Response to reviewer 1 (RC1, Anonymous Referee #1)

Reviewer's comments are presented here by italics

Comments:
1) general comments
The paper deals with lidar measurements to improve the understanding of microphysical process of mid-level stratiform clouds. The results of this study are based on two case studies observed in 2017 and 2019. The authors also highlight, that lidar observations of precipitating cloud systems where the whole precipitation process can be studied are rare but needed to understand the process from origin till rain hits the ground
The data are obtained by two lidar systems, a depolarization and a water vapor Raman lidar. The radar systems are designed to be able to measure also during light rain – optics of the systems are protected by a glass window in the roof of the institute.
The measurements depict two warm front cloud systems overpassing the measurement site. These lidar observations are described and related to precipitation formation processes. While the liquid microphysical processes seam to dominated the analysis.
Generally, the structure in the paper is not clear enough. The result section 3 is missing a red line to follow. It might be helpful to make more paragraphs and structure them better. It is not always easy to connect the information with the actual microphysical processes observed. So having more explanation of what process is happening and explain the resulting observation signatures would help. Perhaps use a sematic sketch? If this could be improved the quality of the paper would rise for sure.
Authors' response:
The authors greatly appreciate this reviewer for his affirmative remark, constructive criticism and kind suggestions. Taking all the comments into account, the manuscript has been revised. In particular, more paragraphs to explain the observed results have been added, and they are carefully structured in the revised manuscript. With respect to the schematic sketch to explain the lidar-observed results, please allow us to do this in future (the lidar and disdrometer observations are continuing at our site) because the authors' capability to make a satisfied artwork appears to be immature at present.

Comments:
2) specific comments
•Section 2.1. line 73-75 and section 2.1.1 line 111-114
Are there data or plots available to show the results of the water splashing experiment? From my site the performed technique is new, so results of it should be presented or at least citations given to similar performed experiments.

Authors' response:

Taking the reviewer's suggestion, an example about the results of the water splashing experiment has been given in the revised manuscript (please see Figure 1 in the revised manuscript). The pertinent description (section 2.1.1 lines 111-114 in the previous manuscript) has changed to "An artificial water splashing experiment was performed on the lidar roof windows to examine the effects of water accumulation. A comparison of the lidar profiles with and without water accumulation on the lidar roof windows is given in Figure 1. Enhanced lidar signal (X) and depolarization (δ_v) values at altitudes around 4.0 km resulted from an optically-thick (opaque) water-droplet cloud layer because there existed a high X value and near-zero δ_v value (~0.008) on the cloud base (~3.9 km) (Wang and Sassen, 2001), and also there initially existed a monotonic rapid increase in both the values of X and δ_v with increasing penetration of laser light into the layer. The cloud-related structures shown in both the X and δ_v profiles were consistent before and after water splashing (particularly, cloud base altitudes). This comparison clearly shows that water accumulation on the lidar roof windows yielded nearly height-independent lidar signal (X) attenuation, and neither the cloud-related X vertical structure nor the profile of the volume depolarization ratio δ_v (the magnitude and vertical structure) were altered. This result is physically reasonable." (please see lines 128-138)

