Assessment of Disdrometer Data Quality Control Methods for Precipitation Measurements Based on Wet-Bulb Temperature

By H. J. Kim *et al*.

Reply to the referees' comments

In the following, the comments made by the referees appear in black, while our replies are in red, and the proposed modified text in the typescript is in blue.

Referee #2 comments

The manuscript evaluates three data quality control methods for disdrometer measurements based on wet-bulb temperature. This work is valuable as it may promote the application of disdrometer observations across diverse types of precipitation. In current version, imprecise expressions are present throughout the manuscript, particularly in the descriptions of the figures, which hinders general readers from clearly understanding the study. There is still considerable room for improvement in the scientific expression. In addition, the rational for selecting the three quality control methods needs to be further justified, as their comparison does not reveal significant differences. Several specific comments are provided below for possible improvement.

Authors are grateful for reviewer's interest in this study and the many helpful suggestions for improving this manuscript. Replies to each major comments and minor comments are listed below.

1. The current Title may be refined to more clearly reflect the central focus of the manuscript.

We appreciate your constructive feedback. The title has been revised as follows to more clearly convey the content of this study.

♧ Page 1, line 1-2

Validation of Rainfall Data Analysis Observed by Using Disdrometer under Wet-Bulb Temperature Conditions

2. The Introduction section occasionally presents results that should be placed in later sections, and lacks appropriate references. For examples, in Lines 117-119: "the authors noted a tendency for PARSIVEL to overestimate the number of small droplets measuring between 0.2 and 0.4 mm and larger particles measuring 2.4 mm or more. Furthermore, the measured fall velocity of larger droplets was lower than the actual terminal velocity". Any appropriate reference? In Lines 129-131: "Given the diverse shapes and fall speeds of snow particles, the mixing of raindrops and snow during precipitation events may lead to an underestimation of errors when applying conventional disdrometer QC methods." Any references? Similar issues exist elsewhere in the manuscript. For example, in Lines 181: "numerous studies", any citations?

Thank you for your detailed comments. According to Raupach et al. (2015), the PARSIVEL disdrometer overestimates the number of small drops with diameters of 0.7 mm or less, and specifically overestimates in all channel sections up to 4 mm under rain rate conditions weaker than 0.1 mm h^{-1}. Furthermore, Tokay et al. (2013) also noted that the PARSIVEL disdrometer overestimates particle counts for particles larger than 2.44 mm. Furthermore, channels 1 and 2 of the PARSIVEL disdrometer's diameter channels do not collect data valid for analysis due to signal-to-noise issues. Therefore, the effective minimum diameter can be considered 0.2 mm. According to the findings of Raupach et al. (2015), PARSIVEL shows lower particle fall speeds compared to the 2DVD (Two-dimensional Video Disdrometer).

- […] between the values in the P (i) curve and the rain intensity. The most notable feature of Fig. 8 is that the numbers of small drops (under about 0.7 mm) were overestimated by the Parsivel. […], For low rain rates, below 1 mm h^{-1} , the Parsivel overestimated drop counts in all classes up to 4 mm . (Raupach et al., 2015)

- […] Tokay et al. (2013) found that Parsivel disdrometers were less sensitive to small drops than the 2DVD, and that they overestimated the numbers of drops over 2.44 mm in diameter, […]. (Raupach et al., 2015)

** Tokay, A., Petersen, W. A., Gatlin, P., & Wingo, M. (2013). Comparison of raindrop size distribution measurements by collocated disdrometers. Journal of Atmospheric and Oceanic Technology, 30(8), 1672-1690.)

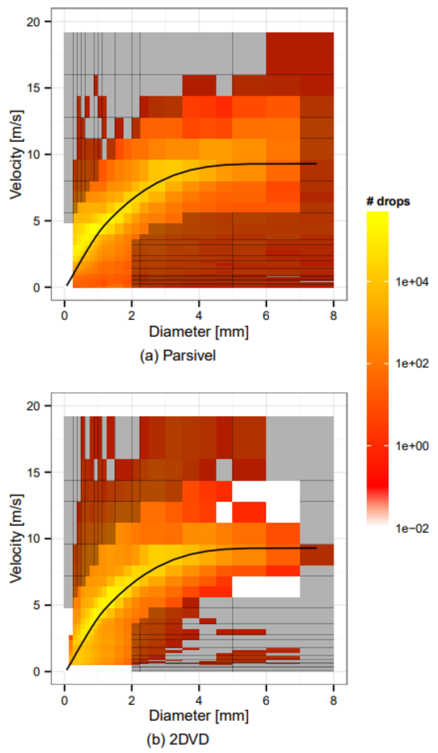

Fig. a1. Sum of raw drop occurrences per Parsivel class, for the 2012 and 2013 campaigns. Parsivel counts are summed at stations Pradel 1 (for 2012) and Pradel Grainage (for 2013). The filtered areas are overlaid in grey. The black line is the expected terminal drop velocity calculated by Beard (1976). Drop counts are specified by colour on a log scale. (Raupach et al., 2015)

