Santiago Beguería, March 6th 2018

I am pleased to submit a revised version of our manuscript. This is a much improved version, and we thank the three anonymous reviewers for their insightful reviews.

Addressing all the suggestions has implied changes in all the sections of the manuscript. Although the main conclusions of the study do not change, we believe that the analyses are now much more robust, and the discussion has also improved a good deal.

The most relevant change has been to implement a new filtering and correction technique, as suggested by two of the three reviewers. This helped comparing the two disdrometers in a fairer way, and it has also allowed for a more in depth discussion of the differences between the two devices. Since the calculations were new, we also had to re-do the plots, analyses and tables. As requested, we have further discussed the results, including those of the Gamma GLMM regression.

In the following pages we provide a point-by-point reply to the specific comments to the three reviewers. We also provide an annotated version of the manuscript in which all the changes have been highlighted.

Response to Anonymous Referee #1

General comments

- This paper discusses a comparison between two the outputs of 4 disdrometers of two different types. The data set is interesting and worth analysing. The topic is relevant for the hydrometeorologists and could be published in HESS provided that some major modifications are carried out on the manuscript.

Presentation should be improved, notations are not clear and change through the text (as an example the rain rate is referred by three notations R Pr I...), references to figure numbers are often erroneous, methodologies implemented are not properly described.

Not all figures are properly discussed within the manuscript. Some results are not properly justified from figures or tables. The authors insist on the differences for small drops. Plots of DSD (N(D)) could be helpful in the discussion.

We thank the reviewer for the insightful review and useful comments. We have tried to address all the issues raised, we hope in a satisfactory manner.

We have carefully checked the notations used, references to figure numbers, and other general issues mentioned.

We have improved the discussion of all the figures, and have better related the discussion of results with the figures or tables. We have included new plots of the particle density ND (included now in Figures 3 and 4, since they did not fit in only one figure as before), as suggested.

Specific comments: Data and methods section

- Figure 1: It seems that there is also a wind sensor, at least for direction. Since all the devices are oriented in the same direction, did you check whether this parameter had an influence on the similarities or discrepancies. Were the devices always oriented this way or part of the experiment was done with devices oriented perpendicularly?

The four sensors were oriented in the same direction and they were maintained as such during the experiment. We have stressed this in the manuscript, and we have improved Figure 1 by adding labels to the four devices and by including a graphic scale.

A wind sensor was installed later during the experiment, but we had issues with the wind direction sensor which had a strong bias. As a result, we have valid wind data only for a small fraction of the events, and decided to not use it. We do not know, thus, if the differences between the two devices varied under different wind conditions. We have a new experimental setup since 2017 that includes disdrometers oriented in different directions. This is an undergoing experiment that will be the subject of another report.

- p.5 l.8 0.005m2, it might be helpful for the reader to express in cm2.

We have expressed the surface of the sensor in cm^2.

- p.5 l.19: is the relation between axis-ration and equivolumic diameter the same for both devices?

It seems so, although there are very few details from the manufacturers. We have not found explicit information for the Thies, but in the case of Parsivel this is better known. We have included information on this in the detailed description of the differences between both disdrometers, in section

2.1.

- Eq 1 : KE is not defined in the text. I would replace N by a $N_{i,j}$ which makes more visible that it is a number per bins of size and velocity. Provide units for 'a' and 'Pr'. Why not use R for 'Pr'

We have provided units for all the variables, and included the formulas for computing all the integrated variables mentioned in the text. We have also used $N_{i,j}$ to indicate the particle count per size and velocity classes.

- p.7 l.19-20 : I guess that it is pretty minor, but did you check if the given realization of random affectation of a diameter within a bin had an influence on the results.

Given the high number of particles detected, the random component of this scheme has a negligible effect on the results, as we confirmed by repeating the procedure a number of times with different random seeds. This has been specified in the text.

- Table 2 : Please define all variables somewhere in the text (KeM, Npm...)

All variables in Table 2 have now been defined in the text.

- Section 2.3 : It is quite hard to follow and presentation should be strongly improved. The last paragraph (p.8 l. 24-26) should also be written for non R users.

We have reworked this section substantially, and we believe it will now be an easier read.

Regarding the reference to the R library and functions used in the analysis, it is mentioned for the benefit of clarity and reproducibility. Although this reference could be deleted, we are used to clearly stating the software used in all of our analyses, so we propose to leave the reference. This information is only useful for those who would be interested in replicating the analysis, but it is not substantial for understanding the methodology.

Specific comments: Results section

- p.9 l.4-8 : it could be interesting to discuss the number of time steps when Thies records some data and not Parsivel to understand more their sensitivity differences (keeping in mind potential issues already mentioned in the text).

We have added new data on Table 3 indicating the exact number of minutes with data, with errors, with detection of rain, etc. This data shows that Thies devices detected rain in 30.7% of the minutes, while Parsivel nº 1 only did so in 27.5%. We do not compare it with Parsivel nº 2 because its record is shorter due to malfunctioning, and it missed some important events.

The table also shows that only the common, high quality rain minutes were used in the analysis.

- Table 3: clarify the the meaning of Nr. The fact that N records = 26.8% for Parsivel M1 is the greatest one seems in contradiction with the text mentioning a greater sensitivity (or false alarm) for the Thies.

As explained above, we have included new data on Table 3, that now clearly shows the number of minutes recorded by each device, the number of error flags, minutes with rain, and common minutes.

- p. 9 l.22: the differences between the two parsivels seem very high with regards to other similar studies. Do you have any explanation or interpretation? I think that this should be mentioned.

We have corrected an error that affected the computation of rainfall totals, that was not done considering only the common minutes in the four disdrometers. The values now show differences between disdrometers of the same type, but these are low and compatible with being random. For instance, total precipitation was 244.9 and 254.5 mm for Thies 1 and 2, and 220.4 and 228.1 mm for Parsivel 1 and 2.

- p. 9 l.15-22: the figures given do not seem to be in agreement with the plot in Fig. 2 (ex 400 mm for Thies in the text and 250-300 on the graph....

It is true, and it was due to the calculation error mentioned above. It has been corrected now. Please, note that we have modified Figure 2 so it now includes the same cumulative variables (precipitation and kinetic energy), but as given by the devices firmware and calculated from the PSVD data.

- Fig. 3: it could be interesting to add plot of DSD (N(D)) for the whole events. And discuss them.

It is true, and we have included the particle density (for which we use the symbol ND) in the figure, and in all the analyses. Since adding ND implied modifying the plot with one more row of plots, we also included the time series of the median particle size, which we believe complements in a good way the information on the plot. This has forced us to split Figure 3 in two, one for each event (now Figures 3 and 4).

- Fig. 4: did you apply a filter based on discrepancies of velocity with expected velocity for terminal fall velocities formula as some authors do?

No filter was applied, but it is an interesting suggestion. Since we got the same suggestion from the other reviewers, we have decided to include a filtering in our work. In what affects this figure (now split in two, one for each event), we have indicated with a different color the size and velocity bins that would be filtered out based on a 50% discrepancy with respect to the terminal velocity model of Beard (referenced).

- p. 10 l.13: please explain more in detail what is a kernel plot, it might not be obvious for all the readers.

A kernel density estimation, or kernel density plot, is a non-parametric way to estimate the probability density function of a random variable. We have added one line at the beginning of section 2.3 to make this clear to the unfamiliar reader.

- p. 10l. 19: ref to Fig. is a mistake.

True. It has been corrected.

- p.10 l.20-23: should be mentioned that it is Fig. 6 that is discussed. Discussion should be extended by starting by explaining more precisely what is plotted (the short figure caption is not enough).

We have corrected the references to tables and figures on this paragraph.

We have explained the kernel density plots at the begining of section 2.3, and we have re-written this section in order to make it clearer.

- Section 3.3: It is not clear what you mean and how you show it from the results (not sure that it is Fig. 6 that is discussed).

Section 3.3 discusses the differences between disdrometer types found at the event scale, while it was at the minute scale before. We have stressed this, and we believe that it is now much more clear. The results discussed are now in Figure 8 and Table 5.

- section 3.5: the limited impact of rain rate is somehow sur-

prising since I would have expected the that exceedance smaller drops would affect more strongly small rain rates (for which their influence on the total rainfall amounts is greater).

I would not say that the influence of rain rate was limited. The rain rate modulated strongly the differences found at a more general level, and the differences (more, but smaller particles sensed by Thies with respect to Parsivel) were amplified at higher intensity rates. We have rephrased the paragraph to make this clearer. We have also moved the results of the analysis at different intensities to a separated table (Table 6).

- Table 6 is not well discussed and quite hard to "digest" for the reader. It should be improved (may be a graphical representation would be more helpful for the reader).

The results of the statistical analysis are now split in Tables 4, 5 and 6. We have completely reformatted them, and the explanation of the terms and values shown has been extended. This is a formal statistical analysis that confirms what we could see in the graphical representation on Figure 7 (kernel densities) and 8 (violin plots).

Graphical results (kernel density plots) for the variables at varying intensities are given in the Appendix due to space limitations (figures A.4, A.5 and A.6).

Specific comments: Discussion and conclusions section

- Should be updated according to improvements.

We have rewritten the discussion section, and some modifications have been also done to the conclusion (now a section of its own).

– Some 'technical' issues with references (ex. P. 13, l. 22-23).

We have checked the references.

Response to anonymous Referee #2

General comments

This article compares the performance of two models of optical disdrometers in terms of rainfall accumulation, number of drops, kinetic energy (flux?), and radar reflectivity. This is an important topic, as optical disdrometers allow the continuous measurement of rainfall properties that are otherwise difficult to observe, such as drop-size and ve- locity distributions, kinetic energy flux, radar reflectivity, etc. However, there are a multitude of poorly understood sources of uncertainty associated with such measurements. The authors collocate two widely used models of disdrometers and compares their outputs for a large number of events, which is really a strong point of this article.

I'm puzzled that the experimental setup does not include tipping buckets. They are inexpensive, their uncertainties are well understood, and they would provide another independent measure of rainfall accumulation, useful to help us understand which of the models (or both models?) are likely to be overestimating rainfall volumes during the study period. As a shortcoming that should be improved before acceptance for publication, I would like to point out that some of the plots are underexplored. For example, Figure 2 shows a striking difference between the behaviors of KE and rainfall accumulation, however, there is little interpretation of the plot (more on this under specific comments). Figure 3 is not called in the text, although the discussion mentions the events. Finally, the acronyms for variables and the instruments should be unified throughout the text.

We thank the reviewer for the thorough review and useful comments.

We have improved the interpretation and discussion of the plots, unified the acronyms for variables and instruments, and undertaken a careful revision of most sections. We believe that the article has been greatly improved thanks to these amendments.

Regarding the tipping buckets, the main objective of the experiment was to compare the two disdrometer types and their recording of the particle size and velocity distribution (PSVD) and related moments. Deploying a tippying bucket pluviometer would allow us compare one of these moments, the rainfall amount, with yet another instrument, but that's all. One simple tipping bucket does not provide a valid reference for rainfall amount, since they are also subject to many uncertainties. At this respect, we participate in an ongoing experiment in which different rainfall sensors are compared against a Double-Fence Automated Reference(DFAR) pluviometer, which provides a validated reference. This would be the objective of a different study, however.

Specific comments

Page 2 Lines 12-14: "Disdrometers are also widely used to validate the reflectivity values obtained by weather radars, for what the studies on small scale PSD spatio- temporal variation and its influence in modeling PSD and rainfall rate - reflectivity (Z(R)) relations are particularly important". This sentence is a bit confusing. Please consider rephrasing. Moreover, more important than the validation of reflectivity values measured by a radar, disdrometer observations of drop-size distribution are used to derive relationships between radar reflectivity and rainfall rates (Z-R relationships). The biggest difficulty when one compares disdrometer and Radar measurements is the mismatch between the sensing area of a disdrometer (few cm2) and a radar pixel (km2). It would be interesting to point this out here.

We have rephrased this sentence as suggested.

Page 5 Lines 5-15: The authors describe the principle of operation and list sources of biases in the instruments. One missing source of biases in laser disdrometers is the uneven power distribution across the laser beam as described by Frasson et al. [2011]. Please consider adding it.

We have included uneven power distribution (in space and also in time) as a potential bias source. We have added a citation to Frasson et al. 2011, whose reference was already in the reference list.

Page 9 Lines 2-4: "Missing values were found in all disdrometers and can be attributed to technical issues (power supply failures, data communication problems, or spurious measures), being Ott PARSIVEL2 disdrometers the ones with the highest number of missing values." I worked with Thies disdrometers quite a few years back. During my data acquisition campaign, I had several records showing rainfall when in fact there was no rain. Did you experience such events? Could such "phantom" events be a cause for some of the "missing PARSIVEL data", in which case it wouldn't be rain missed by the PARSIVEL unit, but rather a problem in LPM?

Here we refer only to periods when one of the devices did not work due to technical problems due to power supply, communication issues, or directly to device hangouts. We have removed the reference to 'spurious measures', that was not correct. We have added more details on this on Table 3.

Regarding the 'phantom events', sometimes we found one of the devices recording particles during one single minute when the others did not record anything. These were automatically removed, since we only considered those minutes when the four devices recorded particles. This procedure has been made clearer in the manuscript, and numerical details are also provided.

Page 9 Lines 15-20: It is interesting to see that for KE only, T1, T2, and P1 showed remarkable agreement until October 2014, when suddenly T2 steeply increased its KE and caught up to P2. The pattern is different for cumulative rainfall, which shows more similarity in instruments of the same type and showed that the difference between Thies and Parsivel measurements increased gradually. Were there any anomalies in T2's measurements of velocity in November or December 2014? This figure deserves a bit more discussion. This event is likely a good candidate to be shown on its own, alongside the other events in figure 3. I find it quite interesting that before this event, there was a bias in volume measurements, but not in KE among three of the four disdrometers. Especially because for this type of instrument, errors in drop diameter are strongly correlated with velocity errors. As a minor comment, the text discusses instruments in terms of T1 and T2, P1, P2, but the figure labels them as Par1, Par2, Th1, Th2. It might be best to make the names more consistent.

Revising the figure, we have found an error that affected the filtering of the minutes specifically on this figure. Thus, some minutes were included where not all the four disdrometers had record. We have therefore re-done the plots. At the request of another reviewer, the figure now include the values calculated internally by the disdrometers ('measured') and also the values computed from the PSVD data. We have extended the discussion of the figure in the text.

I am not sure that the same effect can be seen now. The event E365, depicted on Figures 3 and 5, corresponds to the end of November 2014, and yes, in this case T2 recorded faster velocities than T1. The median particle size was also higher, and as a result both the radar reflectivity and kinetic energy were higher. In a previous event on the same month (E338, on 03/11/2014) this effect was not found.

Regarding the symbols used to refer to the four devices, we have generalised T1, T2, P1 and P2 throughout the article.

Page 10 Line 7: "These particles, as well as relatively large ones with low falling velocities, seem to be filtered out from the PARSIVEL2 output" Did the authors attempted to reach out to OTT and ask if there is any filtering of drops based on departures from expected the velocity-diameter curves? This would be particularly helpful to users who deploy the instrument in situations when drops are expected to deviate from theoretical drop size-velocity curves.

Yes, we have attempted to get more information from OTT regarding the (likely) filtering of the raw data, but we have not been given any more details. We have, however, stressed out the details that can be inferred from the literature (mostly from Löflfer-Mang and Joss, 2000, and from Tokay et al., 2013).

Figure 10 Line 14: Thies disdrometers recorded a much higher number of particles NP (a mean difference of 422 vs. 219). What does the mean number of particles represent? The mean number of particles across all events? Considering the magnitudes of the NPs in figure 3, it is difficult to believe that the average number of drops per event is a couple hundreds. Please consider defining how the average NP was computed and what it represents (averaging a drizzle and an intense thunderstorm doesn't seem to be useful).

NP refers to the number of particles detected **per minute**. We have made this clearer in the text. However, we have in general opted to use the more representative particle density number (ND), which represents the number of particles per cubic meter of air and mm of rain.

Section 3.4 – data filtering. Was the data presented in Figure

2 before or after filtering? Page 11 lines 26-27: "In brief, PARSIVEL2 tended to underestimate the number of particles recorded, and tended to record a larger number of bigger particles than Thies. At the same time, Thies recorded a very large number of small particles that may mask the amount of bigger particles recorded." Did you compute rainfall rate from the classified drop counts (from the matrix that shows drop counts per diameter-velocity class) or did you use the rainfall rates from the telegrams. It appears that the Thies disdrometer is overestimating the number of small drops in the first diameter class. Could the authors examine what happened when the rainfall moments (NP, Rainfall rate, kinetic energy flux, reflectivity, etc) are computed without considering the first class of drops? Knowing that the Parsivel disregards the first two classes due to noise induced by the power supply (as pointed out in the discussion), it would be fair to compute rainfall moments for the Thies also without considering the first two classes. Furthermore, if the authors compute the moments themselves, they might be counting classes that the Thies manufacturer already disregards. By no means I suggest replacing all plots, however, it would be interesting to add to the cumulative rainfall and KE in the beginning of the Results section computed with and without filtering the first two classes of the Thies disdrometer. The authors mention in the discussion the following sentence (Page 13, lines 13-14): "When PSVD data were filtered, considering only particles with diameters greater than 0.3 mm, these differences were reduced although the tendency remains and increases for high intensity rains." However, I could not find the recomputed totals or to know for sure if figures such as figure 2 showed rainfall totals after excluding the Thies' first diameter class.

This is a central issue in our comparison, and we present alternative results using the raw data and filtered (removing the small drops from the

Thies PSVD matrix). We now see that it was not very clear which results belong to which dataset, and we have worked to make it clearer in the revised manuscript.

