P3.35 INSTRUMENTATION EFFECTS ON ESTIMATED DROP SIZE DISTRIBUTION AND RADAR PARAMETERS

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1. INTRODUCTION

Much of what is known about drop size distributions (DSDs) has been determined with observations from ground-based raindrop disdrometers. While seemingly a straightforward task, inferred DSD properties are subject to a number of error sources. The size of the raindrop sample (Joss and Walvogel 1969; Smith et al. 1993, 2009; Smith and Kliche 2005; Mallet and Barthes 2009), the appropriateness of the assumed DSD model to which the observations are fitted and fitting method (e.g., Smith 2003; Kliche et al. 2008; Mallet and Barthes 2009), wind affects (Nešpor et al. 2000), and splashing all contribute error. The controlling parameters of the assumed drop distribution are usually computed from various moments of the observed drops (e.g., Tokay and Short 1996) and vary somewhat according to the particular moments used (Zhang et al. 2003; Smith and Kliche 2005; Cao and Zhang 2009; Smith et al. 2009). However, the above error sources may be secondary to instrumentation limitations and related biases.

Of interest here is the role that instrumentation deficiencies play on derived DSD properties. Specifically, we examine measurements from a Joss-Waldvogel impact disdrometer (JWD) and a two-dimensional video disdrometer (2DVD). The JWD, manufactured by Distromet LTD of Basel, Switzerland, long has been used for obtaining drop size distribution attributes. Technical descriptions are given by Joss and Waldvogel (1967), Sheppard and Joe (1994), and Tokay et al. (2001). The 2DVD is manufactured by Joanneum Research at the Institute of Applied Systems Technology in Graz, Austria. Descriptions are given by (Schönhuber 1997; Tokay et al. 2001; Kruger and Krajewski 2002).

Cursory comparisons of integral DSD attributes such as radar reflectivity computed from JWD or 2DVD measurements typically show good agreement when compared to radar observations (Waldvogel 1974; Sheppard and Joe 1994; Tokay et al. 2001; Zhang et al. 2001; Brandes et al. 2003, 2004a). The agreement may be due in part to the fact that reflectivity is usually presented in decibels. The measurements are frequently extended to estimate other DSD attributes, such as the governing parameters of assumed exponential and gamma DSD models (e.g., Tokay and Short 1996; Tokay et al. 2001; Zhang et al. 2001; Brandes et al. 2003, 2004a, 2006). Estimated attributes are difficult to verify. Cao et al. (2008) use the side-by-side 2DVD measurements to quantify the error, but the two 2DVDs may have the same limitations. Furthermore, more than one instrument is rarely available; hence, the measurements are often simply accepted.

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Sheppard and Joe (1994) compared a Joss-Waldvogel impact disdrometer with a Particle Measuring Systems (PMS) 2DG spectrometer and a Precipitation Occurrence Sensor System (POSS). In general, DSD shapes and estimated 1-min rainfall rates agreed. Estimated drop spectra were influenced by differences in sampling volumes and truncation. Campos and Zawadzki (2000) derived radar reflectivity–rain rate relations from drop measurements obtained with a JWD, an optical spectro-pluviometer, and a POSS. Relationships for a stratiform rain event depended strongly on sensor type. Differences were comparable to that found for different climatic regimes.

Previous comparative studies with the JWD and 2DVD include Williams et al. (2000) and Tokay et al. (2001). Both studies found that the JWD detected fewer small drops and that the largest drops could be beyond the maximum size limit of the JWD. Although observations from the same field program were used in both studies, conclusions reached concerning small drop impacts on derived DSD properties were quite different. Williams et al. examined a single convective event. They determined that, even after an adjustment was applied for missed drops, the JWD consistently had lower small drop concentrations than a collocated 2DVD and that the disagreement increased with radar reflectivity. For rainfalls with radar-measured reflectivity greater than 40 dBZ, the mass-weighted diameter estimated with the JWD was more than 13% greater and the rainfall rate more than 25% less than that estimated with the 2DVD.

