Error Characteristics of Rainfall Measurements by Collocated Joss–Waldvogel Disdrometers

Ali Tokay

Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, Baltimore, and NASA Goddard Space Flight Center, Greenbelt, Maryland

Paul G. Bashor

Computer Sciences Corporation, NASA Wallops Flight Facility, Wallops Island, Virginia

Katherine R. Wolff

Science System Applications, Inc., NASA Goddard Space Flight Center, Greenbelt, Maryland

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ABSTRACT

Error characteristics of rainfall measurements were studied using six collocated Joss–Waldvogel (JW) disdrometers that are located at NASA's Wallops Flight Facility. The six disdrometer means of rain rate R, reflectivity Z, and differential reflectivity ZDR, for a given minute were considered as a reference. The maximum deviations of R, Z, and ZDR from the mean in a rain event were 0.6 mm h^{-1}, 1.3 dB, and 0.05 dB, respectively. Rainfall statistics were then examined between disdrometer pairs. The root-mean-square (rms) difference of R, Z, and ZDR between paired disdrometers in a rain event were as high as 3.2 mm h^{-1}, 3.7 dB, and 0.3 dB, respectively. The rms difference of R and ZDR were even higher when the disdrometer observations were stratified based on reflectivity intervals. The differences in disdrometer rainfall measurements have a potential impact when the disdrometers are considered as calibration tools for vertically pointing and scanning radars. The differences between the disdrometer measurements also result in differences in coefficients and exponents of the derived relations between radar parameters and rain rate. Among the four different relations between radar parameters and rain rate, the absolute difference in rain rate $|\Delta R|$ from two different JW disdrometers was highest in R(ZH, ZDR) and lowest in R(KDP, ZDR). The other two relations were $R(Z)$ and R(KDP). The $|\Delta R|$ increases with increasing horizontally polarized reflectivity ZH, and differential specific phase KDP in both single- and dual-parameter rainfall estimators, while the $|\Delta R|$ increases with decreasing ZDR in dual-parameter rainfall estimators. Several sources of JW disdrometer malfunctions were also presented. The hardware problems were the leading cause for the malfunction of the JW disdrometers, as identified by the manufacturer. A single JW disdrometer could have inherent measurement errors that can only be identified in the presence of collocated (preferably two) rain-measuring instruments.

1. Introduction

Knowledge of the raindrop size distribution (DSD) is essential for formulation of radar-rainfall algorithms. Radar measurements and rainfall are integral products of DSD. In addition to radar meteorology, the DSD has a wide range of applications in precipitation physics and modeling, hydrology, and agricultural and soil sciences. Many applications require long-term (from several months to years) measurements of the raindrop size distribution.

The disdrometer is an instrument that measures the DSD at the ground. Impact and radar disdrometers assume that the particles are falling at terminal fall speed, while optical disdrometers are able to measure both size and fall velocity of individual drops. Similar to rain gauges, disdrometers provide only *point* measurements. Although the sampling volume of radar disdrometers is relatively larger than impact and optical disdrometers,

Corresponding author address: Ali Tokay, NASA Goddard Space Flight Center, Code 912.1, Greenbelt, MD 20771.
E-mail: tokay@radar.gsfc.nasa.gov

it is far smaller than a conventional, horizontally scanning radar volume, regardless of the range and beamwidth of the radar. Among these three types of disdrometers, the impact-type Joss–Waldvogel (JW) disdrometer has been considered a standard for DSD measurements to date (Joss and Waldvogel 1967).

The JW disdrometer has been widely used in investigating characteristics of the DSD and deriving relations between radar measurements and rain rate. Almost all of these studies were based on a *single* JW disdrometer operation, mainly due to cost. A rain gauge is often collocated with the JW disdrometer for the self-consistency of rainfall measurements. The manufacturer states that the measured rainfall between the rain gauge and JW disdrometer should not differ by more than 15% for an event that had a rain total of more than 5–10 mm. For self-consistency checks, the manufacturer recommends employing an event with a continuous rain rate of between 1 and 10 mm h^{-1}, lasting for several hours with light winds. Several studies reported that the event rain total differences between gauge and JW disdrometer were mostly between 10% and 20% (McFarquhar and List 1993; Sheppard and Joe 1994; Tokay et al. 2001, 2002, 2003b). Hagen and Yuter (2003), on the other hand, presented daily rainfall from two collocated JW disdrometers resulting in less than 10% differences for the days with rainfall over 10 mm. Aside from natural variability of rain, the shortcomings of each instrument can play a significant role on differences of rain totals between the collocated gauge and JW disdrometer.

The JW disdrometer is often used as a reference for testing a new gauge or disdrometer (Donnadieu 1980; Sheppard 1990b; Löffler-Mang and Joss 2000; Förster et al. 2004). In this study, we present our experience regarding the performance of the JW disdrometers and characteristic differences in rainfall parameters derived from disdrometer measurements through a *unique* instrument site at the National Aeronautics and Space Administration (NASA) Wallops Flight Facility (WFF) in Wallops Island, Virginia. The characteristics of JW disdrometer, instrumentation at experiment site, and data processing are described in sections 2, 3, and 4, respectively. Sections 5 and 6 address several sources of JW disdrometer malfunctions for the periods when two and four disdrometers were collocated, respectively. The available 2D video disdrometer (2DVD) and tipping-bucket rain gauge measurements were instrumental in identifying malfunctions of the JW disdrometer. Section 7 presents the measurements of six collocated JW disdrometers that performed without malfunctions. Error characteristics of rainfall parameters and the relations between them due to the differences in disdrometer measurements are presented in sections 8 and 9, respectively. We offer conclusive remarks in the last section.

2. Joss–Waldvogel disdrometer

The JW disdrometer consists of a sensor head and signal processing electronics. Like other types of disdrometers, it requires power and a shelter for its processor, which is linked to a personal computer. This limits the selection of remote sites for the disdrometer, particularly for short-term field campaigns. A cable length of 100 m provides some flexibility for an adequate site selection of the JW disdrometer. The manufacturer reports that the sensitivity of the disdrometer will be reduced by about 0.5% in drop diameter when using a 100-m cable. When a raindrop hits the 50 cm^2 surface of the JW disdrometer, a conical Styrofoam body transmits the mechanical impulse of the impacting drop to a set of two moving coil systems in magnetic fields. A voltage is then induced in the sensing coil. This voltage is amplified and applied to the driving coil, producing a force that counteracts the movement. The amplitude of the pulse at the amplifier output is a measure of the size of the drop. The JW disdrometer measures drops from a 0.3- to about a 5.5-mm diameter within $\pm 5\%$ accuracy. The JW disdrometer has been commercially available for 35 yr, and there have been no major changes in its measuring principles. However, the composition of the cone has been changed several times, and in 2001 the nonlinear analog-to-digital converter was added to the processor box (RD-80), eliminating the separate processor (RD-69) and converter (ADA-90) housings.

Among the shortcomings of the JW disdrometer, the influence of air motion on falling raindrops has been addressed through simulations of JW disdrometer measurements by an optical disdrometer (Salles and Creutin 2003; Tokay et al. 2003a). The optical disdrometer measurements showed that the large drops were falling significantly slower than their terminal fall speed, resulting in a shift in raindrop spectra toward smaller sizes. A laboratory study by Kinnell (1976) showed the influence of both fall velocity and drop shape on the measured drop size from the impact. Because the functional dependency of drop fall velocity to the drop size is very weak for drops larger than 5 mm in diameter, the JW disdrometer cannot determine these very large drops. Rather, the number of drops is grouped in the last size bin, classified as 5.0–5.5 mm in diameter. This would cause an underestimation in calculated rainfall and radar parameters (Tokay et al. 2002).

Two or more drops impacting the disdrometer cross section at the same time results in an undercounting of the small drops because the largest drop registers in these instances. This is known as disdrometer dead time and it occurs in heavy rain. Although the manufacturer recommends a correction matrix, it is generally not accepted simply because of the fact that the matrix is in multiplicative form and, therefore, it does not add any drops when the corresponding size bin has no drop (Tokay and Short 1996). The reduction of small drops in JW disdrometer spectra is also evident in the presence of background noise (Tokay et al. 2003b). For remote locations, the power for the disdrometer is often provided through a generator that could be an audible noise source. The ambient noise level of the generator should be tested in the presence and absence of rain for the reliability of the JW measurements.

