Authors' Response to Reviews of

Secondary Ice Formation in Cumulus Congestus Clouds: Insights from Observations and Aerosol-Aware Large-Eddy Simulations

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

Reviewer #1

https://doi.org/10.5194/egusphere-2025-2730-RC1

1. Overall comments

RC: Calderón et al. presents a detailed analysis of the process-level evolution of ice microphysics in a developing cumulus congestus cloud. They provide airborne in situ measurements from the SPICULE campaign and utilize the sophisticated UCLALES-SALSA model to simulate various secondary ice production (SIP) mechanisms, including rime–splintering, droplet shattering, and ice–ice collisional breakup. The authors find that the simulated cloud with the inclusion of SIP produced higher total water content and taller cloud top heights. They also find that there may be SIP–induced invigoration related to positive buoyancy from water phase changes.

The authors do an excellent job showing the evolution of the cumulus congestus cloud and the influence of SIP on the droplet size distributions and accumulated precipitation through the cloud's lifecycle. This paper also provides new insights that expand upon recent modelling and observational studies highlighting the chain of events of ice microphysics prior to cloud glaciation.

This paper is suitable for publication after the following minor comments have been addressed.

AR: We deeply appreciate your insightful analysis, comments and suggestions. We will proceed to address your indications one by one.

2. Minor comments

2.1. Line 28

RC: "...in situ vertical profiling", I think you mean sampling at different altitudes. Vertical profiling is not possible with aircraft in convective clouds.

AR: You are right. The sentence was changed to clarify the achievement of new sampling techniques as follows:

> ~~The use of cloud~~ Cloud particle imager (CPI) and holographic imaging systems for ~~in situ vertical profiling of~~ sampling at different altitudes the number, size, shape and thermodynamic phase of hy-

drometeors have provided a solid base of evidence of the SIP occurrence in different cloud types.

2.2. Line 29-34

RC: Patnaude et al. [2025] also provided evidence of fragmented droplets from a CPI. They also used in situ INP measurements to demonstrate the presence of SIP.

AR: Thank you for informing us about this study. We have included the reference as follows:

> CPI and holographic images suggest that secondary ice formation can be identified by the simultaneous presence of small individual faceted ice particles (i.e. maximum length below 100 μm) coexisting with fragments of frozen drops or frozen drops with bulges, spikes or cracks (Korolev et al.,2020, 2022; Korolev and Milbrandt, 2022; Pasquier et al., 2022; Lawson et al., 2023b, Patnaude et al., 2025). Similarly, it can also be indicated by the concurrent presence of heavily rimed ice particles, dendrites and broken branches of dendrites (e.g Schwarzenboeck et al.,2009; Ramelli et al., 2021).

2.3. Line 39

RC: Korolev and Leisner 2020 is a review paper. It would be better to cite the specific laboratory studies you may be referring to.

AR: We cited the review paper that summarizes laboratory experiments related to secondary ice production to simplify the text. However, we understand your point and have included the references for the most relevant studies used in the formulation of SIP parameterizations. In case of rime splintering parameterizations those by Hallet and Mossop [1974] and Mossop [1976]; in case of droplet shattering those by Brownscombe and Thorndike [1968], Takahashi and Yamashita [1970], Takahashi [1975], Takahashi and Yamashita [1977], Kolomeychuk et al. [1975] and Pruppacher and Schlamp [1975] used in the formulation of Phillips et al. [2018]; and finally, in the case of ice–ice collisional breakup the study by Takahashi et al. [1995].

> ~~Although their~~SIP parametrizations are based on observed ice multiplication factors (IMF) that come from a common set of laboratory experiments ~~(Korolev and Leisner, 2020)~~. In case of rime splintering those by Hallet and Mossop (1974) and Mossop (1976); in case of the droplet shattering parameterization by of Phillips et al. (2018) the studies of Brownscombe and Thorndike (1968), Takahashi and Yamashita (1970), Takahashi (1975), Takahashi and Yamashita (1977), Kolomeychuk et al. (1975) and Pruppacher and Schlamp (1975); and finally, in the case of SIP parameterizations for ice–ice collisional breakup the study by Takahashi et al. (1995). Despite this common background, IMF values can be different in different parameterizations even when they are meant to describe the same physical mechanism at the same atmospheric conditions (e.g. Sotiropoulou et al. (2021) versus Sullivan et al. (2018)). Also, SIP rates for the same mechanism can be different in different cloud modelling studies depending on how hydrometeor sizes and process related size limits are treated.

2.4. Lines 138-145

RC: Does this scheme allow for heterogeneous freezing of cloud droplets only? Does it also include heterogeneous freezing of raindrops?

AR: Yes, our implementation of the scheme accounts for heterogeneous freezing via immersion of both, cloud droplets and raindrops, as long as they contain a volume of insoluble species larger than a threshold value (e.g. volume equivalent to a sphere of 10 nm in diameter).

The immersion freezing mechanism in our simulation is the primary pathway for ice formation. Their rates are calculated using the parametrization of Savre et al. (2014) that uses a time—evolving probability density function of the contact angle parameter (i.e. angle formed between liquid water, the INP surface and the ice embryo during nucleation that gives a measure of the composition-dependent INP affinity to the ice embryo (Barahona, 2018)). The use of a distribution allows to account for heterogeneities in surface properties among a given aerosol population. Both, cloud droplets and raindrops can experience immersion freezing as long as they contain as they contain a volume of insoluble species larger than a threshold value (e.g. sphere of 10 nm in diameter).The model keeps track of the fraction of nucleated INPs and uses it to increase the lower limit of the contact angle distribution once the most efficient INPs nucleate ice. The contact angle distribution is updated every time mixing and entrainment processes replenish the cloud with fresh INPs (Tonttila et al., 2022).

