

## Assessment of OTT Parsivel<sup>2</sup> Raindrop Fall Speed Measurements

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**ABSTRACT:** This study was to assess the raindrop fall speed measurement capabilities of OTT Parsivel<sup>2</sup> disdrometer through comparisons with measurements of a collocated High-speed Optical Disdrometer (HOD). Raindrop fall speed is often assumed to be terminal in relevant hydrological and meteorological applications, and generally predicted using terminal speed–raindrop size relationships obtained from laboratory observations. Nevertheless, recent field studies have revealed that other factors (e.g., wind, turbulence, raindrop oscillations, and collisions) significantly influence raindrop fall speed, necessitating accurate fall speed measurements for many applications instead of reliance on laboratory-based terminal speed predictions. Field observations in this study covered rainfall events with a variety of environmental conditions, including light, moderate, and heavy rainfall events. This study also involved rigorous laboratory experiments to faithfully identify the internal filtering and calculation algorithm of OTT Parsivel<sup>2</sup>. Our assessments revealed that, for the smaller diameter bins, Parsivel<sup>2</sup> filters out many of the observed raindrops that fall faster than predicted terminal speeds, bringing down the mean fall speed for those size bins without observational evidence. Furthermore, Parsivel<sup>2</sup> fall speed measurements exhibited notable artificial bell-shaped deviations from the predicted terminal speeds toward subterminal fall starting at around 1 mm diameter raindrops with peak deviations around 1.625 mm diameter bin. Such bell-shaped fall speed deviation patterns were not present in collocated HOD measurements. Assessment results along with the faithfully identified Parsivel<sup>2</sup> algorithm are presented with discussions on implications on reported raindrop size distributions (DSD) and rainfall kinetic energy.

**KEYWORDS:** Rainfall; In situ atmospheric observations; Instrumentation/sensors

### 1. Introduction

Accurate and precise raindrop fall speed measurements have significant importance for many applications including those related to radar meteorology, agriculture, atmospheric physics, and hydrology. For example, Dual-Frequency Precipitation Radar (DPR) uses raindrop fall speed measurements to characterize the type of rain for assisting flood forecasting and warning system (Awaka et al. 2016). Raindrop fall speed is an important microphysical quantity also for calculating other rainfall quantities such as raindrop size distribution (DSD) and kinetic energy. In various rainfall applications, it is commonly assumed that raindrops fall at predicted terminal speeds based on laboratory-observed terminal speed–size relationships (e.g., Cotton and Anthes 1992; Testik and Barros 2007; Pruppacher and Klett 2012). However, observations have shown that, in addition to raindrop size, there are other factors such as wind, turbulence, raindrop collisions, and oscillations (Montero-Martínez et al. 2009; Montero-Martínez and García-García 2016; Pinsky and Khain 1996; Testik et al. 2006) that significantly affect raindrop fall speeds. Therefore, precise and accurate raindrop fall speed measurements are essential.

Disdrometers are instruments that are used to measure raindrop size, fall speed, DSD, and often rain rate. There is a wide range of applications for disdrometer measurements.

For example, disdrometer measurements have been used for quality control in quantitative precipitation estimations using dual-polarization radars (e.g., Aoki et al. 2016). There are different types of disdrometers with different working principles for raindrop measurements. Both Parsivel<sup>2</sup> and High-speed Optical Disdrometer (HOD) are optical-type disdrometers with differing optical sensor technologies to measure the raindrop characteristics. HOD is an image-based optical disdrometer that uses a high-speed camera and light-emitting diode (LED) light to capture the silhouettes of raindrops to measure raindrop characteristics using image processing techniques. On the other hand, Parsivel<sup>2</sup> is a laser-based optical disdrometer that measures raindrop size and speed using voltage changes as the raindrops traverse through the laser sheet. Differing working principles and sensor technologies lead to differing measurement limitations and accuracy issues for certain raindrop size and fall speed ranges. Furthermore, these disdrometers may face different calibration issues (e.g., Lanza et al. 2021; Baire et al. 2022). In this study, we assessed raindrop fall speed measurements by Parsivel<sup>2</sup> disdrometer, which is manufactured by OTT Hydromet Inc. as their second generation of particle size velocity disdrometer (Parsivel<sup>2</sup>). This instrument was selected for this study because of its widespread use among researchers due to its simple operation, robust, and low-cost features, and also because of availability of a large volume of data from this instrument. A simple online search of publications with optical disdrometers between 2000 and 2022 revealed that Parsivel was mentioned in more than half of the first 200 research documents. Despite its

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popularity, there is a limited number of investigations on its measurement capabilities, especially in terms of accuracy of fall speed measurements (Angulo-Martínez and Barros 2015; Lin et al. 2021; Park et al. 2017; Tokay et al. 2014).

OTT Parsivel disdrometers have first (Parsivel<sup>1</sup>) and second (Parsivel<sup>2</sup> used in this study) generations. Parsivel was first developed by PM Tech AG, Pfingsttal, Germany, which was later transferred to OTT Hydromet, Kempten, Germany, in 2004. OTT Hydromet modified the instrument as Parsivel<sup>1</sup> in 2005. The OTT and PM Tech models were distinct in key ways. The PM Tech and OTT Parsivel<sup>1</sup> output voltages were sampled at 10 and 50 kHz, respectively (Battaglia et al. 2010). In comparison to the PM Tech Parsivel, the OTT Parsivel<sup>1</sup> used a laser sensor that has reduced homogeneity across the laser beam (Tokay et al. 2013). The World Meteorological Organization conducted a 1.5-yr field experimental campaign in central Italy with 30 rain gauges and optical disdrometers including Parsivel<sup>1</sup> (Lanza and Vuerich 2009). In comparison to selected reference gauges in this campaign, Parsivel<sup>1</sup> received a 3 out of 5 rating for 1-min rain-rate measurements. Lanza and Vuerich (2009) reported that Parsivel<sup>1</sup> overestimated rain intensity, and the overestimation worsened with increasing rain rate. In 2011, OTT launched Parsivel<sup>2</sup>, a new model of the Parsivel<sup>1</sup>. Parsivel<sup>2</sup> is a new design, in which the electronics are housed in the sleeve rather than the two heads of the sensor as was the case for Parsivel<sup>1</sup>. According to the manufacturer, the main improvement is the use of a more advanced laser sensor and better homogeneity in the laser sheet for raindrop measurements. Manufacturer reported measurement accuracies for raindrops up to 2 mm in diameter are  $\pm 1$  size class for Parsivel<sup>2</sup> and  $\pm 3$  size classes for Parsivel<sup>1</sup>, and for raindrops that are larger than 2 mm in diameter, the reported measurement accuracies are  $\pm 0.5$  size class for Parsivel<sup>2</sup> and  $\pm 2$  size classes for Parsivel<sup>1</sup>.

Previous studies have demonstrated that both Parsivel<sup>1</sup> and Parsivel<sup>2</sup> are susceptible to errors in raindrop concentration measurements, particularly for small ( $D < 1$  mm) and large ( $D > 4$  mm) raindrop size bins (Thurai et al. 2011; Tokay et al. 2013; Raupach and Berne 2015; Park et al. 2017). Thurai et al. (2011) reported Parsivel<sup>1</sup>'s overestimation of the number of large raindrops in terms of mass weighted mean diameter ( $D_m$ ) by 20%–30% for higher rain rates ( $>20$  mm h<sup>-1</sup>) by comparing collocated measurements from a two-dimensional video disdrometer (2DVD) and a Parsivel<sup>1</sup>. Moreover, by comparing Parsivel<sup>1</sup> measurements with collocated Joss–Waldvogel (JWD) and 2DVD disdrometer measurements, Tokay et al. (2013) concluded that Parsivel<sup>1</sup> underestimated the number of small raindrops ( $D < 0.76$  mm) and measured relatively higher raindrop concentration when diameter is larger than 2.44 mm for rain rates and raindrop counts more than 2.5 mm h<sup>-1</sup> and 400 drops min<sup>-1</sup>, respectively. More recently, Raupach and Berne (2015) and Park et al. (2017) evaluated the second-generation Parsivel<sup>2</sup> measurements using a collocated 2DVD disdrometer and found that, during high intensity rain ( $>20$  mm h<sup>-1</sup>), Parsivel<sup>2</sup> still has significant biases that cause it to overestimate the quantity of large raindrops while underestimating the number of small raindrops.

In addition to the aforementioned sampling uncertainty, there are other previously reported Parsivel measurement issues related to, for example, the laser beam, raindrop splash, wind, coexistence of multiple raindrops in the laser beam, and raindrop fall through the edge of the laser sheet known as margin fallers (Habib et al. 2001; Kruger and Krajewski 2002; Loh et al. 2019; Nešpor et al. 2000; Raupach and Berne 2015; Tokay et al. 2001; Yu et al. 2016). When compared to the predicted terminal speeds, Upton and Brawn (2008) reported underestimations in Parsivel<sup>1</sup> fall speed measurements, especially for midsize raindrops ( $D = 1$ –3 mm). While the study by Upton and Brawn was for the earlier version of Parsivel (Parsivel<sup>1</sup>), Tokay et al. (2014) and Angulo-Martínez et al. (2018) showed that this measured fall speed behavior is systematic for raindrops 1.09 mm and larger also for the current Parsivel version (Parsivel<sup>2</sup>). Tokay et al. (2014) reported that the difference between the mean Parsivel<sup>2</sup> measured and predicted terminal fall speeds for 1.09 mm raindrops was approximately 1 m s<sup>-1</sup> and the difference decreased with increasing raindrop size. Consequently, they suggested the use of terminal speed predictions in calculating DSD and rainfall parameters to alleviate the error. Another potential source for measurement issues is related to the assignment of Parsivel observations within preset size intervals (i.e., diameter/size bins) to the mean sizes of the corresponding intervals, compromising the measurement accuracies near the interval boundaries. Parsivel<sup>1</sup> was reported to be prone to this issue, known as the quantization error, particularly for size bins  $\geq 2$  mm (Yuter et al. 2006). It is important to emphasize that fall speed measurement inaccuracy has important effects. For example, systematic underestimation of fall speed may lead to increased equivalent volume drop concentration and radar reflectivity and decreased kinetic energy (Jaffrain and Berne 2011).

Friedrich et al. (2013) noted that particles falling oblique to the Parsivel measurement area (laser sheet) can be a cause for misclassification of fall speed. Their laboratory experiments showed increased concentration of larger drops ( $>3$  mm) and decreased fall speeds when drops fall oblique to the measurement area. Friedrich et al. (2013) confirmed these laboratory findings in high wind speed and/or heavy rainfall events during Hurricane Ike in 2008 and convective storms, showing the influence of strong winds on particle size distributions measured by Parsivel<sup>1</sup> disdrometers. Raindrop shape deformation and oscillations may be another source of fall speed measurement uncertainty, especially for the case of large raindrops (Yu et al. 2016; Testik and Rahman 2016; Pei et al. 2014; Testik et al. 2006). Assumed oblate shapes of hydrometeors, hence inaccurate equivolume diameters, may also be a source of measurement uncertainty for Parsivel disdrometers (Battaglia et al. 2010).

Parsivel and other disdrometers use methodologies to filter out and correct erroneous measurements based on predicted terminal speeds (Jaffrain and Berne 2011; Tokay et al. 2013; Raupach and Berne 2015; Testik and Pei 2017). For example, Tokay et al. (2013) and Jaffrain and Berne (2011) removed raindrops exceeding  $\pm 50\%$  and  $\pm 60\%$  of the terminal speed predictions, respectively. There are a number of available relationships for terminal speed predictions in the literature.

