

Authors' Response to Reviews of

Investigating ice microphysical processes in the dendritic growth zone by combining Monte-Carlo Lagrangian particle modelling with multi-frequency polarimetric radar observations

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RC: Reviewers' Comment, AR: Authors' Response, ☐ Manuscript Text

1. Reviewer 1

RC1.1: This is an interesting study combining multi-frequency polarimetric radar observations with the McSnow Lagrangian particle model to investigate microphysical processes in the dendritic growth zone. I like the use of radar to constrain the modelling.

AR: We would like to thank the reviewer for their constructive review.

RC1.2: My main concern is that the conclusions about collisional fragmentation are stronger than can be supported by the modelling framework as currently described. The new fragmentation treatment requires substantially more implementation detail, including how physical ice–ice collisions and fragment production are represented in the super-particle framework, the values and sensitivities of key parameters, and how fragment size, habit, collision energy and particle type/rime state are treated. Is it just the fragmentation of the initialised ice with the same ice.

AR: We thank the reviewer for this comment. It made us realise that our description may have suggested a more sophisticated parametrization than is actually implemented. We have rewritten Sect. 2.2.3 to state clearly that the scheme is deliberately simple, added the missing implementation details, and summarised all parameters in a new Table.

Existing formulations of collisional ice breakup (Phillips et al., 2017b,a; Grzegorzczak et al., 2023) are constrained by data for collisions involving graupel or hail. Collisions between unrimed crystals and aggregates in the DGZ occur at considerably lower collision kinetic energies (CKE). For this regime, no laboratory data exist to constrain fragment numbers, sizes or habits. We therefore designed a minimal scheme to test one hypothesis: can collisional fragmentation of unrimed ice at low CKE explain the observed DGZ radar signatures? The scheme is a process sensitivity experiment, not a quantitative representation of fragment production. We now state this explicitly and refer to it as a “simplified fragmentation scheme” throughout the manuscript.

Which collisions fragment. The scheme considers only ice–ice collisions. Any ice particle, monomer or aggregate, can fragment regardless of where it was nucleated, provided four conditions are met:

- $-18^{\circ}\text{C} \leq T \leq -12^{\circ}\text{C}$;
- the air is not subsaturated with respect to ice;
- $\text{CKE} > 10^{-9} \text{ J}$.

In Simulation 3, where primary nucleation is restricted to temperatures below -20°C , this means that fragmenting particles are crystals and aggregates sedimenting into the DGZ, as well as aggregates containing earlier fragments. Fragmentation is evaluated for every physical collision, regardless of whether the particles stick. Once exception applies: monomers that were themselves produced by fragmentation do not fragment again.

Fragment properties. Each colliding particle produces $N = N_f a_T$ fragments, with $N_f = 10$ and a triangular temperature function a_T peaking at -15°C . Fragment masses are drawn from an exponential distribution with a mean corresponding to a $75\text{ }\mu\text{m}$ plate (Grzegorzczak et al., 2023). They are limited so that at most half of the parent’s ice mass is converted into fragments. Fragments are initialised as plates (Pruppacher and Klett, 1997) and then evolve like any other ice crystal. The CKE threshold acts only as an on/off criterion: fragment number, size and habit depend neither on CKE nor on the parent particle’s habit.

Super-particle framework. Fragmentation is evaluated within the same stochastic collision algorithm as aggregation (Shima et al., 2009). A fragmenting super-particle (SP) is first split so that only its colliding real particles fragment. The fragments of each parent SP are then added as one new SP, with a multiplicity equal to the number of fragments per real particle times the parent multiplicity. The parent particles lose exactly the fragment mass, and the remaining particles may subsequently aggregate.