We have also added a few new figures in which we used the filtered dataset. For instance, the cumulative variables represented in Figure 2 now include the values calculated by the disdrometer software and the values calculated from PSVD, after filtering.

Regarding the filtering scheme, a major change has been done as per recommendation of another reviewer. Thus, in addition to fixing the drop size to a common range (which was, in fact, 0.250 to 8 mm), it was suggested that we removed the particles with unlikely combinations of size and velocity. We have implemented this filter, which implied repeating all the analyses. For assessing the influence of this filtering, and of the required adjustment of the sensing area, we have also included results without filtering, which are shown in the Appendix (Figures A.1, A.2, A.3 and Table A.1).

As mentioned by the authors in the discussion, two further causes for differences in the drop counts may be related to turbulence and splashing. Due to the Thies bulky electronics enclosure, this instrument might be especially susceptible to splashing and to turbulence induced errors (please see [Constantinescu et al., 2007] for an evaluation of turbulence effects on tipping buckets). Particularly at high intensity events, splashing from the Thies electronics case could be producing droplets that end up falling inside its sensing area. The Parsivel heads are less bulky and have a protection to decrease splashing (although I'm sure it still happens). I'm eager to see a future study employing high speed video to examine the occurrence of splashing and possible effects on the data.

This is indeed a very relevant issue in our opinion, and we have further stressed it in the discussion section.

Technical corrections

Page 2 Line 10: you could also add interactions of rainfall with crop and forest canopies [Frasson and Krajewski, 2011; Nanko et al., 2004; Nanko et al., 2013].

We were not aware of these references, which are relevant examples of another field where disdrometers provide useful data. We have therefore included them.

Page 2 Line 17: "helping developing better sensors" please consider changing to "helping the development of better sensors".

We have rephrased this sentence as suggested.

Page 2 Line 21: "radar reflectivity or rainfall kinetic energy" I suggest replacing the "or" with a comma.

Done.

Page 2 Lines 21-22: "rain rate, liquid water content, radar reflectivity or rainfall kinetic energy, among others, can also be calculated from PSD moments" Aren't the rain rate, radar reflectivity, kinetic energy flux et al DSD moments themselves instead of quantities "calculated from DSD moments"?

You are right, these are referred to normally as DSD moments. We have changed it.

Page 2 Lines 29-30: "Pressure disdrometers, however, can only measure the PSD": Impact based and pressure disdrometers cannot directly measure particle size distribution. As the authors mentioned in the beginning of the sentence, such disdrometers measure impact (a discussion on whether they see kinetic energy or drop

momentum can be found in Licznar et al. [2008]). In order to estimate the PSD, the velocity of the hydrometeors is taken from theoretical terminal velocity curves. I believe that this is what the authors referred to here. Please rephrase.

This is right, and we have rephrased the sentence to better express the idea that impact / pressure disdrometers rely on theoretical terminal velocity models.

Pages 2-3 Lines 30-33: "More recent disdrometers are based in optical principles (Löffler-Mang and Joss, 2000), either from the occlusion of a laser light beam between an emisor and a receptor device produced by the particle passing through; or based on light scattering measurements from particles passing through the light beam." I suggest rephrasing the first part of the sentence to something along the lines of: "the occlusion of a light or laser beam between an emitter and a receiver or between an array of emitters and receivers, caused by the passing of a particle through the disdrometer's sensing volume". This would include the working principle used by the two dimensional video disdrometer.

We are not sure about this rephrasing. From one hand, it would omit the light scattering mechanisms, that we mention in our text. And on the other hand, the 2DVD is explained later in the same section. Considering this, we have preferred maintaining the current phrasing.

Page 3 Line 24-25: "more accurate disdrometers such as the 2DVD, the JWD, or by taking a pluviometer as a reference". I suggest replacing "more accurate disdrometers" with "other disdrometers". Although there is literature supporting the claim of higher accuracy of the 2DVD, I'm unsure if it is fair to claim that JWD is more accurate than the LPM and Parsivel, especially when measuring DSD.

We totally agree with this comment, and we have substituted ‘more accurate’ with just ‘other’.

Page 3 Lines 28-29: “with the results obtained linked to the purchased PARSIVEL version of the time, with its drawbacks” I did not understand it. Please rephrase.

Yes, the original phrasing did not make sense. We have rephrased it to ‘PARSIVEL disdrometers have been evaluated since its first version became commercially available from PM Tech Inc (Sheppard and Joe, 1994), with slightly different results depending on the version of the device analysed’.

Page 4 Line 11: “if conclusions drawn from measurements made with these two disdrometers want to be compared”. Please consider replacing want by another verb. Maybe are?

We have rephrased it to ‘if measurements made with these two disdrometers are to be compared ’.

Page 4 Line 12: “This study aims at comparing the” Aims to compare?

I just learnt that ‘aim at’ is not good style. We rephrased it to ‘ The objective of this study is to compare...’.

Page 5 Line 11: “Correct measurements are also limited to one input point” I didn’t understand this. Please rephrase.

We have rephrased it to ‘ Other source of biased measurements is due to the co-ocurrence of simultaneous drops...’.

Page 6 Lines 21-22: “PARSIVEL2 disdrometers detect raindrops from 0.25 mm of diameter”. This is redundant with the previous line. I suggest deleting it.

Quite right, and we have deleted it.

Page 7 Line 29: "plOtting" Please fix the typo, where O appears capitalized.

We have corrected this typo.

Page 9 Line 8: "a highest sensitivity of Thies disdrometers" I believe this should read "higher sensitivity" as opposed to the superlative highest.

Right again. Corrected.

Page 11 Line 20: "The differences between disdrometer types were similar at different rainfall intensitites" This is a bit confusing. Please consider rephrasing. Were the differences between disdrometer types homogenous with respect to rainfall intensities?

We have rephrased the whole paragraph, and we hope that now reads clearer.

Page 11 lines 22-23: "During minutes with rainfall intensity higher than 10 mm h-1, for instance, NP was almost nine times higher for Thies than for PARSIVEL". This sentence makes me believe that the difference between instruments was not homogeneous among different rainfall rates. I'm a bit confused here.

We agree that our phrasing was confusing. We have avoided using the word 'similar', and we clearly state that the magnitude of the effects varied with the rainfall intensity. We believe that the sense of the paragraph is much more clear now.

Page 13 line 15: "Frasson et al. (2011) and ? also noted the same result". I believe the question mark was a typo or a problem

with the citation program. Please fix.

The missing reference was Lanzinger et al. We have corrected it.

Page 13 lines 23-22: "previously noted by citetupton2008 and shown by our results". Typo here. Please fix.

We have fixed the citation.

Page 13 line 25: "PARSIVEL manufacture recognized...' I believe this should read PARSIVEL manufacturer recognized.

Yes, it should read 'manufacturer'. We have corrected it.

Response to anonymous Referee #3

General comments

The paper presents a comparison of two optical disdrometers: the OTT Parsivel2 and Thies LPM. The work is well written and generally clear, with a good review of existing literature and the instruments compared. The results are of interest to researchers using optical disdrometers. This work should be published, but there a few revisions required to strengthen the manuscript. In particular, more filtering of raw data is required, the GLMM results need better explanation, and you should reconsider highlighting the results for which the DSD size classes are similar (the "filtered" results).

We thank the reviewer for the insightful review and useful suggestions. We have tried to improve the manuscript, including new (extended) explanations, most especially of the results of the Gamma GLMM analysis. We have also stressed the results using filtered data.

Regarding the filtering scheme, in addition to fixing the drop size to a common range (which was, in fact, 0.250 to 8 mm), we have implemented a filtering + correction scheme. Unlikely combinations of size and velocity were removed, and the sensing area has been modified for each drop size class. This implied repeating all the analyses. For assessing the influence of this filtering, and of the required adjustment of the sensing area, we have also included results without this filtering + correction scheme, which are shown in the Appendix (Figures A.1, A.2, A.3 and Table A.1).

The writing contains numerous small English errors, so I suggest a thorough proof-reading of the paper to fix these. There is a lot of repetition between the introduction (Section 1) and the discussion (Section 4). It reads as though Section 4 was written

separately and put into the manuscript after the rest was written. I suggest that you carefully combine these sections so that the introduction contains background information about disdrometers, instrument types etc, and the discussion is more a discussion of your results with relation to previous findings in the literature. Please also better explain what the results mean for the community and researchers interested in using these instruments.

We have carefully checked the manuscript for language errors, and we believe that the language is now better.

We agree that the discussion section was somehow repetitive, so we have completely rewritten it. Some of the references have been moved to the introduction section, were they make more sense.

We also have better explained what the results mean for the community and researchers interested in using these instruments.

For the time steps tested and when bulk rainfall variables are calculated, I think it is important to carefully filter the data returned by the instruments. Two filters should be applied - the first to ensure no solid precipitation is included in the results and that the instrument lasers were functioning correctly (Parsivel flags can be used for this), and the second to remove particles that are unlikely to be raindrops (using a relationship between particle size and expected velocity, as per for example in Jaffrain and Berne (2012)).

We filtered out records when there were error flags or did not correspond to liquid precipitation (rain). We have highlighted this in the revised text (section 2.1), and we have also reported the number of minutes with errors and the number (and proportion) of minutes with rain in Table 3.

The only point where we use the bulk variables as given by the devices firmware now is in Figure 2, and we make this clear. For the rest, we have computed our own values based on the PSVD data, according to formulas provided explicitly in section 2.2.

Except for discussing the effects of filtering, which are shown in the Appendix, all the results presented correspond to filtered and corrected PSVD data, as suggested. We agree that this allows for a fairer comparison between the two devices. We therefore implemented a filtering scheme as suggested, which included: i) restricting the comparison to common drop size classes, i.e. between 0.25 and 8 mm; ii) filtering out highly unlikely drop size and velocity combinations, according to the theoretical fall velocity model of Beard (1976); and iii) correcting the sampling area of the disdrometer as a function of the drop size. This is explained in detail in section 2.2.

It appears that one of the main differences between Thies and P2 disdrometers shown here is that Thies records many more small particles (and lower velocities) than Parsivel. But, Thies can record from 0.125 mm and Parsivel can record from 0.25 mm. I think it's important to carefully show which differences arise from this simple instrumentation difference. You have done this with your filtered results, but I feel that the filtered results are mentioned rather as an aside when they are in fact a fairer comparison between the instruments. Indeed in the abstract you mention that Thies records nine times as many particles as Parsivel for some rain rates, yet in the paper this reduces to about three times if the different class definitions are taken into account by your filtering. It should, at the least, be emphasised that some of the differences shown can be explained by the different drop size ranges.

It is true, and that is the reason why we repeated the analysis using a filtered dataset in which we removed the data from the first size of the

Thies PSVD, so both devices started at 0.25 mm. Since we have re-done the analysis with further filtering, now the main results refer to the filtered data, which incorporates the common lower and upper detection limits. The comparison between the two disdrometers **without filtering**, i.e. using the raw PSVD data, has been moved to the Appendix (Figures A.1, A.2, A.3 and Table A.1).

You use a Gamma generalised linear mixed model (Gamma GLMM) to analyse whether the differences between the instruments and location are significant. This is a nice, rigourous idea, but then the writing in the paper does not analyse the results in enough detail. I have the feeling that while the GLMM results are shown in tables, most of the conclusions shown in the paper were rather drawn from kernel densities which are easier to interpret by eye. It's important to explain the results so that for example the meaning of the different coefficients found using Gamma GLMM are clear. For example, possible random differences caused by the mask are controlled for, but there is no discussion in the text of the influence shown by this random variable and therefore it is difficult for the reader to interpret the results shown in Tables 4, 5, and 6.

We agree again with this comment, and have very much improved the description of the results of the statistical analysis in the revised manuscript. We have further developed the tables showing the results of the analysis (for instance, there was only one p-value when in fact there should be two, one per model coefficient, and we have better expressed the random effects by stating the standard deviation attributed to the mast location and to the random residual). We have split the results in four tables (Tables 4, 5 and 6). And we have extended the interpretation and discussion of the results of the analysis, carefully explaining the interpretation of the model coefficients.

Specific comments

1. Page 2, line 30: Please carefully define what you mean by PSD here. Your point is that pressure disdrometers do not measure velocities, which is correct, but the PSD is often used to refer to volumetric particle size distributions which are calculated using a velocity (either measured or estimated).

We agree that the phrasing was not totally clear, and we have rephrased these lines.

2. Page 3, lines 10–15: the 2DVD is perhaps considered a reliable reference, but it should also be noted that it has been found unreliable for small drops (see e.g. Tokay et al. (2013) and Thurai et al. (2017)). Is the 0.3 mm limit mentioned on line 13 from Tokay et al. (2013) or another article that can be cited?

The reference is taken from Tokay et al., 2013, p. 17: ' Since the 2DVD severely underestimates the number of drops in the first size bin, 0.3mm should be considered the minimum drop diameter'. We have added the missing reference, and also cited Thurai et al., 2017.

3. Pages 3 and 4: Your literature review showing the different version histories of Parsivel and Thies disdrometers is excellent. However you mention that they have each been compared to more accurate disdrometers, but without saying what the comparisons found. I think you should briefly outline the results of these comparisons.

Thank you for the comment. It is very true that the main conclusions of the latest studies that checked the performance of the two disdrometers should be mentioned here, and not in the discussion section. We have followed your advice and incorporated them here, which we believe improves significantly the introduction section.

4. Page 4, line 24: These statements on the average annual precipitation at the field site need a reference. Also, you should include a brief further description of the properties of the site – e.g. is it in complex terrain? What types of precipitation does it experience? etc.

We have included more information regarding the study site, including precise references to the pluviometry as recorded by the official AEMET (Spanish Weather Service) station, which is located in the same experimental site.

5. Figure 1: It would be helpful to label the different disdrometers in the image.

That is a good suggestion. We have included labels to identify the devices.

6. Page 5, line 13: I believe that recent Parsivels automatically remove margin fallers. Please confirm and mention this here. Do the Thies instruments also remove margin fallers?

Both manufacturers indicate in the technical documentation that unlikely drop combinations are removed, although they do not give any details of the procedure. Some information can be inferred from the literature in the case of Parsivel, but we have found nothing for the Thies. From looking at the raw PSVD data, it seems clear that Parsivel implements some sort of filtering, while Thies present the data in a rawer state. Our filtering scheme has been able to make the outputs of the two disdrometers more comparable, although substantial differences still remail. We have stressed this points in the manuscript.

7. Page 6, line 11: Define units for Pr. Equation 1 would benefit from having Nij instead of just N.

We now provide equations for all the integrated units used in the article. We used $N_{i,j}$ as needed. The units for all the symbols have also been provided, and the notation issues have been fixed.

8. Equation 1: What units does KE have? By my calculation the equation results in J m-2 cm-3 mm2 and it is not clear why the 1/12 appears. Please check this equation.

In order to simplify, we now use E only. We have used a less compact (and more self-explanatory) version of the formulas.

Regarding the development of the kinetic energy formula, it is as follows:

$KE = 1/2mv^2$

where v is velocity and m is mass of the raindrop. The mass is obtained as the product of the drop volumen, V, and the density of water, ρ, equal to 1 g cm^{-3}:

$m = \rho V$

The volume of (an equivolume spheric) drop is:

$V = 4/3\pi R^3 = 1/6\pi D^3$

where D is the drop diamater in mm, so we arrive at:

$KE = 1/12\rho\pi D^3 v^2$

The 10^{-3} term, finally, is a conversion factor to go from mm^3 (used for V) to cm^3 (used for ρ), so they cancel out.

9. Page 6, line 24: The normal sampling area quoted here is correct, but normally an adjustment is made for large drops because margin fallers are uncertain or removed. See e.g. Battaglia

et al. (2010). Note that they use D/2 to account for bias due to edge-fallers, but if margin fallers are automatically completely removed this should be D. I see that in your paper you are focussing on computing variables calculated by the instrument hardware, so I think all that is required is that you mention this adjustment at this point in the article. For variables calculated from the DSD, you should use such an adjustment of sampling area, or justify why you choose not to.

Since we have implemented a filtering scheme that involves removing the particle size and velocity combinations that were 50% or more different from a theoretical model, we also implemented a correction of the effective sampling area. This is detailed in equation 7 in the manuscript. Since we are not removing all the particles that do not fit the model (some random variation can be accepted, as done by all previous researchers), correcting the sampling area using D would be an overkill, so we have preferred to use D/2 as done commonly. However, as we discuss in section 4, the exact calibration of the filtering and the correction is something that will require further analysis, probably with the resource to numerical simulation.

10. Table 2: If these are one-minute values, what is the difference between rain rate R, mean rain rate Rm and max rain rate RM? (Same for kinetic energies and number of particles).

In addition to one-minute data, the mean (m) and maximum (M) values of these variables (*Rm*, *RM*, *KEm*, *KEM*, *Em*, *EM*, *NPm*) were computed for each rainfall event. We have made this clear in the text.

11. Page 7, line 24: The 2DVD has a resolution of roughly 0.2 mm so it can measure drops smaller than 0.3 mm; but other studies (e.g. Tokay I referenced earlier) have shown it is not reliable for these drops.

We have rephrased this sentence, and removed the reference to the 2DVD which is not needed here. We refer to the 0.3 limit in the introduction section.

12. Page 7, paragraph around line 25: disdrometers often record particles that are very unlikely to be raindrops (they could be droplets caught in spider webs, in- sects, snow etc). It is common to filter drop counts using some constraints on the particle size to particle velocity relationship, against expected velocities (see for example Jaffrain and Berne (2012)). For the variables that you calculate yourself using the raw data, I think it is important to perform such a filter. Also, Parsivel disdrometers give a weather type indicator that can be used to determine when the instrument has detected solid precipitation. They also provide laser status that can indicate if the laser is dirty or malfunctioning. Did you use these indicators to subset the data to only rainfall and remove any possible solid precipitation? Again I think this is an important filter to apply.

