

**A comparison of
rainfall
measurements by
multiple instruments**

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A comparison of rainfall measurements by multiple instruments

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Abstract

Simultaneous observations of rainfall collected by a tipping bucket rain gauge, a weighing bucket rain gauge, an optical rain gauge, a present weather detector, a Joss–Waldvogel disdrometer, and a 2-D video disdrometer during January to October 2012 were analyzed to evaluate how accurately they measure rainfall and drop size distributions (DSDs). For the long-term observations, there were different discrepancies in rain amounts from six instruments in the order of 0 to 27.7%. The ORG, JWD, and 2DVD underestimated, and the TBRG overestimated the rain rate when $R < 20 \text{ mm h}^{-1}$; the TBRG agreed well with the reference values, while the PWD and 2DVD overestimated, WRG and JWD underestimated the rain rate when $R > 20 \text{ mm h}^{-1}$. The TBRG and WRG underestimated more than 50% of rainfall duration substantially in the light rainfall, ORG underestimated the rainfall duration for about 12.7%, while the JWD and 2DVD overestimated the rainfall duration for more than 30%. The overall DSDs of JWD and 2DVD agreed well with each other, while the JWD had a higher volume mean diameter, lower raindrop numbers and liquid water content than that of 2DVD. The overestimation of small-size drops ($D < 1 \text{ mm}$) and underestimation of very large-size drops ($D > 4 \text{ mm}$) by JWD suggests the JWD's inaccuracy of measurement of small-size drops and very large-size drops; the underestimation of small raindrops by 2DVD suggested that DSDs in the heavy rainfall by 2DVD should be handled carefully.

1 Introduction

Measurements of precipitation have been widely applied in meteorology, hydrology, environmental, agricultural, and soil sciences. There are many instruments available to measure precipitation; conventional rain gauge is the most widely used instrument in the world wide, which can only measure the precipitation intensity and duration. With the development of optical and electronic techniques since 1970s, a variety of instruments based on different principles have been developed, which can measure

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the size, shape, velocity of precipitation particles. In particular, the disdrometer that can measure the drop size distributions (DSDs) have been widely used in the cloud modeling and climate studies, rainfall estimation by radar, hydrological modeling, soil erosion, and etc. Although the comparative observations with the disdrometers and rain gauge verify the accuracy of rain rate measured by disdrometers, there's no reference instrument that can obtain the true values, nor standard environment that can simulate the precipitation, the DSD, number concentration, and other micro-physical variables of precipitation measured by different instruments show different discrepancies (Chandrasekar and Gori, 1991; Tokay et al., 2001, 2003; Löhnert et al., 2011), which makes it difficult to the effective application of micro-physical data of precipitation.

At present, the Joss–Waldvogel disdrometer (JWD), 2-D video disdrometer (2DVD), and OTT PARSIVEL disdrometer are the most widely used disdrometers for comparisons and validations of weather radar (Sheppard and Joe, 1994; Schuur et al., 2001; Thurai et al., 2009) and TR MM (Baquero et al., 2005; Wolff et al., 2005), but the accuracy of measurements are still been under examination. There are significant discrepancies in rainfall amounts from JWD and rain gauges in the order of 10 to 20 % (Sheppard and Joe, 1994; Tokay et al., 2003), and the JWD underestimated the number concentration of small drops (Caracciolo et al., 2002). The 2DVD had a better agreement with the rain gauges, but it underestimated small to medium drops (Tokay et al., 2001). The 2DVD and OTT PARSIVEL disdrometer had close agreement in DSD parameters when R was less than 20 mm h^{-1} , while the mass-weighted mean diameter, the standard deviation of the mass-spectrum, and the rainrate of PARSIVEL were higher than that of 2DVD when rainrate was particularly above 30 mm h^{-1} (Thurai et al., 2011).

In order to evaluate the accuracy of rainfall measurements by different instruments based on different principles, especially the DSDs; we analyzed the rainfall observations collected during the Atmospheric Radiation Measurement (ARM) Climate Research that was operated at Darwin, Northern Territory, Australia from January to



rainwater drains from the catchment basin into the measurement chamber, and the sampling interval (Nystuen, 1999). however, rainfall measurement is invalid during the collecting pan drains when the collecting pan fills with water.

The optical rain gauge (ORG for short) measures the scintillation of infrared light produced by the liquid water drops falling between a light source and a receiver (Nystuen et al., 1996). The variation of light intensity caused by a given drop is a function of drop size, fall velocity, shape, and coherence of the light source. However, limited by the measurement principle, the ORG should not be used for frozen precipitation particles. The Model ORG-815 has a precision of 0.1 mm and an uncertainty of $\pm 0.1 \text{ mm h}^{-1}$ in this study. Compared with the other gauges, the ORG overestimates rain rate when there are more small drops, and underestimates rain rate when there are more large drops, it might bias high during higher winds (Nystuen, 1999).

2.2 Present weather detector

The present weather detector (PWD for short) is a multi-variables sensor for automatic weather observing systems. The Model Vaisala PWD22 combines an optical sensor for visibility, a capacitive device Vaisala RAINCAP[®] rain sensor with double-plate for precipitation and a Pt100 thermistor for temperature, these three independent measurements together provide prevailing visibility, precipitation, and present weather type (January 2004).

