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 #2

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) *Ramelli et al. presents remote and in situ observations of a mixed phase cloud in the Swizz Alps and discusses the processes responsible for the origin of the ice. The paper is well written, and the figures are high quality. The range of measurement techniques in this study are impressive and should provide a useful dataset for further process studies. However, I found the discussion of the origin of ice speculative and I am not sure how much it adds over previous studies other than stressing the importance of secondary ice processes and the difficulties in quantifying them. Despite this, I did find the case study interesting and the paper should be suitable for publication with relatively minor revisions.*

   I would like to see further discussion regarding the instrumentation used in the paper and their respective uncertainties. Currently uncertainties are not discussed making it difficult to assess the strength of the relationships between INP and ice number concentration.

   Thank you for these comments. We agree that the discussion of the origin of ice in generating cells is rather speculative, as no in situ observations were available within generating cells (e.g. aircraft observations). The analysis is solely 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. As highlighted on page 21, line 416-419, in situ observations within generating cells are necessary for a more comprehensive analysis: *"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."*

   To assess the strength of the INP-ICNC relationship we included the uncertainty of the ICNC and an upper and lower estimate of the INP concentration (see responses to specific comments). In addition, we extended the discussion about the uncertainty of the different processes and instrumentation in the revised manuscript, as addressed in the responses to the specific comments.

Specific comments

2) *Section 2- The paragraphs in this section are very long. At a minimum each type of instrument should be a separate paragraph. You could also have separate subsections for remote sensing and in situ instruments.*

Thank you for this comment. Following your suggestions, we separated the remote sensing and in situ instruments in different subsections. Furthermore, we divided the instruments by cloud, wind, precipitation and INP observations to ensure a better overview of the instruments.

3) *Page 4 line 105 to 107. More information is needed about how LWP is retrieved and its uncertainty.*

Thank you for this comment. We added more information about the LWP retrieval and its uncertainty in the revised manuscript (page 5, line 130-133): *"The atmospheric parameters are derived from the measured multi-frequency brightness temperatures following a statistical approach based on a least squares linear regression model (Löhnert and Crewell, 2003). Previous studies reported retrieval uncertainties on the order of 0.5-0.8 kg m^{-2} for IWV (Steinke et al., 2015) and 16 g m^{-2} for the LWP (Crewell and Löhnert, 2003)."*

In addition, we extended the paragraph about the cloud radar observations in the revised manuscript (page 4, line 111-127): *"The radar was operated at a pulse-repetition frequency of 6000 Hz and a pulse length of 208*10^{-9} s, resulting in a vertical resolution of 31.17 m and a maximum unambiguous velocity range of 25.6 m s^{-1}, which spans from -12.8 to 12.8 m s^{-1}. The return signals of the emitted linearly polarized pulses were detected separately in the co- and cross-polarized planes. For both channels, Doppler spectra are derived from Fourier transformations of the return signals from a series of 512 consecutive pulses, corresponding to a Doppler-velocity resolution of 0.05 m s^{-1}. The final temporal resolution of the acquired cloud-radar dataset of 10 s is obtained from incoherent averaging of 100 consecutive Doppler spectra.*

The 10-s averages of Doppler spectra are the prerequisite for the subsequent data analysis. The moments of the Doppler spectrum provide information about volume-mean radar reflectivity, Doppler velocity and Doppler spectral width, based on which the abundance and turbulent properties of clouds can be inferred (Görsdorf et al., 2015). From the ratio of the co- and cross-polarized signal components, the linear depolarization ratio (LDR) is obtained. During the RACLETS campaign, the minimum detectable LDR, which is defined by the quality of decoupling of both detection channels (Myagkov et al., 2015), was found to be -27 dB. The individual Doppler spectra contain valuable information about the microphysical structure of the observed clouds. They can be screened for the presence and properties of multiple spectral peaks in order to evaluate the abundance of different hydrometeor types. In here, such a peak separation is realized by means of the newly developed peakTree retrieval (Radenz et al., 2019). The microphysical properties of ICNC and size are retrieved with the method of Bühl et al. (2019). Both retrievals are further elaborated on in Section 2.3."

