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Correction of raindrop size distributions measured by Parsivel disdrometers, using a two-dimensional-video-disdrometer as a reference

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Abstract

The raindrop size distribution (DSD) quantifies the micro-structure of rainfall and is critical to studying precipitation processes. We present a method to improve the accuracy of DSD measurements from Parsivel disdrometers, using a two-dimensional-video-disdrometer (2DVD) as a reference instrument. Parsivel disdrometers bin recorded raindrops into velocity and equivolume diameter classes, but may mis-estimate the number of drops per class. We define a filter for raw disdrometer measurements to remove particles that are unlikely to be plausible raindrops. In our correction method, drop velocities are corrected with reference to theoretical models of terminal drop velocity. Non-plausible measurements are removed. Lastly, drop concentrations are corrected such that on average the Parsivel concentrations match those recorded by a 2DVD. The correction can be trained on and applied to data from both generations of Parsivel disdrometers. The method was applied to data collected during field campaigns in Mediterranean France, for a network of first and second generation Parsivel disdrometers. We compared the moments of the resulting DSDs to those of a collocated 2DVD, and the resulting DSD-derived rain rates to collocated rain gauges. The correction vastly improved the accuracy of the moments of the Parsivel DSDs, and in the majority of cases the rain rate match with collocated rain gauges was improved.

1 Introduction

The raindrop size distribution (DSD) quantifies the micro-structure of rainfall. The DSD describes the statistical distribution of falling drop sizes: it is the number of drops with a given equivolume diameter per unit volume of air. The DSD plays a fundamental role in the analysis of rainfall. Interception of precipitation by vegetation canopies or city environments, erosion of soil through raindrop impact, and pollutant dispersal both on the ground and in the atmosphere are all fields in which the DSD is important (e.g. Uijlenhoet and Sempere Torres, 2006). Knowledge of the DSD is required in order to study the behaviour of electromagnetic waves in the atmosphere, so it is highly relevant to weather radar and microwave communication links (Jameson and Kostinski, 2001; Uijlenhoet and Sempere Torres, 2006). Moreover, all bulk rainfall variables of interest can be derived as weighted moments of the DSD (e.g. Ulbrich, 1983; Testud et al., 2001). In order to study rainfall micro-structure effectively, we require accurate measurements of the DSD.

Disdrometers are instruments that measure the DSD at a point location. There are various types, each with advantages and disadvantages. In this paper we are concerned with the OTT Hydromet Particle Size and Velocity (Parsivel) disdrometer, and the two-dimensional-video-disdrometer from Joanneum Research. The Parsivel is a laser optical disdrometer that uses a sheet of light through which drops fall. The diameter and velocity of a drop is then determined by sensing the shadow it casts and for how long it casts it (Löffler-Mang and Joss, 2000). Parsivel disdrometers bin drops into classes of velocity and diameter and record the number of drops measured per class over an integration time. Parsivel disdrometers have been shown to be susceptible to errors in the recorded drop concentrations, particularly for small and large drops (Krajewski et al., 2006; Tokay et al., 2013). The Parsivel measurement technique assumes properties of the precipitation that are far more appropriate for rain than for solid precipitation; for example that particles will be spheroidal, have a horizontal orientation of their major axis, and that only one particle will be in the beam at once (Yuter et al., 2006; Battaglia et al., 2010). The Parsivel is, however, a low cost, durable, and reliable instrument that makes it particularly well-suited for deployment in networks to study the small-scale variability of the DSD (e.g. Tapiador et al., 2010; Jaffrain et al., 2011).

The two-dimensional-video-disdrometer (2DVD)[1] uses two perpendicular high-speed line-scan cameras, each with an opposing light source, to measure particles from orthogonal angles and thus record their shape (e.g. Thurai and Bringi, 2005) as

[1]The 2DVD was called the 2-D-video-distrometer by Schönhuber et al. (2008), to emphasise that the instrument collects information on the distribution of particles. To avoid confusion we use the standard spelling of disdrometer.

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well as their size and velocity (Kruger and Krajewski, 2002; Schönhuber et al., 2008). Information on each individual particle that falls through the measurement area of the 2DVD is recorded. A particle's fall speed is determined by the difference in time between its detection in the two camera planes, which are offset vertically by 6.2–7 mm. Thus the 2DVD uses no literature-derived estimates for raindrop shape or velocity; these parameters are measured directly (Schönhuber et al., 2008). Some drawbacks of the 2DVD have been noted. In particular, drops with diameters less than 0.2 mm have been found to be unreliably measured (Tokay et al., 2001); Tokay et al. (2013) recommend taking 0.3 mm as a minimum measured diameter in 2DVD data due to underestimation of drop counts below this diameter. In earlier designs of the instrument, the reliability of measurements decreased with increasing wind speed (Nešpor et al., 2000). This has subsequently been addressed through design improvements (Schönhuber et al., 2007).

Several comparisons between 2DVD and Parsivel disdrometers have been reported on in the literature. In experimental trials the 2DVD has been found to produce better matches to rain gauges than Joss and Waldvogel (Tokay et al., 2001) and Parsivel (Thurai et al., 2011; Tokay et al., 2013) disdrometers. Krajewski et al. (2006) showed that Parsivel disdrometers measure higher numbers of small drops (0.2 mm to 0.4 mm) than the 2DVD and generally report higher rain rates. In a study in Alabama, USA, Tokay et al. (2013) found that Parsivel disdrometers are less sensitive to small drops than the 2DVD, and that Parsivel overestimated the numbers of drops over 2.44 mm in diameter, while underestimating the numbers of drops under 0.76 mm in diameter. Further, they found that Parsivel measured fall velocities lower than the expected terminal fall speeds for drops larger than 2.44 mm in diameter. Tokay et al. (2013) concluded that inhomogeneous laser beams in first generation Parsivel disdrometers were the cause of the mis-estimation of drop counts. Thurai et al. (2011) found that Parsivels record higher mass-weighted mean diameter and rain rate than 2DVD, with the effect especially prominent when the rain rate was over 30 mm h^{-1}.

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Disdrometers can record erroneous measurements due to wind turbulence, splashing, mismatching between cameras (in the case of the 2DVD), multiple drops appearing at the same time, margin-fallers, or external interference from, for example, insects or spider webs. Minimal data treatment for disdrometer measurements usually involves removing outlier points by reference to expected terminal fall velocity (e.g. Tokay et al., 2001; Kruger and Krajewski, 2002; Thurai and Bringi, 2005). For example, Tokay et al. (2013) removed drops exceeding ±50 % of an expected terminal fall speed, while Jaffrain and Berne (2011) used a threshold of ±60 % of the expected fall speed. This existing approach removes particles that are obviously erroneous, but it has some short-comings. By only removing measurements, it does not allow for the fact that the disdrometer may under-estimate the number of drops falling. Most importantly, the treatment is based solely on bulk variables such as rain rate, and does not test whether the resulting DSDs after the correction are physically viable.

In this paper we present a correction method for DSD measurements provided by Parsivel disdrometers, using a 2DVD as a reference instrument. The correction is designed to ensure that the DSDs recorded by Parsivel disdrometers are accurate, in terms of both the DSD itself and its moments. We define a filter to screen for particles that are unlikely to be raindrops. The correction method adjusts two properties of the recorded DSDs. First, drop velocities per diameter class are shifted such that the mean velocity per diameter class aligns with the theoretical terminal drop velocity for raindrops of that diameter; these raw measurements can then be screened for implausible measurements. Second, per-diameter-class volumetric drop concentrations are scaled such that they match, in a statistical way, the concentrations measured by a collocated 2DVD.

The rest of this paper is organised as follows: the DSD is introduced in detail in Sect. 2. The data used are described in Sect. 3. Measurement of the DSD and the instruments we are concerned with in this work are discussed in Sect. 4. The correction is introduced in Sect. 5. The results of the correction applied to the data are shown in Sects. 6 and 7, and concluding remarks are made in Sect. 8.

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2 The drop size distribution of precipitation

On average, during precipitation, 1 m^3 of air contains about 10^3 raindrops, with many more small drops than large ones (Uijlenhoet and Sempere Torres, 2006). Small raindrops are close to spherical, but drops larger than about 1 mm in diameter form oblate spheroids as the bottom of the drop flattens out progressively with drop size (Andsager et al., 1999; Pruppacher and Klett, 2000; Thurai and Bringi, 2005). For this reason the size of a raindrop is generally characterised by its equivolume diameter, which is the diameter of a sphere containing the same volume of water as the drop. Raindrops are primarily between 0.1 mm to 6 mm in equivolume diameter, and they fall at speeds of between 0.1 $m\,s^{-1}$ to greater than 9 $m\,s^{-1}$ (Uijlenhoet and Sempere Torres, 2006; Roe, 2005), with the terminal fall speed of a drop dependent on its size, plus the atmospheric temperature, relative humidity, and altitude a.s.l. (Beard, 1976). The volumetric drop size distribution (DSD) is written $N(D)$, and is the number of raindrops with equivolume diameter D per unit volume of air (Jameson and Kostinski, 2001).

The drop size distribution $N(D)$ [$m^{-3}\,mm^{-1}$] can be described as the total drop concentration multiplied by a probability density function $f(D)$, such that

$$N(D) = N_\mathrm{t} f(D). \tag{1}$$

The total drop concentration N_t [m^{-3}] is the total number of drops falling per meter cubed of air. It is the zeroth moment of the DSD, such that

$$N_t = \int_{D_\mathrm{min}}^{D_\mathrm{max}} N(D)\mathrm{d}D. \tag{2}$$

The great power of the DSD comes from the fact that, because the shape and fall velocity of a raindrop can be reliably described once its equivolume diameter is known, all integral rainfall parameters of interest can be derived as weighted moments of the

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DSD. These are also known as bulk rainfall parameters. Any bulk rainfall parameter P can be written as

$$P = a_P \int_{D_{\min}}^{D_{\max}} w_P D^p N(D) dD, \tag{3}$$

where a_P and p are constants (Ulbrich, 1985) and w_P is a weight that possibly depends upon D. Here we briefly define the bulk parameters that will be used later in this document.

The mass-weighted drop diameter D_m [mm], also called the mean volume drop diameter, can be thought of as an indicator of the average drop size; it is one way to describe the centre of $f(D)$ (Testud et al., 2001). It is the ratio of the fourth to the third DSD moments, so that

$$D_m = \frac{\int_{D_{\min}}^{D_{\max}} N(D) D^4 dD}{\int_{D_{\min}}^{D_{\max}} N(D) D^3 dD}. \tag{4}$$

The rain rate R [mm h^{-1}] is defined from the DSD as

$$R = 6\pi 10^{-4} \int_{D_{\min}}^{D_{\max}} N(D) v(D) D^3 dD, \tag{5}$$

where $v(D)$ [m s^{-1}] is the terminal fall velocity for drops with equivolume diameter D [mm]. Terminal fall velocities can be calculated using, for example, the algorithm of Beard (1976).

