Answers to reviewer 2

We would like to thank the reviewer for his time and effort reviewing our study and for providing useful and constructive comments. We believe the comments have helped improve the manuscript and strengthen the statistical analysis. The comments of the reviewer are marked in black, our answers to the reviewer in red and the new text and lines of the revised document where the adjusted text can be found in blue. In the revised document, all new text is marked in blue, and deleted text is crossed out in red.

General comments:

One improvement that should benefit this manuscript is using more quantitative methods or language to illustrate differences between radar profiles that are grouped by the aggregate size class or cloud top temperature. For example, differences between the median profiles of a given radar variable from two different classes could be described relative to the standard deviations of the profiles within each class. Or, for example, the lower quantile of one class exceeds the upper quantile of another class at a certain height (or temperature).

A: We agree with the reviewer that we have neglected the description of the distributions/quantiles, and we have included a more detailed description of the quantiles especially in section 4 and 5.2.

As the descriptions in section 4 are currently presented, it is unclear how robust the presumed relations between the radar profiles and these classes (aggregate size and cloud top temperature) are without knowing whether they could be explained simply by random variability from subsetting the data.

A: In order to test the robustness of our statistics, we performed a bootstrapping analysis. We therefore randomly subsampled our dataset into 50% portions 50 times and analysed the distribution of medians of the different subsamples. The shaded areas in figure 2 represent the 25 and 75 percentile of the distribution of medians if we subsample our dataset and then classify it into CTT classes. The solid line is the median of the entire dataset as our best estimate for the median of the medians. The spread within the 25 and 75 percentiles is low. We therefore think that the medians presented in the paper are made out of robust statistics. We did the same analysis on the DWR-classes statistics. The results are similar: the spread between the 25 and 75 percentile is small. Hence, the statistical analysis of the DWR-classes appears to be robust. We therefore conclude that the differences in radar variable profiles that we see between the classes is beyond what we would expect from randomly grouping into different classes.

Adding more quantitative language to these areas of the manuscript (especially section 5.2) should help better qualify whether the relations are physical or incidental.

A: We agree and changed section 5.2 accordingly (see also answer to first comment)

I also think that the evaluation of the aggregate contribution to KDP requires more discussion of the impact of particle orientation. The single-particle calculations of KDP shown in Appendix C are acceptable for the purposes of illustrating the scattering behavior with respect to size, but likely overestimate the KDP of natural aggregates if a fixed horizontal orientation is used rather than a distribution that accounts for flutter or tumbling. As such, the claims in section 5.1 regarding the aggregate contribution to KDP should also be qualified as highly uncertain.

A: We agree that the calculation and estimated contribution of the aggregates to KDP strongly depends on the aggregate orientation chosen. With this ad hoc calculation we aimed to demonstrate the importance to take aggregates into account when interpreting KDP. It also shows that aggregates alone cannot explain the observed KDP signature even if they are assumed to fall perfectly oriented. In this way, our calculations should be seen as an upper limit estimate of the aggregate contribution to KDP. We have changed the text to underline the uncertainty of our method and that the ⅓ contribution is only to be thought of as the upper limit. In future studies we aim to estimate this in more detail by undertaking studies using Monte-Carlo lagrangian particle model simulations. By doing so, we do not need to explicitly assume a PSD and also different orientations can be accounted for.

Specific comments:

Line 102: I believe this relation should be reversed; the Rayleigh regime is valid for particles with size much smaller than the wavelength.
A: agreed, fixed in the manuscript (see Line 102 in revised document)

Lines 180-183: Is the spectral mask simply the region outside of the spectral edges determined by the bins exceeding the noise floor? Please clarify.
A: Yes, with the spectral mask we mask all areas which are outside of the estimated spectral edges from the Ka-Band radar. We have adjusted the text to make it more clear.
New text Line 183: *Our spectral mask is defined by the Doppler velocity bins identified by this method to contain real signal*

