Response to reviewer 3 (RC3, Anonymous Referee #4)

Reviewer's comments are presented here by italics

Comments:
The paper contains interesting lidar observations of virga below mixed-phase clouds and a detailed, however often speculative interpretation of the virga observations. My overall impression is that the paper in its present form is not in a good shape. The manuscript is also quite long and should be shortened.
Authors' response:

The authors sincerely thank this reviewer for his/her constructive criticisms and valuable suggestions after well-considered reading of our manuscript. Taking all the comments into account, the manuscript has been revised and some parts shortened. Since another reviewer (reviewer 1) suggests that "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.", we have added more (physically reasonable) explanations and paragraphs in the revised manuscript with the ice nucleating processes being not covered.

Comments:
First of all, the lidar setup (zenith pointing, large receiver FOV of 1 mrad) can lead to very low depolarization ratio values introduced by specular reflection (because of zenith pointing). Furthermore, the can sensitively influence the depolarization ratio observations via multiple scattering by droplets. Nothing is mentioned to these instrumental influences. The interesting finding of a local maximum of the depolarization ratio around 600 m height is in the near-range of the lidar so that systematic instrumental effects cannot be excluded. I mean, the overlap profile (incomplete overlap between laser beam and receiver FOV in the near range) is usually not well known and can vary with time (and diurnal cycle). All this causes artefacts. Nothing is mentioned to this problem.
Authors' response:

In terms of our lidar setup, the instrumental effects on the depolarization ratio values (multiple-scattering-induced depolarization enhancement, incomplete overlap between laser beam and receiver FOV in the near range, and an uncertainty of low depolarization ratios in discriminating cloud droplets and falling, oriented ice crystals) have been addressed in the revised manuscript. Please see the following statements:
"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 $\delta_v \geq 0.1$." (please see lines 259-269 in the revised manuscript)

With a compactly-designed lidar configuration (20-cm Cassegrain telescope), accurate transmitter-receiver alignment and steady lidar environment temperature (with waterproof transparent roof windows), the complete-overlap altitude of our polarization lidar, that the laser-beam receiver-field-of-view (FOV) overlap function becomes unity, is reliably less than 400 m. In fact, the local maximum of the depolarization ratio around 600 m height represents an altitude range from ~1.2 km down to ~0.3 km in which the depolarization ratio values show a precipitation-related enhancement. Therefore, the local δ_v maximum around 600 m reflects a natural phenomenon rather than an instrumental artefact.

"Such an example is shown in Fig.6. The lidar profiles above the dark band clearly exhibit the typical structure characteristics of a liquid-topped mixed-phase cloud (virga) (see Fig.6 in (Wang and Sassen, 2001)). The mixed-phase cloud top layer was of large X values and very low δ_v values (~0.01), while lower part of the cloud was characterized by significantly-smaller X values and large δ_v values (with a maximum up to ~0.33). Furthermore, the cloud top layer had a maximum water vapor mixing ratio q_v and a temperature of ~−8.5 °C (based on radiosonde data at ~2000 LT on 27 December). These observed results suggest that the cloud top layer should be composed of liquid droplets (that was not dense enough to yield detectable multiple scattering), and the lower part of the cloud was mainly precipitating ice crystals (falling ice virga)." (please see lines 318-326)

Comments:

The observations concentrate on the virga zone below the main altocumulus layers. More precise, the investigation is mainly focusing on the part of the virga from the 0°C level towards the surface. Nothing is said, why the ice crystals can survive such a long time at heights below the 0°C height level. Obviously, the melting crystals cool the surrounding air and keep the temperatures close to 0°C, even up to 1 km below the 0°C height level where the radiosonde (obviously ascending outside of virga) indicated temperatures up to 6°C.

Authors' response:

The authors thank the reviewer's friendly suggestion. In the revised manuscript, a sentence that explains why the ice crystals can survive such a long time at heights below the 0°C height level has been added.

"Long survival time of falling ice crystals at altitudes below the 0°C level might be ascribed to cooling of the surrounding air during their evaporation and melting."(please see lines 173-174)

Comments:

Nothing is mentioned, why raindrops lead to enhanced depolarization ratios! Maybe I overlooked it. Is that because the shapes of the rain drops are no longer spherical during falling, the shape is like the one of pears with the flat side in falling direction…? Please explain!

Authors' response:

The authors appreciate the reviewer's reminding and suggestion, an explanation about why raindrops lead to enhanced depolarization ratios has been inserted in the revised manuscript.

"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 diameters ≤ 1.0 mm roughly) are quasi-spherical (Pruppacher and Klett, 1997) and yield small δ_v values (generally less than 0.1), whereas falling large-sized raindrops (equivalent diameters > 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)." (please see lines 252-256)

Comments:

Nothing is mentioned about the impact of multiple scattering in layers with high droplet concentration. Maybe the raindrop maximum at 600 m is just caused by multiple scattering by numerous small droplets and not by 'a few big', nonspherical rain drops. In the paper, there are no profiles of particle backscatter and extinction coefficients. So, there is no opportunity to conclude on the multiple scattering effect. I was puzzled by the fact that the depolarization maximum was always around 600 m height, why not at 800 or 400 or at 1000~m height? I speculate that may have to do with systematic instrumental problems in the near-range of the lidar.

Authors' response:

Taking the reviewer's comments into account, the impact of multiple scattering in layers with high droplet concentration has been addressed. With respect to the raindrop δ_v maximum at ~600 m, we have added the following explanation (considering a fact that the range-corrected signal X is a good proxy for the particle backscatter measure).