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The radar reflectivity Z_h [mm^6 m^{-3}] at horizontal polarisation is defined as

$$Z_h = \frac{10^6 \varpi^4}{\pi^5 \left| \frac{m^2-1}{m^2+2} \right|} \int_{D_{\min}}^{D_{\max}} \sigma_{B_h}(D) N(D) dD, \quad (6)$$

where m [-] is the complex refractive index of water, σ_{B_h} [cm^2] is the backscattering cross section at horizontal polarization, and ϖ [cm] is the radar wavelength (Bringi and Chandrasekar, 2001). The backscattering cross section can be calculated using the algorithm and FORTRAN code of Mishchenko and Travis (1998), and a drop shape model (e.g. Andsager et al., 1999; Thurai and Bringi, 2005). Vertical reflectivity is calculated similarly, using the vertical polarization backscattering cross section σ_{B_v} [cm^2].

The definitions given in this section assume a continuous DSD function of which the integral can be taken. When measured by an instrument, however, the DSD is usually provided as the concentration of drops per discrete class of equivolume diameter. In this case the above equations are modified, such that the integration becomes a sum over all classes, $N(D)$ becomes N_i [mm^{-1} m^{-3}], the drop concentration for the ith class, and dD becomes ΔD_i [mm], the width of the ith class. When the diameter D of drops in a class is required, for example in Eqs. (5) and (6), we use the centre of the ith diameter class, which we call D_i [mm].

3 Data

The Parsivel DSD correction was developed and tested on first generation Parsivel data collected during two consecutive autumns in Ardèche, France, as part of the Hydrological Cycle of the Mediterranean Experiment (HyMeX[2], Drobinski et al., 2013). The method was then also tested on second-generation Parsivel (Parsivel 2 hereafter)

[2]See http://www.hymex.org

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data collected in the same region in 2013. In this section these datasets are briefly described.

3.1 HyMeX SOPs 2012 and 2013

Two autumn campaigns in the same region in Ardèche, France provided the primary data used in this work. The campaigns were special observation periods (SOPs) run between September and November in both 2012 and 2013. The field site was a roughly 5 km × 5 km area in the Cévennes region; see the map in Fig. 1. In 2012, seven first generation Parsivel disdrometers (two of which were collocated) and a 2DVD were deployed. In 2013, the same network was deployed with the addition of two more first generation Parsivel disdrometers. The 2DVD was collocated with a Parsivel and a tipping bucket rain gauge in 2013. Collocated rain gauge measurements were available for all disdrometers, with the exception of Montbrun in 2013. Further, we used data from a network of five Parsivel 2 disdrometers that was deployed in the same region during the 2013 campaign. Station information is summarised for all the disdrometers in Table 1. In this paper we refer to the two campaigns as SOP 2012 and SOP 2013. For our purposes, the main difference between the setup of the two campaigns was that in SOP 2013, there was a Parsivel, Parsivel 2, and rain gauge collocated with the 2DVD at the Pradel Grainage site. In SOP 2012, the closest Parsivel and rain gauge to the 2DVD were at the site of Pradel 1 and Pradel 2, about 480 m away. For some analyses we combined data from SOP 2012 and SOP 2013 into a single dataset, which we refer to as the "combined SOPs" dataset.

Due to a clock error with the 2DVD, a variable clock drift was present in the 2DVD data. Parsivel clocks were synchronised using inbuilt Global Positioning System (GPS) receivers and were thus more reliable than the 2DVD clock. Adjustments were made to the 2DVD data for SOP 2013 in order to synchronise the clocks of the instruments, for events where it was possible to do so. This synchronisation was done manually, by comparing timeseries of the rain rate from the 2DVD and a collocated Parsivel. The 2DVD timeseries was shifted forward in time to match the Parsivel timeseries as closely

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as possible, at 30 s temporal resolution. The adjustment was then applied to the series of individual 2DVD drops. Table A1 shows the adjustments made per event in SOP 2013, which were between 30 and 60 s.

4 Processing of disdrometer measurements

Disdrometer measurements must be processed to convert raw measurements into more useful forms. In this section we describe how we processed data from the Parsivel disdrometer and 2DVD.

4.1 Parsivel

Parsivel disdrometers bin measured particles into particle counts per velocity and diameter class. There are 32 velocity classes and 32 diameter classes, with varying widths. Parsivels also determine the rainfall intensity (or rain rate), and two status flags: one provides an indication of the type of precipitation being observed (liquid or solid, for example), and another provides information on the quality of the measurement. For example, if the glass in front of the Parsivel's laser beam is dirty and reliable measurements are no longer possible, that will be indicated by quality flag with value 2. Value 0 indicates normal operation, while value 1 indicates dirty glass but that measurements are still possible. Value 3 indicates that the laser is damaged. We make use of these flags to restrict our analysis to high-quality measurements.

The effective sampling area of the Parsivel disdrometer is about 54 cm^2, but is different for different diameter classes, due to the fact that the whole drop diameter must be included in the sampling area for the drop to be counted. So-called "margin-fallers" are automatically removed, which reduces the effective sampling area. For the ith class, the sampling area is (Löffler-Mang and Joss, 2000; Battaglia et al., 2010):

$$S_i^{\mathrm{Pars}} = 10^{-6} \times L \left(B - \frac{D_i}{2} \right), \tag{7}$$

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where S_i^{Pars} [m^2] is the effective sampling area, D_i [mm] is the class-centre equivolume drop diameter for the ith diameter class, L [mm] is the length of the Parsivel beam (180 mm), and B [mm] is the width of the beam (30 mm).

Let $C_{v,i}$ [-] be the raw number of particles recorded by the Parsivel for the vth velocity class and the ith equivolume drop diameter class. Let Δt [s] be the measurement integration time, V_v [ms^{-1}] the class-centre velocity of the vth velocity class, and ΔD_i [mm] the width of the ith diameter class. Then we can convert the raw number of particles into a per-diameter-class volumetric drop concentration N_i^{Pars} [m^{-3} mm^{-1}] using

$$N_i^{\mathrm{Pars}} = \frac{1}{S_i^{\mathrm{Pars}} \Delta D_i \Delta t} \sum_{v=1}^{32} \frac{C_{v,i}}{V_v}. \tag{8}$$

It is worth noting that the Parsivel instrument itself calculates and provides an estimate of the rain intensity. In this paper we always refer to the estimate of rain rate provided by the Parsivel as the “Parsivel-derived intensity”, to avoid confusion with the DSD-derived rain rate R, which is defined by Eq. (5). The values of these two variables are usually very similar, but they are not exactly the same; differences are possibly due to peculiarities of the implemented Parsivel processing algorithm that is not public.

4.2 Two-dimensional-video-disdrometer

The 2DVD records details of individual drops, including the diameter and velocity of each and the effective sampling area of the instrument at the moment the drop was recorded. For our purposes it is practical to bin the drops into diameter classes. Let M be the number of drops that were recorded within one integration time of length Δt, and let S_j^{2DVD} [m^2] and V_j [m s^{-1}] be respectively the effective sampling area and fall velocity for the jth recorded particle. Then the ith equivolume diameter class, where the class width is ΔD_i [mm], will have a drop concentration N_i^{2DVD} [m^{-3} mm^{-1}] of

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$$N_i^{2DVD} = \frac{1}{\Delta D_i \Delta t} \sum_{j=1}^{M} \frac{1}{S_j^{2DVD} V_j}. \tag{9}$$

While most 2DVD-derived bulk rainfall variables are calculated using this N_i^{2DVD}, the rainfall rate R [m h^{-1}] for a given time step can be calculated directly from the individual drop measurements without binning the drops into classes. The rain rate is given by

$$R^{2DVD} = \frac{6\pi \times 10^{-4}}{\Delta t} \sum_{j=1}^{M} \frac{D_j^3}{S_j^{2DVD}}, \tag{10}$$

where D_j [mm] is the equivolume diameter of the jth recorded drop. The difference between the drop-wise rain rate and the rain rate calculated from a binned DSD is very small; in the 2DVD data used in this paper, the mean relative difference between DSD-derived rain rate and rain rate calculated drop-wise is less than 0.5 %.

While the classes for the Parsivel disdrometer are pre-defined, we can choose any class definition for the 2DVD data. For comparisons of drop concentrations with the Parsivel records, we have used Parsivel diameter classes for the 2DVD. For computation of the other bulk parameters from 2DVD data we have used diameter classes with a constant width of 0.2 mm, corresponding to the resolution of the 2DVD.

4.3 Criteria for suspicious particles

Before converting our raw drop counts into per-diameter-class volumetric drop counts, we perform some data processing, the aim of which is to filter out particles recorded by the Parsivels and the 2DVD that are very unlikely to be raindrops. These measurements are assumed to be caused by external interferences such as insects, or droplets of water caught in spider webs inside the measurement area. We use simple thresholds to exclude classes of velocity and diameter which are infeasable. To decide on the

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values for the thresholds, the 2DVD was used as the reference because it is not as easily affected by these external factors as Parsivel disdrometers.

Drops can only reach a certain size (about 10 mm) before they break up into smaller drops due to aerodynamic forces (Pruppacher and Klett, 2000). Figure 2 shows the distribution of drop sizes recorded in rain events from HYMEX (2012 and 2013) by the 2DVD. Table A2 shows the number of drops per diameter class for larger drops. Based on this information, and by looking at the velocity/diameter combinations that the 2DVD hardly ever recorded, we chose a filter that removes a drop with diameter D [mm] and velocity V [m s^{-1}] if any of the following conditions are true:

$$D > 7.5, \tag{11}$$

$$V > v(D) + 4, \tag{12}$$

$$V < v(D) - 3, \tag{13}$$

where $v(D)$ is the terminal velocity for a drop of equivolume diameter D as defined by Beard (1976). Figure 3 shows the occurrence of velocity/diameter combinations recorded by the 2DVD during the combined SOPs. Figure 4 shows similar plots for sums of drop counts per Parsivel diameter and velocity class, for both the 2DVD and Parsivel. In these figures, the gray area is the region in which drops will be removed. Over the combined SOPs dataset, the filter removed 0.2 % of the drops recorded by the 2DVD. This filtering of suspicious records was applied to both Parsivel and 2DVD data before resampling to any different time resolutions. To resample Parsivel records, the mean DSD was found over each new time period and bulk rainfall variables were then calculated from each mean DSD. The Parsivel precipitation type flag was resampled, to give an indication of the proportion of the time period for which solid precipitation was recorded. The worst quality flag was kept for each resampled time step, to give an indication of whether any low quality flags were raised during the resampled integration time.

