Response to Referees

Explicit Numerical Simulations of Hailstorm Seeding with a Three–Moment Microphysics Cloud–Resolving Model: A Comparison of Two Operational Methodologies for Hail Suppression

Darko Savić, Vladan Vučković, and Dragana Vujović

Dear editor and referees,

We would like to thank the Referees and Editor for the time invested in reading and evaluating the manuscript. We highly appreciate the constructive comments, which have been addressed in detail in the document below. The Referee's comments are shown in blue, while the author's responses are provided in plain text.

Kind regards,

Darko Savić et al.

Response to Referee #1

Summary

The study investigates the feasibility and impact of hail suppression using a numerical model with a three-moment cloud microphysics scheme and a two-moment aerosol microphysics scheme at a high horizontal resolution of 500m. The authors evaluate two operation seeding methods, RHSS and AB23, with respect to their skill to reduce hail damage. A proper introduction to the topic is given and the authors try to cover the huge range of processes interacting in an convective, hail-producing cloud by showing detailed analyses of process rates. Before I can recommend the study for publication, I believe my major comments below need to be addressed first.

Major comments

- Statistical significance: The authors rightly point out the chaotic and non-linear nature of convective storms. They also reference studies, such as Papaevangelou et al., (2025, 2026), who employed ensemble strategies to exactly account for this. Why was not a similar strategy employed here? Having at least a small ensemble (e.g., 10 members) would already help robustly quantifying the effect of hail suppression techniques. I strongly recommend to perform additional simulations, where the radio-sounding profile is (slightly) adapted to initialize the storm. I believe only then concluding remarks can be drawn in terms of hail suppression efficiency. Currently, I am missing any statistical measures in the analysis. To me, it is not clear, why the total number/mass is usually shown. In Figure 6, it also looks like the differences to CTRL in the hydrometeors are very small? Except for snow and raindrops. I would like to see difference plots at least for the process rates from Figure 7 onward, but also for the data shown before. It is very hard to distinguish anything. I also think the mass and number plots should be combined into two-column subplots, with maybe 3 rows, where the process rates are distinguished by liquid, ice, and mixed processes. Currently, it takes quite a long time to do a comparison (visually). Combining figures and conducting a statistical analysis (e.g,. in the form of box plots etc.) will help the reader to better grasp what are the take-aways, and will drastically reduce the large number of figures, that appear to be repetitive but are not. Along the same lines is the issue of numerical noise. Are the authors sure, they are not looking at numerical noise for process rates, such as in Fig. 12 (not exclusively here)? That is why, I believe an ensemble simulation approach is required to overcome these issues. Consistent usage of colors for the same processes across all figures would also help to make comparing them more straightforward. I know that Figure 19 shows differences, but exactly these look to me like numerical noise, because of the switching of neg/pos high exponents. Unfortunately, it is next to impossible to read anything from this figure. The authors also mention that these are 1 min averages, so what is the data output frequency of the model? Here the method sections needs to be expanded, such that is clear what quantities over what spatial / temporal range are looked at.

This work investigates the effects of glaciogenic reagent on hailfall characteristics in a supercell cloud, using a numerical model. As we discussed in the manuscript, the investigation is based on a case study of a well-known supercell storm, and the conclusions apply only to this situation. On the other hand, this is an idealized study where the textbook example of a supercell was simulated using radiosounding data and no orography. The effects of seeding, in a more complex setup, e.g. where the model is initialized with a realistic three-dimensional field and with orography, where a much more complex convective cloud might form, may vary significantly. Although the use of an ensemble such as that explained in Papaevangelou et al., (2025, 2026) would greatly improve the generality of the results and extend the significance of the conclusions, there is an issue with the computational costs of such explicit high-resolution modeling. In our model, we used very detailed three-moment microphysics by Milbrandt and Yau (2005). Furthermore, we improved and upgraded the model by implementing a two-moment aerosol microphysics. Within this framework, we use non-monodisperse aerosols that follow a gamma distribution, all the known scavenging mechanisms are explicitly calculated (Table 1 of the manuscript), and all four freezing modes of AgI particles are calculated according to DeMott (1995). All this combined makes it very computationally expensive to run the model in this setup. As a reference, running these three experiments (CTRL, RHSS, and AB23) took around 30 days to complete. For this reason, a full ensemble approach was not feasible within the scope of this study. This is a valid point, and we have noted it as a limitation of the study. Furthermore, the ensemble approach is planned in the future after the provision of a more powerful machine.

