Reviewer comment (RC) #1

General comments

The manuscript describe the performance of Thies Clima disdrometer with respect to OTT pluviometer and 2D video disdrometer in terms of precipitation detection, precipitation amount and intensity and classification between rain, snow and mix phase. Furthermore the manuscript describe two methodology to correct the Thies data and analyzed the effects of these methods on the precipitation intensity. The paper is well written and organized. Following there are some specific comments. I suggest the publication on AMT after addressing my comments.

Specific comments

1.1 Page 2. Lines 20-25: Several studies have been done to evaluate the performance of Thies Clima and some references related to this topic need to be added in the Introduction section. At that regard, following there are some suggestions

- Lanza et al. 2012 and Lanzinger et al. (2006) described the result of a a WMO experiment that showed a bias that range between 5% and 20% comparing rain gauge and Thies Clima disdrometer rainfall amount
- In Upton et al. (2008), Angulo-Martínez et al.(2017), and Adirosi et al. (2018), the Thies Clima perfromance has been evaluated with respect to Parsivel disdrometer.

Response: Thank you very much for this comment and for suggesting additional literature. Also in accordance with a short comment (SC), we have added the suggested literature and reformulated this part of the introduction (please also see corresponding SC).

Changes in the manuscript (section 1): However, there are only few studies which assess the uncertainties of the Thies disdrometer, mostly comparing the instrument to OTT Parsivel disdrometers (e.g., Adirosi et al., 2018; Angulo-Martínez et al., 2018; Guyot et al., 2019; Upton and Brawn, 2008) and in a few cases to rain gauges (e.g., Lanza and Vuerich, 2012; Lanzinger et al., 2006).

1.2 Section 2: Did the Authors applied any filtering method to eliminate the so called "spurious drops" due to win, splashing, or mismatch? Several studies that used disdrometer measured DSD applied a filter criterion based on fall velocity such as the one adopted in Tokay et al. 2001 and valid only for rain.

Response: Thank you very much for this comment. Indeed, this effect exists and several studies apply filter algorithms to remove spurious measurements of mostly larger particles from 2DVD or other video disdrometer measurements by applying a filter based on the combined velocity-diameter information (e.g., von Lerber et al., 2017; Raupach and Berne, 2015). However, as shown by Friedrich et al. (2013) such effects mostly occur at high wind speeds (exceeding 20 m/s) and as our study is extremely wind sheltered we did not see the need of applying such a filter in this study. This is described now in the revised manuscript.

Changes in the manuscript (section 2.1): Note that in some studies using 2DVD or other video disdrometer measurements, additional filters are applied to remove spurious measurements of mostly larger particles, usually being based on a validity check of the combined diameter and velocity information (e.g., Raupach and Berne, 2015; von Lerber et al., 2017). However, as investigated in detail by Friedrich et al. (2013) such spurious measurements mostly occur at wind speeds exceeding 20 m/s. As our study site is extremely wind sheltered (see also section 4) we thus did not apply such a filter in this study.

1.3 Section 2: Different classification methods are applied to Thies disdrometer and 2DVD data to distinguish between rain, snow and mixed phase. Is it possible to applied the proposed classification method to Thies data (of course applying the method to binned data instead of drop-by-drop data)? In this way the obtained results can be compared with the classification provided by the Thies software. If not, why do not apply a classification method that can be easily applied to 2DVD and Thies data? It can help to exclude the possible effect of the application of different classification methodologies on the obtained results

Response: Thank you very much for this comment and proposal of this additional analysis. It is indeed possible to apply the proposed classification method to the Thies data, given the limitation that only binned data instead of drop-by-drop data is available as you mention correctly.

As you proposed, we have applied the classification method to the binned Thies data, using the "centroid" (i.e. the mean velocity V and mean diameter D) of each V-D class to assign a precipitation type to all particles within the corresponding V-D class. The result is shown in Fig. 1 and 2 in analogy to Table 5 and Fig. 11 in the manuscript.

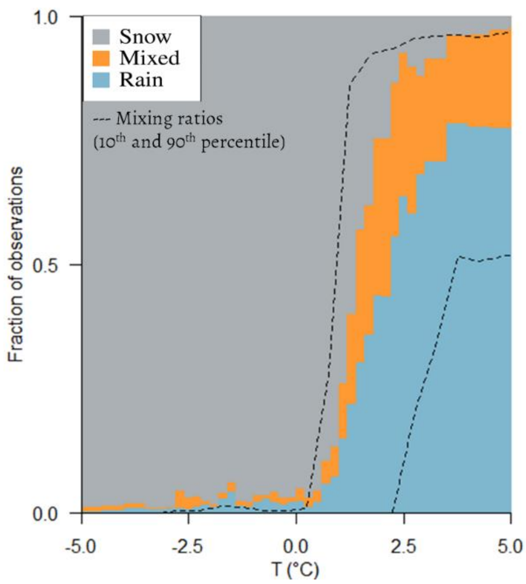

Figure 1: Relative frequency of the observed dominant precipitation phase by the classification algorithm applied to binned Thies disdrometer data as a function of air temperature during two years of measurements (2,533 h of precipitation). The mixing ratio of liquid precipitation obtained at different temperatures is indicated by the 10th and 90th percentile of its distribution (dashed lines).

	Rain	Mixed	Snow	Total
Rain	45.2	1.4	0.1	46.7
Mixed	6.8	2.6	0.8	10.1
Snow	0.6	0.3	42.3	43.2
Total	52.6	4.3	43.2	100.0
Hit rate (\\%)	86.0	60.2	98.0	NA
False alarm rate (\\%)	3.1	7.9	1.6	NA

Figure 2: Comparison of the precipitation phase detected by the Thies disdrometer (rows) and the two-dimensional video disdrometer (columns), applying the classification algorithm proposed in section 2.2 to both instruments. The numbers are given as percentages of the total number of 1 min observations during two years of measurements, which are equal to 2,533 h of precipitation.

As can be seen in Fig. 1 compared to Fig. 11 in the manuscript, the proposed classification method results in a very similar classification of snow when applied to binned Thies disdrometer data and 2DVD data, respectivly. The hit rate of the Thies disdrometer with respect to the 2DVD is even slightly higher than for the classification of the Thies software (98.0% compared to 95.3% in Table 5 of the manuscript). For liquid and mixed precipitation, higher differences exist: when applying the proposed classification method to the binned Thies data, more “mixed”precipitation is detected at temperatures > ~1°C than when applying the same classification to 2DVD data. The hit rate of the Thies disdrometer with respect to the 2DVD for liquid precipitation therefore also drops to 86% and at the same time the hit rate for mixed precipitation increases to 60.2% (as compared to 99.7% and 16.6% in Table 5 of the manuscript, i.e. when using the Thies classification software).

The most interesting result in our opinion is here that we find that the classification of liquid vs. “mixed” precipitation is very sensitive to the choice of the thresholds used for the assignment of “mixed” precipitation. In our opinion, the problem of consistently defining “mixed” precipitation already exists for human observations, but will be more pronounced when replacing human with automated observation. We also have included the following statement in the original manuscript: “In this context, we would like to point out that the agreement during mixed precipitation with any reference observation will depend on the mixing ratios, which are explicitly or implicitly considered as mixed.”

The additional analysis presented here indicates that any reasonable definition of mixing ratios considered as “mixed” precipitation will furthermore depend on the instrument used, which we state now also in the revised manuscript.

Changes in the manuscript (sections 2.2 and 4): 2.2: To investigate the effect of applying different classification methodologies on obtained results, the classification algorithm described above was also applied to Thies data. Given the binned data, the mean velocity and diameter of each V-D class were used for the classification rather than information about individual particles. 4: Our analysis indicates that the distinction between liquid and mixed precipitation is particularly sensitive to the choice of such a threshold. Furthermore, the application of the proposed classification algorithm to both disdrometers indicates that a reasonable choice of these thresholds might differ between different instruments.

1.4 Section 2: Is there a minimum values of precipitation amount that can be detected by OTT pluviometer? Such as the 0.2 mm for the tipping bucket gauge?

Response: Thank you for this comment. We added the sensitivity according to the manual of the OTT pluviometer as well as a description of insights from a study applying a minimum threshold for weak precipitation to this instrument in the description of the measurement devices (2.1). Regarding a careful interpretation of results, we have already covered this aspect in the manuscript in our opinion and refer to the corresponding response of reviewer #2 for further comments.

Changes in the manuscript (section 2.1): According to the operating instructions of the OTT pluviometer, the instrument provides the raw precipitation values every 6 seconds using a resolution of 0.001 mm. After the application of special filter algorithms (e.g. a correction for wind effects), non-real time 1-min outputs are available at a resolution of 0.01 mm. Of course, it can be questioned whether very weak precipitation can actually be measured so accurately. For example, Tiira et al. (2016) found in their mass retrieval (performed approximately every 5 minutes) that the output seems to fluctuate and used a threshold 0.2 mm/h for their analysis.

1.5 Page 6 last sentence: it is not clear to me. Please clarify.

Response: Thank you for this comment. The sentence was indeed not very clear. Also, it is rather an interpretation than a description of the result, so we moved this statement to the discussion (section 4) and try to explain the meaning/ interpretation of the false alarm rate in more detail there. This is also in accordance with a comment of reviewer # 2 (please check the corresponding comment for more details).

To understand our interpretation please consider the following:

- Given is a number of corresponding Thies and OTT pluviometer observations in terms of precipitation yes/ no.
- Using the OTT pluviometer as a reference, the false alarm rate of the Thies disdrometer is defined as:
  FAR = # false alarms / (# false alarms + # correct negatives),

  or in other words:
  FAR = # of cases where Thies = precip and OTT pluviometer = no precip / # of cases where OTT pluviometer = no precip.

  To make this even more intuitive, we can interpret the FAR as follows:
  Given a period without precipitation according to the reference instrument (OTT pluviometer), the FAR can be interpreted as the probability of the evaluated instrument (Thies disdrometer) nevertheless indicating precipitation during this period.
- Observed behaviour in Figure 4 (left): The FAR of the Thies disdrometer increases with increasing length of the observations considered, i.e.: given a very long ‘dry period’ (= no percip) in the reference instrument, the probability of the Thies disdrometer to indicate precipitation is higher than for a very short ‘dry period’.
- Interpretation: This behaviour can be expected when assuming that the Thies disdrometer is wrongly indicating precipitation at more or less regular time intervals. In this case, “the chance of misinterpreting a signal as precipitation is increasing with increasing integration time” as stated in the text. This could either be due to a regularly occurring misinterpretation of a signal/ disturbance as precipitation or indeed be related to very weak precipitation events which are not detected by the OTT pluviometer. This critical view on the reference instrument (OTT pluviometer) is also emphasized by reviewer # 2 and has led to some changes in the revised manuscript (please check the corresponding comment for more details).

Changes in the manuscript (sections 3.1 and 4): The statement was removed from the results (section 3.1). Instead, we added the following to the discussion (section 4): The false alarm rate, which indicates the probability of the Thies disdrometer detecting precipitation during a dry period, is increasing with increasing integration time. This can be somewhat expected, as the chance of misinterpreting a signal or disturbance as precipitation is increasing with increasing duration of this period. Furthermore, false alarm rates might be affected by the sensitivity of the reference instrument, but are comparable to findings of Bloemink. and Lanzinger (2005) who use human observations as a reference.

1.6 Page 7, first paragraph: which is the range of variability of the thresholds used to obtain the ROC diagram? The threshold are applied to both disdrometer and gauge data?

Response: Thank you for this comment. We used fixed thresholds TH_{ROC} in mm/h for all integration times with $TH_{ROC} = \{0, 0.001, 0.002, \ldots, 0.05, 0.1, 0.15, \ldots, 1, 1.2, 1.4, \ldots, 3\}$. The thresholds are only applied to the measurements of the Thies disdrometer, as the OTT pluviometer is used as a reference instrument representing the “ground truth”. This was indeed not clarified in the text and was added in the revised manuscript together with a more detailed description of the concept of ROC curves (see comment 2.6 of reviewer #2).

Changes in the manuscript (section 2.3): In the case of precipitation detection (yes/ no), we further investigate the effect of minimum precipitation thresholds applied to measurements of the Thies disdrometer on hit and false alarm rates by investigating the so-called Receiver Operating Characteristic (ROC) curves (e.g., Jolliffe and Stephenson, 2012). A ROC curve thereby depicts the variation of hit and false alarm rates with the variation of such a threshold. For example, using a threshold of 0 mm/h for precipitation detection (i.e. always reporting precipitation regardless of the measurement) will result in both a hit and a false alarm rate of 1. On the other hand, choosing an indefinitely high minimum precipitation threshold will result in both a hit and a false alarm rate of 0. Between these extremes, the resulting hit and false alarm rates depend on the capabilities of the Thies disdrometer to detect precipitation as compared to the reference instrument, while the theoretical optimum (hit rate of 1 and false alarm rate of 0) can usually not be achieved. To establish ROC curves for different integration times we use the fixed thresholds $TH_{ROC} = \{0, 0.001, 0.002, \ldots, 0.05, 0.1, 0.15, \ldots, 1, 1.2, 1.4, \ldots, 3\}$ in mm/h.