The precipitation intensity is based on both the optical and capacitive measurements. Optical precipitation intensity is proportional to the volume of particles, as an adjustable parameter; capacitive precipitation intensity is calculated by RAINCAP[®] data, of which the signal is proportional to the rain amount on the sensing surfaces. The capacitive intensity is higher than the optical intensity in liquid precipitation, PWD multiplies the optical intensity with a scaling factor to get the water equivalent intensity in frozen precipitation. If the relative humidity of air is more than about 70 %, the surfaces could produce a signal even with no precipitation, which produce false precipitation. Also the PWD might overestimate the precipitation intensity during higher winds.

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2.3 Joss–Waldvogel disdrometer

The Joss–Waldvogel disdrometer (JWD for short) was originally developed by Joss and Waldvogel (1967) to measure radar reflectivity (Tokay et al., 2003), which is an impact type device and measures the drop size by a styrofoam cone with a sampling cross-sectional area of 50 cm². The JWD's output is proportional to the size and fall velocity of the impacting drops, and the drops' size can be retrieved based on an assumption of the relationship between diameter and fall velocity in still air (Tokay et al., 2001). The Model RD-80 were used in this study, the drops are sorted into 20 size intervals ranging from 0.3 to 5.4 mm, and the boundaries of each channel increase with drop size from 0.1 to 0.5 mm.

It should be noted that the accuracy of JWD is sensitive to background noise; it could underestimate the small raindrops in heavy rain when the Styrofoam cone is hit by much more drops (Tokay et al., 2001). Since the largest size of the JWD is 5.4 mm, any drops larger than 5.4 mm would be counted in the largest size, which causes an underestimation of rain rate in heavy rain. Velocities of raindrops can diverge from the assumed empirical fall speed in the presence of updrafts and downdrafts, causing an underestimation or overestimation of drop size.

2.4 2-D video disdrometer

2-D video disdrometer (2DVD for short) comprises of two light sources and two CCD line-scan cameras with 34.1 kHz rate perpendicular to each other, two light sheets spaced 6.2 mm vertically form the virtual measurement area (10 cm × 10 cm) (Kruger and Krajewski, 2002). Three-dimensional shape information of particles can be recorded when it passing the sampling area, based on which the shape, size, volume, equivalent drop diameter, and oblateness can be calculated. The vertical velocity of each particle can be determined according to the distance between the two light sheets and its traveling time. The precipitation intensity, drop size distribution, velocity distribution can be obtained by time integration (Schönhuber et al., 2007). The drops

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are sorted into 50 size intervals ranging from 0.1 to 9.9 mm; the boundaries of the 50 channels are 0.2 mm uniformly.

The size resolution of 2DVD is 1 pixel of linear CCD or finer than 0.2 mm; therefore it cannot measure the drops smaller than 0.2 mm. The enclosure of 2DVD can cause errors in the detection of small drops, some of them might be counted more than once when they pass across the measurement area while others are not counted at all (Nespor et al., 2000). Also the spatial distribution of raindrops cross the measurement area could be distorted by the wind. A drop seen by the above light sheet might be matched to a different drop by the below light sheet, this mismatching could cause errors in shapes and velocities of particles (Leijnse and Uijlenhoet, 2010).

3 Intercomparison analysis

The rainfall measurements used in this study were collected during the Atmospheric Radiation Measurement (ARM) climate research that was operated at Darwin, Northern Territory, Australia from January to October 2012. The rainfall observations are from a TBRG, a WRG, an ORG, a PWD, a JWD, a 2DVD, where the DSDs are obtained from the JWD and 2DVD.

3.1 General analysis

Table 1 presents the rainfall duration (T_{rain}), max rain rate (R_{max}), and rainfall accumulations (R_{acc}) for 27 rainfall events observed by six instruments, of which the missing records, operational failures, and obvious discrepancies of observations are excluded. In general, the maximum value of T_{rain} was recorded by JWD, the maximum values of R_{max} and R_{acc} were recorded by PWD, while the minimum values of T_{rain} , R_{max} , R_{acc} were recorded by WRG. The rainfall duration of TBRG and WRG is far less than that of ORG, PWD, JWD, and 2DVD, while there's no such obvious difference of rainfall accumulation by six instruments.

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Table 2 presents the bias (ΔR) of total rainfall accumulations by six instruments, which can be calculated as:

$$\Delta R = \frac{R_1 - R_2}{R_1} \quad (1)$$

where R_1 and R_2 denotes the total rainfall accumulation of all the 27 events by two instruments (R_1 is the bigger one).

There are significant discrepancies in rainfall accumulations from different instruments, ORG presents the best agreement with the JWD ($\Delta R = 0\%$), the ORG, JWD, and 2DVD present an excellent agreement with the TBRG ($\Delta R = 5.9, 5.8, 5.0\%$), while the PWD and 2DVD present the worst agreement with the WRG (more than 20%).

The comparisons of event rain amounts between TBRG and other five instruments are presented in Fig. 2. The correlation coefficient and standard deviation (σ) are used to quantify their discrepancies. It can be found that the ORG and TBRG have the best correlation coefficient and the least σ , the probable reason is that the ORG is calibrated by the TBRG, while the PWD and TBRG have the worst correlation coefficient and the largest σ . Compared with the TBRG, The WRG and ORG underestimated the rainfall accumulation obviously, while the PWD and 2DVD overestimated the rainfall accumulation significantly. However, bias does not quantify event by event agreement; details of specific rainfall events will be discussed in the following section.