"We examined the multiple-scattering-induced depolarization ratio enhancements for an opaque cloud layer composed of dense spherical water droplets by putting a motorized iris on our polarization lidar system. It is indicated that for a receiver FOV of 1 mrad, the enhanced depolarization ratio δ_v values due to multiple scattering increased from ~0.03 at the X peak altitude to a maximum value of ~0.27 at the weak-signal cutoff altitude with increasing penetration of laser light into the opaque water-droplet cloud layer. Note that for the same receiver FOV (~1 mrad), the multiple-scattering-induced depolarization ratio δ_v values were all less than 0.04 within the laser light penetration range in a lightly-dense water-droplet cloud layer (Hu et al., 2006). Combining the earlier multiple-FOV polarization lidar measurements (Hu et al., 2006) and our similar observations yields a suggestion that for the 1-mrad receiver FOV, the multiple-scattering-induced depolarization ratio values larger than 0.10 should result from an opaque water-droplet cloud layer (see Figs. 2 and 4 in (Yi et al., 2021)). In other words, for the 1-mrad receiver FOV, the vertical structure of hydrometeors and aerosols present above a dense water-droplet cloud layer with δ_v values larger than 0.1 is undetectable by ground-based lidars." (please see lines 118-128)

"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 cases, 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 $\delta_v \geq 0.1$." (please see lines 259-269)

With respect to the question that the depolarization maximum was always around 600 m height, why not at 800 or 400 or at 1000~m height, further observational and modelling efforts are obviously needed in future. This phenomenon might presumedly reflect a feature for a variety of light mid-level stratiform precipitations. Considering a fact that falling raindrops suffer from strong evaporation during their minutes-long descent in a subsaturated environment, there were no raindrops reaching the surface if no (sparse) large raindrops formed midway. Recently, an optical disdrometer (Parsivel, with 1-min sampling interval) has been installed beside our lidar systems and a newly-developped off-zenith polarization lidar has been placed at our observation site. This allows us in future to detailedly examine the relation between the depolarization maximum around 600-m altitude and precipitation that reached the surface.

With respect to the possible instrumental problems in the near-range of the lidar, please allow us to revisit our previous explanation.

With a compactly-designed lidar configuration (20-cm Cassegrain telescope), accurate transmitter-receiver alignment and steady lidar environment temperature (with waterproof transparent roof windows), the complete-overlap altitude of our polarization lidar, that the laser-beam receiver-field-of-view (FOV) overlap function becomes unity, is reliably less than 400 m. In fact, the local maximum of the depolarization ratio around 600 m height represents an altitude range from ~1.2 km down to ~0.3 km in which the depolarization ratio values show a precipitation-related enhancement. Therefore, the local δ_v maximum around 600 m reflects a natural phenomenon rather than an instrumental artefact.

Reference added

Hu, Y., Liu, Z., Winker, D., Vaughan, M., Noel, V., Bissonnette, L., Roy, G., and McGill, M.: Simple relation between lidar multiple scattering and depolarization for water clouds, Opt. Lett., 31(12), 1809–1811, doi:10.1364/OL.31.001809, 2006.

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:

The most important point of concern is the following: I have a severe problem with the ‘theory’ of the authors how ice crystals are nucleated via heterogeneous ice nucleation. The authors believe that large (1mm in size) droplets fall out of an altocumulus layer and then they immediately freeze right below cloud base. I have never heart about such an ice nucleation process. Furthermore, I asked myself: How can 1 mm droplets form in an altocumulus cloud layer where typical droplet sizes are 10-20µm ...)

The established, common ‘theory’ of ice nucleation in altocumulus layers is the following:

Ice nucleation (dominated by immersion freezing for temperatures >-25°C) starts at the coldest point of the cloud, i.e., at cloud top. At cloud top the probability of ice nucleation is largest because ice nucleation is a strong function of temperature. The probability increases by an order of magnitude when temperature decreases by 5K. Thus in cases of 500-600m thick cloud layers the ice nucleation probability at cloud top is an order of magnitude higher than at cloud base.

So, most probably first ice crystals nucleate at cloud top via immersion freezing (liquid water droplets freeze), in the liquid-water droplet environment of the altocumulus layer. Then, in the next step, these ice crystals grow fast and immediately start falling. They grow to about 100µm within 60-120s! During falling they continuously grow as long as ice supersaturation is given. When ice subsaturation levels are reached the ice crystals start to shrink and to evaporate. When entering the air mass below the 0°C height level the crystals start to melt but during this process they consume so much energy that they are able to keep the temperatures of the ambient air close to 0°C (in your cases down to almost 1000m below the 0°C height level) although the radiosonde may have measured 6°C.

Finally, the manuscript tells us nothing about the true ice nucleation. There is no information about the altocumulus layer (e.g. cloud top height and temperature), there is no information and discussion about potential seeder/feeder effects (no *information about ice cloud layers above the altocumulus), and there is no information about secondary ice formation (triggered by the Hallett Mossop effect) dominating in the height range in which the temperatures are between -5 and -8°C. All this influences the virga properties that are exhaustingly discussed in the paper. It should be clearly said in the introduction that the ice nucleating processes are not covered by the paper. The paper exclusively focus on the virga.*

Authors' response:

The authors sincerely appreciate the reviewer's pertinent criticism. The current lidar observations indeed cannot tell anything directly about the true ice nucleation processes. In the revised manuscript, a sentence that "the ice nucleating processes are not covered" has been put into the introduction and appropriate corrections have been made to some earlier wordings.

Comments:

Many aspects mentioned above (but not discussed in the manuscript) triggered many questions! Please do not misunderstand me! I like the approach and want to help to improve the paper. I know that readers appreciate if the authors are critical to their own observations!

Major revisions are needed.

Authors' response:

The authors sincerely appreciate this reviewer for his/her great effort in improving the quality of the paper. The manuscript has been revised in light of content in the **Details**.

Comments:

P1, l18: surface rainfall.....? is not just self-explaining: better use: precipitation that reached the surface. You may define 'surface rain' in the introduction, but I personally do not like such wording.

P1, l19: parent cloud ...? Is also not self-explaining: better: ...falling out of a shallow mixed-phase cloud layer. Why do we need such a wording? And in the case of seeding from above, then we have grandparent clouds…? I would just call or denote such a clouds ... shallow cloud layer or altocumulus layer.