1.7 Figure 8 right and Table 3: How do the Authors compute the correction factor in these cases?

Response: Thank you for this comment. We follow the method proposed by Raupach and Berne (2015) simply using the ratio of drop concentrations per diameter class as correction factors. While Raupach and Berne (2015) use the median ratio over multiple time periods, we use the ratio of the summed drop concentration over the whole calibration period. The description can be found in section 2.3 (p. 6 line 10ff in the original manuscript) and was slightly extended in the revised manuscript.

Changes in the manuscript (section 2.3): The correction factors used for this scaling correspond to the ratio of summed 2DVD drop concentrations to summed Thies drop concentrations in the calibration period (2017-07-01--2018-06-30), and are separately calculated for rain and snowfall.

1.8 Page 9, third line: “This suggest…….intensities”. Looking at the results obtain for rainy minutes in terms of bias it seems that the adjustment to the OTT pluviometer is the one that reduces the bias while the other adjustment provides same or higher bias values. In all the other columns of Table 4 the differences between the uncorrected data, the data corrected with

OTT pluviometer and the data corrected with 2DVD are negligible! Please provide a more detailed comment on this

Response: Thank you very much for this valuable comment. This was also brought up by reviwer # 2 and we have indeed not interpreted Table 4 detailed enough. As you state correctly, the adjustment to the OTT pluviometer is able to reduce the bias for liquid precipitation also in the validation period whereas the adjustment to the 2DVD introduced a positive bias. With regard to snowfall, both correction methods have only a small impact and even slightly increase the bias. With regard to correlation, the linear adjustment has no effect by nature, while the adjustment to the 2DVD can slightly improve correlation with respect to snowfall.

Based on these observations, we would clearly recommend to use the proposed adjustment to the OTT pluviometer for correcting the estimation of liquid precipitation intensities and state this in the revised manuscript. If interested in the drop spectra the adjustment to the 2DVD could nevertheless be of interest. Also, the analysis of the PSD is seen as valuable in this study to investigate possible reasons of the biases in precipitation intensity estimates, which we state in the conclusions (section 4).

Changes in the manuscript: (please see answer to corresponding comment of reviewer # 2 for more information on changes in sections 3.2 and 4 in the revised manuscript.)

Minor comments

1.10 Figure 3: please move the legend. In this position it covers the data

Response: Thank you for this comment. We have moved the legend accordingly in the revised manuscript.

Changes in the manuscript (Figure 3): The legend is plotted outside the plot window.

1.11 Figure 6: Check x-label

Response: Thank you very much for this comment and observation. We changed the x-label so that the full date (2019-07-01) is displayed in the revised manuscript.

Changes in the manuscript (Figure 6): Change in x-label so that the full date (2019-07-01) is displayed

References

Adirosi, E., Roberto, N., Montopoli, M., Gorgucci, E., & Baldini, L. (2018). Influence of disdrometer type on weather radar algorithms from measured DSD: Application to Italian climatology. Atmosphere, 9(9), 360.

Angulo-Martínez, M.; Beguería, S.; Latorre, B.; Fernández-Raga, M. Comparison of precipitation measurements by Ott Parsivel2 and Thies LPM optical disdrometers. Hydrol. Earth Syst. Sci. Discuss. 2017.

Lanza, L.G.; Vuerich, E. Non-parametric analysis of one-minute rain intensity measurements from the WMO Field Intercomparison. Atmos. Res. 2012, 103, 52–59.

Lanzinger, E.; Theel, M.; Windolph, H. Rainfall amount and intensity measured by the Thies laser precipitation monitor. In Proceedings of the WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO), Geneva, Switzerland, 4–6 December 2006

Tokay, A., Kruger, A., & Krajewski, W. F. (2001). Comparison of drop size distribution measurements by impact and optical disdrometers. Journal of Applied Meteorology, 40(11), 2083-2097.

Upton, G.; Brawn, D. An investigation of factors affecting the accuracy of thies disdrometers. In Proceedings of the Technical Conference on Instruments and Methods of Observation (TECO-2008), St. Petersburg, Russia, 27–28 November 2008.

Reviewer comment (RC) #2

General comments

The manuscript describes the capabilities of Thies disdrometer in both quantifying the amount and identifying the type of precipitation. To this end, OTT pluviometer and 2DVD are used as reference, respectively. The results show an underestimation of the precipitation amount, while a good capabilities in identifying the precipitation type. The analysis about the precipitation detection in terms of categorical scores (i.e. hits, false alarm, miss, etc.) has to be improved since it is not too clear and a number of questions arise: in particular, the analysis about ROC and the use or not of a minimum precipitation threshold. On the other hand, the comparison with 2DVD is clearer and useful.

The paper is useful since it shows how much reliable is the Thies disdrometer in measuring the precipitation, but before to be accepted for publication the authors have to address the following comments.

Specific comments

2.1 Figure 2 has to be improved. The size of 2DVD picture may be reduced.

Response: Thank you for this comment. I reduced the size of the compound image to 0.7 of its original width and also tried to visually separate the two subfigures. I am not sure in what other way I should improve the figure in your opinion. Please bring this up again if you had other changes in mind.

Changes in manuscript (Figure 2): Figure reduced to 0.7 of its original width.

2.2 Page 3, line 27: please, modify the sentence because the 2DVD is not based on a similar principle than Thies.

Response: Thank you for this comment. We removed this statement in the corresponding sentence of the revised manuscript.

Changes in the manuscript (section 2.1): The 2DVD, developed by Joanneum research, [statement removed] is able to derive more direct and more detailed information about individual hydrometeors than the Thies disdrometer.

2.3 Page 4, lines 29-30: it is not clear if the Eq. 1-5 are applied in the Thies precipitation classification algorithm or if different relationship are applied. Please, clarify this.

Response: Thank you very much for this comment, this was indeed not stated clearly enough. Unfortunately, the exact empirical relations used in the Thies precipitation classification algorithm (except Gunn and Kinzer, 1949) are not reported by the manufacturer. We were also not able to get more insight into other details of their algorithm. We made this now more explicit in both the description of the Thies distrometer (2.1) as well as in the description of the classification algorithm used to process the 2DVD data (2.2). Following a suggestion of reviewer #1 on this topic, we also applied our classification method to the raw data of the Thies disdrometer and mention implications of this analysis in the discussion of the revised manuscript (please see corresponding comment of reviewer #1).

Changes in the manuscript (sections 2.1 and 2.2): 2.1: The exact functioning of this classification algorithm as well as other equations used are thereby not reported by the manufacturer. 2.2: To investigate the effect of applying different classification methodologies on obtained results, the classification algorithm described above was also applied to Thies data. Given the binned data, the mean velocity and diameter of each V-D class were used for the classification rather than information about individual particles.

2.4 Page 6, lines 16-20: in my opinion, the correlation coefficient is not one of the best indicators for this type of analysis (the Table 4 confirm this, showing high CC values before and after the Thies correction). Figure 7 shows that the data are distributed along a straight line, but this is not close to the one-to-one line (as should be). A more indicative indicator to associate to the bias could be the root mean square error.

Response: Thank you very much for this comment. The advantage of the CC compared to many other metrics (including the RMSE) is that it is independent of any bias, i.e. reflects the scatter between the two observations independent of any systematic deviations. Our original intention was to provide the CC as a metric of how this scatter can be reduced by an adjustment of the Thies PSD to the 2DVD. However, as you point out correctly, the CC only changes very little before and after the adjustment to the 2DVD, i.e. the correction is mainly affecting the bias. Also, in case of the linear adjustment to the OTT pluviometer, the CC remains by nature unaffected. As the paper is actually focusing on biases and the added value of including the CC is limited, we agreed to remove the CC from Table 4 and we agree that this helps to keep the paper more focused. However, we still mention in the text that a slight improvement of the CC can be achieved with respect to snowfall intensities when using the adjustment to the 2DVD.

Regarding the characterisation of the bias, we would however like to stick to the used metric of the absolute bias for the following reasons. The advantage of this metric is that it is unaffected by the scatter and furthermore can be easily interpreted by the reader. The RMSE, on the other hand, can increase with both increasing bias or increasing scatter, and is a more complex measure probably less intuitive for the reader to interpret.

Changes in the manuscript (Table 4, sections 2.3, 3.2 and 4, Equation 7): The correlation coefficient in Table 4 and related descriptions in section 3.2 are removed. Also, the description of the methodology in section 2.3 is shortened and equation 7 is removed. Note that we keep the statement related to the improvement of snowfall intensity estimates in the discussion (please see 3rd paragraph of section 4 in revised manuscript).

2.5 Page 6, lines 27-28: what does it mean "…with respect to precipitation detection…"? Is it a minimum precipitation threshold or what? And, is it referred to the OTT pluviometer or to the Thies? It is almost impossible to understand by reading the text.

Response: Thank you for this comment. It means that we have investigated the capability of the Thies disdrometer to distinguish precipitation from no precipitation (binary variable). The hit and false alarm rates are given for the Thies disdrometer as stated in this sentence. The OTT pluviometer is used as a reference (i.e. representing the 'ground truth'), which is stated multiple times in the manuscript, e.g. in the first sentence of 3.1, page 6, line 23. The hit and false alarm rates described in this sentence refer to the comparison without introducing thresholds. The effect of applying minimum precipitation thresholds is described in the following paragraph (page 7, lines 1ff.). I have tried to reformulate the sentence in the manuscript.

Changes in the manuscript (section 3.1): The capability of the Thies disdrometer to distinguish precipitation from no precipitation is described in terms of its hit and false alarm rate when using the OTT pluviometer as a reference. In a first step, hit and false alarm rates are calculated over the whole time series and are indicated with circles in Fig. 4 (left) for different integration times. […] In a second step, we tested the application of minimum precipitation thresholds to the Thies disdrometer observations in order to reduce false alarm rates for longer integration times.

2.6 Page 7, lines 1-3: by looking at Figure 4, the combination of hits and false alarm can exceed or not 100%. Obviously, when the sum is lower than 100% it is because of miss and/or correct negative, but what about when the sum exceed 100? Is it always because they are calculated with respect to precipitation detection? This reviewer (and this could be true for a reader) is not familiar with ROC, but the text should allow to understand the methodology.

Response: Thank you for this comment. You are right that we have not explained the concept of a ROC curve sufficiently in the original manuscript and we added a more detailed description in the revised manuscript, also following a more technical comment (1.6) of reviwer #1. Regarding the concept of hit and false alarm rates, we would like to keep the reference to Jolliffe and Stephenson (2012) as we think with the given example a reader will get the correct understanding of these concepts.

To clarify your specific question: yes, the sum of hit and false alarm rate can exceed 1, as they both can take values from 0 to 1 independent from each other. Considering the following example: an overly sensitive measurement device which always reports precipitation will achieve a hit every time there is actually precipitation and no misses. The hit rate = hits/(hits+misses) will be 1. However, the same instrument will always produce a false alarm every time there is actually no precipitation and no correct negatives. The false alarm rate = false alarms/(false alarms+correct negatives) will also be 1. Thus, the sum of hit rate and false alarm rate will be 2. When imagining the opposite, i.e. a totally insensitive instrument which never reports precipitation, it will be clear that both the hit rate and the false alarm rate will be 0. In reality, the combination lies somewhere between these extremes, depending on the capabilities of the instrument, and can be further changed (ex-post) by introducing a minimum precipitation threshold for the instrument. The theoretical optimum (hit rate of 1 and false alarm rate of 0), however, can usually not be achieved.

Changes in the manuscript (section 2.3): For the evaluation of categorical variables, i.e. precipitation detection (yes/ no) and precipitation phase (rain/ mixed/ snow), hit and false alarm rates with respect to the reference instrument are calculated according to Jolliffe and Stephenson (2012). In the case of precipitation detection (yes/ no), we further investigate the effect of minimum precipitation thresholds applied to measurements of the Thies disdrometer on hit and false alarm rates by investigating the so-called Receiver Operating Characteristic (ROC) curves (e.g., Jolliffe and Stephenson, 2012). A ROC curve thereby depicts the variation of hit and false alarm rates with the variation of such a threshold. For example, using a threshold of 0 mm/h for precipitation detection (i.e. always reporting precipitation regardless of the measurement) will result in both a hit and a false alarm rate of 1. On the other hand, choosing an indefinitely high minimum precipitation threshold will result in both a hit and a false alarm rate of 0. Between these extremes, the resulting hit and false alarm rates depend on the capabilities of the Thies disdrometer to detect precipitation as compared to the reference instrument, while the theoretical optimum (hit rate of 1 and false alarm rate of 0) can usually not be achieved. To establish ROC curves for different integration times we use the fixed thresholds $TH_{ROC} = \{0, 0.001, 0.002, …, 0.05, 0.1, 0.15, …, 1, 1.2, 1.4, …, 3\}$ in mm/h.

2.7 Page 7, lines 8-9: I am always skeptic when an instrument like a disdrometer or pluviometer is considered to be able to detected so weak precipitation.

Response: Thank you very much for this comment. Of course, we are also sceptic towards the capability of these instruments to detect so weak precipitation – although according to the user manuals, the OTT pluviometer can detect precipitation > 0.01 mm and the Thies disdrometer even provides minimal intensities of 0.001 mm/h for drizzle.