Parameter values. The parameter values are not constrained by laboratory data for this regime; $N_f = 10$ is at the upper end of what Grzegorzczak et al. (2023) report at their lowest CKE. We therefore do not interpret our results as a quantitative estimate of fragment production rates in the DGZ. Our conclusion is limited to two findings: collisional fragmentation at low CKE is a plausible mechanism, and it is the only one of the tested hypotheses that reproduces the full set of observed signatures. We emphasise in the revised conclusions that laboratory measurements at low CKE are needed to constrain such a scheme.

RC1.3: Is there any graupel? I think not as you say there was no riming; however, frontal clouds often contain embedded convection. Therefore I am also concerned that the 1-D shaft configuration excludes other potentially important secondary-ice pathways by construction. The treatment and initialisation of cloud liquid water, drizzle and rain are not clear - I don’t think there is any initialised, and the absence of embedded convection/vertical transport makes it difficult to generate or maintain supercooled liquid drops. Freezing-drop fragmentation and fragmentation associated with liquid–ice collisions could therefore be important alternatives that are not tested. The observations should be used, where possible, to establish whether supercooled liquid/drizzle/rain and rimed particles were present or can reasonably be excluded.

AR: We thank the reviewer for this important comment. We agree that the absence of supercooled liquid and riming needs to be established from the observations rather than assumed, and we have added a corresponding discussion to Sect. 3. Several independent observations indicate that supercooled liquid water, riming and embedded convection played at most a minor role during the analysed period:

- **Thermodynamic conditions:** The radiosonde launched at 04:21 UTC shows that the relative humidity with respect to liquid water remained below 100 % throughout the DGZ (Fig. B1). The formation and maintenance of supercooled liquid droplets is therefore unlikely. Only the radiosonde launched at 03:02 UTC indicated liquid saturation near -15°C , suggesting that liquid water may have been present intermittently before the analysed period.
- **Absence of rimed particles:** Throughout the day, the mean Doppler velocity (MDV) above the melting layer is around 1 m s^{-1} (Fig. 3b), consistent with unrimed aggregates. Within the DGZ in the analysed profile (Fig. 4), the MDV is even below 1 m s^{-1} . Based on the riming retrieval of Kneifel and Moisseev (2020), strongly rimed particles (rime mass fraction above about 0.6) would be expected to fall faster

than 1.5 m s^{-1} when referred to surface pressure. Since fall velocities increase with decreasing air density, the MDV observed aloft corresponds to even lower near-surface values. Graupel would be expected to fall at about $2\text{--}3 \text{ m s}^{-1}$. We therefore find no indication of rimed particles or graupel.

- **Absence of embedded convection:** The Doppler spectra in Fig. 4 show no signatures of strong vertical air motion (such as upward moving small ice particles or droplets). The eddy dissipation rate retrieved following Chellini and Kneifel (2024) is about $10^{-6} \text{ m}^2 \text{ s}^{-3}$, which lies within the lowest quantile of comparable clouds (Sect. 2.3). Both observations argue against embedded convection during the analysed period.

Freezing-drop fragmentation requires supercooled drizzle or rain drops. Fragmentation in liquid–ice collisions requires supercooled droplets and, typically, riming. Neither supercooled liquid nor rimed particles are supported by the observations. In addition, the most prominent rime-related SIP mechanism, rime splintering (Hallett and Mossop, 1974), is active at temperatures between about -3 and -8 °C, i.e. outside the DGZ. We therefore consider these SIP pathways unlikely to explain the DGZ signatures in this case. We acknowledge, however, that the 1-D shaft configuration excludes them by construction. We now state this limitation explicitly in Sect. 4.1, and note that liquid-dependent SIP pathways may become important in DGZ situations with embedded convection or liquid layers, which were not the focus of this study.

