

Research Highlights

- An analysis of almost 100,000 one-minute precipitation observations recorded by two types of optical disdrometer, Thies LPM and OTT Parsivel², is presented.
- Disdrometer data processing was made by a custom software developed for R environment which overcome binning differences when calculating particle size distribution statistics, allowing for disdrometer type comparison.
- Thies LPM recorded on average double number of particles than OTT Parsivel², with a greater number of small particles resulting in kinetic energy underestimation.
- Differences between disdrometer type increased with precipitation intensity, with Thies LPM recording nine times higher number of particles than OTT Parsivel², influencing all precipitation variables.

Comparison of precipitation measurements by OTT Parsivel² and Thies LPM optical disdrometers

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Abstract

Optical disdrometers are present weather sensors with the ability of providing detailed information of precipitation such as rain intensity, radar reflectivity or kinetic energy, together with discrete information on the particle size and fall velocity distribution (PSVD) of the hydrometeors. Disdrometers constitute a step forward towards a more complete characterization of precipitation, being useful in several research fields and applications. In this article the performance of two extensively used optical disdrometers, the most recent version of OTT Parsivel² disdrometer and Thies Clima Laser Precipitation Monitor (LPM), is evaluated. During two years four collocated optical disdrometers, two Thies Clima LPM and two OTT Parsivel², collected up to 100,000 minutes of data and up to 30,000 minutes with rain in more than 200 rainfall events, with intensities peaking at 277 mm h⁻¹ in one minute. The analysis of these records show significant differences between both disdrometer types for all integrated precipitation parameters, which can be explained by differences in the raw particle size and velocity distri-

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bution (PSVD) estimated by the two sensors. Thies LPM recorded a larger number particles than Parsivel² and a higher proportion of small particles than OTT Parsivel², resulting in higher rain rates and totals and differences in radar reflectivity and kinetic energy. These differences increased greatly with rainfall intensity. Possible causes of these differences, and their practical consequences, are discussed in order to help researchers and users in the election of the sensor, pointing out at the same time limitations to be addressed in future studies.

Keywords: Optical Disdrometer, Particle-size distribution, Precipitation measurement, Instrumental intercomparison, Rainfall kinetic energy

1. Introduction

Disdrometers are devices designed to measure the particle size distribution (PSD), or size and velocity distribution (PSVD), of falling hydrometeors. The PSD describes the statistical distribution of falling particle sizes from the number of particles with a given equi-volume diameter per unit volume of air. The PSVD includes also information about the distribution of the particle fall velocities.

Information on the PSD / PSVD is required for a proper understanding of hydrometeorological regimes (Iguchi et al., 2000; Krajewski et al., 2006; Adirosi et al., 2016), soil erosion (Sempere-Torres et al., 1998; Loik et al., 2004; Cruse et al., 2006; Petan et al., 2010; Fernández-Raga et al., 2010; Shuttleworth, 2012; Iserloh et al., 2013; Angulo-Martínez and Barros, 2015; Angulo-Martínez et al., 2016) and other applications such as pollution wash off in urban environments (Kathiravelu et al., 2016; Castro et al., 2010) or interactions of rainfall with crop and forest canopies (Frasson and Krajewski, 2011; Nanko et al., 2004; Nanko et al., 2013). Rainfall estimation by remote sensing, radar and satellite, also rely on PSD information (Olsen et al., 1978; Atlas et al., 1999; Uijlenhoet and Sempere-Torres, 2006; Tapiador

et al., 2017). Disdrometer observations of PSD are also used to derive relationships between radar reflectivity and rainfall rates (known usually as Z-R relationships), despite the difficulties due to differences in altitude of the measurement—surface vs. cloud base—and the sensing area—a few cm^2 vs. km^2 —(Krajewski et al., 1998; Löffler-Mang and Blahak, 2001; Miriousky et al., 2004; Thurai and Bringi, 2008; Marzano et al., 2010; Jaffrain and Berne, 2012; Jameson et al., 2015; Raupach and Berne, 2016; Gires et al., 2016). Many of these studies took place within Precipitation Measurement Missions helping the development of better sensors and algorithms for precipitation detection and quantification; some examples are: Ioannidou et al. (2016) for the Tropical Rainfall Measurement Mission (TRMM), Liao et al. (2014) and Tan et al. (2016) for the Global Precipitation Measurement Mission (GPM), Adirosi et al. (2016) for the Hydrological cycle in the Mediterranean Experiment (HyMex), or Calheiros and Machado (2014) for the Cloud Processes of the Main Precipitation Systems in Brazil (CHUVA) campaign.

In addition, bulk precipitation variables can also be calculated from the PSD (sometimes called the ‘PSD moments’), including the rain rate, liquid water content, radar reflectivity, rainfall kinetic energy, among others (Ulbrich, 1983; Testud et al., 2001; Jameson and Kostinski, 1998). As such, disdrometers have been incorporated in operational meteorological networks as present weather sensors and pluviometers.

Current commercial disdrometers are based mainly on two physical principles to measure the PSD or the PSVD. The first ones are electro-mechanical impact devices recording the electrical pulses produced by the pressure of falling drops when impacting over a surface. Impact disdrometers such as the Joss and Waldvogel disdrometer (JWD, Joss and Waldvogel, 1967) or piezoelectric force transducers (Jayawardena and Rezaur, 2000) were largely used in the 1980s and 90s. The JWD disdrometer gives good results for light to moderate intensity but underestimates the amount of small size drops during heavy rainfall events, and it cannot detect raindrops smaller than 0.2 mm

49 of diameter (Tokay et al., 2001). Impact based and pressure disdrometers,
50 however, rely on theoretical terminal velocity curves to determine the PSD.

51 More recent disdrometers are based in optical principles (Hauser et al.,
52 1984; Löffler-Mang and Joss, 2000), either from the occlusion of a laser light
53 beam between an emisor and a receptor device produced by the particle
54 passing through; or based on light scattering measurements from particles
55 passing through the light beam. Both types use an emissary and a receiver
56 of the laser signal generally in a horizontal plane, and the emissary can
57 be punctual or an array of emissaries. Commercial examples of the first
58 type are the particle size and velocity disdrometers Parsivel and Parsivel²
59 by OTT Hydromet, and the Laser Precipitation Monitor (LPM) by Thies
60 Clima. An example of the light scattering principle is the light scatter sensor
61 PWS100 (Campbell Scientific Inc.). Optical disdrometers provide full PSVD
62 measures from the unique light beam horizontal plane (~ 1 cm thick) by the
63 amplitude and duration obscuration when particles pass through the beam,
64 respectively. Laser disdrometers are not devoid of detection problems related
65 with the effects of uneven power distribution across the laser beam, wind,
66 splashing, multiple drops appearing at the same time (double detections),
67 edge events ('margin-fallers', or partial detections), as reviewed by several
68 studies (Nespor et al., 2000; Habib and Krajewski, 2001; Tokay et al., 2001;
69 Kruger and Krajewski, 2002; Frasson et al., 2011; Raupach and Berne, 2015).

70 An improvement over laser disdrometers is the two-dimensional video
71 disdrometer (2DVD, Joanneum Research). The 2DVD uses two perpendic-
72 ular high-speed line-scan cameras, each with an opposing light source, to
73 record particles from orthogonal angles. The 2DVD provides reliable mea-
74 sures of particles fall velocity, size and shape (Kruger and Krajewski, 2002;
75 Schönhuber et al., 2008). Currently this disdrometer is considered a reliable
76 reference for particles larger than 0.3 mm (Tokay et al., 2013; Thurai et al.,
77 2017), although its use is mostly restricted to experimentation due to its
78 higher cost and data processing requirements.

79 A bibliography search by the key phrase ‘optical AND disdrometer’ on
 80 publications between 2000 and 2017 in Scopus showed that the two models
 81 most currently used are OTT Parsivel (mentioned in 50% of a total of 200
 82 documents) and Thies LPM (mentioned in 25%). In some disciplines, both
 83 disdrometers have been used interchangeably. This is the case, for instance, of
 84 soil erosion studies, where Thies LPM was used for monitoring rainfall char-
 85 acteristics, most notably the kinetic energy, in relation with splash erosion
 86 experiments (Angulo-Martínez et al., 2012; Fernández-Raga et al., 2010), and
 87 also in the calibration of the European portable rainfall simulator (Iserloh et
 88 al., 2013). Parsivel disdrometers, on the other hand, have been used to deter-
 89 mine the kinetic energy - rainfall intensity relationship (Petan et al., 2010 ;
 90 Sánchez-Moreno et al., 2012). Both disdrometers were used interchangeably
 91 in Slovenia to estimate rainfall parameters, including kinetic energy (Petan
 92 et al., 2010; Ciaccioni et al., 2016), and to inter-compare solid precipitation
 93 observations in the Tibetan Plateau (Zhang et al., 2015).

94 The performance of Parsivel and Thies disdrometers has been compared
 95 to other disdrometers such as the 2DVD, the JWD, or by taking a pluviome-
 96 ter as a reference. Parsivel disdrometers have been evaluated since its first
 97 version became commercially available from PM Tech Inc (Sheppard and
 98 Joe, 1994; Löffler-Mang and Joss, 2000), with slightly different results de-
 99 pending on the version of the device analysed (Krajewski et al., 2006; Lanza
 100 and Vuerich, 2009; Battaglia et al., 2010; Jaffrain and Berne, 2011; Thurai
 101 et al., 2011; Park et al., 2017). In 2005, OTT Hydromet purchased the rights
 102 of Parsivel disdrometer and redesigned the instrument. Differences between
 103 the PM Tech and the first version of OTT Hydromet Parsivel are described
 104 in Tokay et al. (2013), who found important biases in the frequency of small
 105 and large drops with respect to a JWD disdrometer. In 2011, OTT Hydromet
 106 redesigned the device and presented the Parsivel². This is the current ver-
 107 sion of the disdrometer, and includes a more homogeneous laser beam and
 108 some other modifications that improve its performance (Tokay et al., 2014;
 109 Angulo-Martínez and Barros, 2015). The Parsivel² has been compared to

110 other disdrometers. Tokay et al. (2014) compared it with the JWD, and
 111 found good agreement in the PSD spectra between both devices for particles
 112 sizes larger than 0.5 mm. They also reported systematic underestimation of
 113 fall velocities in the Parsivel², for drop diameters of 1.09 mm and higher.
 114 Raupach and Berne (2015) and Park et al. (2017) compared the two ver-
 115 sions of Parsivel with a reference 2DVD, and found that Parsivel², although
 116 improving the performance of the first iteration of the disdrometer, still had
 117 important biases that resulted in underestimation of small drops and overes-
 118 timation of large drops, especially during high intensity rains.

119 Thies LPM, on the other hand, became commercially available in 2005
 120 from Adolf Thies GmbH & Co. Early analysis of the performance of the Thies
 121 disdrometer for detecting different hydrometeors was presented by Bloemink
 122 and Lanzinger (2005) at the WMO Technical Conference on Meteorological
 123 and Environmental instruments and methods of observations (TECO-2006,
 124 Geneva, Switzerland), while an evaluation of its capacity for measuring rain-
 125 fall intensities and amounts was presented in the same conference one year
 126 later (Lanzinger et al., 2006). Since then, this disdrometer has been used
 127 worldwide with several firmware updates. Frasson et al. (2011) evaluated
 128 the performance of four collocated Thies disdrometers and found that sys-
 129 tematic biases existed between the devices, and attributed them to miscalcu-
 130 lation of the disdrometer’s sensing area. Lanzinger et al. (2006) found that
 131 three LPMs measured higher rainfall amounts than a collocated reference
 132 rain gauge, especially during higher intensities, and also reported system-
 133 atic biases between the three disdrometers. Upton and Brawn (2008) also
 134 found discrepancies in the velocity records by three collocated Thies, while
 135 the number of particles and their sizes were more consistent.

136 There number of studies inter-comparing Thies and Parsivel disdrometers,
 137 however, is very reduced. Brawn and Upton (2008) evaluated the paramet-
 138 ers of fitted gamma distributions to the PSD data, and found substantial
 139 differences between Thies and Parsivel. Upton and Brawn (2008) found that

Parsivel tended to underestimate the number of small drops (up to three times less for the two lowest size bins) with respect to Thies, while it tended to over-estimate the number of drops larger than 2 mm. They also reported an underestimation of particle fall velocity in comparison with Thies and with the theoretical terminal velocity, especially for midsize drops (1 mm - 3 mm), and underestimation of total rainfall volume by Parsivel with respect to Thies. These studies were based on the earlier version of the Parsivel disdrometer, and no study up to date has focused on comparing the Thies LPM and the Parsivel². Such a study, however, is highly needed if measurements made with these two disdrometers are to be compared.

The objective of this study is to compare the measurements recorded by Thies LPM and OTT Parsivel² optical disdrometers, with the goal of providing a quantitative assessment of both sensors and highlighting the associated uncertainties. Measurements of PSVD and integrated rainfall variables as rain rate, kinetic energy, reflectivity and number of drops per volume of air under natural rainfall events are compared, either at the one-minute, the event and the whole season scales. Some technical problems that arise from the different binning of the PSVD matrix by the two devices, which hinder the comparison between their measurements, are dealt with. In the following section a description of the two sensor types and the sampling site is given, together with details of the data processing. Section 3 analyses the results obtained, which are discussed in section 4. Section 5 concludes.

