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Interactive comment on "Observing ice particle growth along fall streaks in mixed-phase clouds using spectral polarimetric radar data" *by* Lukas Pfitzenmaier et al.

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General Comment: This study collected polarimetric Doppler spectra at an elevation angle of 45 degrees. The observed spectra were realigned with height along with retrieved fall streaks and analyzed the reflectivity and differential reflectivity spectra changing with height to discuss ice particle growth. The novelty technique and idea used in this study are very interesting, but sometimes I was confused by increase/decrease of fall speed when looking at the observed spectra. Because horizontal wind components would be larger than vertical wind components in slant pointing Doppler spectra measurements, it would be good if components of horizontal wind

could be removed from each Doppler spectrum plot, so that readers can track growth processes which can be represented by increases/decreases of reflectivity and absolute values of Doppler velocity.

We would like to thank the reviewer for the time and effort provided for the review. Lukas Pfitzenmaier, Christine Unal, Yann Dufournet, and Herman Russchenberg

1) I was confused by increase/decrease of fall speed when looking at the observed spectra changing with height. The TARA-observed Doppler spectra include horizontal wind component in addition to particle fall speed component. From the observed spectra (e.g., Figures 7, 11, and 13), it was difficult to see particle growth, which can be represented by particle fall speeds, because the spectra included large components of horizontal wind. I recommend extracting the horizontal wind component from the observed spectra. I think that this is not so difficult because the authors nicely retrieved horizontal wind.

Answer 1) We agree than the removal of the horizontal wind would help in the interpretation of the measured Doppler spectra. The implementation in the original manuscript was considered during the writing process. Because the results were not as expected we decided to show the not corrected spectra. One reason for this is the measurement geometry of the TARA radar and the design of wind retrieval. In the wind retrieval at high time resolution, homogeneous conditions with the 3 probing beams is assumed, which is not the case for all cloud conditions. This leads to some problems especially for dynamically inhomogeneous cloud systems as discussed in the paper. Second reason is, that at that stage, we did not remove the contribution of the mean horizontal wind in the measured Doppler velocities. If we would correct the Doppler velocities for the mean horizontal wind, we have still in the Doppler velocity measurement, a residual component of the horizontal wind (difference between the actual horizontal wind and the mean horizontal wind) AND the actual vertical wind AND the actual Doppler fall velocity. We show non-averaged spectra. Therefore, presently, we cannot provide the Doppler fall velocity, which would be, of course very useful to interpret growth processes.

2) Polarimetric variables have an elevation dependency; for instance, Zdr values decrease with elevation angle for horizontally-oriented oblate particles. Particularly, the Zdr values can significantly decrease above an elevation angles of 20 degrees. Did you correct the observed Zdr for elevation angles?

Answer 2) The shown Zdr values are not corrected for elevation at which they are observed. Also, we perform only qualitative analyzes of the values and relate the values to a specific particle type. Therefore, we did not correct the values for elevation.

3) Section 4, Figure 3: As the authors mentioned, the differential reflectivity is influenced by particle densities. One example is that aggregation can reduce its density, resulting in decreasing in Zdr (this was mentioned in the text). Another example is that initial riming of branched crystals can increase the density as gaps between branches are filled, resulting in increase in Zdr. I recommend mentioning this effect in the text as well.

Answer 3) Indeed riming of branched crystals increases the particle density. This leads to an increase of the Zdr-values. This scenario is not implemented in the article. We focus on the possible scenarios of growth processes which can explain the discussed measurements.

4) Section 5: Please explain how to take into account individual particle fall speeds to retrieve fall streaks and discuss particle growth of individual particle populations. Particles included in the radar sampling volume have different fall speeds. In the next range bin, the composition of particles in the volume can be different from that in the previous range bin volume above, because individual particles can have different fall speeds (i.e. size sorting effect). This is true even for retrieved fall streaks. When discussing ice particle growth using Doppler spectra at different heights (Figures 7, 11, and 13), I think that different particle fall speeds should be considered. Please explain if some assumptions were used in the discussion.

Answer 4) This effect is not taken into account in the fall streak retrieval, see Pfitzenmaier et al., 2017, doi:10.1175/JTECH-D-16-0117.1. The fall streak retrieval is based on Doppler measurements (mean Doppler velocities) and do not take into account the distribution of Doppler velocities. Therefore the retrieval consists of a mean fall streak. In the fall streak retrieval article, Section 4a explains the limitations of the horizontal wind retrieved by TARA, which have an impact on the fall streak retrieval. With the current retrieval the mean movement of the particle population can be tracked. Therefore size sorting cannot be taken into account, if it occurs.