Tokay et al. (2001) analyzed several storms. An adjustment for missed drops was not applied. Tokay et al. note that many more small drops were measured with the 2DVD. However, when the measurements from the JWD and 2DVD were averaged over several storms there was good agreement between instruments. Rain rate and radar reflectivity were 8% and 1% less with the JWD. Agreement was explained by the fact that small drops contributed only 0.1 % to reflectivity and 1.8% to rain rate. Moreover, estimated governing parameters of assumed exponential and gamma DSD models also agreed. This may stem from the averaging of numerous 1-min samples which tends to make derived DSDs more exponential (e.g., Joss and Gori 1978; Sheppard and Joe 1994).

Knowledge of raindrop size distributions is important for understanding microphysical processes in storms, parameterizing these processes in numerical forecast models, estimating rainfall rates with radar, interpreting polarimetric radar observations, and retrieving storm microphysical properties from polarimetric radar measurements. We believe further investigation of disdrometer measurements is in order. Documenting observational uncertainties has value because they help define the limits of our knowledge. A short description of the two disdrometers and known short comings is given. Observations from a JWD and a 2DVD are then compared and the influence of instrument differences on derived DSD properties is examined. Impacts on radar reflectivity–rain rate relations and estimates of evaporation and accretion rates are highlighted.

2. GAMMA DROP SIZE DISTRIBUTION MODEL

A widely accepted model applied to raindrops is the gamma distribution

$$N(D) = N_0 D^{\mu} \exp(-\Lambda D) \quad , \qquad (1)$$

where N_0 ($\mathrm{mm}^{-\mu-1}$ m^{-3}) is a number concentration parameter, μ is a distribution shape parameter, Λ (mm^{-1}) is a slope term, and D (mm) is the drop equivalent volume diameter. Here, the governing parameters of the distribution were determined using the 2nd, 4th, and 6th moments of observed 1-min drop samples. While the moment method may not be optimum for all applications (changed), it is widely used. Besides, issues raised here are are not believed to depend on the fitting procedure.

Comparative parameters also computed are the drop median volume diameter (D_0) defined as

$$\int_{D_{\min}}^{D_0} D^3 N(D)dD = \int_{D_0}^{D_{\max}} D^3 N(D)dD \quad , \qquad (2)$$

rain rate (R)

$$R = 6\pi \times 10^{-4} \int_{D_{\min}}^{D_{\max}} D^3 v_t(D) N(D)dD \quad , \qquad (3)$$

and radar reflectivity at horizontal polarization (Z_{H})

$$Z_H = \frac{4\lambda^4}{\pi^4 \left|K_w\right|^2} \int_{D_{\min}}^{D_{\max}} \left|f_H(D)\right|^2 N(D)\,dD \quad . \qquad (4)$$

Truncated DSDs are assumed where $D_{\max}$ is the diameter of the largest observed drop in the distribution and $D_{\min}$ is the smallest drop. Drop terminal velocities $v_t(D)$ are computed as in Brandes et al. (2002). Radar reflectivity is computed following Brandes et al. (2004b) where λ (cm) is the radar wavelength, K_w is the dielectric factor for water, and $f_{\mathrm{H}}(D)$ is the drop backscattering amplitude for a horizontally polarized wave (changed).

3. INSTRUMENTATION

Briefly, the sensor head of the JWD has a circular surface area of 50 cm^2 that is displaced downward when struck by a raindrop. The displacement causes a voltage that induces a restoring voltage, related to the drop diameter, which repositions the sensor head. During restoration drops which strike the instrument are not recorded. Drops are assigned to twenty irregularly-sized bins with mean diameters ranging roughly from 0.3 to 5.3 mm. Still larger drops are assigned to the largest size bin. Calibration is performed by the manufacturer. Number counts in each size bin are recorded.

List (1988) declared that, while the JWD may be fine for radar reflectivity calculations, instrument limitations regarding missed drops, most evident at small drop sizes, makes it less than ideal for microphysical study. He presents an example in which small drop populations were entirely absent during heavy rain. This shortcoming is well known. A procedure has been developed to adjust observed number counts for missed drops (e.g., Sheppard and Joe 1994). Adjustments can be significant and tend to make the estimated distribution more exponential. The instrument is also susceptible to wind and acoustic noise which can be interpreted as small drops. The instrument was placed on an artificial turf surface to reduce splashing.