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4.4 2DVD as reference instrument

Given that the 2DVD has previously been shown to produce better matches to independent rain rate measurements than Parsivel (e.g. Tokay et al., 2001; Krajewski et al., 2006), and that it provides higher resolution DSD measurements than Parsivel, both temporally and in the drop sizes it can discern, we use the 2DVD as the reference instrument in this work. To test the reliability of the 2DVD we compared the 2DVD measurements to collocated rain gauges for the HyMeX SOP 2013 campaign. Two separate instruments were collocated with the 2DVD during SOP 2013: a Vaisala weather station equiped with a rain cap, and a tipping bucket rain gauge. We compared the rain rate derived from the 2DVD drop data (Eq. 10) to rain gauge records. To remove solid particles we considered only time steps for which the collocated Parsivel recorded at least 90 % liquid precipitation, and for which the 2DVD and rain gauge both recorded a rain rate greater than or equal to 0.1 mm h^{-1}. One outlier time step, for which the 2DVD was only partially working (4 October 2013 18:00 UTC), was removed. The comparisons are shown in Fig. 5.

It is worth noting here the performance statistics we use in this work. In all scatterplots in this paper, the one-to-one line is shown in dashed red, while the blue line indicates the line of best fit found using linear least squares regression, with standard error shaded in gray. The reference instrument is always on the x axis. The regression slope ("reg. slope") is the slope of the regression line. For a given time t, let the reference value be R_t and the observed value be O_t. Let the total number of time steps be T. Then the mean ratio is defined as the reference mean divided by the observed mean:

$$\text{Mean ratio} = \langle R \rangle / \langle O \rangle. \tag{14}$$

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Let E_t be the difference for the tth time step, defined as $E_t = O_t - R_t$. RMSE is the root mean squared error,

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{T} E_t^2}{T}}. \tag{15}$$

r^2 is the squared Pearson correlation coefficient between reference and observed datasets. Bias is the mean of the differences, $\langle E \rangle$. Relative bias ("rel. bias") is the median of the relative errors, a percentage defined as

$$\mathrm{Rel.\ bias} = \mathrm{median}((O_t - R_t)/R_t \times 100). \tag{16}$$

We are only concerned with liquid precipitation in this paper, so we subset time steps to those in which the Parsivel recorded no solid precipitation (for five-minutes resolution) or at most 10 % solid precipitation (for one-hour resolution), and for which the Parsivels recorded no non-zero quality status flags. Further, we only ever compare timesteps for which both instruments being compared recorded non-zero rain amounts. We take 0.01 $\mathrm{mm\,h^{-1}}$ as the minimum rain rate the Parsivel can record in one 30 s integration time. Thus we use a non-zero rain rate threshold of 0.001 $\mathrm{mm\,h^{-1}}$ at five-minute resolution and of 8.3×10^{-5} $\mathrm{mm\,h^{-1}}$ at one-hour resolution. Because each tip of the tipping bucket rain gauges indicates 0.1 mm of accumulated precipitation, the minimum rain rate that a rain gauge can measure in five minutes is 1.2 $\mathrm{mm\,h^{-1}}$, and in one hour the minimum is 0.1 $\mathrm{mm\,h^{-1}}$. When comparing to rain gauges, the non-zero rain rate threshold therefore becomes 1.2 $\mathrm{mm\,h^{-1}}$ for five-minute resolution and 0.1 $\mathrm{mm\,h^{-1}}$ for one-hour resolution. Because our correction affects the DSD-derived rain rates from the Parsivels, we use the Parsivel-derived intensity when applying the non-zero threshold to Parsivel data. We refer to timesteps that satisfy these criteria as those with non-zero liquid DSDs.

The 2DVD shows excellent agreement with the tipping bucket rain gauge and Vaisala weather station, with high correlation coefficients (r^2 at least 0.98) and low bias

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amounts for both comparisons (absolute bias less than or equal to 0.2 mm h^{-1}). In both cases the 2DVD tends to slightly underestimate the rain amount given by the other gauge. We conclude, however, that the 2DVD provides reliable measurements of the rain rate. Note that the relative bias between 2DVD and gauge is −14 %, and between 2DVD and Vaisala is 9 %. The difference in these relative biases can be explained largely by differences in measurements of very small rain rates. This is equivalent to the relative bias we observed between two collocated Parsivels (Pradel 1 and Pradel 2) using the same constraints to choose comparison time steps, and also at one-hour resolution. Using Pradel 1 as reference, the relative bias was −8 % (15 %) in 2013 (2012). Using Pradel 2 as reference, the relative bias was 9 % (−13 %) in 2013 (2012). This means that when we compare Parsivel rain rates to rain gauges or to the 2DVD, we can not distinguish the level of agreement when the relative bias is less than about 10 %, due to instrumental uncertainty.

5 Correction of Parsivel DSDs

The correction of Parsivel DSDs is made in two steps. First, the raw Parsivel data is corrected so that per-diameter class mean velocities match the expected terminal velocity for each class. At this point the raw data can be screened for unfeasible measurements as described in Sect. 4.3. Second, a per-diameter-class adjustment factor is applied to Parsivel classes, in order to make the drop size distribution match, in a statistical way, that recorded by a 2DVD. In this section we address each correction in turn.

5.1 Correction of per-diameter-class drop velocities

Figures 3 and 4 show the density of particles recorded at each diameter/velocity combination, by the 2DVD and Parsivel disdrometers. Both the 2DVD and Parsivel record drops at a range of velocities for a given equivolume diameter or diameter class. In these plots, the black line is the expected terminal velocity per drop diameter, calculated using the method of Beard (1976). The 2DVD records the highest concentrations of drops on and very near the expected terminal velocities. Indeed in SOP 2013, for time steps for which the nearest Parsivel recorded liquid precipitation, the bias between expected terminal velocity and velocity recorded by the 2DVD was $0.04\,\mathrm{m\,s^{-1}}$ and the relative bias was 2 % (over the combined SOPs the bias was $0.2\,\mathrm{m\,s^{-1}}$ and relative bias was 6 %). We hence consider the terminal fall velocity from Beard (1976) as the reference value for fall velocity. The Parsivel tends to overestimate the velocities of small drops. To correct the velocities in the Parsivel data, we take the set of recorded velocities for each drop diameter class, and shift the values such that the mean velocity is equal to the expected terminal velocity as calculated by the algorithm of Beard (1976). Because the velocity classes do not have constant width, the classes are first subsampled into classes of width $0.1\,\mathrm{m\,s^{-1}}$, then shifted and regrouped into the original class sizes. Except when some drops were counted in very low velocity classes and are shifted out of the valid velocity range, the number of drops per diameter class remains the same before and after the velocity shift. An example plot of drop counts per velocity and diameter class before and after the velocity shift is shown in Fig. 6. The velocity shift is equivalent to shifting each column up or down such that the mean velocity for each column (which is usually close to the brightest point) aligns with the line that indicates the expected terminal velocity. As an example, for the average drop counts per velocity and diameter class for SOP 2013, using the Parsivel at Pradel Grainage, the mean shift required per diameter class from 0 to 5 mm was $-0.29\,\mathrm{m\,s^{-1}}$. Once the velocities are corrected in the raw Parsivel data, any suspicious particles are removed using the criteria shown in Sect. 4.3, and the volumetric drop concentrations per diameter class are found using Eq. (8). This correction and filtering was applied before resampling to any lower time resolutions.

5.2 Correction of diameter-class concentrations

With the velocities per diameter class accurate on average, we turn to correcting the drop concentrations per diameter class with reference to the 2DVD. Let $P(i)$ be the

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ratio of 2DVD drop concentration to Parsivel drop concentration, defined such that for the ith equivolume diameter class with centre-diameter D_i mm, at any given time step,

$$P(i) = \frac{N_i^{\mathrm{2DVD}}}{N_i^{\mathrm{Pars}}}. \tag{17}$$

$P(i)$ is thus the correction factor for that time step: when the Parsivel drop concentration for class i is multiplied by $P(i)$ it will match the 2DVD drop concentration for class i. We found median values of $P(i)$ per class of Parsivel-derived rain intensity. Parsivel-derived intensity was used as it is a measurement of the rain intensity that is always available with Parsivel disdrometers, and is independent of our DSD correction. The result was a collection of correction factors for each Parsivel-derived intensity class. When Parsivel records are multiplied by these correction factors, the per-diameter-class drop counts are scaled to match the corresponding 2DVD drop counts.

To explain the correction in more detail, we take as an example the HYMEX 2012 and 2013 SOPs and show each step of the correction calibration. We use data from SOP 2013 to train the correction, because there was a Parsivel collocated with the 2DVD at Pradel Grainage in that campaign. We use a time resolution of one hour, in order to increase the chance of a time step sampling large drops, and in order to smooth outliers. Assuming the obtained correction is not dependent on the temporal resolution, it will be applied at resolutions higher than one hour in order to have reliable Parsivel DSD measurements for studies of small-scale DSD variability. A strict set of criteria is used to choose which time steps the comparison should be performed on. We use time steps for which the 2DVD and the collocated Parsivel recorded a non-zero liquid DSD. For all of SOP 2013 there are 234 such time steps, corresponding to 234 h of rainfall over which we train the correction factors. For each valid time step, we compare the mean DSD recorded by the 2DVD and collocated Parsivel.

Values of $P(i)$ are calculated for each time step in the training set, by comparing the Parsivel DSD to the 2DVD DSD. The result is a distribution of P values for each drop

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diameter class. To investigate the effect of rain intensity on the values of $P(i)$, we divide the time steps into classes of intensity, using the Parsivel-derived intensity modelled by the sensor. The median $P(i)$ values of each intensity and diameter class are shown in Fig. 7. There is clearly an dependency between the values in the $P(i)$ curve and the rain intensity.