We have added the following paragraph to section 3:

Throughout most of the day, the mean Doppler velocity (MDV) above the melting layer in Figure 3b is predominantly around -1 m s^{-1} , indicating the presence of mostly unrimed snow. Strongly rimed particles with rime mass fractions above about 0.6 would be expected to fall faster than 1.5 m s^{-1} when referred to surface pressure (Kneifel and Moisseev, 2020), and graupel at about $2\text{--}3 \text{ m s}^{-1}$. Since fall velocities increase with decreasing air density, the MDV observed aloft corresponds to even lower near-surface values. We therefore find no indication of significant riming or graupel during the analysed period. This is consistent with the radiosonde profiles, which show that the relative humidity with respect to liquid water remained below 100 % throughout the DGZ (Fig. B1), making the presence of supercooled liquid droplets unlikely. Only the radiosonde launched at 03:02 UTC indicated liquid saturation near -15 °C, suggesting that supercooled liquid may have been present intermittently before the analysed period (see also Sect. 4.3). Furthermore, the Doppler spectra (Fig. 4) show no signatures of strong vertical air motion, and the retrieved eddy dissipation rate of about $10^{-6} \text{ m}^2 \text{ s}^{-3}$ lies within the lowest quantile of comparable clouds (Sect. 2.3). Taken together, these observations provide evidence against embedded convection during the analysed period.

And the following paragraph to Section 4.1:

McSnow supports riming and associated SIP processes (Seifert et al., 2019), but no supercooled liquid water is initialised in our simulations. This is justified for the analysed case because the relative humidity in the DGZ remained below water saturation and neither signatures of rimed particles nor indications of embedded convection or strong updrafts were observed (Sect. 3). Consequently, all SIP pathways that require supercooled liquid water are inactive in our simulations. These include fragmentation of freezing drops (e.g. Phillips et al., 2018), fragmentation in collisions involving rimed particles, and rime splintering (Hallett and Mossop, 1974). Rime splintering would in any case be restricted to temperatures between about -3 and -8 °C and is thus not expected to operate in the DGZ. In DGZ situations with embedded convection or supercooled liquid layers, these liquid-dependent pathways may contribute to or even dominate secondary ice production. They should therefore be

considered alongside the collisional fragmentation of unrimed ice investigated here.

RC1.4: There are uncertainties in the primary ice nucleation profile and in the representation of ice habits at colder temperatures. These assumptions may affect the comparison between particles sedimenting from above and particles generated locally within the DGZ.

AR: We thank the reviewer for this comment and agree that both the primary ice nucleation profile and the representation of ice habits at temperatures colder than the DGZ are uncertain. We address both aspects below.

Primary ice nucleation: As no INP measurements are available for this case, the nucleation profile cannot be prescribed from observations. It is, however, not arbitrary. Its shape follows the general increase of INP concentrations with decreasing temperature (Kanji et al., 2017), and its magnitude was chosen such that the simulated Z_e matches the observed Z_e at temperatures colder than -20°C (Sect. 4.1). The resulting concentrations of nucleated particles lie near the middle of the range of INP concentrations compiled by Kanji et al. (2017) (Fig. D1). Since Z_e depends on both the number and the size of the particles, this does not constrain the nucleation rate uniquely, but it limits it to a plausible range. Within the DGZ, the nucleation rate in Simulation 2 was deliberately set close to the upper bound of observed INP concentrations to assess the maximum possible impact of primary nucleation (Sect. 4.3).

When setting up the nucleation profile, we also performed simulations with the nucleation rate scaled by factors of 0.5 and 1.5. As expected, a higher nucleation rate increases the number of ice particles sedimenting into the DGZ, which enhances aggregation and leads to larger Z_e and DWR, while a lower nucleation rate reduces both. With fragmentation enabled, the number of fragments, and hence K_{DP} , also increases with the nucleation rate, since the collision rate scales with the number concentration of colliding particles. However, these changes affect only the magnitude of the simulated radar variables. In all sensitivity runs, the observed K_{DP} enhancement could only be reproduced when ice particles were generated within the DGZ. We have added a short description of these tests to the revised manuscript (new Sect. 4.5):