The 2DVD consists of two horizontally pointing line-scan cameras whose beams are separated in the vertical by approximately 7 mm. Measurements are made within a common 10 × 10 cm area. Recorded information for each raindrop includes orthogonal silhouette images and estimates of equivalent volume diameter, oblateness, and terminal velocity. Horizontal resolution for the unit used in this study is approximately 0.2 mm. Vertical resolution depends on particle terminal velocity and is 0.1−0.2 mm for raindrops. The instrument is calibrated by dropping pellets of known size into the device. Although particles as small as 0.2 mm can be detected, derived characteristics become increasing more suspect as dimensions fall below about 0.5 mm, especially those during heavy rain periods when splashing occurs (left as is, the issue here is instrument resolution. Splashing is always a problem and is mentioned elsewhere). Observed drops were partitioned into 41 size bins of 0.2 mm width and having central diameters of 0.1 to 8.1 mm. Calibration datasets disclose that the relative standard error in height and width measurements varies from 14% for a spherical particle with a mean diameter of 0.5 mm to <1.5% for a particle with a diameter of 10 mm (Brandes et al. 2007). Wind effects have been studied by Nešpor et al. (2000), who show that drops may be recycled in an eddy that can develop within the orifice of the instrument under windy conditions. Mis-matches are likely during periods of heavy rain. Particles whose estimated terminal velocities are inconsistent with wind tunnel values and those with spurious shapes are ignored. The 2DVD is designed to mitigate splashing. While splashing could be important with both instruments, its affects are ignored in this study. Data processing, other than initial data editing to remove spurious drops, was identical for both instruments.

4. CASE STUDY COMPARISON

Figure 1 presents a raindrop distribution obtained in Florida on September 17, 1998 with a JWD (RD-69 model). [This event was studied by Williams et al. (2000) and included in the dataset of Tokay et al. (2001).] Traces show raw (unadjusted) drop concentrations and adjusted concentrations using the procedure of Sheppard and Joe (1994). In all, 874 drops with diameters up to the 4.86 mm size category were detected by the instrument in the 1-min sample. The adjusted drop total is 1131 (a 29% increase). Small drop concentrations are roughly doubled. [No adjustment is made for size categories in which drops are not observed.] Although no drops were detected in the four smallest drop bins (central diameters of 0.36, 0.45, 0.55, and 0.66 mm) at 1918 UTC, during light rain drops occasionally appeared in even the smallest size category. Other estimated DSD properties are: R = 93.5 mm h^{-1}, Z_H = 54.6 dB*Z*, and D_0 = 3.02 mm.

The DSD found with a collocated 2DVD is shown in Fig. 2. [The adjusted JWD trace is plotted for comparison.] The observed drop count with the 2DVD was 5446 (more than a factor of four greater than the adjusted JWD total). The estimated rain rate (109.6 mm h^{-1}) is 17% higher than the JWD estimate. Radar reflectivity was 54.6 dB*Z*—same as that for the JWD. The 2DVD estimated drop median volume diameter is 2.31 mm.

The 2DVD detected drops in the smallest size category. For drops with $D < 2.5$ mm there are consistently higher concentrations with the 2DVD. There is less DSD downturn at small drop sizes, but the 2DVD probably has its own small drop issues. Although somewhat problematic for small sampling volumes and particular samples, seven drops were recorded in 5.1 to 5.5 mm size bins. While reflectivity values are identical in this example, the DSDs are clearly different. Missed drops with the JWD result in a narrower DSD, manifest by a larger DSD shape factor (2.22 versus –0.60), and a significantly larger D_0 (3.02 versus 2.31 mm).

Figure 3 presents a time history of DSD parameters for September 17 as determined with the JWD and 2DVD. Even though an adjustment has been made for missed drops, estimated drop counts with the JWD are often a small fraction of that detected by the 2DVD. Heavy rain rates measured by the JWD are considerably less than that measured by the 2DVD. Radar reflectivity measurements averaged 0.87 dB higher with the 2DVD, but there were periods during which the JWD was higher (e.g., 2107 to 2128 UTC). During heavy rain, JWD-estimated median volume diameters are more than 0.5 mm larger than those estimated with the 2DVD. Also, during the strong leading convection a number of 2DVD samples show drops larger than the maximum size category for the JWD.

