Review of amt-2021-216 (authors reply to Anonymous Referee #2)

The manuscript "Retrievals of ice microphysics using dual-wavelength polarimetric radar observations during stratiform precipitation events" is improved from its previous version. A minor revision is recommended.

Dear Reviewer,

On behalf of the co-authors of this manuscript I would like to thank you for your review. Our replies to your comments can be found below in blue color. Changed sentences in our manuscript are written in italics.

Thank you a lot once again for your feedback.

Kind regards,
Eleni Tetoni

Specific comments:
Line 90: Define σ_n.
Thank you for this comment. The phrase (line 70) is now changed to: "*$\eta = \sum_{Vol} \sigma_n$; normalized to a specific volume summation of backscattering cross-section, σ_n, of all detected hydrometeors*".

Line 162: Add "differential" to specific propagation phase (KDP – the name is usually defined as specific differential phase).
Thank you for pointing this out. "differential" is now added to – currently – line 123.

Line 172-173: You use capital ZH and ZV (which are common for a log scale), whereas you use linear zH and zV in the definition, eq. (3). Try to be consistent with the definition.
Thank you we have now fixed that typo (lines 132–133).

Lines 210-211: The sentence is somewhat confusing, reformulate it.
Thank you for this comment. After reformulating the sentence, it now reads: "*The same study also concluded that, spheroids are more suitable to represent larger particles (maximum diameter up to 2.5mm) in simulations rather than Mie spheres can, as the latter can lead to a strong overestimation of Z_e*" (lines 168–170).

Line 255: The word "this" is repeated, fix the typo.
We have now fixed that, thank you (line 217).

Lines 1062-1064: This sentence is unclear.
After rephrasing, the sentence is now changed to: "*Statistical results of the retrieved S, D_m as well as IWC are presented in Fig. 14*. For these results it is assumed that *ice hydrometeors are represented by ice spheroids following an exponential PSD and with $m(D_{max})$ corresponding to this of aggregates.*" (lines 724–726).

Lines 1073-1074: The right parenthesis/bracket ")" at the end of the sentence is missing.
A bracket is now added, thank for pointing this out (line 743).

*All line numbers refer to the file with track changes.

Manuscript ID: acp-2021-216 (amt-2021-216, authors reply to Anonymous Referee #4)

Review of "Retrievals of ice microphysics using dual-wavelength polarimetric radar observations during stratiform precipitation events"

Dear Reviewer,

On behalf of all co-authors I would like to thank you for your time to review our manuscript and for the valuable feedback you provided to us. In the following lines you can find our replies to your comments/suggestions written with blue color. New or changed sentences/paragraphs in our manuscript are quoted in italics.

Thank you a lot once again.

Kind regards,
Eleni Tetoni

General Comment

This is my first review of this manuscript, while the manuscript has been revised accounting for comments from the reviews in the previous review process. The manuscript proposed a novel approach for IWC and Dm retrievals that utilize multi parameters available for observation using two polarimetric Doppler radars. Application of this technique is limited to vertical slices of one location only. The authors sincerely revised the manuscripts, and the technique proposed in this study has been evaluated carefully. There are a few points that the authors should address before publication.

Specific comments

1. I suggest changing the title to "Retrievals of ice microphysical properties….". First I saw the current title, I thought that the study discussed microphysical processes such as particle growth processes in cloud. However, this manuscript focused more on retrievals of IWC, Dm, etc., which are microphysical properties.