4.5 Sensitivity to the nucleation rate

When setting up the nucleation profile, we also performed simulations with the nucleation rate scaled by factors of 0.5 and 1.5 (not shown). Since the nucleated particle concentrations of the reference profile lie near the middle of the observed range of INP concentrations (Fig. D1), the scaled profiles also remain within this range. As expected, a higher nucleation rate increases the number of ice particles sedimenting into the DGZ. This enhances aggregation and leads to larger Z_e and DWR, while a lower nucleation rate reduces both. In Simulation 3, the number of fragments, and hence K_{DP} , also increases with the nucleation rate, since the collision rate scales with the number concentration of colliding particles. However, these changes affect only the magnitude of the simulated radar variables. In all sensitivity runs, the observed K_{DP} enhancement could only be reproduced when ice particles were generated within the DGZ, confirming the conclusions drawn in Sects. 4.2–4.4.

Ice habits at colder temperatures: We agree that the habit evolution at temperatures colder than -20°C is uncertain. The inherent growth function used in McSnow produces slightly columnar, near-isometric crystals in this temperature range, whereas in situ observations show that plate-like particles can also occur there. If plate-like particles were already entering the DGZ from above, they could in principle contribute to the polarimetric signatures near -15°C . To assess this, we performed three additional idealised sensitivity experiments:

1. Plate-like particles with maximum dimensions between 10 μm and 1 mm were initialised at -20°C and grown by vapour deposition only, without aggregation.
2. A size distribution of plate-like particles was initialised at -20°C , with particle masses similar to those of the columnar particles entering the DGZ in Simulation 1 and aspect ratios following the relation for plates of Pruppacher and Klett (1997). In this experiment, aggregation was enabled.
3. The inherent growth function was modified such that its value at -20°C is applied at all colder temperatures, resulting in strong plate-like growth above the DGZ. This modification is not constrained by measurements and represents an extreme scenario.

None of these experiments produced a peak in sZDR_{max} near -15°C . In the first experiment, ZDR was enhanced but approximately constant throughout the DGZ. In the second experiment, the spectral ZDR and KDP peaked at -20°C instead of near -15°C . In the third experiment, no sZDR_{max} (or ZDR) peak occurred within the DGZ.

The reason is the same in all three cases: plate-like particles originating from colder temperatures have already grown to substantial sizes before reaching -15°C . Their polarimetric signature therefore either peaks at colder temperatures, or it is not enhanced near -15°C because the particles are efficiently collected by aggregation. This behaviour is also visible in Simulation 1. Since the plate-like growth regime of the inherent growth function used here extends to -22°C (Sect. 2.2.1), particles nucleated between -22 and -20°C already grow plate-like before entering the DGZ. These particles do not experience sufficiently strong growth near -15°C and largely disappear through aggregation before reaching this temperature (Sect. 4.2). Moreover, the density reduction due to dendritic branching near -15°C decreases, rather than enhances, the ZDR of already existing plate-like particles. A pronounced sZDR_{max} peak near -15°C therefore requires small particles that start growing in the vicinity of -15°C , i.e. ice generation within the DGZ. This supports the conclusions of our study.

As these experiments are idealised and the habit evolution at temperatures colder than -20°C is not constrained by observations for this case, we have not included them in the manuscript. We have, however, added a statement to the conclusions noting that the habit evolution at these temperatures is uncertain and needs further investigation:

A further source of uncertainty is the habit evolution of ice crystals at temperatures colder than -22°C . The habit prediction used here produces slightly columnar, near-isometric crystals in this temperature range, whereas in situ observations also report plate-like and columnar polycrystals (Bailey and Hallett, 2009). A representation of habit growth at these temperatures that is constrained by laboratory and in situ observations is needed to draw definitive conclusions on the contribution of particles sedimenting from above to the radar signatures in the DGZ.

RC1.5: Overall, I consider the manuscript suitable for public discussion, but I expect that major revision will be needed. In particular, I think the conclusions should presently be framed as showing that an additional local source of small asymmetric ice particles is required to reproduce the observed radar signatures, with collisional fragmentation being one plausible mechanism, rather than as uniquely identifying ice–ice fragmentation.