The most notable feature of Fig. 7 is that the numbers of small drops (under about 0.7 mm) are severely overestimated by the Parsivel. For these classes, the values of $P(i)$ are low, indicating that the Parsivel drop counts need to be scaled down to match the corresponding 2DVD drop counts. For low rain rates below 1 mm h^{-1}, the Parsivel overestimates drop counts in all classes up to 4 mm. Note that large drops are very rare in these rain rate classes, and as we will see the values of $P(i)$ are more reliable for smaller drop sizes. Across all rain rate classes there is a tendancy for the Parsivel to overestimate the numbers of drops less than 0.81 mm and greater than 1.88 mm diameter, with the best performance occuring in the 1–2 mm drop diameter range. For rain rates above 2 mm h^{-1}, the Parsivel more closely matches the 2DVD and indeed underestimates the numbers of drops between about 0.8 mm and 1.6 mm in diameter.

We identify groups of behaviour of $P(i)$ by ranges of Parsivel-derived intensity, and thus divide the intensities into four classes for ranges $[0, 0.5)$, $[0.5, 1)$, $[1, 2)$ and $[2, 200)$ mm h^{-1}. Using these ranges as the class definitions for Parsivel-derived intensity, we obtain distributions of $P(i)$ per drop diameter and Parsivel-derived intensity class that are shown in Fig. 8. The distributions are over all time steps, and they get larger as the drop diameter increases, which shows that there is much more uncertainty in the correction factors for large than for small diameters.

To train the correction factors, we randomly select sets of 80 % of the valid training time steps. To determine the impact of sampling effect, we rerun the calibration 100 times with different randomly chosen calibration time steps, taking the median of the per-class $P(i)$ distribution each time, and recording the range of resulting values. These ranges are shown per Parsivel-derived intensity class in Fig. 9. We see that the sampling effect for small drops is very small, but that it grows larger for larger drop

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size classes. To ensure a more robust correction, we want to only apply the correction to drop diameter classes for which the training sampling effect (the spread) on $P(i)$ is small. However, in order for the correction to affect all moments of the DSD it is important that it is applied larger drops as well as smaller ones. We decided to apply a threshold on the spread of the sampling effect. The correction is kept for increasing drop diameters until the sampling effect first surpasses this threshold.

There are hence two threshold values that must be chosen for this correction. The first is the minimum allowed volumetric drop concentration for which 2DVD and Parsivel classes will be compared; let this threshold be Q [$\mathrm{mm}^{-1}\,\mathrm{m}^{-3}$]. The second threshold is the maximum allowed spread in values of $P(i)$ over 100 training iterations of the filter; let this threshold be A. Q was set to 1×10^{-5} and acted simply to stop diminishingly small drop concentrations from adversely affecting the correction calibration. A was set to 0.7. A sensitivity analysis showed that the values of Q and A do not affect greatly the outcome of the calibration, so long as Q is low enough and A is large enough to allow for sampling and therefore correction of larger drops sizes.

To derive the final correction factors we iterate over 100 sets of training time steps, selecting randomly 80 % of the available times for each iteration. The per-diameter and per-intensity class correction factor is the mean value of $P(i)$ for each class over all iterations. The calibrated correction factors for SOP 2013 are shown in Table 2. The largest drop diameter class affected by the correction is the 20th Parsivel class, with a centre size of 4.75 mm. Drops up to the 16th class (class-centre diameter 2.75 mm) are affected no matter the Parsivel-derived intensity. Larger drops are affected only when the Parsivel-derived intensity is larger than 1 $\mathrm{mm\,h}^{-1}$ (up to the 17th class) or 2 $\mathrm{mm\,h}^{-1}$ (up to the 20th class). To apply the correction, each time step is taken separately and, depending on the Parsivel-derived intensity of the time step, the appropriate scaling factors are applied to each equivolume drop diameter amount.

The correction ensures that the corrected DSD more closely matches the DSD recorded by the 2DVD. For example, for the HYMEX SOP 2013 data, Fig. 10 shows the distributions of $P(i)$ after the correction, for one example validation set of 20 % of

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the one-hour time steps in SOP 2013. After the correction the DSD much more closely matches that of the 2DVD, especially for small drop diameter classes. For larger drops of greater than about 3 mm the match is not as close, but note this is 20 % of the data and sampling effect changes large drop comparisons much more than small ones. The fact that the large drops differ from the 1 : 1 line reflects the difficulty in training a correction for classes in which there are not many drops to use as a training set, and demonstrates why we chose to train on one-hour time steps and to use the mean $P(i)$ values over many iterations.

6 Drop concentration correction results

In this section we explore the effect of the correction on the moments of the DSD, including the derived rain rate. Our goal in this work is to have reliable DSD measurements from networks of Parsivel disdrometers, in order to be able to study the small-scale variability of the DSD in space and time. We are therefore interested in higher time resolutions than the one-hour resolution we used to train the correction factors. Recall that the choice of one-hour resolution for the training set was made to increase the numbers of sampled large drops, but that we aim to have a correction that is independent of the time resolution. We thus apply the trained correction to five-minute time resolution data to evaluate its effects, for all first generation Parsivels in the SOP 2013 campaign. We also apply the correction to data from SOP 2012, as an independent validation dataset, and to the combined SOPs. Recall that because we are only interested in liquid precipitation, we subset the available time steps for each Parsivel station to those that contained no Parsivel warning flags regarding data quality, and no solid precipitation markers, and we only compare time steps for which both instruments being compared measured non-zero rain rates.

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6.1 DSD moments

To demonstrate the effect of the Parsivel DSD correction on the moments of the DSD, we compare the first seven moments of the DSD recorded by the 2DVD, to the same moments derived from Parsivel DSDs before and after the correction is applied. For these comparisons we use HYMEX SOP 2013 event time steps at five-minute resolution, and the Parsivel collocated with the 2DVD at Pradel Grainage. Comparisons of moments of order zero, one, four, and six are displayed in Fig. 11, QQplots for these moments are shown in Fig. 12, and timeseries statistics are shown in Table 3. We see from the densities and QQplots that the correction shifts the distributions of all the moments towards those of the 2DVD. The statistics show an improvement in the relative bias of all moments, by a maximum of 123 % for moment zero and a minimum of 33 % for moment four. RMSE is improved for all moments. r^2 is improved for moments of order zero, one, and two, and remains very similar for higher moments. These results demonstrate that the correction improves Parsivel DSDs at high temporal resolution even when it is trained from one-hour DSD spectra.

6.2 Effect on rain rates

Having confirmed that the correction shifts the densities of the DSD moments towards those of the 2DVD, we now use independent instruments – collocated tipping bucket rain gauges – to test the effect of the correction on the rain rates produced by Parsivel DSDs. Two tipping bucket rain gauges provided measurements that we considered to be suspicious. The station at Mirabel-Pradel-Ferme-2, which is physically closest to our Parsivels Pradel 1 and Pradel 2, produced a marked overestimate of the rain amounts compared to those Parsivels, the 2DVD, and the tipping bucket raingauge at Mirabel-Pradel-Ferme-1. For this reason we use Mirabel-Pradel-Ferme-1 as the reference gauge at this location. Mirabel-Pradel-Ferme-1 is located approximately 12 m away from Mirabel-Pradel-Ferme-2. Similarly, the rain gauge at Lavilledieu-Ecole-2 was physically closest to our Parsivel at Lavilledieu, but for a period

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of 1.5 h on the 18 September 2012, this rain gauge produced rain rates that were markedly smaller than the rain rates produced by our Parsivel and the nearby tipping bucket gauge Lavilledieu-Ecole-1. This gauge, which was approximately 12 m away, provided measurements that more closely matched the Parsivel during this time. We thus use Lavilledieu-Ecole-1 as the reference rain gauge for this station.

We compile performance statistics for each of the first generation Parsivel stations, before and after the correction is applied, for five-minute time resolution. As an example, Fig. 13 shows a scatterplot of rain rates compared to a collocated tipping bucket rain gauge for Pradel 1, the Parsivel that was closest to the 2DVD and deployed in both 2013 and 2012, for five-minute time resolution across both campaigns. The statistics for this station show that the correction produces a clear improvement in the rain rate; the relative bias is reduced by 12 %, the mean ratio and regression slope are both closer to one and the RMSE is reduced.

Given that the correction was trained only on SOP 2013 data, it makes sense to look at the results from SOP 2012 and SOP 2013 separately as well as together. For SOP 2012 only, the performance effects per statistic are shown in Table 4. For SOP 2013 only, the performance effects are shown in Table 5. The differences shown are between the performance statistics after the corrections (velocity and concentration) have both been made, minus the statistics when no correction has been made. The before and after sets are both screened using the same method to remove implausible measurements. For SOP 2012, the correction improves the RMSE, bias, and relative bias at four of the seven stations. At two of the stations (Pradel 1 and Mirabel) the performance is hardly affected by the DSD correction. At the remaining two stations (Lussas and Lavilledieu) the relative bias is degraded, leaving the final relative bias at these stations as −11 % and −10 % respectively; both these relative biases are close to the instrumental variability we observed in Sect. 4.4. Recall that the 2DVD slightly underestimates the rain rate with respect to collocated gauges. For SOP 2013, the RMSE and bias are improved at six of eight stations, and relative bias is improved at seven of eight stations, and r^2 is hardly changed. The remaining station (Mirabel) shows a degradation of relative bias to an after-correction relative bias of −22 %. At Mirabel, the Parsivel was placed on the edge of a retaining wall, which may have introduced turbulence and affected the Parsivel measurements.

For the combined SOPs dataset, the Parsivel performance statistics before any correction are shown in Table A3, after both velocity and concentration corrections in Table A4, and the changes made to the performance by the DSD correction are shown in Table 6. From these data we can see that RMSE, bias, and relative bias are all improved at six of the eight stations. At the other two stations (Lavilledieu and Mirabel) there is a degradation of performance in terms of rain rate, by about 4 % in terms of relative bias. The relative bias at Lavilledieu after the correction has been applied is −7 %, which is within the instrumental error limits. Mirabel may have suffered from turbulence effects; its relative bias across the combined SOPs is already −17 % before any correction was performed. Despite degradations in R that are limited to two disdrometers, this analysis of the influence of the correction on the combined SOPs dataset confirms its overall benefit to the DSD recorded by Parsivel disdrometers, even at high temporal resolution.