With the analysis provided in the manuscript we are nevertheless able to show that the two instruments agree quite well with respect to precipitation detection. Also, we can show that – when using the OTT pluviometer as a reference – an even better agreement is achieved with the introduction of minimum precipitation thresholds for the Thies disdrometer. Given the difficulties of measuring so weak precipitation, we agree, however, that it is difficult to determine the real 'ground truth' or to make absolute statements about the capabilities of each instrument with respect to this 'ground truth'. That is also the reason, why we state in the discussion that "false alarm rates might be affected by the sensitivity of the reference instrument, but are [at least] comparable to findings of Bloemink and Lanzinger (2005) who use human observations as a reference".

Note that also reviewer # 1 asked to include more information about minimum precipitation amounts detected by the OTT pluviometer, which we included in the revised manuscript.

Changes in the manuscript: (See corresponding comment of reviewer # 1 for more information about minimum precipitation amounts detected by the OTT pluviometer.)

2.8 Figure 5: a logarithmic scale on the y-axis could be better.

Response: Thank you for this comment. Indeed, boxplot ranges for low precipitation intensities can be better read when using a logarithmic scale on the y-axis. We changed the two subfigures accordingly and added a hint to the logarithmic scale in the figure caption.

Changes in the manuscript (Figure 5): A logarithmic scale is used on the y-axis and the following hint is added to the figure caption. “Note that a logarithmic scale is used to display precipitation intensities.”

2.9 Page 8, line 8: or “…described above. Whereas…” or “…described above: whereas…”

Response: Thank you for this comment. We changed the manuscript according to the second suggestion above.

Changes in the manuscript (section 3.2): “…described above: whereas…”

2.10 Page 8, line 11: the mean ratio of what?

Response: Thank you for this comment. We were using the terminology of Raupach and Berne (2015) here, apparently without explicitly stating it. The mean ratio is defined as the reference mean divided by the observed mean, while the ‘mean’ refers to the mean over a certain number of time steps. Alternatively, this can be expressed as the ratio of the reference to the observed precipitation sum in the calibration period, which is probably somewhat easier to understand for the reader and has been changed accordingly in the revised manuscript.

Changes in the manuscript (section 3.2): We thus propose to use the ratio of the OTT pluviometer to the Thies disdrometer precipitation sum as a correction factor and to distinguish between rain and snowfall. Using the first year of measurements, the resulting correction factors for rain and snowfall intensities are 1.20 and 0.96, respectively.

2.11 Page 8, lines 15-16: the PSD shown in Figure 8 are obtained by averaging all the 1-minute PSDs collected during the two years?

Response: Figure 8 actually shows the distribution of the summed (not averaged) 1-min PSDs over two years, which is explained in the figure caption as follows: “Comparison of particle size distribution (PSD) obtained by the Thies disdrometer and the two-dimensional video disdrometer (2DVD) during the whole time series (two years). Left: Summed PSD during all observed rain and snowfall events. The separation into rain and snowfall events is based on the recorded dominant precipitation type by the Thies disdrometer (1 min).” To make this more explicit also in the text, we revised the corresponding sentence in the text of the revised manuscript.

Changes in the manuscript: A comparison of the summed PSD between these two instruments is shown in Fig. 8 for all rain and snowfall events during the whole time series (two years). The separation into rain and snowfall events is based on the recorded dominant precipitation type by the Thies disdrometer (1 min).

2.12 Page 8, lines 34-35: I basically agree that the impact of both correction methods are comparable, but the “2DVD correction” gives higher bias than “OTT pluviometer correction”. This could indicate a slight overestimation of the precipitation by 2DVD if compared to the OTT pluviometer.

Response: Thank you very much for this valuable comment. A similar comment was also made by reviewer #1, and we have indeed not interpreted Table 4 detailed enough. It seems indeed that for liquid precipitation, the adjustment to the 2DVD introduces a positive bias of roughly the same magnitude as the negative bias without adjustment in the validation period. As stated in your comment, this could indicate a slight overestimation of liquid precipitation by the 2DVD when compared to the OTT pluviometer. Therefore, we would clearly recommend to apply the more robust adjustment to the OTT pluviometer. We adjusted the description of Table 4 in the result (section 3.2) as well as the discussion (section 4) accordingly.

Changes in the manuscript (sections 3.2 and 4): 3.2: As can be seen in Table 4 and Fig. 10, the most robust result is achieved by the adjustment of rainfall intensities to the OTT pluviometer, which successfully reduces the underestimation of liquid precipitation in the validation period. The adjustment of rainfall intensities to the 2DVD, however, results in a positive bias in the validation period. For snowfall, both correction methods have a smaller impact and even result even in slightly higher negative biases than are present without any adjustment. 4: To reduce the underestimation of rainfall intensities by the Thies disdrometer, we established an adjustment to 2DVD measurements following the methodology of Raupach and Berne (2015). However, when applying the resulting adjustment in the validation period, we introduce a positive bias, which could indicate a slight overestimation of liquid precipitation by the 2DVD when compared to the OTT pluviometer. A more stable correction is achieved by applying a linear adjustment to the OTT pluviometer. This method is thus proposed as the preferred correction method in this study, especially when the PSD itself is not of interest to the user.

2.13 Page 9, lines 13-14: the sample size information should not be reported here but at the beginning of Section 2.3.

Response: Thank you for this comment. We have moved the corresponding sentence from section 3.3 to 2.3 where the comparison between the two disdrometers with respect to precipitation type detection is described.

Changes in the manuscript (sections 3.3 and 2.3): The following sentence is moved from section 3.3 to 2.3: "Furthermore, we only consider pairwise complete (1 min) observations of both instruments with either rain, snow or mixed precipitation, resulting in a time series of 2,533 h of precipitation."

2.14 Page 10, lines 18-21: to state that the correction method proposed by you and the one proposed in Raupach and Berne (2015) are consistent you should apply their method to your data (only because Thies and OTT Parsivel are based on the principle).

Response: Thank you for this comment. I am not sure if I understand your comment fully, but would like to provide some clarifications before I come to the changes made in the revised manuscript. The application of the exact same correction method as proposed by Raupach and Berne (2015) to our data is not really possible, as they establish their correction to Parsivel disdrometers (generations 1 and 2) and we are evaluating the Thies disdrometer. However, as Raupach and Berne (2015) highlight in their article, the "the correction can be trained on and applied to data from […] any disdrometer in general." So rather than applying their method, we adopt their methodology. This distinction was made more clearly in the revised manuscript.

Furthermore, in the original sentence, we only state that our result is consistent with the result in Raupach and Berne (2015) in so far as the correlation coefficient is only slightly affected by their correction of the Parsivel as well as our correction of the Thies disdrometer. However, as you have expressed yourself critically towards the use of the correlation coefficient in an earlier comment, we have removed this statement from the revised manuscript.

Changes in the manuscript (section 4): (Please see response to earlier comments for corresponding changes in the revised manuscript.)

2.15 Conclusions: the first part pf the Conclusions (i.e. page 11, lines 21-32) is a summary of Section 4. I suggest merging the two sections in only one that could be titled "Discussion and Colclusions".

Response: Thank you for this comment. You are right and we merged the two sections as proposed. We thereby removed lines 21-32, keeping only one statement of it to the new, merged section (see below).

Changes in the manuscript (sections 1 and 4): the Following statement was kept from lines 21-32: "hit rates reaching 99.7% for rainfall and 95% for snowfall using the 2DVD as a reference", the rest was removed. Furthermore, the description of the structure of the paper in the Introduction was changed accordingly: "In section 4, results are discussed and conclusions are drawn with respect to the operational monitoring of precipitation with the Thies disdrometer as well as potential applications in a hydrological context."

Short comment (SC) #1

General comments

Thanks for making your work open to comments. I might be able provide a couple of useful comments hereby, having worked with Thies LPM Clima instruments recently.
I find your paper very well written and organised, and easy to follow. A couple of comments below are listed as dot points in no particular order of importance:

Thanks for making it possible to read and comment on your work, I enjoyed the reading.
With kind regards, Adrien Guyot Monash University, Australia

Specific comments

3.1 I find that your introduction might benefit from adding further explanations, in particular when it comes to the use of laser disdrometers outside of precipitation amounts measurements; e.g. gathering of DSD for parameterisation of models and retrievals. Typically line 20, you mention the "verification of dual-pol radars" but it is not reduced to this, and you could possibly mention all the different usage of the DSD (not only for the Thies) but for disdrometers in general.

Response: You are right. We amended further usages.

Changes in the manuscript (section 1): Beside the calibration and verification of rainfall estimation by radar and satellite, disdrometers are also used for a proper understanding of hydrometeorological regimes and soil erosion, pollution wash off in urban environments or interactions of rainfall with crop and forest canopies (Angulo-Martinez, 2018; Frasson and Krajewski, 2011; Nanko et al., 2004; Nanko et al., 2013).

3.2 Lines 21 and 22: "not many studies have assessed uncertainties of disdrometers" – this is not really correct, and quite perilous to state this without including a succinct literature review. There are plenty of studies assessing uncertainties of disdrometers (usually by comparing disdrometers of different make-up / manufacturers / principles, or/and co-located instruments), but they often investigate the OTT Parsivels (both versions) and 2DVD in their majority. For the Thies in particular, you could mention here Angulo-Martinez et al. (2018) and Guyot et al. (2019), both published in the companion EGU-journal HESS.

Angulo-Martínez, M., Beguería, S., Latorre, B., & Fernández-Raga, M.: Comparison of precipitation measurements by OTT Parsivel 2 and Thies LPM optical disdrometers. Hydrology and Earth System Sciences, 22(5), 2811, https://doi.org/10.5194/hess-22-2811-2018, 2018.

Guyot, A., Pudashine, J., Protat, A., Uijlenhoet, R., Pauwels, V. R. N., Seed, A., and Walker, J. P.: Effect of disdrometer type on rain drop size distribution characterisation: a new dataset for south-eastern Australia, Hydrol. Earth Syst. Sci., 23, 4737–4761, https://doi.org/10.5194/hess-23-4737-2019, 2019.

In these two studies, measurements of rainfall are evaluated using respectively OTT Parsivel1 and 2 and Thies LPM. This could serve as well for your discussion, in particular when it comes to the uncertainties and systematic under-estimation of rainfall by Thies instruments. We find in Guyot et al. (2019) that Thies underestimated liquid precipitation when compared to the OTT Parsivels (1 and 2).

Response: Thank you, you are right. We changed the sentence mentioning that there are only few studies mentioning the uncertainties of the Thies distrometer, including also literature suggested by reviewer #1 (please see corresponding comment). Also, we included a sentence in the discussion mentioning Guyot et al. (2019).

Changes in the manuscript (sections 1 and 4): We changed the sentence in the introduction: However, there are only few studies which assess the uncertainties of the Thies disdrometer, mostly comparing the instrument to OTT Parsivel disdrometers (e.g., Adirosi et al., 2018; Angulo-Martínez et al., 2018; Guyot et al., 2019; Upton and Brawn, 2008) and in a few cases to rain gauges (e.g., Lanza and Vuerich, 2012; Lanzinger et al., 2006). In the discussion we added: Finally, when compared the OTT Parsivels, Guyot et al. (2019) found that the Thies disdrometer […] underestimates liquid precipitation compared to both Parsivel^1 and Parsivel^2.

3.3 Line 28 to 30. I believe these findings have been revisited in Thurai et al. (2016) and later Thurai and Bringi (2018), Raupach et al. (2019)? The 2DVD seems to underestimate droplets in the lower range of diameters (< 0.5 mm), meaning that their use as reference can be questionable in some circumstances in particular over that range. Overall, it would be great to mention that there is no perfect reference that one can use, and each instrument will be affected by uncertainties. For the 2DVD, it would be great to mention that the literature is evolving and previous findings might not hold anymore or only partially.

Thurai, M. and Bringi, V. N.: Application of the generalized gamma model to represent the full rain drop size distribution spectra, J. Appl. Meteorol. Clim., 57, 1197–1210, https://doi.org/10.1175/jamc-d-17-0235.1, 2018.

Thurai, M., Gatlin, P., Bringi, V. N., Petersen, W., Kennedy, P., Notaroš, B., & Carey, L. (2017). Toward completing the raindrop size spectrum: Case studies involving 2Dvideo disdrometer, droplet spectrometer, and polarimetric radar measurements. Journal of Applied Meteorology and Climatology, 56(4), 877-896.

Raupach, T. H., Thurai, M., Bringi, V. N., & Berne, A. (2019). Reconstructing the drizzle mode of the raindrop size distribution using double-moment normalization. Journal of Applied Meteorology and Climatology, 58(1), 145-164.

Response: We think at the end we have to have some reference, but we added that the 2DVD seems to underestimate small particles

Changes in the manuscript (section 1): We added the following to the introduction: "…,even if the 2DVD seems to underestimate droplets in the lower range of diameters, i.e. below 0.5 mm (Raupach et al., 2019; Thurai et al., 2017; Thurai and Bringi , 2018).

3.4 In your manuscript, it would be great to differentiate the two types of Parsivel (1 and 2) using a superscript, as in the second version; the manufacturer has corrected some issues in particular in the lower range of diameters.

Response: Thank you for this comment, we have tried to better make this distinction when referring explicitly to one of these instruments

Changes in the manuscript (section 4): In addition to other comments added during this revision, this was changed in the following sentence of the manuscript: "For example, the OTT Parsivel^1 disdrometer only underestimates drops with sizes ranging between 0.8 and 1.6 mm and only during periods of higher rainfall intensity."