5. DOES IT MATTER?

Disdrometer measurements are often used to derive relationships between radar reflectivity and rainfall rate which are then applied to radar measurements. The September 17 event began with strong convection which became mixed, i.e., stratiform rain with embedded convection, and eventually turned to stratiform rain and convective debris. A subset of reflectivity and rainfall rate measurements in Fig. 3 with R ≥ 1 mm h^{-1} was assembled for the convective periods 1909 to 1938 UTC and 2019 to 2137 UTC. Least-squares fits to the measurements (Fig. 4) with log R as an independent variable gave for the JWD

$$Z \quad 133R^{1.55} \tag{5}$$

and for the 2DVD

$$Z_H \quad 184R^{1.36} . \tag{6}$$

The Z_H – *R* relation for the JWD has a smaller coefficient and a larger exponent (slope). As in Fig. 3, large differences occur at heavy rain rates. For a particular reflectivity the estimated rainfall rate is much higher with the 2DVD relation. The implication is that missed drops may cause heavy rain rates to be underestimated with Z_H – *R* relations derived from JWD observations. At a reflectivity of 50 dBZ, rain rates with the 2DVD relation are 44% higher than that with the JWD. The difference could be important in flash flood situations.

The range in coefficients in (5) and (6) is similar to that found by Campos and Zawadzki (2000) for their disdrometer comparison with a stratiform rain event. The range in exponents is somewhat larger here. This is ascribed to the increased drop loss with the JWD at high rain rates and large drop sizes but could also be due to the fact that the JWD yields a smaller range of drop sizes and narrower DSDs (added).

Computed DSD shape and slope parameters for both instruments are compared in Fig. 5. [The plotted curve, derived by Brandes et al. (2003) for the entire set of 2DVD measurements from the Florida field program, has been added to facilitate the comparison.] Data points group according to rain rate, but the distributions differ for the two instruments. At light rain rates ($R < 5$ mm h^{-1}) data points for the JWD lie close to the curve. At heavy rain rates ($R \geq$ 10 mm h^{-1}) data points generally are displaced well above the curve. With the 2DVD plotted pairs lie close to the curve; and data points move along the curve toward smaller μ and Λ values, i.e., the DSDs become more exponential and D_0s become smaller as the rain rate increases.

The $\mu-\Lambda$ distribution for the JWD behaves like a simulated distribution produced by Moisseev and Chandrasekar (2007). For simulated DSDs truncated at small drop sizes by imposing a minimum D_0 constraint the $\mu-\Lambda$ distribution shifts toward large values of μ and consequently large D_0 from the un-truncated distribution. This behavior is not seen in the 2DVD data. Rather, heavier rain rates associate with small μ and D_0. The influence of data editing procedures on $\mu-\Lambda$ relations derived from observations is discussed further in the Appendix.

The relative impact that reduced small drop populations can have on evaporation and accretion rates in numerically simulated thunderstorms can be estimated using simple Kessler (1969) parameterizations as in Brandes et al. (2006). The evaporation rate of a water drop at a saturation deficit m_e (for simplicity assumed to be 1.0 g m^{-3}) is given by

$$\frac{dM_e}{dt} = 3.55\times10^{-7} m_e D^{8/5} \; . \tag{7}$$

The total evaporation rate for an ensemble of drops is

$$R_e = \int_{D_{\min}}^{D_{\max}} \frac{dM_e(D)}{dt} N(D)dD \; . \tag{8}$$

Similarly, the accretion of cloud water, assuming a collection efficiency of 1.0, is

$$R_c = 10^{-6} \int_{D_{\min}}^{D_{\max}} \frac{\pi D^2}{4} v_t(D) m_c N(D)dD \tag{9}$$

where m_c is the cloud water content (taken to be 1.0 g m^{-3}) and $N(D)$ is the observed drop concentration.