2.5. Line 152

RC: "... including both modes (i.e. collision of drop with smaller crystal...": If you are referring to the two modes of DS from Phillips et al. (2018) I would recommend citing this here since most studies do not consider multiple modes (i.e., Patnaude et al. 2025; Sullivan 2018, Grzegorczyk et al. 2025a). The more agreed upon representation and observed mechanism for DS is the fragmentation of the droplet during the primary freezing process (see Keinert et al. 2020), which is not mentioned here.

Grzegorczyk, P., Wobrock, W., Canzi, A., Niquet, L., Tridon, F., and Planche, C.: Investigating secondary ice production in a deep convective cloud with a 3D bin microphysics model: Part I - Sensitivity study of microphysical processes representations, Atmospheric Research, 313, 107774, https://doi.org/10.1016/j.atmosres.2024.107774, 2025.

Keinert, A., Spannagel, D., Leisner, T., and Kiselev, A.: Secondary Ice Production upon Freezing of Freely Falling Drizzle Droplets, Journal of the Atmospheric Sciences, 77, 2959–2967, https://doi.org/10.1175/jas-d-20-0081.1, 2020.

Sullivan, S. C., Barthlott, C., Crosier, J., Zhukov, I., Nenes, A., and Hoose, C.: The effect of secondary ice production parameterization on the simulation of a cold frontal rainband, Atmos. Chem. Phys., 18, 16461–16480, https://doi.org/10.5194/acp-18-16461-2018, 2018.

AR: Our calculation module for secondary ice production via droplet shattering include the two modes from Phillips et al. [2018] defined as secondary ice formation "during spherical drop freezing (mode 1) or during collisions of supercooled raindrops with more massive ice (mode 2)". We modified the manuscript text to highlight this fact. We have also included additional comments to support our selection for the SIP mechanisms.

... IMF values due to rime splintering (SIP–RS), droplet shattering (SIP—DS) ~~including both modes (i.e. collision of drop with smaller crystal, and accretion of raindrop by more massive ice particle)~~, and ice–ice collisional breakup (SIP—IIBR). IMF values related to SIP-DS rates include secondary ice formation during spherical drop freezing or mode 1 and also during collisions of supercooled raindrops with more massive ice or mode 2, whose representations are supported by the laboratory studies of Keinert et al. (2020) and James et al. (2021), respectively. IMF values related to SIP–IIBR also consider the recent experimental findings of Grzegorczyk et al.(2023). Other parameterizations of ice multiplication factors (IMF) available in UCLALES–SALSA are reported in Table S2.

2.6. Lines 174-179

RC: "It is particularly useful…" Okay I see the fragmentation of droplets is mentioned here. I think that this should be mentioned earlier and perhaps in the introduction. It is also not clear if this mechanism of DS was used in the simulations. Later you mention that in the SIP-ON simulations, you include mode 1 and 2 of Phillips (2018) but in table S2, there are other parameterizations listed (Lawson 2015, Sullivan 2018) that would account for this representation of DS. Please clarify.

AR: You are right, the previous statement about the modes 1 and 2 in the SIP–DS parameterization of Phillips et al. (2018) was needed to avoid confusion. We revised the paragraph at line 152 and mentioned that there are alternative representations of the same mechanism, occasionally based on the same experiments. Thanks. After this, we considered that the text in lines 174–179 does not required modification.

> ... IMF values due to rime splintering (SIP–RS), droplet shattering (SIP—DS) and ice–ice collisional breakup (SIP—IIBR). IMF values related to SIP-DS rates include secondary ice formation during spherical drop freezing or mode 1 and also during collisions of supercooled raindrops with more massive ice or mode 2, whose representations are supported by the laboratory studies of Keinert et al. (2020) and James et al. (2021), respectively. IMF values related to SIP–IIBR also consider the recent experimental findings of Grzegorczyk et al.(2023). There are other IMF parameterizations available for the SIP–DS and SIP–IIBR mechanisms (e.g. Lawson et al., 2015 and Sotiropoulou et al., 2021) that were not considered in this study but have been implemented in UCLALES-SALSA as reported in Table S4.~~Other parameterizations of ice multiplication factors (IMF) available in UCLALES–SALSA are reported in Table S2.~~

2.7. Lines 192-200

RC: A kappa value of 0.54 is quite low. Do you have a sense of how much this changes the wet diameter?

AR: Figure 1 depicts the time series of the aerosol hygroscopicity parameter κ derived from measurements at the Atmospheric Radiation Measurement (ARM) user facility in the Southern Great Plains (SGP) Lamont, OK, USA on 05 June 2021 between 17:57 and 20:43 UTC during the SPICULE-RF04b research flight [Kulkarni et al., 2024]. The ARM-SGP-Lamont-OK (36.604937° N 97.485561° W) is located around 200 km from the area sampled during the research flight (see Fig.4). In the absence of aerosol composition observations, we assumed that the aerosol hygroscopicity at this site, located among pastures and wheat fields, was representative of background aerosols in natural areas such as those around the Canadian River, which were covered during the SPICULE-RF04b research flight. The average value of κ was 0.5496 but its values varied between 0.4 and 0.9 approximately as it is shown in Figure 1. The average κ helped us to estimate a hypothetical aerosol composition based on sulphate species and mineral dust, as representative soluble and insoluble aerosol constituents driving the number concentrations of cloud condensation nuclei and ice nucleating particles, respectively. Since there was a noticeable degree of agreement between modeled and observed droplet distributions at cloud base, we did not test the model sensitivity to changes in the κ-value. In deep convective clouds such as the SPICULE-RF04b case, the width of the updraft distribution has a stronger effect in the variability in cloud droplet number concentrations at cloud base.

