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# Analysis of Three Types of Collocated Disdrometer Measurements at the ARM Southern Great Plains Observatory

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September 2021



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## Analysis of Three Types of Collocated Disdrometer Measurements at the ARM Southern Great Plains Observatory

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## **Executive Summary**

To better provide U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility's disdrometer deployment strategy and support ARM precipitation-related projects, this study analyzes 18 months of drop size distribution (DSD) observations from six collocated disdrometers deployed at the ARM Southern Great Plains (SGP) site. Emphasis is placed on quantifying the uncertainties related to DSD and rainfall properties using different types of disdrometers and different pairing concepts. The instrument sampling errors are also discussed, which improves our understanding of instrument-specific impacts on rainfall measurements. The key findings are as follows:

- 1. All the disdrometers show consistent behaviors overall regarding accumulated precipitation, mean rainfall rate, DSD parameters, and radar reflectivity values.
- 2. Strong agreement is shown between three disdrometer types in terms of their DSDs for mid-size drop range (D = 1 mm-4 mm). The two-dimensional video disdrometer performance meets expectations as the most accurate unit among all.

The paired disdrometer shows a reduced statistical sampling error in terms of drop counts and other DSD properties. A concept of deploying two or more collocated disdrometers side by side is recommended for future ARM field campaigns.

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# Acronyms and Abbreviations

1D	one-dimensional
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
BNL	Brookhaven National Laboratory
CF	Central Facility
DOE	U.S. Department of Energy
DQR	data quality report
DSD	drop size distribution
ENA	Eastern North Atlantic
FSD	fractional standard deviation
HOU	Houston, Texas
JWD	Joss-Waldvogel disdrometer
LDIS	laser disdrometer
LPM	laser precipitation monitor
MCS	mesoscale convective system
MET	surface meteorological system
RMSE	root-mean-square error
SGP	Southern Great Plains
TRACER	TRacking Aerosol Convection interactions ExpeRiment
UTC	Coordinated Universal Time
VDIS	video disdrometer

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## 1.0 Introduction

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility (Ackerman and Stokes 2003) has been collecting rainfall observations at multiple observatories and ARM Mobile Facility (AMF) locations globally since the mid-2000s to improve the understanding of cloud and precipitation processes. ARM's direct precipitation measurement capabilities include several types of precipitation gauges and disdrometers (Bartholomew 2020). The focus of this report is on disdrometers that provide key details on the raindrop size distribution (e.g., raindrop fall velocity and droplet size distribution [DSD]). Currently, ARM operates four types of disdrometers: (i) the impact-type Joss-Waldvogel disdrometer (JWD, e.g., Joss and Waldvogel 1969), (ii) the second-generation particle size velocity disdrometer or laser disdrometer (LDIS, e.g., Löffler-Mang and Joss 2000), (iii) the two-dimensional video disdrometer (VDIS, e.g., Schönhuber et al. 1997), and (iv) the Thies Clima laser precipitation monitor (LPM). The outputs of these disdrometers have served as the primary data set and complementary reference for a variety of recent ARM studies that range from observational analyses of precipitation processes and climate model evaluation to radar/satellite retrieval monitoring or validation (e.g., Wang et al. 2018, Dolan et al. 2018, Giangrande et al. 2019, Jackson et al. 2020). The LPM has been deployed for solid precipitation measurements at ARM's Alaska observatories and is not included in this analysis.

As recently highlighted by Sisterson (2017), more ARM instruments (and therein, downstream product generation) need to provide sufficient information to potential users on instrument calibration and/or other forms of uncertainty in associated estimates or measurements. To better support precipitation-related research activities using disdrometers (e.g., rainfall retrievals, model evaluation), this study investigates the precipitation observations and associated radar quantities collected by co-located gauges and multiple disdrometers deployed at the ARM Southern Great Plains (SGP) facility near Lamont, Oklahoma (Sisterson et al. 2016). The uncertainties related to DSD and rainfall properties are quantified by comparing three types of disdrometers (six units in total), with emphasis on how instrument uncertainties vary as a function of rainfall intensity and radar reflectivity. The instrument sampling errors are also analyzed to improve the understanding of instrument-specific impacts on rainfall measurements, which will provide guidance on deployment strategies for future ARM deployments.

## 2.0 Rainfall Instruments and Data Processing

### 2.1 Overview of the ARM Disdrometers

#### 2.1.1 Joss-Waldvogel Disdrometer

Two impact-type Joss-Waldvogel disdrometers (JWDs) manufactured by Distromet Ltd., Switzerland are currently deployed at the SGP Central Facility (CF) site (JWD-C1 since 28 February, 2006, JWD-E13 since 09 January, 2017) and are located within one meter of each other. These units are the oldest disdrometers that ARM deploys, and are the only ones of this type used by ARM. The JWDs measure raindrop sizes in 20 uneven size intervals (see Table 1) over the range of 0.3 to 5.4 mm in diameter, with an accuracy of  $\pm$  5% of the measured drop diameter (*D*) if the drops are evenly distributed over the sensitive surface of the sensor cone (Joss and Waldvogel 1969). The standard ARM JWD output includes

drop counts at 20 bin sizes at 1-min intervals. The JWD does not measure drop fall speed directly, but assumes that all drops fall at their terminal fall speed (e.g., Gunn and Kinzer 1949). Additional information about the JWD instrumentation and basic processing techniques can be found in the ARM JWD handbook (Bartholomew 2016), and at the Distromet company website (https://www.distromet.com/).