We appreciate the Referee #1 comment regarding the complexity of Fig. 7 onward. We carefully considered the suggestion to combine the mass and number process rates into multi-panel subplots grouped by liquid, ice, and mixed processes. However, since there are 56 microphysical process rates for hydrometeor mass and 63 for number concentration, such a presentation would likely produce overly dense, difficult-to-read figures.

The Referee #1 suggestion to present difference plots is very useful, as it both reduces the total number of figures and makes the seeding signal easier to identify visually. However, by depicting only difference plots, we lose the range of magnitudes of the microphysical processes and their relative differences. Therefore, we decided to depict all three experiments in a single figure. This allowed us to remove the appendix, reducing the revised version of the manuscript by 14 pages and 16 figures. Furthermore, this allowed for a direct comparison of the effects of both methodologies.

Our intention was to provide a comprehensive overview of the effects of cloud seeding on all resolved microphysical processes. For this reason, processes that did not exhibit a clear seeding signal were still included in the figures to provide context and to illustrate the relative magnitude of seeding effects across different processes, while the discussion focused primarily on those processes showing the most pronounced response.

To first answer your question about the model output frequency. The main fields (hydrometeors mixing ratio and number concentration, thermodynamic field, etc.) are written every minute, while the data for diagnostic files (Fig 4-20) are written in every time step. The numerical noise is certainly present in the data, and the averaging over a period of 1 minute was done exactly to reduce it and to make the figures easier to read. An example of a numerical noise reduction can be seen in Fig. 1 (note that the line width is the same in Fig. 1a and b). Regarding the frequent switching of the processes in Fig. 19 of the manuscript, these are most likely the result of a nonlinear response to seeding, rather than the numerical noise. For this reason, we only investigated the processes with a clear seeding signal (those that do not exhibit the switching). Note that the revised manuscript does not include difference plots, as they do not provide additional information and are relatively hard to read.

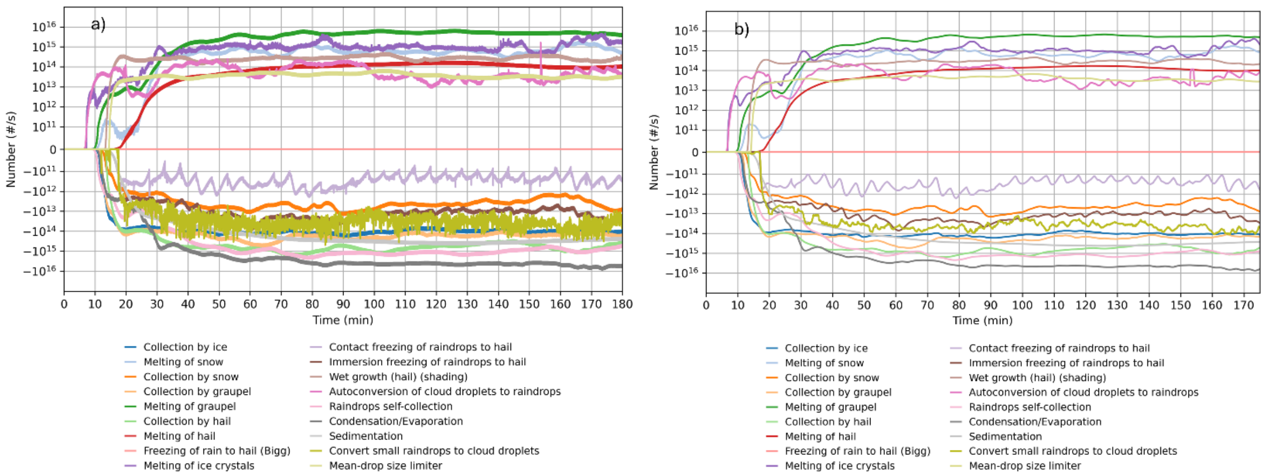

Figure 1. The time series of source/sink terms for the total number of raindrops in the domain for RHSS. Different microphysical processes are depicted with different colors indicated in the figure's legend at the bottom. The model data (a) and their 1-minute averages (b) are depicted.