RC: Did you consider using the clear-sky CDP for measurement of supermicron aerosols?

AR: Honestly, we did not. In Figure 2 we have compared the aerosol size distribution used for model initialization with dry-size based aerosol size distributions derived from PCASP and CDP observations below 1050 m of altitude. These distributions agree for submicron particles but show differences for supermicron particles.Despite this disagreement, modeled and observed droplet size distributions at 1.2 km of altitude correlate well at the

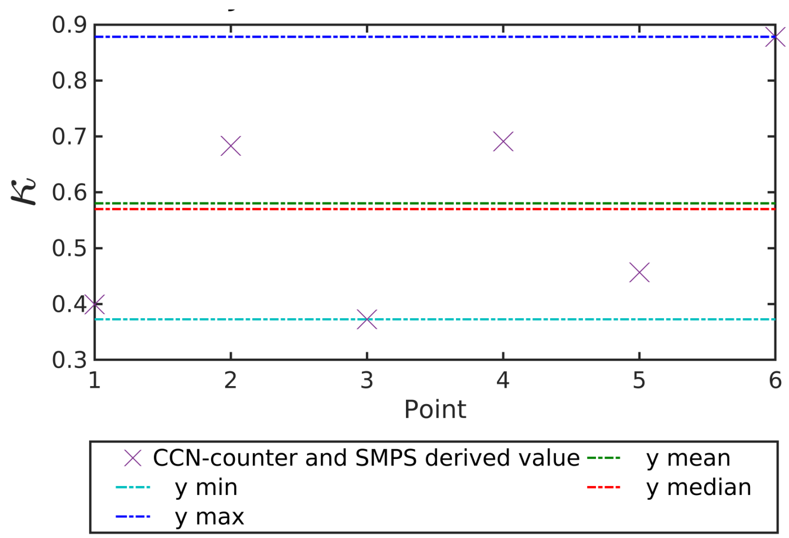

Figure 1: Cloud Condensation Nuclei (CCN) derived hygroscopicity parameter κ (AOSCCNSMPSKAPPA) derived from measurements at the Atmospheric Radiation Measurement (ARM) user facility in the Southern Great Plains (SGP) Lamont, OK, USA on 05 June 2021 between 17:57 and 20:43 UTC during the SPICULE-RF04b research flight [Kulkarni et al., 2024]

supermicron size range as it was shown in Figure S6a, and we did not explore beyond due the low number of CDP measurements below the expected cloud base altitude during the selected time interval (i.e. time interval when both, the GV flight and the Learjet were sampling the same area).

2.8. Lines 238-247

RC: Patnaude et al. (2025) also showed evidence of DS and CPI images of fragmented frozen droplets in fresh updrafts from RF06 of the SPICULE campaign.

AR: Yes, thank you. We included a reference to these findings to strengthen the hypothesis of SIP occurrence in young convective updrafts in cumulus congestus clouds.

> While ice number concentrations (INC) were as high as 23 L^{-1}, number concentrations of ice nucleating particles (INP) only reached a maximum of 1 L^{-1} at 255.1 K indicating that secondary ice production was active and responsible for the ice concentration in updraft cores. Images taken with the Cloud Particle Imager (CPI) and the Optical Array Probe (OAP) during the Learjet cloud penetrations showed pieces of fragmented frozen drops coexisting with 100–300 μm stellar dendrites and hexagonal plates ice crystals likely formed from monocrystalline ice particles (Lawson et al., 2023b). The profuse amount of small columnar particles and the presence of fragmented frozen drops in measurements from the CPI and OAP imaging systems, combined with the occurrence of high reflectivity regions in Ka-band Doppler radar profiles characteristic of large water drops, support the hypothesis that the droplet shattering was mainly responsible for the observed ice multiplication (Lawson et al., 2023b). The coexistence of fragmented frozen droplets and small ice crystals of around 100 μm in maximum length was also observed at 256.25 K in young convective updrafts of cumulus congestus during the

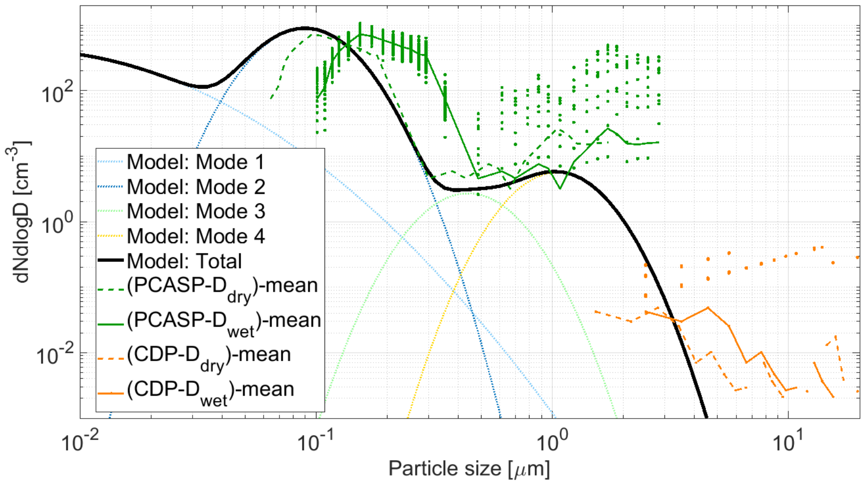

Figure 2: Aerosol size distribution used for model initialization compared to observations with the Passive Cavity Aerosol Spectrometer Probe (PCASP-100X) below 1.05 km during the SPICULE-RF04b-GV flight [Heymsfield et al., 2024]. Observations with the Fast Cloud Droplet Probe (CDP) are included for comparison purposes. In both cases, the dry particle size was estimated by resolving the κ-Köhler equation with κ equal to 0.5496. Observations are reported with dots, average values in terms of particle wet size with continuous lines and average values in terms of particle dry size with dashed lines.