Table 3 presents the ΔR of rainfall durations by six instruments, it can be found that there is the least bias between the TBRG and WRG ($\Delta R = 3.2\%$), and the largest bias between TRBG and JWD ($\Delta R = 86.2\%$), which can be validated by Fig. 3. The comparisons of rainfall durations between TBRG and other five instruments show that the TBRG and WRG have the best correlation coefficient and the least σ , while the JWD and TBRG have the largest σ , 2DVD and TBRG have the worst correlation coefficient. The overall rainfall duration by ORG, PWD, JWD, and 2DVD bias much higher than TBRG and WRG.

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3.2 Event analysis

Since general rain rate and rainfall duration of long term could not reflect the specific performance of each instrument, details of selected rainfall events with typical features during the precipitation process are discussed, differences and discrepancies between different instruments are analyzed in this section.

Figure 4a and b show the evolution of the rain rate by six instruments on 13 January and 2 March 2012. It can be found that the TBRG, WRG, and ORG have a good agreement when rain rate is more than 20 mm h^{-1} , JWD bias lower and the PWD and 2DVD bias higher. The largest and the smallest rain rate are recorded by PWD and JWD respectively at the same time. The ORG, JWD, and 2DVD show a good agreement, while WRG bias lower and PWD bias a little higher when the rain rate is less than 20 mm h^{-1} . The rain rate of TBRG shows an obvious and discrete variation, the main reason is that its bad resolution of 12 mm h^{-1} . The TBRG has a bad timeliness, one tip of compartment bucket with water in light rainfall need take a long while, therefore rain rate less than 12 mm h^{-1} can not be detected in time.

Although the variations of rain rate recorded by six instruments show great discrepancy, the rainfall accumulation by six instruments have relative small bias. In Fig. 4a, the WRG have the smallest record of rainfall accumulation (16.4 mm), the PWD have the largest record of rainfall accumulation (26.6 mm), and the TBRG, ORG, and JWD have a good agreement (21.2, 20.7, and 19.1 mm), while the 2DVD bias a little higher (26.0 mm). The similar result can be found in Fig. 4b.

The rainfall durations recorded by six instruments agree well when the rain rate is more than 20 mm h^{-1} , while there are much greater discrepancy in the light rainfall ($R < 20 \text{ mm h}^{-1}$). The TBRG and WRG have a good agreement (42, 37 min), while the ORG, PWD, JWD, and 2DVD recorded much longer rainfall duration (198, 208, 234, and 236 min). The main reason is that the optical measurement is sensitive to the light rainfall and small raindrops, while the light rainfall and its small change should take

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a long while to be sensed by compartment bucket or weighing sensor, causing the underestimation of rainfall duration of TBRG and WRG.

Due to the disadvantages and shortcomings of each instrument, rain rate by any instrument treated as the reference is inappropriate. Therefore we propose a reference algorithm based on a weighting of different instruments to obtain a reference value, shown as follows:

$$R_r = \frac{\sum_{i=0}^4 R_i \cdot W_i}{\sum_{i=0}^4 W_i} \quad (2)$$

where R_r is the reference rain rate, R_i is the rain rate by the i th instrument (where 0 for WRG, 1 for ORG, 2 for PWD, 3 for JWD, 4 for 2DVD), the rain rate by TBRG is excluded because of its bad resolution, W_i is the weighting value for the i th instrument. The averaging method is the simplest and easiest weighting function, but it is inaccurate because of different biases of different instruments, therefore we propose a dynamic weighting function:

$$W_i = \frac{R_i}{\sum_{i=0}^4 R_i} \quad (3)$$

Figure 5 shows the comparison of individual instruments against the reference values (13 January 2012). The correlation coefficient and standard deviation (σ) are used to quantity their discrepancies. The TBRG and reference have the worst correlation coefficient; the JWD and reference have the largest σ , while the WRG and reference have the best correlation coefficient and smallest σ . The rain rate by TBRG in Fig. 5a has the largest scatter, while rain rate by PWD, JWD, and 2DVD have a smaller scatter

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about the 1 : 1 line. Compared with the reference values, The WRG and ORG underestimated the rainfall accumulation obviously. In generally, the PWD and 2DVD overestimated, WRG and JWD underestimated the rain rate during heavy rainfall; the TBRG overestimated the rain rate obviously during light rainfall, while the WRG and ORG underestimated the rain rate slightly.