2. Data and Methods

2.1. Sampling site and instrumentation

Rainfall characteristics under natural conditions were monitored at Aula Dei Experimental Station (EEAD-CSIC) in the central Ebro valley, NE Spain (41°43'30"N, 0°48'39"W, 230 m.a.s.l.). The experimental site is located in a

research farm located on a flat river terrace, classified as having a cold semi-arid climate (BSk, Köppen-Geiger). The average annual precipitation was 344.4 mm in the period 1990-2017 (recorded at the Aula Dei meteorological station which belongs to the network of the Spanish national weather agency, AEMET) with equinoctial rainfalls (monthly maxima in May, 44 mm, and October, 39.3 mm; and minima in July, 16.2 mm, and December, 21.7 mm).

Four disdrometers, two Thies Clima LPM and two OTT Parsivel², were operated in continuous record during the period between 17/06/2013 and 21/07/2015. Two disdrometers of both types were placed in two masts (Mast-1 and Mast-2), which were located 1.5 m apart from each other (Figure 1). Each mast consisted in a pole with two arms 0.5 m apart from each other where two devices, one of each model, were installed. The four sensors were oriented in the same N-S direction. One-minute rainfall PSVD observations were recorded automatically during the period, and rainfall episodes were identified according to the following criteria: a rainfall episode started when rainfall was continuously recorded by at least two disdrometers of different type during at least 10 minutes; and two rainfall episodes were delimited by, at least, one entire hour without rain in at least two disdrometers of different type. Observations corresponding to solid or mixed precipitation were disregarded, as were those with internal error or bad quality flags.

[FIGURE 1: Sampling site with four collocated disdrometers]

Both optical disdrometers, Thies Clima LPM and OTT Parsivel², are based on the same measurement principle. Their external structure is formed by two heads that connect the sheet of laser light through which falling drops are measured. Drop diameter and fall velocity are determined from the obscurations amplitude and duration in the path of an infrared laser beam, between a light emitting diode and a receiver, within a sampling area of approximately 50 cm² (Donnadieu et al. 1969; Löffler-Mang and Joss, 2000).

195 Raindrops are assumed spherical for sizes less than 1 mm in diameter, and
 196 therefore the size parameter is the equivalent diameter for raindrops below
 197 this size. For larger raindrops, a correction for oblateness is made, and
 198 the size parameter is interpreted as an equi-volume sphere diameter. The
 199 laser signal is processed by a proprietary software, and the size (equi-volume
 200 particle diameter) and velocity of each particle is determined. The meteor
 201 type (drizzle, rain, hail, or snow) is determined based on typical size and
 202 velocities, and weather codes (SYNOP and METAR) are generated. A PSVD
 203 matrix counting the number $N_{i,j}$ of particles for given size (i) and velocity (j)
 204 classes is recorded at desired intervals, usually one minute. Several integrated
 205 variables are also computed and stored at the same intervals. These include
 206 the number of particles detected (NP , min^{-1}), the particle density (ND ,
 207 $\text{m}^{-3} \text{ mm}^{-1}$), the rainfall amount (P , mm) and intensity (R , mm h^{-1}), the
 208 radar reflectivity (Z , $\text{dB mm}^6 \text{ m}^{-3}$), visibility (m) and kinetic energy (J m^{-2}
 209 mm^{-1}).

210 This operational principle is subject to a number of potential sources of
 211 bias, as reviewed by Frasson et al. (2011). One of such sources of bias is the
 212 uneven power distribution across the laser beam, or variations of this power
 213 with time. Also, the geometry of the laser beam limits the estimation of
 214 fall velocity to the vertical component, producing biased measures when the
 215 particles fall with a different trajectory or angle due to wind or eddy drag
 216 (Salles and Poesen, 1999). Other source of biased measurements is due to the
 217 occurrence of coincident particles, which are perceived as just one single drop
 218 by the sensor. Similarly, the event of one drop falling at the edge of the laser
 219 beam ('margin faller'), therefore being only partially observed, leads to biased
 220 measurements. Both sensors mention in their technical data some correction
 221 for edge-detection (margin fallers) and coincident particles, although there is
 222 little information on how these two events are identified and treated. More
 223 details of both instruments and the measurement technique, along with the
 224 assumptions used to determine the size and velocity of hydrometeors, can
 225 be found in Löffler-Mang and Joss (2000), Battaglia et al. (2010), Tapiador

et al. (2010), Frasson, et al. (2011) Jaffrain and Berne (2011), Tokay et al. (2013 and 2014), Raupach and Berne (2015), and in their respective technical manuals.

There are slight hardware variations between the two instruments, as well as differences in how the raw data are treated and converted into the outputted variables. Since these differences may have an impact on the final records, we review the relevant characteristics of each device in the following paragraphs.

Thies Clima Laser Precipitation Monitor

The Laser Precipitation Monitor (LPM) uses a 780 nm laser beam which is 228 mm long, 20 mm wide, and 0.75 mm thick on average, resulting in a sampling area of 45.6 cm². Geometric deviations from this standard are reported by the manufacturer for each particular disdrometer, and for instance the sampling areas of the two devices used on the experiment were 46.65314 and 49.04051 cm². It records particles starting from 0.16 mm of diameter, and precipitation starting from 0.005 mm h⁻¹. The Thies technical documentation indicates that the size and velocity measurements are ‘checked for plausibility’ to prevent issues such as edge events, implying that some particles are filtered out, although the details of this procedure are not specified. From the raw particle data several bulk variables (‘PSVD moments’) are integrated internally by the device’s firmware. Drop diameters and velocities are then grouped into 22 and 20 classes ranging between 0.125 mm up to 9 mm and 0 m s⁻¹ up to 12 m s⁻¹, respectively (see Table 6), and the number of particles recorded at each size and velocity pair bin is stored. The bulk variables computed by the Thies LPM does not include the kinetic energy. In addition, several status flags are provided in the data telegrams informing about voltage oscillations, sensor temperature, and an evaluation of the measurement quality.

[TABLE 1]

OTT Parsivel² disdrometer

The Parsivel disdrometers used in this study belong to the second generation manufactured by OTT Hydromet Inc (Parsivel²). The Parsivel² uses a 780 nm laser beam which is 180 mm long, 30 mm wide, and 1 mm thick on average, with no indication about deviations from these values from the manufacturer. The sampling area for the two Parsivel disdrometers was therefore 54 cm². The Parsivel² records particles starting from 0.2 mm of diameter, and precipitation starting from 0.001 mm h⁻¹. The measured particles are stored in drop diameter and fall velocity bins in a 32 x 32 matrix with uneven intervals starting at 0 mm diameter up to 26 mm and from 0 m s⁻¹ up to 22.4 m s⁻¹ (Table 6). The first two size categories, which correspond to sizes of less than 0.25 mm, are left empty by the manufacturer because of the low signal-to-noise ratio. The Parsivel², similarly to the Thies, also provides a sensor status flag and several control variables in its data telegram.

According to Battaglia et al. (2010), particles up to 1 mm are assumed spherical, and between 1 and 5 mm they are assumed as horizontally-oriented oblate spheroids with axial ratio linearly varying from 1 to 0.7, with this ratio being kept constant at 0.7 for larger sizes. The Parsivel technical documentation mentions that the device filters out edge events, although the exact details of this procedure are not given. Battaglia et al. (2010) mention that the newest Parsivel units include two extra photo-diodes at the edge of the laser beam to detect and remove the edge events, but the manufacturer provides no information about this. Independently to filtering our edge events, Löffler-Mang and Joss (2000) indicate that a correction of the effective sampling area is used depending on the particle size. Some sources (Tokay et al., 2013) also refer that a correction to the fall velocity is applied to drop sizes between 1 and 5 mm, although once again there is not more information on this correction. Parsivel² disdrometers external structure differs from the

283 Thies LPM in incorporating a splash protection shield above the laser heads,
 284 which aims at minimising the effect of splashed drops that interfere with a
 285 high velocity with the laser beam and result in biased measurements.

286 2.2. Processing disdrometer data

287 One minute disdrometer data telegrams were stored in an industrial
 288 miniature PC (Matrix 504 Artilla Inc). The PC included custom software
 289 to collect, pre-process and send data telegrams to a central server. Time
 290 synchronisation was performed once per day using the Network Time Proto-
 291 col (NTP), allowing bias correction of the internal disdrometer clocks that
 292 have a tendency to drift. Direct reading of the data telegrams generated
 293 by the disdrometers resulted in one-minute time series of the variables of
 294 interest for this study: PSVD matrices ($N_{i,j}$), bulk variables (P , R , NP , ND ,
 295 Z , E), SYNOP codes, and status and error flags. An exception were Thies
 296 disdrometers, which do not compute the kinetic energy, E . Parsivel, on the
 297 other hand, gives the kinetic energy expressed in J, so it was divided by the
 298 sampling area and the rainfall amount to obtain E .

299 In addition to the bulk variables computed by the internal software of the
 300 devices, the bulk variables were computed again from the PSVD matrices,
 301 using the following expressions:

$$P = \frac{4}{3} \pi \sum_{i,j} \left(\frac{1}{A_i} N_{i,j} \left(\frac{D_i}{2} \right)^3 \right) \quad (1)$$

$$R = \frac{P}{\Delta t} \quad (2)$$

$$NP = \sum_{i,j} N_{i,j} \quad (3)$$

$$ND = \frac{1}{R \Delta t} \sum_{i,j} \left(\frac{1}{A_i} \frac{N_{i,j}}{V_j} \right) \quad (4)$$

$$Z = \log \left(\frac{1}{\Delta t} \sum_{i,j} \left(\frac{1}{A_i} N_{i,j} \frac{D_i^6}{V_j} \right) \right) \quad (5)$$

$$E = \frac{4}{3} \pi \frac{\rho}{P} \sum_{i,j} \left(\frac{1}{A_i} N_{i,j} \left(\frac{D_i}{2} \right)^3 \frac{V_j^2}{2} \right) \quad (6)$$

where ρ is the density of water (1000 kg m⁻³), D_i is the mean diameter of class i , V_j is the mean velocity of velocity class j , and Δt is the sampling frequency (s). The effective sampling area, A_i (m⁻²) depends on the particle size, since in order to be correctly sensed the particles need to be inside the light beam in its entirety, so:

$$A_i = A \left(1 - \frac{D_i}{2w} \right) \quad (7)$$

where A is the sampling area of the disdrometer and w is the width of the laser beam. As it can be seen, the effective sampling area gets reduced as the drop size increases, and the magnitude of the correction applied is inversely proportional to w .

This allowed, on one hand, obtaining E for Thies disdrometers, but also permitted to apply a number of corrections that simplified the comparison between the two types of disdrometer. Thus, we ignored the particle counts in the first size bin of Thies disdrometers and the counts in the size bins larger than 8 mm, so the two disdrometer types were measuring the same range of drop sizes (0.25 to 8 mm). We also applied a filter to remove highly unlikely drop size and velocity combinations, as done in many studies (e.g., Tokay et al., 2001; Jaffrain and Berne, 2011; Tokay et al., 2013; Raupach et

al., 2015). In order to do that, each size and velocity bin was compared with the terminal fall velocity model of Beard (1976), and the bins for which a difference larger than 50% existed with the theoretical model were excluded.

In order to compare PSVD data between disdrometer types, the 10th, 50th and 90th percentiles of the particle size ($D10$, $D50$, $D90$) and velocity ($V10$, $V50$, $V90$) were computed (Table 2). One problem that arises when percentiles are computed from binned data is that the resulting percentiles may be biased depending on the binning structure of the data. If all the particles recorded in one bin are assigned the mean value of the bin (the easiest option), different bin configurations will lead to different computed percentiles, even if the raw data before binning were the identical. When data from different binning structures are compared, as it is the case here between Thies and Parsivel disdrometers, an interpolation scheme needs to be used for distributing the range of values within each bin across all the particles corresponding to that bin. Here we used a random distribution over the range of values in the bin following a linear probability distribution constructed by fitting a line between two points determined as the average of the number of particles in the bin and the corresponding values on the neighbouring bins. Given the high number of particles detected, the random component of this scheme has a negligible effect on the results. Once all the number of particles by minute were assigned particle size and velocity values, the percentiles were calculated, allowing for a comparison between disdrometers.

In addition to one-minute data, the mean (m) and maximum (M) values of some of these variables (Rm , RM , KEm , KEM , Em , EM , NPm) were computed for each rainfall event. A summary of the variables analysed is provided on Table 2.

[TABLE 2]

347 All data processing, including reading the raw telegrams, computing the
 348 integrated variables (erosivity for Thies LPM and size and velocity per-
 349 centiles), and plotting, was performed using a custom package for the R
 350 environment, `disdRo` (Beguería et al., 2017).

351 *2.3. Comparison of disdrometer measurements*

352 Prior to any analysis, minute observations with low-quality or bad sensor
 353 status flags were removed from the comparison dataset. Minutes with miss-
 354 ing data, precipitation below 0.1 mm h^{-1} or less than 10 particles detected
 355 in any of the four disdrometers were also removed. This way, only minutes
 356 with good quality data in the four devices were considered in the analysis.
 357 The comparison was made primarily on the bulk variables computed from
 358 the PSVD matrix stored in the one-minute telegrams outputted by the four
 359 disdrometers, by applying equations 1 to 6. We also compared the bulk vari-
 360 ables calculated by the internal firmware of the devices, in order to check the
 361 impact of the effective sampling area correction and the removal of unlikely
 362 size-velocity bins.