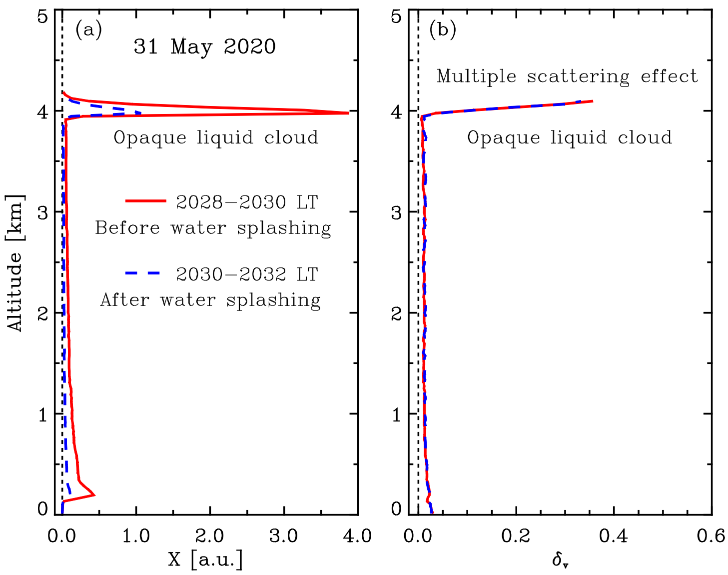

Figure 1: Comparison of the lidar profiles with (integrated from 2030 to 2032 LT on 31 May 2020, dashed blue line) and without (integrated from 2028 to 2030 LT on the same day, solid red line) water accumulation on the lidar roof windows. (a), Range-corrected 355-nm signal X profiles; (b), 355-nm volume depolarization ratio δ_v profiles. The water accumulation was produced by the artificial water splashing experiment.

Citation added

Wang, Z., and K. Sassen: Cloud type and macrophysical property retrieval using multiple remote sensors, J. Appl. Meteorol., 40(10), 1665–1682, https://doi:10.1175/1520-0450(2001)040<1665:CTAMPR>2.0.CO;2, 2001.

Comments:

2) specific comments

•*Section 2.1.1 line 103-108*

The explanation of the dark band is hard to follow. Could you split the sentence into two or 3 parts and extend the explanation a bit so that it is better to read?

Authors' response:

In light of the reviewer's suggestion, the relevant sentences (section 2.1.1 lines 103-108 in the previous manuscript) have been revised as "The magnitude of the δ_v value allows us to identify whether the dominant backscattering is attributed to ice crystals or water droplets in a given backscatter volume (Shupe, 2007). In general, liquid water droplets suspended in the atmosphere are nearly spherical and produce a very low depolarization ratio (close to zero) for single scattering at exact 180°, while ice crystals, which are usually nonspherical, generate a quite large depolarization ratio in the 180° backscattering direction. For some mid-level stratiform precipitations, gravitationally-falling hydrometeors form initially at altitudes above the 0 °C isotherm level. They fall often as mixed-phase hydrometeors (supercooled liquid drops and ice crystals/snowflakes) at sub-zero temperature during their early descent. After the falling mixed-phase hydrometeors pass through the 0 °C isotherm level, the snowflake (ice)-to-raindrop transition can yield a shallow layer of relatively smaller lidar echoes (a local X minimum), that is called "lidar dark band" (Sassen and Chen, 1995; Di Girolamo et al., 2012). The lidar dark band can be used to differentiate between the altitudinal regions with ice-containing particles above the dark band and pure liquid raindrops below the dark band. Hence, at altitudes above the dark band, the discrimination criteria in terms of the depolarization ratio magnitude are $\delta_v < 0.1$ for water droplets/drops and $\delta_v > 0.2$ for ice crystals (Intrieri et al., 2002; Shupe et al., 2008), while an enhanced depolarization ratio ($\delta_v > 0.1$) at altitudes below the dark band indicates the presence of large raindrops." (please see lines 103-116)

Comments:

2) specific comments

•*Section 3.1. Figure 1*

The text below the Figure is too long. Describe what the graphs show, do not give any interpretation or highlight things the graphs show the caption. All interpretations or highlights that can be seen have to be in the main text of the article.

Authors' response:

Taking the reviewer's suggestion, the caption of Figure 2 (Figure 1 in the previous manuscript) has been shortened as "Figure 2: Time-height contour plots (1 min/30 m resolution) of the (a) range-corrected signal X, (b) volume depolarization ratio δ_v measured by a 355-nm polarization lidar, and (c) water vapor mixing ratio q_v measured by a water vapor Raman lidar on 26–28 December 2017, which exhibited the passage of a warm front and the resulting hours-long light rain. A sliding average of 60 min was applied to the Raman lidar data. The precipitation streaks surrounded by magenta lines are zoomed in to show their details. Shown on the top of the figure are the corresponding photographs of the sky taken by a ground-based camera at our lidar site, with the third photograph exhibiting the sky illuminated by a 532-nm laser beam during the onset of rainfall." (please see lines 660-665). The interpretations and highlights have been moved to the main text.