Calibration of the JW disdrometers is essential for the accuracy of DSD measurements. Sheppard (1990a) and McFarquhar and List (1993) emphasized the importance of the recalibration of the disdrometer, demonstrating the role of the calibration curve in DSD measurements and derived integral rainfall parameters. Calibration errors can result in both underestimation and overestimation of the drop counts; therefore, deployment of multiple collocated disdrometers is recommended for a period of 1 month or more, depending on rainfall, to determine the self-consistency of the instruments. Two or three well-calibrated rain gauges could be an alternative to diagnose disdrometer calibration error.

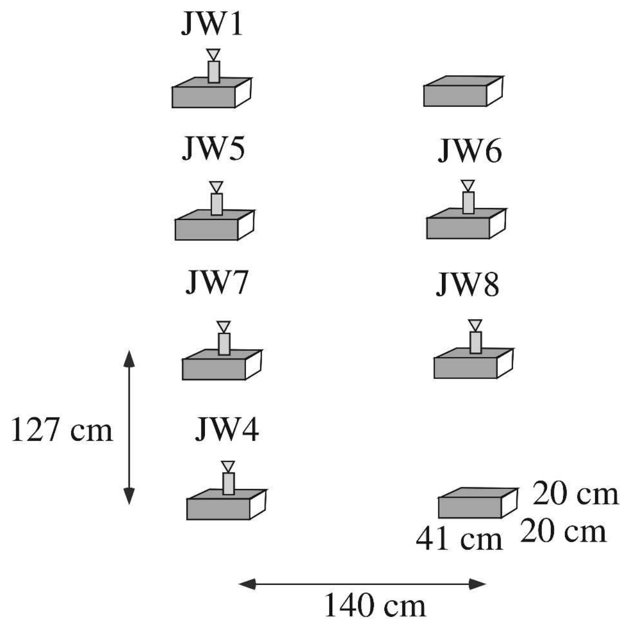

FIG. 1. Layout of the Joss–Waldvogel disdrometers at Wallops Island as of Dec 2003. The platforms are vacant for testing the units that operates other field campaigns. JW2 is operating at Florida Keys, while JW3 is under evaluation.

3. Wallops Island Instrument Park

As part of the NASA Tropical Rainfall Measuring Mission (TRMM) Ground Validation program, a disdrometer and rain gauge test facility has been operating at NASA WFF in Wallops Island during the past 4 yr. Wallops Island (37.84°N, 75.48°W), located along the mid-Atlantic coast of the United States, annually receives 98 cm of precipitation with only a 2.8-cm difference between the months that receive maximum and minimum precipitation. It is subject to wintertime frontal and summertime convective rainfall as well as remnants of Atlantic hurricanes. Following TRMM field campaigns, NASA's 2DVD was deployed to Wallops Island in support of the Microwave Link Facility in May 2000. Two JW disdrometers were then set up at Wallops Island in September and October 2000, respectively. The site had four JW disdrometers from February 2001 to September 2003 except for July–October of 2001 and 2002, where several JW disdrometers were deployed to the Florida Keys (Tokay et al. 2003b,c). All the instruments were removed from the field as a precaution prior to Hurricane Isabel's landfall in mid-September 2003. Since then, six JW disdrometers have been operating at the site. The disdrometers were installed in a rectangular grid where the spacing was 127 cm × 140 cm. They sit on a thin water-absorbing material placed on cinder blocks. Figure 1 shows the current layout of the JW disdrometer network. The network is designed for eight or more JW disdrometers where two platforms are allocated for testing disdrometers that operate at other ground validation sites. A number of optical disdrometers, and tipping-bucket and weighting-bucket gauges are also located in the instrument park but are only available for limited periods of operation (Fig. 2).

4. Disdrometer data processing

A registering raindrop is recorded on one of the 127 channels of the JW disdrometer and the channel counts are stored in 10-s intervals. As part of the standard data processing adapted by the TRMM Satellite Ground Validation Office, we average the measurements over 1 min and group the drops into 20 standard-sized bins of the JW disdrometer. The midsize diameter of each bin is calculated based on a vendor-supplied calibration table that is unique for each disdrometer. The bulk descriptors of rainfall, namely, total number of drops, concentration, liquid water content, rain rate, and reflectivity at the Rayleigh regime, are calculated for each minute of spectra without dead-time correction. A separate set of tables is generated for other DSD-derived quantities of interest, such as polarimetric variables. In this study, rain rate (R), reflectivity at Rayleigh regime (Z), polarimetric parameters of horizontally polarized reflectivity (ZH), differential reflectivity (ZDR), and differential phase shift (KDP) were of interest. The formulation of these parameters, except rain rate, depends on a relationship between the terminal fall speed and the drop diameter (Tokay et al. 2001, 2002). Table values of terminal fall speed and drop di-

FIG. 2. A picture of Wallops Island Instrument Park as of Jun 2003. There are five Joss–Waldvogel disdrometers just behind the Micro Rain Radar. Several tipping-bucket rain gauges and 2D video disdrometer are among the other precipitation measuring sensors.

ameter were used following Beard (1976). The polarimetric variables were calculated for a 10.7-cm wavelength (S band) employing the drop shape versus diameter relationship of Andsager et al. (1999). Equilibrium drop shapes are used for drops larger than 4 mm in diameter.

Raindrop spectra containing fewer than 10 drops, or with a rain rate less than 0.1 mm h^{-1}, is disregarded as noise. The summary of rain events is then presented in table form where the table includes the day of the year, start and end times, number of rainy periods, maximum rain rate, and rain total for each rain event. The events less than 3 min long are also disregarded. Rain events are separated in time by nonraining periods of at least 30 min.

A similar data-processing procedure was also used for optical disdrometers, including the 2DVD. Because the optical disdrometers measure the fall speed of the drops, there is no need to employ the terminal fall speed versus drop diameter relationship. Drops falling at speeds beyond ±50% of terminal fall velocity were excluded from the spectra (Tokay et al. 2001, 2002).

5. Disdrometer measurements (November 2000 and February 2001)

During November 2000, DSD measurements were collected by two collocated JW disdrometers. Also, 2DVD measurements were available for the entire month. November 2000 was a dry month with 26.4 mm of precipitation, which is 36% less than the climatological average. There were only five rainy days with two major rain events (rain total >1 mm). A well-calibrated tipping-bucket rain gauge was available for these two rain events. All sensors were within 8 m of each other.

The first major rain event occurred on 16 November 2000, with light-to-moderate (maximum rain rate <10 mm h^{-1}) intensity. The 2DVD and tipping-bucket rain gauges recorded 6.13 and 6.09 mm, respectively, and one of the JW disdrometers (JW2) had 5.88 mm of rainfall. The other JW disdrometer (JW1) recorded only 3.48 mm of rainfall, nearly 43% less than the rain gauge. The composite DSD from three disdrometers showed excellent agreement between the two JW disdrometers for small drop sizes (diameter, D <1 mm) (Fig. 3a). JW1 recorded far fewer drops than JW2 for sizes above 1-mm diameter, where the agreement between JW2 and the 2DVD was very good. The maximum drop diameter was only 3.4 mm for JW1, while JW2 and the 2DVD observed drops up to 4.8 and 4.3 mm, respectively. The second major rain event had DSD and rainfall characteristics similar to the first major event. In this event, JW1 recorded 25% less rainfall than the rain gauge. JW1 was returned to the manufacturer for evaluation and was found to have a severe loss