As explained above, we filtered the minute readings by considering the meteor type. We used the SYNOP code for rejecting any observations that did not correspond to liquid precipitation (rain). We also used the laser status flags of the Parsivel^2 and the quality flag of the Thies to remove any suspect records. We have explicitly mentioned it in the revised manuscript, and the number of minutes removed by each criterion is given in Table 3.

We also have implemented a filtering of ulikely particles, which correspond to a large part to double detections and edge events ('margin fallers', or partial detections).

13. Equation 2: please define N here; I gather it is the normal distribution, but then the symbol also clashes with your N in Equation 1.

Yes, we refer to the Normal distribution. It was a formatting mistake, it should be $\mathcal{N}$. This way it does not clash with N in equation 1.

14. Table 3: Is there a reason why the Parsivel on M2 recorded such different propertions of spring/winter/autumn records than the Parsivel on M1 (and the Thies disdrometers)? Here again I wonder whether you accounted for possible snow in winter?

We did not record any snow, which is very unlikely in the central Ebro valley. The reason why the P2 recorded a different proportion of records in the different seasons is because this device did not work due to different technical issues during part of the experiment. This has been conveniently explained, and the data has been detailed in Table 3.

Anyway, as it is explained, we only used the common minutes where high quality, rain data existed in the four disdrometers simultaneously.

15. Page 9, lines 21-22: The filter here is just removing drops below 0.3 mm in diameter, if I understand correctly. I think the differences, while slightly smaller than in the unfiltered case, are still significant between the disdrometers in this case.

Yes, the differences were still significant after removing the smaller particle sizes.

Please, note that in the new version of the manuscript we focus on the filtered data, according to the new scheme, and we leave the un-filtered results in the Appendix.

16. Figure 3: Please differentiate between M1 and M2 in the caption.

We have done it.

17. Page 9, line 26: "number of drops per minute" – is this what is shown, ie the raw number of drops recorded every minute, or are you showing Nt [m-3] in Figures 3?

Yes, it was the number of drops per minute. In the new version of the manuscript, however, and following recommendation by another reviewer, we have used the particle density (ND), expressed in number of drops per m-3 and mm-3.

18. Figure 4: It strikes me as strange that the theoretical velocities for large drops (the black line) are smaller than those for drops of 4-5 mm diameter. How does this model compare to other terminal velocity models?

We have done this figures again, using the terminal velocity model of Beard (1976) instead of the Uplinger approximation, which is known to do not hold true for very large drops.

19. Page 10, line 7: Can you be sure that the larger spread of particles are filtered out of the P2 output, or is it instrumental effect of the Thies disdrometers that increases the spread of velocities? As a comment, the large number of drops with low velocities recorded by the Thies disdrometers would explain large values of total drop concentration Nt [m-3], because the calculation of the DSD contains a division by the velocity.

We do not know the nature of the filtering of unlikely particles that is done by Parsivel, so we can not reject the possibility of an instrumental effect of Thies disdrometers. This is an interesting remark, and we have incorporated it to the discussion. In fact, we indicate that the smaller width of the laser beam on Thies (20 mm) over Parsivel (30 mm) plays against the former, which by geometric considerations alone is more prone to be affected by edge events. Therefore, the short answer is yes, there is combination of instrumental and (most likely) software sources of differences between both devices.

20. Table 4: Why is the sample size lower than the number of samples available? And how were the samples chosen?

We used a random sample of 250 minutes (so N=1000, since there are four disdrometers) to avoid size effects affecting negatively the statistical significance tests used in the anslysis (Type I error inflation; see, for instance, Sullivan and Feinn, 2012, or Lin et al., 2013). The samples were taken at random. Details have been added in the methods sections.

Sullivan GM, Feinn R. Using Effect Size - Or Why the P Value Is Not Enough. Journal of Graduate Medical Education. 2012;4(3):279-282. doi:10.4300/JGME-D-12-00156.1.

Lin, M., Lucas, H. C., & Shmueli, G. (2013). Too big to fail: Large samples and the p-value problem. Information Systems Research, 24(4), 906-917. DOI: 10.1287/isre.2013.0480.

21. Table 4: Very little analysis of these numbers is given in the text, and most conclusions seem to be drawn instead from the kernel densities in Figure 5. Please indicate how the reader is to interpret the numbers in Table 4: what are the meanings of the coefficients (the means for each group for Thies and Parsivel? What about for the mast?). How do you interpret the results for the mast, which show that the mast is sometimes important (e.g. for K e)?

This was a drawback of the first manuscript, and we have much worked on it. The tables showing the results of the statistical analyses have been improved, and the results are now extensively explained and interpreted. The objective is that both analysis (graphical and statistical) now complement each other in a good way.

22. Figure 5: In this plot and the discussion on page 10 the meaning of NP is unclear (note in Table 2, NP has a unit of "unit").

We have discarded NP in benefit of ND, which has units of number of drops per m-3 and mm-1.

23. Page 10, line 16: You mention that Z and R were higher on Thies but E was lower. Can this be explained physically, ie through differences in the numbers of small drops? Some variables (reflectivity, rain rate) influenced much less than others (total drop concentration) by the numbers of small drops recorded.

This is indeed a very relevant remark. The influence of the number of particles detected, their size and velocity, on the computed variables vary and some times cancel each other. We have now discussed the results in light of these influences.

24. Page 11, line 23: As shown by the filtered results, the large difference in numbers of particles can be in large part explained by the different drop sizes measured by Thies and Parsivel disdrometers. I think the fairer comparison is shown in the filtered results, in which NP was about three times higher in Thies than in Parsivel data.

We have compared the results of the analysis with filtering and without it, now in section 3.4. The results show that the filter and correction affected largely the distribution of particle size and velocities, and interestingly for the median particle size and velocity the effect of the filtering and correction had a different sign for Thies than for Parsivel. With respect to the integrated variables, the effect of filtering was very large for some variables such as the particle density, moderate for others such as the precipitation intensity or the kinetic energy, and smaller for the radar reflectivity.

25. Page 11, line 27-28: Without another external and more accurate reference, I think you can not say whether one instrument or the other over- or under- estimated the numbers of small particles. What you can say is that there were significant differences between the two instrument types.

The intended meaning of this sentence was that one device tended to overestimate with respect to the other, but it is true that the phrasing is not adequate. We have tried to make this clearer in the new manuscript.

26. Figure 6: Are these violin plots for event totals or means or both?

The violin plots refer to event means and maxima. This has been made clearer in the figure caption.

27. Page 12, line 12: I think “complete” might be a strong word here, given the difficulties current disdrometers have in measuring small drops.

Agreed. We have replaced ‘complete’ by ‘thorough’, which does not imply completion.

28. Page 12, line 28: In more recent Parsivel disdrometers, margin fallers are detected by extra photo-diodes and removed (Battaglia et al., 2010); so please confirm whether this is the case with the disdrometers used in this study.

We have found no reference that the disdrometers used in this study have extra photo diodes to detect margin fallers.

29. Page 12, line 33: Again I believe that 0.3 mm is not built

in to the 2DVD but rather a recommended lower limit.

Yes, that's right, it is a recommended limit but not a built-in one. We have, anyway, rewritten the discussion section and this sentence does no longer exist.

30. Page 13, line 5: The differences in the numbers of particles measured by the two disdrometers could possibly be due to the P2's splash shield that the Thies does not have. You mention in this paragraph that abnormal size-fall velocity pairs could be used to remove irregular particles; why not apply this kind of filter?

We agree, and we have re-analysed our dataset using the filtered and corrected data.

31. Page 13, line 15 and line 23: Two references are missing here.

This has been corrected.

32. Page 13, line 16: There are differing conclusions about Parsivel2 performance by drop size reported in the literature. While Raupach and Berne (2015) included some Parsivel2 comparisons, their study was primarily based on Parsivel 1 data and large variability meant comparisons for larger drop sizes were only performed for higher rain rates. Tokay et al. (2014) compared the Parsivel2 specifically but did not conclude that Parsivel2 overestimates small drops. The recent and in- depth study by Park et al. (2017) shows underestimation of small drops and over- estimation of large drops by Parsivel2 . I suggest you generalise your phrasing here to account for these differing results.

This lines have been moved to the introduction section. We have also rephrased them, so they better express the conclusions of the studies cited.

33. Page 13, line 27: There is no discussion in the rest of the article about hydrometeorological regimes, so the claim that there are no differences by regime is not backed up. By "small raindrop spectra" do you mean spectra that exhibit many small raindrops?

This is a fair remark, and we have removed this line.

34. Page 13, line 31: The paper by Jaffrain and Berne (2011) used Parsivel 1 disdrometers, not Parsivel2.

Right. We have removed removed the reference to the device version since this conclusion is general for Parsivel disdrometers.

35. Page 14, lines 10-11: Please be careful about statements that are speculation – it is not shown by this study whether or not the raw data matrices by P2 disdrometers are post-processed or not.

This is a fair remark, and we have removed the comment about the post-processing of the PSVD data. However, we wanted to stress that some crucial aspects of the internal functioning of both devices are hidden from the final user, which limits their usability in research environments.

Minor/typographical comments

All the minor issues and typos have been corrected.

Research Highlights

- An analysis of ~~58761~~ almost 100,000 one-minute precipitation observations recorded by two types of optical disdrometer, Thies LPM and ~~Ott~~ OTT Parsivel^2, 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~~ OTT Parsivel^2, 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~~ OTT Parsivel^2, influencing all precipitation variables.

Comparison of precipitation measurements by ~~Ott PARSIVEL~~OTT Parsivel^2 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, ~~kinetic energy or radar reflectivity~~ radar reflectivity or kinetic energy, together with discrete information on the ~~distribution of particle sizes and fall velocities~~ particle size and fall velocity distribution (PSVD) of the hydrometeors. Disdrometers constitute a step forward towards a more complete ~~characterisation~~ characterization of precipitation, being ~~highly~~ useful in several research fields and applications. In this article the performance of ~~the two optical disdrometer most extensively used~~ two extensively used optical disdrometers, the most recent version of ~~Ott PARSIVEL~~OTT Parsivel^2 disdrometer and Thies Clima Laser Precipitation Monitor (LPM), is evaluated. During two years four collocated optical disdrometers, two Thies Clima LPM and two ~~Ott PARSIVEL~~OTT Parsivel^2, ~~recorded 58761 common one-minute precipitation observations,totalling~~

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~~221 natural~~ 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 ~~220~~ 277 mm h^{-1} ~~. The results~~ 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 distribution (PSVD) estimated by the two sensors. Thies LPM recorded ~~in average double number of particles than PARSIVEL~~a larger number particles than Parsivel^2 ~~. PSVD percentile comparison showed Thies LPM measuring more~~ and a higher proportion of small particles than ~~Ott~~ OTT Parsivel^2, resulting in higher rain rates and totals and differences in radar reflectivity and kinetic energy. These differences increased greatly with rainfall intensity. ~~At rain rates above 10 mm h^{-1} Thies LPM recorded nine times the number of particles of PARSIVEL^2, affecting all precipitation variables. The practical consequences of~~ Posible causes of these differences, and ~~possible reasons~~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 ~~fixed in future versions~~addressed in future studies.

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

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1. Introduction

Disdrometers are devices designed to measure the ~~particles~~ 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 ~~equivolume~~ equi-volume diameter per unit volume of air. The PSVD includes also information about the distribution of the ~~particles~~ 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; Shuttlewort, 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). ~~Disdrometers are also widely used to validate the reflectivity values obtained by weather radars, for what the studies on small scale PSD spatio-temporal variation and its influence in modeling PSD and rainfall rate - reflectivity (Z(R)) relations are particularly important (~~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 ~~developing~~ 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 ~~CHUVA campaign.~~ Cloud Processes of the Main Precipitation Systems in Brazil (CHUVA) campaign.

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

Current commercial disdrometers are based mainly ~~in~~ 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 ~~0.3~~ 0.2 mm of diameter (Tokay et al., 2001). ~~Pressure~~ Impact based and pressure disdrometers, however, ~~can only measure the PSD, and the velocity of the meteors is inferred based~~ rely on theoretical terminal velocity ~~models.~~ curves to determine the PSD.

More recent disdrometers are based in optical principles (Hauser et al., 1984; Löflfer-Mang and Joss, 2000), either from the occlusion of a laser light beam between an emisor and a receptor device produced by the particle passing through; or based on light scattering measurements from particles passing through the light beam. ~~A third type uses photographic principles (Testik and Rahman, 2016).~~ Both types use an emissary and a receiver of the laser signal generally in a horizontal plane, and the emissary can be punctual or an array of emissaries. Commercial examples of the first type are the particle size and velocity ~~disdrometer PARSIVEL and PARSIVEL~~disdrometers Parsivel and Parsivel[2] by ~~Ott~~ OTT Hydromet, and the Laser Precipitation Monitor ~~LPM~~ (LPM) by Thies Clima. An example of the light scattering principle is the light scatter sensor PWS100 (Campbell Scientific Inc.). Optical disdrometers provide full PSVD measures from the unique light beam horizontal plane (∼1 cm thick) by the amplitude and duration obscuration when particles pass through the beam, respectively. Laser disdrometers are not devoid of detection problems related with the effect of effects of uneven power distribution across the laser beam, wind, splashing, oscillations in the laser current and temperature, multiple drops appearing at the same time , (double detections), edge events (‘margin-fallersresulting in partial detections, and others (’, or partial detections), as reviewed by several studies (Nespor et al., 2000; Habib and Krajewski, 2001; Tokay et al., 2001; Kruger and Krajewski, 2002; Frasson et al., 2011; Raupach and Berne, 2015).

An improvement over laser disdrometers is the two-dimensional video disdrometer (2DVD, Joanneum Research). The 2DVD uses two perpendicular high-speed line-scan cameras, each with an opposing light source, to measure record particles from orthogonal angles. The 2DVD provides reliable measures of particles fall velocity, size and shape (Kruger and Krajewski, 2002; Schönhuber et al., 2008). Currently this disdrometer provides is considered as the most accurate PSVD measurements of particles from is considered a reliable reference for particles larger than 0.3 mm of diameter, (Tokay et al., 2013; Thurai et al., 2017), although its use is mostly restricted to experimentation due to its higher cost and data processing requirements.

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

The performance of Parsivel and Thies disdrometers has been ~~evaluated by comparison with more accurate~~ compared to other disdrometers such as the 2DVD, the JWD, or by taking a pluviometer as a reference. ~~PARSIVEL~~ Parsivel disdrometers have been evaluated since its first version became commercially available from PM Tech Inc (Sheppard and Joe, 1994~~). Several versions of this device have been used for disdrometer evaluation and precipitation comparisons through time, with the results obtained linked to the purchased PARSIVEL~~ ; Löffler-Mang and Joss, 2000), with slightly different results depending on the version of the ~~time, with its drawbacks~~ device analysed (Krajewski et al., 2006; Lanza and Vuerich, 2009; Battaglia et al., 2010; Jaffrain and Berne, 2011; Thurai et al., 2011; Park et al., 2017). In 2005, ~~Ott~~ OTT Hydromet purchased the rights of ~~PARSIVEL~~ Parsivel disdrometer and redesigned the instrument. Differences between the PM Tech ~~(P0)~~ and the first version of ~~Ott Hydromet PARSIVEL (P1)~~ OTT Hydromet Parsivel are described in Tokay et al. ~~,~~ (2013), who found important biases in the frequency of small and large drops with respect to a JWD disdrometer. In 2011, ~~Ott Hydromet redesigned P1 and made available Ott PARSIVEL~~OTT Hydromet redesigned the device and presented the Parsivel^2~~(P2). This new PARSIVEL version included a more expensive and~~ . This is the current version of the disdrometer, and includes a more homogeneous laser beam and some other modifications that improve its performance (Tokay et al., ~~2013; Tokay et al.,~~ 2014; Angulo-Martínez and Barros, 2015). The ~~current version of Ott PARSIVEL~~Parsivel^2 ~~(P2) is the best PARSIVEL version commercially available, as it has been explained by Tokay et al., 2014. The P2 has been compared with other accurate disdrometerssuch as the JWD (~~has been compared to other disdrometers. Tokay et al. ~~,~~ (2014) ~~and the 2DVD (~~compared it with the JWD, and found good agreement in the PSD spectra between both devices for particles sizes larger than 0.5 mm. They also reported systematic underestimation of fall velocities in the Parsivel^2, for drop diameters of 1.09 mm and higher. Raupach and Berne ~~,~~ (2015~~,~~) and Park et al. ~~,~~ (2017) ~~.~~ compared the two versions of Parsivel with a reference 2DVD, and found that Parsivel^2, although improving the performance of the first iteration of the disdrometer, still had important biases that resulted in underestimation of small drops and overestimation of large drops, especially during high intensity rains.

Thies LPM, on the other hand, became commercially available in 2005 from Adolf Thies GmbH & Co. ~~The first evaluation of the sensor, in terms of rain rate and amount,~~ Early analysis of the performance of the Thies disdrometer for detecting different hydrometeors was presented by ~~Lazinger et al. (2006~~Bloemink and Lanzinger (2005) at the WMO Technical Conference on Meteorological and Environmental instruments and methods of observations (TECO-2006, Geneva, Switzerland)~~.~~, while an evaluation of its capacity for measuring rainfall intensities and amounts was presented in the same conference one year later (Lanzinger et al., 2006). Since then, this ~~type of~~ disdrometer has been used worldwide with several firmware updates. ~~The Thies LPM performance was thoroughly analyzed later by~~ Frasson et al. (2011) ~~.~~ evaluated the performance of four collocated Thies disdrometers and found that systematic biases existed between the devices, and attributed them to miscalculation of the disdrometer's sensing area. Lanzinger et al. (2006) found that three LPMs measured higher rainfall amounts than a collocated reference rain gauge, especially during higher intensities, and also reported systematic biases between the three disdrometers. Upton and Brawn (2008) also found discrepancies in the velocity records by three collocated Thies, while the number of particles and their sizes were more consistent.