Comments:

2) specific comments

•Section 3.1.1 sentence line 160-160 and following sentences

I had a hard time to follow the text here and connect the information you give to the story you want to tell. Please structure this paragraph clear. What can be seen in the graph and what do you follow from your observations. Perhaps make some paragraphs to give the text more structure.

Authors' response:

The authors sincerely appreciate the reviewer for his kind suggestion. In light of this suggestion and a comment ("I found this section is too long") from another reviewer (reviewer 3), the text in subsection 3.1.1 has been reorganized as follows.

"Figure 3 presents the radiosonde profiles that are pertinent to the warm-front cloud at different stages and during precipitation, together with the 1-h mean lidar profiles obtained during the radiosonde launches. The temporally-varying cloud properties (e.g., falling cloud base, increasing cloud thickness and variable cloud types) between 2000 LT on 26 December and 2000 LT on 27 December 2017 coincided with the classical picture of preceding upglide clouds of an advancing warm-front system. Accordingly, a downgoing moist layer was observed strengthening and broadening with time during this period (Figs. 3b and 3c). At the cloud base (except cirrus), the relative humidity over ice had values close to the relative humidity threshold of 84% that is conventionally used to determine the cloud base heights (Wang and Rossow, 1995; Zhang et al., 2018). Furthermore, the radiosonde data exhibited that the southwesterly wind mostly prevailed at the cloud altitudes (Figs. 3d, 3e and 3f), and the air pressure at altitudes of ~0−5 km dropped continuously by ~3−5 hPa in the period (not shown here), which did belong to the typical warm-front features.

The radiosonde released at 0800 LT on 28 December 2017 provided measurements of the meteorological conditions when precipitation reached the surface, although the lidar measurements had already terminated (at 0538 LT) ~ 2 hours earlier. As seen from Figure 3b (red), the relative humidity reached a maximum of 98% with respect to water in an altitude range of ~3−4 km, immediately above the tops of the liquid precipitation streaks (at ~3 km, see Figs. 2a and 2b). Water vapor at altitudes of ~3−9 km was advected from the southwest, as seen in the wind component profiles (Figure 3f, red). The high water vapor mixing ratios observed at altitudes below ~3 km came from the evaporation of falling raindrops." (please see lines 182-198)

Comments:

2) specific comments

•Section 3.1.2 line 201-204

This explanation has to be given when you explain the water splashing experiment! So move this up in the section above!

Authors' response:

The explanation has changed to "Although the rainfall-induced water accumulation on the roof window of the lidar varied with time, the precipitation streaks and dark band were steadily reasonably displayed in the X and δ_v time-height plots (Figs. 2a and 2b). This is consistent with the result of our water splashing experiment." in the revised manuscript (please see lines 211-214).

Comments:

2) specific comments

Section 3.1.2 line 210-211

Can you explain these in more detail or give a citation? Is there a relation to the signature and the distance to the 1km or higher origin layer of the initiation? Can signatures be used to identify the high of initiation?

Authors' response:

Taking the reviewer's suggestion, we have added the following explanations and citation in the revised manuscript.

"Note that the formation of gravitationally-falling ice-containing hydrometeors requires ambient temperatures colder than −4°C (Rangno and Hobbs, 2001; Yi et al., 2021) and ice nucleation (via contact freezing) is active at temperatures around −10°C (Ansmann et al., 2008). Given a mean lapse rate of 6.5°C km^{-1}, it is expected that the mixed-phase stratiform precipitations would begin at altitudes more than 1 km above the 0°C isotherm level. In fact, the existing cloud/precipitation radar observations also have indicated that the stratiform precipitations with the snowflake-to-raindrop transition (where the radar bright band occurs corresponding to the lidar dark band) initiate usually at altitudes more than 1 km above 0°C isotherm level (e.g., Di Girolamo et al., 2012, Fig. 2; Pfitzenmaier et al., 2018, Fig. 4)." (please see Subsection 3.1.2 lines 221-228)

Citation added

Rangno, A. L. and Hobbs, P. V.: Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations, J. Geophys. Res., 106(D14), 15,065-15,075, https://doi:10.1029/2000JD900286, 2001.