363 Kernel density and violin plots, i.e. non-parametric graphical estima-
 364 tions of the probability density functions of the variables, were used as a
 365 preliminary analysis tool. A formal comparison between the two disdrom-
 366 eter types was performed using a Gamma generalised linear mixed model
 367 (Gamma GLMM), with the bulk variables listed in Table 2 as response
 368 variables. Mixed models allow incorporating both fixed-effects and random-
 369 effects in the regression analysis (Pinheiro and Bates, 2000). The fixed-effects
 370 describe the values of the response variable in terms of explanatory variables
 371 that are considered to be non-random, whereas random-effects are treated
 372 as arising from random causes, such as those associated with individual ex-
 373 perimental units sampled from the population. Hence, mixed models are
 374 particularly suited to experimental settings where measurements are made
 375 on groups of related, and possibly nested, experimental units. If the group-

ing factor was ignored when modelling grouped data, the random (group)
 effects would be incorporated to the error term, leading to an inflated esti-
 mate of within-group variability. This allowed us to assess for differences in
 the response variables as a function of the disdrometer type (fixed factor),
 while controlling for possible differences due to the location of the two masts
 (random factor). Since the explanatory variable is a dichotomic variable
 (the disdrometer type), this configuration is equivalent to a random-effects
 Analysis of Variance (ANOVA). A Gamma distribution was used to model
 the response variables, since this distribution is best suited to positive data
 with variance increasing with the mean, as it is the case of the disdrometric
 variables analysed here. This model configuration can be described as:

$$\begin{aligned}
 y_i &\sim \text{Gamma}(\theta_i, \nu) \\
 \theta_i &= \nu / \mu_i \\
 g(\mu_i) &= \mu + \beta_{t(i)} + \alpha_{m(i)} + \epsilon \\
 \beta_{t(j)} &\sim \mathcal{N}(0, \sigma_\beta^2) \\
 \alpha_{m(i)} &\sim \mathcal{N}(0, \sigma_{m(i)}^2) \\
 \epsilon &\sim \mathcal{N}(0, \sigma^2)
 \end{aligned} \tag{8}$$

where y_i is the i th observation of the response variable Y ; ν is a shape
 parameter; θ_i is a scale parameter, which can be expressed in terms of ν
 and a mean value corresponding to the i th observation μ_i ; μ is a global
 mean; $\beta_{t(i)}$ is a parameter accounting for the effect of the disdrometer type
 corresponding to observation i , $t(i)$; and $\alpha_{m(i)}$ is a parameter accounting for
 the location (mast) corresponding to observation i , $m(i)$. In our case, we
 counted with four disdrometers grouped into $t(i) = (T, P)$ disdrometer types
 (Thies and Parsivel, respectively), and located in $m(j) = (1, 2)$ masts, and
 we set $\beta_1 = \alpha_1 = 0$. For the link function $g(\mu_i)$ we used an identity link,
 $g(\mu_i) = \mu_i$, except for R , Z , E and NP for which a log link, $g(\mu_i) = \log \mu_i$,
 was used.

398 The model in eq. (8) was fitted by generalized least squares (GLS), using
399 the function `lme` from the R library `lme4` (Pinheiro and Bates, 2011). A
400 random sample of $N=1000$ records, corresponding to 250 minutes, was used
401 in the analysis, in order to avoid size effects affecting negatively the statistical
402 significance tests (Type I error inflation; see, e.g., Lin et al., 2013).

403 3. Results

404 A summary report on the data acquired by the four disdrometers is re-
405 ported on Table 3. Almost 100,000 minutes of data were obtained from
406 each device. Missing values due to technical issues (power supply failures
407 and device hangouts, data communication problems) were found in all dis-
408 drometers, although they were more prevalent on one of the Parsivels (P2),
409 resulting in a significantly lower number of records by this device. The num-
410 ber of errors, as reported by the status flags of the devices, was low, albeit
411 larger in Parsivel than in Thies devices. Some records were discarded due to
412 quality issues, either based on the quality flag reported by Thies (only data
413 with quality flags above 90% were accepted), or on non-consistent data in the
414 telegram (saturation of the PSVD bins or excessively large intensity values)
415 in the Parsivels. Since Parsivel does not report the data quality, no quality
416 threshold could be used. Around 31% of the minutes recorded rain hydrome-
417 ters in both Thies, while this percentage was lower for Parsivel (27.5% in
418 P1; the value of P2 was even lower, but can not be considered since this
419 device recorded a significantly reduced number of minutes due to technical
420 issues). The larger amount of minutes with rainfall in Thies disdrometers
421 can be attributed to their highest sensitivity, since they are able to records
422 smaller raindrops (more on this later).

423 All types of precipitation events occurring in the sampling site were repre-
424 sented, with the majority of observations corresponding with autumn rains,
425 as corresponds to the climatology of the area. Rain rates varied between

426 0.014 mm h⁻¹ and 277 mm h⁻¹. The minimum precipitation rates were be-
 427 tween 0.014 and 0.020 mm h⁻¹, with no differences between devices. The
 428 absolute maximum precipitation rates measured during the experiment de-
 429 pended on the disdrometer type, with Thies being the ones recording the
 430 highest values.

431 As mentioned in section 2.1, only the common minutes were selected from
 432 the complete dataset, defined as those having high quality data and detection
 433 of rainfall particles in each of the four disdrometers. This led to a total of
 434 46,636 records, corresponding to 11,659 minutes belonging to 157 rainfall
 435 episodes.

436 [TABLE 3]

437 When considering only the records for which data of the four disdrometers
 438 existed, the total accumulated precipitation as measured by the disdrome-
 439 ters internal software was 244.9 mm (T1), 254.5 mm (T2), 220.4 mm (P1),
 440 and 228.1 mm (P2). This values were slightly different to those calculated
 441 from the PSVD data, which were slightly lower at 240.1 mm (T1), 253.0 mm
 442 (T2), 218.6 mm (P1), and 222.0 mm (P2). A graphical comparison of the
 443 cumulative time series for the computed and internal precipitation is pro-
 444 vided in Figure 2. Some discrepancies in total precipitation were therefore
 445 found between the devices, with the two Thies LPM devices recording more
 446 precipitation than the Parsivel ones. Between locations, mast 2 tended to
 447 record larger precipitation in both devices, although the magnitude of this
 448 difference was much lower than the difference between disdrometer types.

449 Differences were also found with respect to cumulative kinetic energy, for
 450 which larger values were also found for Thies (2100 and 2101 J m⁻² mm⁻¹)
 451 than for Parsivel (1749 and 1829). This corresponds to values obtained from
 452 the PSVD data, since Thies disdrometers do not calculate the kinetic energy
 453 internally. Unlike with P , for E there were important differences between

454 the values measured by the Parsivel² disdrometers (2100 and 2181) and those
455 calculated from the PSVD, reported above.

456 This result suggests that differences between devices could be done, to
457 a certain extent at least, to Thies LPM devices being more sensitive in the
458 lower range of the PSVD spectrum, although this hypothesis requires further
459 analysis, as done in the following sections.

460 *3.1. Example events*

461 Two events, representative of low and high precipitation intensity rates,
462 were selected to illustrate the differences between disdrometer outputs. Time
463 series of some bulk variables are shown in Figures 3 and 4. In both events,
464 Thies devices consistently reported higher rainfall intensity and cumulative
465 precipitation. This is related to a larger number of rain particles detected, as
466 shown by the number density (which factors out the different rain intensities).
467 There were differences, too, in the median particle size, which was much
468 larger in the Parsivel devices. Interestingly, it seems that these differences
469 (larger number of drops in Thies, but larger mean size in Parsivel) somehow
470 cancelled out for radar reflectivity and kinetic energy, which depend both on
471 the number of drops, their size and velocity.

472 These differences were most evident in the high intensity event, and were
473 also higher if no corrections for unlikely drops and effective sampling area
474 were performed (Supplementary material, Figures A.1 and A.2).

475 [FIGURES 3 and 4]

476 The PSVD plots (Figures 5 and 6), depicting the number of drops de-
477 tected for each combination of drop size and velocity classes during the event
478 by each disdrometer, help explain the differences found. A first and evident

479 difference is that Thies disdrometers had a much wider distribution of the
 480 PSVD spectra than Parsivel ones. The terminal velocity of raindrops as a
 481 function of their size according to Beard (1978), also depicted in the figure,
 482 was used to filter out unlikely combinations of size and velocity. Combina-
 483 tions which differ by more than 50% with the theoretical fall velocity are
 484 represented in the figure with a 50% transparency. Although a majority of
 485 particles were found to lie in a region close to the theoretical line, Thies de-
 486 vices had a much larger number of particles far from the theoretical model,
 487 both in the high and low intensity events. Particularly, a large number of very
 488 small particles at much higher velocities than expected was very prominent,
 489 as were the drops with a large diameter but a fairly low velocity. Typically,
 490 the first case (small, fast raindrops) are attributed to edge events (partial
 491 recognition or larger drops falling in the edge of the laser beam), or splashed
 492 particles, while the second case are interpreted as double detections (two or
 493 more simultaneous drops). Both effects tend to increase with the precipita-
 494 tion intensity, as the anomalous events become more frequent.

495 The frequency of anomalous raindrops was much lower in the Parsivel
 496 output, for which the vast majority of cases fell within the theoretical model
 497 limits. This can be attributed to a number of facts. From pure geometrical
 498 considerations, a larger prevalence of edge events can be expected from Thies,
 499 since its laser beam has a reduced width (20 mm) with respect to Parsivel
 500 (30 mm), so the proportion of edge events with respect to the number of
 501 particles detected is higher. Other reasons such as a larger proneness to
 502 splashing or differences in the internal processing of the data (that, as stated
 503 by the manufacturers, includes some filtering of anomalous data), may also
 504 help explain this differences.

505 Finally, and interestingly, an underestimation of drop velocities with re-
 506 spect to the theoretical model could be found in Parsivel devices, most no-
 507 tably in the high intensity event and for particles larger than 1 mm.

508 A formal analysis of these differences, considering the whole data set, is
509 presented in the following section.

510 [FIGURE 5 and 6]

511 3.2. Integrated variables, minute scale

512 When the whole dataset was analysed, differences between disdrometers
513 were also evident, as shown by the exploratory kernel density plots (Figure
514 7). This was further confirmed by the Gamma GLMM analysis (Table 4).
515 The coefficients reported in the Table for the fixed effects correspond to β_T
516 and β_P when μ is set to zero in equation 8, and can be interpreted as the
517 mean values of the response variables for each disdrometer type, when other
518 factors (the mast, in this case) are accounted for. The table includes also the
519 p-values corresponding to these coefficients, as well as the residual and mast
520 standard deviation (σ and $\sigma_{m(i)}$, respectively).

521 [FIGURE 7 and TABLE 4]

522 The analysis yielded significant differences between disdrometer types for
523 all the response variables analysed, while the random effect (the mast) had
524 a negligible effect as shown by its small variance with respect to the random
525 error (residual). There were substantial differences in the number of particles
526 detected, NP , and in the PSVD percentiles. Thus, Thies disdrometers had
527 a lower coefficient for NP (230 vs 194), indicating a tendency to detect a
528 higher number of particles (an increase of circa 20%). Thies also had much
529 lower coefficients for $D10$ and $D50$ (0.59 vs 0.74 for the median drop size,
530 i.e. a decrease of circa 20%), as well as for $V10$ and $V50$ (2.4 vs 2.9, i.e. an
531 18% difference). The magnitude of the difference was lower for the highest
532 percentiles ($D90$ and $V90$), where Thies even had a higher coefficient for
533 velocity, indicating a larger spread of velocities compared to Parsivel.

534 These differences in the number of particles and in the PSVD were trans-
535 lated to the bulk variables, which also showed significant differences in all
536 cases. The magnitude of the effect, i.e. the mean differences between the two
537 disdrometer types, were high for the particle density (21,600 vs 15,920, a 36%
538 increment) and kinetic energy (11.09 vs 9.66, i.e. a 15% difference), while
539 they were smaller (albeit significant) for R and Z (12% and 7% difference,
540 respectively).

541 The differences found in the PSVD percentiles allows for a better un-
542 derstanding of the differences in the integrated variables, since the particle
543 size and velocity have contrasting effects on R , ND , Z , and E . In general,
544 a higher number of particles implies increasing values of all these variables,
545 which favours Thies devices since it tended to detect a higher number of par-
546 ticles. The particle size, on the other hand, has a similar effect of increasing
547 all the variables for which it is relevant (R , Z and E). Since the particle
548 size was in general higher in Parsivel devices, this effect partially cancels out
549 the effect of the increasing number of particles. Particle velocity, which was
550 in general higher in Parsivel (except for the largest drops), has a positive
551 effect in E , but a negative effect on Z , which further explains the differences
552 found. The particle density (ND), finally, is not affected by the drop size and
553 is negatively affected by fall velocity, and that the reason why this variable
554 showed the highest difference between both disdrometers.

555 3.3. Integrated variables, event scale

556 Although one of the benefits of the optical disdrometers is their ability
557 to provide large amounts of information at very fine temporal scales (as one-
558 minute data analysed here), very frequently these data are aggregated
559 over larger time periods or rainfall events for practical issues. For instance,
560 it is typical the computation of kinetic energy totals for rainfall events, for
561 instance for soil erosion applications. When considering the same variables
562 at the event level, looking at the mean and maximum values over the event,

563 similar results were found (Figure 8 and Table 5).