Line 252: Please add what specific measurements this correlation refers to.
A: The correlation always refers to the reflectivities of the reference radar (Ka) and one of the other two radars it is compared to (X or W).
New Text Line 253-254: *Further, regions for which the variance of the DWRs exceeds 2 dB^2*, or *where the correlation between Zes from the reference radar (Ka) and one of the other radars (X, W) is less than 0.7 are discarded*

Line 268: What is the maximum range used for the W-band measurements taken at 30-degree elevation angle? Please add what the horizontal distance is between data at this maximum range and the location of the vertically pointing radars.
A: The maximum range of the polarimetric W-Band radar is 16km (noted in Table 1). At an elevation angle of 30° this range corresponds to a maximum height above ground of 8km. The maximum horizontal distance at maximum range between the polarimetric radar and zenith radars is 13.86km. We have added a short text in the manuscript.
New Text Line 269-271: *At a maximum range of the polarimetric radar of 16 km (see also Table 1), the height above ground is 8 km and the maximum horizontal distance between the vertically pointing radar and the polarimetric radar is cos(30°) · 16 km = 13.86 km*

Line 305: I think using “slower than” is a bit more confusing than “greater than.” Maybe if there is a mention in the text of negative MDV corresponding to motion towards the ground, comparisons to specific values of MDV would be more appropriate than indirectly referring to the absolute value of MDV.
A: We agree and have adjusted the manuscript accordingly. We have also added a short explanation of the magnitude of MDV (and other velocity related variables such as spectral edge velocities)
New Text Line 317-319: *The MDV (Figure 2b) throughout the case are found to be larger than –1.5 m s−1 which indicates unrimed or only slightly rimed particles (Kneifel and Moisseev, 2020). Here we use the convention that negative (MDV) velocities correspond to motion towards the ground. Faster falling particle therefore have smaller (more negative) values than slower falling particles*

Lines 313-315: Please add that the ZDR at an elevation angle of 30 degrees will always be less than that measured at side incidence. It’s important to mention this difference because other studies of ice microphysics often observe ZDR at elevation angles closer to side incidence (i.e., < 5 degrees).
A: We agree and mention it now explicitly in the manuscript.
New Text Line 332: *Note that at 30° elevation ZDR is expected to be in general smaller than ZDR measured at lower elevation angles which have often been used in previous studies where data from lower frequency scanning radar systems have been analysed*

Line 338: It is preferable to say that the spectrum shifts rightward or towards larger values since there are weakly positive velocities in Fig. 3e near -15 degrees C.
A: Agreed. We changed the manuscript accordingly (see adjustment in Line 359 in revised manuscript)

Line 340-341: The wording here is a bit unclear. Do the authors mean something like: the main mode contributes more power to the spectrum than the secondary mode and therefore shifts of the main mode with respect to Doppler velocity dominate changes in MDV with height? Please clarify.
A: Yes this is what we were trying to say. We have reworded the phrase and hope it is clearer now!
New Text Line 361-363: *The main mode contributes more power to the spectrum than the newly formed secondary mode. Therefore, shifts of the main mode towards slower or faster velocities dominate changes in MDV. Hence, the slow-down of the main spectral mode at –12.5 ° C reduces the MDV at this temperature.*

Line 342: At -12 degrees C?
A: Yes, roughly at -12°C

Line 345: How much of these oscillations in KDP are due to noise in the PhiDP profiles compared to a microphysical signal?
A: We have investigated the variability of KDP due to the noise in PhiDP by analysing PPI scans btained at 85° elevations. At such high elevations, KDP is expected to be close to 0, deviations from 0 would correspond to the uncertainty due to noise in PhiDP. We applied the same processing to the PPI scans that we used on the 30° elevation data. However, we were only able to average over one PPI scan which lasted 1 minute in contrast to the 5 minute average we applied to the 30° elevation observations. Figure 1 shows the statistical analysis of KDP obtained from these PPI scans. The variability of KDP is rather small. For most temperature regions the median KDP oscillates between -0.05 and 0.01. Even the quantiles are within -0.15 and 0.1°/km. Since we were only able to apply a 1 minute average to the KDP from the PPI scans (as opposed to the 5 min average we apply on the 30° elevation data), we expect the variability of KDP at 30° elevation to be even less.

