Reviewer comments on 'Influence of low-level blocking and turbulence on the microphysics of a mixed-phase cloud in an inner-Alpine valley' by Fabiola Ramelli et al.

Response to Dmitri Moisseev

We would like to thank Dmitri Moisseev for his constructive and helpful feedback and suggestions on the manuscript. We incorporated the suggestions within the revised manuscript, which significantly improved the quality of the manuscript. In the following, we will address the reviewer's comments and present our responses and changes in the revised manuscript. Reviewer comments are reproduced in blue and author responses are in black. All line numbers in the author's response refer to the revised manuscript.

General comments

1) *The authors investigate the influence of low-level blocking and shear induced turbulence on the cloud microphysics. They find associated changes in the cloud microphysics associated. Additionally, a low-level feeder cloud is observed and seems to be caused by the low-level blocking. This study is of great interest and importance for our understanding of the cloud processes in mountainous regions. I believe this paper can be published after major revisions. I am not sure if I completely agree with the authors' interpretation of radar observations and would like to see more explanations and answers to my questions. Please find my comments below.*

   Thank you for your comments and for raising several points, which in particular improved the interpretation of the radar observations. We included riming and the Hallett-Mossop process as possible microphysical mechanisms active within the mid-level cloud. The interpretation and discussion of the case study changed accordingly, as addressed in the responses to the specific comments.

Specific comments

2) *Lines 157-162. The interpretation of LDR (or any other dual-polarization radar variable) is a bit more complex. It is true that LDR depends on an apparent shape of a hydrometeor. However, to make matters more complex, it also depends on the particle refractive index, in case of ice particles the refractive index is related to the particle density. Therefore, increase in the ice particle density, i.e. by riming, may increase LDR. That is why changes in LDR are not necessary indicative of the changes in particle shape (see for example Fig. 2.8 page 65 in (Bringi and Chandrasekar, 2001)).*

   Another example is the change of LDR in the melting layer of precipitation, it is driven by the changes in the refractive index due to melting and not changes in particle shape.

   Thank you for this comment and the references. Indeed, as you pointed out the LDR signal depends on both the shape and density of the hydrometeors. We have now added a short description about the dependence of the LDR on the particle refractive index and included the proposed references (page 7, line 166-169): *"Furthermore, the LDR depends on the particle refractive index. Liquid water has a higher refractive index (0.93) than ice (0.197) (Houze Jr, 2014). For ice particles, the refractive index is related to the particle density, such that hail and graupel have a higher refractive index compared to snowflakes (Bringi and Chandrasekar, 2001). Therefore, changes in the LDR are indicative for changes in the particle shape and/or particle density (e.g. riming)."*

3) *Line 237. “an increase in the LDR was observed within the shear layer (Fig. 8e, f), which is indicative of a change in the hydrometeor shape” Actually, to my eye the increase in LDR starts above the shear layer. It may be related to the increase in Doppler velocity as shown in Fig. 10. Such an increase in Doppler velocity may be indicative of riming (Mosimann, 1995; Kneifel and Moisseev, 2020), which affects LDR as well.*

   Thank you for this comment and the references. We agree that the increase in the Doppler velocity might be related to riming. Especially, since the LDR of the faster falling part of the spectrum was observed to increase (Fig. 10). As no in situ observations were available within the upper part of the shear layer, we cannot draw any conclusions regarding the dominant microphysical processes. Thus, we discuss both riming and aggregation as possible ice growth mechanisms within the shear layer. We extended the interpretation as follows and included the suggested references (page 14, line 267-274):*” The increase in the Doppler velocity might be indicative of riming. Previous studies observed that an increase in the Doppler velocity can be indicative of riming, which leads to a higher terminal fall velocity of particles due to the rapid gain of ice particle mass (e.g., Mosimann, 1995; Kneifel and Moisseev, 2020). This is further supported by the increase in the LDR of the faster falling population of the spectrum as a consequence of the higher particle density. In addition, turbulence within the shear layer could increase the number of collisions between ice particles and promote the formation of aggregated particles (e.g., Pinsky and Khain, 1998).”*

4) *Line 248-249: “This is in agreement … with the ice particles observed by the MASC at the surface (Fig. 11a).” Actually, MASC observations do show presence of rimed particles as well.*

   Thank you for pointing this out. We changed the sentence as follows (page 16, line 273-274): *“Indeed, the hydrometeors observed by the MASC and HOLIMO show indications of rimed particles and large aggregates (Fig. 11), suggesting that both processes were occurring.”*

5) *Line 250: “Below 3000 m, the LDR increased up to -20 dB within the fallstreak (Fig. 10b).” It is not clear what you are referring to. Please indicate on the spectra which part has LDR values up to -20 dB.*

   If this is the faster falling part of the spectrum, then it cannot be due to newly formed ice crystals. In this case, in my opinion it would be riming. If the increase in LDR occurs in the slow falling part then it is cause by newly formed ice particles.

