First, we would like to thank the two anonymous Reviewers for having carefully read the manuscript and for providing their helpful and constructive reviews, which improved our manuscript. Point-by-point replies to the comments are here below.

For clarity and easy visualization, the Referee's comments are shown from here on in black.

> The authors' replies are in blue font with an increased indent below each of the referee's statements. The Line numbers (L.) in our responses refer to the unrevised manuscript.

> The relevant changes in the revised manuscript are below in green.

Authors' response to anonymous Referee #3 (https://doi.org/10.5194/acp-2022-98-RC1)

Overall Quality

This manuscript utilizes a merged-instrument approach to characterize precipitating ice particle habits at a remote site in inland Finlind. Primarily using 12-hourly soundings and the Multi-Angle Snowflake camera (MASC), the study determines via knowledge of ice particle history and growth regimes that approximately three-quarters of ice particles originate from cloud layers with top temperatures outside of the mixed-phase region (i.e., sub-liquid RH saturation [<99%]), suggesting that the majority of cloud layers are fully glaciated. Using an empirical formulation, they finally determine that the number of ice nucleating particles (INP) were likely sufficient to explain heterogenous ice production, suggesting an inactive ice multiplication mechanism (outside of possible collisions). Overall, the manuscript is of excellent quality in terms of science, documentation, figures, and structure. The authors clearly made a significant effort to explain their data processing in a concise manner. After addressing a few specific comments and technical corrections, I recommend this manuscript pursue publication in ACP.

> We thank the referee for reviewing our manuscript. We appreciate the positive feedback and helpful comments.

Specific Comments

Fig 6. & ~Line 183: I would point out to the reader that the color-scales on each panel are different.

> Thank you for commenting on this. We have added the following sentence in the caption of Fig. 6. We also added a sentence in captions of Fig. 4 and Fig. A6, which are figure that have had similar issues.

> The color scale ranges from zero to the total number of events for each group, so the color scale for each panel is different.

Line 159 & Fig. 3: What exactly is "visibility"? If it is similar to cloud base height, then these are an order of magnitude off. It would also be good to mention how cloud base height was detected within the instrumentation at the site. If it is a nm-wavelength active remote sensor, then I would expect my interpretation of visibility to closely optically correspond with cloud base height.

The cloud base height was measured by Vaisala CT25K ceilometer (Ceilometer CT25K User's Guide, Vaisala, available at: https://www.rish.kyoto-u.ac.jp/ear/ceilometer/ct25k.pdf, last access: 11 August 2022). The visibility was measured by Vaisala FD12P with an optical forward-scatter sensor that sees fog and precipitation particles (see https://www.livedata.se/images/Vaisala/Nederbord/FD12P.pdf, last access: 11 August 2022). The visibility measurement range is 10 to 50 000 m. This is basically documented in L. 116 with reference to the FMI web page (https://litdb.fmi.fi/luo0015_data.php, last access: 11 August 2022). We replaced the "visibility" with "horizontal visibility" throughout the manuscript. Consistently, we adapted the sentence in L. 159.

During snowfall, the horizontal visibility was on average 2020 m, the average base height (or vertical visibility) of the lowest cloud was 213 m, […].

Fig 3: I'm confused about the sea level pressure measurements. If the station is only 179 m ASL, these values are way too low.

Thank you very much for this valuable comment. It brought to our attention that we have made a mistake in calculating the ground-based meteorological parameters for the 15 minutes intervals. We have corrected this and updated the Fig. 3. Amongst other variables, the sea level air pressure values are higher than before and now make sense. In addition, the related values mentioned in the text (L. 154 – 160, L. 192 – 194) and Fig. A6 were corrected.

Fig 2 & Line 134: Why 15 minutes prior to sounding release? Wouldn't 15 minutes aftertward be more representative of the cloud that is producing the precipitation?