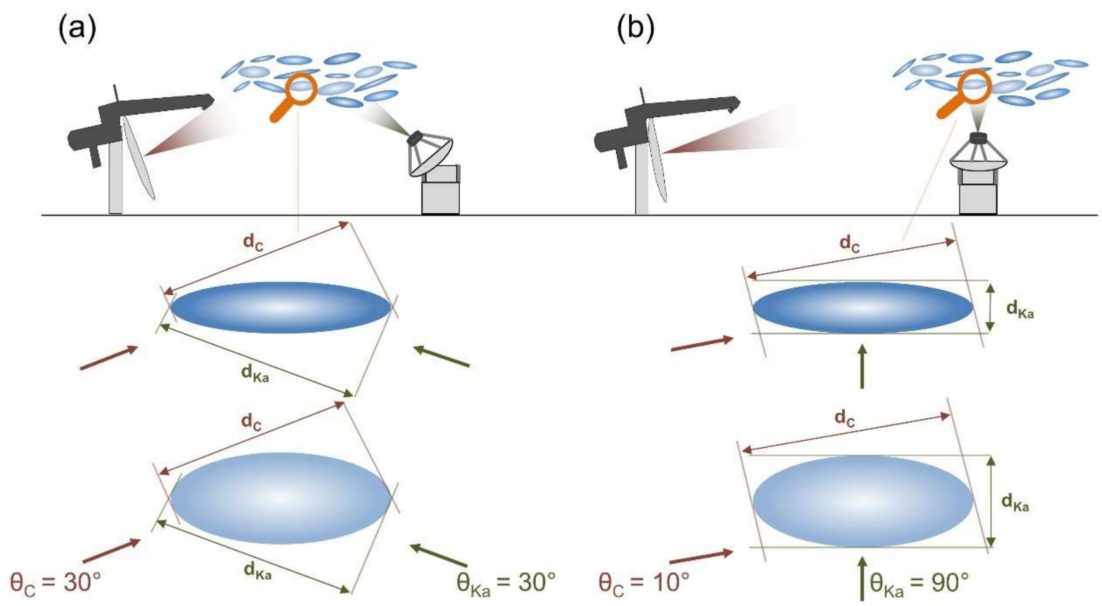
Thank you very much for this suggestion. We have now changed the title of the manuscript to: *"Retrievals of ice microphysical properties using dual-wavelength polarimetric radar observations during stratiform precipitation events*".

2. What is the advantage of this method over the conventional method such as Z-only and Z+polarimetric variable-only retrievals? I agree that the DWR could be an additional constraint, but this study did not demonstrate comparisons.

To our opinion, our approach has multiple advantages. First of all, in a possible Z-only retrieval we should keep in mind that the radar reflectivity can be sometimes affected by non-Rayleigh/Mie effects especially at higher-frequency radars (e.g., Ka- band) resulting to lower values than Z measured by lower frequency radars (e.g., C-, X-band). However, we exploit this difference in radar reflectivities by using DWR to infer information about the size of the atmospheric hydrometeors. DWR has been used so far in many conventional size retrievals, usually by making an a-priori assumption of the ice particles shape, e.g., specific value of aspect ratio assumed to retrieve the particles size. In our approach, next to the DWR which is used to infer size information, polarimetry variables, i.e., ZDR, obtained from a scanning radar can be efficiently used to provide shape information, especially when the other scanning radar is pointing upwards. This advantage has been stressed out in a lot of parts of our manuscript, e.g., lines 26–29 or 886–889. It is common that multi-wavelength techniques are applied to vertically pointing radars. This option though, doesn't allow for polarimetric measurements as e.g., oblate ice particles would appear like spheres. On the contrary, our scanning radars can provide such an observations combination making the simultaneously size and shape retrieval of the detected hydrometeors, possible (see also our new Fig. 19). Furthermore, in our study we prove that two spatially separated radars can be combined to provide ice microphysics information. Therefore, operational weather radars located throughout Germany can be used in synergy with already established cloud radar sites to monitor precipitation but also to obtain microphysical properties of atmospheric hydrometeors.

3. Figure 19: I do not think that this image represents a natural situation properly. This image seems to assume that there is a single ice particle in a sampling volume and presents only one radar beam incidence at a single point of the particle. However, the radar observables represent ensembles of PSD and scattering by multiple incident points.