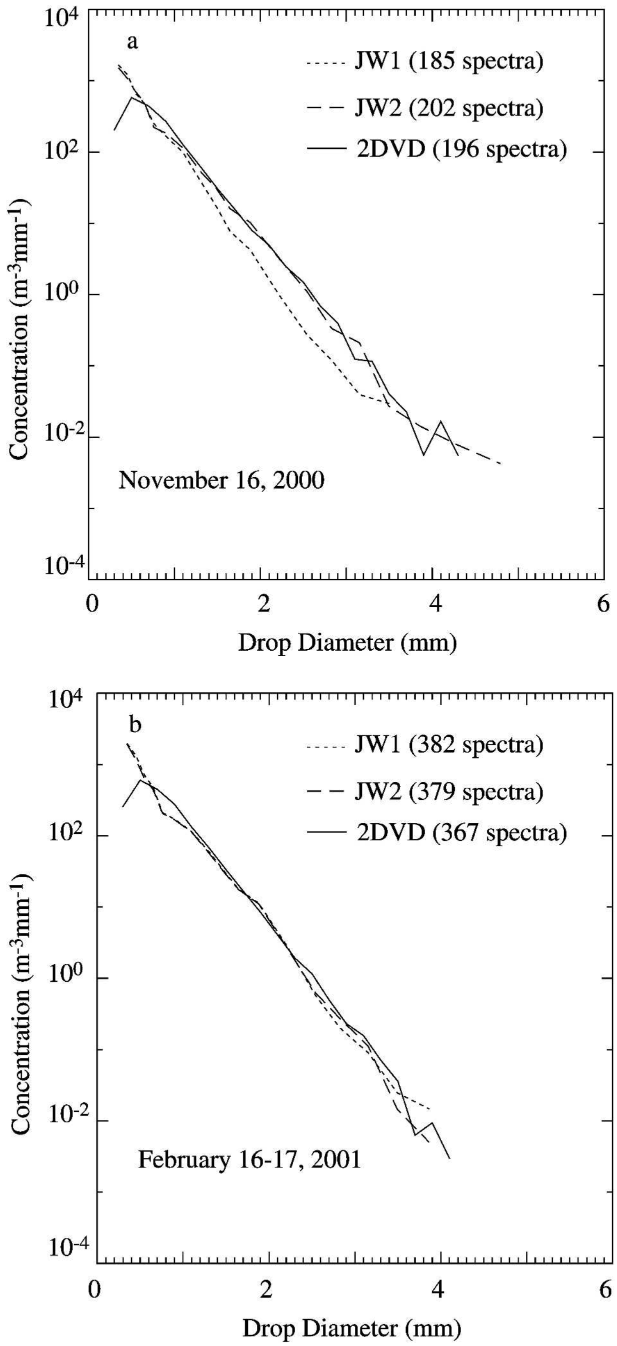

FIG. 3. Composite drop size distributions from two collocated Joss–Waldvogel and 2D video disdrometers for rain events that occurred on (a) 16 Nov 2000 and (b) 16–17 Feb 2001. The number of 1-min spectra in each composite is given in parentheses.

in sensitivity, which was caused by mechanical friction in the magnetic coils. The transducer was subsequently realigned and recalibrated (D. Högl, Distromet, Ltd., 2000, personal communication).

The agreement between the two JW disdrometer measurements was excellent following calibration of the JW1. The composite DSD of the two JW disdrometers from a moderate rain event that occurred on 16–17 February 2001 is an example of excellent agreement (Fig. 3b). The composite 2DVD DSD agrees well with the JW measurements for sizes larger than 1-mm diameter. The rain totals of the 2DVD, JW disdrometers, and rain gauge were within 6% of each other.

The experience with JW1 that is presented here revealed that the JW disdrometer should be operated with a well-calibrated rain gauge. The operation of two collocated JW disdrometers allows for diagnosing an instrument malfunction and provides self-consistency of each sensor.

6. Disdrometer measurements (March–May 2002)

During spring 2002, four collocated JW disdrometers recorded 152.42–197.21 mm of rainfall for the period when all units were operated (Fig. 4a). Among the four disdrometers, JW1 and JW3 showed excellent agreement in overall rain total, while JW2 and JW5 recorded 15% higher and 12% lower than an average of four disdrometers rain total of 170.75 mm. The mean overall rain totals do not necessarily represent the truth, and are considered merely as a reference because no additional measurements were available for this observation period. The 2DVD measurements were available for 13 out of 16 rainy days, while no reliable gauge data were available for any observational period. The 2DVD measured 4.5% and 8% more rainfall than JW3 and JW1, respectively, and 17.5% more than JW5. However, the 2DVD had 11% less rainfall than JW2.

The composite raindrop spectra from four collocated JW disdrometer measurements agreed well with one another, except that JW2 recorded more drops larger than 1.3 mm in diameter (Fig. 4b). This feature was observed in almost all major rain events. The JW5 composite spectra, on the other hand, had slightly lower drop concentrations for the drop sizes between 1.1- and 3.1-mm diameter. JW1 and JW3 had excellent agreement except for drop sizes larger than 4.0 mm where the drop counts were relatively low. The number of spectra in each composite was different due to the data processing. It is feasible that one of the disdrometers record only 9 drops in 1 min and, therefore, was considered to be noise while the other disdrometers had 10 or more drops at the same minute. One of the disdrometers could also record rain rate less than 0.1 mm h^{-1}, within noise level. We also constructed the composite spectra when all of the disdrometers were recording rainfall, but no noticeable differences were found from Fig. 4b.

Rainfall statistics based on event rain totals confirmed the excellent agreement between JW1 and JW3. If we consider the mean event rain total between the

TABLE 1. Event total rain statistics comparing measurements of paired disdrometers during spring 2002.

Disdrometer pair	⟨ΔRT⟩; SD (mm)	RT(D1) > RT(D2) (%)
JW1, JW2	−1.51; 1.93	0
JW1, JW3	−0.23; 0.42	16
JW1, JW5	0.67; 0.80	100
JW2, JW3	1.28; 1.70	100
JW2, JW5	2.18; 2.60	100
JW3, JW5	0.90; 1.05	95

four disdrometers as a reference, JW3 had no bias on average for 19 major rain events, while JW1 had 3% lower than the mean on average. JW2 and JW5, on the other hand, were 15% higher and 11.5% lower than the mean on average, respectively. These statistics are consistent with those presented for rain totals of the entire observational period. Further analysis of the event rain totals is presented in Table 1. The statistics presented here includes the mean rain total difference between the jth and kth disdrometers and its standard deviation, and the fraction of rain events where one of the units had higher rain totals. The mean rain total difference and its standard deviation are given as follows:

$$\langle \Delta \mathrm{RT}_{j,k} \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathrm{RT}_{j,i} - \mathrm{RT}_{k,i}, \tag{1}$$

$$\mathrm{SD}\langle \Delta \mathrm{RT}_{j,k} \rangle = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [(\mathrm{RT}_{j,i} - \mathrm{RT}_{k,i}) - \langle \Delta \mathrm{RT}_{j,k} \rangle]^2}, \tag{2}$$

where $\mathrm{RT}_{j,i}$ and $\mathrm{RT}_{k,I}$ represent the ith event rain totals of disdrometer pairs of j and k, and N is the number of rain events.

Although JW3 had higher rain totals than JW1 in most of the rain events, the event rain total differences were within 10% in all rain events (Fig. 4c). JW2, on the other hand, had higher rain totals than the other disdrometers in all rain events, including several events where the differences were larger than 15% when the accumulation was more than 10 mm. If we consider any disdrometer other than JW2 as a reference, the JW2 rain totals exceeded the manufacturer's acceptable limits in several rain events. JW5 had mostly lower event rain totals but no more than 15% with respect to JW1 and JW3.