3.5 In terms of rainfall, we have found in Guyot et al. (2019) that the Thies starts to underestimate the number of droplets from 0.75 mm onwards towards larger diameters (instead of 0.5 mm as mentioned in your paper) when compared to Parsivel1. Since we do not use the same reference (in your case 2DVD), this might explain the difference but again here I think it is good to keep in mind that 2DVD is not an absolute reference and has been questioned for his accuracy in the recent literature.

Response: Thank you for this hint, as you are mentioning we are using the 2dvd as a reference. As Raupach and Berne (2015) are writing: If a better reference becomes available, exactly the same approach could be applied to correct the Parsivel (or indeed any other disdrometer) and to improve the agreement with the reference.

Changes in the manuscript (section 4): Guyot et al. (2019) found that the Thies disdrometer starts to underestimate the number of droplets from 0.75 mm onwards towards larger diameters when compared to Parsivel[1]…

3.6 Data availability: It adds a great value to the work to make the data accessible openly on a repository (and possibly the code as well, mentioning libraries having been used if any to give credits to the authors). One of the strengths of open-access articles is also to promote that accessibility of data and code so that work can be re-produced, and data shared easily.

Response: Thank you for this comment. We now published the following data on Zenodo (doi: 10.5281/zenodo.3895297):

- Thies disdrometer measurement outputs: daily .csv files.
- OTT pluviometer measurement outputs: daily .csv files.
- 2DVD measurement outputs: daily .sno files (containing the information of successfully matched hydrometeors) provided in ASCII format.
- Metadata, i.e. user manuals and specifications for these 3 measurement instruments.

We have only used standard libraries (in the R software environment) for the processing of the data. Regarding the classification algorithm applied to 2DVD measurements, we were in close exchange with Joanneum Research and partly used empirical relationships derived by them, which we mention in the methodology section (2.2) as well as in the acknowledgements.

Changes in the manuscript (data availability section): The data used in this study, i.e. measurement outputs of the Thies disdrometer, the OTT pluviometer as well as the two-dimensional video disdrometer (2017-07-01–2019-06-30), can be found in Fehlmann et al. (2020).

Automated precipitation monitoring with the Thies disdrometer: Biases and ways for improvement

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Abstract. The intensity and phase of precipitation at the ground surface can have important implications for meteorological and hydrological situations, but also in terms of hazards and risks. In the field, Thies disdrometers are sometimes used to monitor the quantity and nature of precipitation with high temporal resolution and very low maintenance and thus provide valuable information for the management of meteorological and hydrological risks. Here, we evaluate the Thies disdrometer with respect to precipitation detection as well as the estimation of precipitation intensity and phase at a pre-alpine site in Switzerland (1060 m a.s.l.), using a weighing precipitation gauge (OTT pluviometer) as well as a two-dimensional video disdrometer (2DVD) as a reference. We show that the Thies disdrometer is well suited to detect even light precipitation, reaching a hit rate of around 95%. However, the instrument tends to systematically underestimate rainfall intensities by 16.5%, which can be related to a systematic underestimation of the number of raindrops with diameters between 0.5 and 3.5 mm. During snowfall episodes, a similar underestimation is observed in the particle size distribution (PSD), which is, however, not reflected in intensity estimates, probably due to a compensation by snow density assumptions. To improve intensity estimates, we test PSD adjustments (to the 2DVD) as well as direct adjustments of the resulting intensity estimates (to the OTT pluviometer), ~~which are both able to~~ the latter of which being able to successfully reduce the systematic deviations during rainfall in the validation period. For snowfall, the combination of the 2DVD and the OTT pluviometer seems promising as it allows improvement of snow density estimates, which poses a challenge to all optical precipitation measurements. Finally, we show that the Thies disdrometer and the 2DVD agree well insofar as the distinction between rain and snowfall is concerned, such that an important prerequisite for the proposed correction methods is fulfilled. Uncertainties mainly persist during mixed phased precipitation or low precipitation intensities, where the assignment of precipitation phase is technically challenging, but less relevant for practical applications. We conclude that the Thies disdrometer is not only suitable to estimate precipitation intensity, but also to distinguish between rain and snowfall. The Thies disdrometer therefore seems promising for the improvement of precipitation monitoring and the nowcasting of discharge in pre-alpine areas, where considerable uncertainties with respect to these quantities are still posing a challenge to decision making.

Copyright statement.

1 Introduction

The intensity and type of precipitation falling on the ground surface (e.g. rain, snow, drizzle, or hail) often determines the absence or occurrence of subsequent processes. A detailed knowledge on the nature and intensity of precipitation is therefore decisive in terms of hazards and ensuing risks. For example, for the management of traffic roads, it is important to know whether falling snow or mist will likely hamper road conditions or visibility (Toivonen and Kantonen, 2001). For example, Juga et al. (2012) show that very poor visibility due to intense snowfall combined with reduced road surface friction caused a severe flow of accidents in Helsinki on 17 March 2005. Likewise, the occurrence of freezing rain at the ground surface can lead to the collapse of trees and power supply lines with potentially catastrophic cascading effects, as was experienced during a recent case in Slovenia (Kämäräinen et al., 2017; Schauwecker et al., 2019). Last not least, both precipitation intensity and its phase (i.e. rain or snowfall) are decisive for runoff formation and the occurrence of flash floods in (pre-)alpine catchments (e.g., Fehlmann et al., 2018; Tobin et al., 2012).

To support decision making and intervention in such situations, the Thies Clima laser precipitation monitor (in the following referred to as Thies disdrometer) offers the possibility to measure precipitation intensity and type with a high temporal resolution; the monitor can therefore replace present weather observations from manned stations to a certain degree (Merenti-Välimäki et al., 2001). Due to their low maintenance requirements, disdrometers have ~~ben~~ been used widely for operational weather monitoring for road or air traffic. More recently, the Thies disdrometer has also been tested with the aim of verifying dual-polarimetric weather radars, and in particular their hydrometeor classification algorithms (Pickering et al., 2019). Beside the calibration and verification of rainfall estimation by radar and satellite, disdrometers are also used for a proper understanding of hydrometeorological regimes and soil erosion, pollution wash off in urban environments or interactions of rainfall with crop and forest canopies (Angulo-Martínez et al., 2018; Frasson and Krajewski, 2011; Nanko et al., 2004, 2013). In the future, disdrometers will likely be employed more often for hydrological purposes as well, with the aim of monitoring heavy precipitation and the ensuing nowcasting of river discharge, particularly in mountainous environments where precipitation phase estimates are still uncertain (e.g., Unterstrasser and Zängl, 2006). ~~Although the Thies disdrometer has been tested previously with the aim of verifying dual-polarimetric weather radars, and in particular their hydrometeor classification algorithms (Pickering et al., 2019), not many studies have assessed uncertainties of disdrometer measurements so far~~However, there are only few studies which assess the uncertainties of the Thies disdrometer, mostly comparing the instrument to OTT Parsivel disdrometers (e.g., Adirosi et al., 2018; Angulo-Martínez et al., 2018; Guyot et al., 2019; Upton and Brawn, 2008) and in a few cases to rain gauges (e.g., Lanza and Vuerich, 2012; Lanzinger et al., 2006). Furthermore, weather radars still suffer from limitations in the detection of convective precipitation or due to the blocking of the radar signal at lower elevations by mountain topography (Besic et al., 2016), therefore rendering reliable ground observations even more important in these areas.

In this study, we evaluate the Thies disdrometer with respect to precipitation detection as well as the monitoring of precipitation intensity and phase at a well-instrumented measuring site in Switzerland (Innereriz, 1060 m a.s.l.). To this end, we have used a weighing precipitation gauge (OTT pluviometer) as well as a two-dimensional video disdrometer (2DVD) as reference instruments over a measurement period of two years. The 2DVD provides accurate information about the volume and velocity of falling hydrometeors and has already been used previously as a reference to correct particle size and velocity (Parsivel) distributions of laser disdrometers during either rainfall (Leinonen et al., 2012; Raupach and Berne, 2015) or snowfall (Battaglia et al., 2010). , even if the 2DVD seems to underestimate droplets in the lower range of diameters, i.e. below 0.5 mm (Raupach et al., 2019; Thurai et al., 2017; Thurai and Bringi, 2018). In this study, we include both solid and liquid precipitation events and point to differences in resulting correction methods. Furthermore, we develop a hydrometeor classification algorithm for the 2DVD measurements as a basis for the evaluation of precipitation phase estimates. Whereas other studies have developed such algorithms using bulk variables for the classification (e.g., Grazioli et al., 2014), we have implemented here a particle-by-particle classification method allowing to explore resulting mixing ratios in the case of mixed-phased precipitation.

The paper is organized as follows: In section 2, the measurement devices are presented in more detail and the processing of the raw data is described. In section 3, biases and proposed corrections of the Thies disdrometer are presented with respect to precipitation detection as well as the monitoring of precipitation intensity and phase. Results are discussed in section ??, before conclusions In section 4, results are discussed and conclusions are drawn with respect to the operational monitoring of precipitation with the Thies disdrometer as well as potential applications in a hydrological contextare drawn in section ??.

2 Data and methods

2.1 Measurement devices

The Thies disdrometer is evaluated in this study by using a weighing precipitation gauge (OTT pluviometer) and a 2DVD as a reference. Measurements have been taken over a duration of two years (2017-07-01–2019-06-30). These instruments have been set up at Innereriz, Switzerland (1060 m a.s.l., Fig. 1) and are described in more detail in the following.

The Thies disdrometer is designed to estimate precipitation intensity as well as different types of precipitation (e.g. drizzle, rain, hail, snow or mixed precipitation). Precipitation type and intensity are estimated on the basis of an optical principle, i.e. by the generation of a laser beam (786 nm) attenuated by falling particles (Fig. 2, left). The strength and duration of this attenuation allows inference of the diameter and velocity of the falling particles, such that precipitation type can be estimated by using empirical relationships between these two quantities (e.g., Gunn and Kinzer, 1949). The exact functioning of this classification algorithm as well as other equations used are thereby not reported by the manufacturer. To derive precipitation intensity from raw particle data, several assumptions have to be made, also regarding particle shape and density. Whereas for liquid precipitation, an oblate shape (Chuang and Beard, 1990) and a density of 1 g/cm^3 is assumed, a spherical shape is considered for solid precipitation. The density of a snow particle (ranging from 5–450 g/cm^3) is estimated taking its diameter and velocity as well as the ambient temperature into account. As the exact relationship used is not reported by the manufacturer, a simplified relationship between particle diameter and density is derived in this study to estimate precipitation intensities in case of snowfall (Section section 3.2). The dominant precipitation type (WMO table 4680) as well as precipitation intensity is reported by the instrument every minute. Furthermore, particle diameter and velocity distributions are summarized by the number of particles recorded in paired classes of diameters (20 classes, ranging from 0.125–9 mm) and velocity (22 classes, ranging from 0–12 m/s), yielding a total of 440 classes.

The 2DVD, developed by Joanneum research, is ~~based on a principle similar to that of the Thies disdrometer, but the 2DVD is~~ able to derive more direct and more detailed information about individual hydrometeors than the Thies disdrometer. Maintenance requirements for the instrument are not negligible and it is mainly used in the research context and in combination with radar observations (e.g., Bringi et al., 2015; Gorgucci and Baldini, 2015; Huang et al., 2010, 2015; Thurai et al., 2012). Furthermore, the 2DVD has been used for the correction of laser disdrometers (Raupach and Berne, 2015). As shown in Fig. 2 (right), falling hydrometeors are detected by two optical cameras from two perspectives, which allows to derive more detailed information about the shape and volume of individual particles as well as about their velocity. Information about these quantities is reported for each individual particle, including the exact time of the observation (in ms). Precipitation type is not (yet) reported by the instrument, but can be estimated on the basis of the raw particle data. To validate precipitation type estimates by the Thies disdrometer, a classification algorithm was developed in this study, allowing an estimation of the type of each individual hydrometeor (~~Section~~ section 2.2). Note that in some studies using 2DVD or other video disdrometer measurements, additional filters are applied to remove spurious measurements of mostly larger particles, usually being based on a validity check of the combined diameter and velocity information (e.g., Raupach and Berne, 2015; von Lerber et al., 2017).However, as investigated in detail by Friedrich et al. (2013) such spurious measurements mostly occur at wind speeds exceeding 20 m/s. As our study site is extremely wind sheltered (see also section 4) we thus did not apply such a filter in this study.