AR: We agree that collisional fragmentation should be presented as one plausible mechanism rather than as the uniquely identified one, and we believe the main text largely reflects this already. For example, the conclusions state: “The observed KDP enhancement within the DGZ can only be reproduced in our model simulations when ice number concentrations are increased via secondary ice production, here caused by

collisional fragmentation.” The key requirement identified here is secondary ice production, with collisional fragmentation as the SIP mechanism represented in our simulations, not as the only possible candidate. However, the reviewer’s comment made us realise that the abstract did not make this distinction, as it stated that “the results identify collisional fragmentation as a key unifying mechanism”. To clarify this, we have made two changes:

- The abstract now reads: “The results identify secondary ice production (in this case collisional fragmentation) as a key unifying mechanism, with the DGZ radar fingerprint emerging from the interplay of depositional growth, aggregation, and secondary ice production.”
- The final paragraph of the conclusions now reads: “These results demonstrate that the DGZ radar fingerprints are likely to arise from a combination of interacting microphysical processes, with secondary ice production playing a key role in reproducing the observed polarimetric and spectral signatures.”

2. Reviewer 2

RC2.1: This is an interesting and insightful study by von Terzi et al., which works to address questions which remain regarding processes active in the dendritic growth zone. The manuscript is clear, well structured, and enjoyable to read. This study is worthy of publication, subject to changes made in response to some minor comments detailed below.

AR: We would like to thank the reviewer for this positive and constructive review!

RC2.2: L32: It would be good to specify at what temperatures it is thought that collisional ice fragmentation contributes to the discrepancy between INP and ice particle concentrations. Is it specifically in the DGZ, or at a wider range of temperatures?

AR: We thank the reviewer for this comment. The preceding sentence (L28–30) states that the DGZ is a potential hotspot for SIP, since the fragile, branched crystals growing at these temperatures are particularly susceptible to breakup. Laboratory studies support this, with fragment numbers in graupel–graupel collisions peaking near 16 °C (Takahashi et al., 1995). However, fragments were also observed outside the DGZ, particularly towards warmer temperatures, so the contribution of collisional fragmentation to the discrepancy between INP and ice particle concentrations is not necessarily restricted to the DGZ. We have added the following sentence to the manuscript:

While fragmentation is most efficient within the DGZ, fragments have also been observed at warmer temperatures in laboratory studies (Takahashi, 1993).

RC2.3: L45: It is interesting that approximately a quarter of your observations had regions of high KDP within the DGZ; this is broadly consistent with the frequency of multimodal spectra identified in the DGZ from other studies (<https://amt.copernicus.org/articles/18/6569/2025/amt-18-6569-2025.pdf>, Figure 8, <https://egusphere.copernicus.org/preprints/2026/egusphere-2026-2928/>, Figure 14).

AR: Thank you for pointing out these studies! We have added the following sentence to the manuscript:

This frequency is consistent with the appearance of multimodal Doppler spectra found in recent studies (Mammatt et al., 2026; Wugofski and Kumjian, 2025).

RC2.4: L58-9: "Similar signatures have also been identified in spectrally resolved observations, where the slowdown tends to be most pronounced among slowly falling particles." The way this sentence is worded is confusing. Which slowly falling particles are you referring to - slowly falling secondary ice populations, or particles which fall slowly due to their open geometry, like dendrites? If I understand correctly, you are referring to the latter, but this should be clarified.

AR: We think from the radar observations alone it is not possible to tell if the secondary mode in the Doppler spectrum comes from dendrites or any other slow falling population of ice particles. We have reworded the sentence to make it clear that we are talking about a secondary spectral mode of slow falling particles here.

Similar signatures have also been identified in spectrally resolved observations, where a secondary mode of slowly falling particles frequently emerges in the DGZ and shifts the slow edge of the Doppler spectrum towards lower fall velocities.