While liquid droplets such as raindrops can be assumed to have a fixed density, solid particles like snow exhibit density variations relative to their diameter and possess a lower density compared to raindrops. Consequently, the fall velocity of snow particles is lower than that of raindrops. Applying the QC method designed for raindrops to snow particles may therefore yield underestimated results (Fehlmann et al., 2020; Lachapelle et al., 2024).

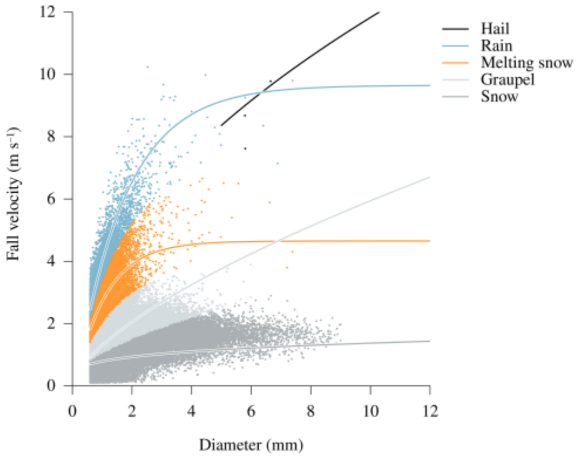

Fig. a2. Example of the classification algorithm developed in this study during a transition from rain to snowfall (17 February 2018, 17:00 to 23:00 UTC). After a plausibility check, each hydrometeor detected by the two-dimensional video disdrometer is classified as one of five precipitation types (hail, rain, melting snow, graupel, snow). This classification is based on empirical relationships between particle diameter and fall velocity. (Fehlmann et al., 2020)

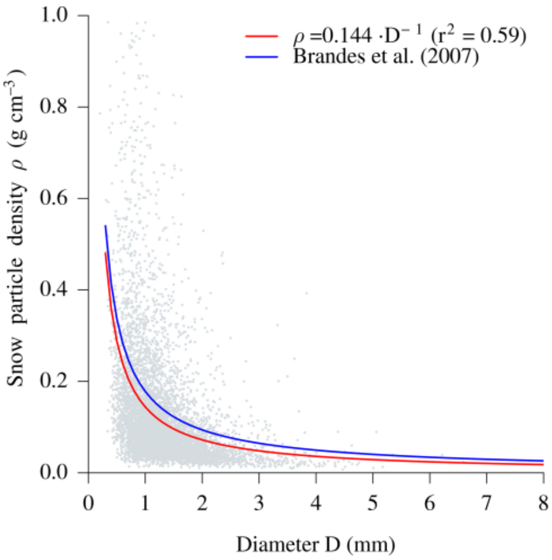

Fig. a3. Relationship between snow particle density and mean particle diameter based on 1 min observations during the first year of measurements. Snowfall events are identified based on the recorded dominant precipitation type by the Thies disdrometer. Snow particle density is then calculated by comparing the precipitation volume measured by the two-dimensional video disdrometer (2DVD) and precipitation mass measured by the OTT pluviometer and is related to mean particle diameter as measured by the 2DVD. The fitted curve is used to translate particle size distribution into snowfall intensities during the second year of measurements. Note that the corresponding relationship established by Brandes et al. (2007) is shown as a reference. (Fehlmann et al., 2020)