Expectedly, differences in the observed DSDs have a pronounced effect on estimated evaporation and accretion rates (Fig. 6). During heavy convection evaporation rates computed with the JWD are factors of two to three less than that computed with 2DVD observations. Accretion rates were a nearly a factor of 2 less. Such differences would influence the development of cold pools by evaporation thereby altering the motion of predicted storms.

Studies that may have been influenced by small drop issues include that of Zawadzki and de Agostinho Antonio (1988) who examined tropical rains with a JWD and noted a small drop deficit for heavy rain rates (their Fig. 2). They suggested that the absence of small drops was an indication that some proposed drop breakup and coalescence models are incompatible with observations. To their credit, Zawadzki and de Agostinho Antonio mention this conclusion simply may be due to instrumentation and that the issue may be resolved with improved measurements.

Small drop issues may explain the polemic of Atlas and Ulbrich (2006) regarding $\mu - \Lambda$ relations found with 2DVD data by Zhang et al., (2001, 2003) and Brandes et al. (2003). Based on JWD observations, Atlas and Ulbrich assert that the $\mu - \Lambda$ relations of Zhang et al. (2001, 2003) and Brandes et al. (2003) miss DSDs with large D_0s. Instead, missed drops with the JWD may have caused their estimates of D_0 (and μ) to be too large.

SUMMARY AND CONCLUSIONS

A comparison of drop measurements obtained with a Joss-Waldvogel impact disdrometer and a two-dimensional video disdrometer revealed significant differences in the measurements, derived DSD properties and integral physical parameters (changed). The JWD detected far fewer small drops than the 2DVD. Consequently, estimated DSDs with the JWD are more peaked (larger μ) and have larger D_0s than that estimated with the 2DVD. Estimated rain rates, radar reflectivity, and evaporation and accretion rates are less with the JWD. Our purpose here is not to belittle the JWD nor the importance of the numerous studies conducted with it. Undoubtedly the 2DVD has its own issues. For example, fitted curves and $\mu-\Lambda$ distributions in Figs. 5 and A1, derived with 2DVD observations, show significant differences. Cao et al. (2008) suppose that rain DSDs in Florida (Fig. 5) tend to be narrower (larger μ) than in Oklahoma. However, different 2DVDs were used in the analyses.

Our knowledge of drop distributions and ability to deduce storm properties is limited by the instruments available to us. We believe instrumental deficiencies have not been fully appreciated when describing the microphysical properties of storms. Knowledge of raindrop size distributions (DSDs) is requisite for understanding microphysical processes. The numerical weather forecasting community has realized the importance of detailed DSD descriptions in models and begun to use sophisticated two and three-moment microphysics schemes. Such schemes must be based on and validated by reliable observations not subject to instrumentation peculiarities. Progress will entail comprehensive instrument intercomparisons and perhaps the development of new sensors.

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APPENDIX

The Impact of Data Editing Constraints on $\mu-\Lambda$ Relations

Moisseev and Chandrasekar (2007) have derived $\mu-\Lambda$ relations using simulated drop size distributions in which a drop concentration parameter, drop median volume diameter, and gamma DSD model shape parameter are varied randomly over observed ranges. In their simulation imposing a minimum rain rate of > 5 mm h^{-1} as an analysis constraint dramatically shifts the distribution of $\mu-\Lambda$ points to larger values of μ for a specified Λ, effectively increasing the D_0s of the resulting DSDs. Also, imposing a constraint for drop count (> 1000 in their study) reduces the number of simulated DSDs with large D_0.

The imposition of similar constraints on a large set of observed DSDs obtained in Oklahoma is examined in Fig. A1. The upper left panel shows all observations for which DSD could be computed. Right-hand panels show the distributions after applying constraints for rain rate and drop count. Imposition of these constraints mainly serves to reduce scatter. Close inspection reveals a few data points with relatively large μ persist in the Λ range 1−5 mm^{-1} range in the panel with the rain rate constraint, and a number of points with relatively small μ in the Λ range 9−16 mm^{-1} range can be seen in the panel with the number count constraint. But overall, rain rate and drop count constraints have little if any effect on the mean relation between $\mu-\Lambda$. The discrepancy between the simulations of Moisseev and Chandrasekar (2007) and the observed DSDs may arise from the fact that the relationship between $\mu-\Lambda$ is not random as assumed in the simulations but represents a fundamental property of DSDs (Seifert 2005; Khvorostyanov and Curry 2008).