The OTT pluviometer is designed to automatically determine precipitation intensities and amounts. Unlike tipping bucket rain gauges, this instrument is based on the weighing of the precipitation amount in a high-precision load cell. Advantages compared to a tipping bucket rain gauge are particularly related to the measurement of solid precipitation amounts, resulting in fewer losses due to the evaporation as well as the avoidance of a temporal lag effect in the measurement (Savina et al., 2012). The instrument is thus able to measure precipitation amounts with high accuracy and is therefore used as a reference for precipitation amounts at the ground surface in various applications, including the validation of disdrometers (e.g., Raupach and Berne, 2015). ~~A~~ According to the operating instructions of the OTT pluviometer, the instrument provides the raw precipitation values every 6 seconds using a resolution of 0.001 mm. After the application of special filter algorithms (e.g. a correction for wind effects), non-real time 1-min outputs are available at a resolution of 0.01 mm. Of course, it can be questioned whether very weak precipitation can actually be measured so accurately. For example, Tiira et al. (2016) found in their mass retrieval (performed approximately every 5 minutes) that the output seems to fluctuate and used a threshold 0.2 mm/h for their analysis. Furthermore, a well-known problem when using precipitation gauges mounted above ground is ~~, however,~~ the undercatch due to the influence of wind, which has been extensively studied for rainfall (e.g., Pollock et al., 2018) and in particular for snowfall (e.g., Fassnacht, 2004; Kochendorfer et al., 2017; Yang, 2014; Wolff et al., 2015). The undercatch is thereby found to be larger for snowfall than for rainfall and to increase with increasing wind-speed. In this study, however, we do not explicitly correct for wind effects as wind speeds at the study site are generally very low (on average 0.46 m/s during the investigated time period). The maintenance requirements of the instrument are relatively low - only the container, which holds 750 mm for the model used, must be emptied regularly. Precipitation intensity and amount are reported every minute.

Finally, temperature and wind measurements of a LUFFT weather sensor are used in this study. This sensor was located at the same measuring station (Fig. 1, left) and provided corresponding measurements every minute. Temperature is measured by way of a highly accurate NTC-resistor in a ventilated housing with radiation protection in order to keep the effects of external influences (e.g. solar radiation) as low as possible. The wind meter uses 4 ultrasonic sensors which take cyclical measurements in all directions. The resulting wind speed and direction are calculated from the measured run-time sound differential.

2.2 2DVD classification algorithm

As precipitation type is not reported by the 2DVD by default, a classification algorithm was developed in this study, to assign one of the following precipitation types to each observed hydrometeor: hail, rain, melting snow, graupel or snow. Unlike other algorithms (e.g., Grazioli et al., 2014), the algorithm used here is based on a particle-by-particle classification rather than on bulk information, which even allows for the explicit quantification of hydrometeor mixtures during a given time period. For the validation of the Thies disdrometer, the dominant precipitation type during 1-min observations was then estimated on the basis of these mixing ratios.

Similar to the Thies disdrometer, the classification algorithm is based on the empirical relationship between particle diameter D and fall velocity V, which varies among different types of precipitation. The equations used (equations 1–5) are based on literature (Gunn and Kinzer, 1949; Locatelli and Hobbs, 1974; Mitchell, 1996) as well as measurements and analyses conducted by Joanneum Research.

$$V_{Hail} = 3.74 \cdot D^{0.5} \tag{1}$$

$$V_{Rain} = 9.65 - (10.3 \cdot e^{-0.6 \cdot D}) \tag{2}$$

$$V_{Melting} = 4.65 - (5 \cdot e^{-0.95 \cdot D}) \tag{3}$$

$$V_{Graupel} = 1.3 \cdot D^{0.66} \tag{4}$$

$$V_{Snow} = 0.79 \cdot D^{0.24} \tag{5}$$

A particle is considered for classification only if its diameter D and velocity V lie within a valid range (0.6 mm < D < 9 mm, V < 17 m/s) and if no major differences exist in particle size between the two cameras ($0.8 < H_A/H_B < 1.25$, where H_A and H_B denote the particle height in camera A and B, respectively). For each valid particle, theoretical fall speeds for different precipitation types are calculated according to its diameter and equations 1–5. The estimated values are then compared to measured velocity, whereas precipitation type is determined according to the closest match between these values. In addition, snow or melting snow above 10 °C is reclassified as rain - a plausibility check which is also applied by Thies Clima for the processing of Thies disdrometer data. An example of the resulting particle-by-particle classification is given in Fig. 3 for a transition from rain to snowfall during 6 h.

After the inspection of 1-min mixing ratios of different precipitation types obtained by this classification algorithm (not shown here), we determined the dominant precipitation phase during 1 min as follows (Table 1): Rain is considered dominant if more than 70% of the particles are classified as rain, whereas snow and/or graupel are considered dominant if more than

80% of the particles are classified as snow, melting snow or graupel. Furthermore, hail is already assigned for mixing ratios greater than 1% as the chance of (larger) hailstones being captured by the relatively small measuring area is quite small. In the remaining cases, mixed-phased precipitation is assigned.

To investigate the effect of applying different classification methodologies on obtained results, the classification algorithm described above was also applied to Thies data. Given the binned data, the mean velocity and diameter of each V-D class were used for the classification rather than information about individual particles.

2.3 Comparison of measurements and performance measures

The Thies disdrometer is evaluated by using the OTT pluviometer as a reference for precipitation detection and intensities and the 2DVD as a reference for PSD and precipitation type. The following comparisons refer to a time period of two years (2017-07-01–2019-06-30) during which all these instruments have been installed simultaneously. Whereas the first year of measurements (2017-07-01–2018-06-30) is used for the design of the proposed correction methods, the second year of measurements (2018-07-01–2019-06-30) is used for the independent validation of the methods.

When comparing the Thies disdrometer with the OTT pluviometer, corresponding 1-min observations are merged. Although both instruments are measuring with a resolution of 1 min, they have not been set up to measure synchronously. To avoid mismatches due to temporal shifts between observations, the minimum integration time considered for the evaluation of precipitation detection and precipitation intensities was set to 5 min. As the effect of increasing integration time on the reliability of measurements can be of interest for operational applications, we also report results for integration times up to 4 h (i.e. 5, 10, 20, 30, 60, 90, 120 and 240 min). Intensities for different integration times are calculated based on the cumulative precipitation sum, which is given by both instruments. For all correction methods applied, the variable of interest is first integrated over the considered integration time before any correction is applied.

When comparing the Thies disdrometer (or the OTT pluviometer) with the 2DVD, 1-min observations can be used and the 2DVD data is aggregated accordingly. When comparing the PSD between the two disdrometers, the number of particles is normalised by the so-called effective measuring area. This area slightly deviates from the actual measuring area (being 45.32 cm^2 for the Thies disdrometer and 109.39 cm^2 for the 2DVD) as a function of particle diameter. Essentially, the effective measuring area decreases for larger particles due to the increasing non-recognition of partially observed particles at the border of the measuring area. Whereas the effective measuring area is reported by the 2DVD for each observed particle, it is calculated for each diameter class of the Thies disdrometer after Angulo-Martínez et al. (2018), using the mean diameter of each class. For the adjustment of the particle size distribution (PSD) measured by the Thies disdrometer, we adopt a ~~method~~ methodology proposed by Raupach and Berne (2015), which essentially scales drop concentrations per diameter class to ensure that they on average match those recorded by the 2DVD. The correction factors used for this scaling correspond to the ratio of summed 2DVD drop concentrations to summed Thies drop concentrations in the calibration period (2017-07-01–2018-06-30), and are separately calculated for rain and snowfall. For the consistent comparison of precipitation phase between the two disdrometers, certain precipitation types were aggregated according to Table 1. Furthermore, we only consider pairwise complete (1 min) observations of both instruments with either rain, snow or mixed precipitation, resulting in a time series of 2,533 h of precipitation.

For the evaluation of categorical variables, i.e. precipitation detection (yes/ no) and precipitation phase (rain/ mixed/ snow), hit and false alarm rates with respect to the reference instrument are calculated according to Jolliffe and Stephenson (2012). For the evaluation of precipitation intensityJolliffe and Stephenson (2012). In the case of precipitation detection (yes/ no), we further investigate the effect of minimum precipitation thresholds applied to measurements of the Thies disdrometer on hit and false alarm rates by investigating the so-called Receiver Operating Characteristic (ROC) curves (e.g., Jolliffe and Stephenson, 2012) . A ROC curve thereby depicts the variation of hit and false alarm rates with the variation of such a threshold. For example, using a threshold of 0 mm/h for precipitation detection (i.e. always reporting precipitation regardless of the measurement) will result in both a hit and a false alarm rate of 1. On the other hand, choosing an indefinitely high minimum precipitation threshold will result in both a hit and a false alarm rate of 0. Between these extremes, the resulting hit and false alarm rates depend on the capabilities of the Thies disdrometer to detect precipitation as compared to the reference instrument, while the theoretical optimum (hit rate of 1 and false alarm rate of 0) can usually not be achieved. To establish ROC curves for different integration times we use the fixed thresholds $TH_{ROC} = \{0, 0.001, 0.002, \ldots, 0.05, 0.1, 0.15, \ldots, 1, 1.2, 1.4, \ldots, 3\}$ in mm/h.

For the evaluation of biases in precipitation intensity measurements, systematic deviations are given between the instruments are characterized in terms of the absolute bias B (equation 6) and the scatter is described in terms of the correlation coefficient Corr (equation ??), where $\hat{x}$ denotes the estimation of the Thies disdrometer and x denotes the measurement of the OTT pluviometer for all observations n.

$$B = \frac{1}{n}\sum_{i=1}^{n}\hat{x}_i - x_i Corr = \frac{cov(\hat{x},x)}{\sqrt{var(\hat{x})var(x)}} \qquad (6)$$

3 Results

3.1 Precipitation detection

The capacities capability of the Thies disdrometer to detect precipitation are assessed with is assessed using the OTT pluviometer as a reference. After exploring the full time series, data from the first year of measurements was used to optimize precipitation detection by establishing minimum precipitation thresholds. The application of these thresholds was then evaluated during the second year of independent measurements.

Hit and false alarm rates The capability of the Thies disdrometer with respect to precipitation detection are to distinguish precipitation from no precipitation is described in terms of its hit and false alarm rate when using the OTT pluviometer as a reference. In a first step, hit and false alarm rates are calculated over the whole time series and are indicated with circles in Fig. 4 (left) for the whole time series and for different integration times. Thereby, hit rates are stable and reach values between 95.2 and 95.9%. False alarm rates are low for short integration times (e.g. 5.1% for periods of 5 min) but tend to increase with increasing integration time (e.g. 14.1% for periods of 4 h). This increase is probably related to the fact that - given a dry period - the chance of misinterpreting a signal as precipitation is increasing with increasing integration time.

To In a second step, we tested the application of minimum precipitation thresholds to the Thies disdrometer observations in order to reduce false alarm rates of the Thies disdrometer for longer integration times, we also tested the application of minimum precipitation thresholds. The receiver operating characteristic (ROC). The ROC curves shown in Fig. 4 (left) thereby depict all possible combinations of hit and false alarm rates that can be achieved by the introduction of such a threshold. The application of a minimum threshold will generally reduce both false alarm as well as hit rates. Therefore, an optimal threshold was defined for each integration time by minimising the Euclidean distance to the upper left corner in the ROC diagram (i.e. to the theoretical optimum with a hit rate equal to 1 and a false alarm rate equal to 0), resulting in a balanced solution between the two measures. This optimization was applied to the first year of measurements and the resulting thresholds are listed in Table 2 for each integration time. Noteworthy, these thresholds (expressed in mm/h) are quite stable for different integration times with a mean of 0.04 mm/h.

The effect of applying the proposed thresholds on hit and false alarm rates during the second year of measurements is depicted in Fig. 4 (right) and Table 2. The application of such thresholds is particularly beneficial for integration times exceeding 20 min, as they allow to effectively reduce false alarm rates by up to 8.9 % (for periods of 4 h). For integration times shorter than 20 min, the application of a minimum precipitation threshold only has a negligible effect. Furthermore, by applying the proposed thresholds, a balanced solution with respect to hit rates and false alarm rates can be found for all the integration times considered, resulting in a relatively similar distance to the theoretical optimum in the ROC diagram.

Finally, by applying the proposed minimum precipitation thresholds in Table 2, we analyze missed events as well as false alarms produced by the Thies disdrometer in the validation period in more detail, i.e. with respect to precipitation intensity and phase. Whereas precipitation intensities measured by the OTT pluviometer were of interest during missed events, precipitation intensities indicated by the Thies disdrometer were analysed during false alarms. To investigate whether the phase of precipitation could be relevant for missed events or false alarms, observations were separated according to a temperature threshold of 1.2 °C (Fehlmann et al., 2018). The resulting distributions of precipitation intensities and phase during missed events and false alarms are shown in Fig. 5. Precipitation intensities during missed events are decreasing with increasing integration time, mean intensities being around 0.6 mm/h during periods of 5 min and decreasing to around 0.03 mm/h during periods of 4 h. While precipitation intensities during missed events are very similar above and below the temperature threshold of 1.2 °C, the relative frequency of missed events seems to be slightly higher below this temperature threshold. Precipitation intensities indicated by the Thies disdrometer during false alarms are very low, ranging from 0.12 mm/h for 5-min periods to 0.02 mm/h for 4-h periods, with no remarkable differences above and below the temperature threshold of 1.2 °C.

3.2 Precipitation intensities

The capacities capability of the Thies disdrometer to measure precipitation intensities were is assessed with the OTT pluviometer as a reference for precipitation intensities as well as with the 2DVD as a reference for the PSD. After exploring error patterns in the entire time series, the first year of measurements was used to establish corresponding correction methods. The application of the established correction methods was then evaluated with independent data from the second year of measurements.