3.3 DSD analysis

Generally, the power-law parameters for Marshall and Palmer (Smith et al., 1993) distributions are widely used for describing precipitation. However, the MP model applies only to stable rainfall from stratiform clouds (Joss and Gori, 1987; Carbone and Nelson, 1978; Willis, 1984). It is now widely accepted that the DSDs of precipitation is better represented by the gamma distribution (Ulbrich, 1983; Testud et al., 2001):

$$N(D) = N_0 D^m \exp(-\lambda D) \quad (4)$$

where the N_0 , m , and λ are intercept, shape, and slope parameters, which can be calculated by the method of moments (Tokay and Short, 1996). The x -moment of DSD is defined as:

$$M_x = \int_0^{\infty} N(D) D^x dD = \sum_0^{\infty} N(D) D^x. \quad (5)$$

The N_0 , m , and λ can be calculated by using the M_3 , M_4 , and M_6 :

$$\begin{cases} N_0 = \frac{\lambda^{m+4} M_3}{\gamma(m+4)} \\ m = \frac{11G-8+(G^2+8G)^{1/2}}{2(1-G)} \\ \lambda = \frac{m+4}{D_m} \end{cases} \quad (6)$$

where $G = M_4^3/M_3^2 M_6$, $D_m = M_4/M_3$. The number density N_d , liquid water content W , radar reflectivity factor Z of rainfall can be calculated by using the M_0 , M_3 , and M_6 .

$$\begin{cases} N_d = M_0 \\ W = \frac{\pi \rho_{\text{water}}}{6} M_3 \\ Z = M_6 \end{cases} \quad (7)$$

where ρ_{water} is the density of water.

Figure 6 shows the evolution of the DSD variables obtained by JWD and 2DVD on 2 March 2012. It can be found that the volume mean diameter measured by JWD is larger than that measured by 2DVD, the drop numbers and liquid water content measured by 2DVD is more than that by JWD, while there is little difference of Z between JWD and 2DVD because of a logarithmic transformation. Considering the evolution of rain rate in Fig. 3b, the differences of volume mean diameter, number, and liquid water content between both are getting greater with the increasing of rain rate, while there is somewhat difference of Z when no rainfall, the reasons related to the instruments will be discussed in the following analysis of DSDs.

The individual observed drop size distributions by JWD and 2DVD for four different rain intensity intervals are shown in Fig. 7a–d and for overall rainfall are shown in Fig. 7e. Small drops were the main contributors to the number concentration in light rain ($R < 5 \text{ mm h}^{-1}$), since the minimum size of JWD is 0.3 mm, its concentration was lower than that of 2DVD during the light rain, while the 2DVD shows a better ability to measure the large-size raindrops. Small and moderate drops were the main contributors to the number concentration in moderate rain ($5 \text{ mm h}^{-1} < R < 15 \text{ mm h}^{-1}$), compared with the DSDs of 2DVD, small drops bias higher, moderate and large drops bias lower by JWD.

There are obvious higher concentrations of raindrops in the heavy rain ($15 \text{ mm h}^{-1} < R < 30 \text{ mm h}^{-1}$) and very heavy rain ($R > 30 \text{ mm h}^{-1}$). The comparison of DSDs of 2DVD and JWD in Fig. 7c and d show that the JWD measured less large-size drops ($D > 3.5 \text{ mm}$), 2DVD measured less small-size drops ($D < 1.5 \text{ mm}$), the reason is that

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from January to October 2012 and selected rainfall events by six instruments were compared, a reference algorithm of rain rate were used to evaluate the accuracy of each instrument, DSDs observed by JWD and 2DVD are compared and discussed; the conclusions are obtained as follows.

5 For the long-term observations, there are different discrepancies in rain amounts from six instruments in the order of 0 to 27.7%. The intensity of TBRG shows an obvious and discrete variation due to its resolution of 12 mm h^{-1} , rain rate less than 12 mm h^{-1} can not be detected in time. Compared with the reference values calculated by the reference algorithm, when the rain rate was less than 20 mm h^{-1} , the ORG, JWD, 10 and 2DVD had a good agreement, which underestimated rain rate, while the TBRG overestimated the rain rate; when the rain rate was more than 20 mm h^{-1} , the TBRG agreed well with the reference, while the PWD and 2DVD overestimated, WRG and JWD underestimated the rain rate. There are much more significant discrepancies in rainfall durations from six instruments in the order of 3 to 86.2%, the TBRG and WRG 15 underestimated more than 50% of rainfall duration substantially in the light rainfall ($R < 20 \text{ mm h}^{-1}$). ORG underestimated the rainfall duration for about 12.7%, while the JWD and 2DVD overestimated the rainfall duration for more than 30%. Compared with the TBRG/WRG with bad timeliness, optical instruments are sensitive to the light rainfall and small raindrops, their output can reflect the temoral rainfall event precisely, which 20 could be used for rain monitoring with better performances.

The JWD and 2DVD had close agreement in DSD parameters when R was less than 15 mm h^{-1} , while there are some discrepancies of number concentration of small and very large raindrops when R was more than 15 mm h^{-1} . The DSDs of JWD and 2DVD that included overall rainfall agreed well with each other, while the JWD had a higher 25 volume mean diameter, lower raindrop numbers and liquid water content than that of 2DVD. The overestimation of small-size drops ($D < 1 \text{ mm}$) and underestimation of very large-size drops ($D > 4 \text{ mm}$) by JWD suggests the JWD's inaccuracy of measurement of small-size drops and very large-size drops; the underestimation of small raindrops by 2DVD when R was more than 15 mm h^{-1} is caused by omission of small raindrops

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in the more large raindrops due to the shadow effect. Inaccuracy of small raindrops in the heavy rainfall by 2DVD should be handled carefully.

Simultaneous rainfall measurements by multiple instruments less than one year is far not sufficient; we still need to analyze longer-term experiments and measurements with the same and different types of instruments. During the ARM, various instruments are now being operated at different climatic region; longer observations will provide more rainfall and DSDs and would allow us to evaluated the performances of multi-instruments for different rain intensities and different precipitation types.