Since radiosondes were launched from the same ground station at which we observed falling snow crystals, it was only at ground level and at the moment of launch that both kinds of observations coincided in space and in time. Crystals formed at any point in the profile while it was sounded, have reached ground level downwind the station and at a later point in time. By relating the humidity profile to crystals observed 15 minutes prior to launch we assumed that the profile is, when sounded, still representative of what it was up to 15 minutes earlier upwind the station. If we would have related the sounded humidity profile to crystals observed during the 15 minutes following sounding, we would have had to assume the sounding to be representative of the moisture profile still upwind the station, from where crystals would arrive in the following 15 minutes. Neither assumption is secure, but the first seemed to us more reliable than the second. Anyway, the sky was fully cloud covered (8 octas; see L. 162) during snow events and the choice of assumption probably makes no big difference.

Line 213: Nice conclusion!

Thank you.

Technical Corrections

Line 61: “automatically” should be “automatic”

Done.

Line 63: “summery” should be “summer”

Done.

Fig A1: “lowlight” should be “highlight”

We changed the wording into “The grey areas mark…”.

Line 81: suggest using “length” instead of “height”

Done.

Line 94: Should “An ice particle classified” be “An ice is particle classified”?

We changed this sentence as it was a little confusing.

Unrimed ice particles correspond to riming degrees of 0 and 1, and rimed particles to riming degrees of 2 to 5 according to Mosimann et al. (1994).

Line 153: Should “weighed” be “weighted”?

Yes, thank you. Done.

Authors’ response to anonymous Referee #2 (https://doi.org/10.5194/acp-2022-98-RC2)

The authors use several months of radiosonde soundings and coincident, ground-based hydrometeor imagery at a high-latitude station in northern Finland to infer ice formation pathways during snow events. Relative humidity (RH) profiles (both with respect to water and ice) from radiosonde data are used to develop a simplistic snow event predictor. For snow events, the authors show how imagery-based ice particle habits change as a function of RHw. Using cloud-top temperature the authors conclude that primary ice formation was the main pathway to form snow.

The study is well written and contains many useful plots. I recommend publication after resolving a few major issues.

Thank you very much for reviewing our manuscript, the general assessment and the constructive comments.

Major points

The “Results” section includes a few elements of a discussion. However, I feel the study would benefit from a broader discussion that is also placed into its own section.

Thank you for the suggestion. We have carefully weighed benefits and drawbacks of separating "Results" from a broadened "Discussion". In the end, we decided to keep both combined for better readability and also to avoid stretching interpretation. We hope to have done justice to the valuable specific issues below in the revised "Results and discussion" section.

Following points should be relevant to the reader:

- The authors start their study by mentioning the Arctic surface budget. Do the authors think the site in Finland is representative of the Artic? Or could the continental character and the influence from boreal forests (e.g., Schneider et al., 2021) mislead?

  Indeed, the opening sentence may raise expectations that cannot be fully met. Therefore, we changed some sentences of our manuscript in the Abstract (L. 1, L. 2, L. 9) as well as the Introduction (L. 12 – 14, L. 20). Nevertheless, we still find the more nuance relation to Arctic studies appropriate in L. 40 onward.

- Would other (frequently used) INP parameterization lead to the same conclusions?

  To our knowledge, no aerosol properties were measured continuously at the site over the period of our study, except aerosol optical depth. However, most commonly used INP parameterizations are based on aerosol particle properties such as concentration or size distribution. Lacking such data, we are not able to use such INP parameterizations and thus do not know whether the use of other INP parameterizations would lead to the same conclusion. We added the following sentence in L. 242.

  Since the necessary aerosol properties were not measured at the site at the time period of interest, it was not possible to use other existing INP parameterisations (e.g. DeMott et al., 2015, Ullrich et al. 2017) to qualitatively evaluate the associated uncertainty. However, the here predicted INP concentrations are similar to…

- Could the high-RHw group (Fig. 8) be useful as a proxy of snow events in a warmer climate?

  Conceptually yes. Therefore, we added the following sentence to the conclusion.

  This could lead to snowfall events with a greater proportion of larger snowflakes, rimed ice particles, and such crystal habits that grow above water saturation compared to today. Rime-splintering and other secondary ice formation processes requiring liquid droplets could become more frequent, which would likely increase the ice multiplication factor.

- Is a 15 min window appropriate? How long would it take for a particle to fall from ~2.7 km?