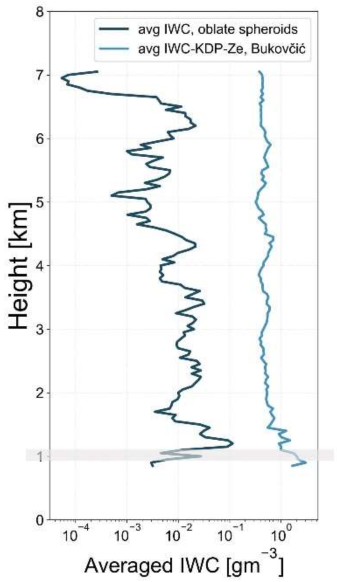
Thank you for pointing this out. We have now created a new version of Fig. 19 (also attached below). The radars setup is also visible in our new plot showing how the radar beams detect ice hydrometeors populations which are assumed to be soft spheroids. We then zoom in in the spheroids ensembles and use a single oblate spheroid to which represents the average aspect ratio of the whole spheroids PSD to describe the effect of the different radar geometries on the apparent shape retrieval.



4. I understand that using a cost function is effective to reduce errors. But, I wonder whether the results from this technique can be consistent with the theory-based retrievals. For example, was the aspect ratio retrieved in this study consistent with that from Matrosov's et al. (2017) technique? Was the IWC retrieved in this study consistent with that from Bukovcic's et al. (2018) technique?

Thank you for this comment. Studying the suggested literature, we proceeded with some comparison plots for the ice water content retrieval.

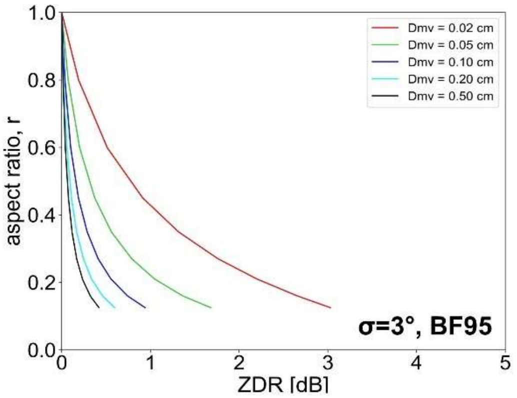
Using our C-band radar KDP (and not S-band as the literature suggests) along with Ze for the presented – in the manuscript – case study, we calculated the IWC from the Bukovčić et al. (2018) formula: $IWC(KDP, Ze) = 0.71 KDP^{0.65} Ze^{0.28}$. The results are shown below. Our retrieval shows lower IWC values using oblate spheroids than the theoretical formula.

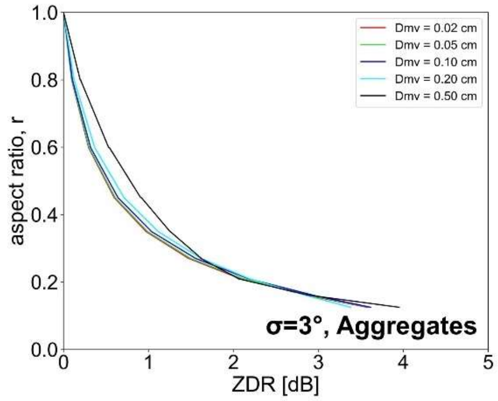


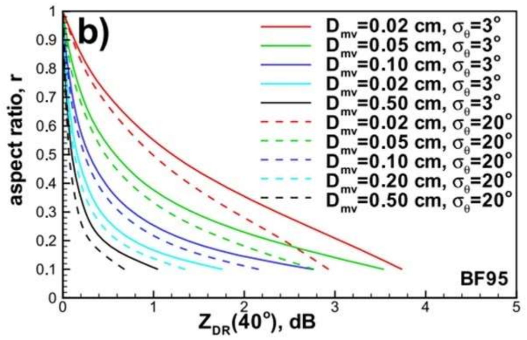
To further evaluate both results we calculated the ice water path (IWP) in both cases and compared it to IWP data from MODIS MYD06_L2 product (Platnick, S., Ackerman, S., King, M. et al., 2017). From MODIS, an averaged value of IWP ~ 90 g m^{-2} was retrieved for the whole radar cross-section. Using our retrieved IWC and integrating with height we obtain IWP ~ 83 g m^{-2} , while we obtain 3622 g m^{-2} when retrieved IWC from Bukovčić et al. (2018) was used.