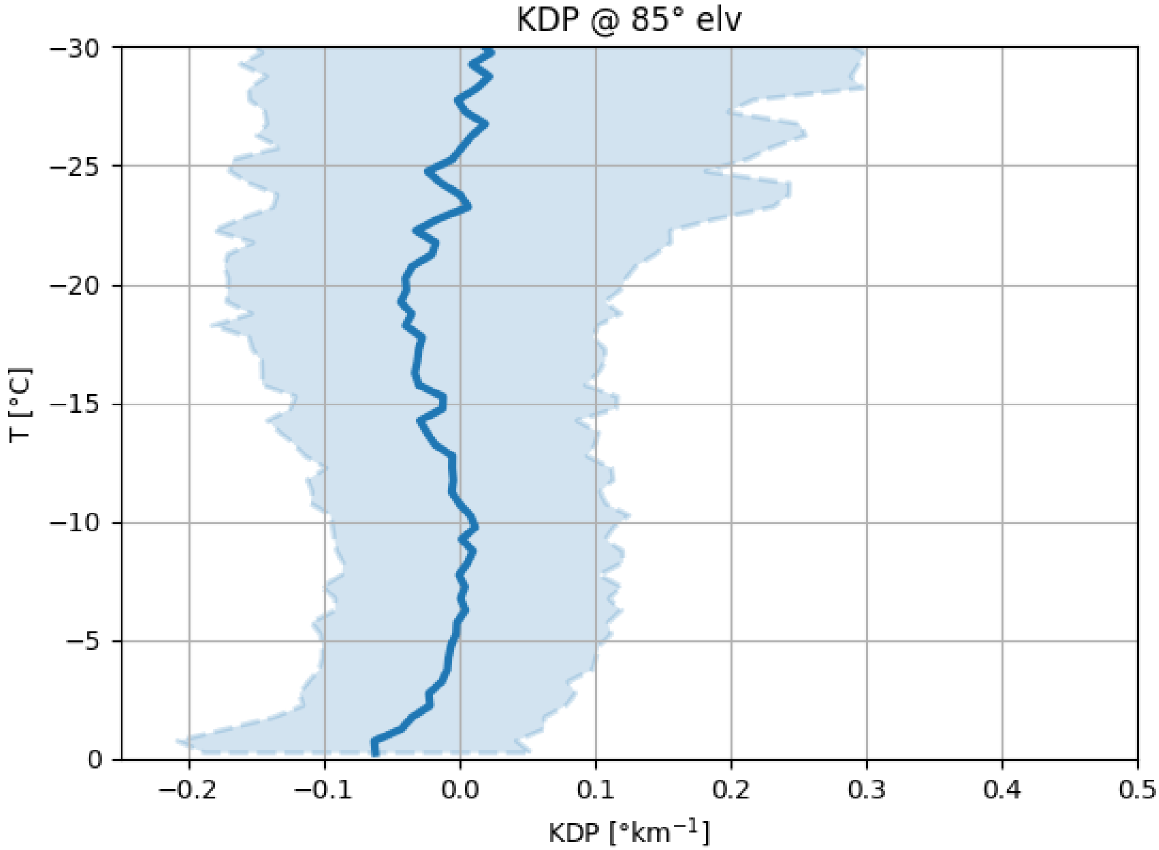

Figure 1: median KDP (solid line) and quantiles (shading) of KDP calculated from PPI at 85° elevation

Lines 351-359: I largely agree with this assessment. However, the lack of layered KDP enhancements observed in this study may also be due to a lack of strong forcing associated with mesoscale snowbands. In these snowband cases, there may be more particles and/or more rapid dendritic growth leading to more intense aggregation and thus a more rapid depletion of pristine ice crystals. The higher sensitivity radars used in this project would be able to detect weaker vapor growth and aggregation cases where the ice crystal depletion is slower, extending the KDP enhancement farther down. KDP observations of these weaker cases at S-band or X-band would likely show near-zero KDP throughout the profile. So in order for the low-frequency radars to detect measurable KDP enhancements in snow, there may need to be more substantial vapor growth and subsequent aggregation. Please address this potential for selection bias with respect to low-frequency radars in the text.