4) *Page 4 line 114 to 119. It is not clear what you mean by classification here. Is it referring to the process of separating 'real' particles from noise in the holograms? You need to discuss the uncertainty in this process and the resulting uncertainty in the ice and droplet concentrations.*

Thank you for pointing this out. We extended the description of the classification step in the revised manuscript (page 6, line 146-148): *"The captured 2D shadowgraphs are classified as cloud droplets, ice crystals and artefacts (e.g. noise in the hologram) based on the particle shape using supervised machine learning (e.g., Beck et al., 2017; Touloupas et al., 2020)."*

Furthermore, we included a paragraph about the analysis and uncertainty of the holographic measurements (page 6, line 149-164): *"In the present study, a total number of 9000 holograms with a sample volume of 12 cm^{-3} each (i.e. total sample volume of 105 L) was utilized for the analysis of the cloud properties. The entire sample volume of 35 cm^{-3} was used for the analysis of the different ice* *habits (see Sect. 4.3) to obtain a significant statistics. As in Henneberger et al. (2013) and Beck et al. (2017), partitioning between cloud droplets and ice crystals was done for particles larger than 25 µm, since for particles smaller than 25 µm it is challenging to differentiate between the ice and liquid phase due to resolution limitations. Cloud droplets were classified using a decision tree, whereas ice particles were classified using a neural network (Touloupas et al., 2020). The uncertainty in the cloud droplet number concentration was around ±5% (Beck, 2017). Additionally, for cloud droplets larger than 40 µm the counting uncertainty ($\sqrt{N}/V$; where N: number of particles; V: measurement volume) was added, due to their relatively small numbers. All predicted ice particles were manually confirmed after the automated classification in order to reduce the number of misclassified ice particles. According to Beck (2017), the uncertainty in the ICNC is in the range of 5 - 10% for ice crystals larger than 100 µm in diameter and around 15% for ice crystals smaller than 100 µm. Again, the counting uncertainty was added to the ICNC*$_{< 100\,\mu m}$ *(i.e., ice crystals smaller than 100 µm) and ICNC*$_{> 500\,\mu m}$ *(i.e., ice crystals larger than 500 µm). Because of the applied size threshold (25 µm) and the visual classification, the reported ice properties (e.g., ICNC, ice water content) can be considered as a lower estimate. Additionally, all ice particles larger than 50 µm in diameter were manually classified into 5 ice habits based on the particle shape: (1) plate-like, (2) column-like, (3) graupel, (4) irregular and (5) aggregates (see Sect. 4.3).”*

5) *Page 5 –Saying the uncertainty in the derived concentration is one order of magnitude needs further justification. The uncertainty is not necessarily the same as Buhl et al., 2019 (different radar, microphysics etc). You need a much more thorough description of this method and its uncertainties.*

Thank you for this comment. The ICNC retrieval is discussed in a separate section in the revised manuscript. The uncertainties are calculated explicitly for each resulting number concentration based on the measurement errors of the input variables. We added a comment to the paper with explanation of the uncertainties (page 8, line 203-213): *“The ICNC is derived from pre-calculated lookup tables containing the measurement variables (here radar reflectivity, Doppler velocity and spectral width) together with the corresponding microphysical state that would lead to exactly these measurements. The particle diameter was estimated from the particle terminal fall velocity and spectral width measured with the cloud radar. The predominant ice particle shape was obtained from LDR measurements of the cloud radar and the ice crystal images observed by HOLIMO. For this case, the particle shapes from Mitchell (1996) were used, assuming ’hexagonal plates’ for ice crystals smaller than 600 µm in diameter and ’aggregates of planar polycrystals in cirrus clouds’ for ice particles larger than 600 µm in diameter. For a particular ice crystal shape, the whole lookup table is searched for matching measurement values within the margins of the corresponding measurement errors. Usually, several results are found that meet these criteria. The standard deviation of the distribution of results is taken as the uncertainty for each derived quantity. The uncertainty in the ICNCs presented in this work is about a factor of four.”*

6) *Page 6 line 145 – What is the instrumental uncertainty and how is it calculated.*

Thank you for this comment. We rephrased the sentence in the revised manuscript in order to be more precise (page 7, line 186-189): *“An intercomparison of an ambient aerosol sample between both instruments showed slightly higher INP concentrations for LINDA compared to DRINCZ for temperatures along the here relevant freezing spectrum (i.e. a factor of 2 for -15 °C < T < -8 °C) (Miller et al., 2020), which can be likely attributed to instrumental differences.”*

7) *Page 8 line 193 – remove 'more easily'.*

Thank you for pointing this out. We changed it in the revised manuscript.

8) *Page 10 line 209 – 'Ice crystals were especially observed when fallstreaks of enhanced. . .' please rephrase e.g. 'Ice crystal concentrations were higher when fallstreaks. . .'*

Thank you for pointing this out. We changed it in the revised manuscript.

9) *Page 12 line 215 – Is the radiometer sensitive to ice crystals.*

Thank you for pointing this out. It is usually neglected, as it is not emissive at HATPRO wavelengths.