~~To our knowledge~~There number of studies inter-comparing Thies and

Parsivel disdrometers, however, ~~only the works of~~ is very reduced. Brawn and Upton (2008) ~~and~~ evaluated the parameters of fitted gamma distributions to the PSD data, and found substantial differences between Thies and Parsivel. Upton and Brawn (2008) ~~inter-compared the performance of Thies and PARSIVEL disdrometers in terms of the PSVD and precipitation bulk variables, as well as in terms of the fitted gamma distribution parameters. In their studies they used data from an older PARSIVEL version~~ 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 rainfal 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 ~~PARSIVEL~~Parsivel^2~~devices~~. Such a study, however, is highly needed if ~~conclusions drawn from~~ measurements made with these two disdrometers ~~want~~ are to be compared.

~~This study aims at comparing~~ The objective of this study is to compare the measurements recorded by Thies LPM and ~~most recent Ott PARSIVEL~~OTT Parsivel^2 ~~comercial~~ optical disdrometers, with the ~~objective~~ 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 ~~sensors~~ 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^o43'30"N, 0^o48'39"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 semiarid climate (BSk, ~~Köppen). Average annual precipitation is 315 mm~~ 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 ~~, which are usually more intense during fall~~(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 PARSIVEL~~OTT Parsivel[2], were operated in continuous record during the period between 17/06/2013 and 21/07/2015. Two disdrometers of ~~every type~~ 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 ~~DSD~~ 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 ~~by~~ 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 PARSIVEL~~OTT Parsivel[2], 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 ~~0.005 m~~50 cm^2 ~~, with slight deviations depending on the sensor~~ (Donnadieu et al. 1969; Löffler-Mang and Joss, 2000). ~~The~~ Raindrops are assumed spherical for sizes less than 1 mm in diameter, and therefore the size parameter is the equivalent diameter for raindrops below this size. For larger raindrops, a correction for oblateness is made, and the size parameter is interpreted as an equi-volume sphere diameter. The laser signal is processed by a proprietary software, and the size (equi-volume particle diameter) and velocity of each particle is determined. The meteor type (drizzle, rain, hail, or snow) is determined based on typical size and velocities, and weather codes (SYNOP and METAR) are generated. A PSVD matrix counting the number $N_{i,j}$ of particles for given size (i) and velocity (j) classes is recorded at desired intervals, usually one minute. Several integrated variables are also computed and stored at the same intervals. These include the number of particles detected (NP, min^{-}1), the particle density (ND, m^{-}3 mm^{-}1), the rainfall amount (P, mm) and intensity (R, mm h^{-1}), the radar reflectivity (Z, dB mm^6 m^{-3}), visibility (m) and kinetic energy (J m^{-}2 mm$-$1).

This operational principle in subject to a number of potential sources of bias, as reviewed by Frasson et al. (2011). One of such sources of bias is the uneven power distribution across the laser beam, or variations of this power with time. Also, the geometry of the laser beam limits the estimation of fall velocity to the vertical component~~(Salles and Poesen, 1999),~~, producing biased measures when the particles fall with a different trajectory or angle due to wind or eddy drag ~~. Correct measurements are also limited to one~~

input point, so other (Salles and Poesen, 1999). Other source of biased measurements is due to the co-ocurrence of simultaneous dropsocurrence of coincident particles, which are perceived as just one single drop by the sensor. Similarly, the event of one drop falling on the border at the edge of the laser beam (“margin faller”‘margin faller’), therefore being only partially observed, leads to biased measurements. The laser signal is then processed by a proprietary software, and the PSVD matrix counting the number of drops for given size and velocity classes, together with several integrated variables, are outputted at regular time intervals (usually one-minute).

Apart from hardware differences, i.e. type of laser and instrument design, the variables and data from each sensor barely differ from one another. Raindrops are assumed spherical for sizes less than 1 mm in diameter, and therefore the size parameter is the equivalent diameter for raindrops below this size. For larger raindrops, a correction for oblateness is made. Both sensors mention in their manuals technical data some correction for edge-detection (particles that are partially measured at the edge of the laser beammargin fallers) and coincident particlespassing at the same time through the laser beam, although there is no little information on how these two events are identified and treated. The main initial difference between the two disdrometer types is in how they store particles by size and velocity. More details of both instruments and the measurement technique, along with the assumptions used to determine the size and velocity of hydrometeors, can 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 a 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) measures the size (diameter) and fall velocity of every raindrop greater than 0.12 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 cm^2. 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 cm^2. It records particles starting from 0.16 mm of diameter. It measures , and precipitation starting from intensities of 0.001 0.005 mm h^{-1}. The Thies technical documentation indicates that 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). The laser beam is 228 mm long, 20 mm wide, and 0.75 mm thick on average, and the geometric deviations from the standard are reported by the manufacturer. From these data several rainfall variables are integrated internally by the device's firmware. In this study we focused on rainfall intensity (R, mm h^{-1}), rainfall amount (P, mm), total number of particles (NP), and radar reflectivity (Z, dB mm^6m^{-3}). In , 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 sensor status and measurement quality variables status flags are provided in the data telegrams informing about voltage oscillations, sensor temperature, and other issues. Rainfall kinetic energy (E, J m^{-2} mm^{-1}, and Ke, J m^{-2}) is an interesting bulk variable because it combines

PSVD with rainfall intensity, informing on the rainfall impact force. The Thies LPM does not provide this variable, so it was calculated from the PSVD as follows: first, total kinetic energy ke_{sum} per minute was determined by multiplying the kinetic energy of every drop belonging to every diameter and velocity bin by the number of drops registered in each size and velocity class. Then, the rainfall kinetic energy per unit surface and precipitation amount was obtained by dividing by the sampling area of the device (in our case, $a_{Thies1} = 0.00467$ m^2, and $a_{Thies2} = 0.00490$ m^2) and by rainfall amount per minute (P_r): an evaluation of the measurement quality.

$$KE = \frac{ke_{sum}}{aP_r} = \frac{\sum N \frac{1}{12} 10^{-3} \pi \rho v_j^2 D_i^3}{aP_r}$$

where N is the number of drops recorded by size and velocity class; D_i is the mean diameter for class i (mm); ρ is the density of water (

[TABLE 1g cm^{-3}); and v_j is the mean speed for the velocity class j in (m s^{-1}).]

Ott PARSIVEL OTT Parsivel ^{2} disdrometer

The PARSIVEL Parsivel disdrometers used in this study belong to the second generation manufactured by Ott Hydromet Inc , which include several improvements in PSVD determination in comparison with the previous generation (Tokay et al. , 2014; Angulo-Martínez and Barros, 2015; Raupach and Berne, 2015; Park et al. , 2017)OTT Hydromet Inc (Parsivel^2). The Parsivel^2 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 cm^2. The Parsivel^2 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 ~~0.25~~ 0 mm diameter up to ~~25~~ 26 mm and from ~~0.05~~ 0 m s^{-1} up to ~~20~~ 22.4 m s^{-1} (Table 6). The first two size categories, which correspond to sizes of less than ~~0.2 mm, have been~~ 0.25 mm, are left empty by the manufacturer because of the low signal-to-noise ratio. ~~PARSIVEL~~The Parsivel^2~~disdrometers detect raindrops from 0.25 mm of diameter. The minimum precipitation rate is 0.007 mm h^{-1}. The PARSIVEL laser beam 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 all PARSIVEL disdrometers is thus 0.0054 m^2.~~ , similarly to the Thies, also provides a sensor status flag and several control variables in its data telegram.

~~PARSIVEL~~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. Parsivel^2 disdrometers external structure differs from the Thies LPM in incorporating a splash protection shield above the laser heads, which aims at ~~minimizing~~ minimising the effect of splashed drops that interfere with a high velocity with the laser beam and result in biased measurements. ~~Integrated variables from PARSIVEL~~

~~disdrometer include the internal calculation of rainfall kinetic energy.~~

~~TABLE 1~~

2.2. Processing disdrometer data

One minute disdrometer data telegrams were stored in an industrial miniature PC (Matrix 504 Artila Inc). The PC included ~~specific~~ custom software to collect, pre-process and send data telegrams to a central server. Time synchronisation was performed once per day using the Network Time Protocol (NTP), allowing bias correction of the internal disdrometer clocks that have a tendency to drift. ~~Minimal processing~~ Direct reading of the data telegrams generated by the disdrometers resulted in one-minute ~~complete time series for the full observation period which included the~~ time series of the variables of interest for this study: PSVD matrices ($N_{i,j}$), bulk variables (P, ~~an error code, and the particles diameter and velocity percentiles (Table 2).~~ R, NP, ND, Z, E), SYNOP codes, and status and error flags. An exception were Thies disdrometers, which do not compute the kinetic energy, E. Parsivel, on the other hand, gives the kinetic energy expressed in J, so it was divided by the sampling area and the rainfall amount to obtain E.

~~TABLE 2~~In addition to the bulk variables computed by the internal software of the devices, the bulk variables were computed again from the PSVD matrices, using the following expressions:

~~As shown in Table 6, Thies LPM and Ott PARSIVEL[2] store the number of particles identified in a matrix classified, by~~

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

$$R = \frac{P}{\Delta t} \tag{2}$$

$$NP = \sum_{i,j} N_{i,j} \tag{3}$$

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

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

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

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:

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

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 ~~, in bins which differ in their length and in the minimum and maximum values.~~ 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, ~~particle size~~ the 10th, 50th and ~~velocity percentiles were calculated~~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~~ 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 this study we compare both disdrometer types primary bulk (integrated) variables obtained directly from the telegram itself and addition to one-minute data, the mean (m) and maximum (M) values of some of these variables (*Rm*, *RM*, *KEm*, *KEM*, *Em*, *EM*, in addition, we do the same comparison calculating all bulk variables after a filter, considering only particles equal or greater than 0.3 mm of diameter, was applied to the data. Due to the low signal-to noise ratio Ott PARSIVEL^2 start measuring particles from 0.25 mm of diameter. Disdrometers as 2DVD or JWD do not consider drops smaller than 0.3 mm of diameter, therefore we also compared both disdrometer types bulk variables and PSVD percentiles calculated once particles smaller than 0.3 mm of diameter were discarded. Only common minutes of precipitation recording at least 0.1 mm h^{-1} and more than 10 particles in all disdrometers, were considered*NPm*) were computed for each rainfall event. A summary of the variables analysed is provided on Table 2.

[TABLE 2]

All data processing, including reading the raw telegrams, computing the integrated variables (erosivity for Thies LPM and size and velocity percentiles), and plOttingplotting, was performed using a custom package for the R environment, `disdRo` (Beguería et al., 2017).

2.3. Comparison of disdrometer measurements

The variables listed in Table 2 were compared between the four sensors. A Prior to any analysis, minute observations with low-quality or bad sensor status flags were removed from the comparison dataset. Minutes with missing data, precipitation below 0.1 mm h^{-1} or less than 10 particles detected in any of the four disdrometers were also removed. This way, only minutes with good quality data in the four devices were considered in the analysis. The comparison was made primarily on the bulk variables computed from the PSVD matrix stored in the one-minute telegrams outputted by the four disdrometers, by applying equations 1 to 6. We also compared the bulk variables calculated by the internal firmware of the devices, in order to check the impact of the effective sampling area correction and the removal of unlikely size-velocity bins.

Kernel density and violin plots, i.e. non-parametric graphical estimations of the probability density functions of the variables, were used as a preliminary analysis tool. A formal comparison between the two disdrometer types was performed using a Gamma generalised linear mixed model (Gamma GLMM)was used to compare between disdrometer types. A Gamma distribution was used to model the dependent variable, since this distribution is best suited to positive data with variance increasing with the mean, as it is the case of the disdrometric variablesanalysed here, with the bulk variables listed in Table 2 as response variables. Mixed models allow incorporating both fixed-effects and random-effects in the regression analysis (Pinheiro and Bates, 2000). The fixed-effects describe the values of the response variable in terms of explanatory variables that are considered to be non-random, whereas random-effects are treated as arising from random causes, such as those associated with individual experimental units sampled from the population. Hence, mixed models are particularly suited to experimental settings where measurements are made on groups of related, and possibly nested, experimental units. If the classification grouping factor was ignored when modelling grouped data, the random (group) effects would be incorporated to the error term, leading to an inflated estimate of within-group variability. In our case, differences on This allowed us to assess for differences in the response variables (Table 2) were examined considering as a function of the disdrometer type as the fixed effect. In order to account (fixed factor), while controlling for possible differences between measurements unrelated to the disdrometer type but arising from random spatial differences in the rainfall characteristics, a location random effect (the mast to which each disdrometer was attached)was also incorporated in the model. Thus, two

~~independent measurements (replicates) were available for each disdrometer type, corresponding to each mast. With the configuration described, the GLMM is set up as~~ 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 ~~, and can be expressed~~ (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:

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

where y_i is the ith observation of the response variable Y; ν is a shape parameter; θ_i is a scale parameter~~that~~ , which can be expressed in terms of ~~the shape~~ ν and a mean value corresponding to the ith 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 ~~$t(i) = (1, 2)$~~ $t(i) = (T, P)$ disdrometer types (~~PARSIVEL and Thies~~ 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 ~~independent~~

variables r, z, e R, Z, E and NP for which a log link, $g(\mu_i) = \log \mu_i$, was used.

The model in eq. (8) was fitted by generalized least squares (GLS), using the function `lme` from the R library `lme4` (Pinheiro and Bates, 2011). Results from these models allow comparing the means between disdrometer types, while controlling for possible random differences due to the distance between the devices.

In addition to GGLMM analysis, the percent bias (PBIAS) and several Goodness of Fit statistics were calculated to quantify the differences between disdrometers measurements, although neither of the two disdrometer types was considered to provide a real PSVD characterization.Therefore, in addition to GGLMM coefficients descriptive statistics describing the differences between the two types were given, considering all the data and sorted by rainfall intensity rangesA random sample of N=1000 records, corresponding to 250 minutes, was used in the analysis, in order to avoid size effects affecting negatively the statistical significance tests (Type I error inflation; see, e.g., Lin et al., 2013).

3. Results

A total of 58,761 one-minute observations were selected according to the above criteria,from 221 rainfall episodessummary report on the data acquired by the four disdrometers is reported on Table 3. Almost 100,000 minutes of data were obtained from each device. Missing values were found in all disdrometers and can be attributed due to technical issues (power supply failures and device hangouts, data communication problems, or spurious measures) , being Ott PARSIVEL^2 disdrometersthe ones with the highest number of missing values. Thies disdrometers recorded rainfall from 0.001 mm h^{-1}, whereas for PARSIVEL disdrometers the lowest value was 0.007 mm

~~h^{-1}. Therefore, Thies disdrometers recorded more minutes of precipitation, sensing it earlier and longer in comparison with PARSIVEL^2 disdrometers. Many of these recordings could be catalogued as 'false alarms", but in any case, they suggest a highest sensitivity of Thies disdrometers. To avoid an over-representation of Thies data only the common minutes were analysed, defined as those having records of precipitation rates higher than 0.1 mm h^{-1} and more than 10 particles in every of the four disdrometers. Table 3 summarizes the data recorded by each disdrometer and selected for the comparison.~~) were found in all disdrometers, although they were more prevalent on one of the Parsivels (P2), resulting in a significantly lower number of records by this device. The number of errors, as reported by the status flags of the devices, was low, albeit larger in Parsivel than in Thies devices. Some records were discarded due to quality issues, either based on the quality flat reported by Thies (only data with quality flags above 90% were accepted), or on non-consistent data in the telegram (saturation of the PSVD bins or excessively large intensity values) in the Parsivels. Since Parsivel does not report the data quality, no quality threshold could be used. Around 31% of the minutes recorded rain hydrometors in both Thies, while this percentage was lower for Parsivel (27.5% in P1; the value of P2 was even lower, but can not be considered since this device recorded a significantly reduced number of minutes due to technical issues). The larger amount of minutes with rainfall in Thies disdrometers can be attributed to their highest sensitivity, since they are able to records smaller raindrops (more on this later).

All types of precipitation events occurring in the sampling site were represented, with the majority of ~~rain minutes~~ observations corresponding with autumn rains, as corresponds to the climatology of the area. Rain rates varied between ~~0.1~~ 0.014 mm h^{-1} and 277 mm h^{-1}. The ~~highest precipitation rates~~ minimum precipitation rates were between 0.014 and 0.020 mm h^{-1}, with no differences between devices. The absolute maximum precipitation rates measured during the experiment depended on the disdrometer type, being Thies with Thies being the ones recording the highest rain ratesvalues.

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

[TABLE 3]

When considering only the records for which data of the four disdrometers existed, the total accumulated precipitation was 397.4 as measured by the disdrometers internal software was 244.9 mm (T1), 421 254.5 mm (T2), 324.1 220.4 mm (P1), and 265.4 228.1 mm (P2), where T and P stand for Thies and PARSIVEL^2, respectively, and 1 and 2 correspond with Mast 1 and Mast 2. Large discrepancies in the cumulative . This values were slightly different to those calculated from the PSVD data, which were slightly lower at 240.1 mm (T1), 253.0 mm (T2), 218.6 mm (P1), and 222.0 mm (P2). A graphical comparison of the cumulative time series for the computed and internal precipitation is provided in Figure 2. Some discrepancies in total precipitation were therefore found between the devices, which were especially noticeable for the Thies disdrometer located on Mast with the two Thies LPM devices recording more precipitation than the Parsivel ones. Between locations, mast 2 (T2), which recorded significantly more rainfall (Figure 2). Nevertheless, differences in accumulated Kinetic energy tended to record larger precipitation in both devices, although the magnitude of this difference was much lower than the difference between disdrometer typeswere smaller than random differences found between masts. As expected, filtered data showed more similarities between disdrometers, since the maximum rain rate was 207.4 mm h^{-1} (T1), 222.6 mmh^{-1} (T2) , 157.3 mm h^{-1} (P1), .