- RHSS vs AB23: I think it would be highly beneficial for the discussion of the results to have a table outlining the pros and cons of each method. While I like the sketch in Figure 1 a lot, I am missing in the comparison of the two methods, why we have this differences, and by that, why should we care about that? Why was RHSS chosen to show the detailed microphysics discussion, and then AB23 is suddenly re-discussed regarding hail reduction? Are these seeding methods actually feasible? RHSS has a rocket-based seeding system, correct? So are they shooting rockets every 5 min into the cloud? What is an approximation and testing setup in the model (which is absolutely fine to do) compared to the operational setting?

We thank Referee #1 for the suggestion to make a table outlining the differences and pros/cons of each seeding method, and we agree that this detail would be highly beneficial for the discussion of the results. We have accepted the suggestion with pleasure: in the revised manuscript, we have inserted a new table (Table 5) in the Discussion chapter and expanded the accompanying text to explain these aspects in detail.

Table 1. Main differences, pros, and cons of the RHSS and AB23 seeding methodologies.

Feature	**RHSS**	**AB23**	**Microphysical reasons**	**Operational implications**
Seeding zone	Strictly inside the cloud (15–45 dBZ), close to the EFZ core.	Broader (1–30 dBZ), extends 5 km into cloud-free inflow	RHSS delivers APs directly to supercooled cloud regions; AB23 relies partly on AP advection into cloud	/
Criteria	Simple: reflectivity and isotherm heights	Complex: Includes VIL, integrated water content of radar echo volumes, and their temporal trends	A more complex criteria may provide information about the amount of supercooled water and whether the storm is intensifying or dissipating.	AB23 requires more advanced radar analysis
Temporal frequency	Fixed 5-minute intervals.	7-min (moderate storms) and 3.5-min (intense storms)	A more continuous and steady supply of APs may reduce “missed windows” during rapid storm intensification	AB23 is operationally more demanding
Aerosol scavenging	Less relative AP mass and especially number remain uncollected; stronger wet deposition; more APs in cloud ice	More APs remain uncollected in the air; weaker deposition; fewer APs incorporated into cloud ice	RHSS scavenges and activates APs more efficiently due to direct in-cloud delivery	/
Pros	Larger reduction in total hail KE flux	Larger reduction in extreme-damage area (KEflux > 300 J m^{-2})	/	/
Cons	Less effective against extreme local kinetic energy (KE_{flux} > 300 Jm^{-2}).	Lower reduction in total KE flux and lower AP utilization efficiency	/	/

In order to explain the differences in hailfall characteristics between the two methodologies, it is necessary to compare the microphysical effects on hail in both cases throughout the storm development and evolution. However, this would be very challenging.

As mentioned in Table 1, in the case of AB23, APs are delivered more steadily compared to RHSS, where APs are injected strictly within the EFZ. On the one hand, this allows AB23 to reduce the chance of "missed windows" during rapid storm intensification. However, because RHSS has a smaller seeding zone volume, it has a higher initial AP concentration; therefore, competition in growth between hail embryos is increased. It is also worth noting that, in the case of RHSS, a lower percentage of APs remains uncollected from the air by hydrometeors (both in terms of mass and number).

To provide concrete physical evidence for the observed differences, we analyzed the microphysical terms within the model domain, focusing on processes that show a clear and robust response to cloud seeding. We do this by comparing a change in microphysical processes for hail. The following conclusions can be drawn by examining Figs. 16 and 17 from the revised manuscript.