A: We have extended our discussion of this potential selection bias and included your suggestions.

New Text Line 380-386: *Another reason for the less layered appearance of KDP and ZDR might be an under-representation of cases with strong forcing conditions during TRIPEx-pol. More intense vertical air motions are expected to result in a larger* *concentration of particles and abundance of dendrites that is expected to lead to stronger aggregation and more intense depletion of ice crystals (e.g. Moisseev et al., 2015; Schrom et al., 2015). Radars operating at longer wavelengths can clearly detect these cases with large concentrations of ice crystals at –15 ° C but might miss cases with weaker forcing due to sensitivity limits. The differences in sensitivity between W-Band and lower frequency radars might cause a selection bias of low-frequency radars with respect to stronger depositional growth and aggregation cases.*

Line 369: Does continuous here refer to profiles without any masked regions?

A: Continuous in this case refers to profiles where there is a signal in all range gates between -10 and -20°C. With this we want to avoid multi-layered cases and therefore weak signals due to sublimation or new cloud tops. Usually this does not refer to masked regions, because during the DWR-calibration, entire profiles were discarded if the mentioned criteria were not met.

Line 388: Please use “dB” instead of “dBZ” for differences in reflectivity values.

A: Adjusted in the manuscript

Lines 396-397: Please change to “magnitude of MDV increases.”

A: Adjusted in the manuscript (see line 429-430 in revised document)

Line 405: Please change “upwind” to “updraft.”

A: Adjusted in the manuscript (see line 441 in revised document)

Line 422: How are the slow and fast edges of the spectra determined? Are they the first and last bins above the noise threshold?

A: The slow and fast edges were determined as described in section 2.2.1. We take the first and last bin 3dB above the noise threshold. In cases of strong Ze signals, there might be spectral leakages that could artificially broaden the spectra. We therefore further neglect all spectral lines which are lower than 40dBz with respect to the maximum spectral line.

Lines 426-427: Does this assumption that new particles decrease the slow edge of the spectrum require that these particles have a minimum fall velocity? For example, if the new particles only become detectable once their fall speed is 0.5 m/s, isn’t it possible that they would have no effect on the slow edge velocity?

A: From our practical experience we see new ice particle modes (can be distinguished from liquid drops by using for example sLDR) typically occurring at 0.2-0.3 m/s. This is also true for temperature regions of preferential columnar or needle growth such as close to the -7°C level. In this region, one would expect the particles to fall fastest even at small sizes due to their small cross sectional area. Rough estimates from scattering computations indicate (assuming typical range of concentrations) that ice crystals exceeding 100um in maximum size are well detectable by common cloud radars. This size range roughly matches the 0.2-0.3

m/s Doppler velocities where the first signal is usually detected (of course large variabilities in terminal velocities exist for individual crystals). Certainly, we cannot completely exclude the scenario which the reviewer described but we consider it as very unlikely. We are quite confident that new ice particle formation leads to a substantial decrease of the slow edge velocity especially if analysing a large dataset as presented in our study.

Line 499: Given that the example case study seems to have much higher skewness, KDP, and maximum spectral ZDR (near 4 dB according to Fig. 3f) compared to the bulk statistics, there should be some brief discussion of the uniqueness of that case relative to the others in the dataset.
A: The example profiles shown in Fig 3 have been selected to show the general behaviour in different radar variables in a more pronounced way as visible in the bulk statistics. The case study itself represents an event with stronger signals but it is certainly not an exceptional case. We mention this now also in the text.

