error bars on the 'pol-tuned' Z-R estimator reflect both measurement error and algorithm error.

Figure 3 shows the time-series of 5 min-averaged rain rates over a single gage location for the event of 15 February 1999. The standard error bars on the 'pol-tuned' Z-R estimate reflect both measurement fluctuation errors as well as algorithm errors (these are based on disdrometer simulations and shown in Fig. 4). Figure 3 also shows the 5 min-averaged gage rain rates as well as rain rate from using the conventional Z-R method after separating stratiform and convective rain types (the separation method is simple and based

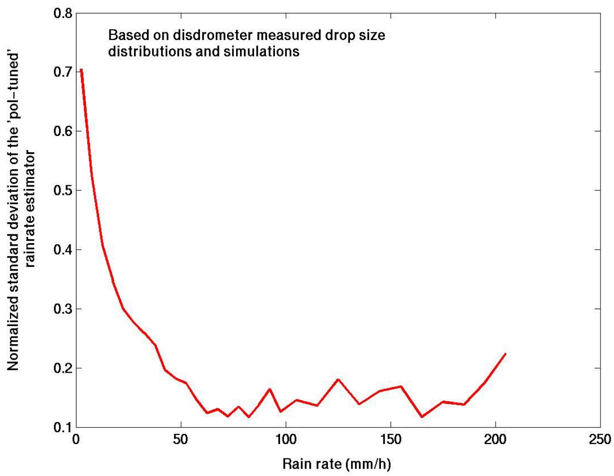

Fig. 4. Normalized standard deviation of R for the 'pol-tuned' estimator based on drop size distribution data from disdrometer and based on simulations.

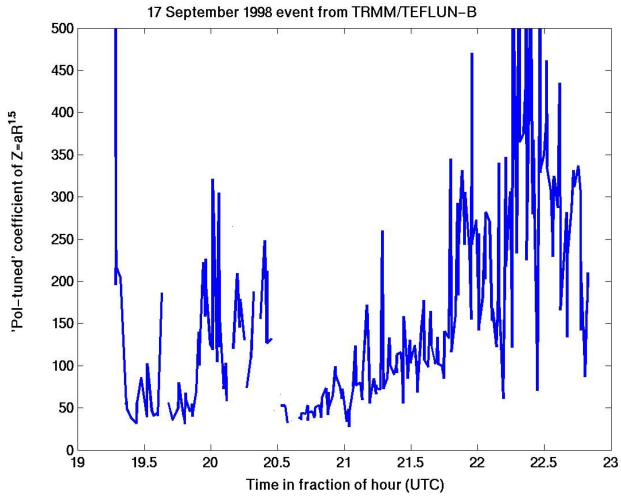

Fig. 5. Time-series of the coefficient $\hat{a}$ of the 'pol-tuned' $Z = \hat{a}R^{1.5}$ estimator (see also Fig. 3).

on the mean and standard deviation of 5 consecutive 1 min gage rain rate samples with stratiform rain classified when the mean is $\leq$ 5 mm/h and the 5-point σ is $<$ 1.5 mm/h). The stratiform Z-R is $Z = 285R^{1.5}$ whereas the convective Z-R is $Z = 113R^{1.5}$ (these relations are marked in Figs. 1a and b in the $\log_{10} < Nw >$ versus D_m plane). Figure 5 shows the time-series plot of the 'pol-tuned' coefficient, $\hat{a}$, which changes continuously (this plot may be compared with Fig. 3). Examination of Fig. 3 and Fig. 5 shows that the fixed Z-R underestimates the peak gage rain rates whereas the 'pol-tuned' Z-R is able to match better the peak gage values (the 'pol-tuned' coefficient $\hat{a}$ is lower than the fixed convective coefficient within the peak rain cell giving higher rain rates for the 'pol-tuned' estimator). This suggests that to avoid rainfall accumulation bias with a non-polarimetric radar, it is necessary to have the 'correct' Z-R relation even after convective/stratiform separation. Data similar to Fig. 3 were generated for event and for small polar areas over each gage. The mean rain rate for each event (over a gage location) is defined as the average of the 5-min estimates for

the whole event over that particular gage location. Figure 6a shows the plot of the mean rain rate for each gage location color-coded for each of the 6 storm events. This plot shows the accuracy of the 'pol-tuned' Z-R estimator when compared against gages. The normalized bias is about 6% and the normalized standard error is around 20% (We use the absolute deviation between radar and gage data as the measure rather than the deviation squared). Figure 6b shows a similar comparison except for the conventional Z-R estimator after convective/stratiform separation. The normalized bias is now about 18% (underestimate relative to gage) and the normalized standard error is 24%. Thus, we conclude that the 'pol-tuned' Z-R method offers higher accuracy and significantly lower bias as compared with conventional Z-R for estimating storm-total rainfall. The continuous 'pol-tuning' of the coefficient $\hat{a}$ in $Z = \hat{a}R^{1.5}$ automatically accounts for evolution of the dsd, and indeed demonstrates that 'tracking' the evolution is necessary for accurate rain rate estimation. Polarimetric radar data also offers significant advantages in establishing data quality and in stable attenuation-correction schemes in intense rain cells (even at S-band significant attenuation exists when $\phi_{dp} \geq 50°$). It also offers a method to 'fine-tune' the system radar constant which is essential to avoid biases in rain accumulation when using Z-R methods. This study shows that careful analysis of polarimetric radar data can yield significant improvement in reducing the normalized bias in storm-total rainfall accumulation over conventional Z-R method (from 18% to 6%).

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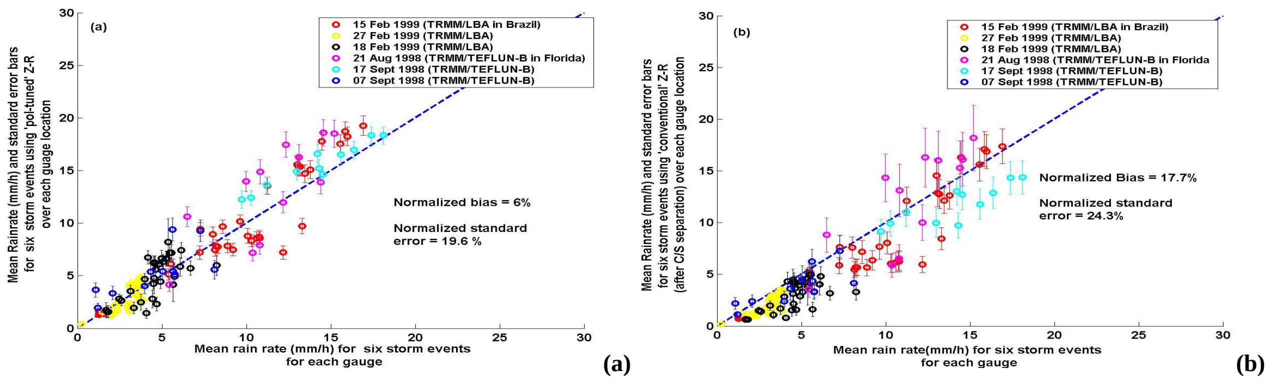

Fig. 6. Comparison of **(a)** 'pol-tuned' mean R versus gauges, and **(b)** fixed Z-R (after stratiform/convective classification) versus gauges. Each data point refers to one gauge location in the network (see Fig. 2). The mean rain rate for the event over a gauge location is the average of the 5 min-rain rates shown, for example, in Fig. 3.

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