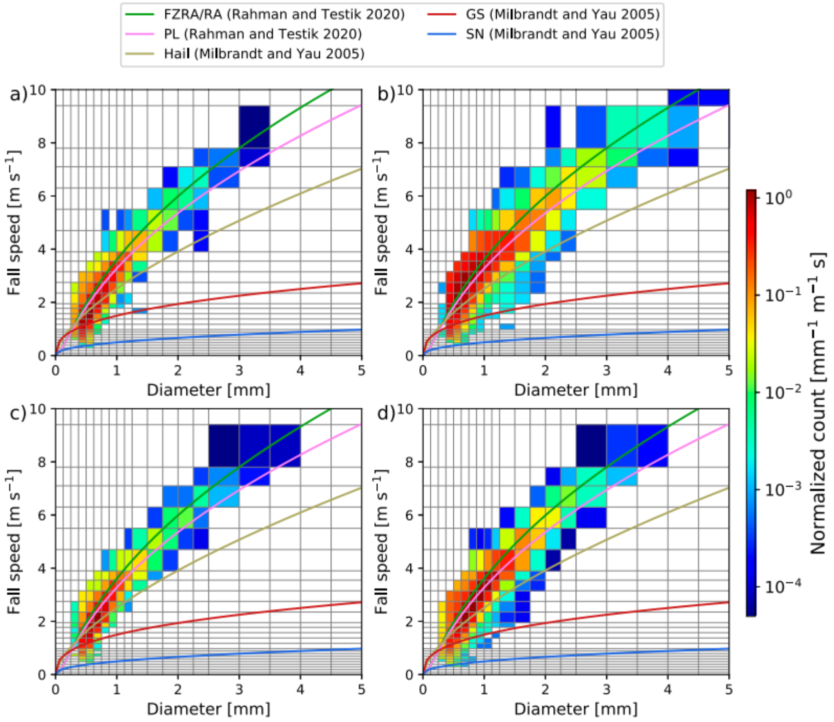

Fig. a4. Representation of laser-optical disdrometer measurements during rain episodes observed on (a) 1200–1500 UTC 19 Nov 2019, (b) 0800–1700 UTC 12 Jan 2020, (c) 1000–1100 UTC 27 Feb 2020, and (d) 0400–0800 UTC 23 Nov 2020. The solid, colored lines are theoretical fall speed curves for FZRA and RA, PL, hail, SN, GS, and SN. (Lachapelle et al., 2024)

** Fehlmann, M., Rohrer, M., von Lerber, A., & Stoffel, M. (2020). Automated precipitation monitoring with the Thies disdrometer: Biases and ways for improvement. Atmospheric Measurement Techniques Discussions, 2020, 1-31.

** Lachapelle, M., Thompson, H. D., Leroux, N. R., & Thériault, J. M. (2024). Measuring ice pellets and refrozen wet snow using a laser-optical disdrometer. Journal of Applied Meteorology and Climatology, 63(1), 65-84.

The revisions with the added references are as follows.

♧ Page 8, line 181-182

"A common QC approach for disdrometer data involves excluding non-meteorological data by analyzing fall velocity. In numerous studies (Kruger and Krajewski, 2002; Jaffrain and Berne, 2011; Raupach and Berne, 2015; Kim et al., 2019), […]"

** Kruger, A., & Krajewski, W. F. (2002). Two-dimensional video disdrometer: A description. Journal of Atmospheric and Oceanic Technology, 19(5), 602-617.

** Jaffrain, J., & Berne, A. (2011). Experimental quantification of the sampling uncertainty associated with measurements from PARSIVEL disdrometers. Journal of Hydrometeorology, 12(3), 352-370.

** Raupach, T. H., & Berne, A. (2015). Correction of raindrop size distributions measured by Parsivel disdrometers, using a two-dimensional video disdrometer as a reference. Atmospheric Measurement

Techniques, 8(1), 343-365

** Kim, H. J., Lee, K. O., You, C. H., Uyeda, H., & Lee, D. I. (2019). Microphysical characteristics of a convective precipitation system observed on July 04, 2012, over Mt. Halla in South Korea. Atmospheric Research, 222, 74-87.

3. The manuscript does not clearly describe the conventional QC methods. Please clarify what these conventional approaches are and explicitly discuss how they differ from the three QC methods selected in this study.

The existing QC methods mentioned in this study are based on setting effective ranges using terminal velocity values for raindrops of different diameters, and they differ in how these ranges are defined. These methods are applicable because they consider the water liquid density to be fixed for raindrops, and the terminal velocity varies with diameter. Methods 1 and 2 set the valid range at ±40% and ±60% of the terminal velocity, respectively. Method 3, however, sets a fixed range rather than a percentage of the terminal velocity value. It considers all small drops smaller than 2 mm to be valid if they have a fall velocity lower than the terminal velocity.