Differences were also found with respect to cumulative kinetic energy, for which larger values were also found for Thies (2100 and ~~181.5 mm h^{-1} (P2); and total precipitation was 387.5 mm (T1) , 406.9 mm (T2), 318.1 mm (P1),~~ 2101 J m^{-2} mm-1) than for Parsivel (1749 and ~~262.3 mm (P2)~~1829). This corresponds to values obtained from the PSVD data, since Thies disdrometers do not calculate the kinetic energy internally. Unlike with P, for E there were important differences between the values measured by the Parsivel^2 disdrometers (2100 and 2181) and those calculated from the PSVD, reported above.

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

3.1. Example events

Two events, representative of low and high precipitation intensity rates, were selected to illustrate the differences ~~by disdrometer type. The chosen events are examples of low and high intensity events.~~ between disdrometer outputs. Time series of some bulk variables ~~(Figure ??) are compared~~are shown in Figures 3 and 4. In both events, Thies ~~consistently reported~~ devices consistently reported higher rainfall intensitity and cumulative precipitation. This is related to a larger number of ~~drops per minute, and also higher rainfall intensitites.~~ rain particles detected, as shown by the number density (which factors out the different rain intensities). There were differences, too, in the median particle size, which was much larger in the Parsivel devices. Interestingly, it seems that these differences (larger number of drops in Thies, but larger mean size in Parsivel) somehow cancelled out for radar reflectivity and kinetic energy, which depend both on the number of drops, their size and velocity.

These differences were most evident in the high intensity event~~. The rate~~

of kinetic energy (Ke, $J\ m^{-2}$) did not show as many differences, indicating differences in PSVD recorded by each disdrometer type, and were also higher if no corrections for unlikely drops and effective sampling area were performed (Supplementary material, Figures A.1 and A.2).

[FIGURES 3 and 4]

The PSVD plots (Figure ??Figures 5 and 6), depicting the number of drops detected for each combination of drop size and velocity classes during the event by each disdrometer, help explain the differences found. Thus, Thies disdrometers where characterized by A first and evident difference is that Thies disdrometers had a much wider distribution of the PSVD spectra than PARSIVEL^2 ones. A line showing the theoretical Parsivel ones. The terminal velocity of raindrops as a function of their size (Uplinger, 1981)is also shown as a referenceaccording to Beard (1978), also depicted in the figure, was used to filter out unlikely combinations of size and velocity. Combinations which differ by more than 50% with the theoretical fall velocity are represented in the figure with a 50% transparency. Although a large majority of drops majority of particles were found to lie in a region close to the theoretical line, Thies devices showed a larger dispersion around the model and also tended to report had a much larger number of particles far from the theoretical model, both in the high and low intensity events. Particularly, a large number of very small particles falling at much higher velocities than those predicted by the theory. These particles, as well as relatively large ones with low falling velocities, seem to be filtered out from the PARSIVEL^2 output. Finally, there seemed to be a slight expected was very prominent, as were the drops with a large diameter but a fairly low velocity. Typically, the first case (small, fast raindrops) are attributed to edge events (partial recognition or larger drops falling in the edge of the laser beam), or splashed particles, while the second case are interpreted as double detections (two or more simultaneous drops). Both effects tend to increase with the precipitation intensity, as the anomalous events become more frequent.

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

Finally, and interestingly, an underestimation of drop velocity velocities with respect to the theoretical line in PARSIVEL[2] model could be found in Parsivel devices, most notably in the high intensity event and for particles between larger than 1 up to $\sim$ 3 mm. mm.

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

[FIGURE 5 and 6]

3.2. Integrated variables, minute scale

Differences between disdrometer types arouse for the integrated variables when the When the whole dataset was analysed, differences between disdrometers were also evident, as shown by the exploratory kernel densities density plots (Figure 7)and by the GGLMM coefficients . This was further confirmed by the Gamma GLMM analysis (Table 4). Thies disdrometers recorded a much higher number of particles *NP* (a mean difference of 422 vs. 219),

~~which in turn had an effect on the rainfall intensitiy R, radar reflectivity Z and kinetic energy E~~ The coefficients reported in the Table for the fixed effects correspond to β_T and β_P when μ is set to zero in equation 8, and ~~Ke, which also showed significant differences between disdrometer types. Interestingly, while Z and R were higher on average on Thies, E was lower. Also, the magnitude of the difference was much smaller for R, Z, Ke~~ can be interpreted as the mean values of the response variables for each disdrometer type, when other factors (the mast, in this case) are accounted for. The table includes also the p-values corresponding to these coefficients, as well as the residual and mast standard deviation (σ and ~~E than it could be expected from the strong effect on NP. In comparison to the fixed effects (differences between sensor types), the random effects (effect of the location, or Mast)had an almost negligible size~~$\sigma_{m(i)}$, respectively).

[FIGURE ~~2 and TABLE 4~~7 and TABLE 4]

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

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

~~This~~ The differences found in the PSVD percentiles allows for a better understanding of the differences in the integrated variables~~between both devices~~, since the particle size and velocity ~~distributions~~ have contrasting effects on R, ND, Z, ~~Ke,~~ and E. ~~A~~ In general, a higher number of ~~drops detected implies increased values of R and also~~ particles implies increasing values of all these variables, which favours Thies devices since it tended to detect a higher number of particles. The particle size, on the other hand, has a similar effect of increasing all the variables for which it is relevant (R, Z and ~~Ke, although the different distribution of drop sizes helps explain why the larger number of drops detected by Thies did not result in very large differences in these integrated variables , since the average~~ E). Since the particle size was ~~lower for Thies which reduces the magnitude of the effect. Also, since~~ in general higher in Parsivel devices, this effect partially cancels out the effect of the increasing number of particles. Particle velocity, which was in general higher in Parsivel (except for the largest drops), has a positive effect in E~~depends strongly on the~~, but a negative effect on Z, which further explains the differences found. The particle density (ND), finally, is not affected by the drop size and is negatively affected by fall velocity, and ~~because it is expressed in units of energy per unit rainfall , the smaller particle sizes recorded by Thies resulted in reduced E.~~ that the reason why this variable showed the highest difference between both disdrometers.

3.3. *Integrated variables, event scale*

When considering event totals, a similar pattern was

Although one of the benefits of the optical disdrometers is their ability to provide large amounts of information at very fine temporal scales (as one-minute data analysed here), very frequently these data data are aggregated over larger time periods or rainfall events for practical issues. For instance, it is typical the computation of kinetic energy totals for rainfall events, for instance for soil erosion applications. When considering the same variables at the event level, looking at the mean and maximum values over the event, similar results were found (Figure 8 , Table **??**). Good agreement by disdrometer type was shown in integrated variables such rain rate (Rm), and reflectivity (Zm) by event. Disdrometer records, by type, slightly differ in maximum rain rate, kinetic energy and mean number of particles by event, with the greatest differencesfound in PSVD percentiles. and Table 5).

[FIGURE 3 and Table 5FIGURE 8 and TABLE 5]

3.4. *Effect of data filtering*

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

When filtered data was used the differences between the two devices were reduced (Table **??** and Appendix Figure 7). Thus, the mean

3.4. *Effect of PSVD data correction*

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

The results are shown in the Supplementary material, in Table A.1 and Figure 7. A comparison with the results shown in the previous section reveals the same general pattern, but with stronger effects. For instance, the coefficient for the number of particles NP was 280 and 220 for Thies and PARSIVEL, respectively. While the differences in R , Kc and Z did not change much with respect to the previous results, E was now much similar between the two devices. Differences in the PSVD percentiles also got reduced, although they remained significant. At the event scale, when filtered data was used, differences were reduced whereas the pattern remainedNP was 62% higher in Thies than in Parsivel. Interestingly, the effect of the correction on the particle size percentiles had a different sign on Thies, for which $D50$ increased from 0.53 (without correction) to 0.60 (with correction), while on Parsivel it decreased from 0.80 to 0.74. For the median particle velocity ($V50$), the coefficient remained very similar before and after correction for Thies, while for Parsivel it increased from 2.88 to 3.09 (7%). The relative magnitude of the differences between Thies and Parsivel disdrometers was 88% for ND, 12% for R, 15% for E and 7% for Z, i.e. much higher than after filtering and correction for ND but similar for the other three variables.

3.5. Effect of rainfall intensity

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

~~The differences between disdrometer types were similar~~

[TABLE 6]

The same effects described above were found at different rainfall ~~intensitites, and had the previously mentioned effects, but the magnitude of those effects varied notably~~intensities. The magnitude of the effects, however, tended to increase with the intensity. Thus, the ~~differences between disdrometer types were reduced for all variables at the lowest intensityrange, while they were maximum for the highest intensity range. During minutes with rainfall intensityhigher than 10 mm h^{-1}, for instance,~~ relative difference between the coefficients of *NP* ~~was almost nine times higher for Thies than for PARSIVEL. The differences in the PSVD percentiles were also magnified at the highest intensities. Although differences between disdrometer types were reduced when filtered data were compared, the above mentioned tendency remains, becoming especially evident for high intensity rain. In brief, PARSIVEL^2 tended to underestimate the number of particles recorded,~~ ranged between 7% (146 vs 136) for low rainfall intensity, 27% for medium intensity and ~~tended to record a larger number of bigger particles than Thies. At the~~

same time, Thies recorded a very large number of small particles that may mask the amount of bigger particles recorded65 % for high intensity, while the median particle size ranged between 16%, 28% and 200%. Equally large were the relative differences between the coefficients of ND, which varied between 33%, 67% and up to 292%, while for the remaining variables the increase of the effect with the rainfall intensity was less pronounced.

4. Discusion and conclusionsDiscussion

Optical disdrometers are widely commercially affordable sensors able to provide a thorough description of precipitation, and they are being increasingly used by national weather services as reliable present weather sensors and even rain gauges requiring low maintenance. Besides their use as present weather sensorsin operational networks, optical disdrometers provide information on precipitation drop spectra relevant to different research fieldsand needed for precipitation intercomaprison and radar calibration experiments. Precipitation remote sensing and precipitation estimation together with soil erosion are most interested in accurate measurements of raindrop size and velocity, since environmental processes are influenced not only by precipitation amount and intensity but also how it is structured in individual drops. Studies on this topic are present in scientific literature, first evaluating impact disdrometers and then optical disdrometers (Kinnell, 1977; Rosewell, 1986; Tokay et al. , 2001; Krajewski et al., 2006; Lanza and Vuerich, 2009; Thurai et al. , 2011). Reliable measurements of precipitation particle spectra have to take into account the influence of sensor type and accuracy in relation with precipitation regimes, since such measurement uncertainty is contained in the final precipitation estimation and subsecuent models results (Angulo-Martínez and Barros, 2015) . Current optical disdrometers are good commercially affordable tools able to provide a complete description of precipitation. that has applications in different fields, and they are being increasingly used in research.

~~The accuracy of optical disdrometers may be affected by a~~ Thies Clima LPM and OTT Parsivel^2 are among the most common, state-of-the-art, optical disdrometers. Despite being based on the same functioning principle and having similar characteristics in terms of sensibility and range of particle detection, there are substantial differences between them that may affect differently their records. We have stressed the differences in the higher and (more important) lower particle size detection ranges of the two devices, with Thies having a lower detection threshold that may induce bias in the records of the two disdrometer types. Filtering the PSVD matrix to a common detection range, as done here, allows for a fair comparison between the outputs of the disdrometers, and should be recommended for any study that aims at presenting general results. However, as we have seen here, despite applying the same detection thresholds to the data outputted by the two disdrometers, significant differences were found both at the level of PSVD spectra (particle size and velocity percentiles) and on the bulk variables (PSVD moments).

There are a number of factors ~~, such as wind and turbulence conditions, which may modify particles vertical trajectory and therefore, measurements (Nespor et al. , 2000; Habib and Krajewski, 2001). The measurement principle is based in laser beam power decrease with beam obscuration, and current interruption, when particles pass through the laser area . Frasson et al. (2011)evaluated the performance of Thies optical disdrometer and found that it underestimated particles diameter by ~ 0.5 mm, indicating as possible reason the non-homogeneous beam power distribution. When power supply for the laser is homogeneous there is a linear relation between the particle shaded area and the amount of energy that reached the receiver photodiode, being this the principle that allows particle size measurement. However, oscillations in the current may drift the estimations. In addition, depending on where on the laser sampling area the particle pass, mis-detection could be greater. For instance, particles passing through the laser closer to the heads of PARSIVEL disdrometer were less sensed than those that passed in the center~~

(Frasson et al. , 2011; Angulo-Martínez and Barros, 2015). Meassurement inaccuracy is also related to their inability to correctly identify simultanous drops, which are sensed as single drops much larger in size. Raasch and Umhauer (that may help explain the differences found. Geometrical differences between the laser beams are highly relevant, since they greatly influence the probability of bias-inducing effects such as edge events ('margin fallers') and double detections. A larger sampling area, for instance, implies a higher chance of double detections. At this respect, the larger sampling area of Parsivel (54 cm^2) over Thies devices (45.6 cm^2 on average) implies that Parsivel disdrometer should be more affected by double detections. Double detections, i.e. time-overlapping drops, may be sensed just as one single drop (hence causing a loss of mass which may translate to a reduced precipitation record); or as a much larger drop at an unusually low velocity. Since these unusual particles are often discarded from the PSVD matrix, this may result in another source of mass loss, which may or not be partially solved by the sampling area correction (more on this later). Although this would require further research, for instance with the help of numerical simulations as in the work by Raasch and Umhauer (1984) investigated with computer simmulations the ability of optical disdrometers for detecting simultaneous drops, founding a probability of 10% during intense events, so this effect must not be disregarded. They provided an algorithm to fix the problem in their prototype internal software (Raasch and Umhauer, 1984). Another measurement problem is related with marging fallers, i.e.drops that partially fall in the sampling area (Yuter et al, 2006) and are sensed with a smaller size than they really are, but with their complete velocity. A correction for this effect has been proposed based on modifying the effective sampling area depending on the particle size (), we suspect that the tendency towards a lower number of particles detected and lower precipitation amounts found on Parsivel devices may have a relationship with this effect.

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

In order to overcome this problems, we applied a correction scheme which is similar to the ones found in other studies (e.g. Löffler-Mang and Joss, 2000; Battaglia et al., 2010; Raupach and Berne, 2015). ~~Hauser et al.(1984)detected an unsuppresed 50Hz rumble noise in~~ The scheme consists on two parts: the first implies removing highly unlikely particle counts, i.e. those with velocities that are far from the theoretical fall velocity corresponding to their size. These unlikely particles are most possibly caused by edge events and double detections, so they are removed from the PSVD data. This causes a loss of mass, and this loss of mass is uneven since it increases with the particle size (due to the geometric effect explained above), so the second part of the scheme consists on correcting the effective sampling area used in calculating the bulk variable from the PSVD (equation 7). The correction, however, is not guaranteed to restitute all the mass loss, and careful calibration is required in order to match the filtering of unlikely particles (which depends on the threshold used for particle removal) with the effective area correction. Here we used a threshold corresponding with a difference higher than 50% with respect to the theoretical fall velocity matched to a factor or 1/2 of the drop diameter for the area correction, but other combinations are possible. Again, numerical simulation should help in determining the best correction parameters, which in turn should consider the different beam geometries.

Our results showed differences between the two disdrometer types, which were not totally removed by the correction scheme (although they were partially diminished with respected to the un-corrected records). Differences in the in the ~~power supply which interfered with the measurement of particles smaller than 0.3 mm. Therefore, common agreement stated from the literature is the baseline of 0.3 mm of diameter as starting point for measuring particle sizes. This threshold has been built in the Joss and Waldvogel impact disdrometer (Joss and Waldvogel, 1967) and in 2DVD (Kruger and Krajewsky, 2002). PARSIVEL disdrometer (all of its versions)leave empty the two initial diameter bins in order to avoid the the low signal-to-noise ratio, as JWD and 2DVD, whereas Thies disdrometer does not , starting drop size measures from 0.187 mm. Thies high sentitivity has been previously pointed out indicating that 0.001 mm h^{-1} rain rate were not sensed by other meteorological devices or observer, declaring the measure as "false alarm" (Upton and Brawn, 2008).~~ internal treatment of the data by the two devices, which is not public, may also help explain this differences. Both manufacturers indicate that some treatment of unlikely detections is performed internally, but very little detail is given. From the examination of the raw PSVD matrices, it seems that the correction applied by Thies, if any, is very subtle, while the output of Parsivel seems to be much more affected by corrections. The technical literature, also, gives more detail in the case of the Parsivel, for which at least a correction for the effective sampling area is reported (Löffler-Mang and Joss, 2000). The exact nature of these corrections, however, is not known, or even if they are applied to the integrated variables only, or also to the PSVD data. This uncertainty makes it difficult to implement an effective correction scheme that makes the outputs of the two disdrometer comparable.

Disdrometer external structure may intercept precipitation particles, which eventually The external structure of the devices also plays an important role and may lead to incorrect drop detections due to turbulence (see, for instance, Constantinescu et al. 2007, for a review of turbulence induced errors on pluviometers) and splashing (particles intercepted by the enclosure of the devices which break and splash away in smaller but accelerated drops. PARSIVEL disdrometers include a splashing shield in their design to reduce such effect, while Thies disdrometers do not. Splashed particles are known in the literature (, see Kathiravelu et al., 2016). They could be removed by abnormal size-fall velocity pairs. It seems that the Thies disdrometer is more prone to having splashed drops interfering with the laser beam, since it contains larger flat surfaces susceptible of splashing particles in the direction of the sensor. The Parsivel units, on the other hand, do not have flat surfaces and include a splash protection shield that seems to effectively reduce the risk of splashing. These morphological differences may also affect differently in case of wind, since the turbulences generated may be very different on both devices, and may also be a cause of systematic bias between the two disdrometers. A future study using high speed video and a wind-tunnel setup could help examine the occurrence and magnitude of these effects, which are poorly quantified up to now.