A compactly growing ice particle falls about 800 m during the first 30 minutes of its growth (Fukuta and Takahashi, 1999). Assuming thereafter a fall velocity of 1 m s^{-1}, the time it will take to reach ground from an initial height of 2.7 km is around 1 hour. Ideally, we would have used slowly descending drop sondes, dropped so far upwind that they would have arrived at the ground station together with the snow crystals they had accompanied during their growth. However, radiosondes launched from ground level travel vertically in the opposite direction of falling crystals. Therefore, temporal and spatial lags between the trajectories of radiosonde and observed crystals are unavoidable. Minimising these lags can only be achieved by choosing a short interval for crystal observation. Still, the interval has to be long enough to detect low precipitation rates. We settled for 15 minutes, which was enough to detect precipitation rates ≥ 0.01 mm h^{-1} (see L. 140 – 144).

Please review the order of the figures. Figure 7 is mentioned earlier (l. 89) than Figure 2 (l. 150). The same review should be applied for supplementary figures.

Thank you. We separated Fig. 7a from Fig. 7b and moved Fig. 7a. Furthermore, Fig. A7 and Fig. A3 are now arranged in a way that it follows the narrative. Consequently, most Figure numbers have changed in the revised manuscript.

Minor points

l. 1 This sentence sticks out. Either specify “properties” and their “role” or write it more general as “clouds” (instead of “cloud properties”).

We generalized.

Clouds and precipitation play a critical role in the Earth’s water cycle and energy budget.

ll. 198-199 Perhaps show examples of unclassifiable particles.

We added some examples of invalid and undefinable particles to Fig. A7 and refer to it in the text. Also, we show some examples of broken-off branches of dendrites (see Figure here below).

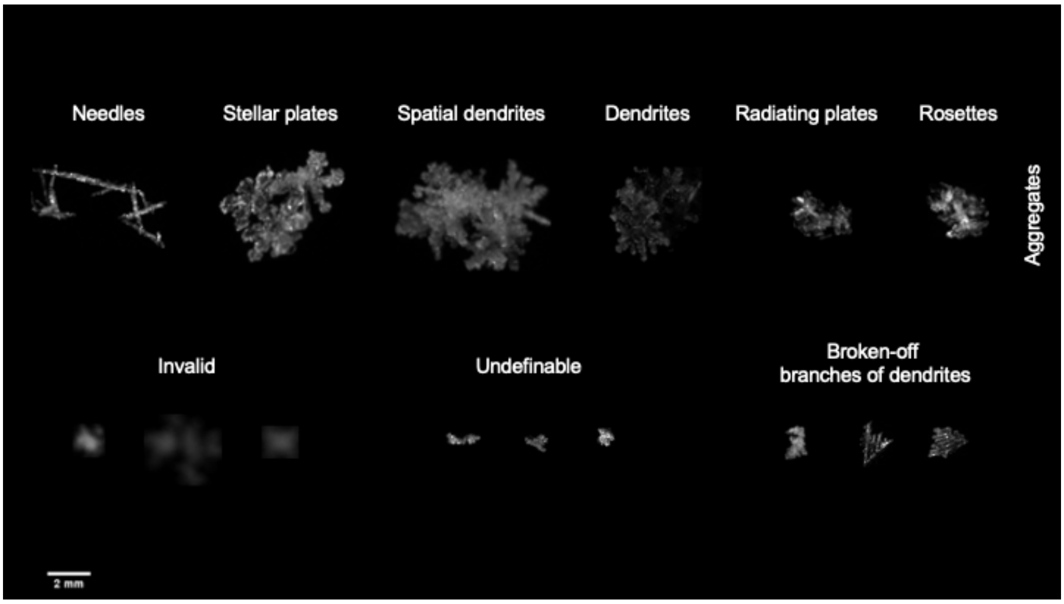

Figure A2. Similar to Fig. 2, but with further examples of images captured by the MASC. Aggregates of specifiable ice particle shapes are arranged in the top row. Invalid and undefinable particle shapes as well as broken-off branches of dendrites are shown in the bottom row.

l. 208 This sentence is redundant as the information was provided in l. 206.

Thank you for spotting the redundancy. We have changed the sentence in L. 206.

l. 225 How is cloud-top temperature obtained?