564 [FIGURE 8 and TABLE 5]

565 Again, significant fixed effects were found for all response variables, while
566 the random effect was marginal in all cases. The average number of particles
567 during the events was much larger for Thies, and the median drop size and
568 velocity was lower. There were also differences, although of smaller size, in
569 the rest of integrated variables.

570 3.4. *Effect of PSVD data correction*

571 The effect that the data correction scheme may have on the integrated
572 variables merits some analysis, since it modifies the PSVD distribution. Here
573 we applied a filter that consisted on eliminated the unlikely drops, which was
574 aimed at eliminating edge events and double detections, while a correction
575 for the sensing area as a function of the drop size was applied to compensate
576 the loss of mass. The results showed in the previous sections were all based
577 on the corrected data, but in order to determine the effect of this correction
578 on the computed variables, the analysis was replicated without applying the
579 filtering and the correction.

580 The results are shown in the Supplementary material, in Table A.1 and
581 Figure 7. A comparison with the results shown in the previous section re-
582 veals the same general pattern, but with stronger effects. For instance, the
583 coefficient for the number of particles NP was 62% higher in Thies than in
584 Parsivel. Interestingly, the effect of the correction on the particle size per-
585 centiles had a different sign on Thies, for which $D50$ increased from 0.53
586 (without correction) to 0.60 (with correction), while on Parsivel it decreased
587 from 0.80 to 0.74. For the median particle velocity ($V50$), the coefficient re-
588 mained very similar before and after correction for Thies, while for Parsivel

589 it increased from 2.88 to 3.09 (7%). The relative magnitude of the differences
590 between Thies and Parsivel disdrometers was 88% for ND, 12% for R, 15%
591 for E and 7% for Z, i.e. much higher than after filtering and correction for
592 *ND* but similar for the other three variables.

593 3.5. Effect of rainfall intensity

594 Data were divided by intensity ranges in order to test if the effect of
595 the disdrometer type changed with different rain intensities. As the rainfall
596 intensity increases, it is expected to find more and bigger drops, which may
597 in turn modify the differences found between disdrometer types. Data were
598 thus divided in three intensity groups: low intensity (from 0.1 mm h^{-1} up to
599 2 mm h^{-1}), medium intensity (from 2 mm h^{-1} up to 10 mm h^{-1}) and high
600 intensity (more than 10 mm h^{-1}). Model coefficients for the three intensity
601 ranges are given in Table 6, and kernel density plots can be found in the
602 Supplementary material (Figures A.4, A.5 and A.6).

603 [TABLE 6]

604 The same effects described above were found at different rainfall inten-
605 sities. The magnitude of the effects, however, tended to increase with the
606 intensity. Thus, the relative difference between the coefficients of *NP* ranged
607 between 7% (146 vs 136) for low rainfall intensity, 27% for medium intensity
608 and 65 % for high intensity, while the median particle size ranged between
609 16%, 28% and 200%. Equally large were the relative differences between the
610 coefficients of *ND*, which varied between 33%, 67% and up to 292%, while for
611 the remaining variables the increase of the effect with the rainfall intensity
612 was less pronounced.

613 4. Discussion

614 Optical disdrometers are commercially affordable sensors able to provide
615 a thorough description of precipitation, and they are being increasingly used
616 by national weather services as present weather sensors and even rain gauges
617 requiring low maintenance. Besides their use in operational networks, optical
618 disdrometers provide information on precipitation drop spectra that has ap-
619 plications in different fields, and they are being increasingly used in research.

620 Thies Clima LPM and OTT Parsivel² are among the most common, state-
621 of-the-art, optical disdrometers. Despite being based on the same functioning
622 principle and having similar characteristics in terms of sensibility and range
623 of particle detection, there are substantial differences between them that
624 may affect differently their records. We have stressed the differences in the
625 higher and (more important) lower particle size detection ranges of the two
626 devices, with Thies having a lower detection threshold that may induce bias
627 in the records of the two disdrometer types. Filtering the PSVD matrix
628 to a common detection range, as done here, allows for a fair comparison
629 between the outputs of the disdrometers, and should be recommended for
630 any study that aims at presenting general results. However, as we have seen
631 here, despite applying the same detection thresholds to the data outputted
632 by the two disdrometers, significant differences were found both at the level
633 of PSVD spectra (particle size and velocity percentiles) and on the bulk
634 variables (PSVD moments).

635 There are a number of factors that may help explain the differences found.
636 Geometrical differences between the laser beams are highly relevant, since
637 they greatly influence the probability of bias-inducing effects such as edge
638 events ('margin fallers') and double detections. A larger sampling area, for
639 instance, implies a higher chance of double detections. At this respect, the
640 larger sampling area of Parsivel (54 cm²) over Thies devices (45.6 cm² on av-
641 erage) implies that Parsivel disdrometer should be more affected by double

642 detections. Double detections, i.e. time-overlapping drops, may be sensed
 643 just as one single drop (hence causing a loss of mass which may translate
 644 to a reduced precipitation record); or as a much larger drop at an unusu-
 645 ally low velocity. Since these unusual particles are often discarded from the
 646 PSVD matrix, this may result in another source of mass loss, which may or
 647 not be partially solved by the sampling area correction (more on this later).
 648 Although this would require further research, for instance with the help of
 649 numerical simulations as in the work by Raasch and Umhauer (1984), we
 650 suspect that the tendency towards a lower number of particles detected and
 651 lower precipitation amounts found on Parsivel devices may have a relation-
 652 ship with this effect.

653 But geometrical effects are not restricted to this. Since the effective sam-
 654 pling area of optical disdrometers depends on the particle size, not only the
 655 total area but also the width of the laser beam plays an important role as a
 656 source of bias. In particular, the proportion of edge events (i.e. particles that
 657 are sensed only partially due to falling at the edge of the laser beam) over
 658 the total number of particle detections of the same diameter class is inversely
 659 proportional to the width of the beam. The smaller width of the laser beam
 660 on Thies (20 mm) over Parsivel (30 mm) plays against the former, which
 661 should be more prone to be affected by edge events. This becomes more
 662 relevant for the higher particle bins. For 5 mm particles, for instance, the ef-
 663 fective width gets reduced to 15 mm for Thies, i.e. a reduction of 25%, while
 664 for Parsivel this reduction amounts to 16.6%. Edge events result in partially
 665 sensed particles, implying a mass loss and an over-estimation of fall velocity.
 666 The high prevalence of over-accelerated, small particles in the PSVD spectra
 667 of Thies disdrometers may be related to this effect, although again further
 668 analysis is required in order to confirm this hypothesis. At this respect, the
 669 Thies manufacturer checks and reports on each device the deviations due to
 670 fabrication tolerances from the theoretical geometrical properties of the laser
 671 beam, whereas this information is not given for Parsivel.

672 In order to overcome this problems, we applied a correction scheme which
 673 is similar to the ones found in other studies (e.g. Löffler-Mang and Joss, 2000;
 674 Battaglia et al., 2010; Raupach and Berne, 2015). The scheme consists on
 675 two parts: the first implies removing highly unlikely particle counts, i.e. those
 676 with velocities that are far from the theoretical fall velocity corresponding to
 677 their size. These unlikely particles are most possibly caused by edge events
 678 and double detections, so they are removed from the PSVD data. This causes
 679 a loss of mass, and this loss of mass is uneven since it increases with the par-
 680 ticle size (due to the geometric effect explained above), so the second part of
 681 the scheme consists on correcting the effective sampling area used in calculat-
 682 ing the bulk variable from the PSVD (equation 7). The correction, however,
 683 is not guaranteed to restitute all the mass loss, and careful calibration is
 684 required in order to match the filtering of unlikely particles (which depends
 685 on the threshold used for particle removal) with the effective area correction.
 686 Here we used a threshold corresponding with a difference higher than 50%
 687 with respect to the theoretical fall velocity matched to a factor or $1/2$ of the
 688 drop diameter for the area correction, but other combinations are possible.
 689 Again, numerical simulation should help in determining the best correction
 690 parameters, which in turn should consider the different beam geometries.

691 Our results showed differences between the two disdrometer types, which
 692 were not totally removed by the correction scheme (although they were par-
 693 tially diminished with respected to the un-corrected records). Differences in
 694 the in the internal treatment of the data by the two devices, which is not pub-
 695 lic, may also help explain this differences. Both manufacturers indicate that
 696 some treatment of unlikely detections is performed internally, but very little
 697 detail is given. From the examination of the raw PSVD matrices, it seems
 698 that the correction applied by Thies, if any, is very subtle, while the output
 699 of Parsivel seems to be much more affected by corrections. The technical lit-
 700 erature, also, gives more detail in the case of the Parsivel, for which at least
 701 a correction for the effective sampling area is reported (Löffler-Mang and
 702 Joss, 2000). The exact nature of these corrections, however, is not known, or

703 even if they are applied to the integrated variables only, or also to the PSVD
704 data. This uncertainty makes it difficult to implement an effective correction
705 scheme that makes the outputs of the two disdrometer comparable.

706 The external structure of the devices also plays an important role and
707 may lead to incorrect drop detections due to turbulence (see, for instance,
708 Constantinescu et al. 2007, for a review of turbulence induced errors on
709 pluviometers) and splashing (particles intercepted by the enclosure of the
710 devices which break and splash away in smaller but accelerated drops, see
711 Kathiravelu et al., 2016). It seems that the Thies disdrometer is more prone
712 to having splashed drops interfering with the laser beam, since it contains
713 larger flat surfaces susceptible of splashing particles in the direction of the
714 sensor. The Parsivel units, on the other hand, do not have flat surfaces
715 and include a splash protection shield that seems to effectively reduce the
716 risk of splashing. These morphological differences may also affect differently
717 in case of wind, since the turbulences generated may be very different on
718 both devices, and may also be a cause of systematic bias between the two
719 disdrometers. A future study using high speed video and a wind-tunnel setup
720 could help examine the occurrence and magnitude of these effects, which are
721 poorly quantified up to now.

722 Finally, we also detected a tendency towards underestimating the velocity
723 of falling particles in the case of the Parsivel units, especially in the range
724 between 1 and 3 mm. This have been shown previously, and according to
725 Tokay et al. (2014) this issue is known to the Parsivel manufacturer who
726 mentioned that it is in process of being fixed. However, at least the units
727 tested, still suffered from the same problem. Underestimation of the fall
728 velocity may have a substantial influence on the bulk variables computed
729 from the PSVD data, since the velocity intervenes in several of the equations.
730 Systematic underestimation of fall velocity has an effect of increasing ND
731 and Z , while it decreases E .

732 Differences in the number of particles detected, and biases in the estima-
 733 tion of particle size and velocity, result in complex biases in the integrated
 734 variables. This is due to the different effect that these factors have on their
 735 computation, since depending on the case there are linear or inverse relation-
 736 ships involved. This stressed the relevance of not only an unbiased estimation
 737 of the PSVD by the disdrometers, but also of any filtering and correction
 738 scheme applied to the PSVD data during post-processing.

739 5. Conclusions

740 The two types of disdrometer analysed showed different PSVD spectra for
 741 the same rainfall events, while the differences between two devices of the same
 742 type were much smaller and compatible with random differences. In particu-
 743 lar, Thies devices recorded a much larger number of drops than Parsivel², but
 744 also a much larger spread of the PSVD spectra, with a significant amount of
 745 drops with unexpected combinations of size and velocity, most notably small
 746 drops with excessively high velocities, compatible with edge events ('margin
 747 fallers'). Parsivel² devices, on the contrary, recorded less drops and a PSVD
 748 spectra which was much closer to the theoretical model. They also had a
 749 tendency towards underestimating drop velocity with respect to both Thies
 750 and a theoretical fall model.

751 Differences in the PSVD spectra resulted in significant discrepancies be-
 752 tween both disdrometers in all bulk precipitation parameters such as rain
 753 intensity and amount, particle density, radar reflectivity, or kinetic energy.
 754 These differences were found when these variables were computed by the in-
 755 ternal firmware of the devices, but also when they were computed by us from
 756 the PSVD data. When the PSVD data were filtered by considering only par-
 757 ticles with diameters between 0.25 and 8 mm and by removing unlikely drop
 758 size and velocity pairs, and a correction for the effective sampling area was
 759 used, the magnitude of the differences was reduced although the tendency

760 remained. In all cases, the differences increased with precipitation intensity,
761 as did the variance between devices of the same type, in agreement with the
762 expectation and with previous studies.

763 The differences found may be explained by hardware or software differ-
764 ences. Geometrical differences on the laser beams of the two devices translate
765 to different prevalence of bias-inducing effects such as edge events and double
766 detections, while differences the external design may also have a large influ-
767 ence on the drop splash. The manufacturers of both disdrometers indicate
768 that corrections have been implemented to prevent or reduce the magnitude
769 of this effects, but the exact procedures are not documented. Different so-
770 lutions can be adopted to limit undesired effects, both at the hardware and
771 the software level, and inspection of the resulting PVSD spectra during the
772 same rainfall events suggests that the level of correction is higher in the case
773 of Parsivel than in the case of Thies. Wether these differences are (total or
774 partially) due to hardware and design differences, or they are caused by hard-
775 ware or software filtering and correction of the PSVD data, is still a question
776 with no clear answer. Since some crucial aspects of the internal functioning
777 of both devices are hidden from the final user, it is very difficult to design a
778 data treatment process that would enable making the records of Thies and
779 Parsivel disdrometers compatible and comparable across studies.