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Table 1. Main rainfall parameters of the used data set. The T_{rain} , R_{max} , R_{acc} denote the rainfall duration, max rain rate, and rainfall accumulations.

Event	Day (UTC)	TBRG			WRG			ORG			PWD			JWD			2DVD		
		T_{rain} (min)	R_{max} (mm h^{-1})	R_{acc} (mm)	T_{rain} (min)	R_{max} (mm h^{-1})	R_{acc} (mm)	T_{rain} (min)	R_{max} (mm h^{-1})	R_{acc} (mm)	T_{rain} (min)	R_{max} (mm h^{-1})	R_{acc} (mm)	T_{rain} (min)	R_{max} (mm h^{-1})	R_{acc} (mm)	T_{rain} (min)	R_{max} (mm h^{-1})	R_{acc} (mm)
1.	20120113	42	72	21.2	39	75.5	16.4	225	74.3	20.8	264	95.5	26.7	349	65.2	19.3	357	95.1	26.2
2.	20120117	39	84	13.6	35	76.7	8.4	252	80.3	11.7	275	66.4	11.6	437	77.5	13.2	406	97.0	15.7
3.	20120119	11	72.0	7.6	12	63.4	6.9	16	62.3	6.7	25	96.3	11.2	120	63.3	7.3	135	85.3	9.9
4.	20120121	43	12.0	8.6	14	6.5	0.9	410	4.9	6.3	422	16.2	11.3	536	6.2	8.6	539	6.3	9.7
5.	20120122	66	72.0	21.2	66	58.4	13.7	271	53.8	18.2	307	79.2	26.4	391	55.5	20.9	394	71.1	24.4
6.	20120123	58	120.0	27.4	58	108.8	23.1	196	96.0	27.1	233	195.4	75.6	322	85.7	25.4	362	147.2	35.6
7.	20120127	24	72.0	7.8	23	63.4	5.5	79	53.3	7.0	83	49.5	2.9	153	61.8	8.2	168	91.7	10.3
8.	20120128	86	84.0	31.4	72	98.0	21.0	485	83.4	28.9	575	144.3	32.3	712	77.7	31.4	725	117.1	39.5
9.	20120129	71	108.0	32.8	70	109.4	27.1	328	98.4	29.9	412	123.8	34.2	615	100.9	32.2	350	60.9	19.8
10.	20120130	78	120	41.0	76	115.3	35.7	426	112.5	39.9	577	121.8	44.9	953	95.9	40.5	1017	152.4	55.3
11.	20120202	11	24.0	2.8	9	16.9	1.2	135	11.9	3.2	173	10.9	3.3	268	14.4	3.7	285	16.6	4.4
12.	20120226	58	60.0	16.8	49	49.0	11.5	314	52.7	14.9	341	71.8	17.8	467	57.4	16.4	102	67.6	14.6
13.	20120228	52	60.0	27.0	51	69.2	24.5	179	58.7	25.4	230	94.5	28.7	364	56.1	26.2	427	74.6	30.7
14.	20120301	127	120.0	73.2	144	137.5	64.2	494	117.3	69.1	605	93.5	65.6	831	111.4	70.3	598	132.1	64.1
15.	20120302	72	60.0	22.6	75	57.2	14.7	292	50.4	20.6	338	83.0	26.4	435	53.1	22.4	454	77.6	26.1
16.	20120305	151	144.0	88.2	142	136.6	83.7	527	138.1	88.9	570	175.9	105.7	729	111.0	83.3	248	170.9	90.9
17.	20120306	39	108.0	29.0	39	109.9	28.2	46	92.4	27.2	47	116.2	36.2	82	84.9	25.3	54	125.5	33.1
18.	20120307	17	36.0	5.2	20	35.9	3.0	63	34.1	5.4	70	56.3	5.5	114	28.	5.2	130	37.9	6.5
19.	20120310	45	84.0	22.8	40	92.6	20.3	224	82.9	23.5	249	110.3	28.5	294	61.0	19.7	319	107.8	24.4
20.	20120328	18	36.0	6.6	1	32.1	5.5	62	29.6	6.1	86	46.9	7.9	192	32.4	6.8	200	35.3	7.7
21.	20120413	19	72.0	10.8	20	61.4	9.32	42	47.1	9.3	43	66.1	12.5	71	55.2	9.8	67	69.9	11.9
22.	20120420	23	48.0	6.4	18	37.3	3.0	123	32.3	6.2	134	53.2	6.6	224	31.2	5.5	246	42.5	7.8
23.	20120423	36	156.0	42.0	35	155.4	39.8	89	144.8	38.2	98	206.4	50.7	174	141.8	35.8	184	178.7	35.6
24.	20120424	9	36.0	2.8	12	27.0	1.5	40	28.5	2.9	44	51.1	3.3	91	32.3	2.9	136	34.9	3.4
25.	20120503	52	84.0	26.4	53	84.5	23.4	121	79.7	23.3	157	123.8	30.7	230	73.7	23.5	235	100.4	30.2
26.	20120929	43	120.0	27.8	60	111.6	25.3	125	110.1	25.9	46	85.6	9.0	180	97.9	22.8	99	119.2	15.0
27.	20121018	5	24.0	1.4	5	19.8	0.8	11	22.0	1.3	10	29.7	1.6	39	24.1	1.5	32	22.3	1.6

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Table 3. Bias of rainfall duration between six instruments.