New Text Line 305-307: *The case study selected shows more pronounced signals then the average profiles discussed later in the statistical analysis. However, the case is not an exceptional event and similar profiles of radar variables can be found frequently at JOYCE-CF during similar winter cases*
New Text Line 555-562: *Comparing the results of the statistical analysis to the case study presented in Section 3, we note the smaller values of KDP, sZDRmax and skewness found in the statistics. In the case study, sZDRmax values of up to 4 dB at around –15 ° C were reached, alongside a maximum KDP of approx. 2 ° km−1 and a skewness of 1.3. However, in the statistics we classify the profiles with the maximum DWRKaW. In Figure 2, one can see that we do not always find an increase in KDP or sZDRmax for increasing DWRKaW. For example, at 06:30 UTC, a strong increase in KDP below –15 ° C coincides with an enhanced sZDRmax and DWRKaW. At later periods of the day, for example at 18:00 UTC, we see enhanced DWRKaW without enhanced KDP and sZDRmax. Those examples explain why the medians in our statistical analysis are shifted to smaller values.*

Line 525: ZDR also tends to saturate as dendritic growth occurs because of the generally decreasing effective density of the particles with size. Please add some mention of this effect.
A: We added that to the manuscript
New Text Line 600: *Further, in case of dendritic growth, the effective density of the particle decreases with size, leading to a saturation of ZDR*

Line 558: The uncertainty in this value for the aggregate KDP contribution needs to be more clearly stated. For example, the orientation behavior of the aggregates can have a large impact on the measured KDP.

A: See also our answer to general comment 2. In general, for a given elevation angle, the strongest polarimetric signatures (both ZDR and KDP) are produced when particles are perfectly alligned either horizontally or vertically. Our assumption of perfect horizontal alignment of all particles is therefore an upper limit estimate for the possible contribution of aggregates to the total KDP. Certainly, the more realistic assumption of aggregate tumbling during their fall will reduce their contribution to KDP. We have added a sentence noting that to the appendix.
New Text Line 851-853: *This high contribution of aggregates to the observed KDP is most likely an upper limit, since we assume the aggregates to be perfectly horizontally aligned. The naturally occurring tumbling and fluttering of the particles within clouds would reduce the KDP (and ZDR) produced by aggregates.*

Lines 561-562: Please add a caveat here that there may be non-Rayleigh effects on KDP at larger size parameters than those examined in this study.
A: added to the manuscript
New Text Line 641-642: *It should be ntoed that this behaviour is expected to change for increasing size parameters (e.g., at radar frequencies higher than W-Band)*

Lines 612-613: Please reword this sentence for clarity.
A: We have adjusted this section to include more quantitative language and discussion of the percentiles. The sentences in this line were changed as well.

Lines 612-616: The comparisons between the radar variable profiles with different cloud top temperatures need to be more carefully stated in terms of how significant they are relative to sampling errors between the different groups. In other words, are the differences in particular radar variable profiles beyond what would be expected from randomly grouping the profiles into different classes?
A: In order to test the robustness of our statistics, we performed a bootstrapping analysis. We therefore randomly subsampled our dataset into 50% portions 50 times and analysed the distribution of medians of the different subsamples. This is also addressed in our answer to general comment 2. We concluded that the differences in radar variable profiles that we see between the classes is beyond what we would expect from randomly grouping into different classes.