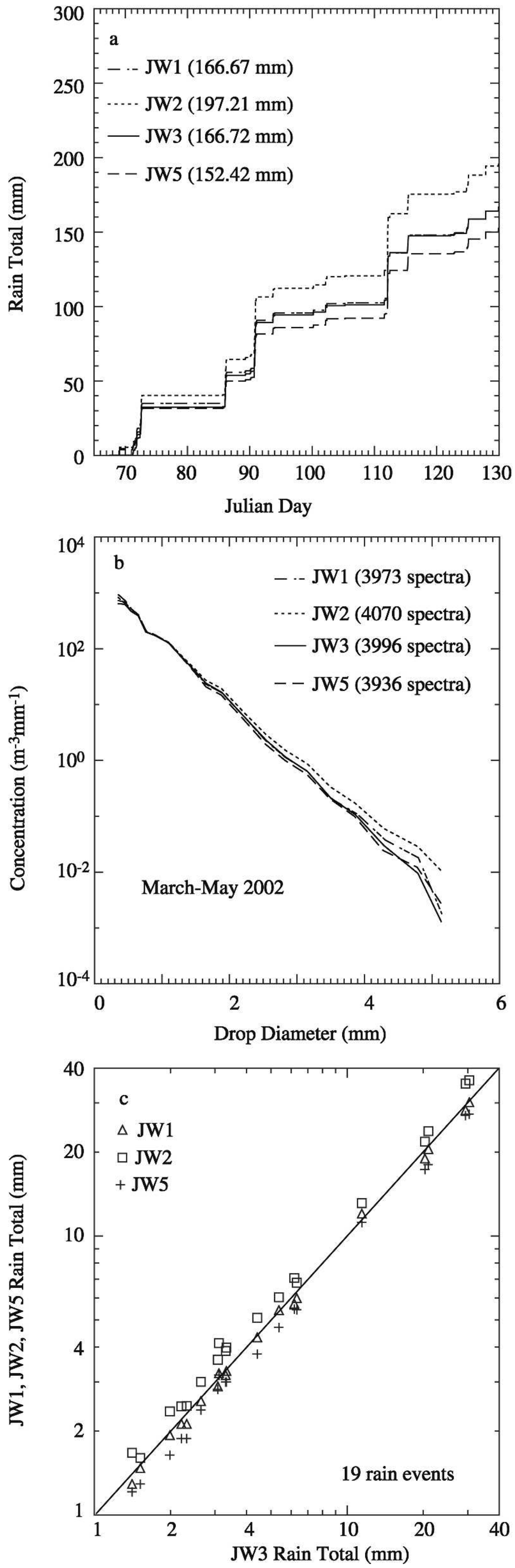

FIG. 4. (a) Accumulative rainfall of four collocated Joss–Waldvogel disdrometers for the period when all units were operated between Mar and May 2002. (b) Composite drop size distributions from four collocated Joss–Waldvogel disdrometers. The number of 1-min spectra in each composite is shown in parentheses. (c) JW3 vs JW1 (Δ), JW3 vs JW2 (□), and JW3 vs JW5 (+) rain totals for 19 rain major rain events.

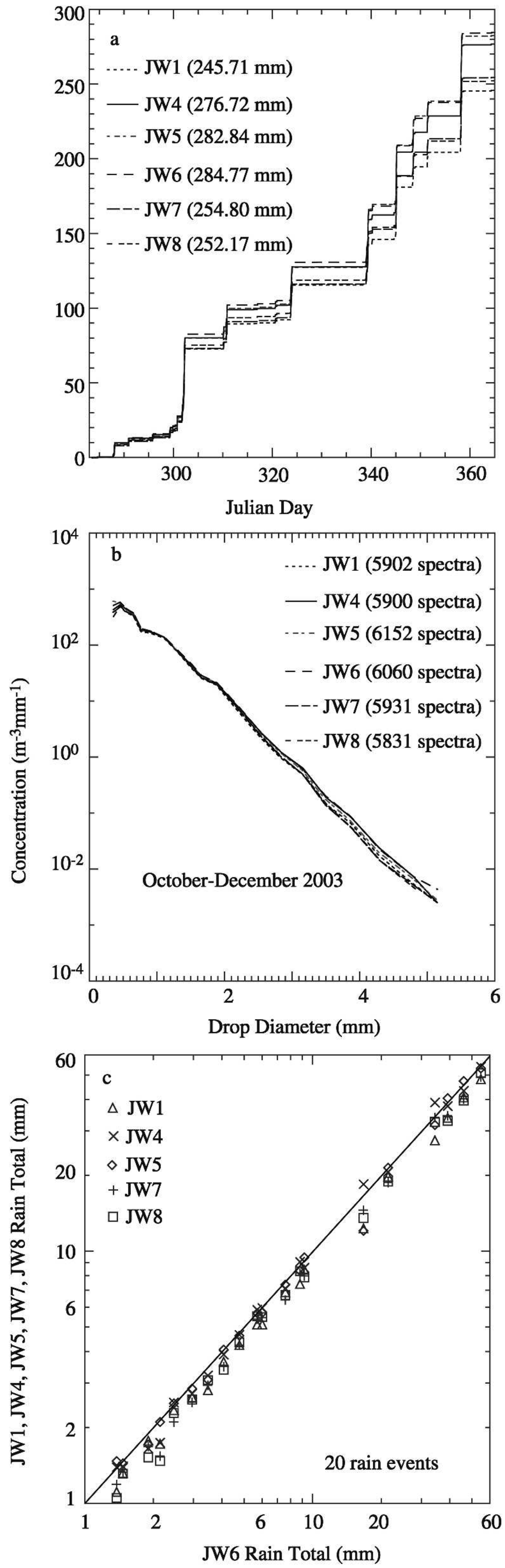

FIG. 5. (a) Accumulative rainfall of six collocated Joss–Waldvogel disdrometers between Oct and Dec 2003. (b) Composite drop size distributions from six collocated Joss–Waldvogel disdrometers. The number of 1-min spectra in each composite is shown in parentheses. (c) JW6 vs JW1 (Δ), JW6 vs JW4 (X), JW6 vs JW5 (◇), JW6 vs JW7 (+), and JW6 vs JW8 (▩) rain totals for 20 rain major rain events.

The cable length was 100 m for all disdrometers, except for JW3, which had a 30-m cable. Excellent agreement between JW1 and JW3 suggests that cable length does not affect DSD measurements as long as the cable length is 100 m or less.

Higher concentrations of medium- and large-sized drops and higher rain totals in JW2 raised a possible calibration issue with this disdrometer. JW2 was returned to the manufacturer for evaluation and recalibration. The manufacturer disassembled and completely replaced the internal components of the sensor. They subsequently noticed the defective cone and replaced it as well (D. Högl, Distromet, Ltd., 2002, personal communication). Since its return to Wallops Island, there have been no indications of instrument malfunction.

The DSD and rainfall analysis presented above did not indicate problems with any of the other disdrometers. However, moisture was occasionally visible in JW5. As pointed out by the manufacturer, moisture inside the sensor is a common cause of instrument failure. Continued exposure to water inside the sensor causes corrosion of the electromechanical unit, which often cannot be repaired. The work required to replace it is very similar to producing a new sensor, because assembly, testing, and calibration are the same. JW5 was returned to manufacturer in April 2003. The plastic foil cap was replaced with a material that resists the influence of the sun and precipitation. To avoid future instrument failure, the manufacturer recommends changing o rings and foil caps routinely every 6 months (D. Högl, Distromet, Ltd., 2003, personal communication).

7. Disdrometer measurements (October–December 2003)

During the last 3 months of 2003, six collocated JW disdrometers recorded 245.71–284.77 mm of rainfall (Fig. 5a). The mean rain intensity ranged from 2.50 to 2.82 mm h^{-1} in rainy periods of 97.2–102.5 h. The low mean rain intensities did not necessarily correspond to relatively fewer rainy hours. The difference in disdrometer rain totals was due in part to differences in rainy minutes and in part to differences in rain intensity. If we consider the mean of the six-disdrometer 3-month rain total (266.17 mm) as a reference, the disdrometers with the highest and lowest accumulations recorded 7% higher and almost 8% lower rainfall. Unfortunately,

TABLE 2. Event rain total statistics comparing measurements of paired disdrometers during Oct–Dec 2003. The statistics between the two groups of disdrometers JW1, JW7, and JW8 (group I), and JW4, JW5, and JW6 (group II) are presented in bold.

Disdrometer pair	⟨ΔRT(D1, D2)⟩; SD (mm)	RT(D1) > RT(D2) (%)	Disdrometer pair
JW1, JW4	**−1.48; 2.21**	**10**	**JW1, JW4**
JW1, JW5	**−1.79; 2.93**	**5**	**JW1, JW5**
JW1, JW6	**−1.88; 2.35**	**0**	**JW1, JW6**
JW1, JW7	−0.44; 1.58	45	JW1, JW7
JW1, JW8	−0.32; 1.39	60	JW1, JW8
JW4, JW5	−0.31; 2.50	55	JW4, JW5
JW4, JW6	−0.40; 1.31	25	JW4, JW6
JW4, JW7	**1.04; 2.33**	**90**	**JW4, JW7**
JW4, JW8	**1.16; 2.40**	**90**	**JW4, JW8**
JW5, JW6	−0.09; 1.36	30	JW5, JW6
JW5, JW7	**1.35; 1.64**	**95**	**JW5, JW7**
JW5, JW8	**1.47; 1.95**	**100**	**JW5, JW8**
JW6, JW7	**1.43; 1.81**	**100**	**JW6, JW7**
JW6, JW8	**1.56; 1.95**	**100**	**JW6, JW8**
JW7, JW8	0.12; 0.70	50	JW7, JW8

neither the 2DVD nor the rain gauge was available for this period of JW disdrometer observation.