The JWDs were chosen as the first permanently deployed disdrometers at the SGP site due to their reliability, ease of maintenance, and relatively low cost. However, the JWD instrument has several limitations, such as well-documented sampling limitations, dead-time correction, atmospheric noise, and quantization issues (e.g., Sheppard and Joe 1994, Marzuki et al. 2018). These issues potentially lead to the under-sampling of smaller drops (D < 1.5 mm; Rowland 1976, Williams et al. 2000). The JWD also underestimates the very large drops with D > 5.4 mm, since sampled raindrops in this size range are all recorded under the largest size bin (centered at 5.14 mm). Such underestimation of large drops, in particular, may have significant impacts on radar quantity estimations, especially the radar reflectivity factor *Z* and the differential reflectivity  $Z_{DR}$ , which are sensitive to the presence of larger and oblate droplets. Moreover, the accuracy of those quantities or other higher-order moments of the DSD is significantly important to the analysis of deep convective systems, which are commonly observed at SGP. The raindrops from these clouds tend to be larger, as originating from melting hail or larger melting aggregates.

#### 2.1.2 Parsivel<sup>2</sup> Disdrometer

Two second-generation particle size velocity (Parsivel<sup>2</sup>) disdrometers (termed 'LDIS' in ARM) are currently in use at the SGP CF site (LDIS-C1 since 02 November, 2016 and LDIS-E13 since 04 November, 2016) within 2 meters of each other. The Parsivels are laser optical devices and were manufactured by the OTT Hydromet GmbH, Kempten, Germany (Löffler-Mang and Joss 2000). These instruments measure the size of falling hydrometeors (0.06 mm-24.5 mm) and their fall velocity (0.05 m/s-20.8 m/s). The ARM raw data files from these instruments contain one-minute accumulations of hydrometeor counts over 32 unevenly spaced bins for both the drop size and drop fall velocity. Note that the bin spacing is finer for small particles as well as for slower-falling particles. Similarly, the native LDIS observations include a precipitation identifier that attempts to classify hydrometeors into eight categories: 'drizzle', 'drizzle with rain', 'rain', 'rain and drizzle with snow', 'snow', 'snow grains', 'freezing rain', and 'hail'. The nominal cross-sectional area of the LDIS is 54 cm<sup>2</sup>, which is slightly larger than the capture area attributed to JWD (50 cm<sup>2</sup>). However, a better description of the LDIS measurement area (or those of most disdrometers) must take into consideration the possible edge effects. In this study, we assume the effective sampling cross-section for the Parsivel is expressed as  $180 \times (30 - L/2)$ , where L is the size parameter. Details about the Parsivel<sup>2</sup> instrument and additional measurement techniques can be found in the ARM Parsivel<sup>2</sup> handbook (Bartholomew 2020a), and on the OTT Hydromet GmbH website (https://www.ott.com).

Overall, the OTT Parsivel<sup>2</sup>s are the most widely used disdrometers in the ARM facility. In total, ARM operates 11 units at four locations (SGP site, Eastern North Atlantic [ENA] and ARM's Mobile Facilities [AMF1 and AMF2]). While the LDIS is considered relatively durable, its measurements share common limitations with the aforementioned JWDs in accurately measuring smaller and larger drops due to Parsivel-specific technical design and limited sampling area (Krajewski et al. 2006, Tokay et al. 2013). For example, the drop size and velocity measurements are largely sensitive to the interplay of wind

direction and speed on the sampling domain (e.g., fall trajectory through the laser beam; Montero-Martínez and García-García 2016), as the LDIS only records the vertical component of velocity and 1D axis of the falling raindrop. In addition, coincident hydrometeors are reported as one, even for situations where several drops fall through the beam simultaneously, which leads to an underestimation of the drop counts (Yuter et al. 2006, Battaglia et al. 2010).