Figure 6 depicts the cumulative precipitation sums of the Thies disdrometer over the full investigation period as compared to the OTT pluviometer. Precipitation sums for both instruments are separated into rain and snow according to 1-min precipitation type estimates of the Thies disdrometer. As rain and snowfall events represent 89.5% of the total precipitation sum, we restrict analysis to these two precipitation types in the following. Total precipitation after two years of measurements is underestimated by 12.4% by the Thies disdrometer. This systematic underestimation is almost entirely related to rainfall events, during which the total precipitation sum is underestimated by even 16.5%. The underestimation during snowfall events is much smaller (4.0%) and seems to be less systematic, but rather related to individual events during the second year of measurements.

As a first approach to improve precipitation intensity estimates by the Thies disdrometer, we tested a direct adjustment to the measurements of the OTT pluviometer. A comparison of precipitation intensities between these instruments during the full investigation period is shown in Fig. 7 for an integration time of 30 min; it confirms the error pattern described above: ~~Whereas~~ whereas a systematic underestimation of rainfall intensities is visible, almost no systematic error can be seen with respect to snowfall intensities. Furthermore, the systematic underestimation of precipitation intensities seems to be well captured by a constant factor (i.e. independent of integration time or precipitation intensity). We thus propose to use the ~~mean ratio as a measure for the adjustment~~ ratio of the OTT pluviometer to the Thies disdrometer precipitation sum as a correction factor and to distinguish between rain and snowfall. Using the first year of measurements, the ~~mean ratio~~ resulting correction factors for rain and snowfall intensities ~~is 0.83 and 1.04, implying correction factors of~~ are 1.20 and 0.96, respectively.

As a second approach to improve precipitation intensity estimates by the Thies disdrometer, we tested an adjustment of the PSD to the measurements of the 2DVD. A comparison of the summed PSD between these two instruments is shown in Fig. 8 for all rain and snowfall events ~~.~~ during the whole time series (two years). The separation into rain and snowfall events is based on the recorded dominant precipitation type by the Thies disdrometer (1 min). Although the overall shape of the PSD is similar for both instruments, systematic deviations seem to exist during both rain and snowfall events. During rainfall events, the number of particles with diameters between 0.5 and 3.5 mm (classes no. 4–12) is systematically underestimated, whereas the number of smaller and larger particles is overestimated by the Thies disdrometer as compared to the 2DVD. When looking at the monthly variability of the resulting correction factors (Fig. 8, right), the overestimation seems to be less stable than the underestimation. During snowfall, the number of particles with diameters exceeding 0.75 mm is overestimated, whereas the number of smaller particles is underestimated as well. Noteworthy, the underestimation (classes no. 4–12 for rainfall and 5–22 for snowfall) will affect resulting estimates of precipitation intensity in particular. In the case of rainfall and assuming the mean PSD obtained by the Thies disdrometer, particles between 0.5 and 3.5 mm (classes no. 4–12) are contributing to 90% of the total rainfall volume. The smallest and largest particles are almost negligible for total volume due to their small volume (smallest particles) and number (largest particles), respectively. Nevertheless, we propose to apply correction factors for the number of particles in each diameter class, and to further distinguish between rainfall and snowfall. Using the first year of measurements, the resulting correction factors for rain and snowfall are listed in Table 3. Given the corrected PSD, rainfall intensity is calculated by assuming a density of 1 g/cm^3. For snowfall, a relationship between particle diameter and density is established by comparing 1-min accumulated volumes (measured by the 2DVD) to the corresponding mass (measured by the OTT pluviometer) and is shown in ~~Figure~~ Fig. 9.

The effect of both correction methods proposed here was subsequently tested during the second year of measurements. The resulting ~~performance measures~~ biases of the Thies disdrometer before and after the correction are given in Table 4 for different integration times. ~~Performance measures~~ These biases are thereby calculated for the whole dataset as well as for all rain and snowfall separately. An example for the integration time of 30 min is further given in Fig. 10. As can be seen in Table 4 and Fig. 10, the ~~performance of both correction methods is comparable, whereas the main effect is the reduction of the bias for rainfall intensities . The correlation for both rain and snowfall events can only be improved through an adjustment to the 2DVD, as the adjustment to the OTT pluviometeris based on a constant factor. Thereby, correlation is slightly improved regarding snowfall events but remains unchanged for rainfall events. This suggests that the~~ most robust result is achieved by the adjustment of rainfall intensities to the ~~PSD has a comparable effect than a linear adjustment of resulting precipitation intensities . During snowfall~~OTT pluviometer, which successfully reduces the underestimation of liquid precipitation in the validation period. The adjustment of rainfall intensities to the 2DVD, however, ~~the relation of particle densities to drop diameter can result in non-linear effects and improve the correlation with respect to the OTT pluviometer. Uncertainties in precipitation intensities are higher during snowfallthan during rainfall, and correlations generally increase with increasing integration time, with this increase being most pronounced when increasing the integration time from 5 to 20 min. This finding also indicates that at least some uncertainties in estimates of precipitation intensities (including small time shifts between observations) are averaged out over longer integration times~~results in a positive bias in the validation period. For snowfall, both correction methods have a smaller impact and even result even in slightly higher negative biases than are present without any adjustment.

3.3 Precipitation phase

The ~~capacities~~ capability of the Thies disdrometer to detect the predominant precipitation type is assessed using the 2DVD as a reference. We thereby focus on the precipitation phase, i.e. the distinction of rain and snowfall, which has been shown above to be an important criterion for the proposed correction methods. ~~Furthermore, we only consider pairwise complete (1 min) observations of both instruments with either rain, snow or mixed precipitation, resulting in a time series of 2,533 h of precipitation.~~

Table 5 shows the agreement of precipitation phase estimates between the Thies disdrometer and the 2DVD during the full time series, while Fig. 11 depicts the relative frequency of observations as a function of temperature for both instruments, including an indication of the mixing ratios obtained by the 2DVD. Thereby, the Thies disdrometer agrees well with the 2DVD insofar as the classification of rain and snow is concerned. By contrast, larger differences exist with respect to the classification of mixed precipitation. Regarding the detection of rain, the Thies disdrometer reaches an almost perfect hit rate (99.7%). However, the overall frequency of rain is slightly overestimated by the Thies disdrometer, being reflected by a false alarm rate of 9.9%. Regarding the detection of snow, the overall frequency of detected cases is almost equal for both instruments. The hit and false alarm rate of the Thies disdrometer with respect to the 2DVD is reaching 95.3 and 1.3%, respectively, reflecting a good agreement between the two instruments. Finally, the Thies disdrometer classifies much less cases as mixed precipitation (1%) than the 2DVD (4.3%), resulting in both a low hit and false alarm rate for these cases.

Most misclassifications are related to cases during which the Thies disdrometer indicates rain, whereas the 2DVD indicates mixed precipitation or snow. As can be seen in Fig. 11, such cases occur at both temperatures above and well below 0 °C. Thereby, the Thies disdrometer seems to overestimate cases of rain below 0 °C and to underestimate cases of snowfall or mixed precipitation above 0 °C as compared to the 2DVD. At least during distinct misclassifications, i.e. in cases where the Thies disdrometer indicated rain while the 2DVD indicating snow, it can be shown that precipitation intensities are very small, i.e. their mean being 0.19 mm/h (while being 0.93 mm/h for all cases).

4 Discussion and Conclusions

In this study, we have shown that the Thies disdrometer is well suited for precipitation detection, reaching hit rates of around 95% with respect to the OTT pluviometer. False alarm The false alarm rate, which indicates the probability of the Thies disdrometer detecting precipitation during a dry period, is increasing with increasing integration time. This can be somewhat expected, as the chance of misinterpreting a signal or disturbance as precipitation is increasing with increasing duration of this period. Furthermore, false alarm rates might be affected by the sensitivity of the reference instrument, but are comparable to findings of Bloemink and Lanzinger (2005) who use human observations as a reference.

We have further demonstrated that the Thies disdrometer systematically underestimated rainfall intensities at the study site by 16.5% during two years of measurements, which we explain to be related to an underestimation of drop concentrations for drop diameters ranging between 0.5 and 3.5 mm. At the same time, larger and smaller drops are overestimated by the instrument; this is, however, less relevant for the resulting estimates of rainfall intensities. Other studies have reported similar patterns in terms of bias in the PSD and while analyzing other disdrometers, such as the Joss–Waldvogel (Leinonen et al., 2012) or the OTT Parsivel (Raupach and Berne, 2015) disdrometers disdrometers (Raupach and Berne, 2015). However, the deviations in the PSD and implications for rainfall intensity estimates can be different between different types of instruments:. For example, the OTT Parsivel[1] disdrometer only underestimates drops with sizes ranging between 0.8 and 1.6 mm and only during periods of higher rainfall intensity. In addition, the device tends to even overestimate rainfall intensities (Raupach and Berne, 2015). Interestingly, an overestimation of rainfall intensities is also reported for the Thies disdrometer at the intercomparison site Wasserkuppe in Germany (Lanzinger et al., 2006). Supposedly, this contrary result to our study is due to differences in wind exposure. While our study site in Innereriz is extremely wind sheltered (average wind speeds being 0.46 m/s during the investigation period), the site at Wasserkuppe is strongly exposed to wind, average wind speeds being 6.4 m/s from 1999–2018 (data obtained by German weather service DWD). Despite these differences, the correction of the PSD as proposed by Raupach and Berne (2015) could successfully be adopted in this study to reduce the bias found in rainfall intensity estimates as given Finally, when compared the OTT Parsivels, Guyot et al. (2019) found that the Thies disdrometer starts to underestimate the number of droplets from 0.75 mm onwards towards larger diameters when compared to Parsivel[1] and also underestimates liquid precipitation compared to both Parsivel[1] and Parsivel[2]. To reduce the underestimation of rainfall intensities by the Thies disdrometer ~~. The correlation coefficient remains mostly unaffected by the correction, which is again consistent with the results reported by Raupach and Berne (2015). Consequently, an analogous effect can be~~ found at our study site, we established an adjustment to 2DVD measurements following the methodology of Raupach and Berne (2015). However, when applying the resulting adjustment in the validation period, we introduce a positive bias, which could indicate a slight overestimation of liquid precipitation by the 2DVD when compared to the OTT pluviometer. A more stable correction is achieved by applying a linear adjustment to ~~a weighing precipitation gauge, which is proposed as an alternative~~ the OTT pluviometer. This method is thus proposed as the preferred correction method in this study, especially when the PSD itself is not of interest to the user. It should be noted further that the overestimation of smaller drops by laser disdrometers with respect to the 2DVD is also found in other studies (Krajewski et al., 2006; Raupach and Berne, 2015), but can at least partly be related to unreliable estimates by the 2DVD for small drops (Tokay et al., 2013). As rainfall intensity or radar reflectivity are not strongly affected by the concentrations of small drops, no further adjustment of the PSD is considered in this study. For the reconstruction of the drizzle mode of the PSD, Raupach et al. (2019) present a method being able to correct for this deficiency and to further improve rainfall intensity estimates for light rain.

Regarding the measurement of snow, we show that the number of particles with diameters exceeding 0.75 mm is slightly underestimated by the Thies disdrometer. However, this bias is not reflected in intensity estimates. Although not systematically biased, a more detailed analysis of the correlation coefficient (not shown here) revealed that uncertainty in snowfall intensity estimates is higher than for rainfall~~as~~. This is most likely related to some of the underlying assumptions (e.g. about particle orientation, shape or density) ~~are~~ being less appropriate for solid than for liquid precipitation (Yuter et al., 2006; Battaglia et al., 2010). Regarding snow density, we propose a simple parametrization of particle density as a function of particle diameter, which is ~~based on a comparison of aggregated snow volumes and corresponding masses measured by the 2DVD and a weighing precipitation gauge, respectively (1-min observations). The proposed parametrization is~~ similar to other studies (e.g., Fabry and Szyrmer, 1999; Brandes et al., 2007) and ~~could~~ found here to substantially improve intensity estimates as compared to a constant density assumption. By applying the proposed adjustment of the PSD and ~~the parametrization of snow density , correlation~~ this snow density parametrization to Thies disdrometer measurements, correlation of the resulting snow intensity estimates with respect to the OTT pluviometer can be slightly improved. ~~We~~ Given the still high uncertainties in the snow density parameterization (apparent in Fig. 9), we further tested the inclusion of information about particle velocity and temperature but could not thereby improve resulting intensity estimates. The analysis of the correlation coefficient for snowfall intensities further revealed that correlations generally increase with increasing integration time (particularly up to 20 min). This indicates that at least some uncertainties in estimates of snowfall intensities including small time shifts between observations are averaged out over longer integration times.