6.3 Results at lower temporal resolution

To further test the effects of the correction on Parsivel DSD-derived rain rates compared to collocated rain gauges, and to test the applicability of the filter to different time resolutions, we perform the same analysis as in the previous section, but for one-hour temporal resolution on the combined SOPs dataset. The differences made by the correction to the DSD moments at one-hour time resolution are shown in Table 7. At one-hour time resolution, the correction improves the bias and relative bias on all moment orders, while RMSE is improved for all orders except the 3rd, for which it is hardly changed. r^2 between moment orders before and after the correction is improved for moments of order one to three, and maintained at the same level for the other moments. The differences made to the rain rate to gauge comparisons at one-hour resolution are shown in Table 8. RMSE is improved at five of the eight stations, and bias at three of

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the eight. Relative bias is degraded in all but two cases. This degradation is attributable to very small rain rates; indeed when we select time steps for which the rain rate was greater than 1.2 mm h^{-1}, the relative bias is improved at five of the eight stations, and only the station at Mirabel has an after-correction relative bias that is greater than the instrumental variability. For rain rates between 0.1 and 1.2 mm h^{-1}, the after-correction bias is negative at all stations and the per-station mean bias is -0.13 mm h^{-1}. This bias is similar to the bias of the 2DVD compared to the gauge for the same rain rates of -0.08 mm h^{-1}. We conclude that the correction works to make the Parsivels match the 2DVD, which itself underestimates rain rate for low rain rates when compared to a collocated gauge. We recommend that care is taken with the application of this correction to rain rates below 1.2 mm h^{-1}.

7 Application to Parsivel 2

We apply our method to second generation Parsivels (Parsivel 2 hereafter) that were also deployed in the HYMEX 2013 campaign. To train the correction for Parsivel 2 we follow the same method of comparing Parsivel records for the station at Pradel Grainage to the collocated 2DVD to train the correction factors per Parsivel-derived rain intensity class. The only difference is that, due to changes between the first and second generation Parsivels, the curves of $P(i)$ per Parsivel-derived intensity class show different and more complex behaviour to those of Parsivel 1. The classes we used were $[0,0.1)$, $[0.1,0.25)$, $[0.25,0.5)$, $[0.5,1)$, $[1,2)$ and $[2,200)$ mm h^{-1}.

Apart from the different Parsivel-derived rain intensity class definitions, the training process is identical to that shown in Sect. 5. The resulting correction factors are shown for the HYMEX Parsivel 2 dataset in Table 9. A comparison of the corrections for Parsivel 1 and 2 is shown in Fig. 14, and shows important differences. Both filters are similar for drops up to about 1 mm in diameter, in that they both show Parsivel overestimating drops in comparison to the 2DVD. Parsivel 2 is shown to underestimate the numbers of drops between 1.38 mm and 3.25 mm diameter. Drops larger than 3.5 mm are overestimated by both generations of Parsivel, but less so by Parsivel 2.

After training the correction factors for each campaign we apply them to Parsivel 2 data for all available stations. Due to small differences in clock times between the rain gauges and Parsivel 2 stations we use one-hour time resolution. We first compare the moments to the 2DVD moments for event time steps only; these results are shown in Table 11. The bias is improved for moments of order zero to three, six, and seven, but is degraded for moments of order four and five. Moments of orders four and five have the two lowest biases before the correction. In contrast, the relative bias is improved for all moment orders except the sixth, where it is maintained essentially at the same level, and the seventh. This indicates that the distribution of differences for moment of orders four and five may include outliers which affect the bias. RMSE and r^2 are improved for all moment orders.

We compare the rain rates after the correction of Parsivel 2 s to those recorded by collocated rain gauges, for all available time steps. Due to timing errors with the Parsivel 2 network, we apply the correction to one-hour time steps. The results are shown in Table 10. Absolute bias is improved at one station, but degraded at the others, while relative bias is improved at two stations. Again, there appears to be an effect of low rain rate on these performance statistics. When we count only time steps with rain rates at or above 1.2 mm h^{-1}, the worst degradation in relative bias drops from 22 % to 15 %. There are many outliers in these datasets, and work is ongoing to further refine the correction on these Parsivel 2 data. Despite this degradation, the correction markedly improves the moments compared to the 2DVD. We hypothesise that training the Parsivel 2 correction factors using more data and therefore a lower time resolution, plus fixing potential clock issues in this dataset, would improve the performance of the correction on Parsivel 2 data.

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8 Conclusions

We have developed a method to correct raindrop size distributions recorded by Parsivel disdrometers, using a two-dimensional-video-disdrometer as a reference instrument. The correction is made in two steps. First, raw Parsivel drop counts binned by velocity and diameter are shifted so that per-diameter-class mean velocities align with expected terminal velocities. The raw data can then be screened for particles that are unlikely to be raindrops, and per-diameter-class volumetric drop concentrations can then be calculated. Second, these volumetric drop concentrations are adjusted by factors trained by reference to the 2DVD. The adjustment causes the drop concentrations to match those of the 2DVD in a statistical way. The correction was applied to Parsivel and Parsivel 2 data from two autumn field campaigns in Ardèche, France. The results show a marked improvement in the accuracy of moments of the DSD, when compared to the 2DVD as the reference instrument. Comparison of the intermediate moment of rain rate to collocated rain gauges shows changes that are acceptable, given the overall improvement in the accuracy of the DSD afforded by the correction. The correction is shown to be timescale-independent through application to both five-minute and one-hour Parsivel records. While in this case the correction is trained on a dataset containing mainly light to intermediate rain rates (mostly below 20 mm h^{-1}), the method is flexible because it is conditioned on the Parsivel-derived rain intensity, and could be trained for higher rain rate classes as required. The correction offers the ability to improve the accuracy of the DSDs recorded by Parsivel disdrometers, which are instruments that are especially suitable for deployment in networks. High-quality DSD measurements from networks of Parsivel disdrometers can be used in valuable work on topics such as the small-scale variability of the drop size distribution. Further work is ongoing to test the transferability of the correction method to other climatologies.

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Table 1. Disdrometer station information, showing the instrument (P1 = Parsivel 1, P2 = Parsivel 2), its WSG84 coordinates of each station, its altitude [m] a.s.l., the number of hours it recorded liquid precipitation ($R \geq 0.01\,\mathrm{mm\,h^{-1}}$) with all quality control flags positive per campaign for 2012 (H12) and 2013 (H13), and the total amount [mm] it recorded for those times in 2012 (A12) and in 2013 (A13).

Inst	Name	Lat [°N]	Long [°E]	Alt	H12	H13	A12	A13
P1	Lavilledieu	44.5772	4.4532	227	169	111	250	221
P1	Les Blaches	44.6008	4.4810	429	148	107	254	207
P1	Lussas	44.6123	4.4706	289	117	102	224	179
P1	Mirabel	44.6069	4.4987	496	168	125	255	237
P1	Pradel 1	44.5829	4.4987	278	145	117	256	201
P1	Pradel 2	44.5829	4.4987	278	149	106	283	155
P1	Pradel Grainage	44.5790	4.5011	271		105		195
P1	St-Germain	44.5551	4.4497	204	158	89	281	97
P2	Mont-Redon	44.6141	4.5148	636		134		213
P2	Pradel Grainage	44.5790	4.5011	271		118		194
P2	Pradel-Vignes	44.5801	4.4950	256		47		126
P2	Villeneuve-de-Berg	44.5547	4.4954	301		111		187
P2	Villeneuve-de-Berg 2	44.5547	4.4954	301		113		196
2D	2DVD	44.5790	4.5011	271	129	96	230	199

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Table 2. Calibrated Parsivel 1 correction factors for Parsivel-derived intensity classes for the SOP 2013 campaign. Each row contains the class number, the centre equivolume diameter for the class (D_i), and the calibrated factors P(i) for each class of Parsivel-derived intensity. Intensity class boundaries are provided in mm h^{-1}.

Class (i)	D_i [mm]	[0,0.5)	[0.5,1)	[1,2)	[2,200)
3	0.31	0.05	0.06	0.09	0.12
4	0.44	0.12	0.15	0.24	0.28
5	0.56	0.39	0.44	0.63	0.66
6	0.69	0.49	0.54	0.71	0.85
7	0.81	0.70	0.78	0.94	1.13
8	0.94	0.74	0.74	0.97	1.09
9	1.06	0.85	0.84	1.03	1.26
10	1.19	0.90	0.85	1.03	1.27
11	1.38	0.85	0.81	1.00	1.22
12	1.62	0.75	0.72	0.89	1.03
13	1.88	0.74	0.58	0.77	0.96
14	2.12	0.66	0.55	0.71	0.88
15	2.38	0.51	0.56	0.62	0.83
16	2.75	0.47	0.45	0.47	0.77
17	3.25	0.42		0.38	0.71
18	3.75			0.46	0.53
19	4.25				0.42
20	4.75				0.19

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Table 3. Timeseries statistics per moment, comparing Parsivel data (at Pradel Grainage) before ("bef.") and after ("aft.") the correction is applied, to the 2DVD, at five-minute resolution. The 2DVD is taken as the reference. Units of bias and RMSE are $m^{-3}\,mm^{p}$ where p is the moment order. "R.b." stands for relative bias.

Moment	Bias bef.	Bias aft.	R.b. bef.	R.b. aft.	RMSE bef.	RMSE aft.	r^2 bef.	r^2 aft.
0	113.21	11.02	139.53	16.26	197.46	43.85	0.57	0.91
1	51.00	9.61	87.08	19.04	89.59	36.78	0.77	0.93
2	30.07	9.69	67.49	21.71	54.46	40.94	0.93	0.95
3	32.21	12.69	63.90	26.40	69.92	62.46	0.96	0.95
4	69.43	24.59	66.18	33.18	213.84	132.61	0.95	0.95
5	218.98	73.58	79.25	42.37	831.12	397.94	0.93	0.93
6	818.32	302.59	97.61	50.73	3481.05	1628.24	0.90	0.89
7	3402.98	1483.87	123.17	63.48	15604.67	8151.77	0.85	0.82

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Table 4. Performance effects of the drop concentration correction on Parsivel data, and stations on which comparisons were performed, for SOP 2012 only at five minute time resolution. N is the number of time steps on which comparison was possible (high quality, liquid precipitation only). ΔRMSE and Δ|bias| are in units of mm h^{-1}, while Δ|r.bias| is a percentage.

Parsivel	Pluvio	ΔRMSE	Δ|bias|	Δ|r.bias|	Δr^2	N
Mirabel	Mirabel-Mairie	0.616	0.486	0.701	0.005	269
Lussas	Lussas-Salle-Polyvalente	0.365	0.496	9.950	−0.001	287
St-Germain	Saint-Germain-Ecole	−0.105	−0.201	−6.107	−0.009	652
Lavilledieu	Lavilledieu-Ecole-2	0.340	0.379	5.771	−0.005	637
Les Blaches	Mirabel-Les-Blaches	−0.147	−0.386	−10.302	−0.005	297
Pradel 1	Mirabel-Pradel-Ferme-1	−0.132	−0.165	−0.925	−0.008	299
Pradel 2	Mirabel-Pradel-Ferme-1	−0.746	−0.538	−12.055	−0.006	325

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Table 5. Performance effects of the drop concentration correction on Parsivel data, and stations on which comparisons were performed, for SOP 2013 only at five minute time resolution. N is the number of time steps on which comparison was possible (high quality, liquid precipitation only). ΔRMSE and Δ|bias| are in units of mm h^{-1}, while Δ|r.bias| is a percentage.