Please change this (surface rain, parent cloud) throughout the article.

Authors' response:

Taking the reviewer's suggestion, the "surface rainfall" changes to the "precipitation that reached the surface" or "reaching-surface precipitation" and the "parent cloud" has been replaced by "a shallow liquid cloud layer" in the revised manuscript. For simplicity of expression, the "apparent source cloud" (e.g., virga and its apparent source cloud) has been used also instead of "parent cloud" in some revised sentences following the wording in an earlier literature ("source cloud" in (Wang and Sassen, 2001)).

A reason for utilizing "a shallow liquid cloud layer" rather than "a shallow mixed-phase cloud layer" is as follows

"Such an example is shown in Fig.6. The lidar profiles above the dark band clearly exhibit the typical structure characteristics of a liquid-topped mixed-phase cloud (a shallow liquid cloud layer and ice virga below) (see Fig.6 in (Wang and Sassen, 2001)). The mixed-phase cloud top layer (at an altitude of ~4.6 km) was of large X values and very low δ_v values (~0.01), while lower part of the cloud was characterized by significantly-smaller X values and large δ_v values (with a maximum up to ~0.33). Furthermore, the cloud top layer had a maximum water vapor mixing ratio q_v and a temperature of ~−8.5 °C (based on radiosonde data at ~2000 LT on 27 December). Combining with the schematic representation of commonly-observed mixed-phase cloud layers (see Fig. 1 in (Bühl et al., 2016)), the current observations suggest that the cloud top layer should mainly be composed of liquid droplets (that were not dense enough to yield detectable multiple scattering), and the lower part of the cloud was mainly precipitating ice crystals (falling ice virga).” (please see lines 318-326)

Comments:

P1, l55-56: I think your hypothesis is wrong: ...suggesting that most supercooled liquid drops falling out of parent clouds rapidly froze into ice crystals on the tops of virga. See my explanation above.

Authors' response:

Taking the reviewer's comments into account, the phrase that "…suggesting that most supercooled liquid drops falling out of parent clouds rapidly froze into ice crystals on the tops of virga." has been replaced by "...indicating that the depolarization ratio values of falling hydrometeors increase rapidly with decreasing altitude on the top of the virgae." (please see lines 55-56)

Comments:

P3,l83: The lidar is pointing exactly vertically! That means you may have very low depolarization ratios from specular reflection by falling, oriented ice crystals. And layers with specular reflection may be misclassified as liquid-droplet layers.

Authors' response:

The authors thank the reviewer for alerting us to the necessary discrimination between liquid-droplet layers and falling, oriented ice crystals when a zenith-pointing polarization lidar has observed very low depolarization ratios. In the revised manuscript, we have inserted the following statements.

"Such an example is shown in Fig.6. The lidar profiles above the dark band clearly exhibit the typical structure characteristics of a liquid-topped mixed-phase cloud (a shallow liquid cloud layer and ice virga below) (see Fig.6 in (Wang and Sassen, 2001)). The mixed-phase cloud top layer (at altitudes of ~4.6 km) was of large X values and very low δ_v values (~0.01), while lower part of the cloud was characterized by significantly-smaller X values and large δ_v values (with a maximum up to ~0.33). Furthermore, the cloud top layer had a maximum water vapor mixing ratio q_v and a temperature of ~−8.5 °C (based on radiosonde data at ~2000 LT on 27 December). Combining with the schematic representation of commonly-observed mixed-phase cloud layers (see Fig. 1 in (Bühl et al., 2016)), the current observations suggest that the cloud top layer should mainly be composed of liquid droplets (that were not dense enough to yield detectable multiple scattering), and the lower part of the cloud was mainly precipitating ice crystals (falling ice virga).” (please see lines 318-326)

Comments:

P3, l84: The receiver field of view is 1 mrad. This means you may have considerable problems with multiple scattering. Multiple scattering in environments with droplets can cause significantly enhanced depolarization ratios. And these high depolarization ratios may be interpreted as ice crystals or as big rain drops. So, there is room for ambiguous interpretation.

That should be commented (zenith pointing, specular reflection, multiple scattering, enhanced depolarization, overlap impact, signal gluing impact).

Authors’ response:

In order to avoid an ambiguous interpretation on the enhanced depolarization ratios at altitudes around 0.6 km, we have added the following comments in the revised manuscript.

“We examined the multiple-scattering-induced depolarization ratio enhancements for an opaque cloud layer composed of dense spherical water droplets by putting a motorized iris on our polarization lidar system. It is indicated that for a receiver FOV of 1 mrad, the enhanced depolarization ratio δ_v values due to multiple scattering increased from ~0.03 at the X peak altitude to a maximum value of ~0.27 at the weak-signal cutoff altitude with increasing penetration of laser light into the opaque water-droplet cloud layer. Note that for the same receiver FOV (~1 mrad), the multiple-scattering-induced depolarization ratio δ_v values were all less than 0.04 within the laser light penetration range in a lightly-dense water-droplet cloud layer (Hu et al., 2006). Combining the earlier multiple-FOV polarization lidar measurements (Hu et al., 2006) and our similar observations yields a suggestion that for the 1-mrad receiver FOV, the multiple-scattering-induced depolarization ratio values larger than 0.10 should result from an opaque water-droplet cloud layer (see Figs. 2 and 4 in (Yi et al., 2021)). In other words, for the 1-mrad receiver FOV, the vertical structure of hydrometeors and aerosols present above a dense water-droplet cloud layer with δ_v values larger than 0.1 is undetectable by ground-based lidars.”(please see lines 118-128)

“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 $\delta_v \geq 0.1$." (please see lines 259-269)

Added references

Hu, Y., Liu, Z., Winker, D., Vaughan, M., Noel, V., Bissonnette, L., Roy, G., and McGill, M.: Simple relation between lidar multiple scattering and depolarization for water clouds, Opt. Lett., 31(12), 1809–1811, doi:10.1364/OL.31.001809, 2006.

