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Comparison of the TRMM Precipitation Radar rainfall estimation with ground-based disdrometer and radar measurements in South Greece

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ABSTRACT

The performance of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) rainfall estimation algorithm is assessed, locally, in Crete island, south Greece, using data from a 2D-video disdrometer and a ground-based, X-band, polarimetric radar. A three-parameter, normalized Gamma drop size distribution is fitted to the disdrometer rain spectra; the latter are classified in stratiform and convective rain types characterized by different relations between distribution parameters. The method of moments estimates more accurately the distribution parameters than the best fit technique, which exhibits better agreement with and is more biased by the observed droplet distribution at large diameter values. Power laws between the radar reflectivity factor (Z) and the rainfall rate (R) are derived from the disdrometer data. A significant diversity of the prefactor and the exponent of the estimated power laws is observed, depending on the scattering model and the regression technique. The Z–R relationships derived from the disdrometer data are compared to those obtained from TRMM-PR data. Generally, the power laws estimated from the two datasets are different. Specifically, the greater prefactor found for the disdrometer data suggests an overestimation of rainfall rate by the TRMM-PR algorithm for light and moderate stratiform rain, which was the main rain type in the disdrometer dataset. Finally, contemporary data from the TRMM-PR and a ground-based, X-band, polarimetric radar are analyzed. Comparison of the corresponding surface rain rates for a rain event with convective characteristics indicates a large variability of R in a single TRMM-PR footprint, which typically comprises several hundreds of radar pixels. Thus, the coarse spatial resolution of TRMM-PR may lead to miss of significant high local peaks of convective rain. Also, it was found that the high temporal variability of convective rain may introduce significant errors in the estimation of bias of the satellite rainfall estimates with respect to data from ground-based radars.

1. Introduction

Understanding the physics of rainfall is essential in a number of contemporary applications including flood estimation, weather forecasting, agriculture, cloud physics, and microwave communications. Thus, rainfall measurements and modeling have drawn strong interest over the years. Special attention is paid to the drop size distribution (DSD) of rain, mainly because the DSD shape reflects the physics of rain. Moreover, it is well established that the relationship between the radar reflectivity factor (Z), simply termed as reflectivity, and the rain rate (R) is strongly affected by the DSD parameters.

Several mathematical shapes have been proposed for the DSD of rainfall. The three-parameter Gamma distribution (Ulbrich, 1983; Ulbrich and Atlas, 1998) may be considered one of the most widely used. Furthermore, Vivekanandan et al. (2004) have proposed a constrained Gamma DSD, i.e., a simplified, two-parameter Gamma distribution, devised from the observation that the shape and slope of the three-parameter DSD are related to each other. The concept of normalized distribution has been adopted by many researchers (Testud et al., 2001; Bringi et al., 2003; Chandrasekar et al., 2005; Kalogiros et al., 2013a; Thurai et al., 2014). Normalization may lead to the determination of two "reference" parameters of the DSD (such as the liquid water content and the mean volume diameter) without any assumption about its shape. A variety of methods may be used in order to retrieve the DSD parameters from disdrometer data. The methods of moments and best fitting (maximum-likelihood) are the most popular techniques (Testud et al., 2001; Bringi et al., 2003; Caracciolo et al., 2006; Thurai et al., 2014). Moreover, the method of truncated moments has been introduced in order to reduce overestimation of the three parameters of the Gamma distribution and especially the shape parameter (Ulbrich and Atlas, 1998; Vivekanandan et al., 2004).

One of the main reasons that there is currently strong interest in retrieving an accurate DSD is that, as mentioned above, it is closely related

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to the Z–R relationship; it is common knowledge that the latter follows a power law of which the coefficients depend on the DSD parameters. A thorough analysis of the relationship between Z and R and its dependence on the DSD is presented by Uijlenhoet (2001). The spatial and temporal variability of the Z–R coefficients and the associated DSD parameters, as well as their dependence on the precipitation type, have been extensively investigated in the literature (Battan, 1973; Chapon et al., 2008; Hazenberg et al., 2011; Ochou et al., 2011).

Current microwave remote sensing systems comprise ground-based radars as well as satellite sensors. Ground-based, polarimetric weather radars are modern and promising active sensors that provide high-resolution rainfall observations over complex terrain. Their basic observables include the radar reflectivity at horizontal polarization, the differential reflectivity, and the specific differential phase. Several rainfall estimation algorithms, derived from polarimetric radar measurements, have been developed, which significantly improve the accuracy of radar rainfall estimations compared to classic Z–R relationships; validation through rain gauge measurements and/or disdrometer data has been performed (Anagnostou et al., 2009; Anagnostou et al., 2010; Kalogiros et al., 2013a; Islam, 2014; Koffi et al., 2014). Furthermore, the DSD parameters, estimated from polarimetric radar data, have been compared to disdrometer measurements (Bringi et al., 2003), whereas the spatial distribution of the DSD has been explored by use of polarimetric radar estimators (Vivekanandan et al., 2004).

Information about rain parameters may, complementary, be obtained from satellite sensors. Comparison between the retrieved products from ground-based and spaceborne radars is a challenging task; difficulties include mismatch between operating frequencies, sampling volumes, and spatial alignment (Chandrasekar et al., 2005). Comparison between reflectivity as measured by the Tropical Rainfall Measuring Mission Precipitation Radar (TRMM-PR) and ground-based radars has been presented by Liao et al. (2001) and Gabella et al. (2006, 2013). Cross-validation of the rainfall algorithms of TRMM-PR and a ground-based, polarimetric radar has also been performed (Chandrasekar et al., 2003), whereas the TRMM's precipitation estimation has been assessed by using data from ground-based radars of the Global Precipitation Measurement (GPM) validation network (Islam et al., 2012) and Kirstetter et al. (2012) over the whole region of United States.