#### 2.1.3 Two-Dimensional Video Disdrometer

Two 2-dimensional video disdrometer (VDIS) units (VDIS-C1 since 28 February, 2011; VDIS-E13 since 20 June, 2018) are deployed at the SGP CF site and are the newest disdrometers in the ARM facility. These instruments were manufactured by Joanneum Research, in Graz, Austria (e.g., Schönhuber et al. 1997). Four units are currently operating in the ARM facility, including two at the SGP site, one at the ENA site, and one at the TRacking Aerosol Convection interactions ExpeRiment (TRACER) site in Houston, Texas (HOU). As arguably the most sophisticated disdrometer, the VDIS records detailed information of individual hydrometeor (i.e., raindrop, hailstone, snowflake) such as hydrometeor size (equivalent diameter), shape (oblateness), orientation, and fall velocity. Each individual falling particle is measured twice through two orthogonally oriented, high-speed line-scan cameras situated in offset measurement planes that are vertically separated by ~ 6 mm. The horizontal and vertical resolutions of the gridded images for the hydrometeors are finer than 0.2 mm in diameter. The sensor sampling area depends on its optical alignment between the light source and camera (< 100 cm<sup>2</sup>), and is reported for each detected drop. The sampling area is at least 1.5 times those of the JWD and LDIS. Additional information can be found in the ARM 2DVD handbook (Bartholomew 2020b) and on the Joanneum Research website (www.distrometer.at).

As discussed in the disdrometer literature (e.g., Tokay et al. 2001, 2013), the VDIS is often considered the most reliable disdrometer under nominal operating conditions, but will still under-sample rain drops that are smaller than 0.2 mm in diameter, with its more significant issues occurring during windy or heavily rainy conditions. For example, under lighter rain/drizzle and windy conditions, it is potentially unavoidable that the smallest drops may pass the VDIS observing domain at very low angles, thus advecting past the unit without falling into the sampling orifice (Nespor et al. 2000). Nevertheless, the VDIS is expected to have improved accuracy (in comparison to previously mentioned types) when sampling most drop sizes including larger drops with D > 5 mm, partially owing to its relatively larger sampling-capture area. Moreover, while VDIS operations are more challenging, the measurements are generally considered reliable and often serve as the 'truth' for ground validation and/or as a reference for other rainfall retrievals (e.g., Schuur et al. 2001, Raupach and Berne 2015, Tokay et al. 2020).

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	JWD	LDIS	VDIS		
Mean diameter drop class [mm]	0.36, 0.46, 0.55, 0.66, 0.77, 0.91, 1.12, 1.33, 1.51, 1.66, 1.91, 2.26, 2.58, 2.87, 3.20, 3.54, 3.92, 4.35, 4.86, 5.37	0.062, 0.187, 0.312, 0.437, 0.562, 0.687, 0.812, 0.937, 1.062, 1.187, 1.375, 1.625, 1.875, 2.125, 2.375, 2.75, 3.25, 3.75, 4.25, 4.75, 5.5, 6.5, 7.5, 8.5, 9.5, 11, 13, 15, 17, 19, 21.5, 24.5	0.1 to 9.9, evenly spaced over 0.2 mm interval		
Mean Fall Velocity classes [m/s]	Assuming all drops fall at their empirical terminal speed	0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95, 1.1, 1.3, 1.5, 1.7, 1.9, 2.2, 2.6, 3.0, 3.4, 3.8, 4.4, 5.2, 6.0, 6.8, 7.6, 8.8, 10.4, 12.0, 13.6, 15.2, 17.6, 20.8	Fall velocity is measured for each individual drop		
Sampling area [cm²]	50	54	~ 100		
Measurement Accuracy	-/+ 5% of measured drop diameter	± 1 size class (0.2 - 2 mm) ± 0.5 size class (> 2 mm)	Fall velocity accuracy better than 4% and drop <i>D</i> accuracy better than 0.17 mm for $V <$ 10 m/s.		
Dimensions of the sensor (L x W x D) [mm]	170 x 100 x 100	670 x 600 x 114	890 x 960 x 960		
Weight [kg]	2.9	max. 6.4	80		
Types of precipitationraindropdrizzle, drizzle/rain, rain, mixed rain/snow grains, sleet, hail		drizzle, drizzle/rain, rain, mixed rain/snow, snow, snow grains, sleet, hail	solid, liquid, molten, frozen		

 Table 1.
 Specifications of the Joss-Waldvogel disdrometer, the Parsivel<sup>2</sup> disdrometer, and the two-dimensional video disdrometer.

### 2.2 Tipping Bucket Rain Gauge

Although disdrometers provide rainfall information, those instruments are not substitutes for rain gauge estimates for rainfall rate and accumulations. Thus, rain gauge measurements are considered as the primary reference for a baseline evaluation of the disdrometer estimates. A tipping bucket rain gauge (260-2500 Series manufactured by NovaLynx Corp., Grass Valley, California) has been deployed at the SGP CF site since April 2006, and is situated 25 meters north of the main disdrometer cluster. This unit consists of a funnel that collects and directs precipitation into a seesaw container that tips after a pre-set amount of liquid enters. When the seesaw tips, an electrical signal is sent to a recording device. The measured rainfall amounts by the tipping bucket gauges are reported every minute, with an uncertainty of 0.254 mm. Rainfall rates from these instruments have an uncertainty of 0.6 mm/hr.

### 2.3 Disdrometer Data Processing

This section describes the basic ARM disdrometer data processing steps, including data quality control and rainfall quantity estimation. We process the raw data using an open-source PyDSD code (Hardin and Guy 2017). The data processing methods primarily follow the concepts documented in several ARM publications (e.g., Wang et al. 2018, Giangrande et al. 2019).