RC2.5: L60: I think it is worth acknowledging the possibility that particles which sediment into the DGZ from above may themselves slow down. I'm not suggesting that this process replaces those you mention, but I believe it is at the very least a contributing factor.

AR: Do you mean that the particles slow down because of microphysical processes such as dendritic growth which would increase the cross-sectional area and thus reduce the fall velocity? We agree that this is also a possibility. We have added it to the manuscript:

These observations have been interpreted as evidence for either dynamical influences, such as localized updrafts, the emergence of a secondary population of slowly falling ice particles, or a reduction in fall velocity of particles sedimenting into the DGZ from above, as they develop dendritic branches and thereby experience increasing drag (Zawadzki, 2013; Mammatt et al., 2026).

RC2.6: Figure 1: This is a useful figure and nicely demonstrates the features you discuss in the text, but I would like to see the same statistics for the subset of data where $KDP < 1 \text{ degree/km}$ in the DGZ. This could be as extra panels, but I think you have room to add extra lines to the existing panels without the plot becoming overly cluttered. I think it would be useful to see a more direct comparison of how the plotted variables change between profiles where $KDP > 1 \text{ degree/km}$ and $KDP < 1 \text{ degree/km}$ in the DGZ.

AR: Thank you for this suggestions. We think that while it is useful for the readers to know how the profiles look like, it might distract from the typical DGZ features we want to discuss in the introduction. Therefore we have included the profiles where $KDP < 1 \text{ km}^{-1}$ in the appendix, as well as this description of the figure:

Complementary to Figure 1, the profiles where the maximum of KDP was below 1°km^{-1} within the DGZ (hereafter called low-KDP cases) are shown in Figure A1. The largest differences to the cases where the maximum of KDP exceeds 1°km^{-1} within the DGZ (hereafter called high-KDP cases) can be seen in Z_e , DWR_{KaW} , DWR_{XKa} , $sZDR_{max}$ and KDP. Low-KDP apparently correlates with smaller aggregates (as seen in the significantly lower DWR_{KaW} and DWR_{XKa}), as well as particles with smaller asymmetry (indicated by the lower $sZDR_{max}$ values). As KDP is driven by the concentration and size of

the particles, it is not surprising that in addition to lower DWR, also Z_e is significantly lower throughout the entire profile.

RC2.7: L213: I would argue that we do not have enough evidence to state that fragmentation activity is "known to be" highest in the DGZ, so would prefer the phrasing here to be softened.

AR: we have softened the statement to "thought to be" instead of "known to be"

RC2.8: L225: I would like to see an explanation of why fragments produced by fragmentation are assumed to be plate-like. Intuitively, the fragments produced would resemble dendritic branches, like those seen in Grzegorzczak et al. (2023, Figure 10a).

AR: Thank you for raising this point. We agree that, physically, fragments produced by collisions of dendritic particles are likely to resemble broken-off dendritic branches, as observed by Grzegorzczak et al. (2023), Fig. 10a. Our choice of initialising fragments as plate-like particles is therefore not meant to represent their exact shape, but follows from how ice particle shape is represented in McSnow.

At first sight, such elongated branches might appear to be better represented by prolate spheroids. In McSnow, however, the spheroid is not merely a geometric approximation of the particle outline. Its symmetry axis corresponds to the crystallographic c-axis, and the habit prediction (Welss et al., 2023) distributes depositional growth between the c- and a-axes according to the temperature-dependent inherent growth ratio. The relevant property for initialising a fragment is therefore not the spheroid that best circumscribes its outline, but the orientation of the crystal lattice within it. A branch broken off a dendrite retains the crystallographic orientation of its parent crystal. Its c-axis is perpendicular to the plane of the branch, i.e. along its thinnest dimension, while both its length and width lie in the basal plane. In the DGZ, growth occurs preferentially along the a-axes, so the fragment continues to grow within its basal plane, as its parent did. This is captured by an oblate initialisation. A prolate initialisation would instead identify the long dimension of the branch with the c-axis, and the habit prediction would grow the fragment towards an isometric shape, not a thin planar one, with correspondingly wrong polarimetric signatures.