RF06 flight of the SPICULE campaign (Patnaude et al., 2025).

2.9. Line 263

RC: ".. too low to reproduce observed ice microphysics despite..." Could you be clear on what you mean here? Too few ice crystals? The INP measurements from RF04 were anomalously high compared to the rest of the campaign (see Patnaude et al. 2025 Figure 4). It may be at there were cases that the INP and ice crystal number concentrations were much lower, and SIP was still occurring as was shown in Patnaude et al. (2025).

AR: Thank you, we understand the point and definitely the sentence requires clarification. We will start with your indication about anomalously high INP concentrations for the SPICULE-RF04b flight. Figure 4 in Patnaude et al. (2025) compares the temperature dependence of number concentrations for ice nucleating particles (INP) during SPICULE flights RF01 to RF10 that were derived from observations of the CSU Ice Spectrometer (IS), and of the Continuous Flow Diffusion Chamber (CFDC) connected to two different sampling lines, one coming from the Counterflow Virtual Impactor (CVI) and one coming from the High-Performance Instrumented Airborne Platform for Environmental Research modular inlet (HIMIL). For the SPICULE-RF04 case, there is a difference of up to two orders of magnitude between INP number concentrations derived from the IS (05-06-2025 15:07:10) and those derived from the CFDC-CVI (05-06-2025 14:59-01 to 15:39:20 UTC). INP-CDFC-CVI concentrations are higher than INP-IS reaching a maximum of 76 L^{-1}. However, during the second observational period (05-06-2025 17:52:58) which is closer to our simulation time and location, the only INP values that are available are those derived from IS observations, and we include them here for the purpose of completeness. These INP concentrations are much lower than those from the early period increasing from 0.01 L^{-1} at 259.15 K to a maximum of 13.7 L^{-1} at 245.15 K as it was shown in Figure S3 of the supplement.

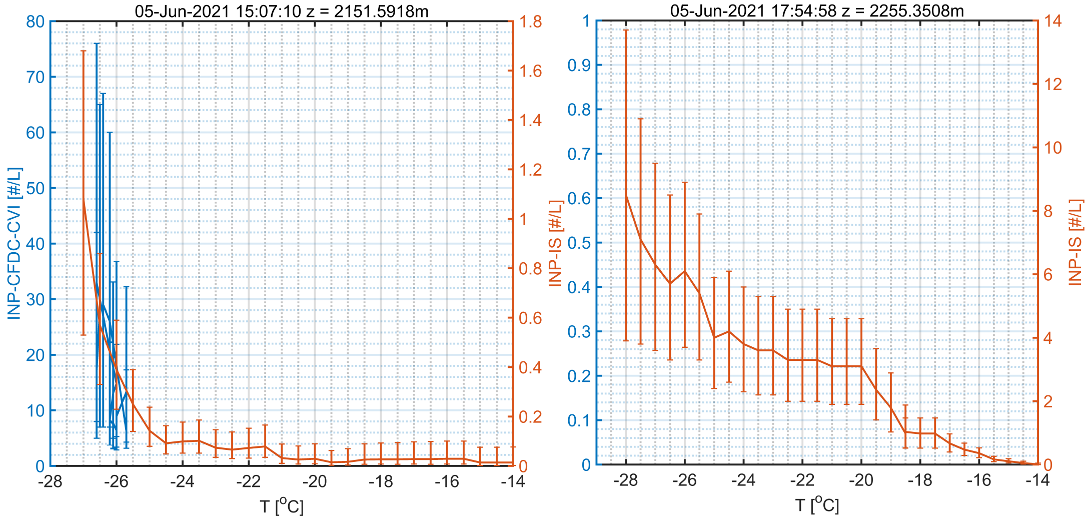

Figure 3: Temperature dependence of INP number concentrations derived from derived from observations with the CSU Ice Spectrometer (INP-IS), and with the Continuous Flow Diffusion Chamber (INP-CFDC-CVI) during the SPICULE-RF04b flight. [DeMott et al., 2024]

INP-IS measurements during SPICULE-RF04b share the trend and range of variation of other research flights according to Figure 4 in Patnaude et al. (2025).

AR: Your comment about the occurrence of SIP in other SPICULE cloud cases with lower IC and INP number concentrations is likely related to the hypothesis presented by Patnaude et al. (2025) that "*the most likely SIP mechanism for ice enhancement during the early stages of the sampled clouds, where higher cloud-base temperatures and stronger updrafts produced conditions favorable for the onset of FFD (fragmentation of freezing droplets)*". Our modelling study for the SPICULE-RF04b supports this statement but suggests two additional constraints: first, the occurrence of SIP in young convective updrafts requires low INP number concentrations to avoid cloud glaciation via primary ice production when the cloud turret rises above freezing level; and second, ice enhancement in these conditions requires the synergistic action of multiple SIP mechanisms. SIP via fragmentation of freezing droplets with or without rime splintering contribution, cannot produce the observed ice enhancement in the SPICULE-RF04b case. The fragmentation of large supercooled freezing drops alone cannot sustain the chain-reaction type mechanism observed in our study.