#### 2.3.1 Disdrometer Data Filtering

In general, error sources and uncertainties for disdrometer measurements may originate from some of the following instrument-sampling limitations: splashing effects, marginal fallers (e.g., drops falling through the edges of the sampling area), non-rain objects (e.g., insects, flying seeds, or grass clippings), other masking effects (e.g., drops falling simultaneously through the device), the role of wind/turbulence around the instrument, or mismatching between cameras or clogging of the sensors therein (e.g., in the case of the VDIS). To improve data quality beyond the manufacturer/system calibration concepts and account for several aforementioned limitations, disdrometer studies often perform a standard set of data processing and filtering. These concepts have been used in many previous disdrometer efforts, including within ARM (e.g., Wang et al. 2018, Giangrande et al. 2019), and often have been applied directly to the '.b1'-level ('calibrated') data sets for the various types of disdrometers previously mentioned. Several processing steps are highlighted in this section, including:

- Drops that exceeded ± 50% of their expected terminal fall speed (Tokay et al. 2013, 2014) are filtered out (margin fallers, splashing effect, or high wind effect). This filter is only applicable to LDIS and VDIS observations, since the JWD does not measure drop fall velocity.
- 2. Drops that fall into the first two size bins for VDIS and LDIS correspond to drop median diameters less than 0.2 mm. The counts of these drops are not considered in the ARM standard processing due to the difficulties for disdrometers in accurately sampling smaller drop sizes (low signal-to-noise ratio, splash effect; Tokay et al. 2013).
- 3. Larger hydrometeors with D > 5 mm are also removed from the ARM standard processing. Note, variability in these drops cannot be distinguished by JWD, while the LDIS has higher uncertainty in recording larger particles owing to its larger bin widths (1 mm between 5 and 10 mm; Tokay et al. 2013). Typically, drop sizes > 5 mm are rare unless in the form of melting hail/aggregates (i.e., questionable as purely 'rain' drops) at the SGP site.
- Processing efforts have included separate aggregation steps that take the 1-min 'raw' DSD data sets to 5-min time intervals. Applying a 5-minute aggregation window further reduces the noisiness in DSD measurements.
- 5. Disdrometer data processing typically assumes a minimum number of drops for a valid rainfall/DSD measurement. For the averaged 5-minute sampling, this is set as a 50-drop threshold. This threshold is also set to remove DSDs having rainfall rates lower than 0.5 mm/hr.
- 6. Questionable data are removed based on ARM's data quality reports (DQRs).

In Figure 2, we show the number of drops per diameter and fall velocity classes as from the LDIS-C1 and VDIS-C1 1-min raw data from June 2018 to December 2019 at the SGP site. The applied fall speed and drop size filters are overlaid on the plots as navy lines. Note that the criteria suggested above remove approx. 24% of the DSDs recorded by the LDIS-C1. As a final note, we restrict our analysis to times when all six disdrometers report drops.



Figure 1. Number of drops (in color) per diameter and fall velocity classes for Parsivel<sup>2</sup> disdrometer (pars2C1) and video disdrometer (vdisC1) 1-min raw data from June 2018 to December 2019 at the SGP C1 site. The solid curve represents the L'hermite (2002) terminal fall velocities and the dashed curves are  $\pm$  50% of the L'hermite (2002). The solid vertical line represents the 5-mm drop size threshold.

#### 2.3.2 DSD Parameter and Radar Quality Calculations

To investigate the raindrop DSD and its variability, several functions have been developed to fit the typical rain DSDs (e.g., gamma distribution; exponential distribution). These efforts have historically also been useful to simplify further retrievals of rainfall properties (e.g., radar-based rainfall relationships; Battan 1973) or to evaluate model performance. In this study, the normalized gamma distribution has been used to parameterize the DSD quantities, following previous precipitation efforts (e.g., Testud et al. 2001, Giangrande et al. 2014, Thompson et al. 2015). This is expressed as:

$$N(D) = N_W D_0^\mu \exp(-\wedge D), \tag{1}$$

where *D* is the drop equivolume spherical diameter,  $N_w$  is the normalized intercept parameter [mm<sup>-1</sup> m<sup>-3</sup>],  $D_0$  is the median volume diameter [mm],  $\mu$  is the normalized shape parameter, and  $\Lambda$  is the slope [mm<sup>-1</sup>]. The median drop diameter  $D_0$  and normalized  $N_w$  are estimated following examples that include those from Bringi and Chandrasekar (2001).

Key radar quantities, including Z,  $Z_{DR}$ , and the specific differential phase ( $K_{DP}$ ), are also estimated from these DSDs. These radar quantities are calculated for S-band radar based on the T-matrix scattering model (Mishchenko et al. 1996) using open-source code PyTmatrix (Leinonen 2014). The raindrops in these estimates are assumed to be oblate spheroid and follow the drop axis ratio-diameter relationship developed by Thurai et al. (2007). The air temperature for these radar estimates is assumed to be 20°C.