♧ Page 8, line 188-190

"[…] predominantly adopted a setting constant of 0.4 (40%) during data processing. Studies that employed PARSIVEL data for analysis frequently applied a setting constant of 0.6, accounting for 60% of the cases […]"

♧ Page 8, line 195-197

"[…] The fall velocity filtering technique employed for the 2DVD and PARSIVEL data involved the exclusion of particles exhibiting a terminal velocity exceeding 4 m s^{-1}, as shown in Eq. (2), those with a fall velocity below 3 m s^{-1} […]"

4. Section 3.1: The manuscript should report the proportion of disdrometer data removed by each QC method to allow for a clearer comparison of their performance. Furthermore, please clarify whether data associated with solid meteorological particles (e.g., snow, as indicated in Lines 204–205) may be removed by these methods.

Thank you for your kind feedback. The removal rates of solid meteorological particles before and after QC are shown in Fig. 13. These results indicate that the removal rate increases when the T_w condition is 1°C or lower, and when T_w drops below -2°C, the removal rate of particles increases to over 90%.

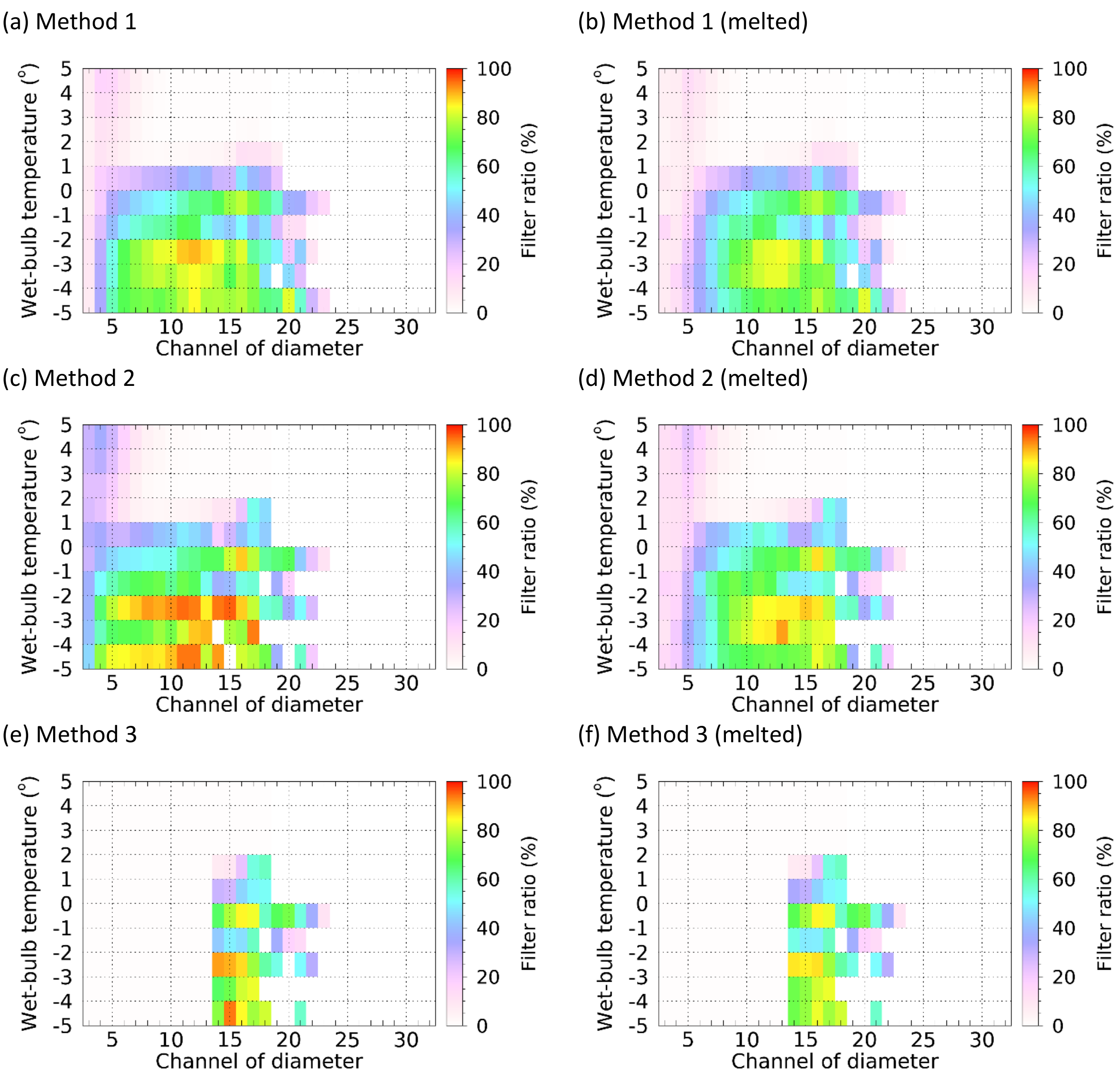

Figure 13: Particle filter ratio by diameter channel for T_w according to the pre-processing method based on falling velocity.

5. In Equation (5), is V(D) used to calculate Videal, i.e., terminal velocity? Please clarify.

We agree. In the expression in Equation 5, V(D) represents the terminal velocity value V_{ideal}, and the expression in the manuscript has also been revised as follows.

♧ Page 8, Equation (5)

$$V_{ideal}(D) = 9.65 - 10.3\exp(-0.6D) \quad (5)$$

6. Is the estimation of Tw from Tair and RH in Equation (15) applicable when Tair < 0? Please clarify.

The relationship equation proposed by Stull (2011) is applicable even under low temperature conditions of -20°C. The Tw estimation equation has a mean error of -0.00528°C and an R^2 of 99.95%, demonstrating high accuracy.

(Mean error is -0.00528C, median error is 0.0268C, mean absolute error is 0.288C, and the fraction of variance (r2) explained by the regression is 99.95%. (Stull, 2011))

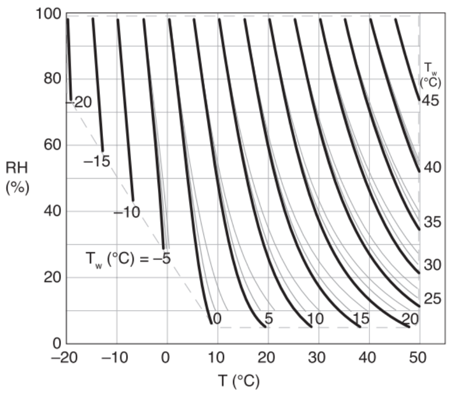