- **Overall mass vs. number**: Both methodologies produce a mixed effect on total hail mass but lead to a steady increase in the total number of hailstones within the domain, indicating a shift toward a larger number of smaller hailstones.
- **Primary hail sources**: Immersion freezing of raindrops is the dominant source for both hail mass and hail number, while contact freezing is crucial strictly for hail number. Both processes respond very similarly under both methodologies.
- **Hail melting**: Seeding causes a decrease in hail melting as a mass sink, and this reduction in mass loss is significantly more pronounced in the RHSS case.
- **Raindrop collection:** The collection of raindrops, a major source term for hail mass, undergoes a substantial decrease following seeding, especially under the RHSS framework.
- **Sedimentation and other**: Hail sedimentation decreases significantly for both mass and number, reflecting smaller, slower-falling stones, with a larger decrease observed in RHSS. Conversely, sublimation acts as a notable sink for hail number, while three-component freezing (graupel–rain collisions) increases as a source term under both methodologies.

These results indicate that seeding the EFZ with a higher local concentration of APs (RHSS) leads to a greater reduction in accreted hail mass, ultimately decreasing the total amount of hail that reaches the ground (resulting in a higher reduction in total regional kinetic energy). On the other hand, a more continuous and steady supply of APs to the updraft core (AB23), by a 5-km upwind extension of seeding zone, seems to be a key to suppressing the formation of giant hailstones, thereby achieving a much greater reduction in the surface area affected by extreme hailfall (KE_{flux} > 300 Jm^{-2}). This more continuous supply of APs in the case of AB23 may reduce the chance of a "missed window" in the seeding, thereby reducing the chance of forming large hailstones, which affects the area of the largest KE flux.

We thank Referee #1 for the constructive guidance to include this discussion. Following this excellent suggestion, the text above has been incorporated into the revised version of the manuscript.

The aim of this study is to investigate the effects of cloud seeding on hailfall characteristics for two operational seeding methodologies, with a focus on their impact on potential hail-induced damage. In the revised manuscript, by adjusting the presentation of the results we have included a direct comparison of the seeding methodologies, as well as a discussion on possible explanations for the differences in surface hailfall characteristics.

Both methodologies rely on rocket delivery systems, and there are some approximations that had to be made in the numerical framework, as well as a few deviations from the given manuals. First, rockets emit aerosol particles along their trajectory; therefore, the seeding zone defined by the radar operator does not receive APs uniformly during the seeding cycle. Operationally, it is preferred to seed a cloud from all directions, but this is not always possible. In the model, the APs are injected uniformly into the seeding zone. Second, to the best of our knowledge, the seeding cycle intervals in operational practices are usually respected; however, there is a subjective factor that can cause deviations from the seeding manual during operations. For example, not all storms form within the territory covered by hail suppression stations (e.g., storms may form in another country). In this case, the seeding of a storm is initiated at a later stage of cloud development. Also, the radar operator sometimes chooses not to seed the storm if they estimate that it will move outside of the country or propagate into a region without agriculture or settlements. An additional, aggravating circumstance is that cloud seeding actions are always controlled by flight control agency. Every seeding cycle must be approved by flight control, and often the seeding is skipped for safety reasons. Furthermore, there is always the question of the availability of the required number of rockets.

One difference between operational practice and the model setup lies in the definition of the seeding zone. In both methodologies, this is partly based on subjective judgment: while radar reflectivity and temperature provide general guidance for the radial and vertical extent, the azimuthal extent is more uncertain and largely depends on operator experience. In the model, this was formalized through fine-tuning, and a fixed 10 km radius, centered on the main updraft maximum, was adopted as an appropriate criterion for seeding, together with the reflectivity and temperature thresholds specified in the operational guidelines. This 10 km radius criterion is depicted in Fig. 1 (manuscript). In our model framework, we tried to reproduce the instructions from the manuals as precisely as possible in terms of determining the seeding criteria and cloud type, defining the seeding zone, and delivering the recommended mass of the reagent.