ΔR (%)	TBRG	WRG	ORG	PWD	JWD	2DVD
TBRG	–	3.2	76.8	79.8	86.2	84.3
WRG	3.2	–	77.5	80.5	86.6	84.9
ORG	76.8	77.5	–	13.1	40.5	32.6
PWD	79.8	80.5	13.1	–	31.6	22.4
JWD	86.2	86.6	40.5	31.6	–	11.8
2DVD	84.3	84.9	32.6	22.4	11.8	–

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Table 4. Drop size distribution parameters of rainfall for different rainrate intervals.

Parameters		$R < 5$ (mmh ⁻¹)	$5 < R < 15$ (mmh ⁻¹)	$15 < R < 30$ (mmh ⁻¹)	$R > 30$ (mmh ⁻¹)	Overall
M_3 (mm ³ m ⁻³)	JWD	1.00×10^3	3.57×10^3	8.09×10^3	1.38×10^4	2.45×10^3
	2DVD	1.06×10^3	5.39×10^3	1.06×10^4	1.56×10^4	2.89×10^3
M_4 (mm ⁴ m ⁻³)	JWD	1.41×10^3	5.34×10^3	1.40×10^4	2.59×10^4	3.87×10^3
	2DVD	1.70×10^3	8.79×10^3	2.01×10^4	3.23×10^4	5.15×10^3
M_6 (mm ⁶ m ⁻³)	JWD	4.28×10^3	1.68×10^4	5.65×10^4	1.23×10^5	1.40×10^4
	2DVD	6.33×10^3	3.10×10^4	9.07×10^4	1.62×10^5	2.17×10^4
N_0 (mm ⁻¹ m ⁻³)	JWD	6.98×10^4	4.78×10^5	6.29×10^5	5.57×10^5	1.31×10^5
	2DVD	4.72×10^4	9.99×10^5	1.33×10^6	2.93×10^6	2.13×10^5
m (mm ⁻¹ m ⁻³)	JWD	2.27	3.99	5.23	5.48	3.23
	2DVD	3.04	5.79	8.48	13.20	5.65
Λ (mm ⁻¹)	JWD	4.46	5.35	5.34	5.05	4.58
	2DVD	4.41	6.00	6.58	8.33	5.42
Z (dB)	JWD	36.32	42.24	47.52	50.88	41.47
	2DVD	38.01	44.92	49.58	52.10	43.37

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(a) Tipping bucket rain gauge (b) Weighing bucket rain gauge

(c) Optical rain gauge



(d) Present weather detector



(e) Joss-Waldvogel disdrometer



(f) 2-D video disdrometer

Fig. 1. Instruments for precipitation. **(a)** Tipping bucket rain gauge. **(b)** Weighing bucket rain gauge **(c)** Optical rain gauge. **(d)** Present weather detector. **(e)** Joss–Waldvogel disdrometer. **(f)** 2-D video disdrometer.

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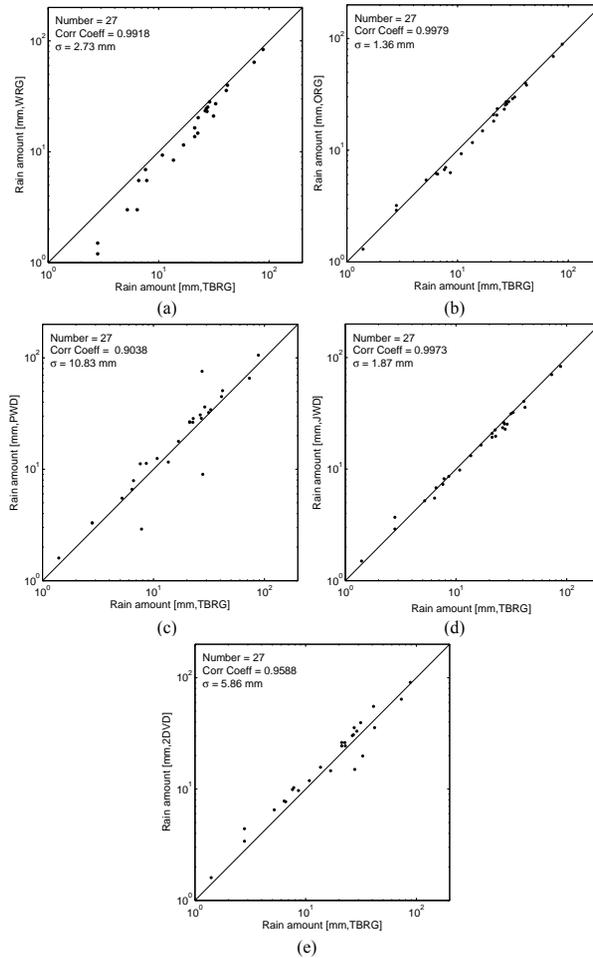


Fig. 2. Comparisons of event rain amount by six instruments. The number, Corr Coeff, and σ are the number of rainfall events, correlation coefficient, and standard deviation.