Yi, Y., Yi, F., Liu, F., Zhang, Y., Yu, C., and He, Y.: A prolonged and widespread thin mid-level liquid cloud layer as observed by ground-based lidars, radiosonde and space-borne instruments, Atmos. Res., 263, 105815, https://doi.org/10.1016/j.atmosres.2021.105815, 2021.

Comments:

2) specific comments

•*Section 3.1.2 paragraph 4 (234-243)*

Can you explain this in more detail? Are there other observations done showing the same, give a citation? It would be nice to get a bit more explanation for people not so familiar with lidar measurements.

Authors' response:

In light of the reviewer's suggestion, with respect to this finding, more explanations have been given and some statements about its novelty have been made in revised manuscript (In brief, our lidar observations reveals for the first time (to our knowledge) the collision-coalescence growth and subsequent spontaneous breakup of falling raindrops, that actually take place in the natural atmosphere. They represent the posterior microphysical processes necessary for the surface rain production.). Thus, the subsection 3.1.2 paragraph 4 has changed to

"At altitudes below the water bright band, the precipitation-related lidar backscattering (X) apparently weakened (Fig. 4a, in which the enhanced X values at altitudes from 0.3–0.7 km resulted from the boundary layer aerosols), indicating low-density raindrops there, whereas δ_v first increased with decreasing height and then decreased after reaching a maximum (0.13–0.16) at an altitude of approximately 0.6 km (Fig. 4b). Here the magnitude and altitude variation of the lidar depolarization ratio δ_v values allow us to identify where large-sized raindrops form and break up. Falling small-sized raindrops (equivalent diameter ≤ 1.0 mm) are quasi-spherical (Pruppacher and Klett, 1997) and yield small δ_v values (generally less than 0.1), whereas falling large-sized raindrops (equivalent diameter > 2.8 mm) become nonspherical (with flat or hollow bottom in falling direction) (Pruppacher and Klett, 1997) and lead to large δ_v values (larger than 0.1). In fact, prominent δ_v peaks (~0.1–0.4) at altitudes of approximately 0.6 km are always observed in the δ_v profiles related to reaching-surface precipitation in the present light rain case (Fig. 2). The δ_v maxima at an altitude of ~0.6 km are much larger than the typical values (less than ~0.07) observed by our 355-nm polarization lidar at approximately the same altitude during rainless days. Here we can exclude a possibility that the δ_v maxima (~0.1–0.4) at ~0.6-km altitude resulted from multiple scattering by dense droplets around this altitude. As mentioned above, for the 1-mrad receiver FOV, a dense water-droplet cloud layer with the multiple-scattering-induced depolarization ratio δ_v values larger than 0.1 is optically opaque. In contrast to this situation, in our case, when the prominent δ_v peak (~0.1–0.4) around 0.6-km altitude occurred, the vertical structure of the precipitation streaks at altitudes far above 0.6 km (e.g., ice bright band, lidar dark band and lidar water bright band) was unambiguously detected by our polarization lidar, indicating that the enhanced depolarization ratios around 0.6-km altitude cannot be caused by multiple scattering from dense spherical water droplets therein. Furthermore, since most falling raindrops evaporated and vanished in the liquid-water bright band as indicated by the enhanced water vapor mixing ratio therein and rapidly-decreasing lidar signal on the bottom of the water bright band, small droplets at altitudes below the water bright band were hardly dense enough to generate a strong multiple scattering with $\delta_v \geq 0.1$. Therefore, our observational results suggest that sparse large raindrops that fall out of the water bright band with higher fall velocities further grow in size by collecting smaller raindrops along their fall paths. They grow to sizes at which spontaneous breakup occurs at an altitude of approximately 0.6 km. In brief, our lidar observations reveal for the first time (to our knowledge) the collision-coalescence growth and subsequent spontaneous breakup of falling raindrops, that actually take place in the natural atmosphere. They represent the posterior microphysical processes necessary for the reaching-surface precipitation production. Interestingly, the size maximization of falling raindrops as shown by the strongest nonspherical shapes (maximum depolarization ratio values) always appeared at an altitude of ~0.6 km for a variety of mid-level stratiform precipitations (in light of our observations). Obviously, the explanation to this ubiquitous feature needs further observational and modelling efforts. As seen in Fig. 2b, the boundary layer aerosols had little impact on the δ_v precipitation streaks. In addition, at altitudes below 1.5 km, the q_v values decreased with increasing altitude, reflecting a normal altitude distribution of the boundary layer water vapor." (please see lines 249-279).