Besides the aspect ratio, McSnow characterises ice particles by their density. Once the fragments grow by vapour deposition in the DGZ, their density decreases rapidly, so that they quickly attain the low effective densities characteristic of dendritic particles. The habit evolution therefore drives the fragments towards dendrite-like properties within a short time after their formation, regardless of their initial shape.

Explicitly initialising the fragments as dendrites would, in contrast, require prescribing an additional free parameter, namely the initial fragment density. This quantity is not constrained by our observations and can vary considerably depending on the structure of the parent particle and on where it breaks. We therefore opted for the simpler plate-like initialisation, which avoids introducing an unconstrained parameter while still capturing the relevant evolution of the fragments. We have added a short explanation of this choice to the manuscript (Section 2.2.3):

Fragments are initialised as plate-like monomers following the size–aspect-ratio relation for plates of Pruppacher and Klett (1997). Although real fragments likely resemble elongated dendritic branches (Grzegorzczak et al., 2023), they retain the crystallographic orientation of the dendritic crystal they broke off from, with the c-axis perpendicular to the branch plane. Since the habit prediction in McSnow distributes depositional growth along the crystallographic axes (Welss et al., 2023), an oblate initialisation ensures that the fragments continue to grow within their basal plane. Initialising fragments as dendrites would additionally require prescribing an initial density, which is unconstrained by the

observations and can vary considerably. Instead, the fragments evolve like any other ice crystal through depositional growth including habit prediction (Welss et al., 2023), which rapidly reduces their density towards dendrite-like values, as well as aggregation and sedimentation.

RC2.9: L302: Again, I would soften the statement that fragmentation is "known to be" active in the DGZ. Whilst I agree that it is likely, my understanding is that our current knowledge of fragmentation is mostly based on lab studies, which, whilst critical to our understanding of certain ice microphysical processes, cannot perfectly replicate real atmospheric conditions.

AR: We have again softened "known to be" to "thought to be".

RC2.10: L333: "Since the observed Ze values lie mostly above the 75th percentile of the statistical climatology in Figure 1, slight underestimations in this temperature range were deemed acceptable." Underestimations of what? Ice nucleating particles? Ze? Please clarify.

AR: Here we mean underestimation of Ze, which consequently also means underestimation of INP. We have added that to the sentence:

Since the observed Ze values lie mostly above the 75th percentile of the statistical climatology in Figure 1, slight underestimations of Ze (and subsequent INP) in this temperature range were deemed acceptable.

RC2.11: Figure 5: In Figure 5IIa, the legend is covering the blue lines and making the detail quite hard to see, particularly where the "monomer" Ze line begins to deviate from the "aggregate" Ze. Personally, I would be happy for these lines to be defined in the figure caption if moving the legend is impractical.

AR: We agree that the legend covers important parts of the figure. We have thus chosen to remove the legend and have described the lines in the caption of the figure.

RC2.12: Figure 6: Figure 6 needs to be discussed in much greater detail in the text; as far as I can see, it is mentioned only once. At a minimum, I would like to see an explanation of the variables plotted and how the panels should be interpreted, as these are non-intuitive to me.