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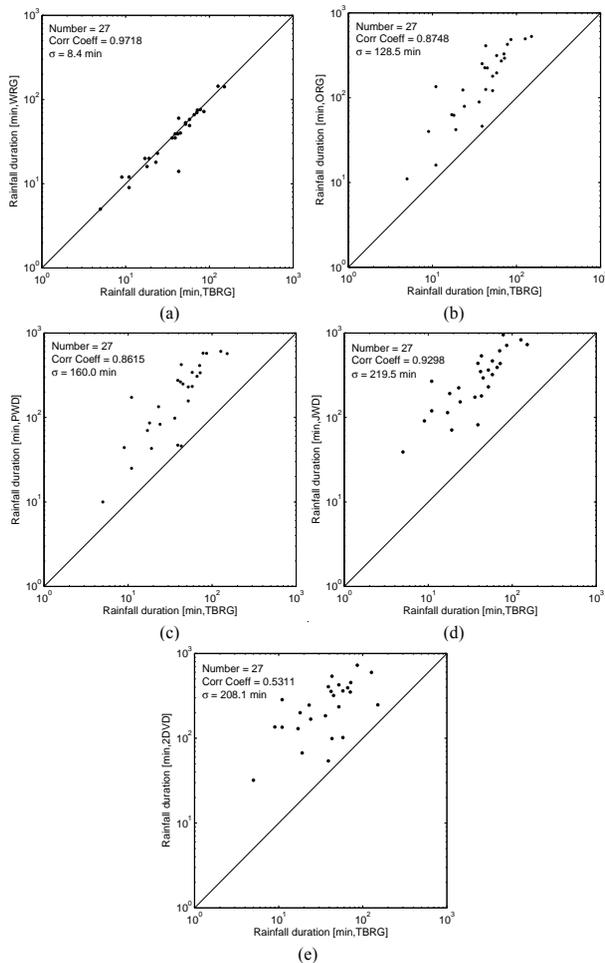


Fig. 3. Comparisons of event rainfall duration by six instruments. The number, Corr Coeff, and σ are the number of rainfall events, correlation coefficient, and standard deviation.

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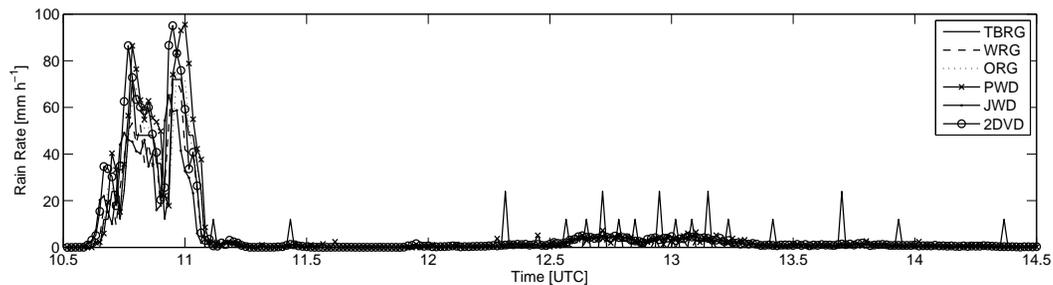
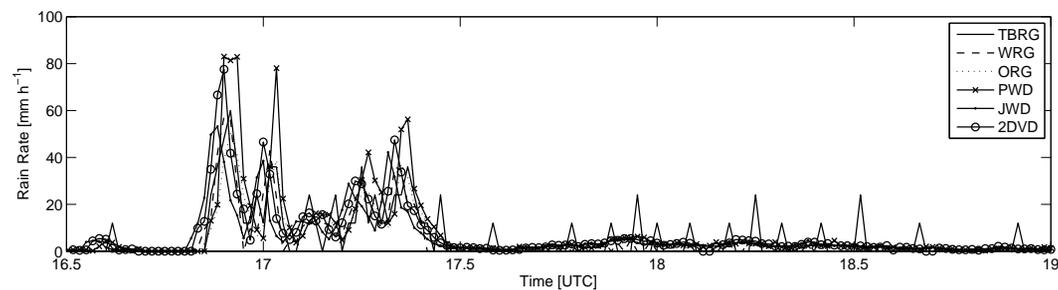
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(a) January 13th 2012(b) March 2nd 2012**Fig. 4.** Evolution of the rain rate recorded by six instruments.

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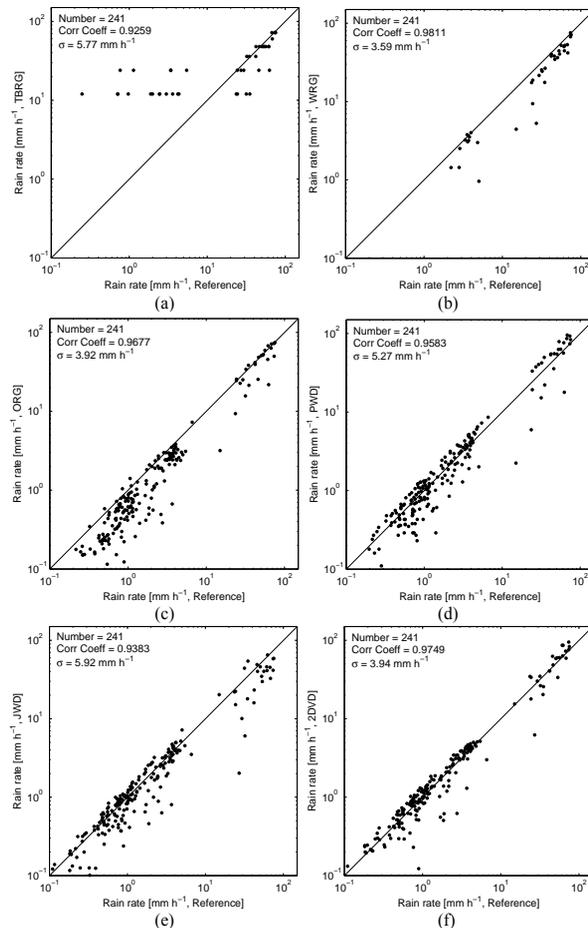