Nevertheless, these predictions are mostly from laboratory observations of water drops in stagnant air (Beard 1977; Blanchard 1950; Epema and Riezebos 1983; Jayawardena and Rezaur 2000; Laws 1941; Gunn and Kinzer 1949, hereafter referred as GK49) and may not accurately represent the actual raindrop fall speeds during rainfall events under certain conditions (e.g., Hosking and Stow 1991; Montero-Martínez et al. 2009; Montero-Martínez and García-García 2016; Testik et al. 2006; Thurai et al. 2013). Therefore, filtering, while essential due to instrumental limitations, has the potential to result in underestimation of the number of raindrops and masking of the signatures of different microphysical processes. Therefore, identification and improvement of instrumental limitations has significant importance.

In this paper, we assess raindrop fall speed measurement capabilities of OTT Parsivel<sup>2</sup> by comparing values with HOD measurements. Brief descriptions of Parsivel<sup>2</sup> and HOD disdrometers are provided in section 2, followed by an overview of our experimental sites, observed rainfall events, methodologies, and identification of Parsivel<sup>2</sup> algorithm for raindrop fall speed measurements. Results, including statistical comparisons among Parsivel<sup>2</sup> and HOD measurements and predicted terminal speeds by an empirical fit equation based on GK49 laboratory data, as well as discussions on the effects of Parsivel<sup>2</sup> raindrop fall speed measurements on DSD observations and rainfall kinetic energy estimations are presented in section 3. Finally, conclusions of this study are provided in section 4.

## 2. Experimentation: Disdrometers, field site, and methodology

### a. OTT Parsivel<sup>2</sup> and HOD disdrometers

Only a brief description of OTT Parsivel<sup>2</sup> is provided here and detailed descriptions of Parsivel<sup>2</sup> can be found in the literature (e.g., Angulo-Martínez et al. 2018; Park et al. 2017; Tokay et al. 2014). Parsivel<sup>2</sup> uses a 780 nm laser beam that forms a nominal measurement cross-sectional area of 54 cm<sup>2</sup> ( $L = 180$  mm long,  $W = 30$  mm wide, and  $T = 1$  mm thick) to detect particles (OTT 2017). However, since particles partially passing through this nominal measurement area at the edges are not counted, the effective measurement area changes for each raindrop diameter bin as  $L \times (W - D/2)$ , where  $D$  represents raindrop diameter bins. When particles pass through the measurement area formed by the laser beam, a portion of the transmitted laser is blocked, resulting in a change in voltage in comparison to when the laser beam is free of particles. The amplitude of the voltage drop is used to determine the size of the particle whereas the duration of the voltage drop is used to determine the fall speed of the particle. In calculating fall speeds, Parsivel<sup>2</sup> also uses assumed particle axis ratios. According to Battaglia et al. (2010), Parsivel<sup>2</sup> assumes particles as spherical up to 1 mm, and as horizontally oriented oblate spheroids with axis ratios linearly varying from 1 to 0.7 between 1 and 5 mm and with a fixed axis ratio value of 0.7 for particles larger than 5 mm. These assumed axis ratio values

impose a notable potential to affect the accuracy of Parsivel<sup>2</sup> measurements during events with strong winds. Note that, given the outlined working principle, size of the measurement area greatly influences the probability of bias-inducing effects such as edge events (margin fallers) and overlapping hydrometeors (Angulo-Martínez et al. 2018). A larger measurement area, for instance, implies a higher chance of overlapping hydrometeors (i.e., multiple hydrometeors coexisting in the laser sheet at the same time and recorded as a single hydrometeor). This may cause missed hydrometeor observations, translating to a reduced hydrometeor count, precipitation amount and rate, and also recordings of larger than actual hydrometeor sizes with fall speeds that are unusually low. Parsivel<sup>2</sup> measures both solid and liquid precipitation. However, for the purposes of our study, here we consider Parsivel<sup>2</sup> for rainfall measurements.

According to the manufacturer's statement, Parsivel<sup>2</sup> measures raindrop characteristics for raindrops with diameters larger than 0.25 mm and during rainfall events with rain rates greater than 0.001 mm h<sup>-1</sup>. Parsivel<sup>2</sup> validates the detected raindrops using its unknown internal algorithm and filters out those particles that are not validated as raindrops. Validated raindrops are assigned to a predefined 32 × 32 matrix, where rows and columns of the matrix indicate raindrop diameter and fall speed classes/bins, respectively. The diameter and fall speed bins have unequal intervals ranging from 0 to 26 mm and 0 to 22.4 m s<sup>-1</sup>, respectively. Bin widths increase from 0.125 to 3 mm for diameter bins and 0.1 to 3.2 m s<sup>-1</sup> for fall speed bins as raindrop diameter and fall speed bins increase. Parsivel<sup>2</sup> software does not provide individually measured raindrop diameter and fall speed values, but rather provides the number of raindrops in each of the predefined Parsivel<sup>2</sup> diameter and fall speed bins along with the average volume equivalent diameter and average particle speed of each bin. For this study, Parsivel<sup>2</sup> was connected to a CR1000 datalogger for automated data storage purposes. A computer program was developed using PC200W software to communicate between CR1000 and Parsivel<sup>2</sup>. This program provided us the opportunity to extract all of the detected raindrop diameter and fall speed values captured by Parsivel<sup>2</sup> before they are processed by the Parsivel<sup>2</sup> internal algorithm for raindrop validation. This capability enabled us to conduct the analyses presented in this study.

Detailed information on the HOD can be found in Testik and Rahman (2016) and only a brief overview of this instrument is provided here. HOD is a recently developed research instrument with one of the design purposes being accurate hydrometeor fall speed observations. It is an optical-type disdrometer that consists of a high-speed camera, an LED light, and a sensor to trigger the camera once a hydrometeor (i.e., raindrop for this study) is detected in the measurement volume that is defined by the camera view frame and sensor detection area (see Testik and Rahman 2016). HOD captures successive high-speed (1000 frames per second for this study) images of each raindrop that passes through the measurement volume, providing both visual and quantitative information on raindrop dynamics. Using image processing techniques and the sequential raindrop images, HOD software determine



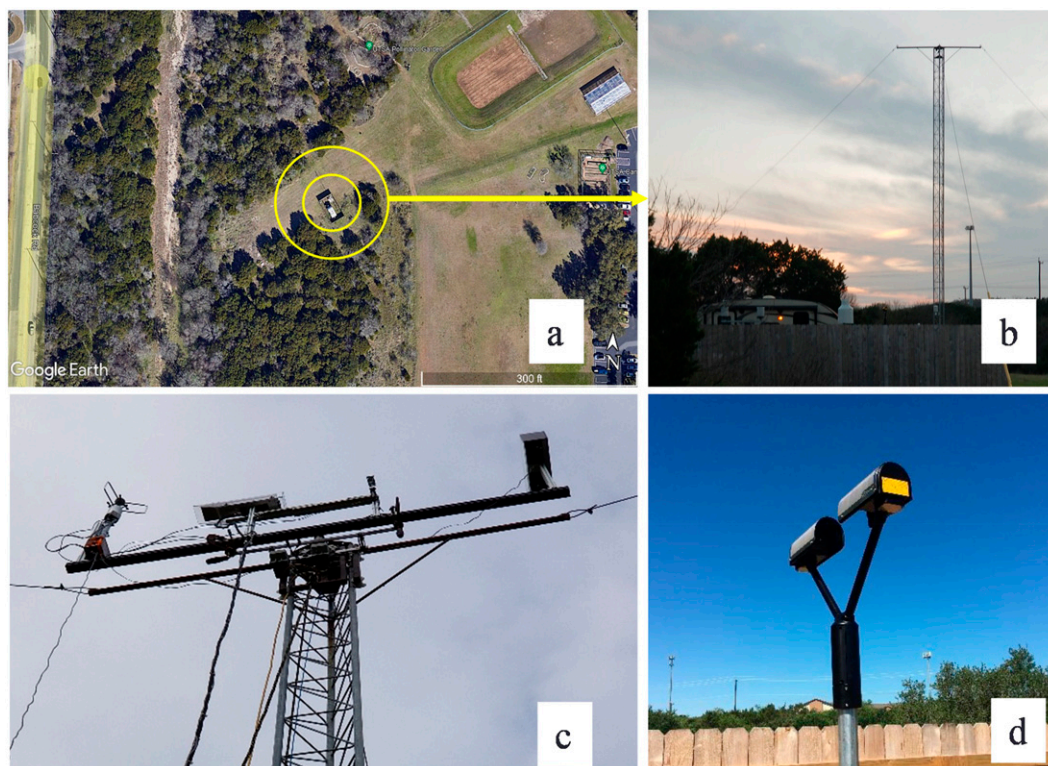


FIG. 1. (a) Satellite image of the field site (circled) and its surroundings. (b) Ground view of the field site and the meteorological tower. (c) Photograph of the HOD and 3D ultrasonic anemometer mounted at the top of the 10-m-tall tower. (d) Photograph of Parsivel<sup>2</sup> disdrometer mounted at 2 m above ground level.

the raindrop diameter and fall speed, which is calculated by utilizing the displacement of the centroid location of the same raindrop in two consecutive images, along with other microphysical quantities. These quantities for the same raindrop are measured multiple times depending on the number of sequential images, and are averaged for improved accuracy. For this study, HOD was set to record 10 images of each of the raindrops passing through the measurement volume. The measurement error of HOD for raindrops that are larger than 0.5 mm is less than approximately 10% of the raindrop diameter and reduces to approximately 2.9% as the raindrop diameter increases to 5 mm. Considering the measurement accuracy, HOD was set to detect only raindrops that are larger than 0.5 mm. Note that actual raindrop images captured by the HOD has an additional benefit of data quality controls, if needed, for raindrop size, speed, and shape. In this study, we used Parsivel<sup>2</sup> binning for HOD measurements of raindrop fall speed and size for adequate comparisons of the measurements from the two instruments.

#### b. Field site

Rainfall observations were conducted at our outdoor rainfall research laboratory (see Fig. 1) that is located in the west campus of The University of Texas at San Antonio, Texas, United States (coordinates and elevation: 29°34'43.19"N, 98°37'50.68"W, and 297 m above mean sea level, respectively). As can be seen in Fig. 1, the field site is situated within a flat

open suburban terrain that is free of tall trees and obstructions. The field site houses a 10-m-high meteorological tower that host the HOD and an R. M. Young 8500 3D ultrasonic anemometer. The site is also equipped with one OTT Parsivel<sup>2</sup> disdrometer, one OTT Pluvio<sup>2</sup> rain gauge, and two TB4 tipping-bucket rain gauges, all of them installed at 2 m above ground level.

#### c. Data collection and analysis methodology

Field experiments consisted of 6 different rainfall events for a total duration of 1456 min (Table 1). In this study, a rainfall event is defined as a period of continuous rain with an accumulation of at least 1 mm rain amount (Tokay et al. 2013). The successive rainfall events are separated from each other by a dry period of at least 1 h. These rainfall events cover a wide variety of light to heavy rainfall (0.01–102.96 mm h<sup>-1</sup>) during calm to high wind conditions (0.08–7.59 m s<sup>-1</sup>) and results from these events were consistent as discussed later in the article. Therefore, selected rainfall events were sufficient for conclusive findings. Ranges of rain intensity and wind speed values reported here and in Table 1 were determined using 1-min rain intensity and wind speed values. All of the aforementioned meteorological instruments were active during these events and collected a wealth of data.