- Seeding: While there are studies already introducing and validating the seeding, I believe a section on how the seeding particles interact with the hydrometeors is required and how they are seeded. I was confused by all the options from the operational setting. DeMott (1995) proposed several freezing pathways for silver iodide, and I believe a short recap would greatly help to better understand the signals in the changes in process rates. Also, sometimes I am not sure if the aerosol particles interact with the hydrometeors, i.e., via immersion freezing, or if they are “only” scavenged and washed out? Am I misunderstanding here some process rates? A clarification woudl be greatly appreciated. This would also help to understand the zigzag and wavey pattern in, e.g., Fig. 5 in the cloud droplets, total, and air. This is also connected to have a proper description in the methods section on how the shown metrics are computed. More of a side note: please ensure that the labeling of the seeding particles is consistent in the manuscript (AP, seeding particles, aerosols, reagent, ...) to avoid any confusion.

Thank you for the suggestion to incorporate the section on AP-hydrometeors interactions. We added it to the revised version of the manuscript.

The submicron-sized aerosols that follow the gamma distribution are injected into the seeding zone, where they are scavenged by different hydrometeor categories through the processes listed in Table 1 (manuscript). When APs get scavenged by a certain hydrometeor, they are removed from the air and are added to that hydrometeor category. In other words, our model calculates the mixing ratio and number concentration of APs in the air and in each hydrometeor category. APs can be transferred from one category to another via microphysical processes. Furthermore, if APs are present in the air, they can serve as a deposition nuclei, creating cloud droplets, or as condensation-freezing nuclei, producing ice. On the other hand, when scavenged by cloud droplets or raindrops, they can initiate ice phase formation through immersion or contact freezing. DeMott's (1995) parameterisation of these four nucleation modes of silver iodide is also implemented in the model.

Minor comments

- Line 109: cloud electrification: I would appreciate a bit more details and why this is important

In Cumulonimbus clouds, a significant amount of electrical charge is generated due to various charge separation mechanisms; therefore, both hydrometeors and aerosol particles (APs) have a certain amount of charge. As a result, an electrostatic interaction between the APs and hydrometeors is present, which leads to AP scavenging by both Coulomb and image charge forces.

In our model, electrostatic scavenging (electroscavenging as mentioned in Table 1 of the manuscript) is resolved in the following way. The standard approach in studying the influence of electrostatic force on APs collection assumes that the mean charge on cloud droplets and raindrops is proportional to their surface, i.e., to the square of the diameter (Andronache 2004; Wang, Zhang, and Moran 2010), and is calculated using an equation:

$$q_x = a\alpha D_x^2, \text{ [C]}$$

where a is the surface charge density and has a value of $0.83 \cdot 10^{-6}$ C m^{-2} for liquid hydrometeors and for graupel, while for cloud ice and snow a has a value of $0.238 \cdot 10^{-6}$ C m^{-2}, and α is an empirical parameter that varies from zero, reflecting the neutral electrical conditions, to seven for the extremely electrified cloud. The x corresponds to APs or a certain hydrometeor.

The APs in the model are submicron in size and are represented by the gamma function. This distribution is observed for the rocket delivery systems (Meyers el al., 1995). The charge distribution on APs is assumed to follow Boltzmann's distribution. Why is it important to consider electroscavenging (ES) in addition to other collection mechanisms? ES is a dominant collection mechanism for larger APs (the upper end of our APs size range, up to 0.2 μm; Vučković et al., 2023). When cloud droplets carry more charge, they scavenge a greater mass and a larger number of APs (Vučković et al., 2025). The charge distribution of APs, as well as the calculation of image charge, significantly influences the precipitation mass and number of APs.

In the case of highly electrified clouds, the value of α typically ranges between 3 and 5. However, in this study, we adopt a value of 3 as a more conservative choice.

More detailed descriptions of the schemes and results of electroscavenging can be found in Vučković et al. (2023; 2025a; 2025b).

- Line 115: Is the ratio of vertical and horizontal grid spacing good enough? What are the experiences of the authors?