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.

The questioning points in brackets have been commented above except "signal gluing impact" that is addressed in the next response.

Comments:

P4, l93: Please state in which height range gluing of signal profiles is performed (for the cases discussed in Sect. 3.)

Authors' response:

The authors sincerely thank the reviewer for his/her reminding. In the revised manuscript, we have added the following statement.

"For the cases in this study, the altitude range of signal gluing was ~1.2–3.3 km. (please see line 94)

Comments:

P4, l104: What about multiple scattering in water-droplet layers, and corresponding increase in depolarization ratios? Please comment on that!

Authors' response:

With respect to the impact of multiple scattering in layers with high droplet concentration, besides the above interpretation, we have further comment as follows:

For a receiver FOV of 1 mrad, the multiple scattering from an optically-thick layer composed of dense spherical water droplets yields initially a monotonic rapid increase in both the lidar signal (X) and depolarization (δ_v) with increasing penetration of laser light into the layer as shown in Figure 1 (revised manuscript) and earlier literatures (e.g., Hu et al., 2006). However, the lidar signal X did not show any visible increase with increasing penetration of laser light into the layer that δ_v value maximized around 0.6-km altitude. Therefore, we can exclude a possibility that the δ_v maxima at ~0.6-km altitude resulted from multiple scattering by dense droplets around this altitude.

Comments:

P4, l111: Below the dark band, enhanced depolarization ratio indicates rain drops. Please explain why? The shape of rain drops during falling deviates from the perfect spherical form? They look like pears? With the flat surface into the falling direction? Please comment on that.

Authors' response:

Regarding why below the dark band, enhanced depolarization ratio indicates rain drops, the relevant sentences have been revised as follows:
"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) in 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 107-116)

With respect to the shape of rain drops during falling, we have added the following statements.
"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)" (please see lines 253-256).

Comments:
P5, l144: An explanation is need why ice crystals can survive as ice crystals over a distance of 600 m below the height of 0°C level, i.e., for about 1200 s (20 min) when falling speed is high with 50 cm/s. To my opinion, cooling of the surrounding air during evaporation and melting… is the reason.
Authors' response:
In light of the reviewer's suggestion, a sentence that explains why the ice crystals can survive such a long time at heights below the 0°C height level has been added.
"Long survival time of falling ice crystals at altitudes below the 0°C level might be ascribed to cooling of the surrounding air during their evaporation and melting."(please see lines 173-174)

Comments:
P6, l 171, 172, 173: parent cloud… I do not like this wording. Furthermore, you do not know whether the crystals were formed in that cloud layer. Maybe ice crystals from above seeded the cloud. So, please be careful with the argumentation. Limit the argumentation to topics and facts that were observed.
Authors' response:
Taking the reviewer's opinion, the "parent cloud" has not been used in the revised manuscript. For simplicity of expression, please allow us to use the "apparent source

cloud" instead of "parent cloud" because mixed-phase hydrometeors (ice virga) were observed falling out of a shallow liquid cloud layer ("apparent source cloud" of ice virga). The "source cloud" came from the same wording in an earlier literature (please see p1674 in (Wang and Sassen, 2001)).

Comments:
P6, Sect 3.3.1: I found this section is too long.
Authors' response:

Taking the reviewer's opinion and some suggestions from another reviewer (RC2, Anonymous Referee #3), Section 3.1.1 has been abbreviated as

"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 3.0–9.0 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:
P7, Sect 3.1.2: Check to what extent multiple scattering effects and specular reflection could have influenced the observations.
Authors' response:

We examined the multiple scattering effects from optically-thick (opaque) cloud layers composed of dense spherical water droplets by using a motorized iris (SID-5714, SmarAct) that was put on our polarization lidar system. An observational example from the multi-field-of-view polarization lidar between 1930 and 1940 LT on 12 November 2019 is shown in the following Figure R1. Each pair of colored lidar X and δ_v profiles represent a 1-min integration at a fixed receiver FOV shown in panel (a) with an assumption that the liquid cloud layer was steady during 10-min varying-field-of-view sampling (1930-1940 LT). The altitude resolution is 3.75 m. The assumption was reasonable, because a steady stratiform cloud persistently covered all the sky of our city on this day (12 November 2019) and the air temperature was warmer than 0 °C at altitudes below 4 km according to local radiosonde data. As seen from Figure R1, for a receiver FOV of 1 mrad, the enhanced depolarization ratio due to multiple scattering was less than 0.15 at atitudes where the strong cloud backscatter (enhanced X values) occurred (at altitudes of 1.93−2.06 km). This altitude range (1.93−2.06 km) actually represented the lidar-detectable altitude range (i.e., penetrable range of laser light into the cloud layer). Above the lidar-detectable altitude range, the X value became very weak (one twentieth of its maximum value or less) where the δ_v value increased from 0.15 at 2.06 km to 0.27 at 2.11 km presumably due to the multiple scattering. This indicated that for a receiver FOV of 1 mrad, the multiple scattering from opaque cloud layers composed of dense spherical water droplets would generate enhanced depolarization ratio values less than 0.27 on their bottom (the lowest part of the opaque cloud layers). In this situation, the lidar is obviously unable to detect cloud layers and/or precipitating hydrometeors occurring at altitudes above the opaque cloud layer. In our cases, 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.