Comments:

2) specific comments

•Section 3.1.2 line 306

Does this comparison make sense here? 1 mm large super cooled droplets? Could you comment on this please and give a reference!

Authors' response:

Taking the reviewer's comments into account, the sentence about this comparison (Their freezing time would be 25−50 s given a falling velocity of 4 ms^{-1} for ~1.0-mm liquid drops.) has been dropped in the revised manuscript.

Comments:

2) specific comments

•Section 3.1.2. line 313-325

This pat was hard to follow. It might be one of the mature parts of the paper. Please, describe what you observed and in a second step what process might be behind. Perhaps it makes also sense to make a summarizing sketch of the processes observed and relate them to the measurements you would expect. Then it is easier to follow for the readers.

Authors' response:

The authors sincerely thank this reviewer for his kind suggestion. Following the suggested expression logic (first describing the observational results and then stating what process might be behind), the related sentences have been revised as

"The local depolarization minimum ($\delta_v \leq 0.04$) was persistently observed immediately beneath (~100 m below) the lidar dark-band minimum (X minimum). This displayed that the completion of the melting process of most falling ice particles took place at altitudes (hundreds of meters) below the 0°C isotherm level. The liquid-water bright band (with a geometrical thickness of ~ 1 km) just below the lidar dark band was characterized by enhanced X values and small δ_v values. There existed a high-concentration moisture (large q_v values) in this bright band. These features indicate that the liquid-water bright band resulted from gravitationally-falling, dense evaporating liquid drops. In terms of the lidar-measured profiles during reaching-surface precipitation, at altitudes below the water bright band, the precipitation-related lidar backscattering apparently weakened, while δ_v first increased with decreasing altitude and then decreased after reaching a prominent maximum at an altitude of ~0.6 km. The lidar profiles for the virgae showed narrower and weaker water bright bands than those observed when precipitation reached the surface. Moreover, during virga occurrence, there was no perceptible depolarization enhancement at an altitude of ~0.6 km. By combining the above-mentioned lidar observations, a picture on the microphysical processes of falling hydrometeors in liquid-phase stage emerged. After going through the dark band, most falling raindrops shrank or vanished in the water bright band due to evaporation, whereas a few large raindrops survived and fell out of the water bright band when the rain rate below the apparent source cloud base was high enough. The large raindrops might come from both the complete melting of large falling ice/snow particles and collision-coalescence formation in the dense water bright band. Sparse, large raindrops with high fall velocities further grew in size by collecting smaller raindrops along their fall paths. At an altitude of ~0.6 km, the large raindrops grew to the sizes at which spontaneous breakup could occur, yielding reaching-surface precipitation. When the rain rate below the apparent source cloud base was low, nearly none of the large raindrops fell out of the water bright band. Consequently, there were only virgae suspended on air (without reaching-surface precipitation)." (please see lines 352-371)

Comments:
3) Technical corrections
•*Line 216-218: Please reformulate this sentence*
Authors' response:
The sentence has been rewritten as
"A liquid water bright band appeared as a layer of relatively large particle backscatter values, located at ~1.50–2.76-km altitudes, just below the lidar dark band (Fig. 4). It is called "weak lidar bright band" in the literatures (Sassen and Chen, 1995; Di Girolamo et al., 2012)." (please see lines 233-235).

Comments:
3) Technical corrections
•*Please have a clearer structure in your sections and paragraphs*
Authors' response:
The structures in the sections and paragraphs have been reorganized in light of the specific suggestions from this reviewer.

Comments:
3) Technical corrections
•*Make more paragraphs*
Authors' response:
More paragraphs have been made in the revised manuscript in order to structure the sections clear.

Comments:
3) Technical corrections

•*Shorten you captions of the figures; some are quite long. Put the information into the text or make more figures*

Authors' response:

The captions of the figures have been shortened and pertinent information has been put into the text.