The horizontal grid spacing in this study is $\Delta x = \Delta y = 500$ m, while the vertical grid spacing is $\Delta z = 250$ m, resulting in an aspect ratio of 2. This corresponds to a near-isotropic configuration commonly used in cloud-resolving models (CRMs). The model we used was also configured in a way that the turbulence and acoustic wave divergence were assumed isotropic in calculations. This is justified in the cases where wind velocity components are of the same order of magnitude, i.e., u~v~w. The authors refer to the work of Bryan et al. (2003), where the required grid spacing for the simulation of deep moist convection is discussed. As noted in this paper, CRMs with the sub-kilometer resolution are able to simulate deep moist convection in a satisfactory manner for the equal vertical and horizontal grid spacing. In addition, our previous experience with similar model configurations has demonstrated that this setup adequately reproduces key characteristics of convective cloud systems without introducing noticeable numerical artifacts.

- Line 116: I do not understand the two model time steps.

In the ARPS model, two time steps are defined for the splitting technique. The small time step is used to resolve acoustic waves, while all the other terms are calculated in every big time step.

- Table 1: Maybe think of having a column with the processes and then the check marks where they are active for each hydrometeor class.

Thank you for the suggestion. This is implemented in the revised version.

- Line 184: the bullet point list can be moved to Table 2 as headers

Thank you for the suggestion. This will be implemented in the revised version. We assume the comment refers to Table 3, as Table 2 addresses the other seeding methodology.

- Line 211: In what way is the movement of the supercell anomalous? You are initializing it with the radiosounding, right?

Correct, the supercell was initialized using the radiosounding data depicted in Fig. 2 of the manuscript. As can be seen on the hodograph (right panel on Fig. 2) and indicated by an arrow, the supercell was moving almost directly northward. In contrast, these types of storms typically propagate from west to east in the Northern Hemisphere. Therefore, the anomalous behavior refers to this atypical propagation direction.

Since supercell storms usually move eastward in the Northern Hemisphere, both seeding methods determine the location of the seeding zone accordingly. Typically, they move eastward with the inflow layer south of them; therefore, both methods' manuals state that the seeding should be conducted on the right, relative to the direction of the storm's movement. If we strictly follow this manual, in the case of the simulated storm, the seeding would be conducted on the east side of the storm, which would miss the hail embryo formation zone.

- Line 213: Location of the maximum updraft in what space? x, y, z?

The maximum updraft is determined at the beginning of each seeding cycle in the following way. First, a radar reflectivity maximum for the entire domain is found. In the beginning of the convection, it is associated with the updraft, and later with the precipitation. In either case, it is in the vicinity of the right-moving cell mean updraft. Then, the level of 0 °C is found in that column. Finaly, the maximum updraft is found on the zero isotherm level, which is usually very close to the location of the maximum reflectivity but at a different height.

This complex algorithm for finding the center of a seeding sector originates from an attempt to replicate the operational seeding as close as possible, but also so that the tracking algorithm works for a very complex system, such as a supercell. In this particular case, after the storm had split, the location of maximum updraft in the domain (x,y,z) switches between two cells. On the other hand, as suggested by operational practice, the seeding is supposed to be done in front of the main updraft. Therefore, this combination of the maximum radar reflectivity and updraft provided a satisfactory algorithm that tracks only the right-moving cell, enabling the proper seeding.

- Maybe an overview of the seeding within the model grid could be useful to easier understand what is done.