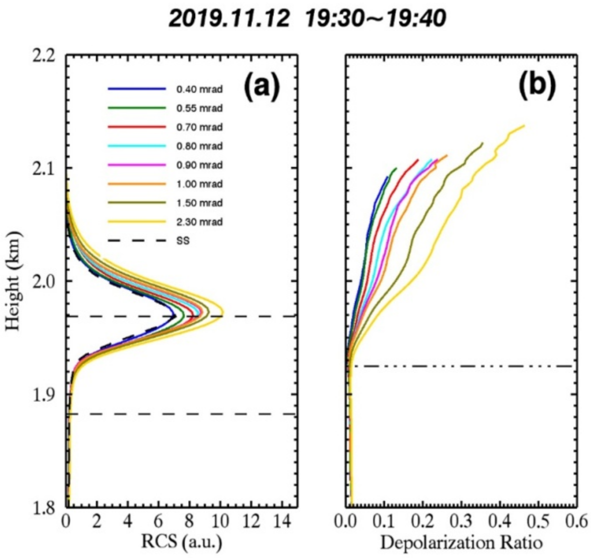

Figure R1. Profiles of (a) range-corrected signal X and (b) volume depolarization ratio δ_v for an opaque stratiform cloud composed of dense spherical water droplets observed by our multi-field-of-view polarization lidar. Each pair of colored lidar X

and δ_v profiles represent a 1-min integration and the altitude resolution is 3.75 m.

With respect to the discrimination between liquid-droplet layers and falling, oriented ice crystals when a zenith-pointing polarization lidar has observed very low depolarization ratios, we have added the following explanation in the revised manuscript.

"The lidar profiles above the dark band clearly exhibit the typical structure characteristics of a liquid-topped mixed-phase cloud (a shallow liquid cloud layer and ice virga below) (see Fig.6 in Wang and Sassen, 2001). The mixed-phase cloud top layer was of large X values and very low δ_v values (~0.01), while lower part of the cloud was characterized by significantly-smaller X values and large δ_v values (with a maximum up to ~0.33). Furthermore, the cloud top layer had a maximum water vapor mixing ratio q_v and a temperature of ~−8.5 °C (based on radiosonde data at ~2000 LT on 27 December). Combining with the schematic representation of commonly-observed mixed-phase cloud layers (see Fig. 1 in (Bühl et al., 2016)), the current observations suggest that the cloud top layer should mainly be composed of liquid droplets (that were not dense enough to yield detectable multiple scattering), and the lower part of the cloud was mainly precipitating ice crystals (falling ice virga)." (please see lines 318-326)

Comments:

P8, l218: Why is the volume depol ratio not close to 0.01? Maybe be because of multiple scattering. The paper does not contain any backscatter and extinction coefficients. So, I have no idea whether multiple scattering could be problem or not.

Authors' response:

In the water bright band (please see Fig. 4 in revised manuscript), the volume depolarization ratios of ~0.03−0.06 (not close to 0.01) might result from somewhat nonspherical raindrops that got slightly large sizes during their descent. The multiple scattering from dense droplets would yield a monotonic increase in the volume depolarization ratio δ_v with increasing penetration of laser light into the water-bright-band layer. However, here the δ_v value showed a slow decrease with increasing penetration of laser light into the water-bright-band layer. Hence the multiple scattering should not be a problem.

Comments:

P8, l229-230: How can droplets evaporate and at the same time others grow….?

Authors' response:

Taking the reviewer's comment into account, "...the suggestion that most falling pristine raindrops shrunk or vanished in the water bright band due to evaporation, whereas a small portion of them grew to large sizes via collision-coalescence processes and fell out of the water bright band." has changed to "...the suggestion that most falling small-sized raindrops shrunk or vanished in the water bright band due to evaporation, whereas a small portion of large-sized raindrops survived via collision-coalescence processes and fell out of the water bright band." (please see lines 245-247)

Comments:

P8, l235: ..Peaks at 0.1-0.4? ...you mean 0.1-0.14? Why is the rain depol peak always at 600 m. Can we have an estimate for the backscatter and the extinction coefficient? Maybe multiple scattering had an influence!

Authors' response:

The δ_v peak values (occurring in Fig. 2 of the revised manuscript) indeed were ~0.1-0.4 (values of ~0.4 occurred at 0536 and 0537 LT on 28 December 2017, the lidar operation terminated exactly at 0539 LT). With respect to the question why is the rain depol peak always at 600 m, further observational and modelling efforts are obviously needed in future. This phenomenon might presumedly reflect a feature for a variety of light mid-level stratiform precipitations. As mentioned above, for a receiver FOV of 1 mrad, the multiple scattering from opaque cloud layers composed of dense spherical water droplets can only result in depolarization ratio values less than 0.27 at altitudes below the weak-signal cutoff altitude. If strong multiple scattering had taken place around 600 m (yielding peak δ_v values of ~0.1-0.4), i.e., an opaque liquid cloud layer had concealed the atmosphere above 600 m, one would not have observed 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). Hence we can exclude a possibility that the large δ_v peak values around 600 m are caused by multiple scattering.

Comments:

P9, l240-l244: To my opinion, this is speculation. ...should be avoided.

Authors' response:

Taking the reviewer's opinion, the speculation that "In their further descent, the large raindrops break up into small raindrops, yielding a decrease in the depolarization ratio at altitudes below 0.6 km." has been dropped in the revised manuscript.

Comments:

P9, l269: Large values of the range - corrected signal coinciding with low depol ratio! That could have been caused by specular reflection by a few falling and oriented ice crystals. One should discuss such influences.

Authors' response:

The relationship that the X maxima corresponded to the local minima of the depolarization ratio was detected at altitudes ~600 m below the 0 °C level. However, the specular reflection by falling, oriented ice crystals occurred only at temperatures below −2.5 °C (−2.5 to −40°C) in light of a lidar-observation-based statistics (Westbrook et al., 2010). Furthermore, the altitude positions of the X maxima (local δ_v minima) showed an irregular variation rather than systematic descent with time. Therefore, we feel difficult to discuss the influences of falling and oriented ice crystals.

Reference:

Westbrook, C.D., Illingworth, A.J., O'Connor, E.J., Hogan, R.J.: Doppler lidar measurements of oriented planar ice crystals falling from supercooled and glaciated layer clouds, *Q. J. R. Meteorol. Soc.,* **136**, 260–276, DOI:10.1002/qj.528, 2010.

Comments:

P9, l279-295: What about seeding by clouds higher up. You have no information about all this. There is so much speculation here. Please avoid that. Keep the discussion short.