Fig. a5. Isopleths of Tw (thick black curves) vs RH% and T, found from Tw Equation. The valid range is enclosed by a dashed line, and the valid pressure is 101.325 kPa. The gray curves associated with each Tw are for P 5 80 kPa (thinner lines) and P 5 60 kPa (thinnest lines, located farther away from each black line). These gray curves [not found from Tw Eq.)] are useful for estimating the error if Tw Eq. is applied to pressures that are not equal to 101.325 kPa.

** Stull, R. (2011). Wet-bulb temperature from relative humidity and air temperature. Journal of applied meteorology and climatology, 50(11), 2267-2269.)

7. Figures 5-6: Is Rainfall[Gauge] the same as Rainfall[TG]? It would be better to keep consistent terminology. It's not easy to find the effect of QC in Figures 5-6. Please clarify the explicit differences between Methods 1 and 2 (Fig. 5b and 5c), or even Method 3 (Fig. 5d), and indicate whether these differences are significant? Including the number of datapoints in each panel would improve clarity and aid interpretation. In Line 256, the term "overestimate" is used—please clarify whether this applies to the comparison between Figure 6a and 6d as well. Significant?

We appreciate your constructive feedback. To improve the readability of the result figures, the figures were modified as follows. These results aim to assess the validity of each QC method for rainfall cases. As shown in Fig. 9, the rainfall cases fall within the valid range of the QC methods, indicating that they do not exhibit significant differences. Particularly for rainfall, QC methods based on fall velocity exhibit low error for large diameters (≥ 3 mm) when observation conditions are well-controlled and non-meteorological values, such as leaves, are not detected. Differences in QC primarily occur for small diameters (≤ 1 mm). As shown in Fig. 6, the Unfiltered case and Method 3 yield very similar results, indicating that raindrops possess a valid fall velocity. The relative underestimation observed in Methods 1 and 2 can be attributed to the partial removal of small drops. Although the Unfiltered results are relatively overestimated compared to those using QC methods, the RMSE for all methods in Figures 5-6 was less than approximately 1 mm, and the correlation coefficient exceeded 0.98. This indicates the high validity of the data.

