Reply

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1. The requirements for valid application of the window probability matching method (WPMM)

Ciach et al. (1997, hereafter C97) made valuable comments about two points that require caution while using the probability matching method (PMM) or WPMM.

1) PMM *always* gives relationships between any two variables.
2) PMM is incapable of distinguishing outliers from valid data.

In order to overcome these weaknesses and benefit from the advantages of WPMM, one must first, *independently*, do the following.

- Establish that a physical and monotonic relationship between the two related variables exists. The relationship can be stochastic (i.e., a random noise is added to the relationship).
- Perform quality control on the data and reject data that are not taken from the same population of pairs.

The requirement of a physical and monotonic relationship was already specified by Rosenfeld et al. (1993) as a prerequisite for the validity of PMM, and WPMM is not different in that respect. The classified WPMM (Rosenfeld et al. 1995b) is a classification of the windows into different rain types having different Z_e–R relationships, in order to ensure the condition of the monotonic relationship for the various rain regimes.

Since relationships are always produced by WPMM, they can be unreal if the two conditions specified above are not fulfilled. C97 suggest that this might have been the case with the interpretation of the results obtained by Rosenfeld et al. (1994, hereafter R94). However, the caution that is the subject of the first part of the C97 comment was already exercised in R94, which fulfilled the following requirements of WPMM.

- R94 related Z_e to R. In this matter, Z_e–R can be regarded as having a monotonic functional relationship with random noise, which is caused by random variations of the raindrop size distribution (Atlas and Chmela 1957; Carbone and Nelson 1978) and by measurement errors. The general use of a power-law Z–R relationship is a testimony to the wide acceptance of this assumption.
- The data used for this study were quality controlled, in several steps, as described in Rosenfeld et al. (1995a). Pairs of Z_e–R contaminated by ground clutter, anomalous propagation, and faulty rain gauges were excluded from the analyses.

2. Simulations of PMM versus WPMM

The windowing of the data pairs in WPMM is made to maximize the likelihood of matching pairs that are physically related, whereas no such mechanism is available for PMM. In accordance with the C97 comment, the existence of such a relationship is necessary for a valid application of WPMM. Therefore, there is a fundamental difference between PMM and WPMM. While the stated purpose of the C97 comment was to ''analyze some of the properties that are common to both PMM and WPMM and discuss their validity,'' they actually simulated only PMM and not WPMM. C97 wrote that the $SD_n(R)$ of PMM reflects ''only the stability of the distribution transformation fitting'' and that $SD_n(R)$ ''does not depend in any way on the pair-wise organization (synchronization) of the data points.'' However, the simulations presented here prove that $SD_n(R)$ strongly depend on the synchronization of the data points.

The simulation was done with observations of 1-min R and Z pairs that were obtained from disdrometer data. The disdrometer was located in Darwin, Australia, for 56 days, during which 5892 nonzero Z–R pairs were obtained, with a total rain accumulation of 711 mm. Here, $SD_n(R)$ was calculated for 1000 permutations of 5% subsamples. The effect of the synchronization was checked by displacement of the Z and R time series by dt minutes with respect to each other, where dt varied between 0 and 15 min. The $SD_n(R)$ are presented in Fig.

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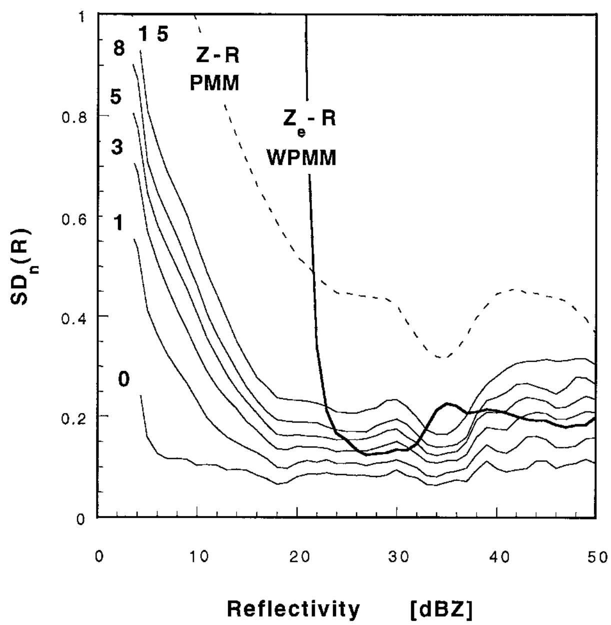

FIG. 1. The $SD_n(R)$ for various time windows (thin solid lines) from 1000 permutations of 5% subsamples from 5892 nonzero *Z–R* pairs, as obtained from a disdrometer in Darwin. WPMM is simulated with a time displacement of *dt* minutes between *Z* and *R*, as posted on the left edge of the lines. The broken line is the $SD_n(R)$ for PMM, where pairs of *Z* and *R* are matched randomly. The thick solid line is the $SD_n(R)$ of Z_e–*R* from radar and gauges in Darwin, as used by R94.