Authors' response:

Taking the reviewer's comments into account, the speculation (suggesting that most supercooled liquid drops falling out of their liquid parent cloud rapidly froze into ice crystals) has been dropped. This paragraph has been revised as

"As seen from the X and δ_v precipitation streaks at altitudes below ~1.5 km (Figs.2a and 2b), precipitation that reached the surface was intermittent. During periods without reaching-surface precipitation, our lidars were able to sample both a complete virga (from the rain to the snow regions) and a shallow mixed-phase cloud layer immediately above the virga under weak optical attenuation conditions. Such an example is shown in Fig.6. The lidar profiles above the dark band clearly exhibit the typical structure characteristics of a liquid-topped mixed-phase cloud (a shallow liquid cloud layer and ice virga below) (see Fig.6 in (Wang and Sassen, 2001)). The mixed-phase cloud top layer (at altitudes of ~4.6 km) was of large X values and very low δ_v values (~0.01), while lower part of the cloud was characterized by significantly-smaller X values and large δ_v values (with a maximum up to ~0.33). Furthermore, the cloud top layer had a maximum water vapor mixing ratio q_v and a temperature of ~−8.5 °C (based on radiosonde data at ~2000 LT on 27 December). Combining with the schematic representation of commonly-observed mixed-phase cloud layers (see Fig. 1 in (Bühl et al., 2016)), the current observations suggest that the cloud top layer should mainly be composed of liquid droplets (that were not dense enough to yield detectable multiple scattering), and the lower part of the cloud was mainly precipitating ice crystals (falling ice virga). The liquid-topped mixed-phase cloud (a liquid cloud layer and ice virga below) (Bühl et al., 2016) might be fundamental monomers that constitute mid-level precipitating stratiform clouds. Interestingly, the δ_v magnitude of the falling virga increased from the liquid-water values of ~0.03–0.10 at an altitude of 4.35 km to the ice/snow values of ~0.21–0.33 at an altitude of 4.0 km. The falling ice crystals yielded a very weak ice bright band at an altitude of ~3.0 km, and then melted into liquid drops at an altitude of ~2.76 km (the local δ_v minimum). During their further descent, the liquid drops fully vanished due to evaporation, leaving a lidar-detectable rain virga (water bright band) without reaching-surface precipitation. In contrast to the situation during precipitation that reached the surface, no clear-cut δ_v enhancement occurred at an altitude of approximately 0.6 km when there were only virgae suspended in air. Similar results were discerned for other lidar profiles shown in Figure 2, in which a complete mixed-phase cloud layer could be detected." (please see lines 315-335)

Comments:

P10, l297-308: Here you present again the erroneous ice nucleation theory! You should at least also present the established one (in the absence of seeding from above, ice crystals nucleate at cloud top, grow fast and start falling through the cloudoand become large before they leave the main cloud layer and show up in the virga as quite large crystals that may further grow as long a supersaturation over ice is given.

Authors' response:

Taking the reviewer's comment into account, the ice nucleating processes are not covered in the revised manuscript. The earlier statements (lines 297-308) have changed to

"During the light warm-front rain event, since the reaching-surface precipitations and virgae occurred alternately on a small time scale from a few minutes to tens of minutes and since their precipitation streaks had nearly the same dark-band structures (Figs.2a and 2b), both reaching-surface precipitation and virgae would come from the same source cloud (because a warm-front cloud system is generally widespread and slowly varying). Reaching-surface precipitation (drizzle) arose when the precipitation rate was high below the shallow water-droplet-dominated cloud layer (apparent source cloud), while virgae without reaching-surface precipitation took place when the subcloud precipitation rate was slightly low. Therefore, the current lidar observations reveal the microphysical process of precipitating hydrometeors related to light warm-front rain. Both reaching-surface rainfall and virgae suspended in air began as mixed-phase hydrometeors fell out of a liquid apprent-source cloud layer at altitudes above the 0 °C isotherm level. The depolarization ratio magnitude of falling hydrometeors increased from the liquid-water values (δ_v< 0.10) to the ice/snow values (δ_v> 0.25) during the first 100–200 m of their descent. Subsequently, the falling hydrometeors yielded a dense layer with an ice/snow bright band occurring above and a liquid-water bright band occurring below (separated by a lidar dark band) as a result of crossing the 0°C level." (please see lines 337-348)

Comments:

The entire Sect. 3.1.2 is very long and contains many speculative statements. The entire section should be shortened and should be based on what was observed.

Authors' response:

In the revised manuscript, a sentence that "the ice nucleating processes are not covered" has been put into the introduction (please see line 67) and all relevant speculative statements in Section 3.1.2 have been dropped. Now the content of revised Section 3.1.2 provides important observational information about microphysical process of precipitating hydrometeors from mid-level stratiform clouds and pertinent (physically-reasonable) explanation based on what are observed. Please allow us to keep its present length (revised content) if there is no erroneous statements (Section 3.1.1 has been shortened greatly), because another reviewer (reviewer 1) suggests that "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."

Comments:

P11, Sect 3.2: Another case, again depol peak caused by rain at 600 m! Why always at 600 m height? Should be clarified and discussed.

Authors' response:

With respect to the question why the depolarization peak caused by rain was always around 600 m height, further observational and modelling efforts are obviously needed in future. This phenomenon might presumedly reflect a feature for a variety of light mid-level stratiform precipitations. Considering a fact that falling raindrops suffer from strong evaporation during their minutes-long descent in a subsaturated environment, there were no raindrops reaching the surface if no (sparse) large raindrops formed midway. Recently, an optical disdrometer (Parsivel, with 1-min sampling interval) has been installed beside our lidar systems and a newly-developped off-zenith polarization lidar has been placed at our observation site. This allows us in future to detailedly examine the relation between the depolarization maximum around 600-m altitude and precipitation that reached the surface.