780 6. Acknowledgments

781 This work has been supported by the research projects CGL2011-24185,
782 CGL2014-52135-C3-1-R and CGL2017-83866-C3-3-R, financed by the Span-
783 ish Ministerio de Economía, Industria y Competitividad (MINECO) and EU-
784 FEDER. The work of M. Angulo-Martínez was supported by a postdoctoral
785 grant by MINECO. We declare that we have no competing interests.

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- 1071 [TABLES AND FIGURES]

Table 1: Classification of particles according to equivalent volume diameter (D) and fall velocity (V) bins by disdrometer type.

Size bins (mm)		Velocity bins (m s ⁻¹)	
Thies	Parsivel	Thies	Parsivel
	0.000–0.125 ^a		0.0–0.1
0.125–0.250	0.125–0.250 ^a	0.0–0.2	0.1–0.2
0.250–0.375	0.250–0.375	0.2–0.4	0.2–0.3
0.375–0.500	0.375–0.500	0.4–0.6	0.3–0.4
0.500–0.750	0.500–0.625	0.6–0.8	0.4–0.5
0.750–1.000	0.625–0.750	0.8–1.0	0.5–0.6
1.000–1.250	0.750–0.875	1.0–1.4	0.6–0.7
1.250–1.500	0.875–1.000	1.4–1.8	0.7–0.8
1.500–1.750	1.000–1.125	1.8–2.2	0.8–0.9
1.750–2.000	1.125–1.250	2.2–2.6	0.9–1.25
2.000–2.500	1.250–1.500	2.6–3.0	1.03–1.2
2.500–3.000	1.500–1.750	3.0–3.4	1.2–1.4
3.000–3.500	1.750–2.000	3.4–4.2	1.4–1.6
3.500–4.000	2.000–2.250	4.2–5.0	1.6–1.8
4.000–4.500	2.250–2.575	5.0–5.8	1.8–2.05
4.500–5.000	2.575–3.000	5.8–6.6	2.05–2.4
5.000–5.500	3.000–3.500	6.6–7.4	2.4–2.8
5.500–6.000	3.500–4.000	7.4–8.2	2.8–3.2
6.000–6.500	4.000–4.500	8.2–9.0	3.2–3.6
6.500–7.000	4.500–5.125	9.0–10.0	3.6–4.1
7.000–7.500	5.125–6.000	> 10.0	4.1–4.8
7.500–8.000	6.000–7.000		4.8–5.6
> 8.000	7.000–8.000		5.6–6.4
	8.000–9.000		6.4–7.2
	9.000–10.250		7.2–8.2
	10.250–12.000		8.2–9.6
	12.000–14.000		9.6–11.2
	14.000–16.000		11.2–12.8
	16.000–18.000		12.8–14.4
	18.000–20.000		14.4–16.4
	20.000–23.000		16.4–19.2
	23.000–26.000		19.2–21.4

^a Left empty by the manufacturer.

Table 2: Disdrometer evaluated variables. M and m stand for maximum and mean, respectively.

Variables	Units	Acronym
Rain rate, mean and max	mm h^{-1}	R, Rm, RM
Precipitation accumulated	mm	P
Number of particles	min^{-1}	NP, NPm
Particle density	$\text{m}^{-3} \text{mm}^{-1}$	ND, NDm
Radar reflectivity	dBZ	Z
Kinetic energy	$\text{J m}^{-2} \text{mm}^{-1}$	E, Em, EM
10th PSD percentile	mm	$D10$
50th PSD percentile	mm	$D50$
90th PSD percentile	mm	$D90$
Mean PSD	mm	Dm
10th PVD percentile	m s^{-1}	$V10$
50th PVD percentile	m s^{-1}	$V50$
90th PVD percentile	m s^{-1}	$V90$
Mean PVD	mm	Vm

Table 3: Disdrometer data summary. Number of minutes recorded, errors, minutes with rain (SYNOP codes 61, 63 and 65), and high quality minutes; percentage of records in each season, and by rain intensity ranges; and maximum rain intensity.

	T1	T2	P1	P2
Total minutes	98,861	99,290	92,029	74,608
Error flags	20	33	240	103
Rain minutes	30,359	30,507	25,299	18,376
% rain minutes	30.7	30.7	27.5	24.6
High quality rain minutes	25,357	25,688	23,895	18,376
Common, high quality, rain minutes	11,659	11,659	11,659	11,659
% rain minutes in winter	27.7	27.7	28.7	33.7
% rain minutes in spring	26.6	26.1	25.3	10.9
% rain minutes in summer	11.1	11.1	11.1	11.9
% rain minutes in autumn	34.6	35.2	35.0	43.5
% minutes 0.1-2 mm h ⁻¹	84.6	83.6	86.8	85.8
% minutes 2-5 mm h ⁻¹	11.9	12.4	10.4	11.1
% minutes 5-10 mm h ⁻¹	2.3	2.8	1.9	2.0
% minutes 10-25 mm h ⁻¹	0.75	0.8	0.7	0.59
% minutes >25 mm h ⁻¹	0.43	0.46	0.3	0.49
Lowest R (mm h ⁻¹)	0.018	0.020	0.015	0.014
Highest R (mm h ⁻¹)	251	277	170	169

Table 4: Gamma Generalized Linear Mixed-Effects Model coefficients for one-minute records (random sample size of $N = 1000$). Refer to Table 2 for a list of acronyms of response variables.

Response variable	Fixed effects				Random effects	
	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
<i>NP</i>	230.1	$<2 \times 10^{-16}$	193.8	$<2 \times 10^{-16}$	0.000	0.8719
<i>D10</i>	0.3374	$<2 \times 10^{-16}$	0.4772	$<2 \times 10^{-16}$	3.614×10^{-3}	0.1730
<i>D50</i>	0.5956	$<2 \times 10^{-16}$	0.7420	$<2 \times 10^{-16}$	1.488×10^{-3}	0.1899
<i>D90</i>	1.012	$<2 \times 10^{-16}$	1.026	$<2 \times 10^{-16}$	0.000	0.209
<i>V10</i>	1.316	$<2 \times 10^{-16}$	1.793	$<2 \times 10^{-16}$	1.716×10^{-2}	0.2097
<i>V50</i>	2.399	$<2 \times 10^{-16}$	2.875	$<2 \times 10^{-16}$	2.450×10^{-2}	0.1646
<i>V90</i>	3.818	$<2 \times 10^{-16}$	3.608	$<2 \times 10^{-16}$	1.200×10^{-2}	0.1445
<i>R</i>	1.440	1.659×10^{-7}	1.254	$<2 \times 10^{-16}$	2.292×10^{-8}	1.467
<i>ND</i>	21,600	$<2 \times 10^{-16}$	15,920	$<2 \times 10^{-16}$	0.000	0.578
<i>Z</i>	24.55	$<2 \times 10^{-16}$	23.23	$<2 \times 10^{-16}$	0.000	0.2828
<i>E</i>	11.09	$<2 \times 10^{-16}$	9.660	$<2 \times 10^{-16}$	2.099×10^{-8}	0.4912

Table 5: Gamma Generalized Linear Mixed-Effects Models coefficients for event totals (sample size $N = 624$). Refer to Table 2 for a list of variable acronyms.

Response variable	Fixed effects				Random effects	
	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
<i>NP</i>	167.5	$<2 \times 10^{-16}$	146.3	$<2 \times 10^{-16}$	0.000	0.8463
<i>D10m</i>	0.3448	$<2 \times 10^{-16}$	0.4909	$<2 \times 10^{-16}$	3.073×10^{-3}	0.1629
<i>D50m</i>	0.6061	$<2 \times 10^{-16}$	0.7560	$<2 \times 10^{-16}$	0.000	0.1564
<i>D90m</i>	0.9971	$<2 \times 10^{-16}$	1.027	$<2 \times 10^{-16}$	0.000	0.1566
<i>V10m</i>	1.351	$<2 \times 10^{-16}$	1.826	$<2 \times 10^{-16}$	2.027×10^{-2}	0.2036
<i>V50m</i>	2.465	$<2 \times 10^{-16}$	2.876	$<2 \times 10^{-16}$	2.607×10^{-2}	0.1375
<i>V90m</i>	3.791	$<2 \times 10^{-16}$	3.597	$<2 \times 10^{-16}$	1.907×10^{-2}	0.1114
<i>Rm</i>	1.051	$<2 \times 10^{-16}$	0.9615	$<2 \times 10^{-16}$	0.000	1.063
<i>RM</i>	3.351	$<2 \times 10^{-16}$	3.430	$<2 \times 10^{-16}$	6.788×10^{-8}	1.584
<i>NDm</i>	20,780	$<2 \times 10^{-16}$	15,930	$<2 \times 10^{-16}$	9.283×10^{-5}	0.4714
<i>Em</i>	11.03	$<2 \times 10^{-16}$	9.505	$<2 \times 10^{-16}$	1.867×10^{-7}	0.3792
<i>Zm</i>	22.75	$<2 \times 10^{-16}$	21.55	$<2 \times 10^{-16}$	1.872×10^{-7}	0.2068

Table 6: Gamma Generalized Linear Mixed-Effects Model coefficients for minutes with varying rainfall intensities.

Response variable	Fixed effects				Random effects	
	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
Low rainfall intensity ($0.1 < I < 2 \text{ mm h}^{-1}$):						
<i>NP</i>	145.8	$< 2 \times 10^{-16}$	136.1	$< 2 \times 10^{-16}$	1.132×10^{-7}	0.7129
<i>D10</i>	0.3481	$< 2 \times 10^{-16}$	0.4723	$< 2 \times 10^{-16}$	3.795×10^{-3}	0.1758
<i>D50</i>	0.5975	$< 2 \times 10^{-16}$	0.7109	$< 2 \times 10^{-16}$	3.160×10^{-3}	0.1765
<i>D90</i>	0.9440	$< 2 \times 10^{-16}$	0.9503	$< 2 \times 10^{-16}$	0.000	0.1650
<i>V10</i>	1.365	$< 2 \times 10^{-16}$	1.762	$< 2 \times 10^{-16}$	2.189×10^{-2}	0.2156
<i>V50</i>	2.416	$< 2 \times 10^{-16}$	2.768	$< 2 \times 10^{-16}$	2.189×10^{-2}	0.2156
<i>V90</i>	3.639	$< 2 \times 10^{-16}$	3.425	$< 2 \times 10^{-16}$	1.145×10^{-2}	0.1202
<i>R</i>	0.6675	1.659×10^{-7}	0.6202	$< 2 \times 10^{-16}$	0.000	0.6570
<i>ND</i>	24,840	$< 2 \times 10^{-16}$	18,710	$< 2 \times 10^{-16}$	9.824×10^{-3}	0.5478
<i>Z</i>	21.44	$< 2 \times 10^{-16}$	20.45	$< 2 \times 10^{-16}$	0.000	0.2281
<i>E</i>	9.434	$< 2 \times 10^{-16}$	7.953	$< 2 \times 10^{-16}$	1.113×10^{-2}	0.4108
Medium rainfall intensity ($2 < I < 10 \text{ mm h}^{-1}$):						
<i>NP</i>	519.2	$< 2 \times 10^{-16}$	408.1	$< 2 \times 10^{-16}$	3.144×10^{-9}	0.4014
<i>D10</i>	0.3122	$< 2 \times 10^{-16}$	0.4944	$< 2 \times 10^{-16}$	1.681×10^{-3}	0.1232
<i>D50</i>	0.5936	$< 2 \times 10^{-16}$	0.8246	$< 2 \times 10^{-16}$	7.793×10^{-4}	0.1592
<i>D90</i>	1.525	$< 2 \times 10^{-16}$	1.772	$< 2 \times 10^{-16}$	1.203×10^{-10}	0.1268
<i>V10</i>	1.177	$< 2 \times 10^{-16}$	1.893	$< 2 \times 10^{-16}$	8.798×10^{-3}	0.1666
<i>V50</i>	2.420	$< 2 \times 10^{-16}$	3.133	$< 2 \times 10^{-16}$	2.348×10^{-2}	0.1587
<i>V90</i>	4.488	$< 2 \times 10^{-16}$	4.147	$< 2 \times 10^{-16}$	3.325×10^{-2}	9.908×10^{-2}
<i>R</i>	4.048	1.659×10^{-7}	3.596	$< 2 \times 10^{-16}$	1.145×10^{-2}	0.1202
<i>ND</i>	13,730	$< 2 \times 10^{-16}$	8,228	$< 2 \times 10^{-16}$	6.932×10^{-3}	0.3899
<i>Z</i>	34.26	$< 2 \times 10^{-16}$	32.22	$< 2 \times 10^{-16}$	7.137×10^{-3}	0.1092
<i>E</i>	15.09	$< 2 \times 10^{-16}$	13.95	$< 2 \times 10^{-16}$	7.105×10^{-3}	0.3521
High rainfall intensities ($I > 10 \text{ mm h}^{-1}$):						
<i>NP</i>	1367.0	$< 2 \times 10^{-16}$	829.7	$< 2 \times 10^{-16}$	9.263×10^{-9}	0.3532
<i>D10</i>	0.287	$< 2 \times 10^{-16}$	0.5391	$< 2 \times 10^{-16}$	0.000	0.1866
<i>D50</i>	0.510	$< 2 \times 10^{-16}$	1.030	$< 2 \times 10^{-16}$	0.000	0.2777
<i>D90</i>	1.525	$< 2 \times 10^{-16}$	1.772	$< 2 \times 10^{-16}$	1.645×10^{-2}	0.1560
<i>V10</i>	1.015	$< 2 \times 10^{-16}$	2.047	$< 2 \times 10^{-16}$	0.000	0.2213
<i>V50</i>	2.012	$< 2 \times 10^{-16}$	3.529	$< 2 \times 10^{-16}$	0.000	0.2672
<i>V90</i>	4.992	$< 2 \times 10^{-16}$	4.467	$< 2 \times 10^{-16}$	0.000	0.1196
<i>R</i>	15.94	1.659×10^{-7}	14.33	$< 2 \times 10^{-16}$	2.374×10^{-2}	0.2910
<i>ND</i>	10,370	$< 2 \times 10^{-16}$	3,544	$< 2 \times 10^{-16}$	0.000	0.428
<i>Z</i>	43.05	$< 2 \times 10^{-16}$	40.88	$< 2 \times 10^{-16}$	9.882×10^{-3}	8.927×10^{-2}
<i>E</i>	19.84	$< 2 \times 10^{-16}$	20.81	$< 2 \times 10^{-16}$	5.844×10^{-9}	0.3198



Figure 1: Sampling site with four collocated disdrometers: two Parsivel² (P1 and P2, with serial numbers 304555 and 304553); and two Thies (T1 and T2, with serial numbers 0436 and 0655).