All these effects increase with precipitation intensity, triggering unreal intensity peaks with high variability among sensors and by sensor type as a consequence of measurement inaccuracies and environmental influences (Donnadieu, 1980; Lanzinger et al., 2006; Lanza and Vuerich, 2009, Frasson et al., 2011). The results shown in this study agree with previous works regarding precipitation spectra measurements during high intensity rains. The two types of disdrometer analysed showed different PSD populations for the same rainfall events. When PSVD data were filtered, considering only

~~particles with diameters greater than 0.3 mm, these differences were reduced, although the tendency remains and increases for high intensity rains. Frasson et al., (2011) and Lazinguer et al., (2006) also noted the same result. Articles in scientific literature comparing Ott PARSIVEL^2 disdrometer measurements with more accurate ones such as 2DVD (Raupach and Berne, 2015) and as JDW (Tokay et al. , 2014) indicated that PARSIVEL^2 overestimated the number of drops smaller than 1 mm and larger than 3.25 mm while underestimating the number of drops between 1.38 mm - 3.25 mm. Very good agreement was found for diameter size estimation between PARSIVEL^2 and JWD between 0.7 mm -~~ Finally, we also detected a tendency towards underestimating the velocity of falling particles in the case of the Parsivel units, especially in the range between 1 and 3 mm~~, while large drops ($\phi >$ 3 mm) may be overestimated by PARSIVEL^2 (Tokay et al. , 2014; Park et al., 2017). The study of~~. This have been shown previously, and according to Tokay et al. (2014) ~~highlighted a better detection of rain/no rain by PARSIVEL^2 in comparison with the previous PARSIVEL versions. This was also noted by Angulo-Martínez and Barros (2015). However, when comparing PARSIVEL^2 with Thies, the last one was more sensitive to precipitation detection, previously noted by Upton and Brawn (2008) and shown by our results. Regarding fall velocity measurements, Thies provided a better estimation in comparison with theoretical terminal velocity, whereas PARSIVEL^2 tended to underestimate fall velocity especially for midsize drops (1 mm - 3 mm). PARSIVEL manufacture recognised a problem in velocity underestimation, which is in fixing process (Tokay et al.~~ this issue is known to the Parsivel manufacturer who mentioned that it is in process of being fixed. However, ~~2014).~~ at least the units tested, still suffered from the same problem. Underestimation of the fall velocity may have a substantial influence on the bulk variables computed from the PSVD data, since the velocity intervenes in several of the equations. Systematic underestimation of fall velocity has an effect of increasing ND and Z, while it decreases E.

~~In the present study there are no differences regarding the influence of the hydrometeorological regimes, nevertheless collocated optical disdrometersshowed differences in precipitation spectra measurements increasing with rain rate. Such differences should be taken into account in relation with the hydrometeorological regime. For instance, in regions prone to small raindrop spectra PARSIVEL^2 disdrometer may underestimate precipitation measurements, since its best performance is achieved between 1 mm - 3 mm particles size (Jaffrain and Berne, 2011; Angulo-Martínez~~Differences in the number of particles detected, and biases in the estimation of particle size and velocity, ~~2015). However, in areas with midsize precipitation hydrometeorological regimes PARSIVEL^2 will perform better.~~ result in complex biases in the integrated variables. This is due to the different effect that these factors have on their computation, since depending on the case there are linear or inverse relationships involved. This stressed the relevance of not only an unbiased estimation of the PSVD by the disdrometers, but also of any filtering and correction scheme applied to the PSVD data during post-processing.

~~Sumarizing~~

5. Conclusions

The two types of disdrometer analysed showed different PSVD spectra for the same rainfall events, while the differences between two devices of the same type were much smaller and compatible with random differences. In particular, Thies devices recorded a much larger number of drops than ~~PARSIVEL~~Parsivel^2, but also a much larger spread of the PSVD spectra, with a significant amount of drops with unexpected combinations of size and velocity~~. Most notably, a large number of~~ , most notably small drops with excessively high velocities~~were consistently reported by Thies disdrometers. PARSIVEL~~, compatible with edge events ('margin fallers'). Parsivel^2 devices, on the contrary, recorded less drops ~~but PSVD spectra~~ and a PSVD spectra which was much closer to the theoretical model~~, with~~. They also had a tendency towards underestimating drop velocity ~~. This~~ with respect to both Thies and a theoretical fall model.

Differences in the PSVD spectra resulted in significant discrepancies between both ~~disdrometer types~~ disdrometers in all bulk precipitation parameters such as rain intensity and amount, particle density, radar reflectivity, or kinetic energy. These differences were found when these variables were computed by the internal firmware of the devices, but also when they were computed by us from the PSVD data. When the PSVD data were filtered by considering only particles with diameters between 0.25 and 8 mm and by removing unlikely drop size and velocity pairs, and a correction for the effective sampling area was used, the magnitude of the differences was reduced although the tendency remained. In all cases, the differences increased with precipitation intensity, as did the variance between devices of the same type, in agreement with the expectation and with previous studies.

The differences found may be explained by hardware or software differences. ~~More stable and homogeneous laser beams translate directly to a better estimation of drop size and velocity. The~~ Geometrical differences on the laser beams of the two devices translate to different prevalence of bias-inducing effects such as edge events and double detections, while differences the external design may also have a large influence on the drop splash. ~~In the technical description of the PARSIVEL^2 disdrometer it is mentioned that its design incorporates protections against double drop and partial drop detections or margin fallers, although~~ The manufacturers of both disdrometers indicate that corrections have been implemented to prevent or reduce the magnitude of this effects, but the exact procedures are not documented. ~~The~~ Different solutions can be adopted to limit undesired effects, both at the hardware and the software level, and inspection of the resulting PVSD spectra ~~plots suggests that these corrections are achieved by post-processing the~~

raw datamatrix, i.e. by filtering-out the anomalous drops with respect to a theoretical model. This would be of course an advantage for the average user, but prevents the advanced user from developing and using custom-made solutionsduring the same rainfall events suggests that the level of correction is higher in the case of Parsivel than in the case of Thies. Wether these differences are (total or partially) due to hardware and design differences, or they are caused by hardware or software filtering and correction of the PSVD data, is still a question with no clear answer. Since some crucial aspects of the internal functioning of both devices are hidden from the final user, it is very difficult to design a data treatment process that would enable making the records of Thies and Parsivel disdrometers compatible and comparable across studies.

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[TABLES AND FIGURES]

Table 1: ~~Mean particle size~~ Classification or particles according to equi-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~~ *M* and ~~m~~ *m* stand for ~~max~~ 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	m^-3 mm^-1	*ND*, *NDm*
Radar reflectivity	dBZ	*Z*
Kinetic energy	J m^{-2} 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. ~~Percentage~~ Number of ~~records from every disdrometer corresponding to the categories. Total one-min records~~ minutes recorded, errors, minutes with ~~$I > 0.1$ mm h^{-1}~~ rain (SYNOP codes 61, 63 and ~~$NP > 10$ are: 58761. Recorded by at least two disdrometers~~ 65), and high quality minutes; percentage of ~~different type~~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 ~~Models~~ Model coefficients for one-minute records ~~. Analysis done with a~~ (random sample size of N = ~~1000.~~1000). Refer to Table 2 for a list of acronyms of response variables.

Response	Fixed effects				Random effects	
variable	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
NP	230.1	$<2 \times 10^{-16}$	193.8	$<2 \times 10^{-16}$	0.000	0.8719
D10	0.3374	$<2 \times 10^{-16}$	0.4772	$<2 \times 10^{-16}$	3.614×10^{-3}	0.1730
D50	0.5956	$<2 \times 10^{-16}$	0.7420	$<2 \times 10^{-16}$	1.488×10^{-3}	0.1899
D90	1.012	$<2 \times 10^{-16}$	1.026	$<2 \times 10^{-16}$	0.000	0.209
V10	1.316	$<2 \times 10^{-16}$	1.793	$<2 \times 10^{-16}$	1.716×10^{-2}	0.2097
V50	2.399	$<2 \times 10^{-16}$	2.875	$<2 \times 10^{-16}$	2.450×10^{-2}	0.1646
V90	3.818	$<2 \times 10^{-16}$	3.608	$<2 \times 10^{-16}$	1.200×10^{-2}	0.1445
R	1.440	1.659×10^{-7}	1.254	$<2 \times 10^{-16}$	2.292×10^{-8}	1.467
ND	21,600	$<2 \times 10^{-16}$	15,920	$<2 \times 10^{-16}$	0.000	0.578
Z	24.55	$<2 \times 10^{-16}$	23.23	$<2 \times 10^{-16}$	0.000	0.2828
E	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	Fixed effects				Random effects	
variable	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
NP	167.5	$<2 \times 10^{-16}$	146.3	$<2 \times 10^{-16}$	0.000	0.8463
D10m	0.3448	$<2 \times 10^{-16}$	0.4909	$<2 \times 10^{-16}$	3.073×10^{-3}	0.1629
D50m	0.6061	$<2 \times 10^{-16}$	0.7560	$<2 \times 10^{-16}$	0.000	0.1564
D90m	0.9971	$<2 \times 10^{-16}$	1.027	$<2 \times 10^{-16}$	0.000	0.1566
V10m	1.351	$<2 \times 10^{-16}$	1.826	$<2 \times 10^{-16}$	2.027×10^{-2}	0.2036
V50m	2.465	$<2 \times 10^{-16}$	2.876	$<2 \times 10^{-16}$	2.607×10^{-2}	0.1375
V90m	3.791	$<2 \times 10^{-16}$	3.597	$<2 \times 10^{-16}$	1.907×10^{-2}	0.1114
Rm	1.051	$<2 \times 10^{-16}$	0.9615	$<2 \times 10^{-16}$	0.000	1.063
RM	3.351	$<2 \times 10^{-16}$	3.430	$<2 \times 10^{-16}$	6.788×10^{-8}	1.584
NDm	20,780	$<2 \times 10^{-16}$	15,930	$<2 \times 10^{-16}$	9.283×10^{-5}	0.4714
Em	11.03	$<2 \times 10^{-16}$	9.505	$<2 \times 10^{-16}$	1.867×10^{-7}	0.3792
Zm	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 ~~Models~~ Model coefficients for ~~event means~~minutes with varying rainfall intensities.~~N = 221.~~

Response	Fixed effects				Random effects	
variable	Thies		Parsivel		Mast	Residual
	coeff	p-value	coeff	p-value	std. dev.	std. dev.
Low rainfall intensity (0.1<I<2 mm h^{-1}):						
NP	145.8	$<2 \times 10^{-16}$	136.1	$<2 \times 10^{-16}$	1.132×10^{-7}	0.7129
D10	0.3481	$<2 \times 10^{-16}$	0.4723	$<2 \times 10^{-16}$	3.795×10^{-3}	0.1758
D50	0.5975	$<2 \times 10^{-16}$	0.7109	$<2 \times 10^{-16}$	3.160×10^{-3}	0.1765
D90	0.9440	$<2 \times 10^{-16}$	0.9503	$<2 \times 10^{-16}$	0.000	0.1650
V10	1.365	$<2 \times 10^{-16}$	1.762	$<2 \times 10^{-16}$	2.189×10^{-2}	0.2156
V50	2.416	$<2 \times 10^{-16}$	2.768	$<2 \times 10^{-16}$	2.189×10^{-2}	0.2156
V90	3.639	$<2 \times 10^{-16}$	3.425	$<2 \times 10^{-16}$	1.145×10^{-2}	0.1202
R	0.6675	1.659×10^{-7}	0.6202	$<2 \times 10^{-16}$	0.000	0.6570
ND	24,840	$<2 \times 10^{-16}$	18,710	$<2 \times 10^{-16}$	9.824×10^{-3}	0.5478
Z	21.44	$<2 \times 10^{-16}$	20.45	$<2 \times 10^{-16}$	0.000	0.2281
E	9.434	$<2 \times 10^{-16}$	7.953	$<2 \times 10^{-16}$	1.113×10^{-2}	0.4108
Medium rainfall intensity (2<I<10 mm h^{-1}):						
NP	519.2	$<2 \times 10^{-16}$	408.1	$<2 \times 10^{-16}$	3.144×10^{-9}	0.4014
D10	0.3122	$<2 \times 10^{-16}$	0.4944	$<2 \times 10^{-16}$	1.681×10^{-3}	0.1232
D50	0.5936	$<2 \times 10^{-16}$	0.8246	$<2 \times 10^{-16}$	7.793×10^{-4}	0.1592
D90	1.525	$<2 \times 10^{-16}$	1.772	$<2 \times 10^{-16}$	1.203×10^{-10}	0.1268
V10	1.177	$<2 \times 10^{-16}$	1.893	$<2 \times 10^{-16}$	8.798×10^{-3}	0.1666
V50	2.420	$<2 \times 10^{-16}$	3.133	$<2 \times 10^{-16}$	2.348×10^{-2}	0.1587
V90	4.488	$<2 \times 10^{-16}$	4.147	$<2 \times 10^{-16}$	3.325×10^{-2}	9.908×10^{-2}
R	4.048	1.659×10^{-7}	3.596	$<2 \times 10^{-16}$	1.145×10^{-2}	0.1202
ND	13,730	$<2 \times 10^{-16}$	8,228	$<2 \times 10^{-16}$	6.932×10^{-3}	0.3899
Z	34.26	$<2 \times 10^{-16}$	32.22	$<2 \times 10^{-16}$	7.137×10^{-3}	0.1092
E	15.09	$<2 \times 10^{-16}$	13.95	$<2 \times 10^{-16}$	7.105×10^{-3}	0.3521
High rainfall intensities (I>10 mm h^{-1}):						
NP	1367.0	$<2 \times 10^{-16}$	829.7	$<2 \times 10^{-16}$	9.263×10^{-9}	0.3532
D10	0.287	$<2 \times 10^{-16}$	0.5391	$<2 \times 10^{-16}$	0.000	0.1866
D50	0.510	$<2 \times 10^{-16}$	1.030	$<2 \times 10^{-16}$	0.000	0.2777
D90	1.525	$<2 \times 10^{-16}$	1.772	$<2 \times 10^{-16}$	1.645×10^{-2}	0.1560
V10	1.015	$<2 \times 10^{-16}$	2.047	$<2 \times 10^{-16}$	0.000	0.2213
V50	2.012	$<2 \times 10^{-16}$	3.529	$<2 \times 10^{-16}$	0.000	0.2672
V90	4.992	$<2 \times 10^{-16}$	4.467	$<2 \times 10^{-16}$	0.000	0.1196
R	15.94	1.659×10^{-7}	14.33	$<2 \times 10^{-16}$	2.374×10^{-2}	0.2910
ND	10,370	$<2 \times 10^{-16}$	3,543	$<2 \times 10^{-16}$	0.000	0.428
Z	43.05	$<2 \times 10^{-16}$	40.88	$<2 \times 10^{-16}$	9.882×10^{-3}	8.927×10^{-2}
E	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 Parsivel^2 (P1 and P2, with serial numbers 304555 and 304553); and two Thies (T1 and T2, with serial numbers 0436 and 0655).

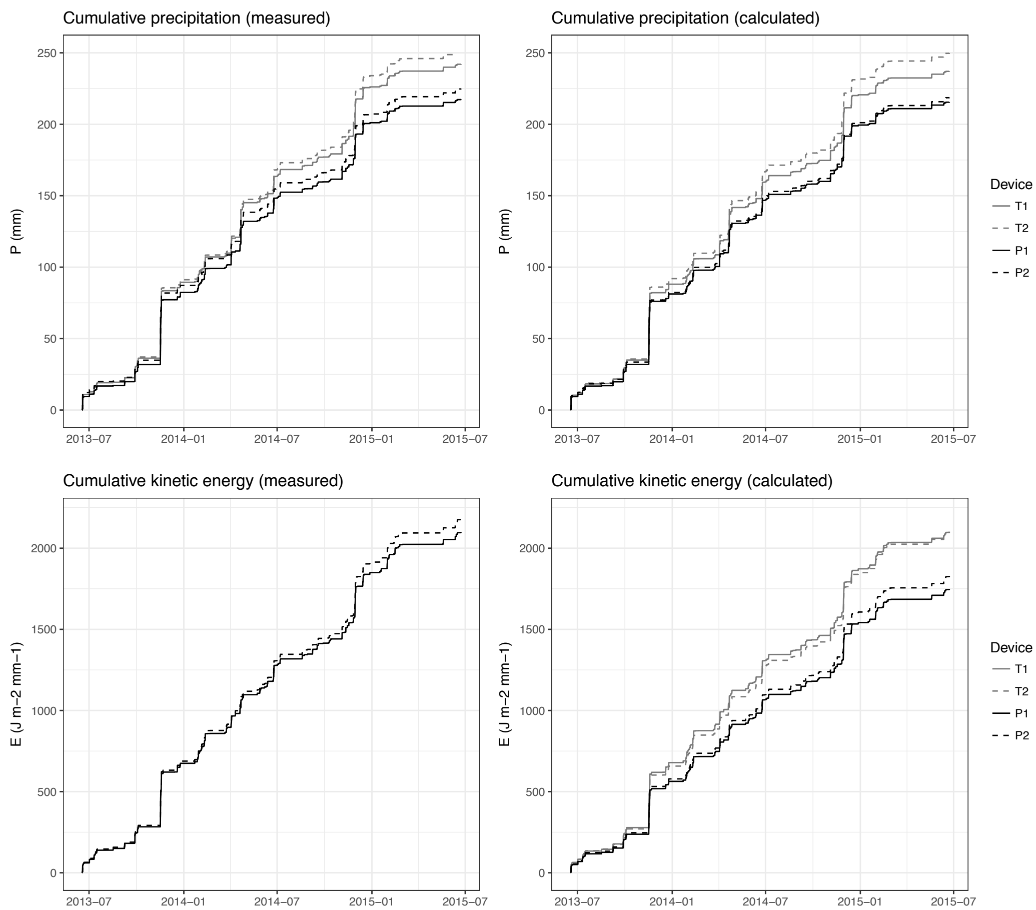

Figure 2: Accumulated precipitation (R, mm) and ~~Kinetic~~ kinetic energy (E, J m^{-2} mm^{-1}) during the two years experiment (only the minutes with data on the four disdrometers are used).