AR: In conclusion, we thank you for your insightful comments and have modified the manuscript text as follows:

> Based on the observational evidence from CPI and OAP images discussed earlier, we ran two simulations: one considering only the SIP mechanism of droplet shattering, and another that also included the rime-splintering mechanism. ~~In both cases SIP rates were too low to reproduce observed ice microphysics despite showing a good agreement between modeled and observed droplet size distribution.~~These simulations showed good agreement between modeled and observed droplet size distributions guaranteeing a realistic onset for the production of secondary ice from supercooled droplets. However, SIP-DS rates alone or with or SIP-RS contributions could not reproduce the observed ice enhancement in the SPICULE-RF04b case. Ice enhancement in these conditions required the synergistic

> action of multiple SIP mechanisms.

2.10. Lines 264-265

RC: "observed ice number concentrations." Is this in reference to the one cloud penetration from Lawson (2023) with > 2000 L ice?

AR: Yes, when we mentioned observed ice number concentrations we refer to the ice size distributions reported in Figure 10 on Lawson et al. [2023] with the properties included in Table 4 for the Learjet flight. We modified the text as follows:

> Once we added the mechanism of ice–ice collisional breakup to the previous scenarios, SIP rates increased allowing closure between modeled and observed ice number concentrations ~~.~~(observations from the Learjet flight reported in Table 4 and Figure 10 in Lawson et al., 2023 also shown here in Figure 4).

2.11. Lines 295-305

RC: Similar to my comment above, it would be helpful to provide more context to the GV and Learjet observations. I assume it is the measurements from Lawson 2023 Table 3 and 4?

AR: Yes, your assumption is correct. We added the indications to the main text as suggested in your previous comment. We kept the description of the GV and Learjet observations to a minimum level to keep this manuscript reasonable long. However, we took care of highlighting that our selected subset from observations comprises cloud penetrations into updraft cores with the presence of liquid water when both, the GV flight and the Learjet were sampling the same area as shown in Figure S1. Although we did not verify the horizontal distance between the two aircraft as it was done in Patnaude et al. (2025), we evaluated data from a common time interval when both flights moves in the same region as show in Figure 4.

2.12. Line 301

RC: "... they increased at higher altitudes..." What is meant by "they"? LWC or the differences?

AR: Your question about the sentence is reasonable. Thank you for pointing out the bad choice of words. We modified the sentence as follows:

> Although, the differences in the LWC vertical profiles of~~between~~the SIP-OFF and the SIP-ON scenarios were minimal in the warm section between cloud base and 2.5 km of altitude, they increased at higher altitudes and became particularly important above 3.5 km in the proximity of the freezing level located approximately at an altitude of 4 km.

2.13. Lines 303-305

RC: It is not clear to me which simulation is being referred to for "lower LWCs in warm cloud..." Please be more specific here.

AR: You are right. We modified the sentence as follows:

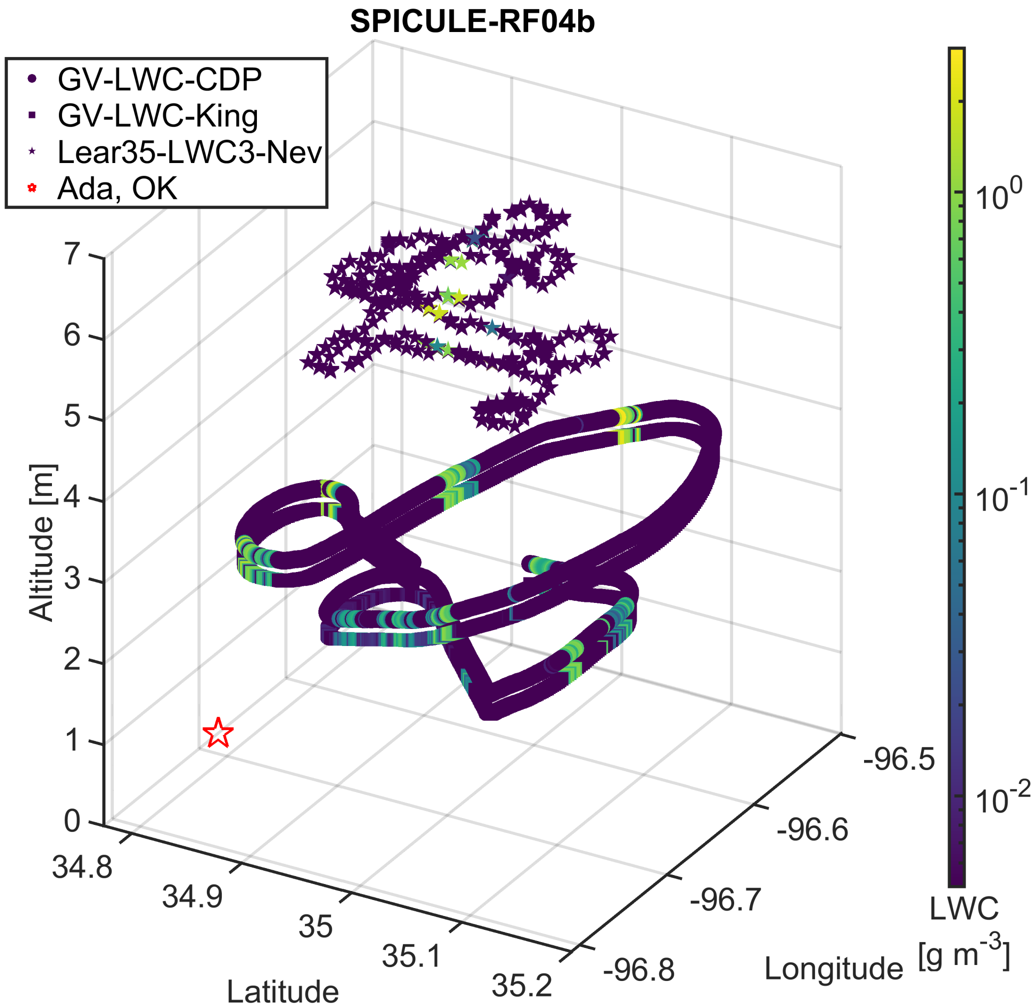

Figure 4: Comparison of 3D flight tracks during the SPICULE-RF04b GV and Learjet flights. Vertical variability in liquid water content (LWC). LWC values derived from measurements of the King Probe, Cloud Droplet Probe, and Nevzorov-LWC/TWC Probe.

Differences in the mean LWC values of the SIP-ON scenario compared to the SIP-OFF scenariomean profiles between the SIP-ON and the SIP-OFF scenarioscan be grouped in three trends, slightly lower liquid water contents in the warm cloud section (i.e. between 3 km and 4 km, higher liquid water content at the beginning of the mixed phase part of cloud tower (i.e. between 4 km and 6 km) and lower liquid water content at the tower top (i.e from 6 km up to 8.5 km).

2.14. Lines 324-326

RC: "we considered that modeled ice…" In the SIP-OFF simulation, does the model not allow for any interactions between liquid and ice hydrometeors? Meaning there would be no freezing of rain droplets via a collision with an ice particle? That would be another source of ice particles besides heterogeneous nucleation of INPs.

AR: In our model, there is phase transformation during droplet–ice collisions (i.e. cloud droplets and raindrops). The ice particle grows to the expense of the liquid gained from the droplet increasing its mass. Droplet–ice collisions do not add new ice particles.

2.15. Lines 361-362

RC: Also agrees with Patnaude et al. (2025) who showed fragmented droplets at -17°C during RF06 of SPICULE.

AR: Thank you. We already included this information in the main text as you suggested previously.

2.16. Lines 374-375

RC: This sentence is a bit confusing as it reads like Figure 7g-i is showing concentrations of large droplets, when I think the point is that the other SIP mechanisms are constrained to smaller areas.

AR: Thanks for pointing out this. The sentence was rephrased.

At the peak of convection intensity in the SIP-ON scenario (46 min after convection initiation), the SIP–IIBR was active along a larger area with higher SIP rates at temperatures below 265 K. Other SIP mechanisms were constrained to smaller areas where sufficient concentration of supercooled large droplets existed as shown in Figure 7(g-i).the SIP-IIBR mechanism was active across the mixed-phase zone, while other SIP mechanisms are constrained to smaller areas as shown in Figure 7(g-i).

2.17. Lines 375-377

RC: Same as previous comment. I think you are making the point that Figure 8c-d is showing the limited existence of liquid water, but it reads like you are stating that those figures are showing strong updrafts carrying liquid water upwards.

AR: Thank you again. The sentence was rephrased as follows:

The mixed-phase zone in the SIP-ON scenariowas almost completely glaciated with only a few areas indicating the existence of liquid water due to the replenishment effect caused by strong updrafts that carry liquid water from lower altitudesas seen in Figure 8(c-d).

2.18. Line 380

RC: Below freezing level sounds like you are saying colder, when I think you are stating the opposite. I would suggest saying "higher" or "warmer", or "lower altitudes".

AR: Thank you for mentioning it. The sentence was rephrased as follows:

> In the SIP-ON scenario, the warm section of the deep convective core (i.e. area with TWC > 3.5 gm^{-3} ~~below freezing level temperature~~at lower altitudes) was smaller but more densely loaded with liquid water in the proximity of the freezing level, suggesting an important role of the ice melting process.

2.19. Lines 409-502

RC: It is difficult to discern in Figure 12 where 40 and 50 minutes are occurring. It may be helpful to highlight those lines on the figure so the reader can more easily observe the DSD.

AR: We have modified the color scale to make Figure 12 more readable. Thank you for your helpful suggestion.

2.20. Lines 503-504

RC: "The larger the supercooled droplet. . . " This is true but I think this statement ignores the fact that the II-BR SIP mechanism had already completely taken over as the dominant SIP mechanism by 48 minutes. II-BR mechanism is likely consuming many of the large droplets not DS. Also, in laboratory studies of droplet fragmentation, Keinert et al. (2020) found that at most 45 % of the large droplets underwent any kind of breakup, likely not enough to significantly deplete the raindrops.

AR: You are right. Thank you for you insightful comment. The sentence was rephrased as follows:

> ~~The larger the supercooled droplet, the higher is the probability of experiencing droplet shattering, which in turn explains why there is a low number of large rain drops in the SIP-ON scenario.~~By 48 minutes, the SIP-IIBR mechanism had already established itself as the dominant secondary ice production pathway. Consequently, the positive feedback associated with SIP(DS+II-BR) is expected to have substantially reduced the number concentration of raindrops, compared with the higher concentrations maintained in the SIP-OFF scenario.

2.21. Technical comments

RC: Line 212: Add a space after the degrees symbol and before "to"

AR: Thank you.

RC: Line 261: AOP should be OAP.

AR: Thank you.

RC: Line 262: ". . . SIP mechanism of droplet shattering and other adding the mechanism of rime splintering." Please revise.