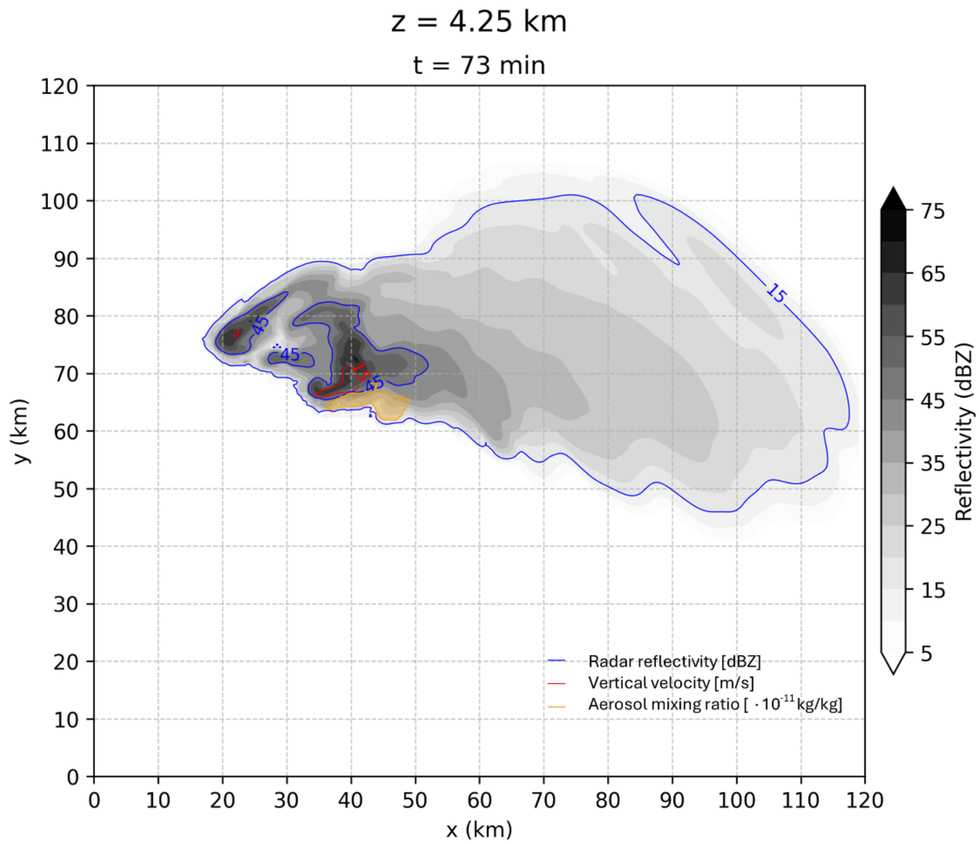

Figure 2. Horizontal cross-section of the radar reflectivity (grey shading). The isolines of radar reflectivity, vertical velocity, and aerosol mixing ratio in the air are depicted in blue, red, and yellow, respectively.

After the procedure explained in the previous bullet is done, the vectors depicted in Figure 1 of the manuscript are constructed, determining the seeding sector. The seeding zone is defined based on the spatial distribution of radar reflectivity and temperature. Specifically, radar reflectivity determines the horizontal extent of the seeding zone, while the temperature determines the vertical extent. Figure 2 (of this document) depicts a horizontal cross-section of the seeding zone (yellow) for a specific seeding cycle, from the model. Vertically, the zone extends from the level of 0 ^{o}C to −10^{o}C.

- Figure 2 has a lot of different time stamps. What is it really? And where was this profile taken? Can not needed and not explained information form this figure be omitted?

The time stamps represent the same moment in time in different formats (local time, UTC, CST). We will change the figure by implementing the single time format to make it easier to read in the revised version. The sounding data was taken at Fort Sill, southeast of Oklahoma City. The exact geographical location is 34^{o} 39.00′ N and 98^{o} 25.12′ W, as indicated in the top right corner of Figure 2 of the manuscript. The figure was generated using a Python-based plotting script, which includes additional variables by default. To the best of our knowledge, there is no option to omit a certain variable.

- Figure 3: I believe the model spun up within 30 min? Is this correct?

The cloud within ARPS model is initialized using a single-column sounding profile. This way, the variables are horizontally uniform in the first time step. Furthermore, the simulation starts without any pre-existing hydrometeors. Unlike simulations nested within larger-scale models, this setup does not involve complex 3D initial conditions and external forcing from lateral boundaries. Spin-up is therefore defined as the time required for the model to develop its own internal circulations and hydrometeor fields from the initial sounding and thermal perturbation. The model's internal dynamic equilibrium is reached relatively quickly. By the time of the first seeding (approximately at t=17 min) a well-defined single cell cloud has already formed with maximum updraft values of 18 ms^{-1}, cloud water mixing ratio 5 gkg^{-1}, and radar reflectivity of 53 dBZ.