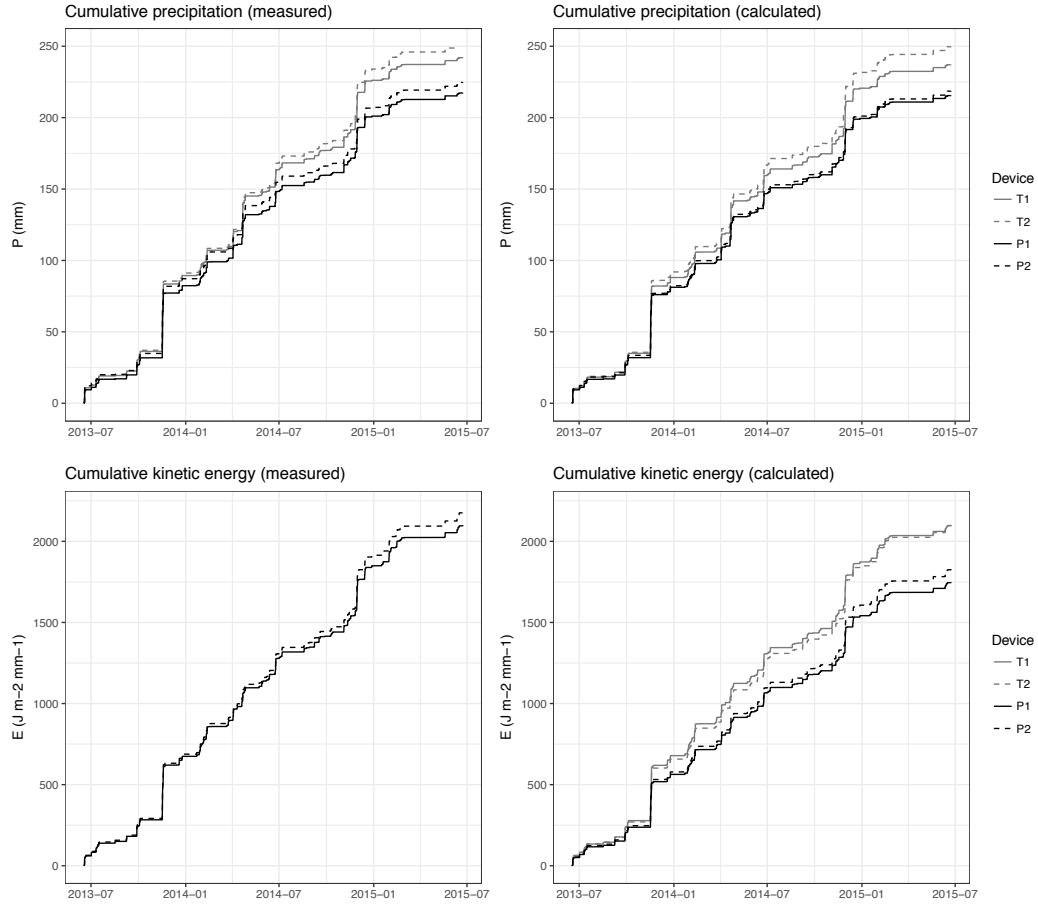


Figure 2: Accumulated precipitation (R , mm) and kinetic energy (E , $\text{J m}^{-2} \text{mm}^{-1}$) during the two years experiment (only the minutes with data on the four disdrometers are used).

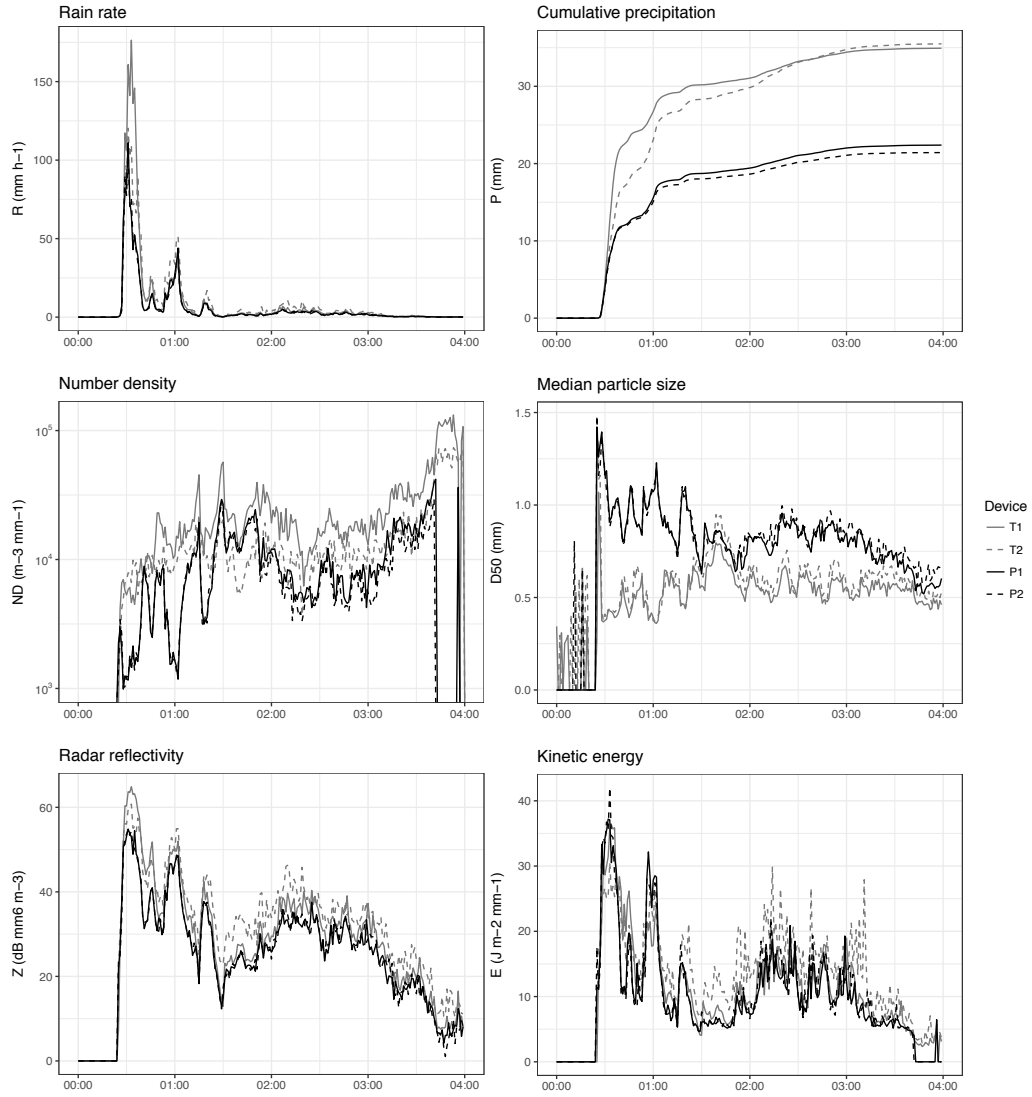


Figure 3: Time series of disdrometer bulk variables during a high-intensity event (E365, 25/11/2014).

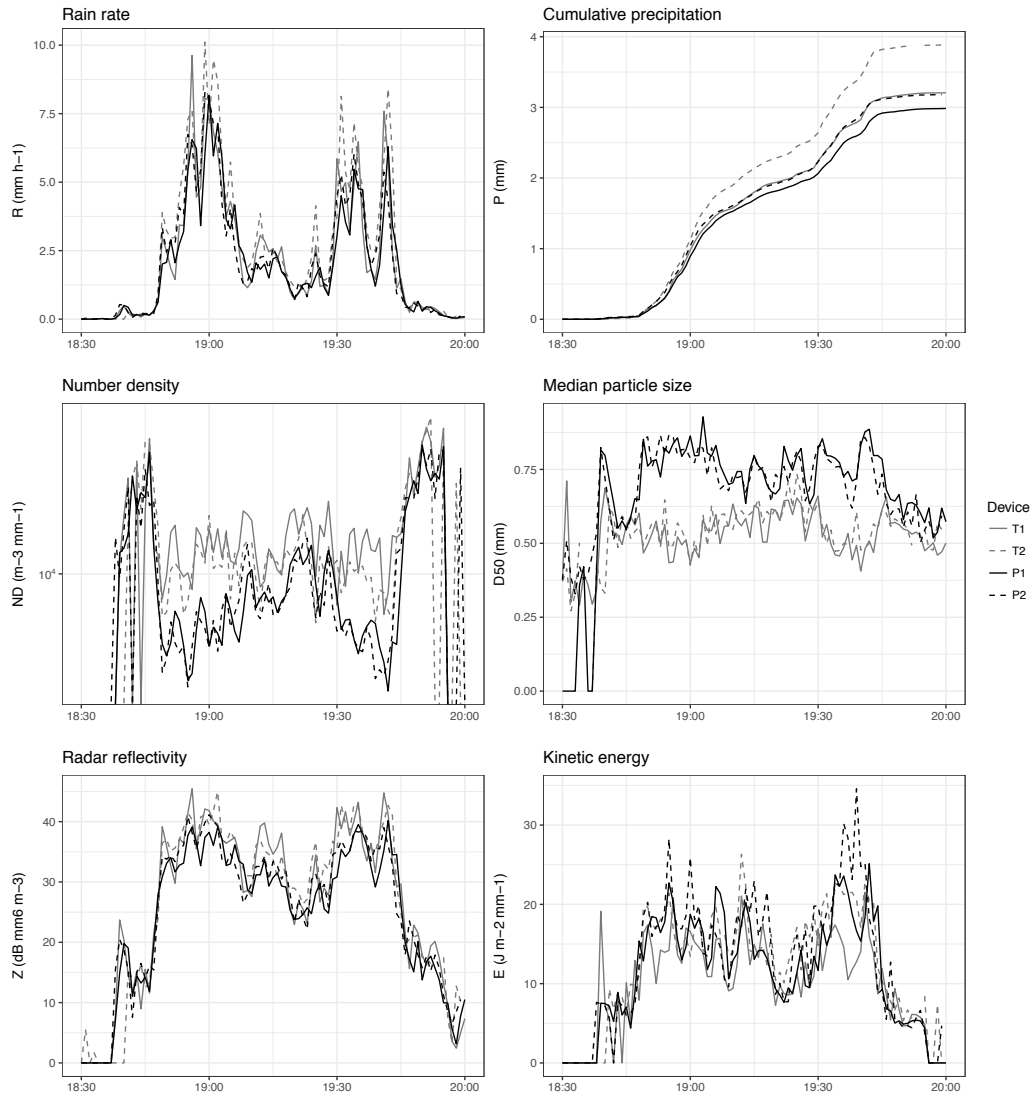


Figure 4: Time series of disdrometer bulk variables during a low-intensity event (E455, 23/02/2015).