Parsivel	Pluvio	ΔRMSE	Δ|bias|	Δ|r.bias|	Δr^2	N
Mirabel	Mirabel-Mairie	1.947	1.279	8.131	−0.000	133
Lussas	Lussas-Salle-Polyvalente	−0.816	−0.698	−11.771	−0.006	371
St-Germain	Saint-Germain-Ecole	0.568	0.141	−3.332	−0.017	204
Lavilledieu	Lavilledieu-Ecole-2	−0.530	−0.562	−12.474	−0.005	386
Pradel Grainage	Pradel Grainage	−0.900	−0.753	−14.833	−0.008	374
Les Blaches	Mirabel-Les-Blaches	−0.278	−0.119	−1.137	−0.004	193
Pradel 1	Mirabel-Pradel-Ferme-1	−0.850	−0.695	−15.526	−0.004	218
Pradel 2	Mirabel-Pradel-Ferme-1	−0.903	−0.691	−16.637	−0.003	166

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Table 6. Performance effects of the drop concentration correction on Parsivel data, and stations on which comparisons were performed, for combined SOPs at five-minute time resolution. N is the number of time steps on which comparison was possible. ΔRMSE and Δ|bias| are in units of $\mathrm{mm\,h^{-1}}$, while Δ|r.bias| is a percentage.

Parsivel station	Rain gauge	ΔRMSE	Δ|bias|	Δ|r.bias|	Δr^2	N
Mirabel	Mirabel-Mairie	1.164	0.752	4.603	0.003	402
Lussas	Lussas-Salle-Polyvalente	−0.369	−0.336	−10.601	−0.004	658
St-Germain	Saint-Germain-Ecole	0.048	−0.122	−6.085	−0.021	856
Lavilledieu	Lavilledieu-Ecole-2	−0.086	0.262	3.785	−0.001	1023
Pradel Grainage	Pradel Grainage	−0.900	−0.753	−14.833	−0.016	374
Les Blaches	Mirabel-Les-Blaches	−0.202	−0.279	−7.374	−0.009	490
Pradel 1	Mirabel-Pradel-Ferme-1	−0.437	−0.593	−12.188	−0.016	517
Pradel 2	Mirabel-Pradel-Ferme-1	−0.798	−0.591	−12.892	−0.010	491

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Table 7. Timeseries statistics per moment, comparing Parsivel data (at Pradel Grainage) before ("bef.") and after ("aft.") the correction is applied, to the 2DVD, at one-hour resolution. The 2DVD is taken as the reference. Units of bias and RMSE are m^{-3} mm^p where p is the moment order. "R.b." stands for relative bias.

Moment	Bias bef.	Bias aft.	R.b. bef.	R.b. aft.	RMSE bef.	RMSE aft.	r^2 bef.	r^2 aft.
0	70.73	−0.25	107.59	−1.84	132.63	44.17	0.45	0.76
1	30.41	0.62	60.87	0.42	65.45	38.04	0.66	0.81
2	16.30	−0.09	42.24	1.73	51.92	46.51	0.82	0.83
3	16.07	−2.74	38.72	7.47	80.21	80.25	0.84	0.82
4	35.78	−10.25	46.74	13.65	201.90	191.19	0.80	0.78
5	120.92	−28.61	63.10	21.57	662.64	586.27	0.72	0.70
6	481.63	−49.52	82.49	28.81	2526.18	2141.62	0.61	0.60
7	2127.64	141.11	102.07	43.65	10688.27	8874.78	0.50	0.49

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Table 8. Performance effects of the drop concentration correction on Parsivel data, and stations on which comparisons were performed, at one-hour time resolution. N is the number of time steps on which comparison was possible. ΔRMSE and Δ|bias| are in units of mm h^{-1}, while Δ|r.bias| is a percentage.

Parsivel station	Rain gauge	ΔRMSE	Δ|bias|	Δ|r.bias|	Δr^2	N
Mirabel	Mirabel-Mairie	0.459	0.309	15.416	0.005	122
Lussas	Lussas-Salle-Polyvalente	−0.072	0.161	16.158	0.006	183
St-Germain	Saint-Germain-Ecole	0.029	0.077	15.328	−0.010	223
Lavilledieu	Lavilledieu-Ecole-2	0.153	0.286	22.680	−0.004	277
Pradel Grainage	Pradel Grainage	−0.088	−0.075	−12.309	−0.019	131
Les Blaches	Mirabel-Les-Blaches	−0.049	0.083	15.706	−0.005	117
Pradel 1	Mirabel-Pradel-Ferme-1	−0.124	−0.008	12.317	−0.009	130
Pradel 2	Mirabel-Pradel-Ferme-1	−0.204	−0.131	−2.581	−0.012	118

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Table 9. Calibrated Parsivel 2 correction factors for Parsivel-derived intensity classes for the HYMEX 2013 campaigns. Each row contains the class number, the centre equivolume diameter for the class (D_i), and the calibrated factors $P(i)$ for each class of Parsivel-derived intensity. Intensity class boundaries are provided in mm h^{-1}.

Class (i)	D_i [mm]	[0,0.1)	[0.1,0.25)	[0.25,0.5)	[0.5,1)	[1,2)	[2,200)
3	0.31	0.02	0.04	0.04	0.05	0.06	0.07
4	0.44	0.03	0.05	0.05	0.07	0.11	0.16
5	0.56	0.11	0.16	0.19	0.22	0.30	0.36
6	0.69	0.20	0.26	0.29	0.36	0.45	0.54
7	0.81	0.36	0.47	0.52	0.53	0.71	0.78
8	0.94	0.55	0.55	0.67	0.67	0.80	0.86
9	1.06	0.86	0.85	0.94	0.89	1.01	1.03
10	1.19	0.74	0.84	1.08	0.90	1.17	1.03
11	1.38	1.04	1.13	1.22	1.12	1.36	1.12
12	1.62	1.10	1.20	1.35	1.19	1.37	1.10
13	1.88	1.14	0.97	1.34	1.17	1.41	1.04
14	2.12			1.25	1.17	1.22	0.97
15	2.38			1.29	1.17	1.43	1.06
16	2.75			1.43		1.37	1.07
17	3.25					1.31	1.02
18	3.75						0.97
19	4.25						0.73
20	4.75						0.58
21	5.50						0.45
22	6.50						0.32

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Table 10. Performance effects of the drop concentration correction on Parsivel 2 network data, and stations on which comparisons were performed. N is the number of time steps on which comparison was possible. ΔRMSE and Δ|bias| are in units of mm h^{-1}, while $\Delta|r.\text{bias}|$ is a percentage.

Parsivel	Pluvio	ΔRMSE	Δ|bias|	Δ|r.bias|	Δr^2	N [h]
Villeneuve-de-Berg	Villeneuve-de-Berg-2	0.07	0.13	7.86	−0.01	129
Mont-Redon	Mirabel-Mont-Redon	0.04	−0.12	−22.09	−0.00	128
Pradel-Vignes	Mirabel-Pradel-Vignes	0.09	0.19	−0.46	0.00	58
Pradel Grainage	Pradel Grainage	0.30	0.35	10.40	−0.01	154
Villeneuve-de-Berg 2	Villeneuve-de-Berg-2	0.18	0.35	18.32	−0.01	132

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Table 11. Timeseries statistics per moment, comparing Parsivel 2 data (at Pradel Grainage) before ("bef.") and after ("aft.") the correction is applied, to the 2DVD, at ten minute resolution. The 2DVD is taken as the reference. Units of bias and RMSE are $m^{-3}\,mm^{p}$ where p is the moment order. "R.b" stands for relative bias.

Moment	Bias bef.	Bias aft.	R.b. bef.	R.b. aft.	RMSE bef.	RMSE aft.	r^2 bef.	r^2 aft.
0	166.10	−3.20	268.90	−0.46	252.12	44.46	0.39	0.78
1	74.22	−1.25	172.75	0.65	113.59	38.17	0.55	0.82
2	34.10	−1.50	90.83	0.78	65.85	45.19	0.77	0.85
3	13.52	−3.76	49.64	0.12	73.42	70.82	0.87	0.88
4	1.56	−11.04	29.01	−0.18	144.25	144.89	0.89	0.90
5	9.54	−35.22	14.18	−3.62	399.39	381.95	0.89	0.91
6	150.37	−122.25	4.64	−4.66	1553.18	1262.01	0.88	0.92
7	1141.04	−459.57	−2.21	−7.28	7617.83	4978.05	0.87	0.91

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Table A1. Clock adjustments for 2DVD events in HYMEX SOP 2013.

Event #	From (UTC)	To (UTC)	Adjustment [s]
24 and 25	20 Oct 2013 00:00:00	24 Oct 2013 00:00:00	60
26	27 Oct 2013 00:00:00	28 Oct 013 00:00:00	30
27	2 Nov 2013 00:00:00	3 Nov 013 00:00:00	60
28	4 Nov 2013 00:00:00	5 Nov 013 00:00:00	60
29	5 Nov 2013 00:00:00	6 Nov 013 00:00:00	30
30	18 Nov 2013 00:00:00	19 Nov 013 00:00:00	30

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Table A2. Numbers of large drops recorded by the 2DVD during the combined SOPs event times.

Diameter class [mm]	Number of drops	% total drops
(5,5.5]	273	0.00531
(5.5,6]	97	0.00189
(6,6.5]	36	0.00070
(6.5,7]	10	0.00019
(7,7.5]	3	0.00006
(7.5,8]	1	0.00002

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Table A3. Performance statistics for rain rate per Parsivel station for the combined SOPs, before the DSD correction is applied. RMSE and bias are in units of mm h^{-1}; relative bias is a percentage.

Parsivel station	RMSE	Bias	r^2	Rel. bias	Fit slope	Mean ratio
Mirabel	1.50	−0.76	0.98	−16.77	1.01	0.88
Lussas	1.50	0.47	0.94	10.95	1.16	1.11
St-Germain	1.03	0.32	0.96	7.14	1.11	1.07
Lavilledieu	1.21	0.18	0.96	3.07	1.13	1.04
Pradel Grainage	1.97	1.08	0.97	25.15	1.28	1.27
Les Blaches	1.27	0.43	0.95	8.82	1.15	1.11
Pradel 1	1.50	0.66	0.95	15.02	1.19	1.16
Pradel 2	1.63	0.83	0.97	19.19	1.28	1.21

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Table A4. Performance statistics for rain rate per Parsivel station for the combined SOPs, after the DSD correction is applied. RMSE and bias are in units of mm h^{-1}; relative bias is a percentage.