AR: We agree that the figure needs more discussion. We have included the following paragraph in the manuscript:

To understand the origin of this slowdown, Figure 6 shows the microphysical properties of the simulated particles in maximum dimension ($D_{\max}$)–temperature space, separately for monomers (top row) and aggregates (bottom row). Each pixel shows the average of the respective property over all real particles within that $D_{\max}$ –temperature bin, i.e. the super-particle properties weighted by their multiplicity. The first column shows the change of fall velocity with temperature; positive values (red) indicate a slowdown of the particles as they sediment to warmer temperatures, negative values (blue) an acceleration. The remaining columns show the aspect ratio (values > 1 correspond to columnar, values < 1 to plate-like particles), the particle density and the cross-sectional area. The aspect ratio reflects the growth history of the monomers: particles nucleated at temperatures colder than $-22\text{ }^{\circ}\text{C}$ grow into columnar crystals, while particles nucleated at warmer temperatures grow plate-like (Sect. 2.2.1). As the particles sediment, their aspect ratio continues to evolve according to the local growth regime. A pronounced slowdown is found for monomers with $D_{\max}$ of approximately $4 - 6 \times 10^{-4}\text{ m}$ between -20 and $-15\text{ }^{\circ}\text{C}$. These are columnar particles that have sedimented from colder temperatures into the plate-like growth regime. Here, their aspect ratio decreases slightly towards unity, indicating growth

along the a-axis, which could, for example, be interpreted as the formation of capped columns. At the same time, their density decreases from about 800 to about 400 kg m⁻³, while their cross-sectional area increases. Since the terminal fall velocity depends on the ratio of particle mass to cross-sectional area (Böhm, 1992), both changes reduce the fall velocity of these particles. The aggregates (bottom row) do not show a comparable slowdown.

RC2.13: L459: Simulation 3 does produce the greatest MDV slowdown, but I would like to see a brief discussion on how realistic the shape of this profile is. The slowdown you see here appears to be very localised between temperatures of -15degC and -12degC, whereas the shape of this profile in previous literature has this reduction in MDV occurring over a broader temperature range.

AR: We thank the reviewer for this comment. We agree that the simulated MDV slowdown is more localised than in the observations and in previous studies. We see several reasons for this, which we now discuss in the revised Sect. 4.4.

First, McSnow does not include turbulence. In reality, turbulent mixing redistributes particles vertically, spreading the slowly falling fragments and newly formed aggregates over a deeper layer. This would broaden the slowdown and reduce its peak amplitude. (Turbulent broadening of the Doppler spectrum is included in the forward simulations, but does not affect the MDV to first order.)

Second, fragmentation is restricted to temperatures between 18 and 12 °C in our scheme. This temperature dependence is loosely based on Takahashi (1993), who found the highest fragmentation activity near 15 °C but also observed fragments outside this range. Since it is unknown how fragmentation at low collision kinetic energies depends on temperature, we restricted it to the temperature range in which dendritic branches are expected to form. However, branched particles formed in the DGZ retain their branches when they sediment to warmer temperatures and may therefore still fragment there. Whether this happens has not yet been investigated in laboratory studies. Allowing fragmentation over a broader temperature range would broaden the layer in which fragments are produced, and thus the simulated slowdown.

We have added the following paragraph to the manuscript:

Compared to the observations, the simulated slowdown is confined to a shallower layer between 15 and 12 °C. This is likely related to the absence of turbulent vertical mixing in McSnow, and to the restriction of fragmentation to the temperature range of dendritic growth (18 to 12 °C), although branched particles sedimenting to warmer temperatures may continue to fragment. In addition, a steady-state simulation is compared with a 30-min observational average.

2.0.1 Typos/formatting points

RC2.14: L42: KDP exceeding 1degree/km does not need to be in brackets.

AR: Fixed

RC2.15: L184: A space is missing after "sedimentation".

AR: Fixed

RC2.16: L214: I believe it should be collisional kinetic energy.

AR: We have rewritten the entire section on collisional fragmentation, but have changed collision kinetic energy to collisional kinetic energy.

RC2.17: L216: There is no capital needed on graupel.

AR: Fixed

RC2.18: L279: "launch time for"

AR: removed "for"

RC2.19: L305: IMP is not defined.

AR: yes it was defined in Line 251

RC2.20: When discussing the slowing down of particles/MDV in the DGZ, be consistent with either "slowdown" or "slow-down"; you currently have a mixture of both.

AR: We changed slowdown to slow-down

References

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