♧ Page 11, line 258-262

This discrepancy in the overestimation of the 2DVD data can be attributed to variations in the conditions under which particles are eliminated, which is contingent on the specific QC method employed. Following the application of the QC methods, the mean absolute percentage error (MAPE) demonstrated an overall reduction compared with the raw data, suggesting that all QC methods possess quantitative reliability for rainfall data, with a maximum reduction of approximately 2.1%.

♧ Page 15, line 307-310

The central value of the fall velocity is consistent with the terminal velocity. This is within the range of fall velocities for raindrops, as established by the three different QC methods based on the fall velocity. It is important to note that precipitation particles (drops) may experience variations in their fall velocities owing to factors such as wind influence or collisions with obstacles during descent.

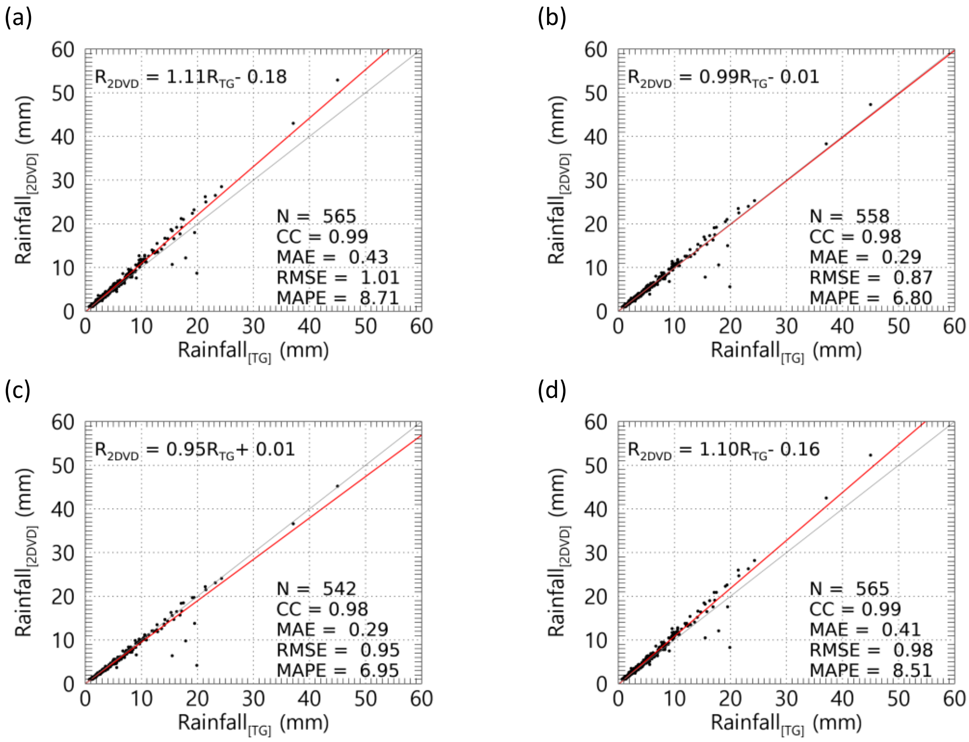

Figure 5: Comparison of rainfall observed using the tipping-bucket rain gauge and 2DVD when $T_w \geq 5$ °C ((a) Unfiltered, (b) Method 1, (c) Method 2, (d) Method 3). R_{2DVD} and R_{TG} denote the rainfall obtained from the 2DVD and a tipping-bucket rain gauge, respectively.