Parsivel station	RMSE	Bias	r^2	Rel. bias	Fit slope	Mean ratio
Mirabel	2.67	−1.51	0.98	−21.37	0.76	0.78
Lussas	1.13	−0.13	0.94	−0.35	0.90	0.97
St-Germain	1.08	−0.20	0.94	−1.06	0.86	0.96
Lavilledieu	1.12	−0.44	0.96	−6.86	0.87	0.91
Pradel Grainage	1.07	0.32	0.96	10.31	0.94	1.07
Les Blaches	1.07	−0.15	0.94	−1.45	0.86	0.97
Pradel 1	1.06	0.07	0.93	2.84	0.91	1.02
Pradel 2	0.83	0.24	0.96	6.30	0.97	1.06

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Figure 1. Parsivel stations (green) and Parsivel 2 stations (blue) in the HYMEX field campaigns. Montbrun and Pradel Grainage first generation stations were deployed only in 2013. Pradel was the location of collocated Parsivel first generation stations. Pradel Grainage was the location for both first and second generation instruments in 2013. Two Parsivel 2 stations were collocated in Villeneuve-de-Berg. The 2DVD was located at Pradel Grainage. The inset map shows the location of the field area in France (not to scale). Map data ©OpenStreetMap (ODbL).

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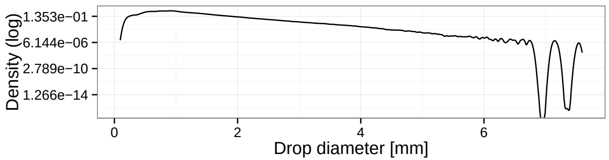

Figure 2. Distribution of drop diameters recorded by the 2DVD in SOP 2012 and SOP 2013 events, with the *y* axis on a log scale.

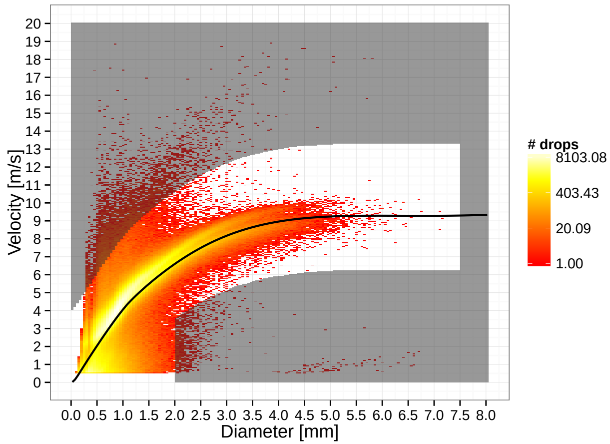

Figure 3. Occurrence of velocity/diameter combinations, with drop counts on a log scale, recorded by 2DVD during the HYMEX campaigns in the autumns of 2012 and 2013. The physical-drop filter is overlaid in grey. The black line indicates the Beard 1976 expected terminal drop velocity.

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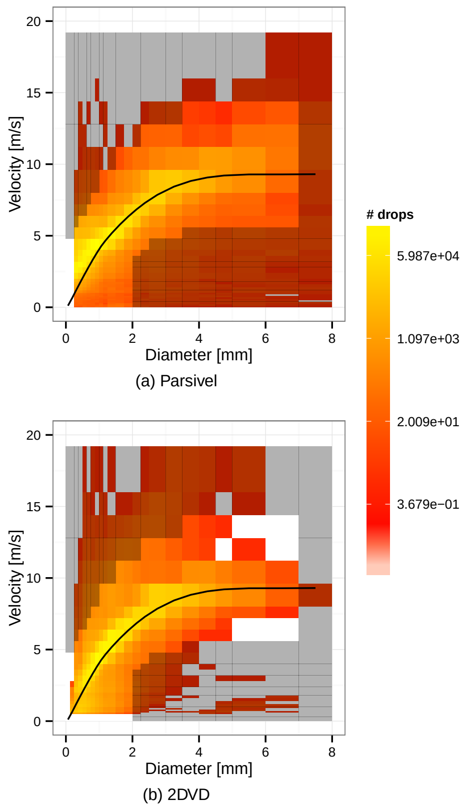
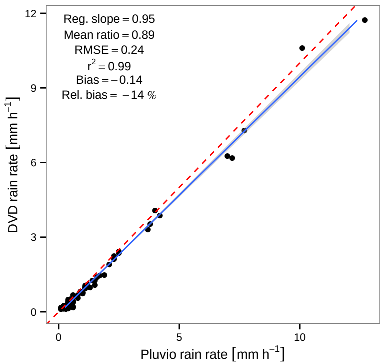
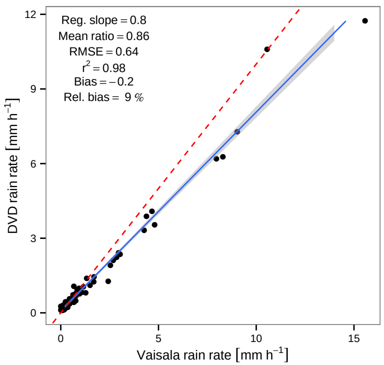


Figure 4. Sum of raw drop occurrences per Parsivel class, for the 2012 and 2013 campaigns. Parsivel counts are summed at stations Pradel 1 (for 2012) and Pradel Grainage (for 2013). The filtered areas are overlaid in grey. The black line is the expected terminal drop velocity calculated by Beard (1976). Drop counts are specified by colour on a log scale.



(a) Pluvio to 2DVD, 2013.



(b) Vaisala to 2DVD, 2013.

Figure 5. Scatterplots showing the comparison between the 2DVD and **(a)** a collocated tipping bucket rain gauge (Pluvio), and **(b)** a collocated Vaisala weather station. Time steps compared are at one hour resolution from HyMeX SOP 2013, and include only those times for which the collocated Parsivel recorded a Parsivel-derived rain rate ≥ 0.1 mm h^{-1}, ≤ 10 % of the time step was marked as solid precipitation, and for which both the 2DVD and gauge recorded rain rate ≥ 0.1 mm h^{-1}.

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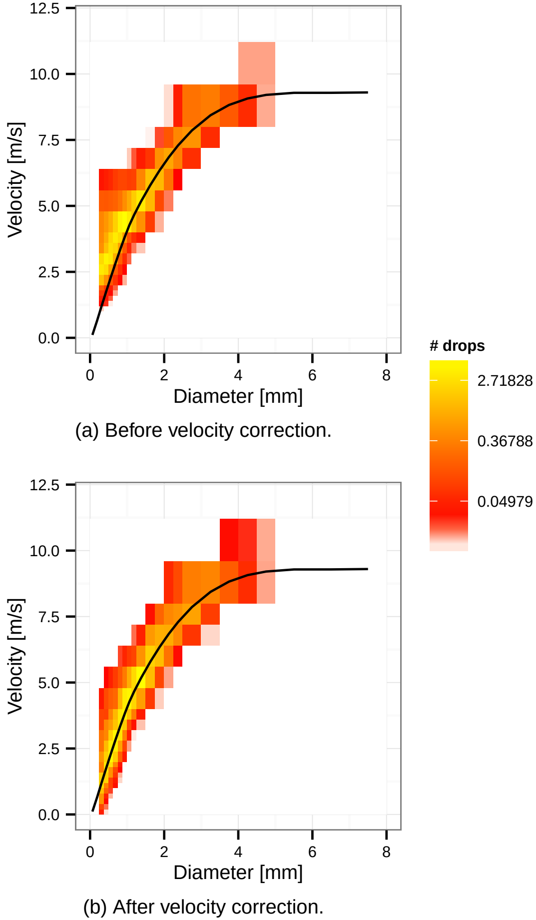

Figure 6. An example of the velocity correction. Average drop counts for the Parsivel at Pradel Grainage for SOP 2013, shown **(a)** before the velocity correction and **(b)** afterwards.

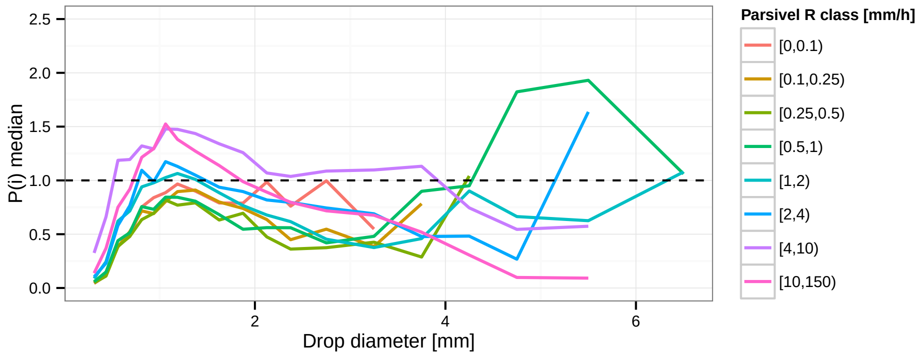

Figure 7. Median $P(i)$ values classed by Parsivel-derived intensity.

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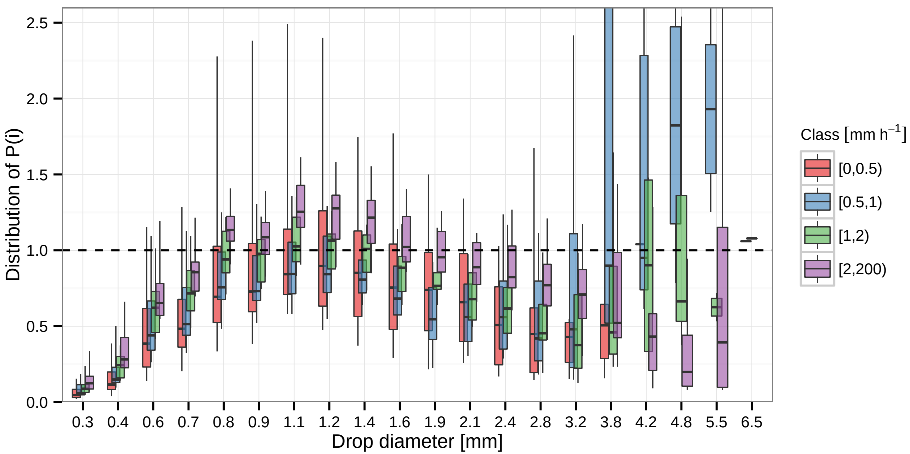

Figure 8. Distributions of $P(i)$ values classed by Parsivel-derived intensity. The correction factors used are the medians of the distributions. The boxes show the interquartile-ranges while lines show the 10 % to 90 % quantiles of each distribution. The y axis is cut at 2.6.