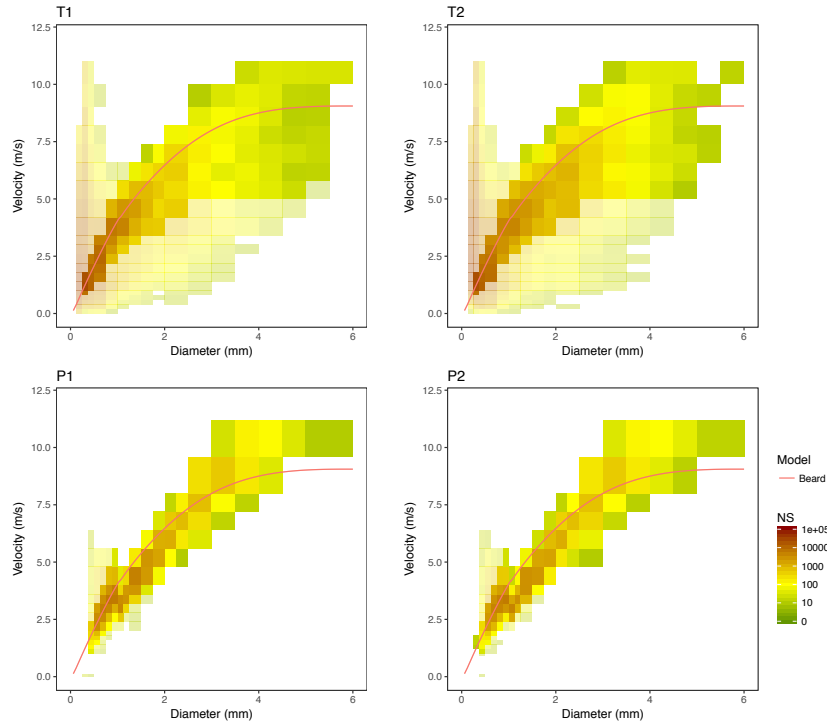


Figure 5: Particle size and velocity density (PSVD) plots of a high-intensity event (E365, 25/11/2014). The color scale indicates the number of particles for each size and velocity class (NP). Deviations larger than 50% from the theoretical terminal velocity model (Beard, 1976; red line) are indicated with a 50% transparency.

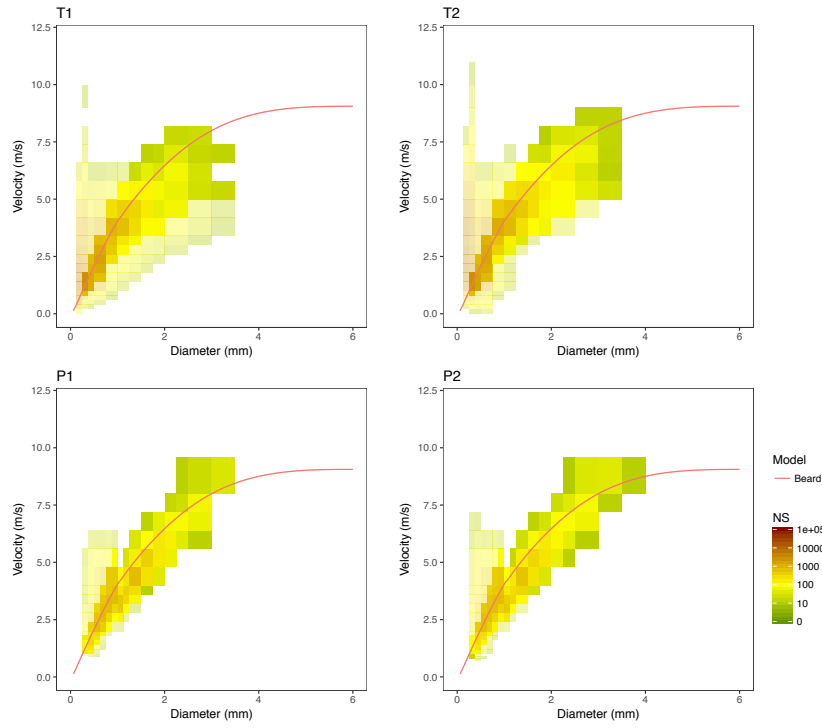


Figure 6: Particle size and velocity density (PSVD) plots of a low-intensity event (E455, 23/02/2015). Legend as in Figure 5.

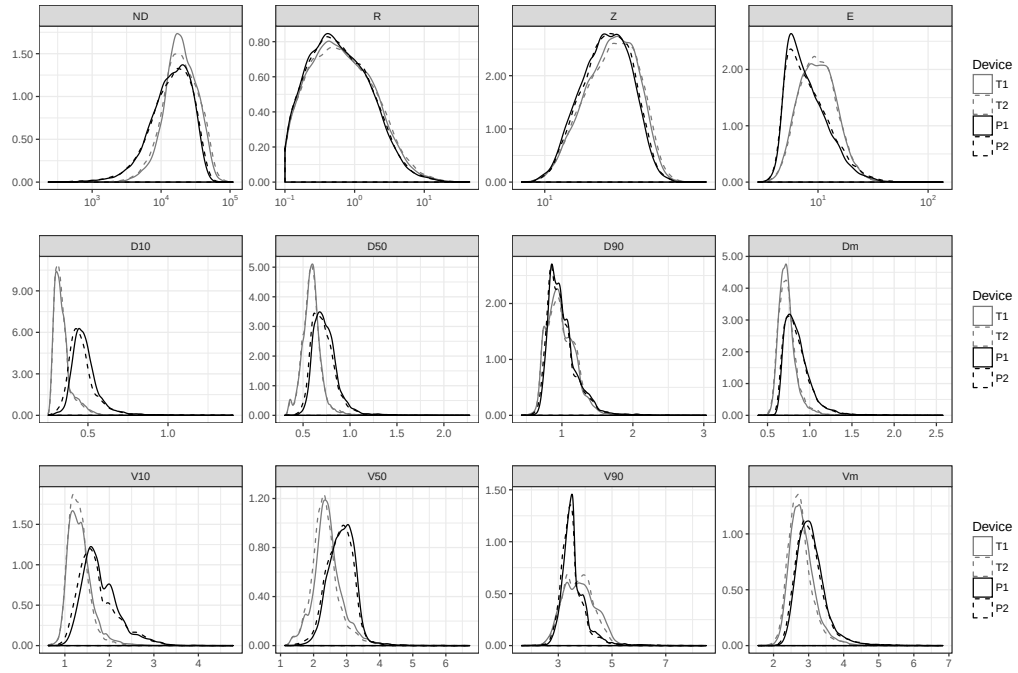


Figure 7: Kernel density plots for one-minute records.

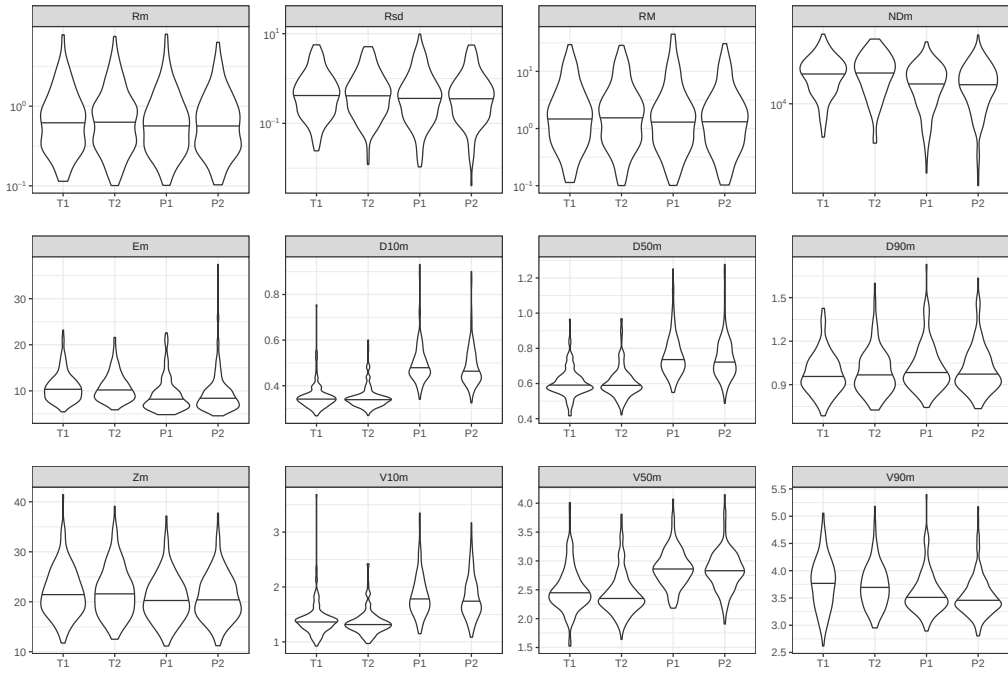


Figure 8: Violin plots for events means and maxima. Refer to Table 2 for a list of acronyms of the variables.

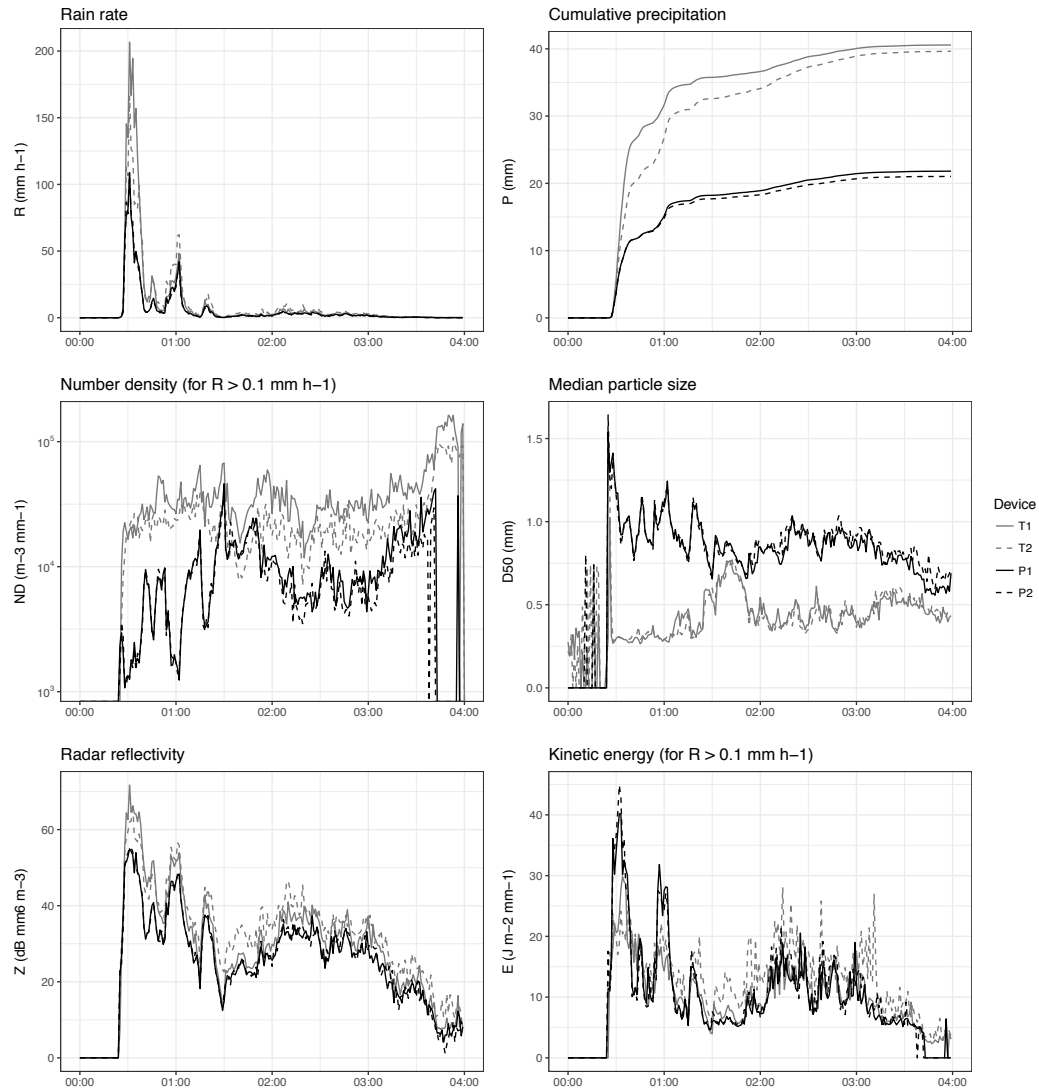


Figure A.1: Time series of disdrometer bulk variables during a high-intensity event (E365), with no corrections of the PSVD data.