Applying a lower bound for D_0, either to simulate the loss of small drops with the JWD or in an attempt to mitigate small drop issues generally, has a pronounced effect on the relation between $\mu-\Lambda$. The resulting distribution is displaced toward relatively large μ (and D_0). This response is akin to that seen for the JWD in Fig. 5 as the rain rate and the number of missed drops consequently increases.

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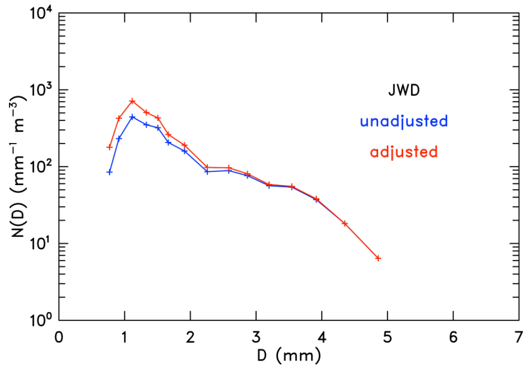

FIG. 1. Measurements obtained with a JWD (RD-69 model) on Sep 17, 1998 at 1918 UTC. Unadjusted and adjusted drop concentrations are shown.

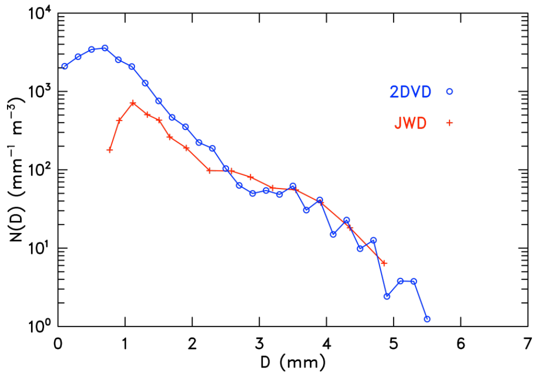

FIG. 2. As in Fig. 1, except for the 2DVD. The adjusted JWD distribution is plotted for comparison.

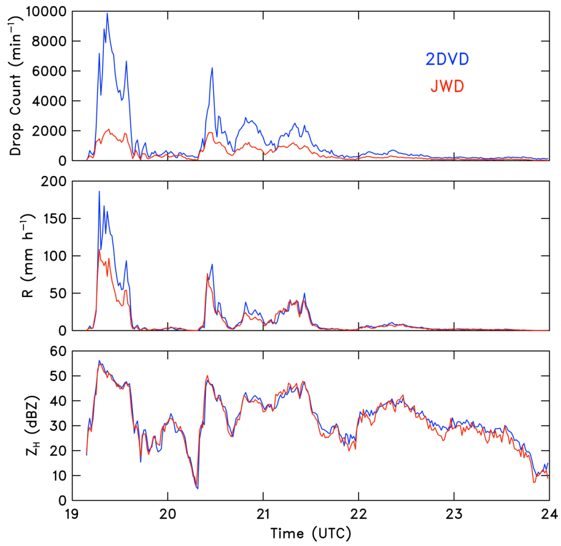

FIG. 3. DSD attributes computed from collocated JWD and 2DVD disdrometer measurements. The data are for Sep 17, 1998.

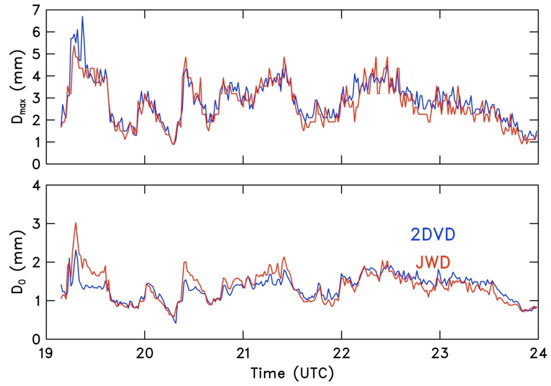

FIG. 3 continued.