The distinction between rainfall and snowfall is not only an important prerequisite for the proposed correction methods, but also relevant with respect to hydrological applications in alpine or pre-alpine areas. In this study, we show that the Thies disdrometer is well suited for a distinction of rainfall from snowfall (hit rates reaching 99.7% for rainfall and 95% for snowfall using the 2DVD as a reference)~~, but that larger differences~~ . Larger differences between the two disdrometers exist for mixed precipitation and particularly small precipitation intensities. As such, our results are in line with other studies in which precipitation phase estimates from disdrometers (including the Thies disdrometer) have been compared to human observations (Bloemink and Lanzinger, 2005; Merenti-Välimäki et al., 2001). In particular the underestimation of mixed phased precipitation by the Thies disdrometer is consistent with results of Bloemink and Lanzinger (2005). At the same time, a recently reported case study suggests that the instrument is able to accurately signal mixed precipitation during changes between snow and rain (Pickering et al., 2019). In this context, we would like to point out that the agreement of the dominant precipitation type during mixed precipitation with any reference observation will depend on the mixing ratios, which are explicitly or implicitly range of mixing ratios implicitly or explicitly considered as mixed . In this study, we presented a particle-by-particle classification algorithm being able to explicitly determine mixing ratios for the reference instrument. Such procedures precipitation. Our analysis indicates that the distinction between liquid and mixed precipitation is particularly sensitive to the choice of such a threshold. Furthermore, the application of the proposed classification algorithm to both disdrometers indicates that a reasonable choice of these thresholds might differ between different instruments. In addition to the validation of dominant precipitation type estimates, the particle-by-particle classification algorithm presented in this study can provide a basis for the validation of explicitly characterized hydrometeor mixtures as for example in polarimetric radar observations (e.g., Besic et al., 2018) or atmospheric models (e.g., Forbes et al., 2014). However, when comparing dominant hydrometeor type or precipitation phase during a certain time interval, the choice of thresholds is required and will affect the classification and the resulting comparison.

5 Conclusions

This study evaluated the Thies disdrometer with respect to precipitation monitoring in a pre-alpine environment; a weighing precipitation gauge (OTT pluviometer) as well as a 2DVD have been used as a reference. We show that the instrument is well suited for precipitation detection. However, in our case, rainfall intensity is systematically underestimated by 16.5%, which may be explained by an underestimation of raindrops with diameters between 0.5 and 3.5 mm. Moreover, we hypothesize that the general underestimation at our measurement location depends mainly on the prevailing wind conditions and may differ at other measurement sites. In the case of snowfall, no systematic deviations could be found, but uncertainty is generally higher than for rainfall, which might be related to uncertainties with respect to particle orientation, shapes and densities. To slightly improve intensity estimates during snowfall events, we propose to apply an adjustment of the PSD and recalculate intensities by assuming a relationship between particle diameter and density. This relationship was established by combining measurements of the OTT pluviometer and the 2DVD. Finally, we show that the Thies disdrometer and the 2DVD agree well with respect to the distinction between rain and snowfall (hit rates reaching 99.7 and 95%, respectively) and that therefore an important prerequisite for the proposed correction is fulfilled.

The Thies disdrometer has the advantage of low maintenance requirements and allows not only the estimation of precipitation intensity but also precipitation type. The reliable distinction between rainfall and snowfall is considered here as an advantage for hydrological applications in mountainous environments, where local estimates of precipitation phase are still uncertain.

We therefore see a potential in installing disdrometers at sensitive elevations in mountainous catchments complementary to precipitation gauge and weather radar data to improve precipitation monitoring and short-term flood forecasting in these areas.

The 2DVD was particularly useful in this study to further investigate the biases of the Thies disdrometer, to establish a parametrization of snow density and to provide a reference for the estimation of precipitation phase. Future studies may focus on a refinement of the proposed snow density parametrization and hydrometeor classification algorithm by taking other parameters such as particle orientation or shape (e.g. roundness, oblateness) into account.

In this study, we could not clarify how the relevant underestimation for liquid precipitation is depending on wind or other influences. We suggest to investigate this dependence in further studies.

Data availability. The data used in this study, i.e. measurement outputs of the Thies disdrometer, the OTT pluviometer as well as the two-dimensional video disdrometer (2017-07-01–2019-06-30), can be found in Fehlmann et al. (2020).

Author contributions. MF designed the framework of the study and evaluation strategy with help from all coauthors. MF processed the data obtained by the measurement devices (i.e. the Thies disdrometer, the two-dimensional video disdrometer, the OTT pluviometer and the LUFFT weather sensor) and implemented the presented evaluation methods. MF, MR, AvL and MS participated in writing and editing the manuscript, as well as investigating and interpreting the results.

Competing interests. The authors declare that they have no conflict of interest.

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References

Adirosi, E., Roberto, N., Montopoli, M., Gorgucci, E., and Baldini, L.: Influence of disdrometer type on weather radar algorithms from measured DSD: Application to Italian climatology, Atmosphere, 9, 360, https://doi.org/10.3390/atmos9090360, 2018.

Angulo-Martínez, M., Beguería, S., Latorre, B., and Fernández-Raga, M.: Comparison of precipitation measurements by OTT Parsivel 2 and Thies LPM optical disdrometers, Hydrology and Earth System Sciences, 22, 2811–2837, https://doi.org/10.5194/hess-22-2811-2018, 2018.

Battaglia, A., Rustemeier, E., Tokay, A., Blahak, U., and Simmer, C.: PARSIVEL snow observations: A Critical Assessment, Journal of Atmospheric and Oceanic Technology, 27, 333–344, https://doi.org/10.1175/2009JTECHA1332.1, 2010.

Besic, N., Figueras i Ventura, J., Grazioli, J., Gabella, M., Germann, U., and Berne, A.: Hydrometeor classification through statistical clustering of polarimetric radar measurements: A semi-supervised approach, Atmospheric Measurement Techniques, 9, 4425–4445, https://doi.org/10.5194/amt-9-4425-2016, 2016.

Besic, N., Gehring, J., Praz, C., Figueras i Ventura, J., Grazioli, J., Gabella, M., Germann, U., and Berne, A.: Unraveling hydrometeor mixtures in polarimetric radar measurements, Atmospheric Measurement Techniques, 11, 4847–4866, https://doi.org/10.5194/amt-11-4847-2018, 2018.

Bloemink, H. I. and Lanzinger, E.: Precipitation type from the Thies disdrometer, in: WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO-2005), pp. 4–7, Bucharest, Romania, https://www.knmi.nl/home, 2005.

Brandes, E. A., Ikeda, K., Zhang, G., Schönhuber, M., and Rasmussen, R. M.: A statistical and physical description of hydrometeor distributions in Colorado snowstorms using a video disdrometer, Journal of Applied Meteorology and Climatology, 46, 634–650, https://doi.org/10.1175/JAM2489.1, 2007.

Bringi, V. N., Tolstoy, L., Thurai, M., and Petersen, W. A.: Estimation of spatial correlation of drop size distribution parameters and rain rate using NASA's S-band polarimetric radar and 2D video disdrometer network: Two case studies from MC3E, Journal of Hydrometeorology, 16, 1207–1221, https://doi.org/10.1175/JHM-D-14-0204.1, 2015.

Chuang, C. C. and Beard, K. V.: A numerical model for the equilibrium shape of electrified raindrops, Journal of the Atmospheric Sciences, 47, 1374–1389, https://doi.org/10.1175/1520-0469(1990)047<1374:ANMFTE>2.0.CO;2, 1990.

Fabry, F. and Szyrmer, W.: Modeling of the melting layer. Part II: Electromagnetic, Journal of the Atmospheric Sciences, 56, 3593–3600, https://doi.org/10.1175/1520-0469(1999)056<3593:MOTMLP>2.0.CO;2, 1999.

Fassnacht, S. R.: Estimating Alter-shielded gauge snowfall undercatch, snowpack sublimation, and blowing snow transport at six sites in the coterminous USA, Hydrological Processes, 18, 3481–3492, https://doi.org/10.1002/hyp.5806, 2004.

Fehlmann, M., Gascón, E., Rohrer, M., Schwarb, M., and Stoffel, M.: Estimating the snowfall limit in alpine and pre-alpine valleys: A local evaluation of operational approaches, Atmospheric Research, 204, 136–148, https://doi.org/10.1016/j.atmosres.2018.01.016, 2018.

Fehlmann, M., Rohrer, M., von Lerber, A., and Stoffel, M.: Data for journal article: "Automated precipitation monitoring with the Thies disdrometer: Biases and ways for improvement", https://doi.org/10.5281/zenodo.3895296, 2020.

Forbes, R., Tsonevsky, I., Hewson, T., and Leutbecher, M.: Towards predicting high-impact freezing rain events, ECMWF Newsletter, 141, 15–21, https://doi.org/10.21957/xcauc5jf, 2014.

Frasson, R. P. d. M. and Krajewski, W. F.: Characterization of the drop-size distribution and velocity–diameter relation of the throughfall under the maize canopy, Agricultural and Forest Meteorology, 151, 1244–1251, https://doi.org/10.1016/j.agrformet.2011.05.001, 2011.

Friedrich, K., Higgins, S., Masters, F. J., and Lopez, C. R.: Articulating and stationary PARSIVEL disdrometer measurements in conditions with strong winds and heavy rainfall, Journal of Atmospheric and Oceanic Technology, 30, 2063–2080, https://doi.org/10.1175/JTECH-D-12-00254.1, 2013.

Gorgucci, E. and Baldini, L.: Influence of beam broadening on the accuracy of radar polarimetric rainfall estimation, Journal of Hydrometeorology, 16, 1356–1371, https://doi.org/10.1175/JHM-D-14-0084.1, 2015.

Grazioli, J., Tuia, D., Monhart, S., Schneebeli, M., Raupach, T., and Berne, A.: Hydrometeor classification from two-dimensional video disdrometer data, Atmospheric Measurement Techniques, 7, 2869–2882, https://doi.org/10.5194/amt-7-2869-2014, 2014.

Gunn, R. and Kinzer, G. D.: The terminal velocity of fall for water droplets in stagnant air, Journal of Meteorology, 6, 243–248, https://doi.org/10.1175/1520-0469(1949)006<0243:TTVOFF>2.0.CO;2, 1949.

Guyot, A., Pudashine, J., Protat, A., Uijlenhoet, R., Pauwels, V. R. N., Seed, A., and Walker, J. P.: Effect of disdrometer type on rain drop size distribution characterisation: A new dataset for south-eastern Australia, Hydrology and Earth System Sciences, 23, 4737–4761, https://doi.org/10.5194/hess-23-4737-2019, 2019.

Huang, G.-J., Bringi, V. N., Cifelli, R., Hudak, D., and Petersen, W. A.: A methodology to derive radar reflectivity–liquid equivalent snow rate relations using C-band radar and a 2D video disdrometer, Journal of Atmospheric and Oceanic Technology, 27, 637–651, https://doi.org/10.1175/2009JTECHA1284.1, 2010.

Huang, G.-J., Bringi, V. N., Moisseev, D., Petersen, W. A., Bliven, L. F., and Hudak, D.: Use of 2D-video disdrometer to derive mean density–size and Ze–SR relations: Four snow cases from the light precipitation validation experiment, Atmospheric Research, 153, 34–48, https://doi.org/10.1016/j.atmosres.2014.07.013, 2015.

Jolliffe, I. T. and Stephenson, D. B.: Forecast verification: A practioner's guide in atmospheric science, Wiley-Blackwell, Oxford, England, 2nd edn., https://doi.org/10.1002/9781119960003, 2012.

Juga, I., Hippi, M., Moisseev, D., and Saltikoff, E.: Analysis of weather factors responsible for the traffic 'Black Day' in Helsinki, Finland, on 17 March 2005, Meteorlogical Applications, 19, 1–9, https://doi.org/10.1002/met.238, 2012.

Kämäräinen, M., Hyvärinen, O., Jylhä, K., Vajda, A., Neiglick, S., Nuottokari, J., and Gregow, H.: A method to estimate freezing rain climatology from ERA-Interim reanalysis over Europe, Natural Hazards and Earth System Sciences, 17, 243–259, https://doi.org/10.5194/nhess-17-243-2017, 2017.

Kochendorfer, J., Rasmussen, R., Wolff, M., Baker, B., Hall, M. E., Meyers, T., Landolt, S., Jachcik, A., Isaksen, K., Brækkan, R., and Leeper, R.: The quantification and correction of wind-induced precipitation measurement errors, Hydrology and Earth System Sciences, 21, 1973–1989, https://doi.org/10.5194/hess-21-1973-2017, 2017.

Krajewski, W. F., Kruger, A., Caracciolo, C., Golé, P., Barthes, L., Creutin, J.-D., Delahaye, J.-Y., Nikolopoulos, E. I., Ogden, F., and Vinson, J.-P.: DEVEX-disdrometer evaluation experiment: Basic results and implications for hydrologic studies, Advances in Water Resources, 29, 311–325, https://doi.org/10.1016/j.advwatres.2005.03.018, 2006.

Lanza, L. G. and Vuerich, E.: Non-parametric analysis of one-minute rain intensity measurements from the WMO Field Intercomparison, Atmospheric Research, 103, 52–59, https://doi.org/10.1016/j.atmosres.2011.04.021, 2012.

Lanzinger, E., Theel, M., and Windolph, H.: Rainfall amount and intensity measured by the Thies laser precipitation monitor, in: WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO-2006), pp. 4–6, Geneva, Switzerland, 2006.

Leinonen, J., Moisseev, D., Leskinen, M., and Petersen, W. A.: A climatology of disdrometer measurements of rainfall in Finland over five years with implications for global radar observations, Journal of Applied Meteorology and Climatology, 51, 392–404, https://doi.org/10.1175/JAMC-D-11-056.1, 2012.

Locatelli, J. D. and Hobbs, P. V.: Fall speeds and masses of solid precipitation particles, Journal of Geophysical Research, 79, 2185–2197, https://doi.org/10.1029/JC079i015p02185, 1974.

Merenti-Välimäki, H.-L., Lönnqvist, J., and Laininen, P.: Present weather: Comparing human observations and one type of automated sensor, Meteorological Applications, 8, 491–496, https://doi.org/10.1017/S1350482701004108, 2001.