5) P. 8, line 22: There could be non-Rayleigh scattering effect in addition to attenuation.

Answer 5) The contribution to non-Rayleigh scattering effects in addition to the attenuation is added to the text.

6) P. 8, line 31 “homogeneous wind”: Does this mean horizontally homogeneous?

Answer 6) Yes, horizontally homogeneous wind conditions are meant. This will be clarified in the text

7) P. 8, line 32 “shear”: vertical shear?

Answer 7) Yes, this is a vertical shear in the wind direction (about 30 deg.). This will be clarified in the text

8) P. 10, lines3-4 “The closer...”: If large particles dominated the total reflectivity, RHOhv may not reflect the particle diversity. In that case, as overall there is little contribution from the non-spherical particles, resulting in high RHOhv.

Answer 8) The statement of the reviewer is right. However, in this case, considering the spectral polarimetric signature, sZdr, which is flat versus Doppler velocity (Fig. 7, from 3076 m to 2524 m), the particles are spherical independently of their size. Therefore, the high RHOhv values are observed in the area 3076-2524 m. The text will be adjusted.

9) Section 6.1, Figures 6 and 10: What is the minimum limitation value of LDR due to the antenna limitation? In Figures 6 and 10, below Region N, LDR seems to be relatively high (âĹij -25 dB) at the edges of spectra. LDR tends to be large with low signal-to-noise ratio. What can the relatively high LDR at the edges of spectra indicate?

Answer 9) First we want to point out that a 10 dB SNR clipping was applied to the Mira sLdr to avoid contributions from low SNR regions near the edges of the spectra. The technical limitation for the Ldr detection is at -35 dB. Tyynelä et al, 2011, (doi.org/10.1175/JTECH-D-11-00004.1) modeled Ldr for vertical pointing radar for a range of frequencies. There it was found that Ldr in the simulations vary more than expected for the two different model approaches discussed. It was found that aggregates seem to produce larger Ldr than smaller ice crystals. One reason they pointed out may be incorrect mass size relation for aggregates. Nevertheless, aggregates have complex shapes and align during the sedimentation in a preferred orientation. Analyzing the Mira spectra, we observed large aggregates (Doppler velocity up to 2 m/s) which can explain the increased Ldr for larger particles. While smaller particles have still a more defined shape and therefore increased Ldr values (modeled values cited in the paper).

10) Section 6.1:, Figure 7: Compared to other studies showing S-band polarimetric radar Zdr in dendritic growth zones (e.g., Kumjian and Lombardo, 2017, doi: 10.1175/MWR-D-15-0451.1; Griffin et al. 2018, doi: 0.1175/JAMC-D-17-0033.1), Zdr values in Fig. 7 are relatively small. Why? Is there an elevation dependency?

Answer 10) Zdr values are indeed relatively small because the measurement is carried out at 45 deg. elevation. Again a trade-off between polarimetric signature and Doppler velocities related to Doppler fall velocities. Although we don't have yet the absolute values of terminal fall velocities.

11) Figure 9: How did the radiosondes measure supercooled liquid droplets? Did they have special sensors?

Answer 11) The radiosondes are standard Vaisala sondes and did not have special sensors. Super-cooled liquid water is assumed when the temperature and the dew point temperature of the radiosonde launch match. In general, this is an indication for the supersaturation of water vapor in this area. In the ice phase of clouds supersaturation of liquid water is also possible, which is assumed here if the relative humidity reaches 100%. This is shown in the light blue shaded areas in the Figure 9.

12) P. 10, line 19: What is the difference between ice particles and snowflakes here? I guess this meant ice crystals and snowflakes (aggregates)?

Answer 12) It means that pristine ice crystals or small aggregates grow via aggregation into larger and denser aggregates and snowflakes, respectively.

13) P. 11, lines 6-9: This does not make sense to me. I am wondering why the seeded case showed slower increase in Zh? I think that the ice seeding could accelerate aggregation, resulting in rapid increase in Zh...