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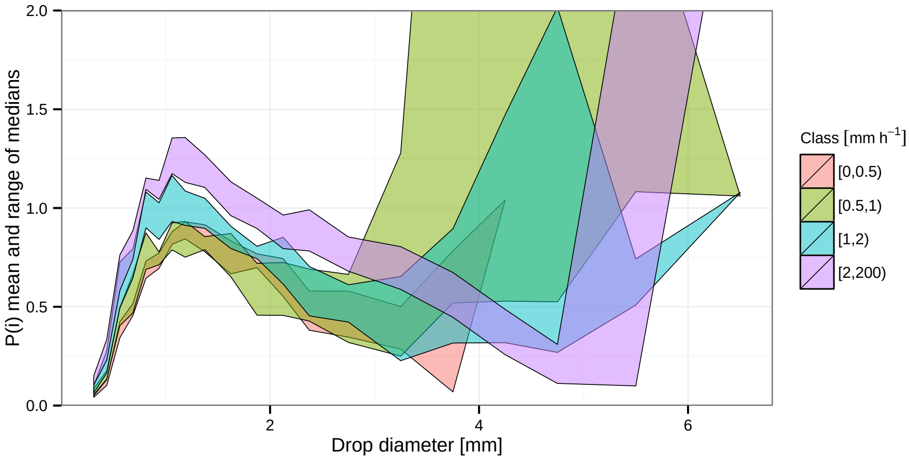

Figure 9. Sampling effect per diameter class, for different classes of Parsivel-derived intensity. The coloured regions represent the minimum and maximum median $P(i)$ per equivolume drop diameter class observed over 100 iterations. The y axis is cut at 2.6.

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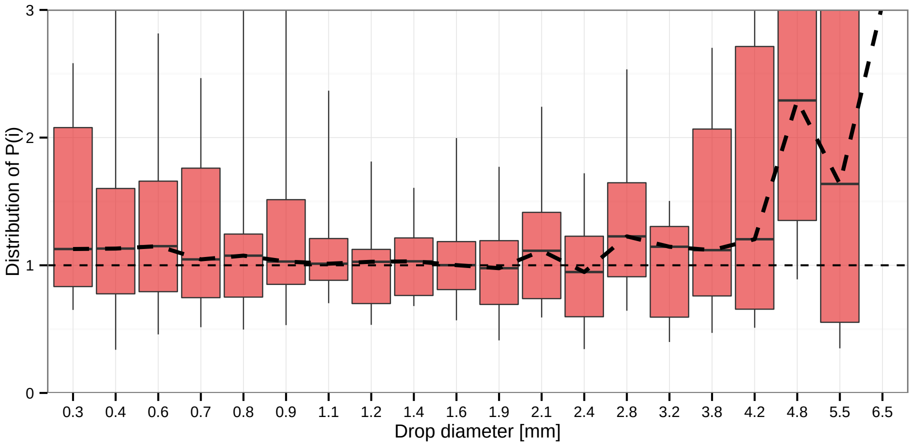

Figure 10. The distributions of $P(i)$ values for the corrected DSD, on an example set of validation time steps from HyMeX 2013, and for all classes of Parsivel-derived intensity, for the Parsivel collocated with the 2DVD. The y axis is cut at 3.

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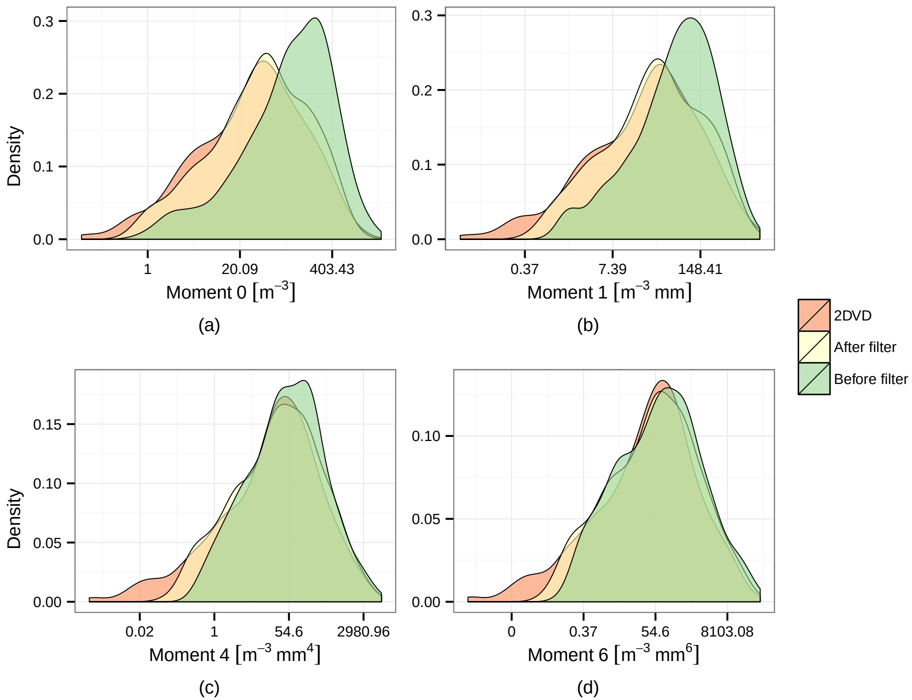

Figure 11. The effect of the correction DSD moments **(a)** zero and **(b)** one, **(c)** four, and **(d)** six, showing the densities of the Parsivel-derived DSD moments before and after the correction was applied, and the 2DVD moments, for HYMEX SOP 2013 event time steps at Pradel Grainage. The x axis has a log scale.

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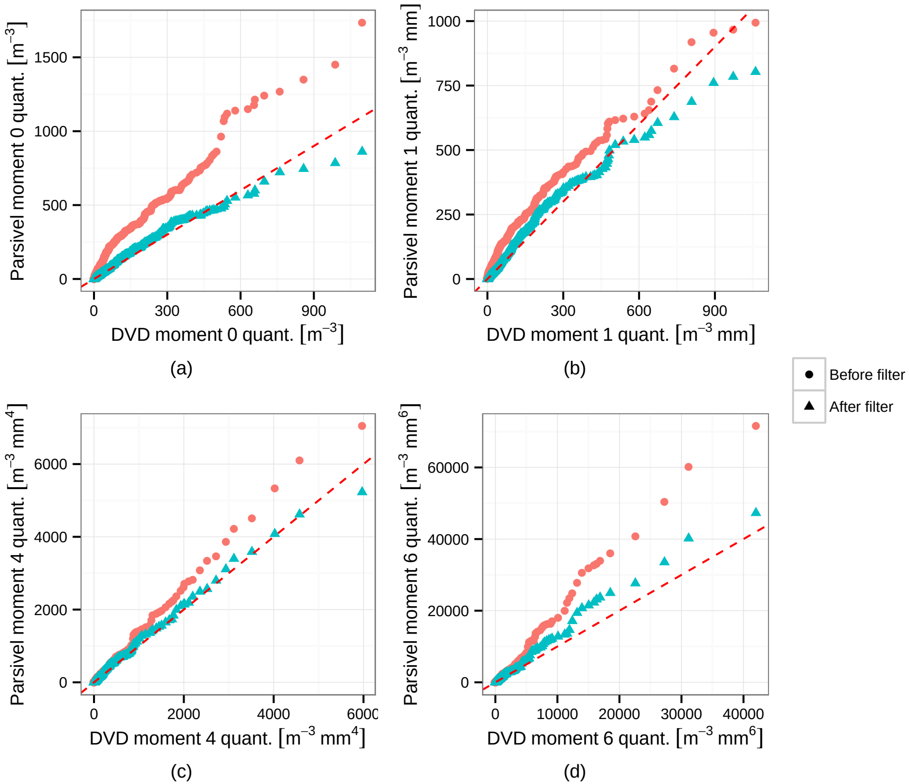

Figure 12. QQplot showing the effect of the correction on Parsivel DSD moments **(a)** zero, **(b)** one, **(c)** four, and **(d)** six, by comparing to the 2DVD moments, for HYMEX SOP 2013 event time steps at Pradel Grainage.

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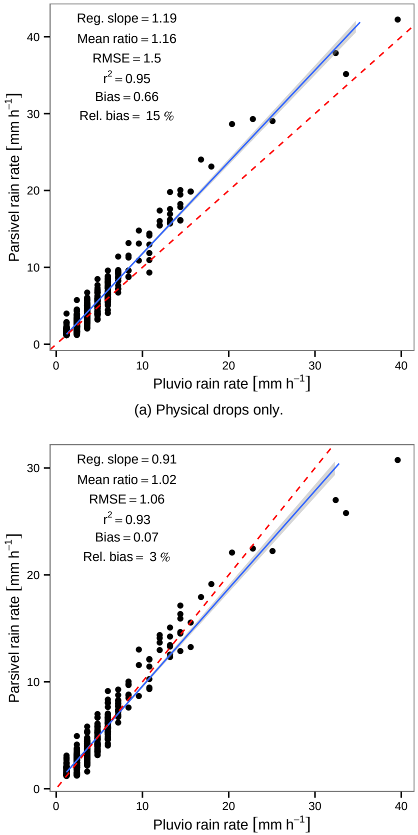

(a) Physical drops only.

(b) Concentrations corrected.

Figure 13. Scatterplots showing the effect of the drop concentration correction, for the combined SOPs, with liquid precipitation only and rain rates over 1.2 mm h^{-1}, for Pradel 1, the closest station to the 2DVD that was present in both 2012 and 2013.

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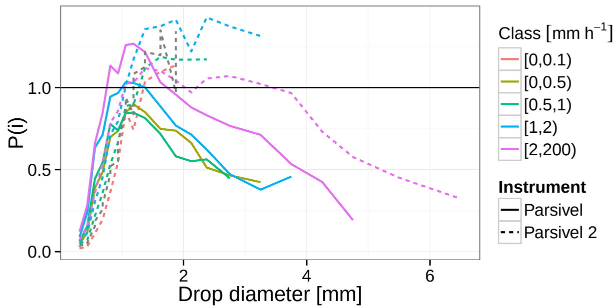

Figure 14. Comparison between correction factors for different campaigns.

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