AR: Thank you. We have modified the sentence as follows:

~~Following the observational evidence from CPI and AOP images discussed before, we ran two simulations, one only considering the SIP mechanism of droplet shattering and other adding the mechanism of rime splintering.~~Based on the observational evidence from CPI and OAP images discussed earlier, we ran two simulations: one considering only the SIP mechanism of droplet shattering, and another that also included the rime-splintering mechanism.

RC: Figure 3. It is quite difficult to see the differences in the model percentile lines. I would recommend using more different line styles or widths for each to make it more obvious.

AR: Thank you for your suggestion. We have changed the color scale used for the model percentile lines. The new Figure 3 is included in the manuscripts, and also here for the sake of completeness.

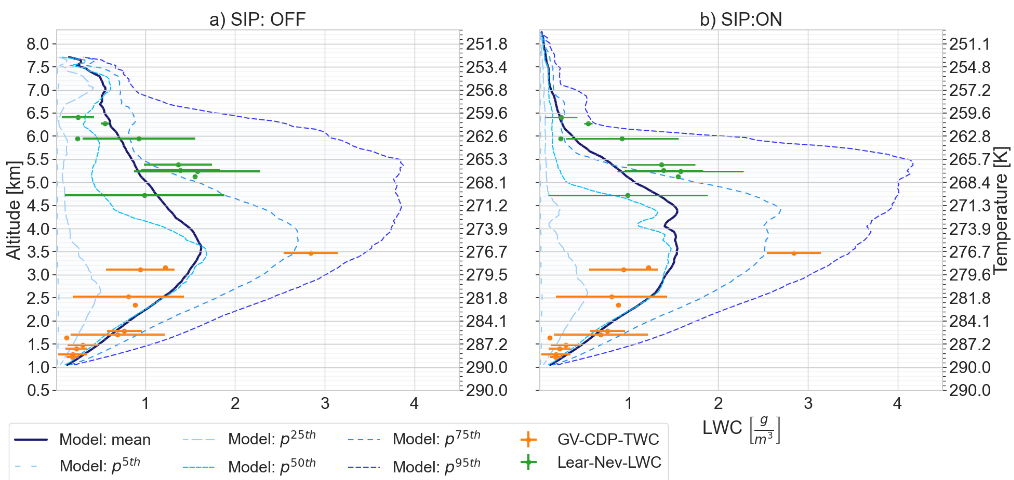

Figure 5: Vertical profile of liquid water content in updrafts with cloudy conditions. The variability in model outputs is depicted using the mean and main percentiles values while observations are shown as the mean ± standard deviation for measurements with the Fast Cloud Droplet Probe in the GV-flight (GV-CDP) and with the SkyPhysTech Nevzorov Probe in the Lear35 flight (Lear-Nev). Panel (a) Simulation scenario without secondary ice processes. Panel (b) Simulation scenario with secondary ice processes including rime splintering (RS), droplet shattering (DS) and ice–ice collisional breakup (IIBR).

RC: Figure 5. It appears that this figure is missing a legend.

AR: Please receive our apologies. It was an unfortunate mistake. We have included here Figure 5 for the sake of completeness.

RC: Figure 6. I do not see a line for 258.15K.

AR: At 40 min, the cloud has not reached 258.15 K and therefore the temperature contour plot does not draw an isotherm at that level. Later in the simulation, the three isotherms for 273.15 K, 265.15 K and 258.15 K appeared clearly in the mixed-phase zone as shown in Figures 7 and 8. We modified the figure caption as follows:

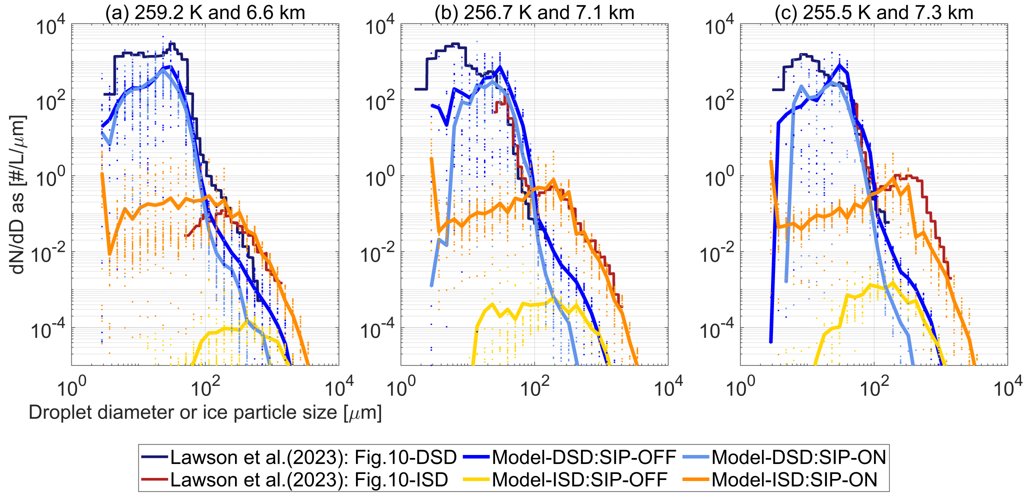

Figure 6: Ice particle size distributions in updrafts at altitudes of (a) 2.6 km above freezing level (b) 3.2 km above freezing level (c) 400 m below cloud top. Observations were taken from Figure 10 in Lawson et al. [2023]. Modeled values are shown as mean horizontal values with dotted lines along size bins indicating variability across cloudy points with mixed-phase conditions defined as LWC $>$ 0.01 gm^{-3}, IWC $>$ 0.001 gm^{-3} and updraft velocity $>$ 0.02 m s^{-1}.