We classify Parsivel<sup>2</sup> data in three levels as follows. Level 1 data consist of diameter and fall speed information for the

TABLE 1. Summary of the rainfall event characteristics observed for this study.  $\Delta T$  = Rain duration. RI = Rain intensity measured by Parsivel<sup>2</sup>.  $W$  = Wind speed measured by the 3D ultrasonic anemometer.  $T$  and RH represent temperature and relative humidity, respectively. Parsivel<sup>2</sup>-detected and -validated raindrop numbers are represented here by DR and VR, respectively.

Event No.	Date	$\Delta T$ (min)	RI <sub>avg</sub> (mm h <sup>-1</sup> )	$W_{avg}$ (m s <sup>-1</sup> )	RI range <sup>a</sup> (mm h <sup>-1</sup> )	$W$ range <sup>a</sup> (m s <sup>-1</sup> )	$T$ (°C)	RH (%)	DR	VR <sup>b</sup> (%)
1	16 Oct 2019	289	2.44	2.22	0.03–7.41	0.87–3.49	21	94	614 36	98
2	24 Oct 2019	319	11.88	5.55	0.02–102.96	1.66–7.59	13	88	178 517	90
3	20 Dec 2019	206	1.46	1.53	0.01–9.82	0.88–2.49	10	97	267 508	98
4	21 Mar 2020	290	1.83	1.87	0.01–8.17	0.08–3.13	11	95	332 253	99
5	15 May 2020	180	6.85	3.37	0.41–42.84	1.97–5.63	18	89	107 505	96
6	13 Oct 2021	172	12.73	2.53	0.05–74.96	0.69–5.48	22	97	107 496	97

<sup>a</sup> RI and  $W$  ranges were calculated based on 1-min time resolution measurements during corresponding  $\Delta T$ .

<sup>b</sup> Percentages of validated raindrop numbers from detected raindrops.

raindrops detected by Parsivel<sup>2</sup> (i.e., raw data) as stored in the raindrop log file. Level 1 data have not been typically available to Parsivel<sup>2</sup> users as access to these data is not available through the instrument software provided by the manufacturer, but they were extracted in this study using a computer program written in PC200W software. The storage of level 1 data requires a large space because the program extracted signals from Parsivel<sup>2</sup> and stored up to a predefined number of cells in each minute whether Parsivel<sup>2</sup> detects any particles or not (e.g., rain or dry). Considering the heavy rain scenario and the limitation of the datalogger scan rate, we set the program to extract diameter and fall speed information for up to 2500 detected particles each minute. This setup generated large datasets from level 1 during long periods of rain. To resolve this storage issue, we installed a Compact Flash Memory Module (CFM100) with CR1000 datalogger. Level 2 data consist of raindrop counts for the validated raindrops in each bin of the  $32 \times 32$  Parsivel<sup>2</sup> diameter–fall speed matrix. Level 2 data are derived by Parsivel<sup>2</sup> software using an internal unknown algorithm from level 1 data by filtering out some of the level 1 data and validating the rest of the raindrop data as level 2 data. Parsivel<sup>2</sup> users have access to level 2 data through the instrument’s software. Level 3 data consist of average raindrop fall speeds for each diameter bin, DSD, integral rainfall parameters (rain rate and amount) that are calculated by Parsivel<sup>2</sup> software using level 2 data. Level 3 data are provided to the Parsivel<sup>2</sup> users as a readymade dataset. In addition, we introduced a new data level, which was not part of Parsivel<sup>2</sup> data collection and processing steps, and called this data level as “pseudo level 2” (described later in the text).

Using level 1 data from laboratory experiments, we were able to faithfully identify the Parsivel<sup>2</sup> internal algorithm to transform the data from level 1 to level 2. We refer to this portion of the internal algorithm as the “Parsivel<sup>2</sup> filtering matrix” (which is provided in Fig. 3 later). To identify the Parsivel<sup>2</sup> filtering matrix, we conducted laboratory experiments with a large number of water drops ( $\approx 1\,000\,000$ ) generated using a pressurized hose (Fig. 2), covering a wide range of drop sizes (0.1–20 mm) and fall speeds (0.1–20 m s<sup>-1</sup>). It is important to note here that we did not generate drops with controlled sizes and fall speeds. Our goal for the laboratory experiments was not to test the accuracy/uncertainty of Parsivel<sup>2</sup>

measurements for drop diameter and fall speed; hence, accuracy of the generated drop sizes and/or terminal and nonterminal fall were not of importance for this study. Instead, since our primary goal for the laboratory experiments was mainly to identify the detected (level 1) and validated (level 2) drops by Parsivel<sup>2</sup>, we generated as many drops as possible that span a wide range of characteristics (i.e., size and speed) to reveal the Parsivel<sup>2</sup> drop validation criteria for the detected drops. Parsivel<sup>2</sup> readings from these experiments included both level 1 and level 2 data in each minute. Parsivel<sup>2</sup> level 1 data clearly showed that drops with different size and fall speed combinations were generated in our laboratory experiments, including those with small size and fast fall speeds that are eliminated by Parsivel<sup>2</sup> filtering matrix as discussed later in the article. Using level 1 data with detected drops, we constructed the  $32 \times 32$  drop diameter and fall speed bin matrix for each minute of observations. Detailed comparisons of the  $32 \times 32$  matrices for level 1 data for detected drops and for level 2 data for validated drops provided by Parsivel<sup>2</sup> software revealed Parsivel<sup>2</sup> filtering matrix for validation of raindrops when transforming data from level 1 to level 2. Figure 3 shows how the Parsivel<sup>2</sup> filtering matrix maps out diameter and fall speed bin combinations for validating the observed particles as raindrops. The results

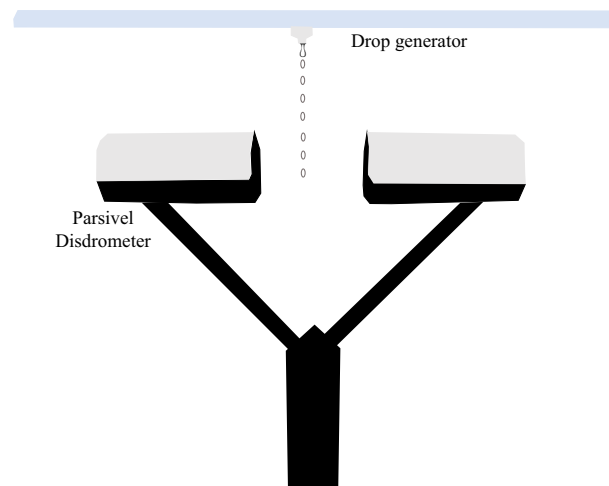


FIG. 2. Illustrative schematic of the laboratory experimental setup that was used to identify the Parsivel<sup>2</sup> filtering matrix.

		Velocity Bin																																Bin no.	Size bin (mm)	Velocity bin (ms <sup>-1</sup> )
		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20	V21	V22	V23	V24	V25	V26	V27	V28	V29	V30	V31	V32			
Diameter Bin	D1																																	1	0.000–0.125	0.0–0.1
	D2																																	2	0.125–0.250	0.1–0.2
	D3																																	3	0.250–0.375	0.2–0.3
	D4																																	4	0.375–0.500	0.3–0.4
	D5																																	5	0.500–0.625	0.4–0.5
	D6																																	6	0.625–0.750	0.5–0.6
	D7																																	7	0.750–0.875	0.6–0.7
	D8																																	8	0.875–1.000	0.7–0.8
	D9																																	9	1.000–1.125	0.8–0.9
	D10																																	10	1.125–1.250	0.9–1.0
	D11																																	11	1.250–1.500	1.0–1.2
	D12																																	12	1.500–1.750	1.2–1.4
	D13																																	13	1.750–2.000	1.4–1.6
	D14																																	14	2.000–2.250	1.6–1.8
	D15																																	15	2.250–2.500	1.8–2.0
	D16																																	16	2.500–3.000	2.0–2.4
	D17																																	17	3.000–3.500	2.4–2.8
	D18																																	18	3.500–4.000	2.8–3.2
	D19																																	19	4.000–4.500	3.2–3.6
	D20																																	20	4.500–5.000	3.6–4.0
	D21																																	21	5.000–6.000	4.0–4.8
	D22																																	22	6.000–7.000	4.8–5.6
	D23																																	23	7.000–8.000	5.6–6.4
	D24																																	24	8.000–9.000	6.4–7.2
	D25																																	25	9.000–10.000	7.2–8.0
	D26																																	26	10.000–12.000	8.0–9.6
	D27																																	27	12.000–14.000	9.6–11.2
	D28																																	28	14.000–16.000	11.2–12.8
	D29																																	29	16.000–18.000	12.8–14.4
	D30																																	30	18.000–20.000	14.4–16.0
	D31																																	31	20.000–23.000	16.0–19.2
	D32																																	32	23.000–26.000	19.2–22.4
		Validated bins for raindrop											Invalid bins for raindrop											Bins not evaluated												

FIG. 3. Visualization of the Parsivel<sup>2</sup> filtering matrix to validate the detected particles as raindrops as part of the Parsivel<sup>2</sup> internal algorithm. Raindrops in light-gray-colored cells/bins are validated and those in dark-gray-colored bins are filtered out. Black-colored bins were not evaluated in this study. Parsivel<sup>2</sup> raindrop size and fall speed bins are also presented on the right side of the matrix.

from these laboratory experiments were also verified through rainfall observations at our field site.