In this paper, a comparison is made between Z–R relationships derived from disdrometer data analysis and Z, R outputs from the TRMM-PR algorithms and datasets in order to validate locally, in an area of south Greece where no other similar validation has been made, this set of algorithms. Furthermore, a case study of direct comparison of rainfall estimation from the TRMM-PR and a high-resolution, ground-based, polarimetric radar is made. Data for this study were acquired by a 2D-video disdrometer (2DVD) and a ground-based, polarimetric, X-band (XPOL) radar located at the northwest part of Crete island (southeastern Mediterranean), in Greece. Crete island is one of the few areas in Greece which was covered sufficiently by TRMM. In Section 2, the disdrometer dataset is presented; it is shown that the dataset can be described sufficiently by a three-parameter, normalized Gamma distribution and a classification in two types of rain, i.e., convective and stratiform. Subsequently, Z–R power laws are derived from the disdrometer data, in Section 3, by implementation and comparison of several scattering models and regression techniques. As far as we know, results from a detailed comparison of many different methods for DSD analysis and estimation of Z–R relationships have not been obtained before in an area of Greece. The aforementioned Z–R relationships are compared to those obtained from TRMM-PR algorithm and data. This is an indirect validation of TRMM-PR precipitation estimates since a direct comparison between disdrometer and TRMM-PR rainfall rates cannot be made, due to the large difference in sampling volume of the two sensors. Section 4 presents a direct comparison between the surface rain rate, as derived from the XPOL radar matched to the satellite data resolution and TRMM-PR. Finally, Section 5 comprises the conclusions of this work.

2. Disdrometer dataset and parameterization of the drop size distribution

The measurements of raindrop size spectra were collected with the 2DVD of the National Observatory of Athens, during an experimental campaign on radar rainfall estimation over complex terrain, in winter 2006–sping 2007, at the northwest part of Crete island, near the city of Chania, Greece (Anagnostou et al., 2009). The time period of the 2DVD operation was only from December 2006 to January 2007 (Anagnostou et al., 2009), due to operational problems thereafter. During its operation, the 2DVD recorded 1852 min of rain. The version of the 2DVD is the one described by Kruger and Krajewski (2002). It records with high-resolution line-scan cameras the shape (outline, shadow) and the fall velocity of each particle passing through two perpendicular optical wide beams which have a vertical distance of about 6.5 cm and their horizontal intersection defines the measurement area; the latter is about 10×10 cm. The 2DVD was calibrated just after its installation at the experimental site by dropping metallic calibration balls through the measurement area. As it was noted by Kruger and Krajewski (2002), flow distortion by the disdrometer, due to its height (about 1.2 m), under significant horizontal wind and drop splashing may lead to DSD underestimation errors. The spatial distribution of drops is distorted under significant wind, while during drop splashing, mismatched drops are recorded by the two light beams of the instrument and rejected. Moreover, comparative studies indicate that the number of small drops with diameter below about 0.8 mm may be underestimated (Tokay et al., 2013). Sampling errors may also occur for large drops due to the finite size of the measurement area, even though the latter is rather large compared to the measurement area of other disdrometer types.

Quality control was applied to the raw detected particles. Bad detections, i.e., secondary drops due to splashing or mismatched drops, were detected and rejected based on a 50% difference criterion between the measured fall velocity and the value corresponding to the measured equivolumetric diameter of the particle according to empirical relations of the fall velocity (Bringi and Chandrasekar, 2001), similar to Kruger and Krajewski (2002) and Tokay et al. (2013). The drop size distributions estimated from the processed disdrometer data are in time intervals of 1 min and represent a diameter range of 0.1–10 mm with a bin (size class) resolution of $\Delta D = 0.2$ mm. The resolution of the raindrop size depends on the detection position in the measurement area and the fall velocity of the raindrop, but, on average, it is about 0.2 mm; thus, the first diameter bin is empty. Using the above diameter bins, the error on the retrieved DSD parameters (using DSD moments), due to the truncation of the DSD, is very small (<5%) for the usual case of median volume diameter between 0.4 and 2.5 mm (Vivekanandan et al., 2004), provided that the sampling interval is large enough to include enough drops in each diameter bin.

The measured DSD is parameterized by fitting a normalized Gamma distribution to each 1-min observed spectrum. Data with rainfall rate value $<10^{-3}$ mm hr^{-1} or number density of drops <1 m^{-3} were considered not reliable and were not used in the analysis. The normalized expression of the Gamma DSD (Testud et al., 2001) is $N(D) = N_w F_\mu(X)$, where $X = D/D_m$, with D and D_m being the diameter and the mass-weighted mean diameter, respectively, both in mm; N_w (mm^{-1} m^{-3}) stands for the intercept parameter, whereas the normalized shape of the DSD is given by

$$F_\mu(X) = \frac{\Gamma(4)}{4^4} \frac{(4+\mu)^{4+\mu}}{\Gamma(4+\mu)} X^\mu \exp\{-(4+\mu)X\} \quad (1)$$

The three parameters N_w, D_m, and μ have been estimated by use of two different methods: (a) A best fitting procedure, based on the absolute log-error minimization, of the normalized Gamma DSD to each 1-min observed spectrum has been applied (hereafter named