The composite raindrop spectra for entire observational period were consistent for the six collocated disdrometers (Fig. 5b). There was no single disdrometer that had significantly higher or lower drop concentrations. The differences in drop concentrations were relatively more noticeable for sizes above 3 mm in diameter due to the relatively smaller sample of large drops. The composite spectra for each of the 20 major events showed more variability among the disdrometers, but there was no particular disdrometer with the highest or lowest drop concentration in all rain events.

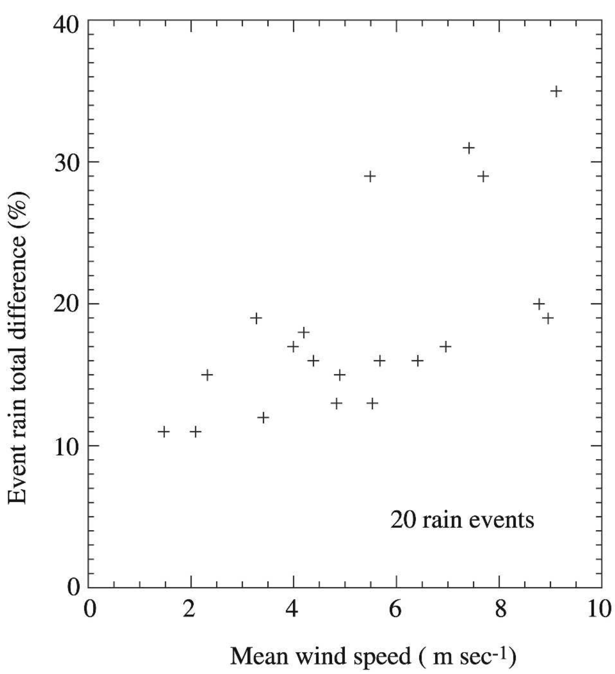

FIG. 6. Event rain total difference between the disdrometer-recorded highest and lowest rainfall as a function of event mean wind speed.

Among the six disdrometers, JW1, JW7, and JW8 recorded relatively less rainfall than JW4, JW5, and JW6 in most of the major rain events (Fig. 5c). There was only one rain event for which JW1 had higher accumulations than JW4 and JW5, while JW7 recorded more rainfall than JW4 in two rain events. If we consider the mean of the event rain total between the six disdrometers as a reference, JW1 was 6.2% lower than the mean and JW6 was 8.2% higher. The other four units showed lesser differences from the mean. Considering rain event statistics between the disdrometer pairs, JW7 and JW8 had the best agreement with a low mean rain total difference of 0.12 mm and its standard deviation of 0.70 mm as shown in Table 2. For half of the rain events, JW7 had higher rain totals than JW8. The agreement in event rain totals between JW1, JW7, and JW8 (group I) and between JW4, JW5, and JW6 (group II) was good, while the agreement between the disdrometer pairs from two different groups was generally poor. For example, the mean event rain total differences ranged from 1.04 (JW4, JW7) to 1.88 (JW1, JW6) mm, as shown in bold in Table 2. Although the mean event rain total differences were above the manufacturer's tolerance of 15%, there was no clear indication of a particular disdrometer malfunction.

The event rain total difference between the disdrometer that recorded the highest rainfall and the disdrometer that recorded the lowest was between 10% and 20% in most events. There were four rain events where the difference was larger than 20%. These four events coincided with moderate breezy conditions having wind speeds higher than 5.5 m s^{-1} (Fig. 6). Although breezy conditions contributed to the larger differences be-

TABLE 3. Rainfall characteristics of the eight major rain events that were observed by six collocated disdrometers during Oct–Dec 2003.

Date	Start time (UTC)	End time (UTC)	Rainy minutes	Max rain rate (mm h^{-1})	Rain total (mm)
14–15 Oct	2220	0803	294–325	32.6	7.95–9.73
28 Oct	2042	1305	940–951	39.6	48.11–54.76
19–20 Nov	2014	0345	411–417	49.2	18.73–21.44
4 Dec	0145	1658	794–851	8.6	27.51–38.89
10 Dec	0155	1105	421–445	103.7	32.88–40.47
14 Dec	0844	2145	349–558	7.6	12.04–18.45
17 Dec	1244	1559	178–183	18.4	7.86–9.45
24 Dec	0604	1522	513–518	46.2	39.54–46.04

tween the two extreme disdrometer rain totals, there were other windy rain events where the difference was less than 20%. Interestingly, events with higher rain total differences did not correlate with higher event mean or event maximum rain rates. To reduce the wind effect, the manufacturer recommends burying the sensor and cable such that only the surface area of the sensor is exposed to the rain. This setup is not always feasible due to logistical limitations.

8. Error characteristics of the rain parameters

Measurements from six collocated disdrometers for eight major rain events were examined to determine the error characteristics of rain rate, reflectivity, and differential reflectivity. The events that were selected for the study lasted at least two rainy hours, accumulating at least 7 mm of rainfall as shown in Table 3. In Table 3, we presented the start and end times and maximum rain rate of the events following JW1 measurements. The event rainy minutes and rain total were presented for the disdrometers that had the lowest and highest readings. All of the rain events except two had heavy rain segments where the maximum rain rate was greater than 18 mm h^{-1}.

The error characteristics of the rain parameters are presented in Tables 4, 5, and 6. To increase the number of samples, we redefined a rain event. An hour of rain-free period was observed between the two consecutive rain events, rather than a 30-min period as in previous sections. The number of samples shown in Table 4 represents the rainy minutes for which all six disdrometers reported rainfall. We adopted two distinct approaches in studying the error characteristics of the rain parameters. First, we examined the mean deviation of a rain parameter from its ensemble mean in a rain event. If X represents a rain parameter, the mean X difference for the jth disdrometer (ΔX_j) from the ensemble mean in lth rain event is expressed as

$$\langle \Delta X_{j,l} \rangle = \frac{1}{N} \sum_{i=1}^{N} (X_{j,l,i} - \langle X \rangle_{i,l}). \quad (3)$$

The ensemble mean denoted by $\langle X \rangle$, is the average X between the six disdrometers for the ith minute of observation and is considered as a reference. It should be noted that the ensemble mean of reflectivity and differential reflectivity were calculated in units of mm^6 m^{-3} and then converted to decibels. The standard deviation of the mean ΔX is also calculated for each disdrometer. Table 4 presents the mean ΔX and its standard deviation for a disdrometer that had lowest (ΔX_low) and the highest (ΔX_high) deviation from the ensemble mean.

Among the eight rain events, three events that occurred during the first half of December had a relatively wider range of deviations from the mean rain rate, with a maximum deviation from −0.5 to 0.6 mm h^{-1} on 10 December 2003, as shown in Table 4. These three rain events also had the largest differences from mean event rain total as shown in Table 3. Regarding reflectivity, the deviations from the ensemble mean were widest on 14 December 2003, ranging from −1.3 to 1.0 dB, while a range from −0.05 to 0.04 dB was observed in differential reflectivity on 17 December 2003. The statistics presented here should be interpreted with caution because the standard deviations

TABLE 4. The range of deviations of rain rate, reflectivity, and differential reflectivity from their ensemble means for the eight major rain events that were observed by six collocated disdrometers during Oct–Dec 2003. The standard deviation of the mean rain parameter is also presented following mean value in the same column.