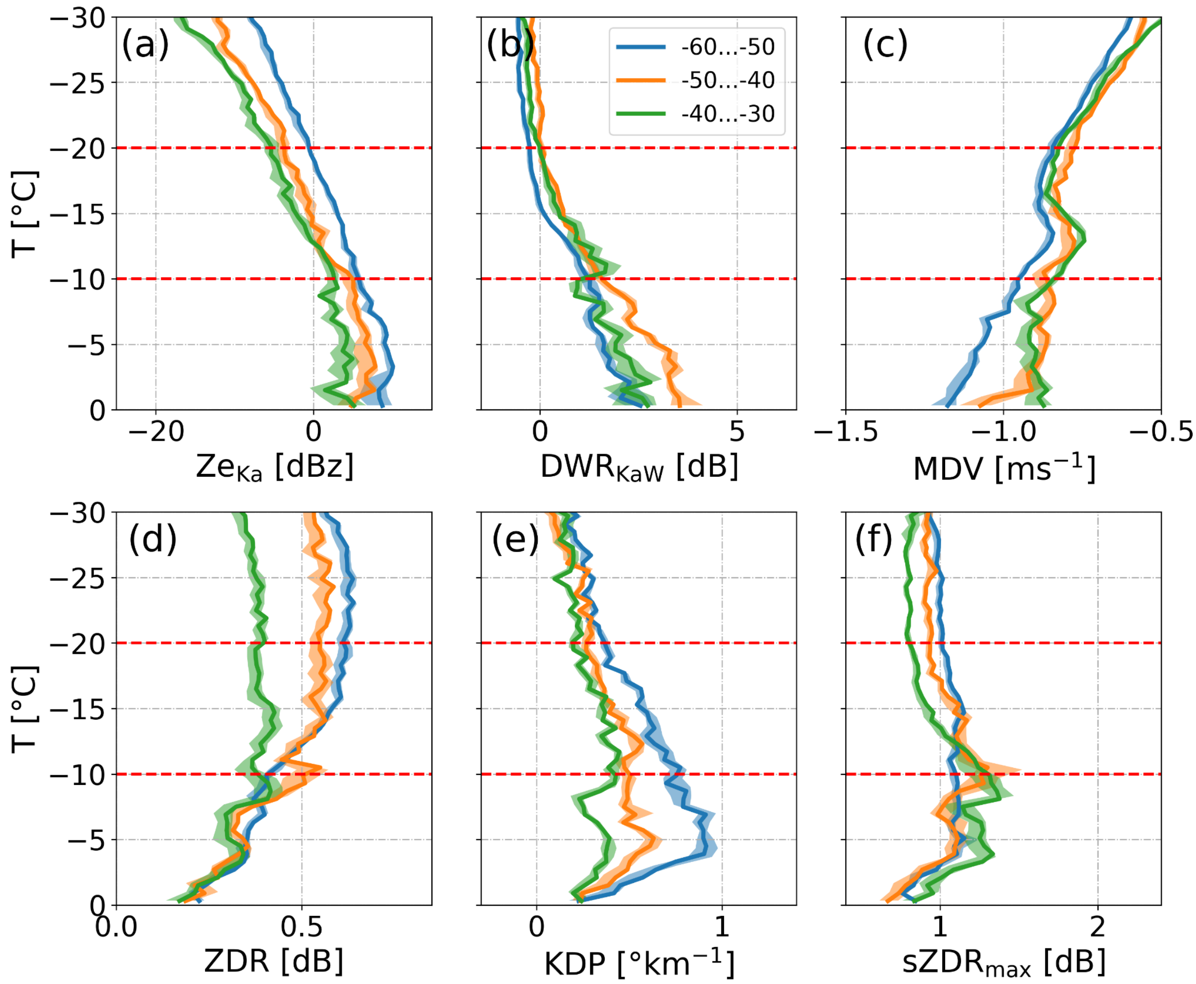

Figure 2: bootstrapping analysis of the CTT-statistics: distribution of medians of 50 subsamples. The subsample size was 50% of the original dataset. The shaded areas indicate the 25 and 75 percentile of the distribution of medians. The solid line is the median of the original dataset.