1 as the solid thin lines, with *dt* (min) posted on their left edge. The broken line is the $SD_n(R)$ for PMM, where pairs of *Z* and *R* are matched randomly, as in the simulations of C97. The degradation of $SD_n(R)$ with the decreased degree of synchronization is clearly evident.

The thick solid line in Fig. 1 is the $SD_n(R)$ of Z_e–*R* from radar and gauges in Darwin, as used in R94. The $SD_n(R)$ was calculated from 1000 subsamples of the same size as that used for the disdrometer *Z–R* pairs. This neutralized the effects of the sample size on $SD_n(R)$ as a possible factor for the differences between the $SD_n(R)$ of the disdrometer and the radar–gauges. It is interesting to note that, for reflectivities greater than 22 dB*Z*, $SD_n(R)$ of the Z_e–*R* data is roughly similar to $SD_n(R)$ of the disdrometer data when desynchronized by about 5 min. According to (1), $t = 5$ min is in agreement with the time that is analogous with the radar beam spread *A* and precipitation horizontal velocity *V* that are typical of Darwin:

$$t = \frac{1.3A^{0.5}}{V}. \qquad (1)$$

Equation (1) (Calheiros and Zawadzki 1987; Zawadzki 1975) is quoted in R94 with the wrong coefficient due to a typographical error.

The subsampling permutations results presented in Fig. 1 show the following.

- The simulations by Krajewski and Smith (1991) and C97 show weaknesses of PMM, but have little relevance to WPMM.
- WPMM, as used in R94, is a valid method for overcoming weaknesses of PMM.

Rosenfeld (1997) has confirmed experimentally that WPMM is much more powerful at finding *Z–R* relationships than is a regression method. Haddad and Rosenfeld (1996) have also shown the theoretical basis for that.

3. Where are the misinterpretations?

After having addressed the major issues, following is a discussion of several specific points.

1) *The interpretation of $SD_n(R)$ as a statistical artifact*
C97's simulations of $SD_n(R)$, presented in their Fig. 2, are irrelevant because 1) the model is not simulating WPMM and 2) the distribution of rain intensities are not gamma distributed. Kedem et al. (1994) showed that, for rainfall data in Darwin and elsewhere, "the lognormal fits outperform the gamma fits by a wide margin."
All that C97 show with their simulations is that, for the distributions that they selected, the *relative* errors of estimate increase sharply at low intensities. It is not a unique property of PMM, but is present in most other data-estimating methods.
2) *The comparisons between WPMM and power-law rain estimates*
The use of disdrometer-based power law with a *G*/*R* (rain gauge/radar rain) bias correction is one of the most extensively used methods for radar rainfall measurements. Therefore, the agreement between radar estimated gauge-measured rainfall is evaluated by the correlations and the normalized standard deviations—$SD_n(R)$, as displayed in R94's Fig. 9 and Table 2. Both parameters are insensitive to fixed bias error such as that caused by radar calibration. This makes them useful for estimating the improvement in performance *after* compensation for overall bias.
3) *Evaluation of performance by the calibration dataset*
The WPMM-derived rain estimates were also applied to independent datasets (Rosenfeld et al. 1995a), and the same improvement in the correlations and $SD_n(R)$ was realized. This was done with the same data used in R94.
4) *The physical interpretation of the large $SD_n(R)$ for low intensities.*
Figure 2 of R94 shows that the *measurement-based* determination of the Z_e–*R* relationship has very poor accuracy at the lower end of the intensities. According to their Fig. 1, the sharp increase in $SD_n(R)$ is unique to the radar–gauge Z_e–*R* pairs, and it is not an artifact of PMM. The cause of that difference is likely routed in the difference between *Z–R* and Z_e–*R*—that is, the distortion of the true reflectivity field by the radar observations, as already suggested in

R94. The large $SD_n(R)$ below about 25 dBZ in Darwin is a direct manifestation of the large variability between R and Z_e in these low intensities, where clear-air echoes, clutter, and other nonprecipitation echoes are often recorded. Therefore, the accuracy of the estimate of the true Z_e–R would also reflect the accuracy of the application of the true Z_e–R, if this were known.

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