Date	Rainy minutes	ΔR_low (mm h^{-1})	ΔR_high (mm h^{-1})	ΔZ_low (dB)	ΔZ_high (dB)	ΔZDR_low (dB)	ΔZDR_high (dB)
14–15 Oct	251	−0.16; 0.59	0.17; 0.69	−1.01; 1.76	0.34; 1.64	−0.02; 0.10	0.02; 0.11
28 Oct	921	−0.23; 0.41	0.20; 0.61	−0.71; 0.97	0.29; 0.93	−0.02; 0.10	0.02; 0.09
19–20 Nov	363	−0.24; 1.92	0.21; 1.01	−0.75; 1.69	0.27; 1.22	−0.03; 0.54	0.02; 0.55
4 Dec	752	−0.45; 0.62	0.44; 0.52	−1.13; 1.37	0.61; 1.15	−0.04; 0.14	0.02; 0.16
10 Dec	403	−0.51; 1.29	0.59; 1.83	−0.89; 1.28	0.44; 1.14	−0.04; 0.13	0.03; 0.17
14 Dec	335	−0.41; 0.54	0.56; 0.53	−1.34; 1.29	0.98; 1.09	−0.05; 0.35	0.02; 0.36
17 Dec	120	−0.29; 0.41	0.32; 1.05	−1.00; 1.31	0.46; 2.01	−0.05; 0.49	0.04; 0.54
24 Dec	498	−0.39; 1.15	0.53; 1.62	−0.80; 1.19	0.41; 1.42	−0.03; 0.57	0.03; 0.60

TABLE 5. The minimum and maximum root-mean-square differences of rain rate, reflectivity, and differential reflectivity between paired disdrometers for the eight major rain events that were observed by six collocated disdrometers during Oct–Dec 2003.

Date	Rms−ΔR (mm h^{-1})	Rms−ΔZ (dB)	Rms−ΔZDR (dB)
14–15 Oct	0.52, 1.79	1.99, 3.69	0.13, 0.19
28 Oct	0.70, 2.07	1.41, 2.56	0.12, 0.17
19–20 Nov	0.76, 2.22	1.74, 2.76	0.20, 0.26
4 Dec	0.49, 1.30	1.76, 2.47	0.18, 0.25
10 Dec	1.34, 3.22	1.81, 2.41	0.21, 0.29
14 Dec	0.59, 1.31	1.88, 2.84	0.16, 0.20
17 Dec	0.52, 1.67	1.64, 3.40	0.16, 0.26
24 Dec	0.95, 3.23	1.48, 2.84	0.18, 0.23

TABLE 6. The minimum and maximum root-mean-square differences of rain rate, reflectivity, and differential reflectivity between paired disdrometers for six different intervals of JW1 reflectivity measurements that were observed by six collocated disdrometers during Oct–Dec 2003.

Reflectivity range (dB)	Rainy minutes	Rms−ΔR (mm h^{-1})	Rms−ΔZ (dB)	Rms−ΔZDR (dB)
<20	422	0.13–0.21	2.28–2.94	0.10–0.19
20–25	695	0.25–0.50	1.97–2.54	0.11–0.14
25–30	1022	0.44–0.82	1.85–2.44	0.16–0.20
30–35	964	0.82–1.41	1.61–2.12	0.20–0.23
35–40	460	1.22–2.77	1.57–2.37	0.26–0.34
>40	80	4.14–9.85	1.17–2.40	0.17–0.28

from the mean are relatively high. This means that an integral parameter can deviate substantially higher from the ensemble mean in 1-min observation than mean values presented here.

As a second approach, we examined the difference of a rain parameter between a pair of disdrometer measurements in a rain event. Rather than mean difference and its standard deviation, the root-mean-square (rms) difference of the integral parameter was employed because the latter statistic seem to better represent the error characteristic of rain parameter when the mean difference is small and the standard deviation is large. If the integral parameter is X, the rms difference between the jth and kth disdrometers in lth rain event is given as

$$\mathrm{rms} - \Delta X_{j,k.l} > = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{j,l,i} - X_{k,l,i})^2}. \quad (4)$$

If we rewrite Eqs. (1) and (2) for a generic rain parameter X, an analytical relationship can be established between Eqs. (1), (2), and (4),

$$(\mathrm{rms} - \Delta X)^2 = (\langle \Delta X \rangle)^2 + [\mathrm{SD}(\langle \Delta X \rangle)]^2. \quad (5)$$

When the mean is zero, the standard deviation is identical to the rms difference. Table 5 shows the minimum and maximum rms differences of R, Z, and ZDR between the disdrometer pairs. Here, we provided a quantitative estimate for the accuracy of disdrometer measurement of three rain parameters in eight different rain events by presenting the range of rms differences. The rms difference of rain rate (rms−ΔR) ranged between 0.83 and 2.03 mm h^{-1} on average between the rain events, while individual pairs of disdrometer measurements had a wider range of rms−ΔR between 0.49 and 3.23 mm h^{-1}, as shown in Table 5. Regarding reflectivity, the rms difference of reflectivity (rms−ΔZ) had a range of 1.78–2.67 dB on average between the rain events, while individual pairs of disdrometer measurements had rms−ΔZ of 1.41–3.69 dB. The rms difference of differential reflectivity (rms−ΔZDR), on the other hand, ranged between 0.14 and 0.25 dB on average between the rain events, while individual pairs of disdrometer measurements had rms−ΔZDR of 0.12 to 0.29 dB.

As a comparable study, Chandrasekar and Gori (1991) examined measurements of four collocated JW disdrometers from a widespread rain event with more than 120 contiguous samples. They concluded that the reflectivity and differential reflectivity could be estimated at accuracies of 1.0 and 0.1 dB, respectively, while the accuracy of rain rate changed with rain rate, ranging from 0.2 to 1.2 mm h^{-1}. In their study, the standard deviations of R, Z, and ZDR between the pairs of disdrometer measurements were calculated and grouped for five reflectivity regimes. Here, we examined rms−ΔR, rms−ΔZ, and rms−ΔZDR between the pair of disdrometer measurements for six reflectivity intervals combining eight rain events. The reflectivity intervals were based on JW1 measurements, but no significant changes were observed in the results presented in Table 6 when any of the other disdrometers were considered as a reference for the reflectivity interval. The rms−ΔR increased with increasing reflectivity with a wide range of 4.14–9.85 mm h^{-1} for a deep convective regime ($Z > 40$ dB). The ranges of rms−ΔZ and rms−ΔZDR were also wider for a deep convective regime. Similar to rms−ΔR, rms−ΔZDR increased with increasing reflectivity, but peaked at $35 < Z \leq 40$ dB. The rms−ΔZ, on the other hand, decreased with increasing reflectivity.

The error characteristics of rain parameters were about the same for differential reflectivity, but were substantially larger for rain rate and reflectivity than the Chandrasekar and Gori (1991) study. This is in part due to the use of different statistics and in part due to the differences in the nature of rain events. The measurement uncertainties presented above should be considered for remote sensing applications, including calibration of vertically pointing radars by disdrometer reflectivity measurements (Gage et al. 2000). Because we derived these statistics based on 1-min-averaged dis-

TABLE 7. Relations between integral rain parameters derived from six collocated disdrometer measurements during Oct–Dec 2003.

Method	A, b, c (JW1)	A, b, c (JW4)	A, b, c (JW5)
$R = A\ Z^b$	0.0287, 0.640	0.0304, 0.631	0.0308, 0.630
$R = A$ KDP^b	41.14, 0.763	39.89, 0.754	39.50, 0.752
$R = A$ ZH^b ZDR^c	0.001 51, 0.9705, −0.552	0.001 49, 0.9710, −0.9620	0.001 56, 0.9667, −0.9415
$R = A$ KDP^b ZDR^c	65.27, 0.9945, −0.5956	65.21, 0.9950, −0.6010	65.09, 0.9928, −0.5953
Method	A, b, c (JW6)	A, b, c (JW7)	A, b, c (JW8)
$R = A\ Z^b$	0.0284, 0.640	0.0305, 0.632	0.0279, 0.643
$R = A$ KDP^b	41.00, 0.763	39.97, 0.753	41.53, 0.766
$R = A$ ZH^b ZDR^c	0.001 44, 0.9740, −0.9765	0.001 55, 0.9755, −0.9376	0.001 50, 0.9780, −0.9495
$R = A$ KDP^b ZDR^c	65.08, 0.9952, −0.6009	65.45, 0.9963, −0.6072	65.37, 0.9973, −0.6033

drometer measurements, they might represent more closely an upper limit of the fluctuations of the rain parameter at a point. Because radar measurements swap greater volumes than the disdrometer or gauge measurement, 3- to 10-min running average disdrometer measurements may be more representative for certain applications.