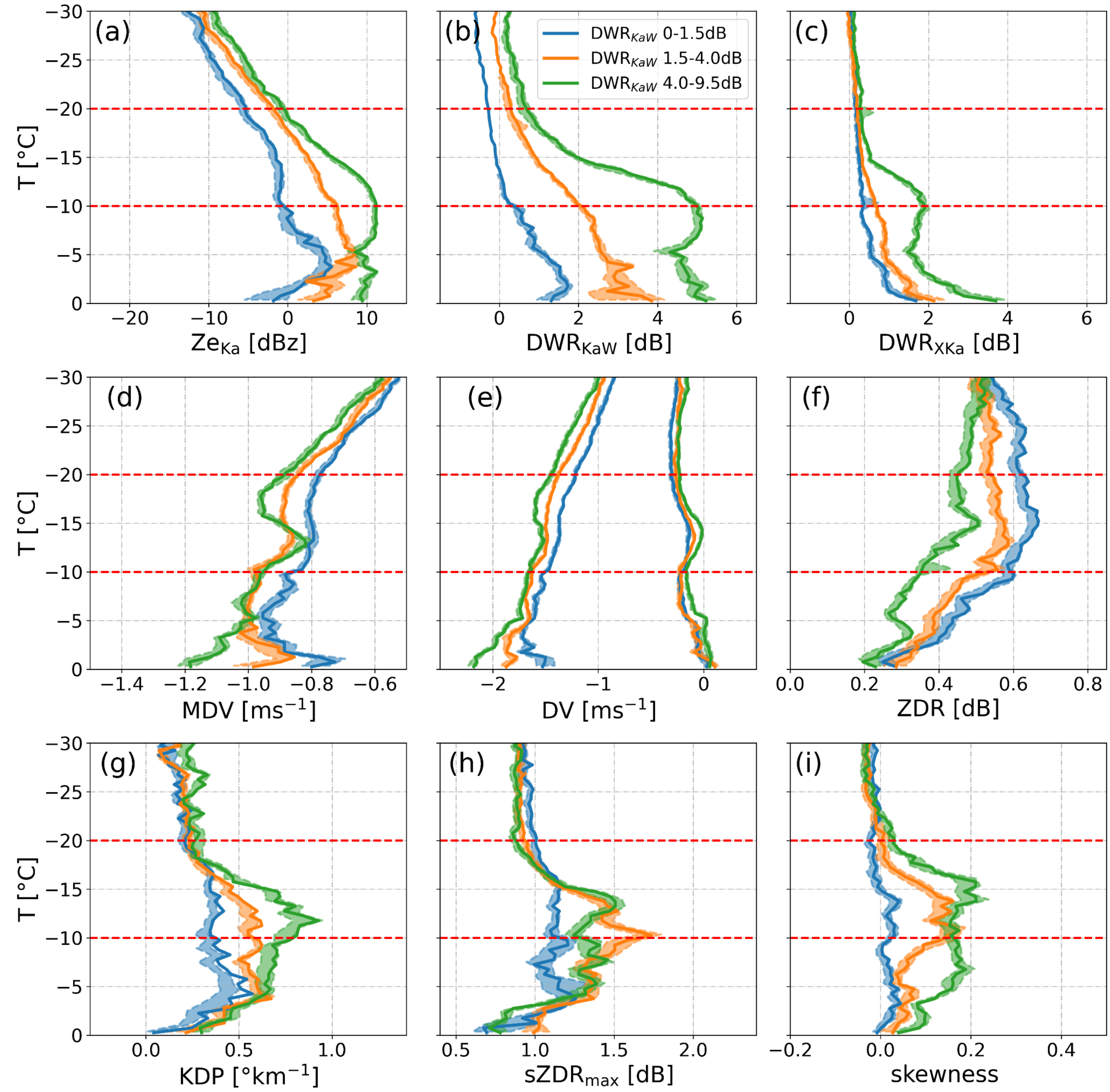

Figure 3: bootstrapping analysis of the DWR-statistics: distribution of medians of 50 subsamples. The subsample size was 50% of the original dataset. The shaded areas indicate the 25 and 75 percentile of the distribution of medians. The solid line is the median of the original dataset.

Line 654: Please clarify what properties of the sedimenting particles are being considered to have no effect on KDP and sZDRmax here.

A: We are not sure if we understand the reviewer here. In this part, we are solely describing the evolution of the observed profiles: "Similar as for KDP, no strong difference is found in $sZDR_{max}$ for particles sedimenting into the DGL from above."

Lines 752-754: What orientation assumptions are being used to calculate the aggregate KDP?

A: We have used horizontally aligned particles. (Already stated in line 713)

Does the simulated ZDR for the aggregates with these PSD assumptions agree with the measurements?

A: We obtain a ZDR of 2.5dB for the perfectly oriented aggregates assumed in our example calculation. This value is certainly larger than the 1.25dB observed at -12°C. sZDRmax in the statistics is quite small. Since there are cases with very small sZDRmax values, the median of our statistics is shifted towards smaller values. Also, fluttering would reduce the ZDR of the aggregates.