Answer 13) It is right that the increase of the Zh slope is less in Case 2 than in Case 1. Also other observations suggest that the aggregation efficiency is less than in Case 1. The increase of the observed mean Doppler velocity is less than during Case 1, in the Mira measurements. This leads to the assumption that falling ice particles have lower density and might be smaller. Reason for that can be lower supersaturation in that height and lower concentration of generated particles at around 3100 m. In the cited paper by Hobbs et al., 1974, a strong relation between the particle number concentration and aggregation efficiency for needles is mentioned. Lower number concentrations would lead to less dense aggregates. Also we do not know the aggregation efficiencies of the seeding and the generated particles. From the observations we cannot confirm the fact that the ice seeding could accelerate aggregation, resulting in rapid increase in Zh. However, to investigate this further in situ measurements or additional sensors would have been needed to compare these observations.

14) P. 11, line 17: To me, the spectrum at 3.1 km does not seem to broaden (Fig. 10c).

Could you snow a zoomed up plot?

Answer 14) Fig. 11 shows the single spectra corresponding to Fig. 10c and e. There it can be seen that the spectra broadens from 3394 m to 3055 m from $\sim$1 m/s up to 1.5 m/s. This in not clearly visible in the spectrograms in Fig. 10. Therefore, the single spectra are shown to give a better and more detailed view into the growth process region, while the spectrograms represent the whole fall streak.

15) P. 11, line 34: Toward 2864 m in Figure 11, sZ values increases, while sZdr kept their values. Does this profile suggest increase in number concentration rather than size? What is the source of nucleated ice?

Answer 15) It is right that the single sZ bins increase more than the spectrum broadens. Therefore, it is right that one could assume that the particle number concentration in that region increases more that the size. This could be due to an ongoing ice multiplication process or to a continuous and ongoing particle generation process. The small ice crystals would grow in size by diffusional growth and keep their size dependence. However, the increase of the single sZ-bins is too large to be explained by only an increase of number concentration. As already pointed out, TARA spectra are not corrected for the mean horizontal wind contribution and therefore no direct link between Doppler velocity and particle size can be drawn. Nevertheless, the vertical pointing Mira shows such an increase of Doppler velocities towards the melting layer and we assumed such an increase for the TARA spectra as well. Assuming a diffusional growth of the smaller particles before aggregation leads to less dense and slightly smaller particles, which may cause such spectral signatures. As also already mentioned, because of the lack of additional information we cannot give more insights into the discussed case.

16) P. 12, line 1: Please mention effects of horizontal wind components. Do the particle populations having Doppler velocity >-8.5 at 3055 m exactly correspond to those at 2864 m?

Answer 16) It is clearly stated in the captions of Figures 6, 10 and 12 that the Doppler

velocity contains the radial wind. Therefore we have to interpret the Doppler velocity only relatively. Concerning Case 2 (altitudes 3055 m and 2864 m), we cannot neglect dynamical influences, although the wind direction at these heights is almost constant.

17) P. 12, line 8, Figure 11: Significant negative values in Zdr were also shown at 3055m. Could you explain the negative values at this altitude?

Answer 17) The variance of sZdr is large, and increase when the SNR and the copolar correlation coefficient decrease. To mitigate this issue, only data with SNR larger than 10 dB are considered. TARA processing provides Doppler spectra with the average number 2. Further 3 of these Doppler spectra are averaged (hh and vv) for this study to obtain consistent trends in sZdr at different times and heights. The total number of averaging is thus 6. Significant negative values are obtained in this case. It might be that during the growth process and due to turbulence some prolate particles are within the volume (sZdr spectrum at 2864 m). Nevertheless, the large negative sZdr are rather uncommon and there is a sharp decrease of the sZdr values at the edge of the spectrum, making them questionable. For the presented spectrum at 3055 m, due to nucleation and growth of the seeded particle from above the probability of prolate particle in the volume is higher. Also the drop into negative values is less sharp.

18) Section 6.2, P. 12, line 22: I am not sure why the authors identified the Zdr signature as needles/columns and why they decided that the TARA-observed Zdr corresponded to the Mira-observed Ldr. As the authors pointed out, the retrieved Zdr profile and the t_0 profile were inconsistent at the region N in Figure 9. This suggested that the TARA radar measurements and Mira radar measurements looked at different locations and different particles.

Answer 18) The hypothesis of the presence of needles/columns is mainly built upon the radiosonde temperature range at the considered altitudes. The radar MIRA is used to confirm this hypothesis, although we know that both radars measure different sampling volumes.

Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2017-1032/acp-2017-1032-AC2-supplement.pdf

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