Comments:

Speculation about break up processes, occurrence of ensembles of small and large droplets, collision-coalescence effects… all this sounds convincing, but is that the truth? … As long as the role of multiple scattering is not clarified, the discussion is not trustworthy.

Authors' response:

With respect to the role of multiple scattering, we have added the following statements in the revised manuscript.

"We examined the multiple-scattering-induced depolarization ratio enhancements for an opaque cloud layer composed of dense spherical water droplets by putting a motorized iris on our polarization lidar system. It is indicated that for a receiver FOV of 1 mrad, the enhanced depolarization ratio δ_v values due to multiple scattering increased from ~0.03 at the X peak altitude to a maximum value of ~0.27 at the weak-signal cutoff altitude with increasing penetration of laser light into the opaque water-droplet cloud layer. Note that for the same receiver FOV (~1 mrad), the multiple-scattering-induced depolarization ratio δ_v values were all less than 0.04 within the laser light penetration range in a lightly-dense water-droplet cloud layer (Hu et al., 2006). Combining the earlier multiple-FOV polarization lidar measurements (Hu et al., 2006) and our similar observations yields a suggestion that for the 1-mrad receiver FOV, the multiple-scattering-induced depolarization ratio values larger than 0.10 should result from an opaque water-droplet cloud layer (see Figs. 2 and 4 in (Yi et al., 2021)). In other words, for the 1-mrad receiver FOV, the vertical structure of hydrometeors and aerosols present above a dense water-droplet cloud layer with δ_v values larger than 0.1 is undetectable by ground-based lidars." (please see lines 118-128)

Reference added

Hu, Y., Liu, Z., Winker, D., Vaughan, M., Noel, V., Bissonnette, L., Roy, G., and McGill, M.: Simple relation between lidar multiple scattering and depolarization for water clouds, Opt. Lett., 31(12), 1809–1811, doi:10.1364/OL.31.001809, 2006.
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.

"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 cases, 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 $\delta_v \geq 0.1$." (please see lines 259-269)

Comments:
Sect. 3.2.1: There is no information about the clouds, the ice nucleation processes, potential secondary ice nucleation processes, seeding effects, nothing. That should be emphasized to keep the entire discussion short. You should concentrate on the virga, because more is not possible. That must be clearly stated in the manuscript.

Authors' response:
In light of the previous suggestion of the reviewer, a sentence that "the ice nucleating processes are not covered" has been inserted in the revised Introduction (please see line 67). Therefore, the relevant speculations have been dropped in the Sections 3.2.1-3.2.2. In addition, the statements that "The (apparent) source cloud for this moderate rain event was invisible by the lidars due to strong optical attenuation. Therefore, the following analysis was limited to the ice bright band and below." have been added (please see line 389-390).

Comments:
P12, l369: Ice crystals detected 960m below 0°C height level…. Again, how can they survive? You have to give a reason!

Authors' response:
In light of the previous suggestion of the reviewer, an interpretation that "Such a long survival time of falling ice crystals at altitudes below the 0°C level was due to cooling of the surrounding air during their evaporation and melting." has been added. (please

see lines 419-420)

Comments:
Sect. 3.3.2: ..again, what is the potential impact of multiple scattering?
Authors' response:

With respect to the impact of multiple scattering, we have added the following interpretation in the revised manuscript.

"As mentioned above, for the 1-mrad receiver FOV, if such large δ_v values (~0.27–0.35) came from the multiple scattering by a dense water-droplet cloud layer around 0.6-km altitude, the cloud layer would be optically opaque. It would conceal the vertical structure of the precipitation streaks at altitudes above 0.6 km. In contrast to this situation, as seen from Fig. 10, the vertical structure of the precipitation streaks at altitudes above 0.6 km was clearly discerned by our ground-based 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, it is suggested that the prominent δ_v peak at an altitude of approximately 0.6 km reflected the collision-coalescence growth of falling large raindrops and their subsequent spontaneous breakup." (please see lines 445-456)

Comments:
Figure 1: The colored figures should be shown from 27 Dec, 00:00 LT to 28 Dec 16 LT, and probably up to 7 km only to see the necessary details. In the present form, the figure is almost useless.
Authors' response:
Figure 1 (i.e., Figure 2 in the revised manuscript) has been replotted with an abscissa from 1600 LT on 26 December to 0600 LT on 28 December 2017 and ordinate from 0 to 12 km. The precipitation streaks have been zoomed in to get a better view of their structure details. We want this figure to exhibit a complete warm-front cloud process and subsequent precipitation based on ground-based lidar observations.

Comments:
Figure 3: Is cloud top at 4 km height? We do not know! The decreased depolarization ratio from 3.6 to 4 km could be caused by specular reflection? Who knows! The decrease of the depolarization ratio below the local maximum at 600 m height may be an instrumental effect (bias) because the observations are performed in the near-range of the lidar where nothing is well defined. Please comment on that! So break up of rain droplets is speculation. Also evaporation could have started and the droplets got smaller and spherical again…
Authors' response:

In the Figure 4 of the revised manuscript (i.e., Figure 3 in the earlier version), the apparent source cloud of falling ice virga is invisible due to optical attenuation. Our description to Figure 4 started from the ice bright band (downward).

Regarding the reliability on the decrease of the depolarization ratio below the local δ_v maximum at 600 m height, please allow us to briefly introduce our lidar system. With a compactly-designed lidar configuration (20-cm Cassegrain telescope), accurate transmitter-receiver alignment and steady lidar environment temperature (with waterproof transparent roof windows), the complete-overlap altitude of our polarization lidar, that the laser-beam receiver-field-of-view (FOV) overlap function becomes unity, is reliably less than 400 m. Therefore, the depolarization ratio decrease below the local δ_v maximum at ~600-m altitude is trustworthy at least at altitudes down to 400 m. The break up of raindrops is a possible physical explanation to the δ_v decrease at altitudes below 600 m. We have noticed that the evaporation effect on the reduction of drop sizes is much more significant for small-sized droplets than large-sized rain drops (because the evaporation reduction rate of the drop size is inversely proportional to the magnitude of drop size). In contrast to the expected evaporation effect, the visible decrease of the depolarization ratios (from > 0.1 to <0.1) occurred in a narrow altitude range (e.g., ~300-600 m, please see Figs. 4b and 5b in the revised manuscript). Therefore, we believe that for large-sized raindrops, the evaporation effect was relatively weaker than the breakup effect.