Since this question and the following one are related, we will answer them together below.

ll. 226-228 This description needs improvement and perhaps an illustration of the concept. What is meant by “gaps” and how do you determine them?

Thank you very much for these questions. First, we have marked the 100 m thick atmospheric layers of the radiosonde profiles with increasing height where the running mean of RH_{ice} is ≥ 100%. Such atmospheric layers are regions where ice crystals are not sublimating and defined here as “clouds”. For each cloud, we determined the cloud bottom height, the cloud top height and cloud top temperature. The cloud top temperature is the minimum temperature between cloud bottom and cloud top height measured by the temperature sensor of the radiosonde. If two clouds were on top of each other, we determined the distance between the cloud bottom height of the upper-level cloud and the cloud top height of the lower-level cloud. In case this distance was below a certain threshold (0.2, 0.5 or 1 km), we considered these two clouds as being potential seeder-feeder clouds. If there were more than two clouds on top of each other, we determined the highest seeder cloud for which the distance threshold with increasing height holds. We assume that ice crystals from the upper-level cloud (seeder) could potentially fall through the unsaturated layer without completely sublimating and therefore "seeding" the lower-level cloud (feeder). Finally, we determined the cloud top temperature of the highest possible seeder cloud for each case. Note that we do not distinguish between cases with a single cloud and those with feeder-seeder clouds.

We added this information to the manuscript and show an example of a case which has had three clouds (see Figure 2 here below).

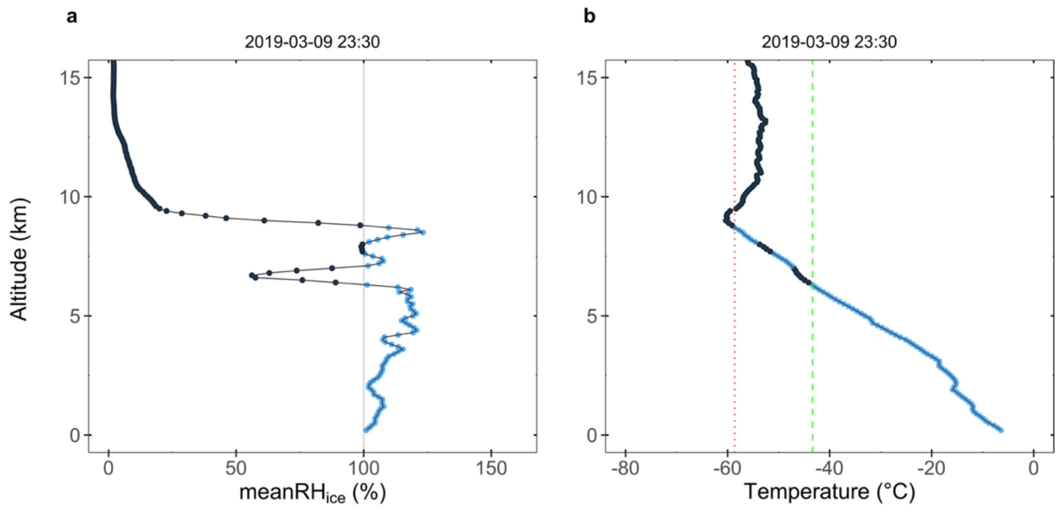

Fig. 2. (**a**) Running mean of five consecutive 100 m averaged RH_{ice} with increasing height up to 15 km on the 9th of March 2019 at 23:30. Vertical line indicates 100% running mean RH_{ice}. The dots colored in blue show the values ≥ 100%. (**b**) Similar to a) except that the temperature (°C) is plotted on the x-axis. Dashed green line shows the cloud top temperature of the highest possible seeder cloud, if we consider a threshold of 0.2 and 0.5 km between potential seeder-feeder clouds. The dotted red line shows the cloud top temperature of the highest possible seeder cloud, if we consider a threshold of 1.0 km between potential seeder-feeder clouds.