Documentation of the Parsivel<sup>2</sup> filtering matrix enabled us to faithfully identify Parsivel<sup>2</sup>'s fall speed calculation algorithm. To identify Parsivel<sup>2</sup>'s fall speed calculation algorithm, we analyzed Parsivel<sup>2</sup> given average fall speed for each diameter bin (level 3) and fall speed of each validated raindrops that were distinguished from detected raindrops by the Parsivel<sup>2</sup> filtering matrix. Considering the number of validated raindrops and midvalue of respective fall speed bin, we calculated weighted-average fall speeds for each diameter bin (represented by open circles in Fig. 4) and compared with Parsivel<sup>2</sup> given average fall speeds of each diameter bin (level 3, represented by open squares in Fig. 4) in Fig. 4. As can be seen in this figure, open circles representing fall speeds that we calculated using the abovementioned procedure and open squares representing fall speeds reported by Parsivel<sup>2</sup> level 3 data overlapped precisely for each of the diameter bins. This comparison in Fig. 4 revealed that Parsivel<sup>2</sup> utilizes midvalue of respective fall speed bin, rather than individual raindrop fall speeds, for calculating average fall speed of each diameter bin in level 3. In this study,

in addition to the Parsivel<sup>2</sup> provided data levels, we included an additional data level, which we called “pseudo level 2.” Pseudo level 2 data (represented by open triangles in Fig. 4) include the average fall speeds for each of the predefined diameter bins that are calculated by averaging the fall speed measurements from level 1 data for all of the raindrops in the corresponding diameter bins and validated through the Parsivel<sup>2</sup> filtering matrix. Level 2 and pseudo level 2 data differ such that while level 2 data provide only the number of raindrops in each of the predefined diameter and velocity bins and they are available through Parsivel<sup>2</sup> software, pseudo level 2 data provide the average fall speeds of the validated raindrops in each of the diameter bins using the individual raindrop fall speed measurements from level 1 data and are not available through Parsivel<sup>2</sup> software. Figure 4 also exhibits that pseudo level 2 fall speed values differ from level 3 fall speed values, and the differences become more pronounced for the larger raindrop fall speeds. The observed difference in fall speeds by pseudo level 2 and level 3 data was due to the nonuniform widths of predefined Parsivel<sup>2</sup> fall speed bins, which increase with increasing fall speed values (see Fig. 3). Using midvalues of predefined fall speed bins instead of average fall speeds of

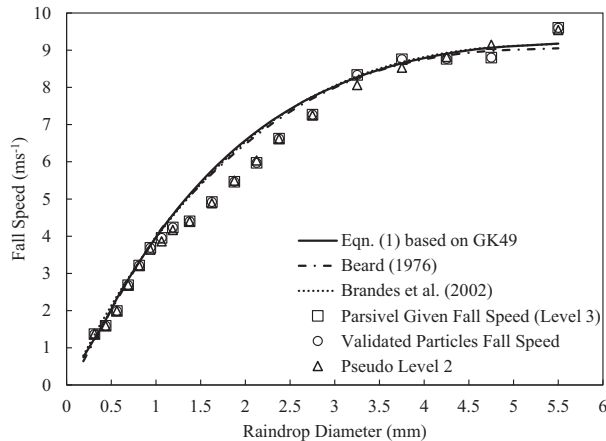


FIG. 4. Comparison of Parsivel<sup>2</sup> given average fall speed (level 3, open squares), pseudo level 2 (open triangles), and fall speeds that we calculated for the validated particles (open circles) to identify Parsivel<sup>2</sup> fall speed calculation algorithm. Raindrop terminal speed predictions by Eq. (1) based on GK49, Beard (1976), and Brandes et al. (2002) are represented by solid, dash-dotted, and dotted lines, respectively (see the legend).

raindrops within the given bin enhances the quantization error. This error would be particularly pronounced for the larger bin widths and bins with smaller number of raindrops as observed in Fig. 4. In this figure, we present terminal speed predictions using an empirical fit equation to GK49 laboratory data [see Eq. (1)] along with two other well-accepted terminal speed parameterizations, specifically by Beard (1976) and Brandes et al. (2002). This was to provide a visual comparison among terminal speed predictions by different parameterizations. The predictions by the empirical equation in Eq. (1) are within  $\pm 1\%$  of the terminal speed measurements by GK49 for water drops within the diameter range of 0.5–6.0 mm:

$$V_t = 0.0623D^3 - 0.9481D^2 + 5.0403D - 0.2054. \quad (1)$$

Here,  $V_t$  is the terminal speed prediction (in  $\text{m s}^{-1}$ ) and  $D$  is drop diameter (in mm). Furthermore, we conducted paired  $t$  test among predicted terminal speed predictions by the above-mentioned parameterizations with 0.05 significance level, which indicated that the mean differences among the predicted terminal speeds were not statistically significant ( $p$  value  $> 0.05$ ). As such, for the rest of this article, we only considered predicted raindrop terminal speeds by Eq. (1) for comparisons with observed raindrop fall speeds, except in Table 2, where terminal speeds prediction by both Eq. (1) and Beard (1976) were considered for statistical comparisons with Parsivel<sup>2</sup> and HOD measurements.

To demonstrate the impact of Parsivel<sup>2</sup> filtering matrix that is implemented by Parsivel<sup>2</sup> by default, we compared the average raindrop fall speeds of Parsivel<sup>2</sup> detected (level 1) and validated (pseudo level 2) raindrops for each diameter bin (Fig. 5). Here, we used pseudo level 2 data because level 2 data did not provide the actual fall speed measurements, but

instead provided only the numbers of validated raindrops in each diameter and velocity bins as described earlier. Due to low signal-to-noise ratio, Parsivel<sup>2</sup> internal algorithm removes data from the two smallest diameter bins ( $D < 0.25$  mm), and then Parsivel<sup>2</sup> filtering matrix is applied to the detected raindrops to validate them. Figure 5 reveals that Parsivel<sup>2</sup> filtering matrix artificially filters out the detected raindrops at the smaller end of the diameter bins ( $D < 1$  mm) and reduces the average fall speed values without any observational evidence. In this figure, it can also be seen that application of the Parsivel<sup>2</sup> filtering matrix does not cause fall speed alterations for the detected and validated raindrops for  $D > 1$  mm. Parsivel<sup>2</sup> filtering matrix was further investigated by implementing it to the HOD fall speed measurements for event 5, and the results are presented in Fig. 6. In this figure, deviations of fall speed observations from terminal speed predictions are presented both in percentages (primary vertical axis) and absolute values (secondary vertical axis). The reasoning behind presenting deviations in terms of both relative (%) and absolute deviations in the same graph was to demonstrate that the importance of the issue was not artificially increased by our choice of relative deviations in terms of percentages for the relevant figures in the rest of this article. This figure demonstrates that implementation of Parsivel<sup>2</sup> filtering matrix increases deviations of the HOD fall speed measurements from terminal fall speed predictions by Eq. (1) for the smaller end of the diameter spectrum ( $D < 0.8125$  mm) and showed no effect for the rest of the diameter spectrum. Once Parsivel<sup>2</sup> fall speed calculations were faithfully determined, we investigated Parsivel<sup>2</sup> fall speed measurement capabilities in comparisons with HOD measurements and terminal fall speed predictions by GK49 as discussed in the next section.

### 3. Results and discussion

Figure 7 presents a typical comparison of raindrop fall speed measurements by HOD and Parsivel<sup>2</sup> (level 1—for detected raindrops) along with terminal speed predictions by Eq. (1) for (Fig. 7a) event 5 on 15 May 2020 and (Fig. 7ab) averages of raindrop fall speed observations during all of the events tabulated in Table 1. Results of the statistical comparisons of fall speed measurements for event 5 are presented in Table 2 later. Event 5 presented in Fig. 7a consisted of about 200 min of rainfall observations, during which 10-min-averaged wind speed values ranged between 2 and 5.5  $\text{m s}^{-1}$ . Note that only raindrop diameter bins with more than 10 raindrops were considered for comparisons presented in this study. While Parsivel<sup>2</sup> software does not present the smallest two diameter bins ( $D < 0.25$  mm) of the level 2 data due to accuracy considerations as noted earlier, in this comparison, we included all Parsivel<sup>2</sup> diameter bins (including the smallest two diameter bins) as our comparison here is for level 1 data with all detected particles before implementation of the internal algorithm. This comparison revealed that, at the smaller end of the diameter bins, fall speeds of the raindrops detected by Parsivel<sup>2</sup> were much faster than the predicted terminal speeds. While omission of the two diameter bins smaller than 0.25 mm nulls the need for detailed considerations for those



TABLE 2. Results of one-sample and two-sample  $t$  tests for terminal speed predictions, and HOD and Parsivel<sup>2</sup> raindrop fall speed measurements for event 5. Mean, standard deviation, and number of observed raindrops for each diameter bin are also included.  $D$  represents the midsize of the diameter bin.  $\mu_{v_f}^{\text{HOD}}$  and  $\mu_{v_f}^{\text{Parsivel}}$  represent HOD- and Parsivel<sup>2</sup>-measured mean raindrop fall speeds, respectively.  $N_{\text{HOD}}$  and  $N_{\text{Parsivel}}$  represent HOD- and Parsivel<sup>2</sup>-measured number of raindrops, respectively.  $\sigma_{v_f}^{\text{HOD}}$  and  $\sigma_{v_f}^{\text{Parsivel}}$  represent standard deviation of HOD- and Parsivel<sup>2</sup>-measured raindrop fall speeds, respectively. Terminal speed predicted by Eq. (1) based on GK49 and by Beard (1976) are represented as  $V_{t_1}$  and  $V_{t_2}$ , respectively.

$D$ (mm)	$V_{t_1}$ (m s <sup>-1</sup> )	$V_{t_2}$ (m s <sup>-1</sup> )	$\mu_{v_f}^{\text{HOD}}$ (m s <sup>-1</sup> )	$N_{\text{HOD}}$	HOD			Parsivel <sup>2</sup>				$p$ value <sup>e</sup>	
					$\sigma_{v_f}^{\text{HOD}}$ (m s <sup>-1</sup> )	$p$ value <sup>a</sup>	$p$ value <sup>b</sup>	$\mu_{v_f}^{\text{Parsivel}}$ (m s <sup>-1</sup> )	$N_{\text{Parsivel}}$	$\sigma_{v_f}^{\text{Parsivel}}$ (m s <sup>-1</sup> )	$p$ value <sup>c</sup>		$p$ value <sup>d</sup>
0.313	1.250	1.199	—	—	—	—	—	1.597	3655	0.583	0.000	0.000	—
0.438	1.750	1.744	—	—	—	—	—	1.814	8459	0.633	0.000	0.000	—
0.563	2.325	2.276	2.011	223	0.910	0.000	0.000	2.155	10290	0.631	0.000	0.000	0.020
0.688	2.828	2.794	2.794	180	1.080	<b>0.673</b>	<b>0.996</b>	2.601	10896	0.648	0.000	0.000	0.018
0.813	3.306	3.294	3.211	212	0.901	<b>0.126</b>	<b>0.186</b>	3.080	11836	0.702	0.000	0.000	0.035
0.938	3.756	3.766	3.667	235	0.770	<b>0.078</b>	<b>0.050</b>	3.453	12070	0.670	0.000	0.000	0.000
1.063	4.178	4.206	3.956	244	0.707	0.000	0.000	3.762	10578	0.642	0.000	0.000	0.000
1.188	4.574	4.574	4.523	264	0.706	<b>0.242</b>	<b>0.240</b>	3.994	7736	0.606	0.000	0.000	0.000
1.375	5.120	5.075	4.951	526	0.774	0.000	0.000	4.265	10922	0.593	0.000	0.000	0.000
1.625	5.765	5.678	5.468	434	0.757	0.000	0.000	4.696	7020	0.629	0.000	0.000	0.000
1.875	6.325	6.223	6.070	290	0.804	0.000	0.001	5.225	4201	0.660	0.000	0.000	0.000
2.125	6.810	6.714	6.555	203	0.850	0.000	0.008	5.771	2570	0.663	0.000	0.000	0.000
2.375	7.228	7.149	6.730	137	0.919	0.000	0.000	6.343	1612	0.625	0.000	0.000	0.000
2.750	7.747	7.700	7.417	129	0.977	0.000	0.001	6.943	1533	0.734	0.000	0.000	0.000
3.250	8.273	8.252	7.942	36	0.842	0.024	0.034	7.741	544	0.864	0.000	0.000	<b>0.173</b>
3.750	8.647	8.625	8.190	10	1.081	<b>0.214</b>	<b>0.235</b>	8.280	177	0.794	0.000	0.000	<b>0.800</b>
4.250	8.903	8.855	—	—	—	—	—	8.406	66	0.953	0.000	0.000	—

<sup>a</sup>  $p$  value of one-sample  $t$  test with null hypothesis of  $H_0: \mu_{v_f}^{\text{HOD}} = V_{t_1}$ .