Comments:

Figure 4: Again the overlap problems in the lowest 500 m! Can we trust the depolarization ratio values at heights below 500 m?

Authors' response:

Please see the interpretation above.

Comments:

Figure 5: Again a layer with low depolarization ratio around 4.5 km height together with large signal! Is that the liquid cloud layer? Or are there falling, oriented crystals producing specular reflection? This time no enhanced depolarization ratio around 600 m height, no big raindrops? This case demonstrates that there is slight decrease of the depolarization ratio from 250 m to 1 km. This is probably the background depol height profile in the absence of any multiple scattering effect.

Authors' response:

With respect to whether the layer with low depolarization ratio around 4.5 km height together with large signal was the liquid cloud layer or falling, oriented crystals yielding specular reflection (please see Figure 6 in the revised manuscript), we have the following explanation

"The lidar profiles above the dark band clearly exhibit the typical structure characteristics of a liquid-topped mixed-phase cloud (a shallow liquid cloud layer and ice virga below) (see Fig.6 in (Wang and Sassen, 2001)). The mixed-phase cloud top layer was of large X values and very low δ_v values (~0.01), while lower part of the cloud was characterized by significantly-smaller X values and large δ_v values (with a maximum up to ~0.33). Furthermore, the cloud top layer had a maximum water vapor mixing ratio q_v and a temperature of ~−8.5 °C (based on radiosonde data at ~2000 LT on 27 December). Combining with the schematic representation of commonly-observed mixed-phase cloud layers (see Fig. 1 in (Bühl et al., 2016)), the current observations suggest that the cloud top layer should mainly be composed of liquid droplets (that were not dense enough to yield detectable multiple scattering), and the lower part of the cloud was mainly precipitating ice crystals (falling ice virga).” (please see lines 318-326). The liquid-topped mixed-phase cloud (a liquid cloud layer and ice virga below) (Bühl et al., 2016) might be fundamental monomers that constitute mid-level precipitating stratiform clouds.

No enhanced depolarization ratio around 600 m altitude corresponded to the period where precipitation did not reach the surface. Considering a fact that falling raindrops suffer from strong evaporation during their minutes-long descent in a subsaturated environment (from an altitude of ~600 m down to the surface), there were no raindrops reaching the surface if no (sparse) large raindrops formed midway. Hence, no enhanced depolarization ratio around 600 m altitude should correspond to no big raindrops there. When there were only virgae suspended in air without surface-reaching precipitation, the δ_v precipitation streaks should reflect vanishing raindrops due to evaporation.

Comments:

Figure 6: Bad quality, like Figure 1: What do you want to show. There is almost nothing to see!

Authors’ response:

Figure 7 (i.e., Figure 6 in the earlier version) has been replotted with the precipitation streaks being zoomed in. We want to show both a complete warm-front cloud process and subsequent precipitation as shown in the lidar profile sequences.

Comments:

Figure 8: Again, one sees the high depolarization ratios indicating ice crystals, one does not see the main cloud layer. One does not know whether the cloud was seeded by higher clouds. One does not see anything. Except the virga of ice crystals, and then the drop in the depolarization ratio, when the crystals melt. Around 600 m again, rain droplets! Always around 600 m! What is the possible reason that the depolarization ratio maximum is always at about 600m. Maybe caused by multiple scattering?

Authors’ response:

In the Figure 9 of the revised manuscript (i.e., Figure 8 in the earlier version), the apparent source cloud of falling ice virga is invisible due to optical attenuation. Our description to Figure 9 was limited to altitudes at the ice bright band and below. With respect to the question that the depolarization maximum is always around 600 m height, further observational and modelling efforts are obviously needed in future. This phenomenon might presumedly reflect a feature for a variety of light mid-level stratiform precipitations. Considering a fact that falling raindrops from mid-level stratiform cloud suffer from strong evaporation during their minutes-long descent in a subsaturated environment, there were no raindrops reaching the surface if no (sparse) large raindrops formed midway.

With respect to the multiple scattering, we have added the following explanation in the revised manuscript.

"As mentioned above, for the 1-mrad receiver FOV, if such large δ_v values (~0.27–0.35) came from the multiple scattering by a dense water-droplet cloud layer around 0.6-km altitude, the cloud layer would be optically opaque. It would conceal the vertical structure of the precipitation streaks at altitudes above 0.6 km. In contrast to this situation, as seen from Fig. 10, the vertical structure of the precipitation streaks at altitudes above 0.6 km was clearly discerned by our ground-based 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, it is suggested that the prominent δ_v peak at an altitude of approximately 0.6 km reflected the collision-coalescence growth of falling large raindrops and their subsequent spontaneous breakup." (please see lines 445-456)

Comments:

Figure 9 again: Depolarization maximum at 600 m! Why always at 600 m?

Authors' response:

With respect to the question why the depolarization maximum is always around 600 m height (Figure 10 in the revised manuscript), further observational and modelling efforts are obviously needed in future. This phenomenon might presumedly reflect a feature for a variety of light mid-level stratiform precipitations. Considering a fact that falling raindrops from mid-level stratiform cloud suffer from strong evaporation during their minutes-long descent in a subsaturated environment, there were no raindrops reaching the surface if no (sparse) large raindrops formed midway.

Comments:

Again, please use all of my comments as a constructive contribution to improve the paper. The topic of the article is interesting and deserves publication!

Authors' response:

The authors greatly thank this reviewer for his/her affirmative remark to our article. Truly taking all the comments as constructive opinion and friendly suggestion, we have carefully revised the manuscript.