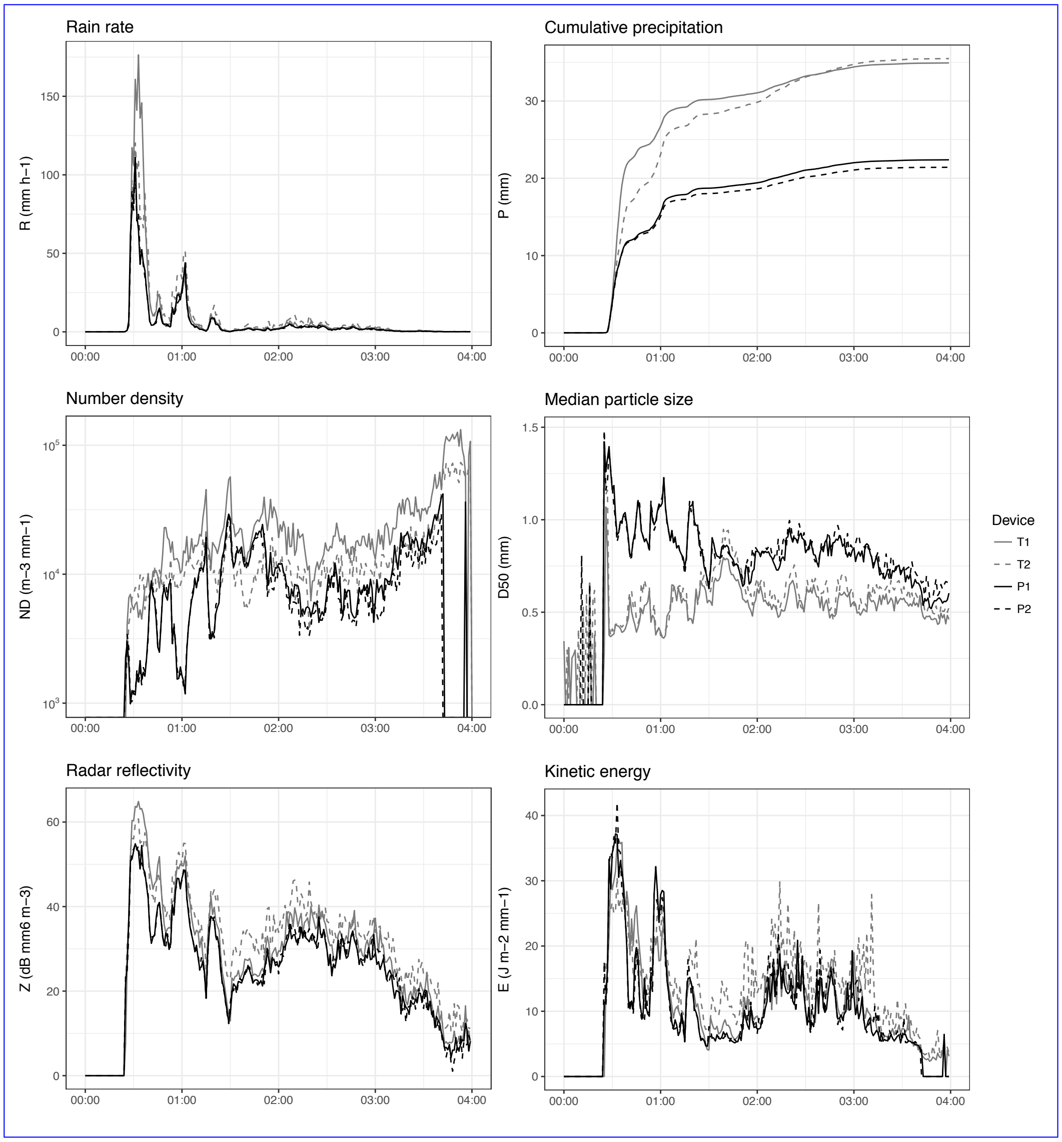

Figure 3: ~~Bulk variables time~~ Time series of ~~high and low intensity events~~disdrometer bulk variables during a high-intensity event (E365, 25/11/2014).~~Thies in blue and PARSIVEL in red.~~

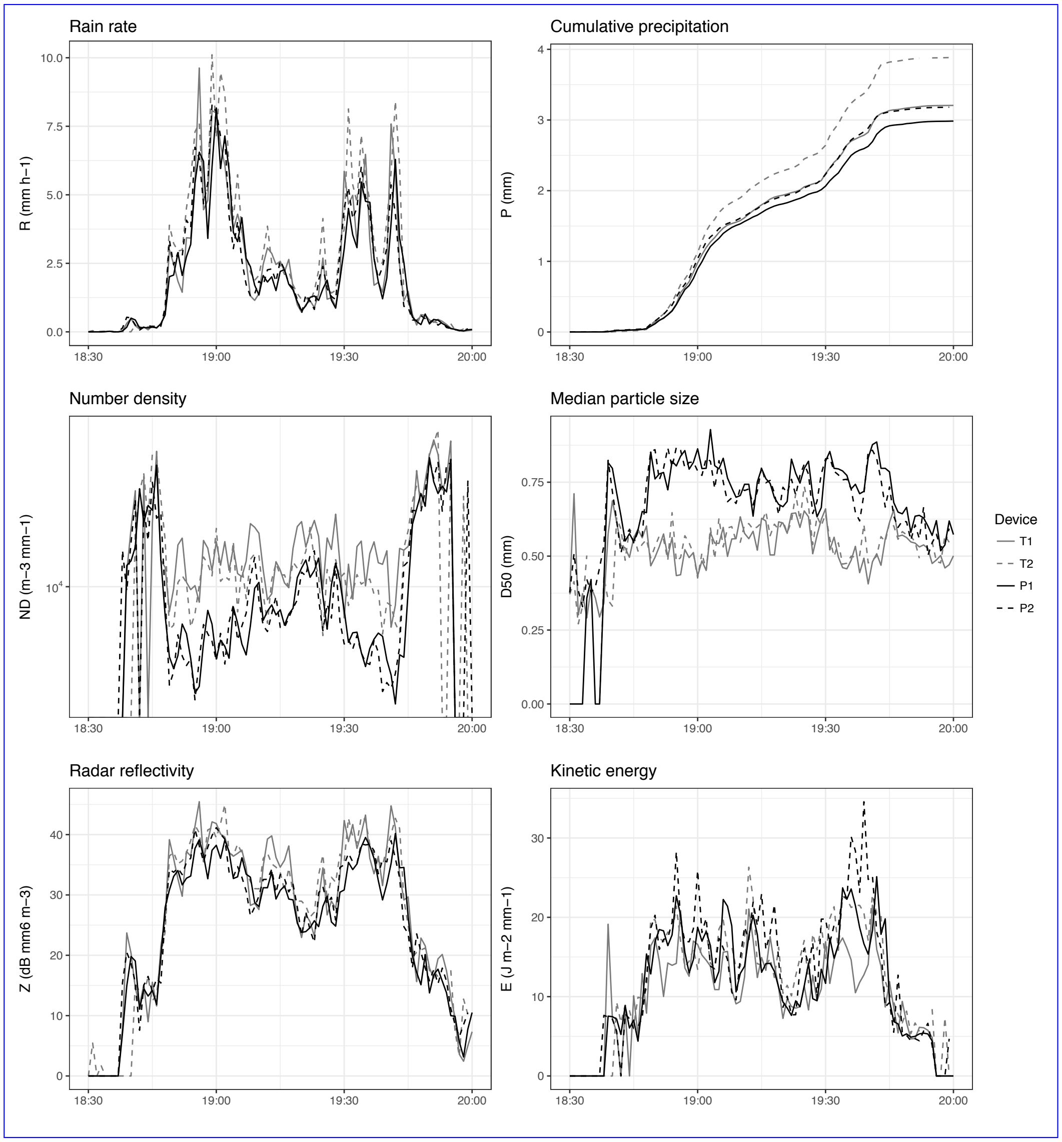

Figure 4: ~~Particle size and velocity density (PSVD) plot~~ Time series of ~~high and low intensity events. Drop size- terminal velocity relationship~~ disdrometer bulk variables during a low-intensity event (~~Uplinger~~E455, ~~1981~~23/02/2015)~~is shown by the black line~~.

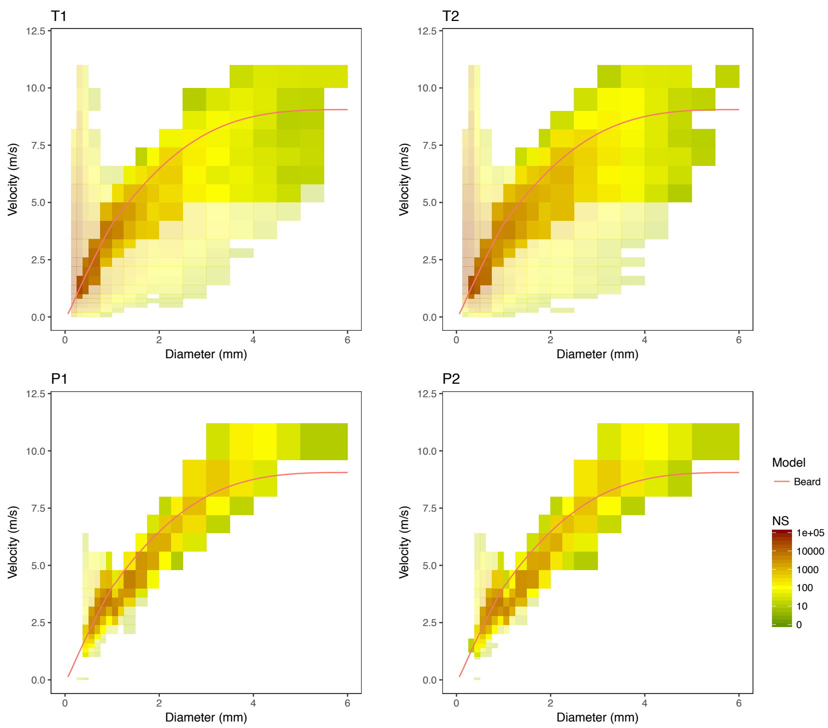

Figure 5: Particle size and velocity density (PSVD) plots of a high-intensity event (E365, 25/11/2014). The color scale indicates the number of particles for each size and velocity class (NP). Deviations larger than 50% from the theoretical terminal velocity model (Beard, 1976; red line) are indicated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

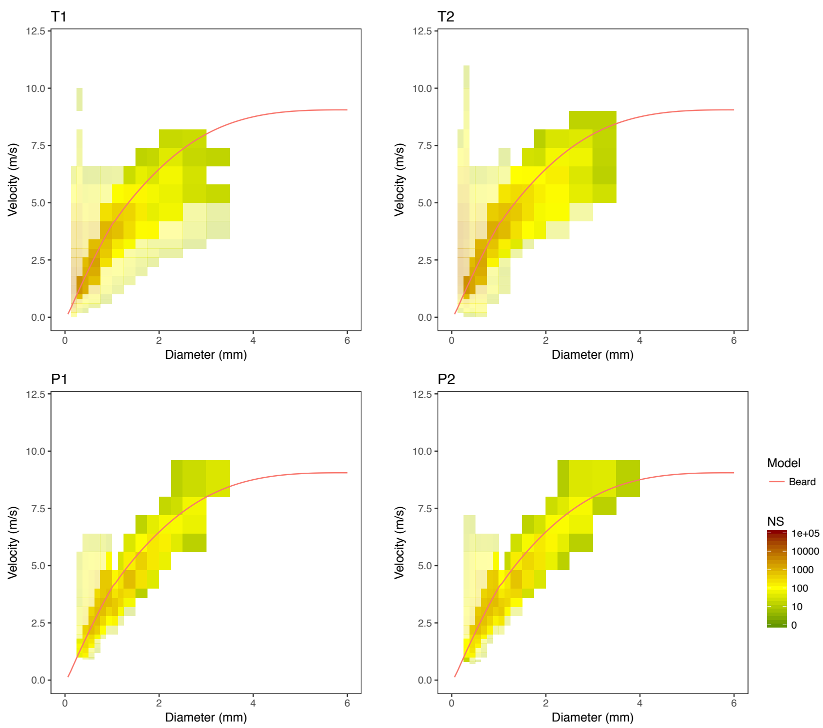

Figure 6: Particle size and velocity density (PSVD) plots of a low-intensity event (E455, 23/02/2015). Legend as in Figure 5.

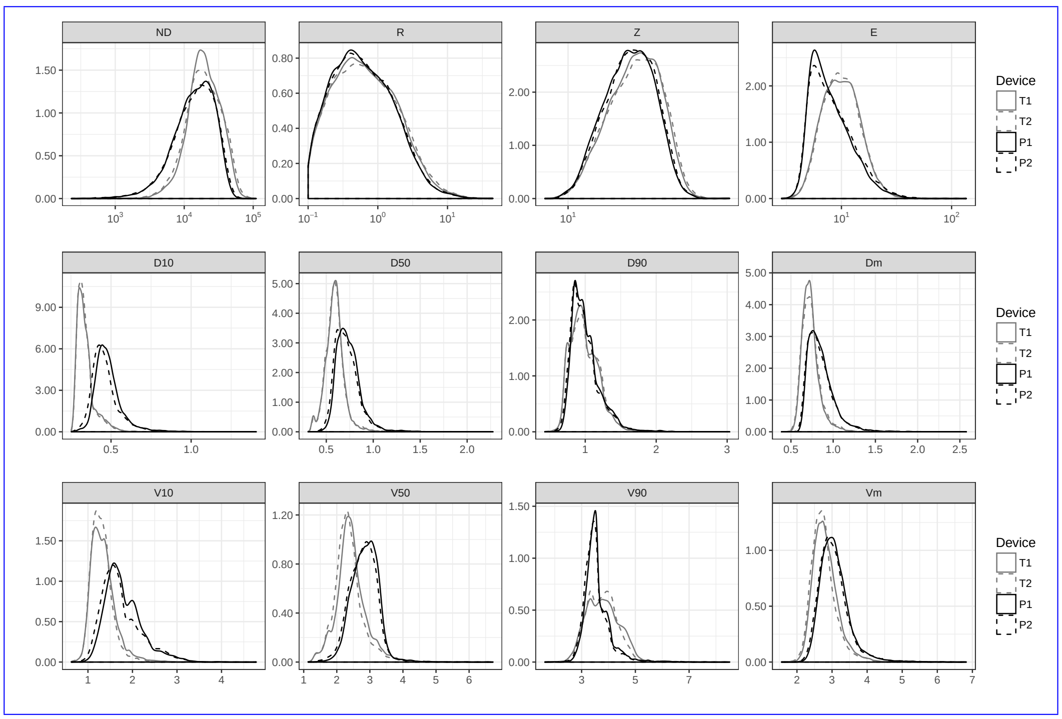

Figure 7: Kernel density plots for one-minute records.

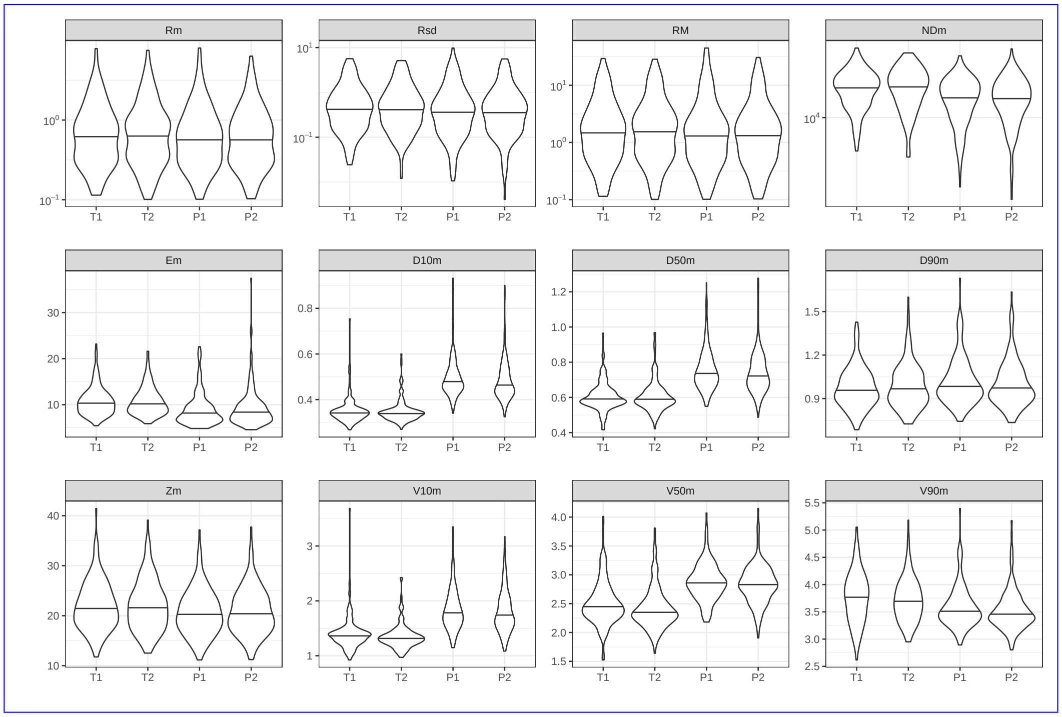

Figure 8: Violin plots for events ~~totals~~means and maxima. Refer to Table 2 for a list of acronyms of the variables.