Deeper investigation of this difference shows that for Bukovčić's retrieval of $IWC_{Bukovčić}$ = 2 g m^{-3} at 1 km, approximately 5 times smaller particles (melted equivalent size is meant here) would be needed to explain the observed reflectivity of e.g., Z_e ~ 15 dBZ. More precisely for the retrieved IWC at 1 km, $IWC_{Bukovčić}$ = 2 g m^{-3} and IWC_{Tetoni} = 0.02 g m^{-3}. Assuming particles size 1 mm for our retrieved IWC and solving $Z_e = ND^6$ for particle size, we obtain a melted equivalent size ~ 200 microns that could explain the $IWC_{Bukovčić}$ retrieval. As Bukovčić's retrieval includes no information about particle size, we consider our IWC to be closer to reality since we retrieve particles size before the IWC.

To answer how consistent our aspect ratio retrieval is, we compared our scattering calculations to Matrosov et al., 2017 their Fig. 3b (attached below). Comparing the simulation lines we observe differences between our calculations and those of Matrosov. For BF95 mass-size relation when the standard deviation would be 3° and the median volume diameter = 0.02 cm, ZDR = 1 dB would give aspect ratio = 0.55 in Matrosov's approach, while the retrieved aspect ratio according our calculations would be 0.45 (i.e., 20% lower values). Differences between our AR-ZDR simulations and Matrosov could arise from the way that a mixture of air-ice is considered in the mixing formula used to calculate the refractive index, i.e., an ice matrix with inclusions of air or an air matrix with inclusions of ice, of the soft spheroid. In our study "*Our soft spheroid model uses the effective medium approximation (EMA) to model the refractive index of the composite material as an ice matrix with inclusions of air following the Maxwell-Garnett (MG) mixing formula given in Garnett and Larmor (1904)*" (lines 439–441), while for Matrosov approach we couldn't spot this information. In our manuscript we mainly used the aggregates m(Dmax) from Yang et al., 2000. In this case, ZDR = 1 dB would give an aspect ratio of ~0.38 when median volume diameter = 0.02 cm. In general, for our both mass-size relation assumptions, the retrieved aspect ratio is lower than this retrieved using Matrosov's approach.





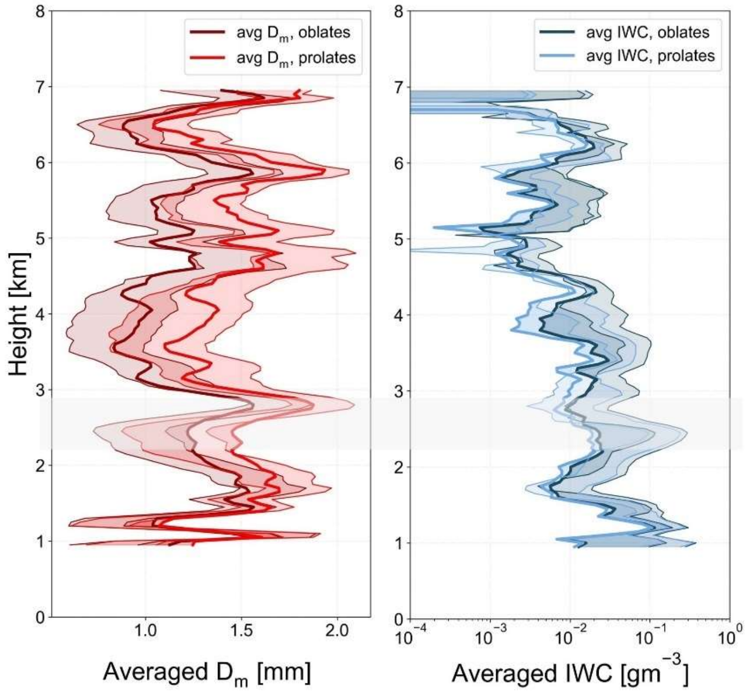


5. Was the attenuation A calculated from the attenuated reflectivity and Zdr values? If so, how can the uncertainty impact the IWC and Dm retrievals?