10) *Page 13 line 260 – Since this is a relatively new analysis technique a bit more information about how the peaktree analysis works would be useful.*

Thank you for this comment. Indeed, the peakTree analysis is a relatively new technique. The peakTree analysis is discussed in more detail in Sect. 2.3.2 in the revised manuscript (page 8, line 215-225): *" The Doppler spectra were analyzed for multi-peak situations with the peakTree approach (Radenz et al., 2019). The (sub-)peaks in the Doppler spectrum are identified and transformed into nodes of a binary tree. By using such a tree structure, it is possible to drop all a priori assumptions on the number and arrangement of the (sub-)peaks, while providing a rigid and unambiguous peak structuring method. The Doppler spectrum from the cloud radar data processing (Sect. 2.1.1) is smoothed in the velocity domain using a 5-bin window. Afterwards the boundaries of noise-floor-separated peaks and internal subpeaks are identified. The latter are only considered valid peaks, if a local minimum of spectral reflectivity is at least 1 dB below the next maximum ('peak prominence'). Starting from the outermost bounds, which provide the root node, the tree is recursively built by splitting nodes into child nodes for each peak boundary from low to high spectral reflectivities. The moments (reflectivity, mean velocity, spectral width, skewness and LDR) are calculated for each node. The root node (index 0) holds the same moments as obtained by 'traditional' spectral processing, when assuming only mono-modal peaks. Detailed explanations and examples are given in Radenz et al. (2019)."*

11) *Page 17 line 291 – You assume that the ice particles >500um formed near cloud top, to place this in context you should include the total ice crystal concentration with your comparison with INP in Figure 11. What is the counting uncertainty on the ice crystal concentrations?*

Thank you for this comment. The analysis in Sect. 4.2 focuses on large ice particles (>400 µm), as those were assumed to have formed near cloud top. The total ICNC and the ICNC of small ice particles (<100 µm) are presented in Sect. 4.3 (e.g. Fig. 14), where the feeder region of the cloud is discussed in more detail. To assess the strength of the INP-ICNC relationship in Fig. 11, we included the uncertainty of the ICNC (including also the counting uncertainty) and an estimate of the upper and lower bound of the INP concentration (estimated from the 95% confidence interval of the fit in Fig. 10).

Furthermore, we show the cloud top ICNC retrieved from the cloud radar observations for three different time periods (page 20, caption Fig. 11): *"The cloud top ICNC retrieved from the radar observations (Sect. 2.3.1) are shown by the red dots. The reported ICNC represent an average over the top ten range gates (300m from cloud top) for three different time periods (14:30 -17:00 UTC, 17:10 - 17:45 UTC, 17:45 - 18:30 UTC). The vertical red lines indicate the error in the retrieved ICNC, whereas the horizontal red lines mark the extent of the time periods."* The $\mathrm{ICNC}_{>400\mu m}$ observed near cloud base is on the same order of magnitude as the radar-retrieved ICNC at cloud top, which further supports the assumption that ice particles larger than 400 µm originated near cloud top.

12) *Page 17 line 295 – The observed INP vs T relationships (Figure 10) show a high degree of variability. Yet none of this variability is accounted for in the INP concentration you derive for cloud top. You could use this variability to estimate the upper and lower bounds of INP concentration.*

Thank you for this comment. Indeed, the observed INP concentrations show high variability. Since only the INP data measured at Weissfluhjoch (i.e., two INP measurements) were included in the analysis in Sect. 4.2, the variability might not be the best method to estimate the upper and lower bound of the INP concentration. Thus, we estimated the uncertainty in the derived INP concentrations by accounting for the uncertainty of the fit. We included the 95% confidence interval of the fit in Fig. 10 and used the upper and lower bound to estimate the uncertainty in the derived INP concentration at cloud top.

13) *Figure 14. Were the ice crystal images manually classified into habits?*

Yes, the ice crystal images were manually classified into habits after visual confirmation of the automated classification. This is highlighted in Sect. 2.2.1 (page 6): *"All predicted ice particles were manually confirmed after the automated classification in order to reduce the number of misclassified ice particles (page 6, line 157-158). […] Additionally, all ice particles larger than 50 µm in diameter were manually classified into 5 ice habits based on the particle shape: (1) plate-like, (2) column-like, (3) graupel, (4) irregular and (5) aggregates (see Sect. 4.3) (page 6, line 162-164)."*

14) *Page 24 line 437 to 439. The uncertainty on the factor 3.3 and 1.2 is likely extremely large. If you are going to include these numbers, you need to include some discussion about their uncertainty.*

Thank you for this comment. Indeed, these numbers are associated with large uncertainties. In the revised manuscript, we provide a range for the different factors (Fig. 12) and included a discussion about the uncertainty of the different processes (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."