While working on the revisions and re-running some code, we noticed that several cases with multiple clouds on top of each other were not handled correctly. We corrected this and updated Fig. 10, which also resulted in changes in the text. The legend of Fig. 10 has been adjusted. Note that in the revised version we don't use the word "gaps" anymore, but replaced it with "distance between clouds". Thank you for this very useful comment.

Here we define successive values of the running mean from five consecutive 100 m averaged RH_{ice} with increasing height ≥ 100% as a cloud. For each cloud, we determined the cloud base height, cloud top height, and cloud top temperature. The cloud top temperature is the minimum temperature between the cloud base and cloud top measured by the radiosonde temperature sensor. When two clouds were on top of each other, we further determined the distance between the cloud top height of the lower-level cloud and the cloud base height of the upper-level cloud. If this distance was below a certain threshold (0.2, 0.5, or 1 km), we considered the two clouds as potential seeder-feeder clouds. If there were more than two clouds on top of each other, we determined the highest seeder cloud for which the distance threshold with increasing height holds. Finally, we determined the cloud top temperature of the highest seeder cloud for each case (also described as cloud top temperature from here on). Hence, we take into account that up to a certain (vertical) distance between clouds, ice crystals from the upper cloud (seeder) could fall through the unsaturated layer without fully sublimating, thus seeding the lower cloud (feeder). It is noteworthy that our threshold for seeder-feeder consideration is based only on the distance between clouds. However, whether an ice crystal fully sublimates between two clouds depends on several factors such as the crystal's size and habit when entering unsaturated conditions or by how much conditions are unsaturated. In the absence of in-cloud crystal information, we cannot make detailed calculations. To compensate for this uncertainty, we show cloud top temperature estimates for three different distance thresholds. Note that we do not distinguish between cases with a single cloud and those with seeder-feeder clouds.