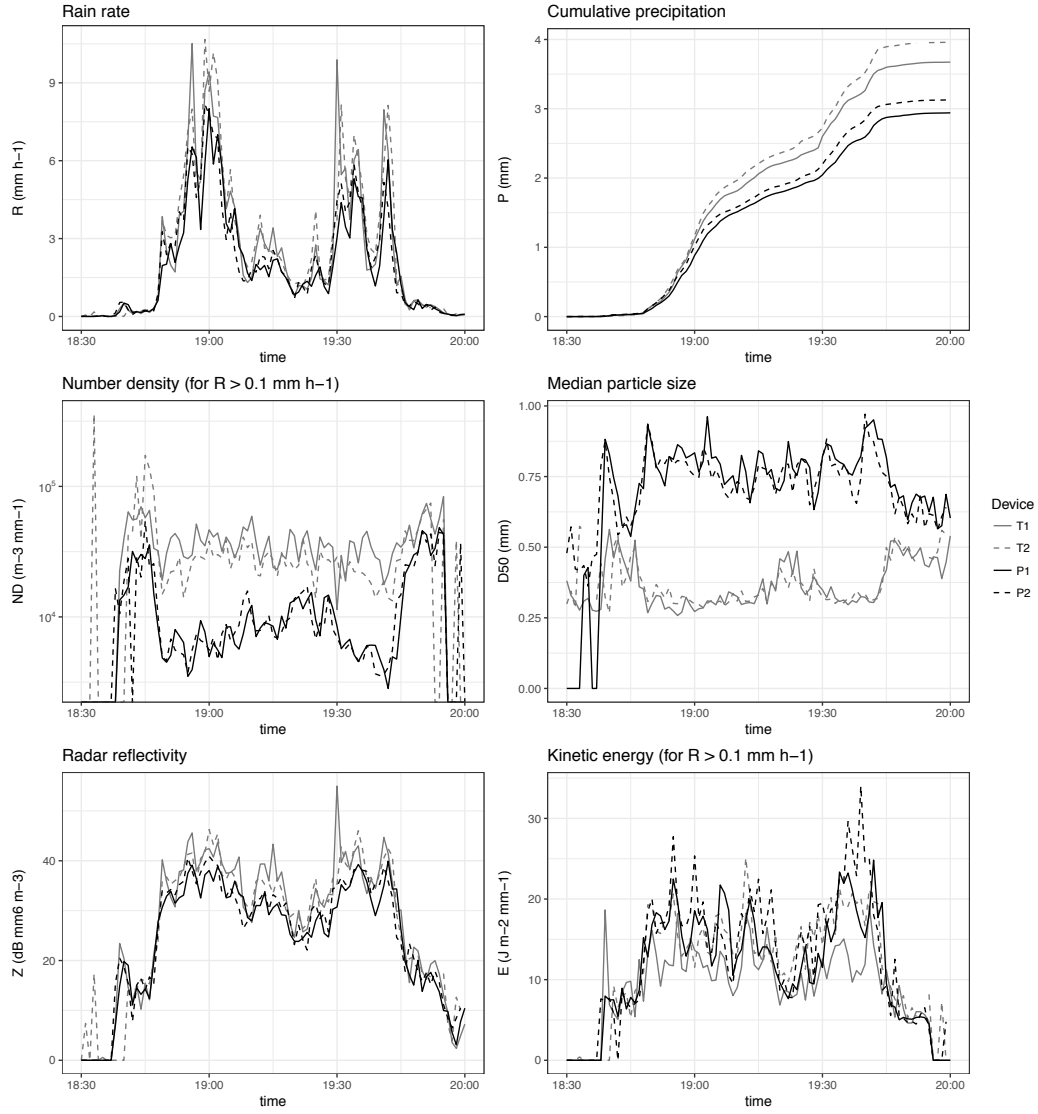


Figure A.2: Time series of disdrometer bulk variables during a low-intensity event (E455), with no corrections of the PSVD data.

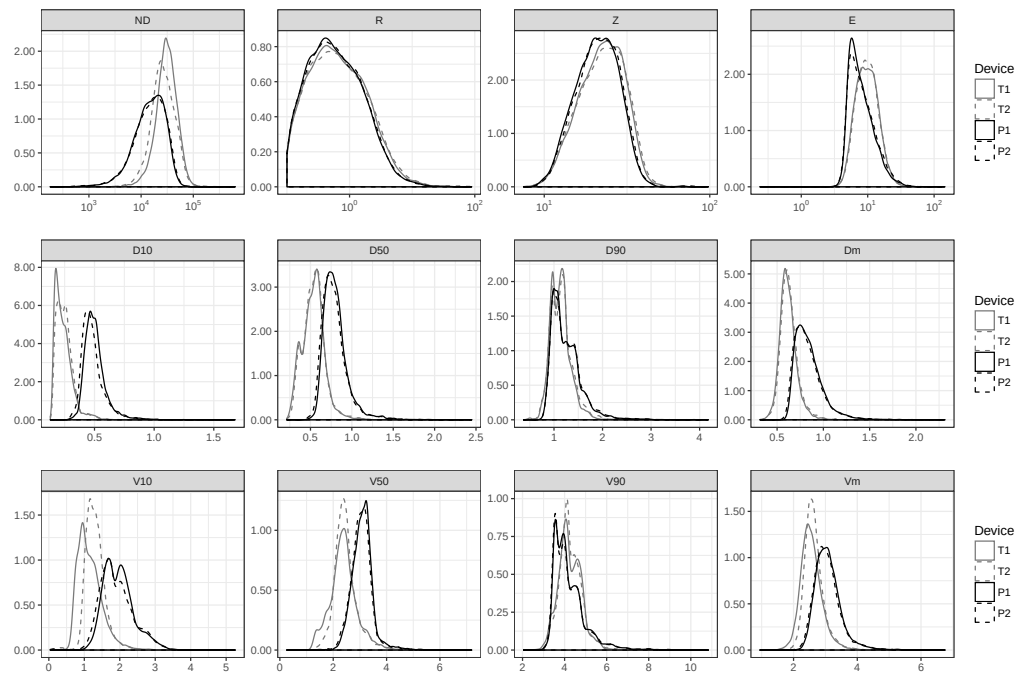


Figure A.3: Kernel density plots for one-minute records, with no corrections of the PSVD data.

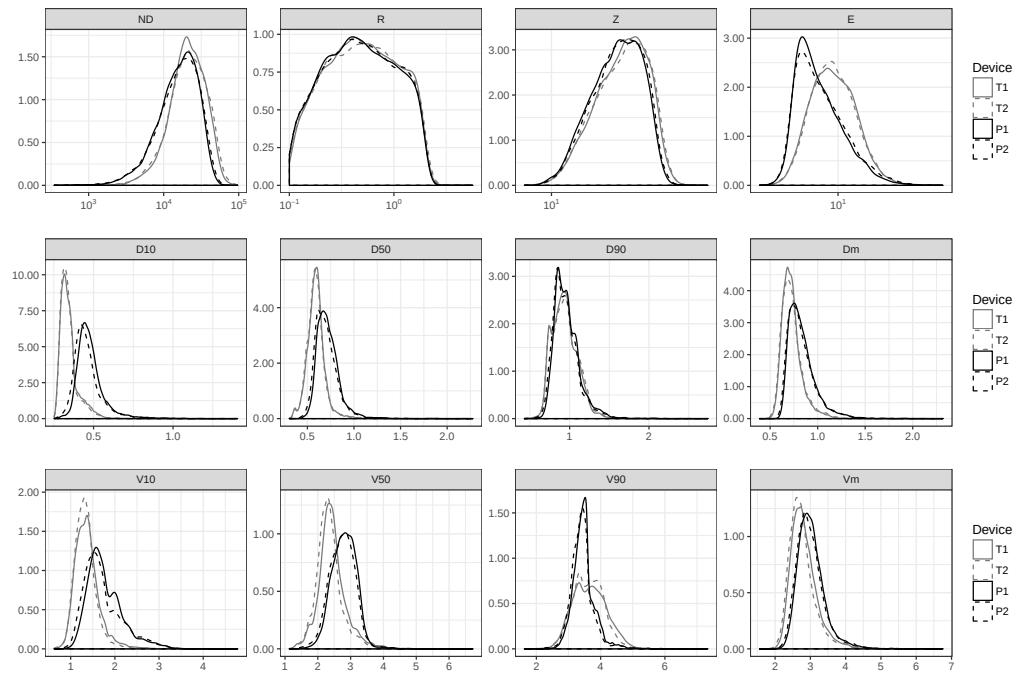


Figure A.4: Kernel density plots for low rainfall intensities ($0.1 < I < 2 \text{ mm h}^{-1}$).

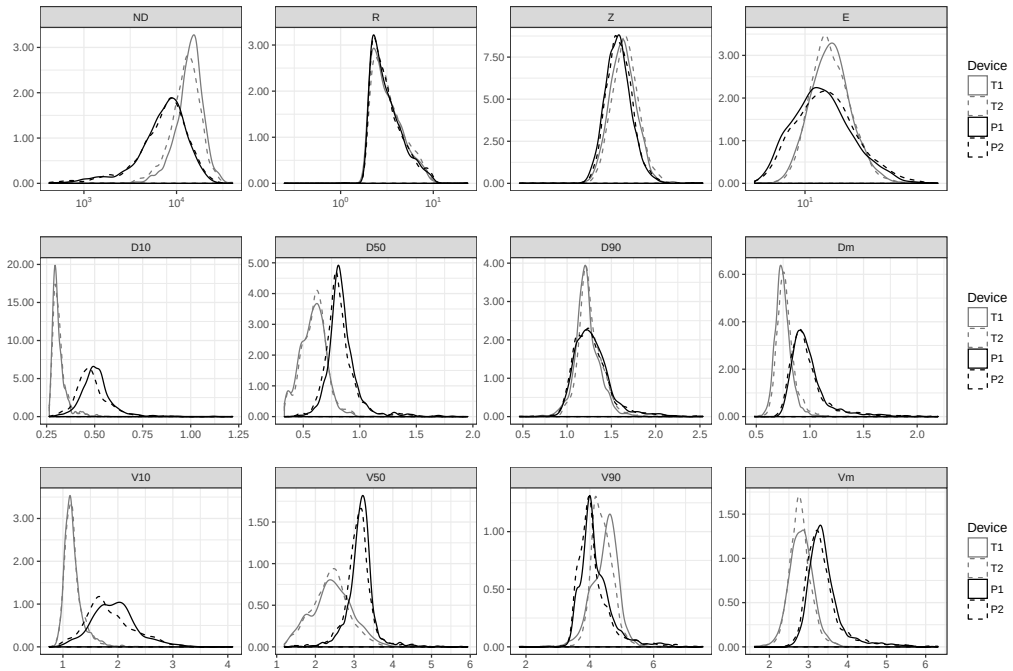


Figure A.5: Kernel density plots for medium rainfall intensities ($2 < I < 10 \text{ mm h}^{-1}$).

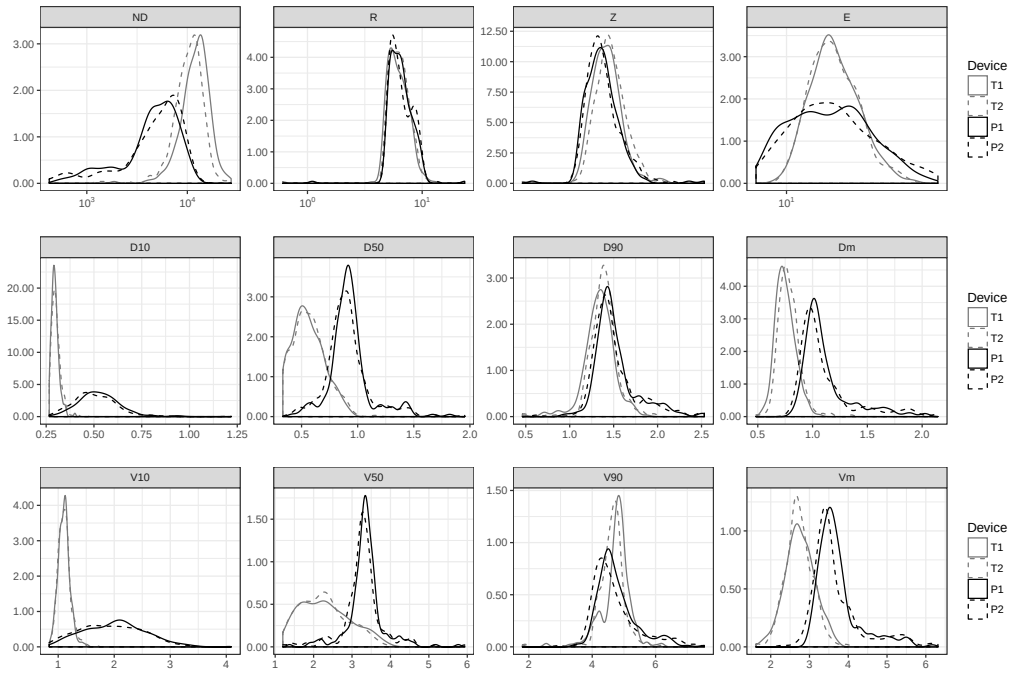


Figure A.6: Kernel density plots for high rainfall intensities ($I > 10 \text{ mm h}^{-1}$).

Table A.1: Gamma Generalized Linear Mixed-Effects Model coefficients for one-minute records, with no corrections of the PSVD data ($N = 1000$).

Variable	Fixed effects				Random effects	
	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
<i>NP</i>	311	$<2 \times 10^{-16}$	192	$<2 \times 10^{-16}$	1.130×10^{-8}	1.027
<i>D10</i>	0.2409	$<2 \times 10^{-16}$	0.5010	$<2 \times 10^{-16}$	8.726×10^{-4}	0.2493
<i>D50</i>	0.5302	$<2 \times 10^{-16}$	0.8040	$<2 \times 10^{-16}$	0.000	0.2420
<i>D90</i>	1.126	$<2 \times 10^{-16}$	1.254	$<2 \times 10^{-16}$	0.000	0.2320
<i>V10</i>	1.199	$<2 \times 10^{-16}$	1.972	$<2 \times 10^{-16}$	3.062×10^{-2}	0.2420
<i>V50</i>	2.392	$<2 \times 10^{-16}$	3.085	$<2 \times 10^{-16}$	0.000	0.1760
<i>V90</i>	4.215	$<2 \times 10^{-16}$	4.203	$<2 \times 10^{-16}$	0.000	0.1641
<i>R</i>	1.326	1.130×10^{-4}	1.183	8.77×10^{-11}	0.000	1.660
<i>ND</i>	33,370	$<2 \times 10^{-16}$	17,750	$<2 \times 10^{-16}$	1.246×10^{-7}	0.6232
<i>Z</i>	24.00	$<2 \times 10^{-16}$	22.45	$<2 \times 10^{-16}$	0.000	0.2968
<i>E</i>	10.370	$<2 \times 10^{-16}$	8.968	$<2 \times 10^{-16}$	0.000	0.4733