9. Relations between integral rainfall parameters

The relations between rain-rate and radar parameters were derived from each disdrometer's measurement that was collected during the last 3 months of 2003. Table 7 presents the coefficients and exponents of the relations of $R(Z)$, R(KDP), R(ZH, ZDR), and R(KDP, ZDR) that were derived for S-band radars through a linear least squares method. In these relations, the units of Z and ZH are mm^6 m^{-3}, while ZDR and KDP are in units of dB and $^\circ$ km^{-1}, respectively. Operationally, we apply these relations for rain retrieval from NASA's newly developed S-band polarimetric (NPOL) radar that operates near Wallops Island. The four relations presented in Table 5 were employed in retrieving rain rate from dual-polarized radar measurements, and each relation has its own advantages and shortcomings as described in detail in Bringi and Chandrasekar (2001). Cifelli et al. (2002) offered a hybrid algorithm that employed all four relations in estimating rainfall from S-band polarimetric radar, while Matrosov et al. (2002) developed a single rain-rate estimator combining X-band polarimetric measurements of ZH, KDP, and ZDR. The noisy feature of differential phase measurements at light rain favors a hybrid algorithm rather than a single rain estimator for low-frequency radars. Because the polarimetric relations were derived mainly for an application of the NPOL radar, we did not further investigate a single polarimetric rainfall estimator. Rather, we evaluated the hybrid algorithm of Cifelli et al. (2002).

The $R(Z)$ and R(KDP) relation underestimated the rainfall by 10%–11% and 6%–7%, respectively, while R(ZH, ZDR) and R(KDP, ZDR) overestimated the rainfall by 1%–2% and 0.7–0.8%, respectively. The hybrid polarimetric rain-rate estimator presented in Cifelli et al. (2002), on the other hand, underestimated rainfall by 5%–6%. Here, the true rainfall is the 3-month accumulation that was calculated directly from disdrometer observations. The 3-month rainfall was also calculated from each of the four relations in Table 7, where the parameters on the right side of the equations were calculated directly from disdrometer observations. It should be noted that polarimetric rainfall estimators perform better at heavy rain. The mean rain rate at Wallops Island was 24%–33%, which is lower than the mean rain rate in the southwestern Amazon region of Brazil where the Cifelli et al. (2002) study was done. Therefore, the hybrid algorithm is expected to perform better in the Amazon region of Brazil.

We determined the absolute difference in rain rate $|\Delta R|$ as a function of reflectivity when the rain rate was derived from $R(Z)$ of two different disdrometers. Among the 15 different disdrometer pairs, the JW5 and JW8 pair resulted in higher differences in absolute rain rate. Therefore, we decided to present the results from JW5 and JW8, representing the upper limit of the rain-rate difference. The $|\Delta R|$ was less than 1 mm h^{-1} for $Z < 47$ dB, while $|\Delta R|$ reached 5 mm h^{-1} at Z of 54 dB (Fig. 7a). The histogram of rainfall as a function of reflectivity showed that there was no rain for $Z > 54$ dB, while only 6%–7% of their rain was recorded by JW5 and JW8 between 47 and 54 dB (Fig. 8a).

Previous studies showed an increase in $|\Delta R|$ with increasing reflectivity when $R(Z)$ relations were derived from the optical and impact-type disdrometers (Tokay et al. 2001, 2002). Similarly, an increase in $|\Delta R|$ with increasing reflectivity was evident when $R(Z)$ relations were derived from disdrometers at two different sites of the same climatological zone (Tokay et al. 2003c); a single disdrometer with different techniques, such as linear versus nonlinear least squares fits (Tokay et al. 2001) and least squares fits versus the probability matching method (Tokay et al. 2003c); and a single disdrometer with different rain versus no-rain thresholds (Tokay et al. 2003b). This reveals that the radar

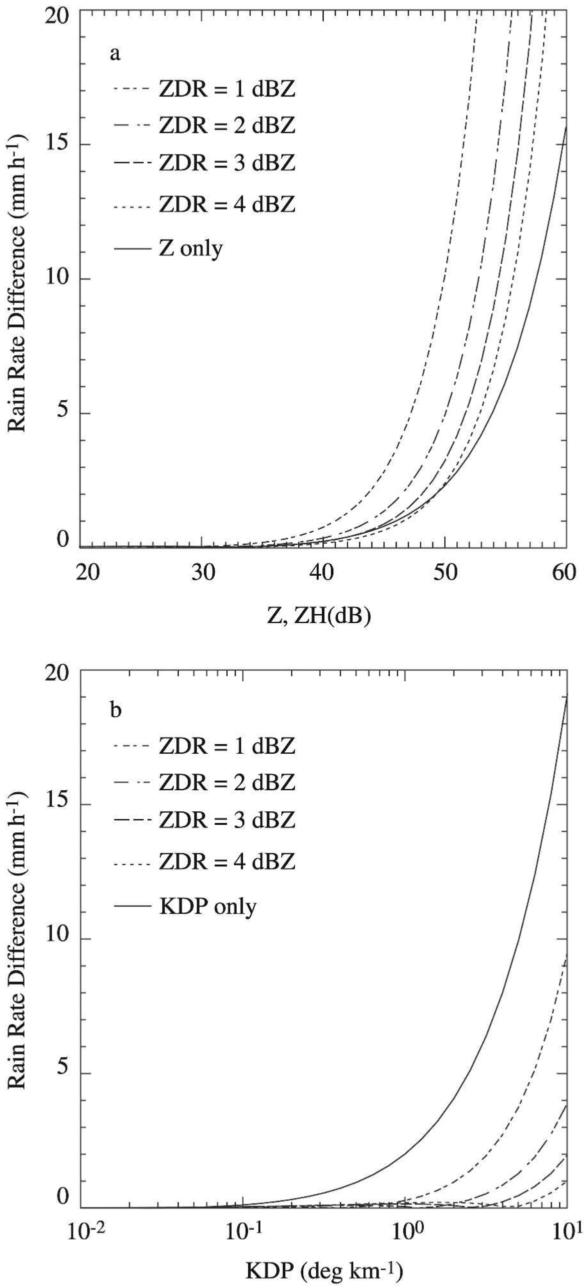

FIG. 7. Absolute difference in rain rate that is derived from JW5- and JW8-based radar-rainfall algorithms. It is expressed as (a) a function of reflectivity (solid), reflectivity at horizontal polarization at differential reflectivity of 1, 2, 3, and 4 dB (dotted, dashed, dash–dotted, and double dash, respectively); (b) specific differential phase (solid), and specific differential phase at differential reflectivity of 1, 2, 3, and 4 dB (dotted, dashed, dash–dotted, and double dash, respectively).

rain estimate derived from the $R(Z)$ relation has higher error bars for deep convective regimes where polarimetric measurements are superior to conventional radar rain estimates.

We then determined $|\Delta R|$ as a function of the polarimetric parameter when the rain rate was derived from R(ZH, ZDR), R(KDP), and R(KDP, ZDR) of two different disdrometers. The $|\Delta R|$ of R(ZH, ZDR) between JW5 and JW8 was the highest among the four different algorithms reaching 1 mm h^{-1} at ZH of 41 dB, and just exceeding 10 mm h^{-1} at ZH of 50 dB when ZDR was 1 dB (Fig. 7a). Because JW5 and JW8 recorded 79%–80% of rain at ZDR $<$ 1 dB, the choice of JW disdrometer had a considerable impact on derived rainfall even though 17%–19% and 2.5%–4.5% of rainfall was above ZH $>$ 41 dB and ZH $>$ 50 dB, respectively (Figs. 8b–c). The $|\Delta R|$ of R(ZH, ZDR) decreased with increasing ZDR at a given ZH. Higher ZDR values correspond to lower axis ratios of large drops, which are typically found at high ZH. Axis ratio is the ratio between the semiminor and semimajor axes of oblate spheroids.

The $|\Delta R|$ of R(KDP) between JW5 and JW8 reached 1 mm h^{-1} at KDP of 0.5° km^{-1} and 5 mm h^{-1} at KDP of 2.4° km^{-1} (Fig. 7b) The histogram of rainfall as a function of specific differential phase showed that there is less than 1% of rain at KDP $>$ 2.4° km^{-1}, while 9%–10% of the rain was recorded by JW5 and JW8 between KDP of 0.5° km^{-1} and of 2.4° km^{-1} (Fig. 8d). The $|\Delta R|$ of R(KDP, ZDR) between JW5 and JW8 was the lowest among the four different algorithms reaching 1 mm h^{-1} at KDP of 2° km^{-1} when ZDR was 1 dB (Fig. 7b). Because only 2%–3% of rain was recorded by JW5 and JW8 at KDP $>$ 2° km^{-1}, the choice of JW has the least impact on derived rainfall even though the majority of rainfall occurs at ZDR $<$ 1 dB (Figs. 8c–d). Similar to the $|\Delta R|$ of R(ZH, ZDR), the $|\Delta R|$ of R(KDP, ZDR) decreased with increasing ZDR at a given KDP.