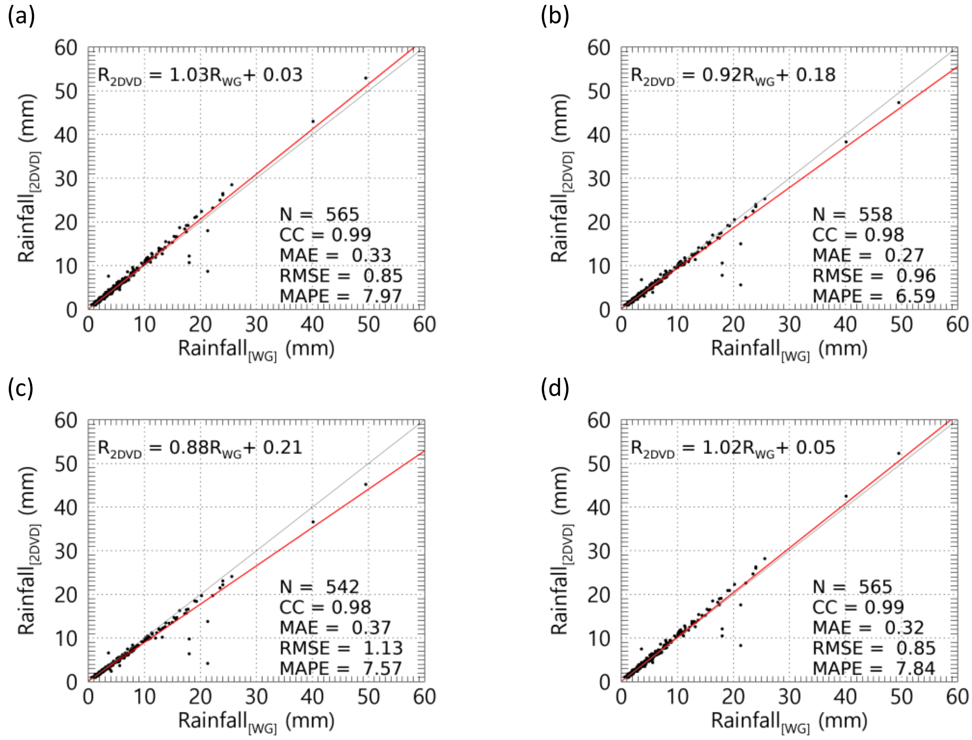

Figure 6: Comparison of rainfall observed using the weighing rain gauge and 2DVD when $T_w \geq 5$ °C ((a) Unfiltered, (b) Method 1, (c) Method 2, (d) Method 3). R_{WG} denotes the rainfall obtained from a weighing rain gauge.

8. Many expressions throughout the manuscript lack rigor. For examples, in Lines 279-280: "However, as the temperature exceeded 0 ℃, the fall velocity for CH 4 to 18 increased under T_w conditions, while the fall velocity for CH 19 to 23 increased under T_{air} conditions? (Fig. 7(a-b))". Can find this result from 7a and 7b? It looks comparable between Figure 7a and 7b. In Lines 280-282: "Notably, when the temperature rose above 1 ℃, there was a notable increase in fall velocity for CH 4 or larger? under Tw conditions, the distribution approached the terminal velocity of raindrops for CH 4 to 13?". The statement "Under T_{air} conditions, the fall velocity increased when temperatures were below 1℃" is unclear. Please clarify how this statement can be determined from the presented data or figure?

Thank you for your detailed comments. The difference in fall velocity variation for T_w and T_{air} conditions can be clearly observed in Fig. 7(a-b). When T_w was below 0 °C, the upper 75% value of fall velocity was less than 2 m s^{-1}. However, as Tw increased above 0°C, fall velocity increased to approximately 1 m s^{-1} or higher in the CH4–15 diameter range. Particularly in the CH8–11 range, the upper 75% value exceeded 3 m s^{-1}. Specifically, up to CH13, fall velocity gradually increased with diameter, reaching large values exceeding 6 m s^{-1}. Conversely, under T_{air} conditions, the upper 75% fall velocity values for the CH1–15 range were 2 m s^{-1} or less in the 0–1°C range. Under T_{air} conditions, the fall velocity increased when the temperature was above 1°C. However, it still differed from the terminal velocity of rainfall and exhibited a lower fall velocity than under T_w conditions. For a clearer explanation, it has been revised as follows.

♧ Page 13, line 282-290

However, as the temperature exceeded 0 ℃, the fall velocity for CH 4 to 18 increased under T_w conditions, while under the T_{air} condition, it exhibited values similar to those observed at temperatures below 0 ℃ (Fig. 7(a-b)). When T_w was below 0 ℃, the upper 75% value of fall velocity was less than 2 m s^{-1}. However, as Tw increased above 0 ℃, fall velocity increased to approximately 1 m s^{-1} or higher in the CH4–15 diameter range. Particularly in the CH8–11 range, the upper 75% value exceeded 3 m s^{-1}. Specifically, up to CH13, the fall velocity gradually increased with diameter, reaching large values exceeding 6 m s^{-1}. Conversely, under T_{air} conditions, the upper 75% fall velocity values for the CH1–15 range were 2 m s-1 or less in the 0–1 ℃ range. Under T_{air} conditions, the fall velocity increased when the temperature was above 1 ℃.