<sup>b</sup>  $p$  value of one-sample  $t$  test with null hypothesis of  $H_0: \mu_{v_f}^{\text{HOD}} = V_{t_2}$ .

<sup>c</sup>  $p$  value of one-sample  $t$  test with null hypothesis of  $H_0: \mu_{v_f}^{\text{Parsivel}} = V_{t_1}$ .

<sup>d</sup>  $p$  value of one-sample  $t$  test with null hypothesis of  $H_0: \mu_{v_f}^{\text{Parsivel}} = V_{t_2}$ .

<sup>e</sup>  $p$  value of two-sample  $t$  test with null hypothesis of  $H_0: \mu_{v_f}^{\text{HOD}} = \mu_{v_f}^{\text{Parsivel}}$ .



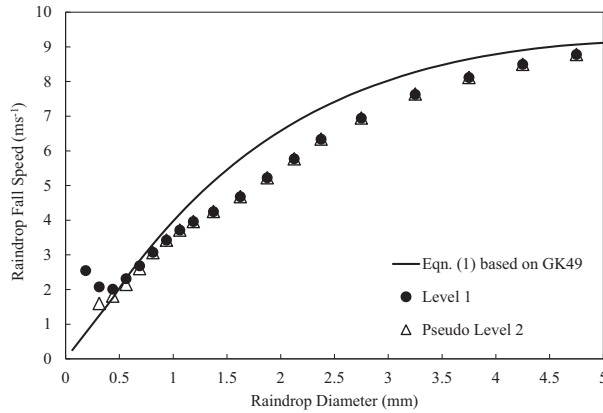


FIG. 5. Comparison of Parsivel<sup>2</sup> fall speed measurements for detected (level 1, solid circles) and validated raindrops (pseudo level 2, open triangles) with terminal fall speed predictions by Eq. (1) (solid line) to demonstrate the effects of Parsivel<sup>2</sup> internal algorithm.

two diameter bins, impact of Parsivel<sup>2</sup> filtering matrix implementation is evident for raindrop diameter bins between 0.25 and 0.5 mm, and care should be taken in microphysical interpretations using Parsivel<sup>2</sup> data for this size range. For raindrops between about 0.5 and 1 mm in diameter, Parsivel<sup>2</sup> fall speed measurements matched closely with both terminal speed predictions and HOD fall speed measurements. For raindrops between about 1 and 3 mm in diameter, Parsivel<sup>2</sup> fall speed observations showed a notable deviation from terminal speed predictions. HOD fall speed measurements did not show this behavior. For raindrops larger than about 3 mm in diameter, Parsivel<sup>2</sup> observations approached closer to terminal speed predictions and HOD measurements with increasing raindrop diameter bins, exhibiting smaller deviations. To show that these observations for event 5 were similar to those for all of the rainfall events, averages of raindrop fall speed measurements for all of the observed rainfall events are presented in Fig. 7b. Parsivel<sup>2</sup> raindrop fall speed observations for all of the rainfall events are presented individually (later in Fig. 10) to further demonstrate that the deviation in Parsivel<sup>2</sup> fall speed measurements from terminal speed predictions follow a similar pattern for all of the events regardless of rain intensity and wind conditions.

To test the statistical significance of the deviations of both HOD and Parsivel<sup>2</sup> (pseudo level 2) mean fall speed measurements from terminal speed predictions by Eq. (1) that is based on GK49 laboratory data ( $V_{t_1}$ ) and by Beard (1976) ( $V_{t_2}$ ) individually for each diameter bin, four separate one-sample  $t$  tests with  $p$  value (probability of obtaining the observed results, assuming that the null hypothesis is true) of 0.05 significance level were performed for event 5. The reason for using predictions by two different terminal speed parameterizations in these analyses was to test whether or not different terminal speed parameterizations alter the statistical results. The  $t$  tests were performed under the assumption of a normal distribution in observed data. Later in Fig. 8, distributions of HOD and Parsivel<sup>2</sup> raindrop fall speed measurements for each diameter

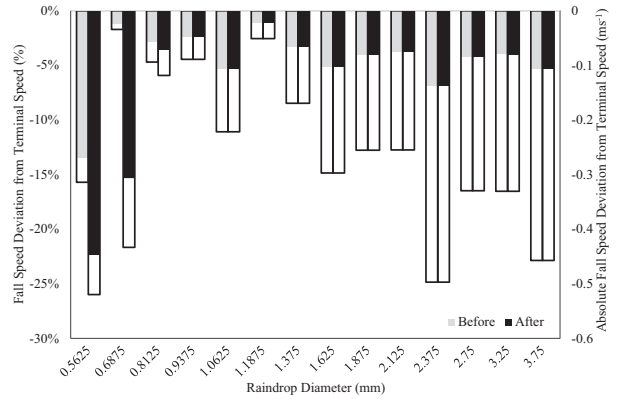


FIG. 6. Demonstration of the relative deviations (primary vertical axis) of HOD fall speed measurements from terminal speed predictions by Eq. (1) before (gray bars) and after (dark bars) implementation of Parsivel<sup>2</sup> filtering matrix to the HOD measurements for event 5. Absolute deviations (secondary vertical axis) of HOD fall speed measurements from terminal speed predictions before (hollow boxes attached to the gray bars) and after (hollow boxes attached to the dark bars) implementation of Parsivel<sup>2</sup> filtering matrix are also presented.

bin are shown. More than 68% of fall speed observations lie within one standard deviation of observed mean fall speeds for each diameter bin for both Parsivel<sup>2</sup> and HOD measurements, supporting the suitability of our normal distribution assumption. It should be noted that numbers of observed raindrops by HOD and Parsivel<sup>2</sup> are different for each diameter bin. The smaller number of raindrop observations by HOD as compared to those by Parsivel<sup>2</sup> was due to the HOD's smaller measurement volume (70 mm  $\times$  70 mm  $\times$  5.25 mm) that was customized for high measurement accuracy and its operating principles (i.e., sequential high-speed image storage and download) as described in Testik and Rahman (2016). The null hypotheses ( $H_0$ ) for the tests for HOD and Parsivel<sup>2</sup> measurements were  $H_0 : \mu_{v_f}^{\text{HOD}} = V_{t_1}$ ,  $H_0 : \mu_{v_f}^{\text{HOD}} = V_{t_2}$ ,  $H_0 : \mu_{v_f}^{\text{Parsivel}} = V_{t_1}$ , and  $H_0 : \mu_{v_f}^{\text{Parsivel}} = V_{t_2}$ , respectively, where,  $\mu_{v_f}^{\text{HOD}}$  and  $\mu_{v_f}^{\text{Parsivel}}$  represent mean fall speed measurements by HOD and Parsivel<sup>2</sup>, respectively, and  $V_{t_1}$  and  $V_{t_2}$  represent terminal fall speed predictions by Eq. (1) and Beard (1976), respectively. The test results are tabulated in Table 2. As can be seen from this table, the deviations of the Parsivel<sup>2</sup> mean fall speed measurements from both Eq. (1) and Beard (1976) terminal speed predictions were statistically significant for all diameter bins ( $p$  value  $< 0.05$ ). The deviations for the HOD measurements from the terminal speed predictions were also statistically significant except for the diameter bins of 0.688, 0.813, 0.938, 1.188, and 3.75 mm. This statistical analysis also demonstrated that raindrop terminal speed predictions using two different sources, GK49 and Beard (1976), do not have any statistically significant ( $p$  value) effect on the results. Therefore, we used only terminal speed predictions by Eq. (1) that is based on GK49 in the rest of this article. To test the statistical significance of the differences between mean fall speed measurements by HOD and Parsivel<sup>2</sup>

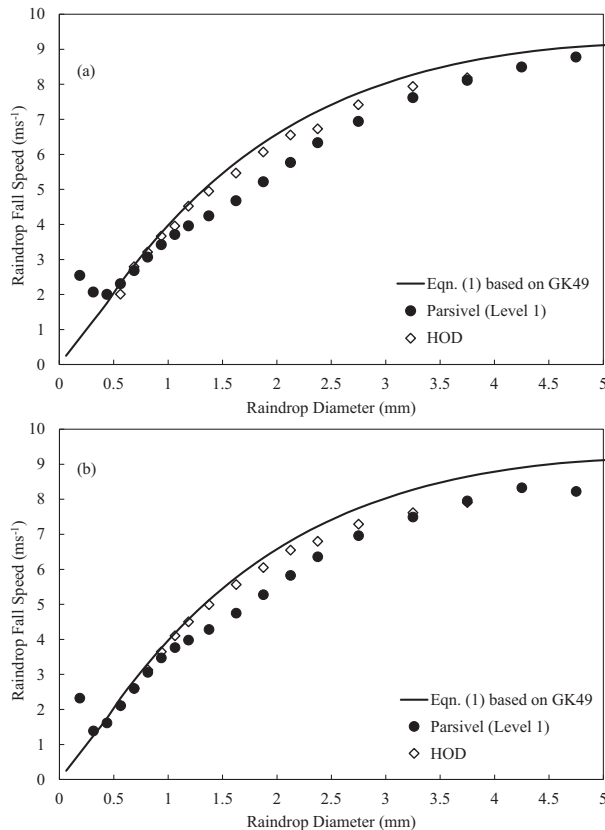


FIG. 7. Comparison of HOD-measured and Parsivel<sup>2</sup>-detected (level 1) raindrop fall speeds along with predicted terminal speeds by Eq. (1) based on GK49 for (a) event 5 and (b) all of the observed events. Fall speed values in (b) are averages of observations for all of the rainfall events.

( $H_0: \mu_{v_f}^{\text{HOD}} = \mu_{v_f}^{\text{Parsivel}}$ ), a two-sample  $t$  test with 0.05 significance level was performed. The two-sample  $t$ -test results showed that the differences between raindrop fall speed measurements by these two disdrometers were statistically significant for all diameter bins  $> 0.5$  mm, except for the diameter bins of 3.25 and 3.75 mm (Table 2). This finding provides sufficient evidence to state that Parsivel<sup>2</sup> raindrop fall speed measurements are significantly different from the HOD measurements.