#### 2.4 Additional DSD Parameter Statistical Analysis

#### 2.4.1 Disdrometer Sampling Errors

Disdrometer measurements inherently imply significant sampling errors that are caused by the limited sampling volume or area of the sensor, especially when considering the sampling of lower-frequency drops in the larger bins that may introduce large uncertainties in DSD higher-order moment estimates (e.g., Joss and Waldvogel 1969, Gertzman and Atlas 1977, Uijlenhoet et al. 2005). Thus, quantifying sampling errors for those DSD parameters and understanding their impacts on interpreting rainfall properties are of primary importance for disdrometer applications. This includes the usefulness for these estimates as anchor points in (relative, absolute) radar calibration (Gage et al. 2004, Berne and Uijlenhoet 2005) and radar-hydrological product generation.

Generally, the sampling fluctuations of DSD measurements are usually associated with their physical variations, and these variations are difficult to identify (in practice) based solely on the observations from a single disdrometer. Moreover, having paired, collocated disdrometers provides two realizations with a similar expected value, assuming these instruments are observing the same DSDs. If this is assumed, the observed differences between the two measurements may be mainly attributed to statistical fluctuations. In this study, the sampling error will be represented by the fractional standard deviation (FSD), following previous disdrometer efforts that include Cao et al. (2008)

$$FSD = \delta x / \langle x \rangle \tag{2}$$

where  $\delta x$  is the standard deviation of sampling errors;  $\langle x \rangle$  is the expected value of x. Since the  $\langle x \rangle$  is unknown in reality, we estimate  $\langle x \rangle$  by taking the mean value of the quantity of interest. Note that this approach may still introduce uncertainties due to the nonergodic nature of the rain process (Cao et al. 2008). More detailed information of calculating FSD for DSD and radar properties can be found in Schuur et al. (2001; their Appendix).

#### 2.4.2 Uncertainty Statistics

For additional uncertainty quantification, we use estimates for the absolute bias (|bias|), absolute fractional bias (frac|bias|), root-mean-square error (RMSE), and correlation coefficient (r) to evaluate the performance of paired instruments. The absolute bias and absolute fractional bias between the two disdrometer measurements (x, y) for n samples are calculated as:

$$|bias| = |xi - yi|, \tag{3}$$

$$\operatorname{frac}|\operatorname{bias}| = |\operatorname{bias}| / \langle x, y \rangle, \tag{4}$$

where  $\langle x, y \rangle$  is the mean of the two variables x and y, that is expressed as

$$\langle x, y \rangle = (xi + yi)/2,$$
 (5)

## 3.0 Rainfall and DSD Properties at the SGP Site

### 3.1 Data Set Overview and Rainfall Characteristics

In this section, we summarize the precipitation properties as collected by disdrometer and rain gauge measurements at the SGP site. The data set was filtered based on processes summarized in Section 2. The SGP record considered in this study contains 1,789 5-min DSD measurements meeting the data processing criteria. These data were collected from over 513 days during an 18-month period (June 2018-December 2019) when six disdrometers were operating. These DSDs are associated with a total precipitation that exceeds 500 mm, with an instrument difference varying from 6% to 18% between those disdrometers and the rain gauge measurements (Figure 3). The maximum total rainfall accumulation among the disdrometers was 703 mm as recorded by the VDIS-E13, which was 36% higher than the lowest total precipitation recorded by the LDIS-C1 (514 mm). As noted, those differences are not unexpected given the differences in instrument sampling areas, as well as some natural/physical variability in intensity or spatial heterogeneity of the rainfall systems. The high wind effects (cross-cutting physical and sampling limitations) may contribute to the differences as well.



**Figure 2**. Rainfall accumulation collected by six collocated disdrometers and a tipping bucket rain gauge from June 20, 2018 to December 30, 2019 at the SGP site.

Monthly accumulation breakdowns for the six collocated disdrometers are shown in Figure 3a. The warmer-season periods show enhanced rainfall amounts (through May to August) from all the disdrometers, which is consistent with previous SGP precipitation studies (e.g., Zhang et al. 2017). More frequent passages of the convective cloud systems and frontal intrusions during these seasons contribute largely to the total accumulations (e.g., Fritsch et al. 1986), especially the organized mesoscale convective systems (MCSs). All disdrometers consistently capture a maximum accumulation peaking in August (approximately 120 mm over the study period), and slightly reduced rainfall in other warmer season months (minimum found in July, approximately 60 mm). Note: while these behaviors are initially suggested as reasonable, the limited samples during this 18-month observational period are not intended to represent the SGP rainfall annual cycles. For example, year-to-year variability in precipitation over the

SGP site may be significant, depending partially on the large-scale moisture transport and convergence (e.g., through low-level jets from the Gulf of Mexico; Helfand and Schubert 1995, Higgins et al. 1997) and soil moisture (Welty and Zeng 2018).