   Thank you for this comment. We specified in which part of the spectra the LDR increased (page 14, line 262-264): *“Below 3000 m, the LDR of the faster falling part of the spectrum increased up to -21 dB (Fig. 10b) and the spectrum broadened (Fig.10a).”* As you pointed out correctly, this suggests that the increase in the LDR was due to riming on the faster falling particles, which then led to the increase in the Doppler velocity. Accordingly, the interpretation of the LDR signal was changed (page 14, line 267-271): “*The increase in the Doppler velocity might be indicative of riming. Previous studies observed that an increase in the Doppler velocity can be indicative of riming, which leads to a higher terminal fall velocity of particles due to the rapid gain of ice particle mass (e.g., Mosimann, 1995; Kneifel and Moisseev, 2020). This is further supported by the increase in the LDR of the faster falling population of the spectrum as a consequence of the higher particle density.”*

6) *Line 254: “An increase in the LDR can be explained by the presence of needles, columns and/or irregular ice particles.”*

Do you observe this in Doppler spectra? You should see bimodal spectra, or at least some indication of bimodality.

Thank you for this comment. The Doppler spectra shows no indications of bimodalities, which would support the formation of a newly formed particle population. However, possible bimodalities might be masked by turbulence or subsaturated regions. The particles observed by HOLIMO show indications of needle growth on existing ice particles. We changed the text as follows (page 16, line 283-286): *"The analysis of the Doppler spectra showed no evidence of discrete multiple spectral peaks (i.e., the presence of multiple particle populations with different fall speed), which would support the occurrence of secondary ice production. However, turbulent regions or sublimation could broaden the size distributions and thus mask the presence of discrete multiple peaks in the Doppler spectra."*

7) *Line 259 – 261: "If fragile ice crystals such as dendrites or needle-like structures collide with large ice particles within the turbulent shear layer, small ice fragments might break off and lead to the production of secondary ice particles upon collision (e.g., Vardiman, 1978; Yano et al., 2016)."*

Of course, it may also be H-M process if the LDR signatures caused by riming.

Thank you for this comment. Indeed, the temperature (-8 °C to -4 °C) was in the temperature range of the Hallett-Mossop process. Thus, it is possible that secondary ice particles were produced upon riming. We added a sentence describing the possible occurrence of the Hallett-Mossop process (page 16, line 275-277): *"The temperature between 3000m and 2500m ranged from -8 °C to -4 °C and was thus in the temperature regime of columnar growth and of the Hallett-Mossop process. Thus, secondary ice particles might be produced upon riming, which could then rapidly grow by vapor deposition into column-like particles."* We also state that due to the missing in situ observations within the upper part of the shear layer it was not possible to draw any conclusions regarding the occurrence of secondary ice mechanisms (page 17, line 290-292): *"It remains unclear whether the Hallett-Mossop process and mechanical break-up in ice-ice collisions contributed to the formation of secondary ice particles (see also Sect. 5)."*

8) *Line 326-327: "Riming was assumed to play only a minor role, due to the low LWP (< 100 g m−2) observed by the microwave radiometer (Fig. 4c)." I am not sure if I agree that we can completely exclude riming based on LWP alone. Riming efficiency does not depend on LWP, but on liquid droplet diameter. So, given that droplets are big enough to take part in riming, riming could take place. We can compute if riming would significantly affect particle properties, by computing rime mass fraction for the observed LWP values. Let's assume that we a plate like crystal is formed at the cloud top. Just to have a first guess, we can choose P1a from Pruppacher and Klett.*

TABLE 2.4a

Mass-size relationships for various types snow crystals. Data taken on Mt. Teine (1024 m, Hokkaido, Japan), based on data of Heymsfield & Kajikawa, 1987.

Crystal type	Mass-size relation m(g), d(cm)	Diameter range (mm)
C1h	$2.63 \times 10^{-2}\ d^{2.68}$	0.3-0.6
P1a	$3.76 \times 10^{-2}\ d^{3.31}$	0.3-1.5

We can compute the expected FR as (see my simple Matlab code):

```
d = 0.3:0.01:1.5; %% mm
m = 3.76 * (10^-2) .* ((d/10).^3.31); %% grams for P1a

LWP = 50; % g/m^2


dm  = LWP.*(pi/4).* (d/100).^2;

%%% Rime mass fraction
FR = dm./(m+dm);
```

This computation gives rime mass fraction value close to 1. Of course, I have assumed the riming efficiency of 1, here. So, the actual FR value could be lower. But notice that I have used LWP of 50 g/m^2 and not 100 g/m^2.

If riming is taking place here, even for the observed low LWP values we can expect a significant impact on particle properties.

Thank you for the comment and the calculation. The calculation clearly shows that riming cannot be excluded based on the LWP alone. Based on your previous comments (see also answers to comments #2 to #4), we included riming as a possible ice growth mechanism in the revised manuscript (especially due to the increase in the negative Doppler velocity and the increase in the LDR of the faster falling population of the spectrum). Furthermore, the ice particles observed by the MASC and HOLIMO show indications of riming. We also discuss the possible role of the Hallett-Mossop process in the revised manuscript (see answer to comment #7).