Because a hybrid algorithm of four different relations is typically used, it is important to assess the contribution of percent time and rain of each of the four relations. If we apply the Cifelli et al. (2002) hybrid algorithm to Wallops Island disdrometer measurements, $R(Z)$ and R(ZH, ZDR) were used 60%–64% and 36%–40% of the time, respectively. This corresponded to 28%–32% and 63%–66% of rainfall for $R(Z)$ and R(ZH, ZDR), respectively. The R(KDP) was never used, while R(KDP, ZDR) was used 0.1%–0.2% of the time and 4%–6% of rainfall.

10. Conclusions

We studied error characteristics of rainfall measurements using six collocated JW disdrometers. First, we considered the six disdrometer means of rain rate, reflectivity, and differential reflectivity, at a given minute as a reference. We then presented the difference of each disdrometer measurement from the mean after taking its average for a rain event. The maximum de-

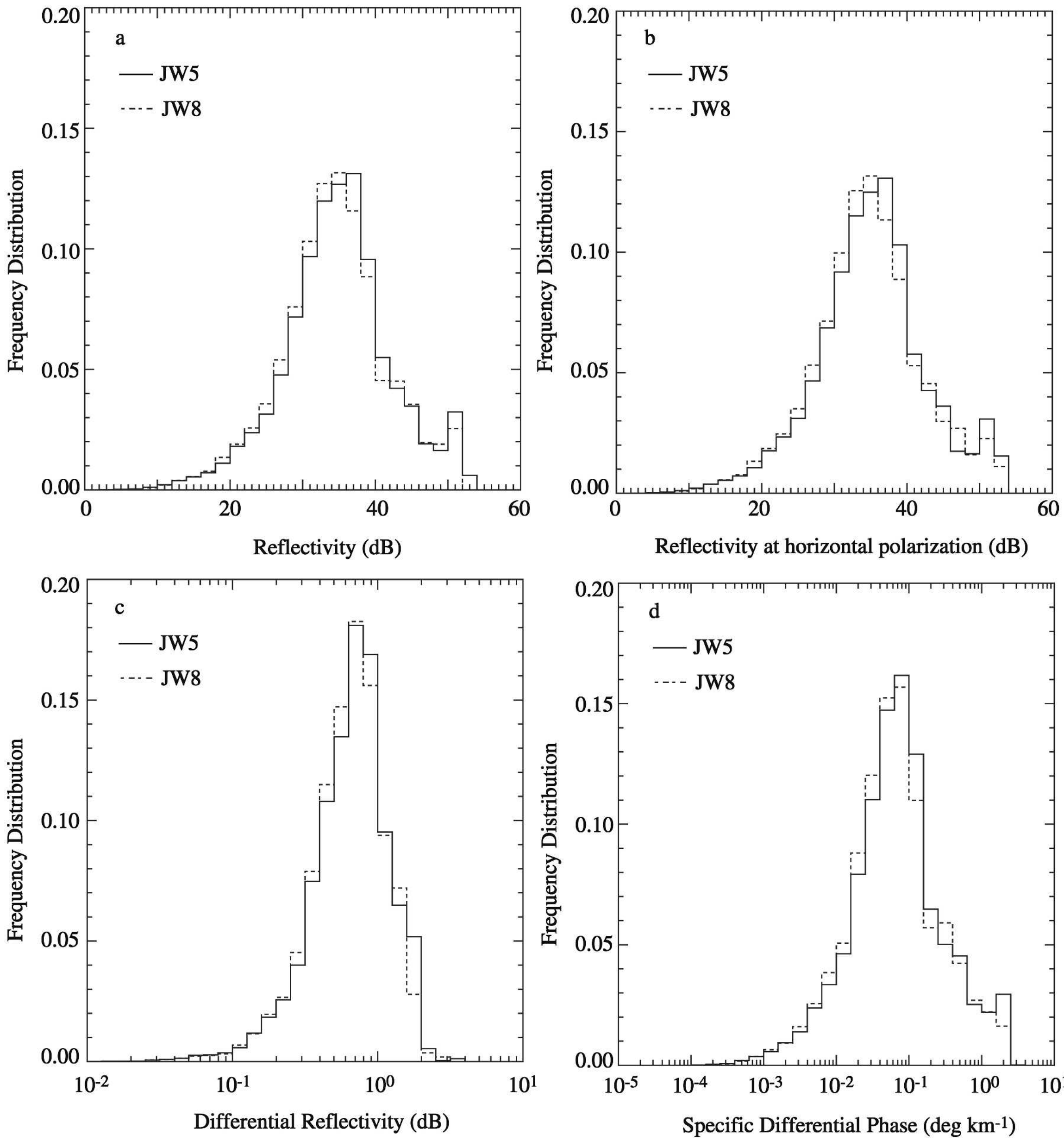

FIG. 8. Frequency distributions of rain amount as a function of (a) reflectivity, (b) reflectivity at horizontal polarization, (c) differential reflectivity, and (d) differential specific phase. The solid and dashed lines represent JW5 and JW8.

viations from the mean were 0.6 mm h^{-1}, 1.3 dB, and 0.05 dB for rain rate, reflectivity, and differential reflectivity, respectively. Then we examined rainfall statistics between paired disdrometers. The root-mean-square diferences of rain rate, reflectivity, and differential reflectivity were as high as 3.2 mm h^{-1}, 3.7 dB, and 0.3 dB, respectively. The rms$-\Delta R$ and rms$-\Delta$ZDR were even higher when the disdrometer observations were stratified based on reflectivity intervals. These results should be considered as an upper limit of the differences between the collocated disdrometer measurements, but it is important to keep in mind these error marks when we use the disdrometers as calibration tools for vertically pointing or scanning radars. As noted, the disdrometer measurements can be averaged over longer intervals, such as 3–10 running minutes. This would reduce the differences between the disdrometer observations.

We also studied the sensitivity of choice of JW disdrometer in derived relations between radar parameters and rain rate. First, we evaluated the performance of four different rain estimators. The R(KDP, ZDR) had the best performance, while $R(Z)$ deviated the most from true rainfall, which is directly calculated from disdrometer observations. The noisy feature of the KDP at low frequencies, however, forces us to use a hybrid algorithm of these four relations. We adopted the hybrid algorithm given by Cifelli et al. (2002) and the algorithm performed substantially better than a single $R(Z)$ relation, particularly for heavy rain. The hybrid algorithm used $R(Z)$ most of the time, but R(ZH, ZDR) had the highest rain volume, R(KDP) was never used, and R(KDP, ZDR) had a very small contribution to the total rainfall. Among the four different rainfall estimators, the differences in absolute rain rate due to the use of two different disdrometers in deriving radar-rainfall relations were highest and lowest for R(ZH, ZDR) and R(KDP, ZDR), respectively. The $|\Delta R|$ increased with increasing ZH, and KDP in both single- and dual-parameter rainfall estimators, while it decreased with increasing ZDR in dual-parameter rainfall estimators. Fortunately, a relatively small fraction of rainfall falls occurs a regime where ZH or KDP is high and ZDR is low.

In this study, we also presented our experience with JW disdrometer malfunctions. Close collaboration with the manufacturer had a positive impact on diagnosing disdrometer problems. The hardware problems were the leading cause for the malfunction of the JW disdrometers, as identified by the manufacturer. Our study revealed that the JW disdrometers should be collocated with a reliable rain gauge. Inconsistencies between collocated tipping-bucket readings are not uncommon (Tokay et al. 2003b,c); therefore, we recommend a minimum of two collocated tipping-bucket gauges for reliable rain accumulation. Two or more collocated JW disdrometers, on the other hand, provides more information regarding disdrometer malfunction through DSD measurements. This study demonstrates that stand-alone JW disdrometer measurements could have inherent measurement error that can only be identified in the presence of collocated (preferably two) rain-measuring instruments.

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