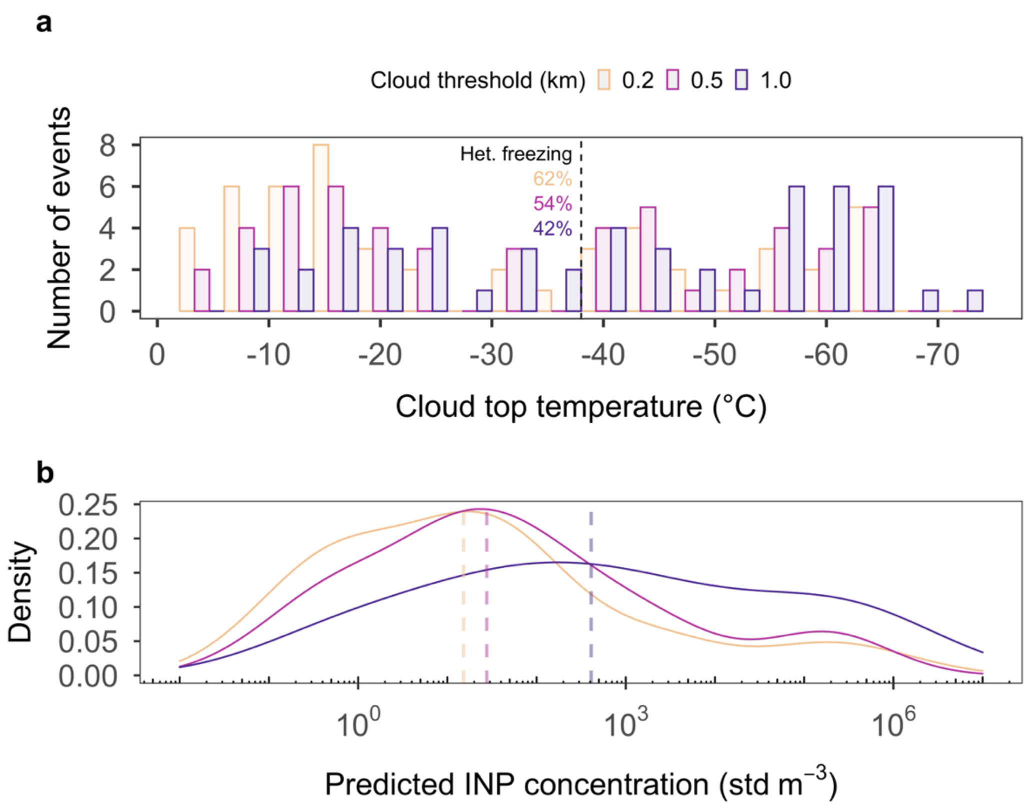

Figure 11. (**a**) The cloud top temperatures of the highest possible seeder-feeder cloud in 4 °C intervals of the 52 events coinciding with running mean RH_{ice} ≥ 97% throughout the lower 2.7 km. The cloud top temperature was derived using the radiosonde measurements which is described in detail in Sect. 3.5. We used the following thresholds for the distance between clouds to be considered as seeder-feeder clouds: ≤ 0.2 km (orange), ≤ 0.5 km (pink), and ≤ 1.0 km (purple). The fraction of events with cloud top temperatures above −38 °C is given in percent next to the dashed line. This is an estimation of the fraction of events for which the first ice crystals were likely formed via heterogeneous freezing. (**b**) Density of the INP concentration for the fraction of events with cloud top temperatures above −38 °C,

using the different thresholds to account for seeder-feeder clouds cloud top height criteria (in color) as shown in panel a. The respective median concentrations are shown by the dashed lines.

ll. 244-247 This seems highly relevant and should be shown as its own plot.

Thank you. We agree with the reviewer and made a new plot, which is shown here below. We discuss the related results in more detail in the last paragraph of Section 3.5 of the revised manuscript.

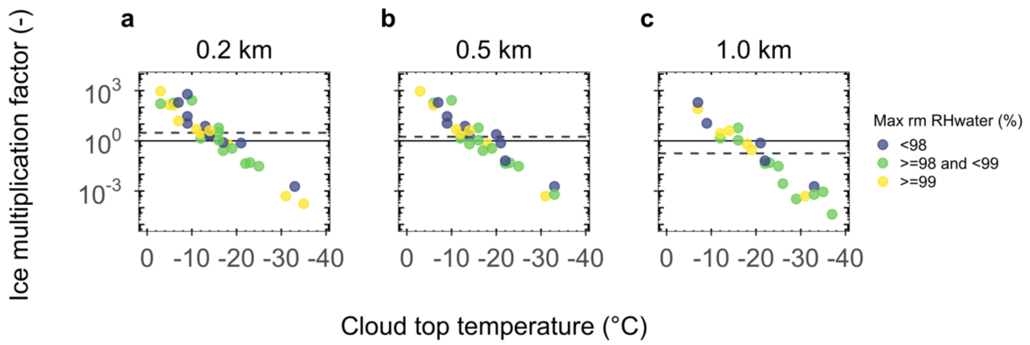

Figure 12. The ice multiplication factor versus cloud top temperature (°C) for each of the 52 snowfall event (coinciding with running mean RH_{ice} ≥ 97% throughout the lower 2.7 km) that were associated with cloud top temperatures warmer than −38 °C determining the highest possible seeder-feeder cloud using a distance threshold of (**a**) 0.2 km, (**b**) 0.5 km, and (**c**) 1.0 km. The colors are indicative of the associated maximum running mean RH_{water} (< 98%, blue; ≥ 98% and < 99%, green; ≥ 99%, yellow). The median ice multiplication factor is shown by the dashed line. The solid line is drawn at an ice multiplication factor of 1.