Appendix A. ~~Additional figures~~Supplementary material

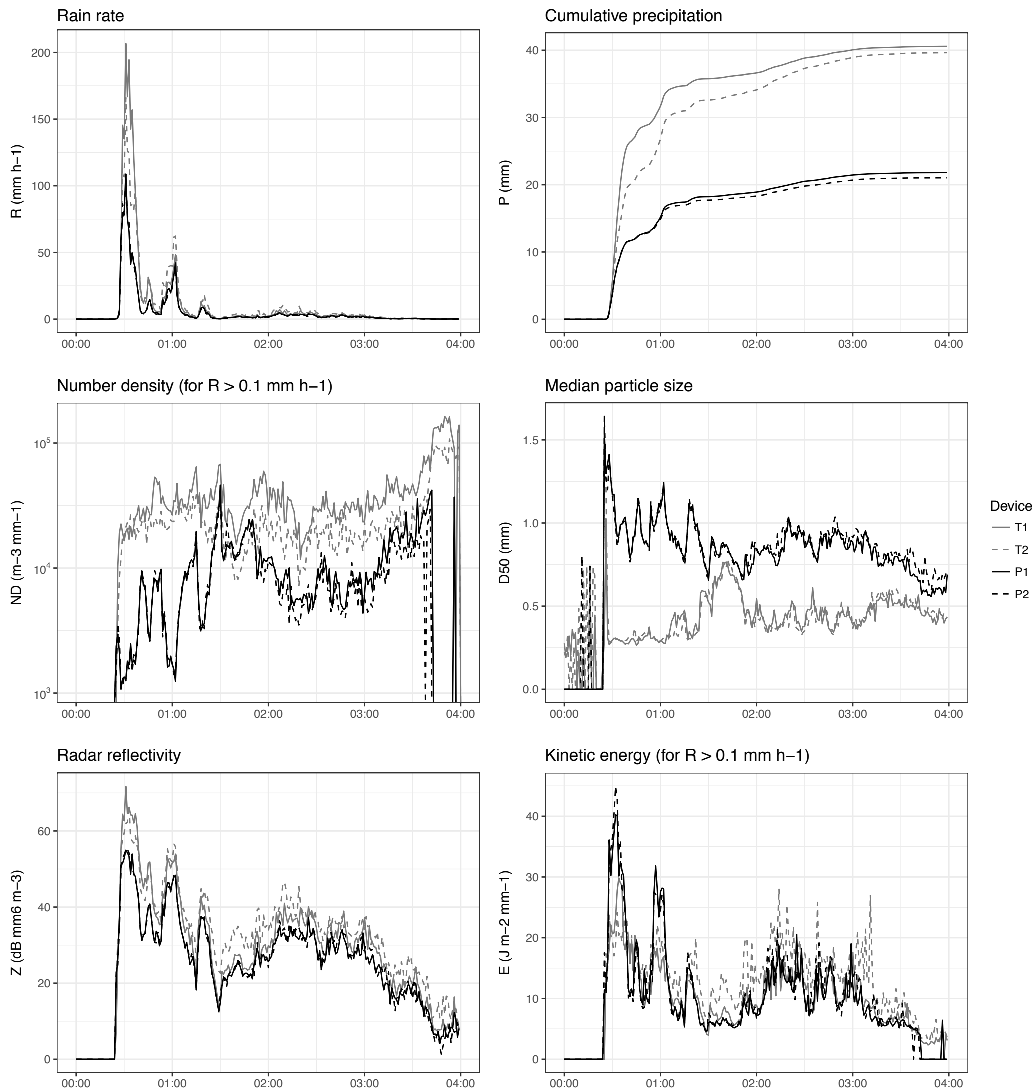

Figure A.1: ~~Kernel density plots for filtered one-minute records~~Time series of disdrometer bulk variables during a high-intensity event (E365), with no corrections of the PSVD data.

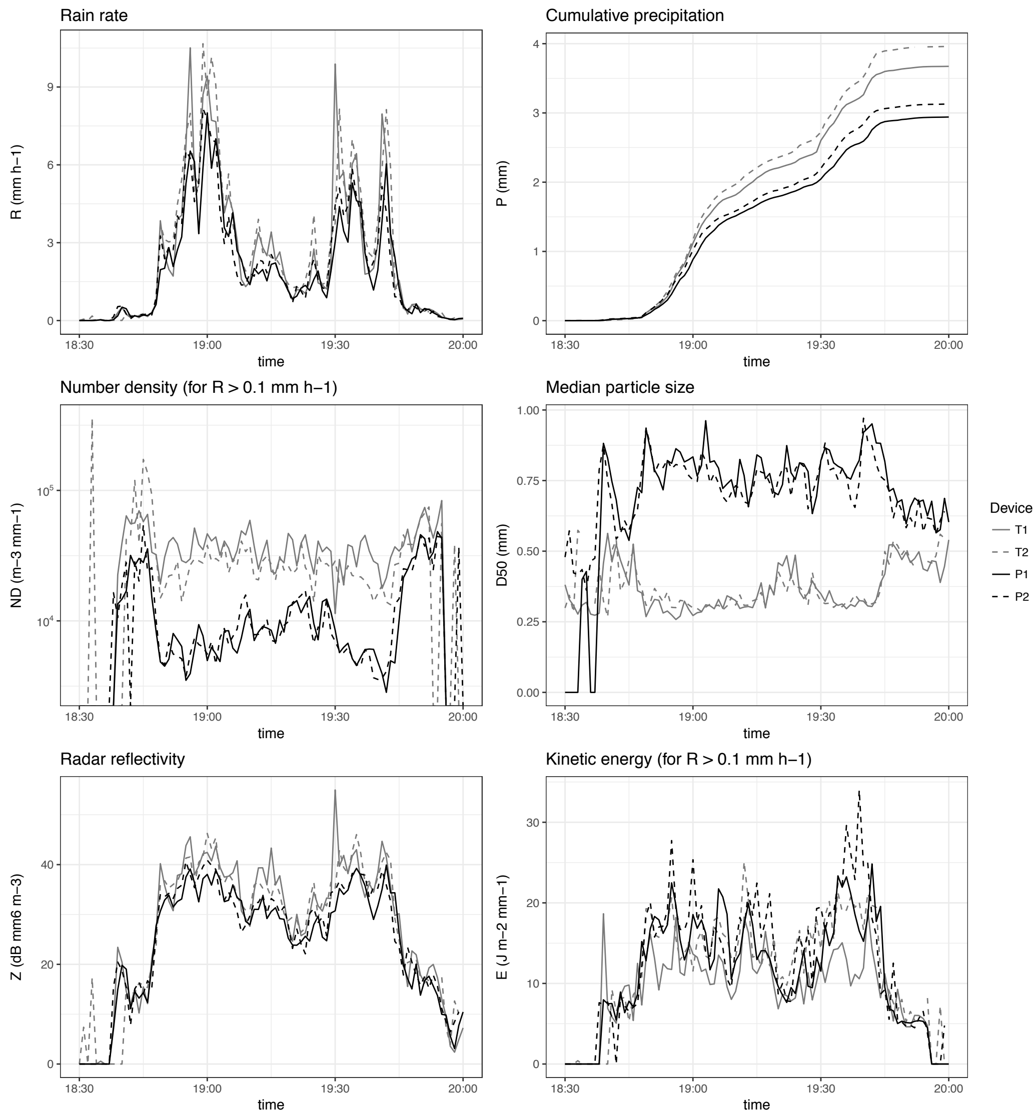

Figure A.2: ~~Kernel density plots for low rainfall intensities~~ Time series of disdrometer bulk variables during a low-intensity event (~~$0.1 < I < 2$ mm h^{-1}~~E455), with no corrections of the PSVD data.

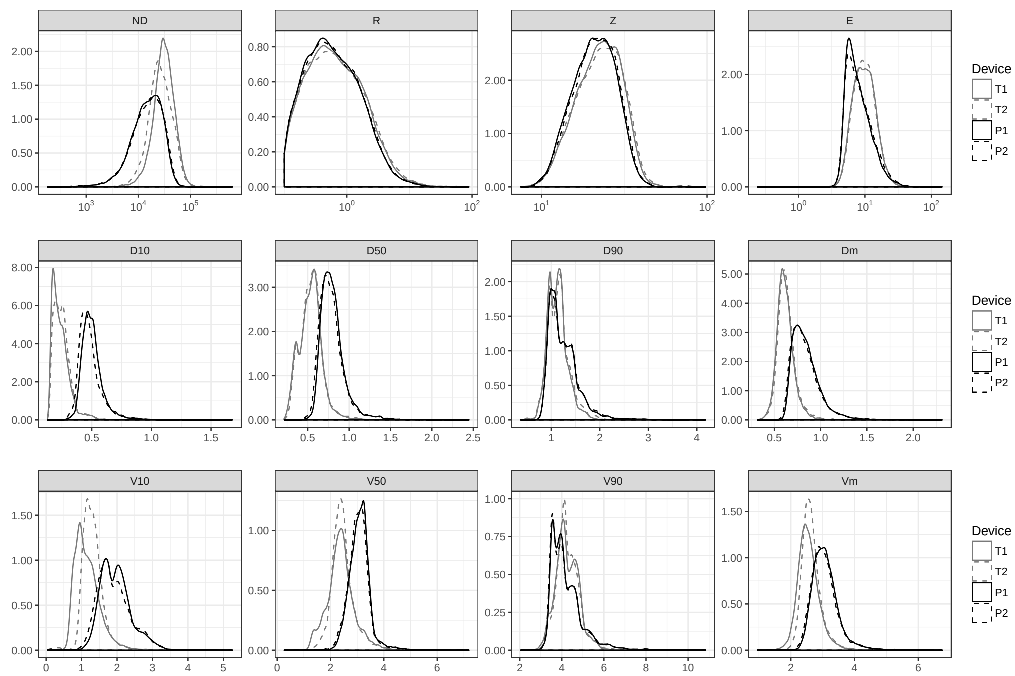

Figure A.3: Kernel density plots for ~~rainfall intensities (2<I<10 mm h^{-1})~~one-minute records, with no corrections of the PSVD data.

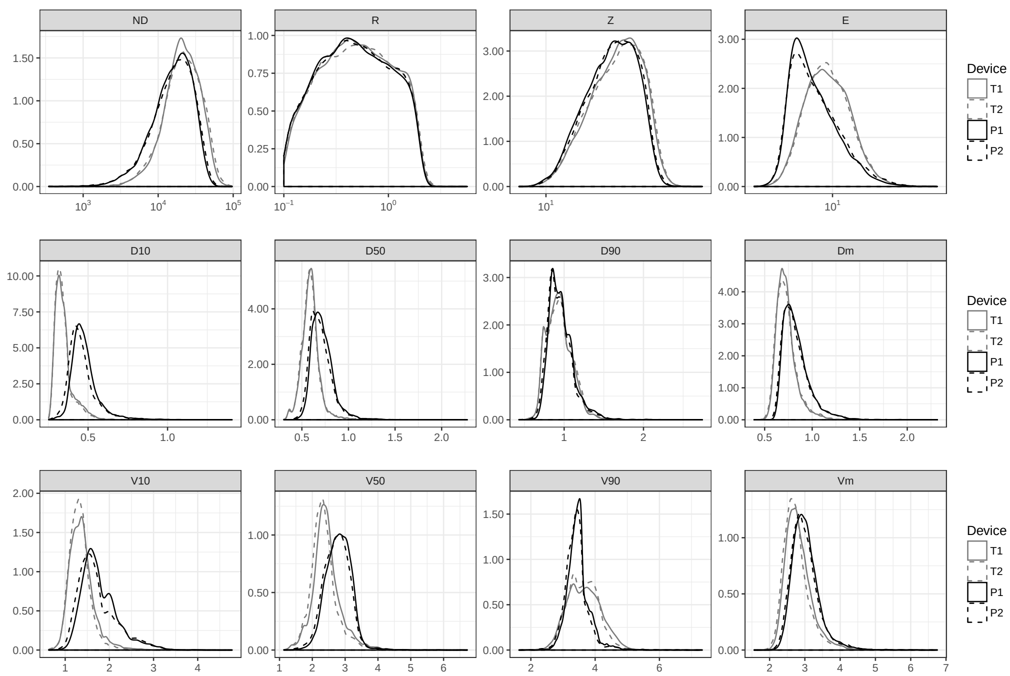

Figure A.4: Kernel density plots for low rainfall intensities (0.1<I~~>10~~ <2 mm h^{-1}).

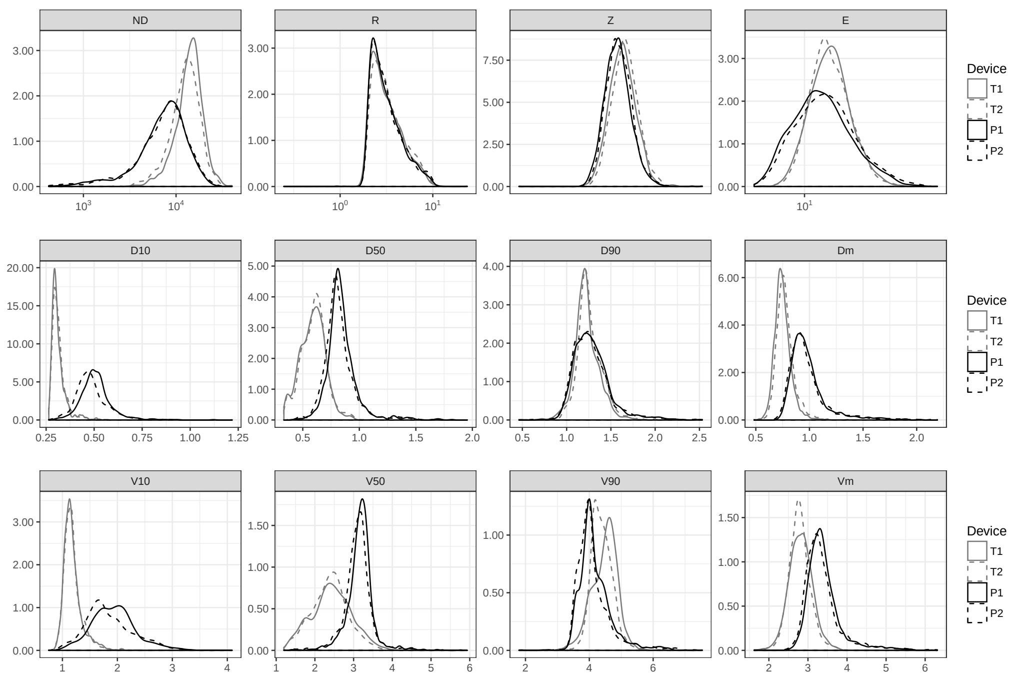

Figure A.5: ~~Filtered kernel~~ Kernel density plots for ~~low~~ medium rainfall intensities (~~0.1~~2<I<~~2~~ 10 mm h^{-1}).

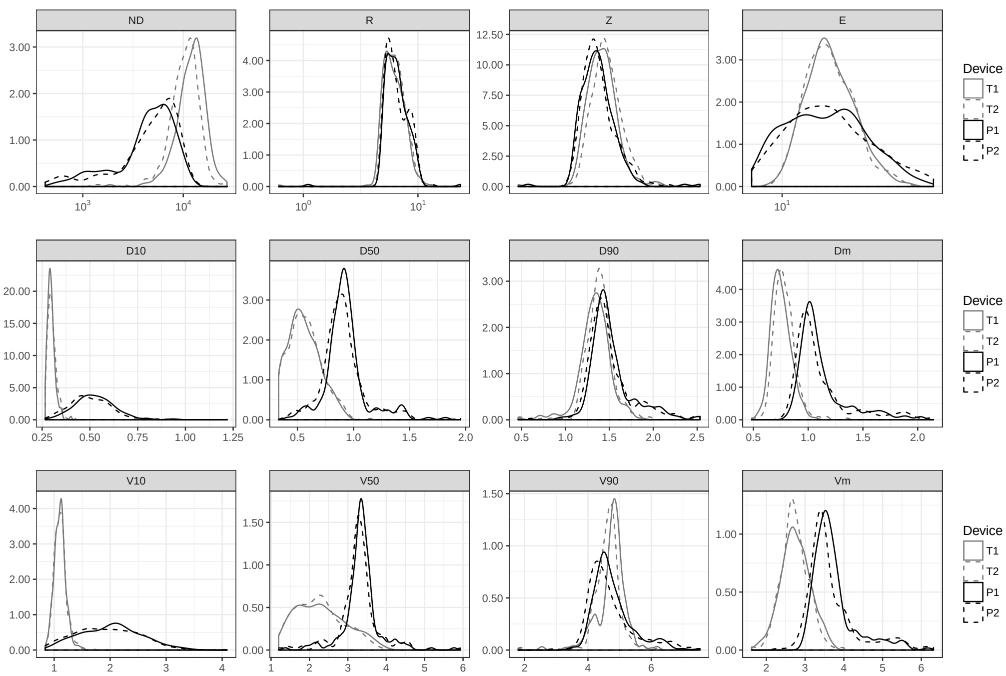

Figure A.6: ~~Filtered~~ Kernel density plots for high rainfall intensities (~~2<~~I~~<~~>10 mm h^{-1}).

Table A.1: Filtered density plots Gamma Generalized Linear Mixed-Effects Model coefficients for rainfall intensities one-minute records, with no corrections of the PSVD data (I>10 mm h^{-1}N = 1000).

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