Vertical profile of liquid water content (LWC) and ice water content (IWC) at 40 min after convection initiation. Contour lines in gray indicate Total Water Content (TWC) values of 0.01 gm^{-3} and 3.5 gm^{-3} to enclose cloudy and core conditions. Continuous black lines indicate altitudes at which temperatures are 273.15 K, and265.15 K ~~and 258.15 K~~corresponding to freezing, andmaximum ice multiplication by rime splintering ~~and by droplet shattering~~, respectively. Panels (a-b) Simulation scenario without secondary ice processes. Panel (c-d) Simulation scenario with secondary ice processes.

RC: Line 434: Do you mean Figure 10 e-f?

AR: Yes, thank you.

RC: Line 448: I do not think this reference is needed here.

AR: The reference was removed.

RC: Line 514: Change droplet size distribution to DSD

AR: Thanks.

RC: Line 541 – 543: missing a second parentheses.

AR: Thanks.

References

J. L. Brownscombe and N. S. C. Thorndike. Freezing and shattering of water droplets in free fall. *Nature*, 220:687–689, 1968. . Letter; Published: 16 November 1968.

P. DeMott, T. Hill, and R. Patnaude. SPICULE: CSU Ice Spectrometer (IS) Measurements. Version 1.0, 2024. URL `https://doi.org/10.26023/HAYW-8STD-KT00`. Accessed 09 Jun 2025.

J. Hallet and S. C. Mossop. Production of secondary ice particles during the riming process. *Nature*, 249: 26–28, 1974. ISSN 1476-4687. .

A. Heymsfield, P. Lawson, and P. DeMott. Spicule | earth observing laboratory, 2024. URL `https://www.eol.ucar.edu/field_projects/spicule`.

R. J. Kolomeychuk, D. C. McKay, and J. V. Iribarne. The fragmentation and electrification of freezing drops. *Journal of Atmospheric Sciences*, 32(5):974 – 979, 1975. . URL `https://journals.ametsoc.org/view/journals/atsc/32/5/1520-0469_1975_032_0974_tfaeof_2_0_co_2.xml`.

G. Kulkarni, M. Levin, and J. Shilling. Atmospheric radiation measurement (arm) user facility. ccn counter derived hygroscopicity parameter kappa (aosccnsmpskappa), 2017-04-12 to 2025-01-14, southern great plains (sgp) lamont, ok (extended and co-located with c1) (e13), 2024. URL `https://adc.arm.gov/discovery/#/results/instrument_code::aosccnsmpskappa/dataLevel::c1`. Accessed on 2024/09/24.

R. P. Lawson, A. V. Korolev, P. J. DeMott, A. J. Heymsfield, R. T. Bruintjes, C. A. Wolff, S. Woods, R. J. Patnaude, J. B. Jensen, K. A. Moore, I. Heckman, E. Rosky, J. Haggerty, R. J. Perkins, T. Fisher, and T. C. J. Hill. The secondary production of ice in cumulus experiment (spicule). *Bulletin of the American Meteorological Society*, 104:E51 – E76, 2023. . URL `https://journals.ametsoc.org/view/journals/bams/104/1/BAMS-D-21-0209.1.xml`.

S. C. Mossop. Production of secondary ice particles during the growth of graupel by riming. *Quarterly Journal of the Royal Meteorological Society*, 102(431):45–57, 1976. . URL `https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.49710243104`.

R. J. Patnaude, K. A. Moore, R. J. Perkins, T. C. J. Hill, P. Lawson, Q. Mo, A. Bailey, S. C. van den Heever, S. M. Saleeby, Q. Bian, J. C. Chiu, P. J. DeMott, and S. M. Kreidenweis. On the role of airborne ice nucleating particles in primary and secondary ice formation processes in convective midlatitude clouds. *Journal of the Atmospheric Sciences*, 82(5):869 – 892, 2025. . URL `https://journals.ametsoc.org/view/journals/atsc/82/5/JAS-D-24-0135.1.xml`.

V. T. J. Phillips, S. Patade, J. Gutierrez, and A. Bansemer. Secondary ice production by fragmentation of freezing drops: Formulation and theory. *Journal of the Atmospheric Sciences*, 75:3031–3070, 2018. . URL `https://journals.ametsoc.org/view/journals/atsc/75/9/jas-d-17-0190.1.xml`.

H. R. Pruppacher and R. J. Schlamp. A wind tunnel investigation on ice multiplication by freezing of waterdrops falling at terminal velocity in air. *Journal of Geophysical Research (1896-1977)*, 80(3):380–386, 1975. . URL `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/JC080i003p00380`.

C. Takahashi. Deformations of frozen water drops and their frequencies. *Journal of the Meteorological Society of Japan. Ser. II*, 53(6):402–411, 1975. .

C. Takahashi and A. Yamashita. Shattering of frozen water drops in a supercooled cloud. *Journal of the Meteorological Society of Japan. Ser. II*, 48(4):373–376, 1970. .

C. Takahashi and A. Yamashita. Production of ice splinters by the freezing of water drops in free fall. *Journal of the Meteorological Society of Japan. Ser. II*, 55(1):139–141, 1977. .

T. Takahashi, Y. Nagao, and Y. Kushiyama. Possible high ice particle production during graupel–graupel collisions. *Journal of Atmospheric Sciences*, 52:4523–4527, 1995. . URL `https://journals.ametsoc.org/view/journals/atsc/52/24/1520-0469_1995_052_4523_phippd_2_0_co_2.xml`.