Finally, for cases with cloud top temperatures warmer than −38 °C, we estimate the likely ice multiplication factor, which is the observed snowflake concentration divided by the estimated INP concentration (Fig. 12). For a distance between potential seeder and feeder clouds of 1 km the median ice multiplication factor was less than 1, indicating that the median number of estimated INPs would have been sufficient to generate the median number of observed ice particles. For smaller thresholds (0.2 and 0.5 km), a median ice multiplication factors of 1.8 and 3 would need to be invoked to explain the median observations. Also, we find higher median ice multiplication factors for cases that are mixed-phase clouds compared to those that are likely ice clouds. A closer look at the individual events shows that in 36% to 66% of the cases the ice multiplication factor was higher than 1, depending on the threshold to determine the highest seeder cloud. Therefore, secondary ice formation processes were probably active in one to two third of the cases (where ice formation was initiated through heterogeneous freezing). Highest ice multiplication factors were found for cloud top temperatures between −3 °C and −10 °C, ranging from 10 to 1000. This could be indicative of rime-splintering (Hallett and Mossop, 1974). For temperatures between −10 °C and −20 °C, the multiplication factors reached values up to 10, which could be indicative of ice multiplication from ice–ice collision of dendrites followed by breakup (Vardiman, 1978; Mignani et al., 2019). This secondary ice mechanism was shown to be linked to the collision force and the riming degree, with a number of observed fragments per collision below 1 for unrimed dendrites and below 8 for lightly rimed dendrites (Vardiman, 1978; Phillips et al., 2017). Note that, we saw some broken-off branches of dendrites (Fig. A2), suggesting at least occasional ice–ice collision followed by breakup was active. Other ice multiplication processes exist (Korolev and Leisner, 2020) and could be active. For cloud top temperatures below −20 °C, sufficient INPs were likely active to explain the observed number of snowflakes. In general, the ice multiplication factors in relation to temperature observed here are consistent with previous observations (see Fig. 14 in Wieder et al., 2022) and show that ice multiplication played a role in the vast majority of the cases associated with cloud top temperatures ≥ −15 °C.

References

DeMott, P. J., Prenni, A. J., McMeeking, G. R., Sullivan, R. C., Petters, M. D., Tobo, Y., Niemand, M., Möhler, O., Snider, J. R., Wang, Z., and Kreidenweis, S. M.: Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dustparticles, Atmos. Chem. Phys., 15, 393–409, https://doi.org/10.5194/acp-15-393-2015, 2015.

Fukuta, N. and Takahashi, T.: The growth of atmospheric ice crystals: A summary of findings in vertical supercooled cloud tunnel studies, J. Atmos. Sci., 56, 1963–1979, 1999.

Hallett, J. and Mossop, S. C.: Production of secondary ice particles during the riming process, Nature, 249, 26–28, 1974.

Korolev, A. and Leisner, T.: Review of experimental studies of secondary ice production, Atmos. Chem. Phys., 20, 11767–11797, https://doi.org/10.5194/acp-20-11767-2020, 2020.

Mignani, C., Creamean, J. M., Zimmermann, L., Alewell, C., and Conen, F.: New type of evidence for secondary ice formation at around −15 ◦ C in mixed-phase clouds, Atmos. Chem. Phys., 19, 877–886, https://doi.org/10.5194/acp-19-877-2019, 2019.

Mosimann, L., Weingartner, E., and Waldvogel, A.: An Analysis of Accreted Drop Sizes and Mass on Rimed Snow Crystals, J. Atmos. Sci., 51, 1548 – 1558, https://doi.org/10.1175/1520-0469(1994)051<1548:AAOADS>2.0.CO;2, 1994.

Phillips, V. T. J., Yano, J.-I., and Khain, A.: Ice multiplication by breakup in ice-ice collisions. Part I: Theoretical formulation, J. Atmos. Sci., 74, 1705–1719, https://doi.org/10.1175/JAS-D-16-0224.1, 2017.

Ullrich, R., Hoose, C., Möhler, O., Niemand, M., Wagner, R., Höhler, K., Hiranuma, N., Saathoff, H., and Leisner, T.: A new ice nucleation active site parameterization for desert dust and soot, J. Atmos. Sci., 74, 699–717, https://doi.org/10.1175/JAS-D-16-0074.1, 2017.

Vardiman, L.: The generation of secondary ice particles in clouds by crystal-crystal collisions, J. Atmos. Sci., 35, 2168–2180, https://doi.org/10.1175/1520-0469(1978)035<2168:TGOSIP>2.0.CO;2, 1978.

Wieder, J., Ihn, N., Mignani, C., Haarig, M., Bühl, J., Seifert, P., Engelmann, R., Ramelli, F., Kanji, Z. A., Lohmann, U., and Henneberger, J.: Retrieving ice-nucleating particle concentration and ice multiplication factors using active remote sensing validated by in situ observations, Atmos. Chem. Phys., 22, 9767-9797, https://doi.org/10.5194/acp-22-9767-2022, 2022.