Figure 8 shows a comparison of the raindrop fall speed distributions of event 5 for Parsivel<sup>2</sup> (pseudo level 2) and HOD measurements for each of the diameter bins. This figure demonstrates that, for each of the diameter bins, mean and median values of the Parsivel<sup>2</sup> measurements almost matched (near-symmetric distribution) whereas HOD measurements showed a skewed fall speed distribution toward subterminal values for the lower diameter bins of 0.563 and 0.689 mm. Moreover, this figure clearly demonstrates that deviations of the measured mean fall speeds from the terminal speed predictions were larger for Parsivel<sup>2</sup> measurements than for the HOD measurements. These deviations were so pronounced for Parsivel<sup>2</sup> measurements that the terminal speed predictions were beyond the standard deviation ranges for fall speed measurements for diameter bins of 1.188, 1.375, 1.625, 1.875,

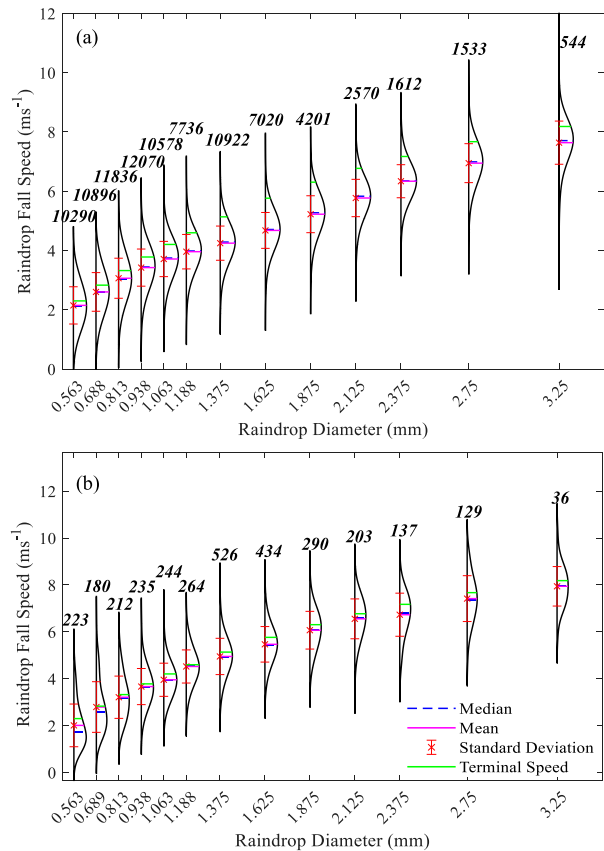


FIG. 8. Raindrop fall speed distributions for each diameter bin for (a) Parsivel<sup>2</sup> and (b) HOD measurements for event 5. Mean, median, and standard deviation of fall speed measurements and terminal speed predictions by Eq. (1) are also shown (see the legend). Numbers provided above the distributions for each diameter bin represent the number of raindrops in the corresponding diameter bin.

2.125, 2.375, and 2.75 mm. This was not the case for HOD measurements for any of the diameter bins (see Fig. 8). Figure 9 presents percentages of fall speed measurement deviations from the terminal speed predictions by Eq. (1) for each of the diameter bins for Parsivel<sup>2</sup> detected (level 1) and validated raindrops (pseudo level 2), and HOD observed raindrops for event 5. Since Parsivel<sup>2</sup> does not consider the smallest two diameter bins, we considered level 1 and pseudo level 2 data for 0.3125 mm and larger diameter bins. When compared to level 1 data, Parsivel<sup>2</sup> filtering matrix for this specific event reduced the fall speed deviation of pseudo level 2 data from terminal speed for the 0.3125 and 0.4375 mm diameter bins. On the other hand, Parsivel<sup>2</sup> filtering matrix caused increased deviations of Parsivel<sup>2</sup> pseudo level 2 data (as compared to level 1 data) between 0.5625 and 0.8125 mm diameter bins toward subterminal fall speeds (see Fig. 9). These results from Figs. 8 and 9 show that selective elimination of the Parsivel<sup>2</sup> filtering matrix yields an instrumental bias for fall speed measurements for the diameter bins between 0.3125 and 0.8125 mm. These biases may result in the underestimation of the number concentrations of small raindrop sizes.

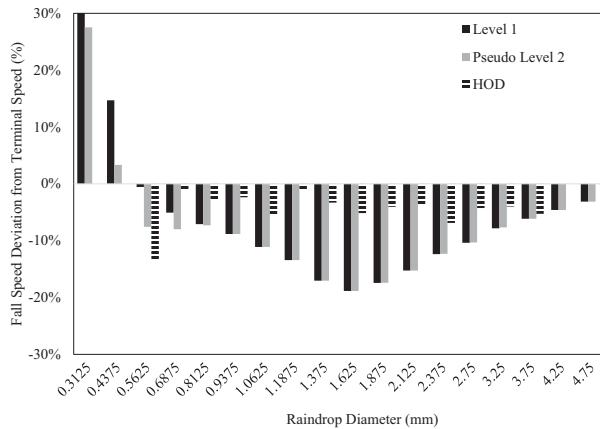


FIG. 9. Deviations of raindrop fall speed measurements from terminal speed predictions by Eq. (1) for Parsivel<sup>2</sup>-detected (level 1), Parsivel<sup>2</sup>-validated (pseudo level 2), and HOD observations for event 5. Here, the fall speed deviation for the 0.3125 mm diameter bin of level 1 data is 66%, exceeding the vertical axis value range shown in the figure.

It is evident from Fig. 9 that a bell-shaped deviation of Parsivel<sup>2</sup> measurements (both level 1 and 2 data) from terminal speed predictions by Eq. (1) for diameter bins between around 0.8125 and 3.25 mm with the maximum deviation at around 1.625 mm diameter bin. HOD measurements did not show such a bell-shaped deviation, but they were rather random within a range of 0% to −5%. We analyzed additional 5 rainfall events (see Table 1), taking into account various wind speed, rain intensity, and other environmental characteristics, in order to verify the findings presented in Fig. 9. Figure 10 presents measured raindrop fall speed deviations from terminal speed predictions by Eq. (1) for (Fig. 10a) Parsivel<sup>2</sup> detected (level 1), (Fig. 10b) Parsivel<sup>2</sup> validated (pseudo level 2), and (Fig. 10c) HOD measured raindrops for all observed rainfall events. As can be seen in this figure, although high wind speed and heavy rain intensity conditions enhanced raindrop fall speed deviations from predicted terminal speeds (for both Parsivel<sup>2</sup> and HOD observations), results for Parsivel<sup>2</sup> measured raindrop fall speed deviations for all of the observed rainfall events demonstrated a similar deviation trend consistently. Parsivel<sup>2</sup> filtering matrix disregarded raindrops having superterminal speeds, which occasionally worsened the average fall speed deviations from terminal speed predictions for the validated raindrops. For example, event 3 of Figs. 10a and 10b exhibited −4% and −10% measured fall speed deviations for the detected and validated raindrops, respectively, from predicted terminal speeds for the 0.3125 mm diameter bin. The impact of Parsivel<sup>2</sup> filtering matrix was evident on validated raindrop fall speed deviations up until 0.8125 mm diameter bin for all of the observed rainfall events and reduced the average fall speeds (see Figs. 10a,b). Differences in fall speed deviations of the detected and validated raindrops were not observed for diameter bins larger than 0.8125 mm diameter bin. Despite the differences in the rainfall event characteristics, deviations of measured raindrop fall speeds from terminal speed predictions for diameter bins

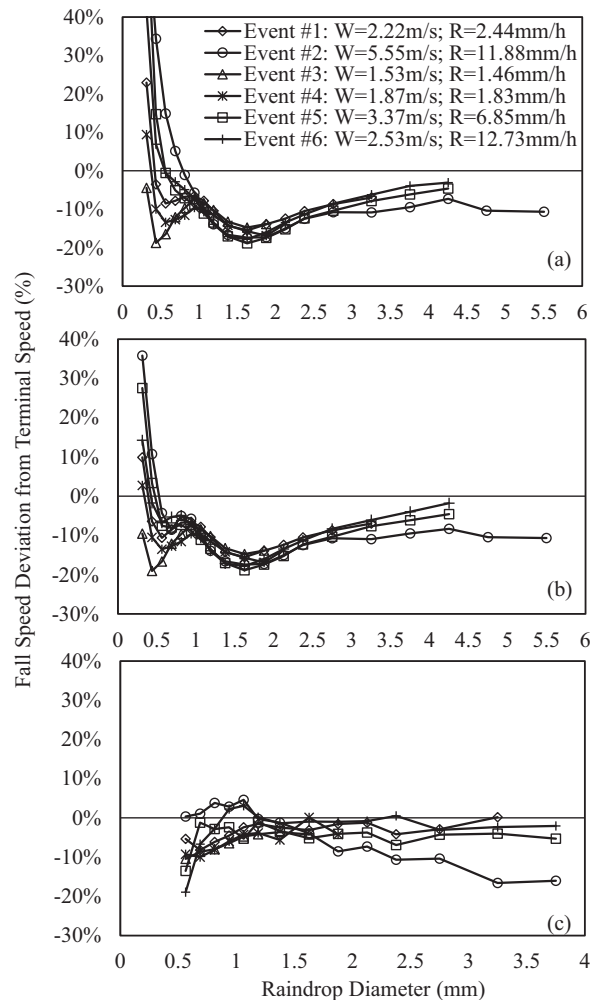


FIG. 10. Deviations of raindrop fall speed measurements from terminal speed predictions by Eq. (1) for (a) Parsivel<sup>2</sup>-detected (level 1), (b) Parsivel<sup>2</sup>-validated (pseudo level 2), and (c) HOD observations for all of the rainfall events in Table 1. Here, fall speed deviations for the 0.3125 mm diameter bin of level 1 data are 66%, 66%, and 42% for events 2, 5, and 6, respectively, exceeding the vertical axis value range shown in the figure. Average values for rain intensity ( $R$ ) and wind speed ( $W$ ) during the observed rainfall events are provided in the legend.

in between around 0.8125 and 3.25 mm showed similar bell-shaped deviations for both Parsivel<sup>2</sup> detected and Parsivel<sup>2</sup> validated raindrops (see Figs. 10a,b). Such a deviation pattern was not present for HOD fall speed measurements (Fig. 10c). Given that results presented in the rest of the article are also consistent for all of the observed rainfall events similar to the consistency in the results presented in Fig. 10, the rest of the results are presented only for event 5 for space and clarity considerations.

There may be several potential causes for this observed bell-shaped deviation behavior for Parsivel<sup>2</sup> measurements, including limitations of the laser sensor, rainfall microphysical processes (e.g., raindrop oscillations), Parsivel<sup>2</sup> filtering

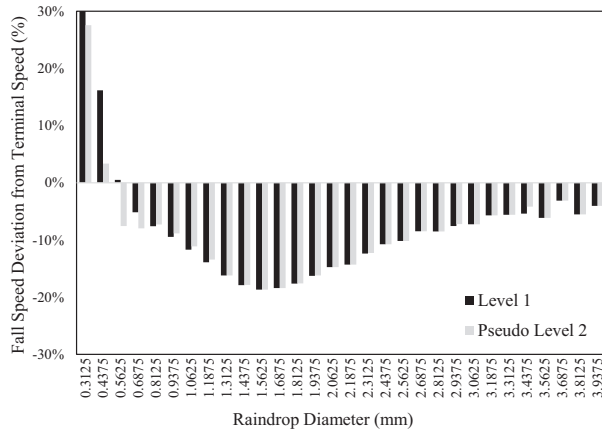


FIG. 11. Deviations of Parsivel<sup>2</sup>-detected (level 1) and -validated (pseudo level 2) fall speed measurements from predicted terminal speed by Eq. (1) for event 5. Deviations are presented for a fixed diameter bin width of 0.125 mm. Here, the fall speed deviation for the 0.3125 mm diameter bin of level 1 data is 66%, exceeding the vertical axis value range shown in the figure.