During our scattering simulations we performed specific attenuation *A* calculations with respect to the three degrees of freedom (mass, size, shape) used for our soft spheroids. Therefore, this parameter was calculated during the retrieval using the first step retrieval's output (Fig. 10) and the indices that minimized the two cost functions for Z_e, ZDR and DWR in our 3D LUTs, and not estimated by empirical relations from literature. The specific attenuation for our presented case study was retrieved relatively small as our ice spheroids were considered to be dry (we consider mainly dry ice particles in our analysis) and with low-density. This resulted to small values of total attenuation at both radar bands (see our Fig. S2, in our submitted supplementary material) and in turn, to almost no difference in the correction of radar reflectivities and thus, in the retrieved parameters. However, we are aware that attenuation from wet snow can be significant, especially for our Ka-band radar. In this case, the largest part of DWR would origin from attenuation effects, resulting to large uncertainties in size retrieval.

6. A region of relatively large Dm in Fig. 11b seems to correspond to a region of estimated DWR error due to the volumetric mismatch error (Fig. 5f). Are the Dm values intrinsic? Can they be used for the IWC retrieval?

Thank you for your question. All retrieved parameters are described along with their errors originated by the thoroughly analyzed different sources (Sect. 3.1.2 of our manuscript). For instance, we attach the Dm as well as IWC results along with their errors, highlighting the area that you indicated. The errors for IWC are indeed large in that area, too. However, we consider the Dm values intrinsic. The DWR error is calculated considering two components. The spatiotemporal and the beam width differences in the measured – from the two radars – volume. In the presence of strong gradient of DWR originated from microphysics, one has to expect large DWR errors. Our error estimation method, in the case of the very thin ~500 m layer around the altitude of 2.5 km, considers this mismatch to origin from the volume mismatch. In these areas the retrieved ice microphysical properties should be carefully treated. In a possible next version of this algorithm we can exclude areas where the calculated DWR error exceeds some limits (also suggested in lines 931–933 of our manuscript). The selection of such criteria needs in depth sensitivity studies but for sure will improve the performance of our retrieval.



7. Provide brief case description for each case to see what kind of snow events this technique was applied to.

Thank you for your comment. Throughout the main body of our manuscript we use one case study to demonstrate our methodology and 59 case studies in total to derive statistics. We have now added a brief meteorological description of the presented case in lines 307–311. The addition is the following: "*At 04:00 UTC of that night, an ice cloud started forming at an altitude of 9 km. During the time of our coordinated measurements the cloud's vertical extension was up to 7 km. Throughout that day, the ambient temperature was mostly below 0°. The wind speed at the surface was very low, while at higher altitudes exceeded 15 m s^{-1} at some cases. The vertical gradient of the wind favored the development of fall streaks (also shown in our radar observations in Fig. 3) and thus, ice particle growth within the ice cloud.*"

8. This technique can be applied to only one vertical cross section (i.e. RHIs directed toward only one azimuth). Please discuss how this can be used to observe microphysical processes and general characteristics of clouds.

Thank you for pointing this out. A small discussion is now added in lines 233–241. In particular we write: "*Our approach considers single RHI scans from each radar instrument resulting to a single radar cross-section. In the special case when the wind direction in this area is aligned to our radars cross-section, we can monitor the evolution of precipitation and the development of fall streaks inside* *the clouds by performing continuous RHI scans according to the precipitation rate. Another approach to deeply investigate the initiation of convection as well as to better observe ice microphysical processes in clouds, in a separate study, we performed sector range-height indicator (S-RHI) using POLDIRAD and MIRA-35 to monitor precipitation cells during convection. In this way, a first scan was executed towards the cell of interest at a specific azimuth. Then, two additional fast RHI scans were executed from each radar deviated ±2° from the initial azimuth. This approach can result nine vertical profiles within the precipitation cell providing additional microphysical information (Köcher et al., 2022, their Fig. 1)."*