Similarly, we plot the diurnal cycles of the rainfall accumulation in Figure 3b. A nocturnal-to-early-morning rainfall maximum is observed by all six units at the site from 0200 UTC-1700 UTC. This behavior is more pronounced during the summertime, as also documented in previous studies (e.g., Wallace 1975, Dai et al. 1999). This nocturnal precipitation maximum has been found to be associated with the eastward-propagating convective cloud systems (e.g., MCSs; Carbone et al. 2002), a reversal of the mountain-plains circulation (Carbone and Tuttle 2008), and an enhanced moisture transport by low-level jet during nighttime (Berg et al. 2015). Interestingly, the differences in Figure 3 between the similar types of disdrometers are consistently distributed to each month of the year and each hour of the day. This behavior suggests that these differences are likely due to specific instrument calibration issues and/or high wind effects (e.g., unit pairings such as LDIS having known and relative biases as contingent on sampling relative to prevailing winds, storm motion).



Figure 3. The annual and diurnal cycles of rainfall accumulation collected by six collocated disdrometers from June 20, 2018 to December 30, 2019 at the SGP site.

#### 3.2 Summary of the DSD Properties

In Table 2, we summarize the key rainfall parameters and radar quantities from disdrometers breaking down according to the rainfall rate intensity (for requests for specific parameters, please contact the <u>instrument mentor</u>). All the instruments show consistent behaviors within each rainfall rate interval in terms of mean *R*,  $D_0$ ,  $N_w$ , *Z*, and  $Z_{DR}$ . For instance, the mean rainfall rate from each instrument is generally

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within 4.5% of the other instruments. The discrepancies between different disdrometer types are most pronounced for  $N_w$ , which is expected due to the known differences associated with smaller drop sampling. For example, the LDIS measurements exhibit lower drop concentrations  $N_w$ (~ 4000 mm<sup>-3</sup> mm<sup>-1</sup>) for the lighter rainfall rate bins (R < 1 or 1 < R < 10 mm hr<sup>-1</sup>) compared to the other types of disdrometers. The VDIS has a higher  $N_w$  (~ 8000 mm<sup>-3</sup> mm<sup>-1</sup>) and smaller D0 (2.02 mm) for the larger rainfall rate bin (R > 30 mm hr<sup>-1</sup>), which has also been found in previous disdrometer studies (e.g., Battaglia et al. 2010, Gatlin et al. 2015, Park et al. 2017, Giangrande et al. 2019). Except for  $N_w$ , the LDIS reports slightly higher values for the other DSD and rainfall parameters compared to JWD and VDIS.

R	# of DSDs	<r> [mm/hr]</r>	<d<sub>0&gt; [mm]</d<sub>							
	JWD-C1, JWD-E13, LDIS-C1, LDIS-E13, VDIS-C1, VDIS-E13									
< 1	450, 301, 571, 393, 326, 225	0.7, 0.8, 0.7, 0.8, 0.8, 0.8	1.06, 1.10, 1.10, 1.12, 1.15, 1.25							
1 - 10	1197, 1370, 1092, 1243, 1310, 1384	3.0, 3.1, 2.9, 3.0, 3.1, 3.1	1.45, 1.49, 1.46, 1.48, 1.47, 1.48							
10 - 30	121, 147, 110, 125, 125, 140	17.1, 17.2, 17.0, 17.4, 16.5, 16.0	2.00, 2.06, 2.02, 2.09, 1.99, 1.97							
> 30	21, 34, 16, 28, 28, 40	39.8, 44.1, 44.1, 43.0, 43.7, 44.0	2.13, 2.23, 2.14, 2.19, 2.02, 2.02							
R	<n<sub>w&gt; [mm-3 mm-1]</n<sub>	<z> [dBZ]</z>	<z<sub>DR&gt; [dB]</z<sub>							
	JWD-C1, JWD-E13, LDIS-C1, LDIS-E13, VDIS-C1, VDIS-E13									
< 1	9244, 10043, 4543, 3997, 5841, 2836	23, 24, 23, 24, 24, 25	0.3, 0.4, 0.4, 0.4, 0.4, 0.4							
1 - 10	4622, 4250, 4704, 4420, 5003, 5789	31, 32, 32, 32, 31, 31	0.6, 0.7, 0.7, 0.7, 0.6, 0.6							
10 - 30	3636, 3627, 3640, 3018, 4113, 4046	43, 43, 44, 44, 43, 43	1.0, 1.1, 1.2, 1.2, 1.1, 1.0							
> 30	4542, 5001, 5527, 4643, 7655, 8342	48, 48, 48, 49, 48, 48	1.1, 1.2, 1.2, 1.3, 1.1, 1.1							

**Table 2.**A summary of 5-min DSD parameter breakdowns for the number of DSDs, rain rate R,<br/>median volume drop size  $D_0$ , normalized DSD intercept parameter  $N_w$ , radar reflectivity Z<br/>and  $Z_{DR}$  at S-band wavelengths, filtered according to rainfall rate intervals.