matrix, and nonuniform bin sizes. Figure 9 shows that level 1 and pseudo level 2 data have nearly identical deviations from the terminal speed predictions, demonstrating that Parsivel<sup>2</sup> filtering matrix is not responsible for this observation. To evaluate the possibility of nonuniform bin sizing as a potential cause of this observation, we reanalyzed rainfall observations of event 5 with uniform bin widths of 0.125 mm and presented in Fig. 11. As can be seen in this figure, uniform bin selection resulted in similar bell-shaped deviation, demonstrating that nonuniform bin sizing is not responsible for this observation. Furthermore, since HOD measurements, for which we can also visually observe individual raindrop behavior, did not show bell-shaped deviations for the same rainfall events, we can also eliminate rainfall microphysics as a potential cause of the bell-shaped deviations seen in Fig. 9 for the Parsivel<sup>2</sup> fall speed measurements. Note that our laboratory experimental observations by Parsivel<sup>2</sup> also showed the same bell-shaped deviation pattern from terminal speed predictions, which implies that we can disregard the outdoor environmental factors such as wind, temperature, humidity for the observed pattern. Therefore, we conclude that the laser characteristics and fall speed calculation methodology from laser sensor data are the potential causes for the bell-shaped deviation pattern. As examples of the laser characteristics, nonuniformity of the laser sheet thickness and laser sampling frequency that determines the raindrop fall time in the laser sheet are potential causes for fall speed measurement inaccuracies due to the fall speed calculation methodology for such sensors. Since we did not have the ability to test the Parsivel<sup>2</sup> laser sheet thickness for uniformity, we cannot make a relevant conclusion. Assuming a uniform laser sheet thickness of 1 mm as noted by Parsivel<sup>2</sup> documentation (OTT 2017) and using Eq. (1) terminal speed predictions for different raindrop sizes ( $D = 0.5\text{--}5$  mm), one can calculate that a raindrop would be observed from 5 to 21 times by the sensor. Therefore, one can expect fall speed measurement errors around 5%–18%,

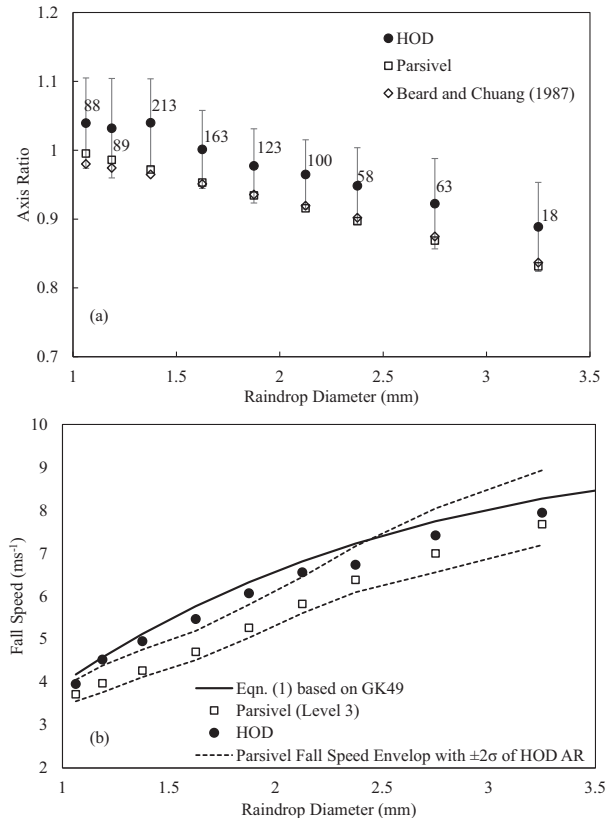


FIG. 12. (a) HOD raindrop axis ratio measurements (solid circles) presented with  $\pm 1$  standard deviation (vertical bars) and number of raindrops (next to vertical bars) for each of the diameter bins larger than 1 mm along with Parsivel<sup>2</sup>-assumed axis ratio values (open squares) and predicted axis ratio values by Beard and Chuang's (1987) model (open diamonds). (b) Parsivel<sup>2</sup> fall speed measurements are presented with an envelope of  $\pm 2$  standard deviations of HOD axis ratio measurements for each of the diameter bins.

depending on the raindrop size, solely due to laser sampling frequency (50 kHz). As an example of the fall speed calculation methodology, there are inherent assumptions (in particular raindrop shape assumptions) for fall speed calculations using laser measurements with significant potential for measurement inaccuracies. For diameters less than 1 mm, Parsivel<sup>2</sup> assumes that raindrops are spherical, whereas for diameters between 1 and 5 mm, raindrops are assumed to be oblate spheroids with axis ratios decreasing linearly from 1 to 0.7 with increasing diameter and reaching an axis ratio of 0.7 for raindrops larger than 5 mm (Battaglia et al. 2010). This axis ratio distribution may not accurately represent the axis ratios of actual observations. Figure 12a shows HOD axis ratio measurements with  $\pm 1$  standard deviations (shown as vertical bars) for raindrops larger than 1 mm along with the assumed axis ratios in Parsivel<sup>2</sup> calculations and predicted axis ratios by the analytical model of Beard and Chuang (1987). It is evident from Fig. 12a that while Parsivel<sup>2</sup> assumed axis ratios are close to the predictions by Beard and Chuang (1987), they distinctly differ from mean values of the actual raindrop axis ratio measurements by the HOD



and lie within the close proximity of the lower bounds of standard deviations for HOD measured raindrop axis ratios. To show the impacts of assumed axis ratio values in Parsivel<sup>2</sup> fall speed measurements, Fig. 12b presents Parsivel<sup>2</sup> fall speed measurements (level 3 data) with an envelope that is calculated by Parsivel<sup>2</sup> level 1 data and using HOD measured axis ratios with  $\pm 2$  standard deviations. While Fig. 12 demonstrates the significant impact of assumed raindrop axis ratio distribution in Parsivel<sup>2</sup> fall speed, it also demonstrates that assumed axis ratio distribution may not be fully responsible for the observed deviations from the GK49 terminal speed predictions [Eq. (1)] and there are likely other factors contributing such as laser sampling frequency as discussed. Furthermore, we conducted a two-sample *t* test with the hypothesis as equal mean fall speeds for HOD measurements and Parsivel<sup>2</sup> measurements with raindrop axis ratio distribution assumed to be  $\pm 2$  standard deviations of HOD measured axis ratio distribution. The results of this test revealed that differences in mean fall speeds by the two instruments were statistically significant for raindrops within the 1 mm–2.125 mm diameter range, where bell-shaped deviation pattern was observed.

Parsivel<sup>2</sup> DSD measurements have been a pillar for a large number of studies for different applications. Given that Parsivel<sup>2</sup> DSD calculations rely on the fall speed measurements with the aforementioned limitations, the relevant impacts on the accuracy of Parsivel<sup>2</sup> DSD measurements grant a discussion. DSD computations for this discussion were conducted using the following formulation in Eq. (2), where  $N(D)_i$  Parsivel<sup>2</sup> ( $\text{m}^{-3} \text{mm}^{-1}$ ) is the raindrop number concentration per unit volume for the *i*th raindrop diameter bin (Raupach and Berne 2015):

$$N(D)_i \text{ Parsivel} = \frac{1}{A_{i \text{ Parsivel}} \Delta D_i \Delta t} \sum_{j=1}^{j=32} \frac{C_{ji}}{v_j}. \quad (2)$$

Here,  $C_{ji}$  is the number of raindrop observations in the *i*th diameter bin and *j*th fall velocity bin during the time interval  $\Delta t$  (s),  $\Delta D_i$  is the width of the *i*th diameter bin (mm),  $v_j$  is the mean fall velocity of the *j*th velocity bin ( $\text{m s}^{-1}$ ), and  $A_{i \text{ Parsivel}}$  is the effective measurement area ( $\text{m}^2$ ) of Parsivel<sup>2</sup> for the *i*th diameter bin. While the actual measurement area of Parsivel<sup>2</sup> is 180 mm  $\times$  30 mm, raindrops passing through the rectangular measurement area partially (i.e., at the edges of the area) are omitted. Therefore, the effective measurement area,  $A_{i \text{ Parsivel}}$  (in  $\text{m}^2$ ), depends on the raindrop diameter bin as follows:

$$A_{i \text{ Parsivel}} = 10^{-6} \times 180 \times \left(30 - \frac{D_i}{2}\right). \quad (3)$$

Here,  $D_i$  is the midbin diameter (in mm) for the *i*th diameter bin. Underestimation bias observed for Parsivel<sup>2</sup> raindrop fall speed measurements for diameters larger than 0.8125 mm (see Fig. 9) would introduce an overestimation bias for Parsivel<sup>2</sup> DSD measurements [ $N(D)$  in  $\text{mm}^{-1} \text{m}^{-3}$ ] due to their inverse mathematical relationship in calculating the  $N(D)$  values. Here, we present event 5 to demonstrate the impact of Parsivel<sup>2</sup> fall speed measurements on the Parsivel<sup>2</sup> reported DSDs; however, it should be noted that all of the observed rainfall events show the same impact. To demonstrate the effect of fall speed

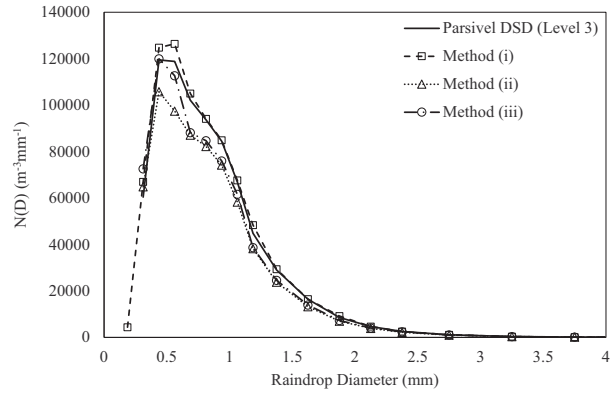


FIG. 13. Comparison among Parsivel<sup>2</sup> given DSD (level 3) with the DSDs estimated based on Parsivel<sup>2</sup>-detected (level 1) raindrop diameter and fall speed measurements [method (i)], Parsivel<sup>2</sup>-validated raindrop counts (level 2) with terminal speed predictions by Eq. (1) [method (ii)], and HOD-measured fall speeds [method (iii)] for event 5.

measurements on DSD calculations, Fig. 13 presents DSDs calculated in the following 3 different ways and compare them with the Parsivel<sup>2</sup> reported DSD measurements (level 3): (i) using Parsivel<sup>2</sup> detected raindrop diameter and fall speed measurements (level 1), (ii) using Parsivel<sup>2</sup> validated raindrop counts (level 2) with terminal speed predictions by Eq. (1) for middiameter values of each diameter bin, and (iii) using Parsivel<sup>2</sup> validated raindrop counts (level 2) with average fall speed measurements by the HOD for each of the diameter bins. As can be seen from this comparison, Parsivel<sup>2</sup> reported  $N(D)$  values are larger than those calculated by (ii) and (iii) for diameter bins larger than 0.5625 mm. For the diameter bin range between 0.3125 and 0.8125 mm, Parsivel<sup>2</sup> reported  $N(D)$  values are smaller than those calculated by (i) for the level 1 detected raindrops. Recall that this diameter range for level 1 data corresponds to the diameter bins with fast-falling raindrop observations that were eliminated by the Parsivel<sup>2</sup> filtering matrix, demonstrating the impact of Parsivel<sup>2</sup> filtering matrix in the reported DSD measurements. Figure 14 presents the relative bias of a typical Parsivel<sup>2</sup> reported DSD with the DSDs calculated using methods (ii) and (iii). Similar to the bell-shaped fall speed deviation pattern (see Fig. 9), Fig. 14 clearly demonstrates the presence of a bell-shaped distribution in around the 0.812–3.75 mm diameter bins with the maximum relative bias of 25% at the diameter bin of 1.625 mm.