Technical comments

1. Fig. 11c, Fig. 12a, and Fig.12c look exactly same. Why?

Figure 11c (sphericity), Fig. 12a (aspect ratio) and Fig. 12c (sphericity) referring to shape results for prolate ice spheroids are indeed identical. This originates from the aspect ratio definition (AR=horizontal to rotational axis; lines 456-457 and Fig. 6) which results aspect ratio values <1 for prolate soft spheroids. The sphericity *S* is defined as the minor-to-major axis ratio (line 167) and in the case of prolate ice spheroids it is found <1. For oblate ice spheroids the sphericity is derived from the reverse of the AR value (see also Fig. 6). Moreover, in line 583–584 we state that for our calculations we use "*0.125, 0.16, 0.21, 0.27, 0.35, 0.45, 0.6, 0.8, 1.0) for the horizontally aligned prolates and the inverse values for the oblate particles*", and resulting the same *S* values for both shape assumptions.

E.g.,

Oblate: $S = 0.6$, AR = 1.67

Prolate: $S = 0.6$, AR = 0.6

2. Please provide scan speeds for each radar observation.

Thank you for this comment. We have now added information about the scan speed of the two radars in line 278–279 (POLDIRAD; elevation velocity 1°/s) and 290 (MIRA-35; elevation velocity 4°/s).

3. Table 2: Provide sample size. How many RHI slices were available for each case?

Thank you. We have now added this information in Table 2 as well as Table 4.

4. How was the DWR from different radar coordinates taken? Were the reflectivity data gridded? If so, how were the data gridded?

The way that DWR was obtained using two radars at different locations is described in lines 322–331. The method how we interpolated the radar data is now added in these lines.
"*During the snow events, Z_e measurements from the two radars were performed and interpolated, using the nearest-neighbor interpolation method, onto a common rectangular grid (50 × 50 m^2). The 0-height of this grid is defined to be the height above MSL, while POLDIRAD and MIRA-35 locate at 602.5 m and 541 m height above MSL. In Fig. 3a and Fig. 3c, the measured Z_e from the two radar systems during the RHI scans from 30th January 2019 at 10:08 UTC is presented. For the MIRA-35 Z_e measurements we applied a calibration offset of 4 dBZ as derived in Ewald et al. (2019). Studying only snow cases no strong effects of hydrometeor attenuation are expected (e.g., Nishikawa et al., 2016). However, an iterative method to estimate hydrometeor attenuation has been developed.*

Additionally, both Z_e datasets are corrected for gaseous attenuation using the ITU-R P.676-11 formulas provided by International Telecommunication Union (ITU) in September 2016 (ITU-R P.676, 2016). Both methods are fully described in Sect. 3.3. After the interpolation of both radar reflectivities in the common radar grid, we calculated the DWR (Fig. 3b) using Eq. (2).“

5. Did you use weights for each term in the cost function?

Thank you for this comment. At the beginning we used weighting factors and one cost function for our ice microphysics retrieval. Therefore, the mass, size and shape of the ice particles were retrieved at once. This selection of the weighting factor values was not objective though and one could reasonably argue about these numbers. Moreover, the residuals between the simulated and measured values for the three different parameters, i.e., radar reflectivity, dual-wavelength ratio and differential radar reflectivity had not the same units and thus, they were not compatible. Hence, we proceeded without the use of weights, but instead of normalized differences, and we additionally introduced one more cost function. In this way we proceeded with the retrieval of the size and shape simultaneously, as we noticed that the DWR and ZDR remain the same for different values of IWC. At the second step we retrieved the mass, i.e., IWC, of the ice hydrometeors. (the invariance of DWR and ZDR can be found in Fig. 9 as well as in lines 589–592)

*All line numbers refer to the file with track changes.