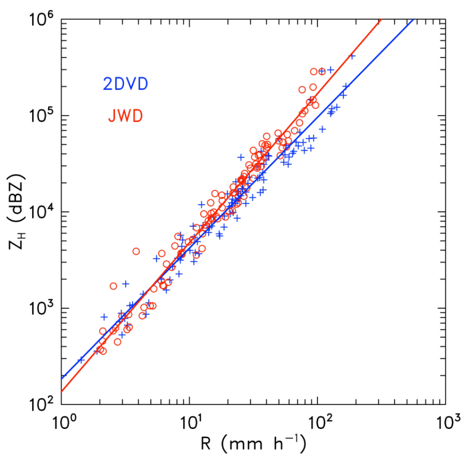

FIG. 4. Rainfall rate plotted vs radar reflectivity. Equations (5) and (6) are overlaid.

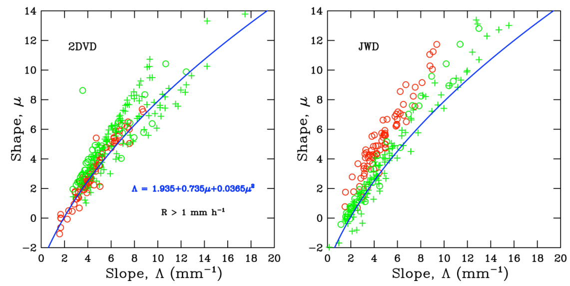

FIG. 5. Gamma DSD shape and slope comparison for the dataset in Fig. 3. Symbols indicate rain rate (green pluses: $1 \leq R < 5$ mm h^{-1}; green circles: $5 \leq R < 10$ mm h^{-1}; red circles: $R \geq 10$ mm h^{-1}).

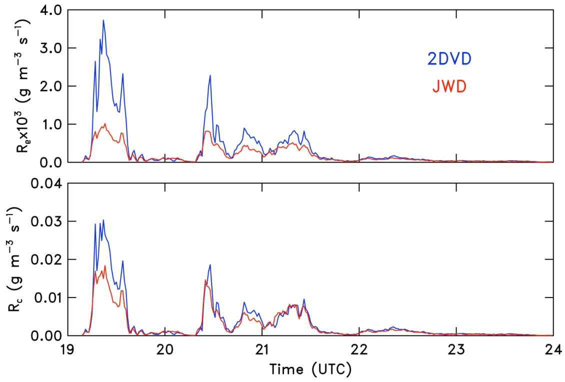

FIG. 6. As in Fig.3, except for estimated evaporation and accretion rates.

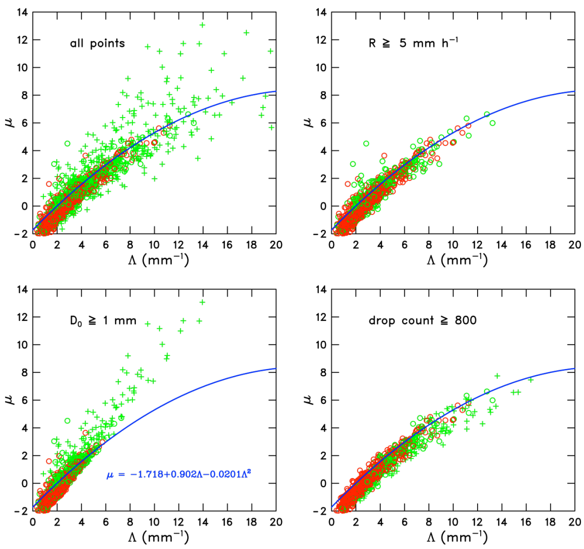

FIG. A1. Distributions of $\mu-\Lambda$ observed in Oklahoma with 2DVDs. The upper left panel shows all observations. Other panels show distributions after imposing constraints for rain rate, median volume diameter, and drop count. The curve, for reference, was derived by Cao et al. (2008).