Mitchell, D. L.: Use of mass- and area-dimensional power laws for determining precipitation particle terminal velocities, Journal of the Atmospheric Sciences, 53, 1710–1723, https://doi.org/10.1175/1520-0469(1996)053<1710:UOMAAD>2.0.CO;2, 1996.

Nanko, K., Hotta, N., and Suzuki, M.: Assessing raindrop impact energy at the forest floor in a mature Japanese cypress plantation using continuous raindrop-sizing instruments, Journal of Forest Research, 9, 157–164, https://doi.org/10.1007/s10310-003-0067-6, 2004.

Nanko, K., Watanabe, A., Hotta, N., and Suzuki, M.: Physical interpretation of the difference in drop size distributions of leaf drips among tree species, Agricultural and Forest Meteorology, 169, 74–84, https://doi.org/10.1016/j.agrformet.2012.09.018, 2013.

Pickering, B. S., Neely III, R. R., and Harrison, D.: The Disdrometer Verification Network (DiVeN): A UK network of laser precipitation instruments, Atmospheric Measurement Techniques, 12, 5845–5861, https://doi.org/10.5194/amt-12-5845-2019, 2019.

Pollock, M. D., O'Donnell, G., Quinn, P., Dutton, M., Black, A., Wilkinson, M. E., Colli, M., Stagnaro, M., Lanza, L. G., Lewis, E., Kilsby, C. G., and O'Connell, P. E.: Quantifying and mitigating wind-induced undercatch in rainfall measurements, Water Resources Research, 54, 3863–3875, https://doi.org/10.1029/2017WR022421, 2018.

Raupach, T. H. and Berne, A.: Correction of raindrop size distributions measured by Parsivel disdrometers, using a two-dimensional video disdrometer as a reference, Atmospheric Measurement Techniques, 8, 343–365, https://doi.org/10.5194/amt-8-343-2015, 2015.

Raupach, T. H., Thurai, M., Bringi, V. N., and Berne, A.: Reconstructing the drizzle mode of the raindrop size distribution using double-moment normalization, Journal of Applied Meteorology and Climatology, 58, 145–164, https://doi.org/10.1175/JAMC-D-18-0156.1, 2019.

Savina, M., Schäppi, B., Molnar, P., Burlando, P., and Sevruk, B.: Comparison of a tipping-bucket and electronic weighing precipitation gage for snowfall, Atmospheric Research, 103, 45–51, https://doi.org/10.1016/j.atmosres.2011.06.010, 2012.

Schauwecker, S., Gascón, E., Park, S., Ruiz-Villanueva, V., Schwarb, M., Sempere-Torres, D., Stoffel, M., Vitolo, C., and Rohrer, M.: Anticipating cascading effects of extreme precipitation with pathway schemes - Three case studies from Europe, Environment international, 127, 291–304, https://doi.org/10.1016/j.envint.2019.02.072, 2019.

Thurai, M. and Bringi, V. N.: Application of the generalized gamma model to represent the full rain drop size distribution spectra, Journal of Applied Meteorology and Climatology, 57, 1197–1210, https://doi.org/10.1175/jamc-d-17-0235.1, 2018.

Thurai, M., Bringi, V. N., Carey, L. D., Gatlin, P., Schultz, E., and Petersen, W. A.: Estimating the accuracy of polarimetric radar–based retrievals of drop-size distribution parameters and rain rate: An application of error variance separation using radar-derived spatial correlations, Journal of Hydrometeorology, 13, 1066–1079, https://doi.org/10.1175/JHM-D-11-070.1, 2012.

Thurai, M., Gatlin, P., Bringi, V. N., Petersen, W., Kennedy, P., Notaroš, B., and Carey, L.: Toward completing the raindrop size spectrum: Case studies involving 2D-video disdrometer, droplet spectrometer, and polarimetric radar measurements, Journal of Applied Meteorology and Climatology, 56, 877–896, https://doi.org/10.1175/JAMC-D-16-0304.1, 2017.

Tiira, J., Moisseev, D. N., von Lerber, A., Ori, D., Tokay, A., Bliven, L. F., and Petersen, W.: Ensemble mean density and its connection to other microphysical properties of falling snow as observed in Southern Finland, Atmospheric Measurement Techniques, 9, 4825–4841, https://doi.org/10.5194/amt-9-4825-2016, 2016.

Tobin, C., Rinaldo, A., and Schaefli, B.: Snowfall limit forecasts and hydrological modeling, Journal of Hydrometeorology, 13, 1507–1519, https://doi.org/10.1175/JHM-D-11-0147.1, 2012.

Toivonen, K. and Kantonen, J.: Road weather information system in Finland, Transportation Research Record: Journal of the Transportation Research Board, 1741, 21–25, https://doi.org/10.3141/1741-04, 2001.

Tokay, A., Petersen, W. A., Gatlin, P., and Wingo, M.: Comparison of raindrop size distribution measurements by collocated disdrometers, Journal of Atmospheric and Oceanic Technology, 30, 1672–1690, https://doi.org/10.1175/JTECH-D-12-00163.1, 2013.

Unterstrasser, S. and Zängl, G.: Cooling by melting precipitation in Alpine valleys: An idealized numerical modelling study, Quarterly Journal of the Royal Meteorological Society, 132, 1489–1508, https://doi.org/10.1256/qj.05.158, 2006.

Upton, G. and Brawn, D.: An investigation of factors affecting the accuracy of Thies disdrometers, in: WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO-2008), pp. 27–29, St. Petersburg, Russian Federation, https://library.wmo.int, 2008.

von Lerber, A., Moisseev, D., Bliven, L. F., Petersen, W., Harri, A.-M., and Chandrasekar, V.: Microphysical properties of snow and their link to Ze–S relations during BAECC 2014, Journal of Applied Meteorology and Climatology, 56, 1561–1582, https://doi.org/10.2307/26179967, 2017.

Wolff, M. A., Isaksen, K., Petersen-Øverleir, A., Ødemark, K., Reitan, T., and Brækkan, R.: Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: Results of a Norwegian field study, Hydrology and Earth System Sciences, 19, 951–967, https://doi.org/10.5194/hess-19-951-2015, 2015.

Yang, D.: Double Fence Intercomparison Reference (DFIR) vs. Bush Gauge for "true" snowfall measurement, Journal of Hydrology, 509, 94–100, https://doi.org/10.1016/j.jhydrol.2013.08.052, 2014.

Yuter, S. E., Kingsmill, D. E., Nance, L. B., and Löffler-Mang, M.: Observations of precipitation size and fall speed characteristics within coexisting rain and wet snow, Journal of Applied Meteorology and Climatology, 45, 1450–1464, https://doi.org/10.1175/JAM2406.1, 2006.

Table 1. Reclassification scheme used for the comparison of dominant precipitation phase (1 min) between the Thies disdrometer and the two-dimensional video disdrometer (2DVD). (Note: Codes in square brackets refer to precipitation types which are not yet identifiable automatically, i.e. these codes are not reported by the instrument.)

Table 2. Minimum precipitation thresholds established in the calibration period to optimize precipitation detection for different integration times. The thresholds are chosen to minimise the distance to an ideal point in a receiver operating characteristic (ROC) diagram (i.e. a hit rate equal to 1 and a false alarm rate equal to 0, Fig. 4). The corresponding reduction in hit and false alarm rates as well as the resulting distance to this point are given for the independent validation period.

Table 3. Correction factors for the number of particles in 22 diameter classes as measured by the Thies disdrometer, resulting from a comparison to the two-dimensional video disdrometer in the calibration period. Measurements are separated into rain and snow based on the recorded dominant precipitation type by the Thies disdrometer (1 min).

Table 4. ~~Evaluation of~~ Biases in precipitation ~~intensities measured by~~ intensity measurements of the Thies disdrometer during the second year of measurement using the OTT pluviometer as a reference. ~~Bias (~~The absolute bias B ~~) und correlation coefficient~~ (~~Corr~~equation 6) of the uncorrected measurements ~~are~~ is given for all events as well as for rain and snowfall separately (left value). Furthermore, the effect of the two proposed correction methods is shown, i.e. the adjustment to the OTT pluviometer (middle value) and the two-dimensional video disdrometer (right value). The correction methods are thereby established during the first year of measurements.

Table 5. Comparison of the precipitation phase detected by the Thies disdrometer (rows) and the two-dimensional video disdrometer (columns). The numbers are given as percentages of the total number of 1 min observations during two years of measurements, which are equal to 2,533 h of precipitation.

Figure 1. Measurement devices located in a pre-alpine area in Switzerland (Innereriz, 1060 m a.s.l.). In this study, the Thies disdrometer is evaluated using both the OTT pluviometer as well as a two-dimensional video disdrometer as a reference during two years of measurements.

Figure 2. Comparison of the measurement principles of the Thies disdrometer (left) and the two-dimensional video disdrometer (2DVD, right): While the Thies disdrometer measures the attenuation of an infrared laser beam (786 nm) by falling particles, the 2DVD detects the shadowing of individual pixels by such particles in images taken by two optical cameras and from two perspectives.

Figure 3. Example of the classification algorithm developed in this study during a transition from rain to snowafall (2018-02-17 17:00 to 23:00 UTC). After a plausibility check, each hydrometeor detected by the two-dimensional video disdrometer is classified as one of 5 precipitation types (hail, rain, melting snow, graupel, snow). This classification is based on empirical relationships between particle diameter and fall velocity (equations 1–5).

Figure 4. Receiver operating characteristic (ROC) curves showing hit and false alarm rates of the Thies disdrometer with respect to the detection of precipitation using the OTT pluviometer as a reference. Left: Exploration of hit and false alarm rates during the whole time series (two years). Right: Effect on applying minimum precipitation thresholds on hit and false alarm rates during the second year of measurements. Note that the proposed thresholds are established during the first year of measurements in order to reduce false alarm rates, particularly for longer integration times.

Figure 5. Distribution of precipitation intensities and phase during missed events (left) and false alarms (right) by the Thies disdrometer during the validation period (each box shows the median and interquartile range of the distribution while the whiskers extend to 1.5 times this range from the box or to the most extreme data point). While precipitation intensities measured by the OTT pluviometer are analysed during missed events, precipitation intensities indicated by the Thies disdrometer are analysed during false alarms. Events are separated according to a temperature threshold (1.2 °C), and the relative frequency of missed events as well as the false alarm rate is given at the bottom of each panel for cases above and below this temperature threshold. Note that a logarithmic scale is used to display precipitation intensities.

Figure 6. Cumulative precipitation sums as measured by the Thies disdrometer (dashed lines) and the OTT pluviometer (solid lines) during the whole time series (two years). Precipitation sums are separated into rain and snow based on the recorded dominant precipitation type by the Thies disdrometer (1 min).

Figure 7. Precipitation intensities during periods of 30 min as recorded by the Thies disdrometer and the OTT pluviometer during the whole time series (two years). Precipitation is separated into rain (left) and snow (right) based on the recorded dominant precipitation type by the Thies disdrometer (1 min). To highlight systematic errors, a linear regression is shown in both panels (red line), which is forced through the origin and has a slope of 0.80 for rainfall intensities and of 1.05 for snowfall intensities.

Figure 8. Comparison of particle size distribution (PSD) obtained by the Thies disdrometer and the two-dimensional video disdrometer (2DVD) during the whole time series (two years). Left: Summed PSD during all observed rain and snowfall events. The separation into rain and snowfall events is based on the recorded dominant precipitation type by the Thies disdrometer (1 min). Right: Resulting correction factors for different diameter classes of the Thies disdrometer, using the 2DVD as a reference. Thereby, the median and variability of these correction factors is shown using monthly results (each box shows the interquartile range of the distribution while the whiskers extend to 1.5 times this range from the box or to the most extreme data point).

Figure 9. Relationship between snow particle density and mean particle diameter based on 1 min observations during the first year of measurements. Snowfall events are identified based on the recorded dominant precipitation type by the Thies disdrometer. Snow particle density is then calculated by comparing the precipitation volume measured by the two-dimensional video disdrometer (2DVD) and precipitation mass measured by the OTT pluviometer, and related to mean particle diameter as measured by the 2DVD. The fitted curve is used to translate particle size distribution into snowfall intensities during the second year of measurements. Note: The corresponding relationship established by Brandes et al. (2007) is shown as a reference.

Figure 10. Precipitation intensities during periods of 30 min as recorded by the Thies disdrometer and the OTT pluviometer during the second year of measurements). Precipitation is separated into rain, snow and other types (e.g. mixed) based on the recorded dominant precipitation type by the Thies disdrometer (1 min observation). The effect of the two proposed correction methods, i.e. adjustment to the OTT pluviometer and the two-dimensional video disdrometer (2DVD), are shown in separate panels (B: Bias; Corr: Correlation coefficient). Note that these adjustments distinguish between rain and snowfall and were established in the first year of measurements.

Figure 11. Relative frequency of the observed dominant precipitation phase by the Thies disdrometer (left) and the two-dimensional video disdrometer (2DVD, right) as a function of air temperature during two years of measurements (2,533 h of precipitation). For the 2DVD, the mixing ratio of liquid precipitation obtained at different temperatures is indicated by the 10th and 90th percentile of its distribution (dashed lines).