Figure 4a shows the DSD composite behaviors for all the disdrometers based on the cumulative data set. This comparison highlights the great agreement between three different types of disdrometers in terms of their average drop number concentrations, especially within the mid-size drop range for D between 1 mm and 4 mm. However, sampling differences between different sensors and instrument types are most pronounced in the smaller and larger raindrop size ranges. The drop number concentration (N) peaks at the first/second available size bin (centered at 0.36 mm/0.3 mm in D) for the JWD/VDIS. For the LDIS, the peak of N is located at the fifth-size bin (centered at 0.56 mm in D), with both units suggesting relative under-sampling of the raindrops at the smaller drop sizes (D < 0.56 mm). Here, these issues may be influenced by LDIS reduced sensitivity in these drop size ranges (e.g., Tokay et al. 2013). As we highlight in Figure 4b, this underestimation tends to be more pronounced for higher-rainfall-intensity

sampling (R > 10 mm/hr). Interestingly, for larger drop sizes (D > 4 mm), an opposite tendency is found. Here, the LDIS relatively overestimates the number of larger drops. This overestimation of larger drops lends explanation for the higher relative R and Z estimates as also reported in Table 2. These discrepancies in sampled DSDs by different disdrometers are nonetheless consistent with previous disdrometer intercomparison studies at other locations (e.g., Park et al. 2017, Tokay et al. 2013, Giangrande et al. 2019).

Focusing momentarily on the JWD measurements, especially those collected by JWD-C1, these units sample the fewest number of large rain drops compared to the other adjacent disdrometers. This may be partially attributed to the fact JWD has the smallest sampling area among the disdrometer types. In addition, the background noise, high wind effects, and dead-time corrections may degrade the accuracy of measuring drop counts using JWD (e.g., Tokay et al. 2003, 2005, Tokay and Bashor 2010). Moreover, a prominent underestimation of drop number concentration is found at the small drop end of the JWD size spectra (0.5 mm < D < 1 mm), as compared to LDIS and VDIS (Figure 4a). This underestimation is more pronounced for the likely deep convective core DSDs having R > 10 mm/hr (Figure 4b). The suggestion is that the JWD fails to capture the largest portion of small raindrops (e.g., those that would experience more efficient rainfall evaporation near convective clouds, e.g., Sauvageot and Lacaux 1995, Atlas and Ulbrich 2000, Tokay et al. 2013). In contrast, the VDIS occasionally report spurious small drops (e.g., Tokay et al. 2002), primarily during intense convective events (Figure 4b) as related to the Velcro-type splash guard material around the orifice that becomes less effective as it saturates quickly with the heavy rainfall. Nevertheless, VDIS performance is consistent with expectations as the most reliable unit among all.



Figure 4. Averaged drop size distributions for all the measurements (a) and for convective rainfall (R > 10 mm hr-1) and stratiform rainfall events  $(R \le 10 \text{ mm hr-1})$ , separately (b).

## 4.0 Uncertainties in Rainfall and Radar Quantities

### 4.1 Biases in Sampling Key Properties

For statistical comparisons, we calculate the bias, absolute bias, fractional absolute bias, RMSE, and correlation coefficient between different disdrometer pairs for key quantity, rainfall (*R*), as shown in Figure 5 and Table 3. Most co-disdrometer (similar instrument type) and cross-disdrometer (different instrument types) pairings indicate a good agreement between the various instruments, with a bias within +-1 mm hr<sup>-1</sup>, a |bias| lower than 1.2 mm hr<sup>-1</sup>, and a fractional |bias| lower than 28%. Among various pairs considered, a considerable reduction in bias is found using the same disdrometer type, with the lowest biases found for the VDIS pairs (|bias| = 0.97, frac|bias| = 24.1 %, Table 3). The measurements from most pairings are also highly correlated (r > 0.9). This confirms these instruments as sampling similar rainfall conditions that supersede select known challenges related to the different disdrometer sampling areas and other limitations in measuring various drop sizes (e.g., Table 1, Figure 5).

We also analyze additional results in a similar form for  $D_0$  and Z (not shown). One consistent suggestion from these additional key parameters is that the non-matching disdrometer pairs exhibit the higher biases and the lowest r, with the worst performances found for a particular LDIS-C1 and VDIS-C1 pairing. Since the LDIS raindrop sampling is sensitive to prevailing winds and sampling areas, such discrepancy from these pairings is not surprising. These issues would be in addition to the spatial inhomogeneity and other complexities that might more randomly complicate most disdrometer intercomparisons.



**Figure 5**. The Bias, absolute bias (|Bias|), RMSE, Frac |Bias|, correlation coefficient in terms of rainfall rate for paired disdrometers.