Kinetic energy of raindrops falling on ground has been widely recognized as a potential indicator of soil erosion, and Parsivel<sup>2</sup> measurements have often been utilized in soil erosion studies for kinetic energy estimations (e.g., Angulo-Martínez and Barros 2015). Therefore, we also investigated the impacts of Parsivel<sup>2</sup> fall speed measurements on rainfall kinetic energy calculations. Time-specific kinetic energy of rainfall (KE with units of  $\text{J m}^{-2} \text{h}^{-1}$ ) is calculated as (Salles et al. 2002)

$$\text{KE}_{D_i} = \left(\frac{\pi}{12}\right) \left(\frac{1}{10^6}\right) \left(\frac{3600}{t}\right) \left(\frac{1}{A_{i \text{ Parsivel}}}\right) n_i D_i^3 (v_{D_i})^2. \quad (4)$$

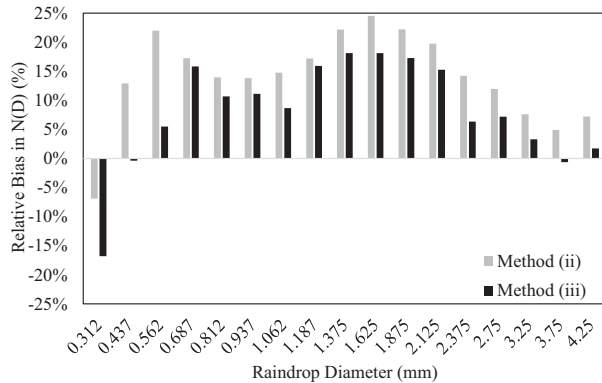


FIG. 14. Estimated relative bias of Parsivel<sup>2</sup> given DSD (level 3) with respect to calculated DSDs based on Parsivel<sup>2</sup>-validated raindrop counts (level 2) with terminal speed predictions by Eq. (1) [method (ii)] and HOD-measured fall speeds [method (iii)] for event 5.

Here,  $n_i$  is the number of raindrops counted in the  $i$ th diameter bin during the time interval  $t$  (s),  $D_i$  (mm) and  $v_{D_i}$  are the midvalue of the  $i$ th diameter bin and average raindrop fall speed ( $\text{m s}^{-1}$ ) for the  $i$ th diameter bin, respectively, and  $\text{KE}_{D_i}$  is the time-specific kinetic energy for the  $i$ th diameter bin. Figure 15 presents  $\text{KE}_{D_i}$  values for event 5 that were calculated using methods (i)–(iii) described earlier and also using pseudo level 2 data. Figure 15 shows that there are major discrepancies in the calculated  $\text{KE}_{D_i}$  values using different methods with different measured and predicted fall speed values as KE is directly proportional to the square of raindrop fall speed. The discrepancies between the calculated  $\text{KE}_{D_i}$  values using pseudo level 2 data and those using methods (ii) and (iii) are particularly notable for the raindrop diameter bins between 0.812 and 3.75 mm. This is due to the bell-shaped deviations of Parsivel<sup>2</sup> fall speed measurements from terminal speed predictions in this diameter range (see Fig. 9), which is an instrumental artifact as discussed earlier. There were no noticeable differences between calculated  $\text{KE}_{D_i}$  values by

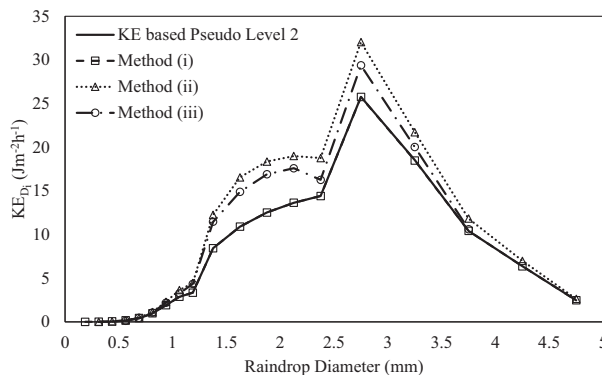


FIG. 15. Comparison among calculated  $\text{KE}_{D_i}$  values using different methods for event 5.  $\text{KE}_{D_i}$  values were calculated using pseudo level 2 data, level 1 data [method (i)], level 2 data with terminal speed predictions by Eq. (1) [method (ii)], and level 2 data with HOD fall speed measurements [method (iii)] (see the legend).

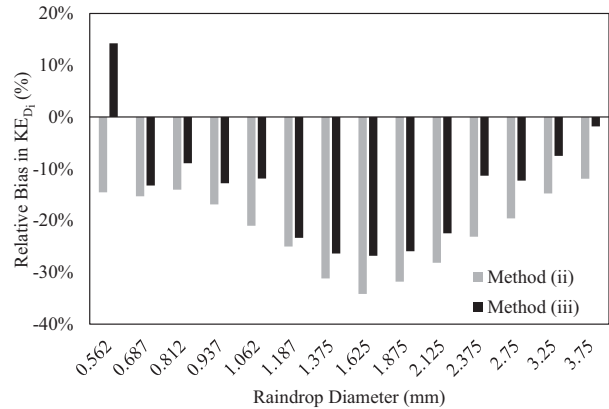


FIG. 16. Estimated relative bias of  $\text{KE}_{D_i}$  calculations using pseudo level 2 data with respect to  $\text{KE}_{D_i}$  calculations using method (ii) [level 2 data with terminal speed predictions by Eq. (1)] and method (iii) (level 2 data with HOD measured fall speeds) for event 5.

level 1 and pseudo level 2 data. This was because the fall speed differences between these two data levels were mainly for raindrop diameter bins smaller than 1 mm that are created by the application of the Parsivel<sup>2</sup> filtering matrix (see Fig. 5), which leads to only small differences in calculated KE values.

Relative biases in  $\text{KE}_{D_i}$  calculations using Parsivel<sup>2</sup> pseudo level 2 data with respect to those calculations using methods (ii) and (iii) are presented in Fig. 16. This figure clearly demonstrates the effects of Parsivel<sup>2</sup> fall speed measurements on calculated  $\text{KE}_{D_i}$  values and indicates that the effects are observed for the same raindrop diameter bin range of approximately 0.812 to 3.75 mm, within which the bell-shaped fall speed deviations are present (see Fig. 9). The maximum bias occurs at the diameter bin of 1.625 mm, which is the same diameter bin for the maximum fall speed deviations (see Fig. 9). The maximum relative bias of calculated  $\text{KE}_{D_i}$  values for event 5 shown in this figure were  $-34\%$  and  $-27\%$  with respect to methods (ii) and (iii), respectively. Therefore, it is expected that Parsivel<sup>2</sup> fall speed measurements result in notable underestimation of the KE values with potential impacts on rain-induced soil erosion estimations and other applications.

#### 4. Conclusions

Capabilities of Parsivel<sup>2</sup> disdrometer for raindrop fall speed measurements with potential impacts on DSD measurements were assessed. For this purpose, rainfall microphysical observations were conducted using collocated Parsivel<sup>2</sup> and HOD disdrometers, both optical-type disdrometers with different working principles, during 6 rainfall events. These rainfall events covered a wide range of rainfall rate, wind speed, temperature, and humidity; and hence, our evaluations utilized disdrometer data collected under a variety of meteorological conditions.

In assessing the measurement capabilities of Parsivel<sup>2</sup>, our efforts involved faithful identification of the data processing

algorithm, which is not available by the manufacturer and in the literature. We would like to note that there were no discussions with the manufacturer on this study and no funding support from the manufacturer for this study. We have identified that Parsivel<sup>2</sup> implements a filtering process of the detected particles and validates them as raindrops using criteria that can be presented in a matrix form (i.e., Parsivel<sup>2</sup> filtering matrix in Fig. 3). Through laboratory experiments, which were later verified using field observations, we faithfully identified the Parsivel<sup>2</sup> filtering matrix that is used to process the level 1 data to form the level 2 data. An important consequence of the Parsivel<sup>2</sup> filtering matrix is that it eliminates faster-falling detected particles within the diameter bins smaller than 0.8125 mm, hence, creating a bias in fall speed measurements for those small diameter bins by bringing the mean fall speed values down without an observational evidence. We also faithfully identified the fall speed calculation methodology by Parsivel<sup>2</sup> and revealed that midvalues of the fall speed bin are used, instead of measured fall speeds of individual raindrops, in relevant calculations. A potential consequence of this, although not investigated in this study, is the quantization errors in DSD and other rain parameter calculations due to the nonuniform Parsivel<sup>2</sup> fall speed bin widths that increase up to  $3.2 \text{ m s}^{-1}$  for the higher end of the fall speed bins. Future research on this can document potential errors and means to avoid such errors, if present, by calculation methodologies using individual raindrops fall speed measurements.

Our investigation revealed that Parsivel<sup>2</sup> fall speed measurements exhibit a bell-shaped deviation from terminal speed predictions by Eq. (1) for raindrop sizes between around 0.8125 and 3.25 mm diameter bins. The peak of the bell shape was at around 1.625 mm diameter bin. This deviation pattern was consistent for the Parsivel<sup>2</sup> measurements from all of the rainfall events and laboratory experiments, indicating that this was independent of the meteorological conditions. Furthermore, such a deviation pattern was absent for the HOD measurements from all of the events, which led us to the conclusion that the observed deviation pattern is an instrumental artifact. As discussed in section 3 with considerations of different potential causes, our conclusion is that Parsivel<sup>2</sup> laser sensor/sheet characteristics was responsible for the bell-shaped deviations. The systematic deviations of fall speed measurements as compared to the GK49 terminal speed predictions and HOD measurements have downstream impacts in processed Parsivel<sup>2</sup> data, in particular in Parsivel<sup>2</sup> DSD observations and KE calculations. Comparisons of Parsivel<sup>2</sup> reported DSDs with the DSDs calculated using Parsivel<sup>2</sup> raindrop counts and terminal speed predictions using Eq. (1) as well as HOD measured fall speeds revealed the presence of relative bias of Parsivel<sup>2</sup> reported DSDs similar to the bell-shaped fall speed deviation pattern for the same diameter range. KE values calculated using Parsivel<sup>2</sup> fall speed measurements showed a similar behavior. Since KE is directly proportional to the square of raindrop fall speed, we observed a substantial underestimation of the calculated KE values using Parsivel<sup>2</sup> fall speed measurements as compared to those calculated using

both terminal speed predictions by Eq. (1) and HOD fall speed measurements. The relative biases for KE values calculated using Parsivel<sup>2</sup> fall speed measurements were a clear reflection of the bell-shaped fall speed deviations in Parsivel<sup>2</sup> measurements.

Level 1 data and Parsivel<sup>2</sup> filtering matrix are not available to the Parsivel<sup>2</sup> users through the commercially available software and only level 2 and level 3 data are available. Processing of data from level 1 to level 2 and from level 2 to level 3 conceals potential instrumental artifacts and data processing information is critical to the Parsivel<sup>2</sup> users and data beneficiaries. Parsivel<sup>2</sup> internal calculation algorithm, including the filtering matrix, faithfully identified in this study reveals the data processing methodology, which can be considered as a “black box” for the user community. Identified data processing methodology is of great importance to the Parsivel<sup>2</sup> data users and beneficiaries in interpretations of the observations, understanding the instrumental limitations, and development of methodologies for data improvements, among various other implementations.

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**Data availability statement.** Data presented in this article will be made available upon reasonable request from the corresponding author (Dr. Firat Y. Testik) and after completion of a fair use agreement.

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