Reviewer comments on 'Microphysical investigation of the seeder and feeder region of an Alpine mixed-phase cloud' by Fabiola Ramelli et al.

Response to Reviewer #1

We would like to thank the anonymous referee for his/her 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 the author responses are in black. All line numbers in the author's response refer to the revised manuscript.

General comments

1) *This is a very well written paper. It is properly referenced, and logically presented. The data are novel and interpreted carefully. The Conclusions are reasonable. The figures are clear and easy to follow. I recommend publication.*

   My only real concern with the paper is the speculative nature of the interpretation of processes within the generating cells. Without in-situ measurements, the interpretations are necessarily speculative, but I think the authors have been careful to keep their speculations constrained by the data available to them. For that reason, I don't believe any changes are necessary.

   Thank you for this comment. Indeed, the interpretation of processes within generating cells is challenging, since no in situ observations (e.g., aircraft measurements) were available within the generating cells during this campaign. The interpretation is based on balloon-borne in situ observations near cloud base, INP measurements obtained at a mountain-top station and remote sensing observations from a cloud radar. To account for the uncertainty in the ICNC and INP concentrations, we included the uncertainty of the ICNC and an estimate of the upper and lower bound of the INP concentration in Fig. 10 and Fig. 11. In addition, we extended the discussion about the uncertainty of the ice multiplication factors (Fig. 12) in the revised manuscript (page 29, Appendix B):

   *"**Appendix B: Potential mechanisms in generating cells and their contribution to ICNC***
   In Section 4.2, we proposed different mechanisms that potentially enhance ice nucleation and growth in cloud top generating cells (convective overshooting, radiative cooling, droplet shattering) on the basis of INP measurements and cloud-base observations of the ICNC and ice particle size. In the following, we estimate the potential contribution of these mechanisms for the observed ICNC and discuss the related uncertainties.

   B1 Convective overshooting
   Generating cells can be associated with an overshooting cloud top, for instance, when static instabilities due to radiative cooling occur at cloud top. In the present case study, convective overshooting of up to 500 m was observed at cloud top (e.g. GC1 in Fig. 8). The consequent decrease in cloud top temperature increases the number of INPs active due to the colder temperatures and thus increases the number of ice crystals likely formed by primary ice nucleation. The enhancement of ICNC due to convective overshooting can be summarized as follows:

$$m_{ice,cos} = \frac{INPC(T_{cos})}{INPC(T_{CT})}\ with\ T_{cos} = T_{CT} - \Gamma_{amb} * h_{cos}$$

where $m_{ice,cos}$ is the ice multiplication factor due to convective overshooting, INPC(T) is the INP concentration at a given temperature, T_{cos} is the cloud top temperature after convective overshooting, T_{CT} is the initial cloud top temperature, Γ_{amb} is the ambient lapse rate and h_{cos} is the height of the cloud top overshooting. As discussed in the main text, these variables were estimated from the available observations. With T_{CT} = -21 °C, INPC(T_{CT}) = 0.27 L^{-1}, Γ_{amb} = 7.2 K/1000 m (±1 K/1000m), h_{cos} = 500 m (± 100 m) and thus INPC(T_{cos} = -23.5 / -26 °C) = 0.61 - 1.4 L^{-1} (from Fig. 10), the ice multiplication factor due to convective overshooting ranges between 2.2 and 5.2 in the present study. However, the contribution of convective overshooting for the ICNC can be significantly different for other cases depending on the ambient conditions (e.g. lapse rate), the magnitude of the overshooting and the temperature dependence of the INP population.

B2 Cloud top radiative cooling

Radiative cooling plays an important role for the formation and maintenance of generating cells. The magnitude of the longwave radiative cooling strongly depends on the microphysical cloud properties (e.g., liquid water content). Large updrafts within the core region of generating cells can enhance the production of supercooled liquid water and thereby increase radiative cooling at cloud top. The enhancement of ICNC due to radiative cooling can be estimated as follows:

$$E_{ice,rc} = \frac{INPC(T_{rc})}{INPC(T_{CT})}\ with\ T_{rc} = T_{CT} - \Delta RHR * t_{GC}$$

where T_{rc} is the cloud top temperature after radiative cooling, ΔRHR is the increase in the radiative heating rate within generating cells compared to their surrounding regions and t_{GC} is the duration of the generating cell. With T_{CT} = - 21 °C, INPC(T_{CT}) = 0.27 L^{-1}, ΔRHR = 1.2 K h^{-1} (±1 K h^{-1}), t_{GC} = 15 min (± 10 min) and thus INPC(T_{rc} = -21 / -22 °C) = 0.27 - 0.37 L^{-1} (from Fig. 10), the ice multiplication factor due to radiative cooling is in the range of 1 - 1.4 for the present case study. The radiative heating rates that were used in our analysis were solely based on literature values (Turner et al., 2018) and thus are associated with large uncertainties. Nevertheless, despite the underlying assumptions, we show that the contribution of radiative cooling on the ICNC is small compared to the contribution of convective overshooting.

B3 Droplet shattering

Drizzle-sized droplets can release small secondary ice particles upon freezing. This process might also be active in cloud top generating cells, if the droplets exceed a diameter of about 40 µm, which has been identified as a critical threshold in previous studies (e.g., Lawson et al., 2015; Korolev et al., 2020). As highlighted by Lauber et al. (2020), the number of secondary ice particles produced by large cloud droplets depends on the droplet freezing rate, the droplet fragmentation probability during freezing and the number of splinters produced per fragmenting droplet. Since no in situ observations of the cloud properties were available within generating cells to obtain these parameters, the contribution of droplet shattering on the ICNC is not investigated further in this study."

We conclude Sect. 4.2 with recommendations for future observational studies of generating cells (page 21, line 416-419): *"However, more targeted studies are necessary to understand which mechanisms are responsible for enhanced ice formation and growth within cloud top generating cells.*

In particular, in situ measurements of the cloud properties within generating cells and their environmental conditions (e.g., temperature, updrafts, INP conditions) are of major importance to address these questions."