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	Bias	Fra Bias  [%]	RMSE	r	Bias	Fra Bias  [%]	RMSE	r	Bias	Fra Bias  [%]	RMSE	r
$D_0 [mm]$				R [mm hr <sup>-1</sup> ]			Z [dBZ]					
JWD pair	0.10	6.8	0.14	0.98	1.12	23.8	3.51	0.95	1.68	5.5	2.13	0.98
VDIS pair	0.08	5.4	0.13	0.97	0.97	24.1	3.48	0.89	1.27	4.2	2.11	0.96
LDIS pair	0.15	10.1	0.23	0.92	1.22	26.4	3.37	0.95	2.07	6.7	2.78	0.96

**Table 3.**A summary of 5-min DSD parameter breakdowns for the number of DSDs, rain rate R,<br/>median volume drop size  $D_0$ , normalized DSD intercept parameter  $N_w$ , radar reflectivity Z.

Among all comparisons between similar disdrometer types, the LDIS pairs suggest the worst performance in terms of the  $D_0$ , R, and Z agreements. It's worth mentioning that we suspect there is an issue with the LDIS-E13 unit according to the ARM DQRs. The paired LDIS performance may be impacted by the LDIS-E13 instrument performance. As suggested prior, even while limiting the potential error sources (as from spatial variability within the rain systems) by reducing the distance between these disdrometers to 2 meters, discrepancies in DSD sampling may reflect device orientation relative to the prevailing or storm-relative winds. In Figure 6, we break down the differences between the  $D_0$ ,  $N_w$ , and R estimates for these side-by-side LDISs (LDIS-E13–LDIS-C1) according to surface wind directions measured by the ARM surface meteorology systems (MET). Because the long axis of LDIS-E13 is north-south, whereas this axis is east-west for LDIS-C1, it is less surprising that easterly/westerly winds promotes higher  $N_w$  for the LDIS-E13 oriented perpendicular compared to LDIS-C1. With regard to median drop size ( $D_0$ ), the LDIS-E13 estimates tend to promote more small drops than those from LDIS-C1 when experiencing easterly/westerly flows, and larger sizing when winds are from the other directions. As an independent reference, note that the distributions of DSD properties from VDIS are far less influenced by the wind direction (not shown).



**Figure 6.** Box-and-whisker plots of the differences of  $D_0$ ,  $N_w$ , and *R* between LDIS-E13 and LDIS-C1 as a function of wind direction. The middle lines show the median values. The colored boxes represent observations inside the 25th to 75th percentile range. The whiskers show the 10th and 90th percentile values.

In Figure 7, we show the biases, RMSE, and correlations between different disdrometer pairs contingent on different *R* intervals. Overall, the absolute bias and RMSE increase with increasing rain rate for most of the pairs in terms of  $D_0$  and *R*. One exception is the VDIS pairs, which show a better performance overall. The correlation coefficient drops dramatically for the higher rainfall rate range (> 30 mm hr<sup>-1</sup>) due to the limited samples in this *R* bin. Interestingly, the JWD-E13 and VDIS-E13 pair shows a comparable performance to the VDIS pairs, which may be attributed to previous discussions on the JWD performing reasonably well for capturing DSD properties, especially for sampling small drops.



**Figure 7.** The bias, absolute bias (|Bias|), RMSE, Frac |Bias|, r shown as a function of rainfall rate (*R*) when comparing  $D_0$ , *R*, and *Z* between paired disdrometers.

### 4.2 Reducing Sampling Errors Using Collocated Measurements

All DSD measurements from disdrometers are subject to statistical sampling errors due to the Poisson distributed fluctuations of the number of samples in each drop size interval. This would extend to the integrated properties such as rainfall rate and radar reflectivity that are estimated based on these DSD parameters. In this study, we use the FSD as introduced previously to quantify the instrument sampling errors following Cao et al. (2008). In Figure 8, we present the FSDs of the rain drop count (*N*) estimated using Equation 2 for each unit (Figure 8a), as well as the paired units (Figure 8b) as a function of drop diameter. The FSDs of *N* increase considerably with drop diameter when D > 1 mm, with a minimum FSD of ~ 2 % for D = 1 mm. This behavior suggests an increased sampling error in these size bins, as due to the under-sampling of the relatively larger raindrops.

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For drops smaller than 1 mm, the sampling error increases with decreasing drop size for all the units. This is because all disdrometers are unable to accurately measure smaller raindrops due to various instrument limitations. Perhaps less surprisingly, the FSDs of *N* agree well for the medium-sized drops between different single units. Once again, these instruments show their largest discrepancies for smaller (D < 1.3 mm) and larger (D > 3 mm) size bins. When considering side-by-side paired disdrometer measurements (Figure 8b), we potentially eliminate the errors associated with physical process variations in the rain drop behaviors, thus significantly reducing the sampling errors (by 2.5 % for D = 1 mm). Co-located disdrometers (all types, pairings) deployed in the field would serve to sizably reduce the statistical sampling errors in DSD measurements.



**Figure 8**. FSD of the observed drop counts over the bin spectrum. The solid line represents the calculation based on a single instrument; the dotted line represents the result from side-by-side paired instruments.

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