Fig. 5. Comparison of individual instruments against the output from the reference algorithm (13 January 2012). The number, Corr Coeff, and σ are the number of rainfall events, correlation coefficient, and standard deviation.

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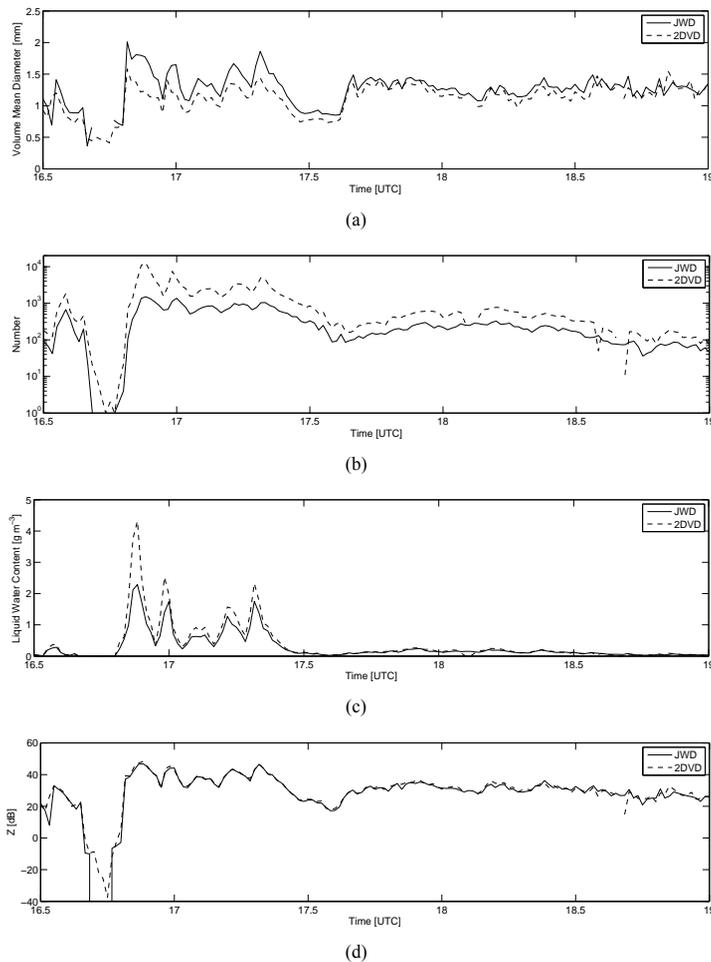


Fig. 6. Evolution of the rain variables on 2 March 2012.

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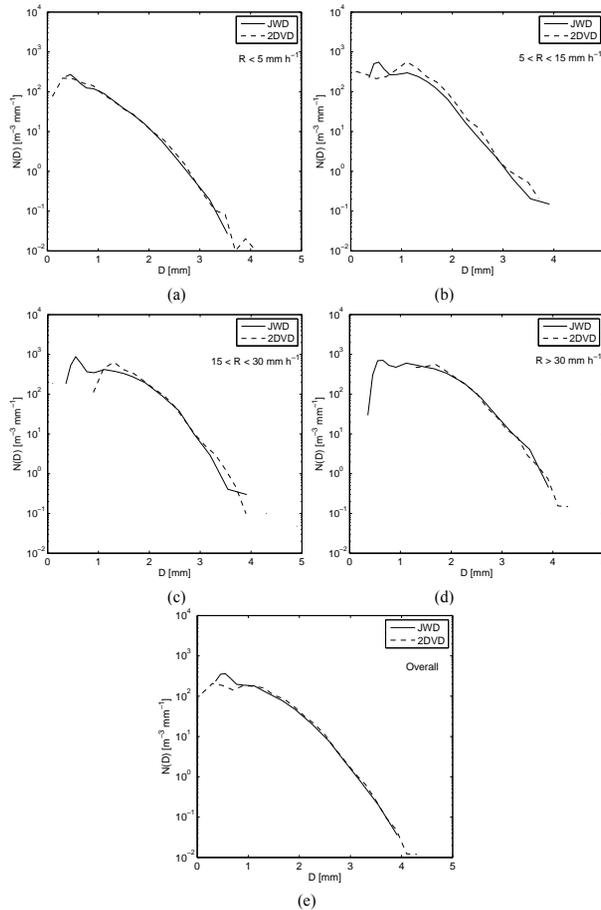


Fig. 7. Drop size distributions for different rain rate intervals.

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