Regarding the duration of the spin-up period, we acknowledge that in studies focusing on convective boundary-layer equilibrium, it is common to discard the first 30-60 min of simulation to allow for fully developed turbulence (Guichard and Couvreux, 2017). However, since this study focuses on the operational methodology of cloud seeding, the early developmental stage of the convective cell is of primary interest.

- Line 261: I do not understand the difference in seeding material in the two methods?

In both seeding methods, the seeding material (APs) has identical properties (size distribution, density, nucleation characteristics). The difference lies in the total mass of APs injected. Due to different seeding criteria, the AB23 method results in approximately 40% larger total AP mass compared to the RHSS method.

- Line 271: Why is the strongest signal in cloud droplets?

The most pronounced signal of seeding in cloud droplets arises primarily because cloud droplets represent the most abundant hydrometeor population within the seeding region (i.e., the supercooled liquid water zone). As shown in our previous studies (e.g. Vučković et al., 2025b), APs are mostly scavenged by cloud droplets, under these conditions, while scavenging by other hydrometers is less efficient. On the other hand, the APs are transferred from droplets to other hydrometeor categories by nucleation and other microphysical processes.

- Line 279: A visual representation of the supercooled liquid zone and how the supply in AB23 is lower would be great.

The slower and more gradual supply of APs in AB23 can be easily explained by differences in the seeding volume between the two methods. Although the total injected mass of APs is comparable, the AB23 seeding region extends up to 5 km outside the cloud, which results in a lower initial AP concentration within the cloud volume. In contrast, in RHSS the APs are injected directly into the cloud region containing hydrometeors, leading to higher local concentrations and an immediate onset of scavenging.

In AB23, a portion of the APs is initially located outside the cloud and must first be advected into the cloud before being scavenged. Because the seeding intervals are relatively short (5 and 7 min), not all APs have reached the cloud before the next injection cycle occurs. As a result, the effective in-cloud AP supply is lower but more continuous compared to RHSS.

- Line 327: What is the mechanism behind the conversion of small raindrops to cloud droplets upon seeding? What is happening and why?

In the ARPS model, a three-moment microphysics is employed (Milbrandt and Yau, 2005). This microphysical scheme recognizes the lower limit of raindrops diameter (82 μm), so-called "hump" diameter. Therefore, for the grid box with a mean diameter smaller than this threshold, raindrops mixing ratio and number concentration are converted to cloud droplets. This decrease in the raindrops mean diameter can be caused by evaporation or raindrops breakup.

- Figure 9b: It looks like the process of converting rain to hail is reduced in RHSS, why? How does this relate to that hail in Fig. 6 remains fairly constant? Is there some compensation?

As you noted, conversion processes from rain to hail mass are reduced as a result of seeding. The most significant processes in this case are the collection of raindrops by hail and the melting of hail. Their change due to seeding can be seen in Fig. 19a (manuscript) in purple and light blue, respectively. As we can see from Fig. 19a, the change in these two processes is comparable. In other words, seeding caused a decrease in both rain collection by hail and the melting of hail. The changes in these two processes seem to balance out; therefore, the change in total mass of hail (Fig 6a) is not that pronounced.

- Line 368: What is sorption freezing?

Sorption freezing refers to a condensation-freezing ice nucleation mechanism in which water vapor is first adsorbed onto the surface of an aerosol particle and subsequently freezes without the formation of a bulk liquid droplet. In the revised version of the manuscript, we will replace sorption freezing with condensation-freezing for better understanding.

- Line 506: How can seeding induce a shifting, stretching, and shrinking of the hail mass and number mixing ratios? What does this mean?

By shifting, stretching, and shrinking, we refer to the changes in the spatial distribution of hail mixing ratio and number concentration as a result of seeding-induced modifications in the microphysical and dynamical evolution of the storm. Specifically, seeding alters the rates of growth and conversion processes (e.g., riming and accretion), which leads to changes in the intensity and location of hail production regions. As a result, the maxima of hail mixing ratios are displaced, while the spatial extent of lower-value contours is modified, as shown in Fig. 3 (1 km height) for all experiments.

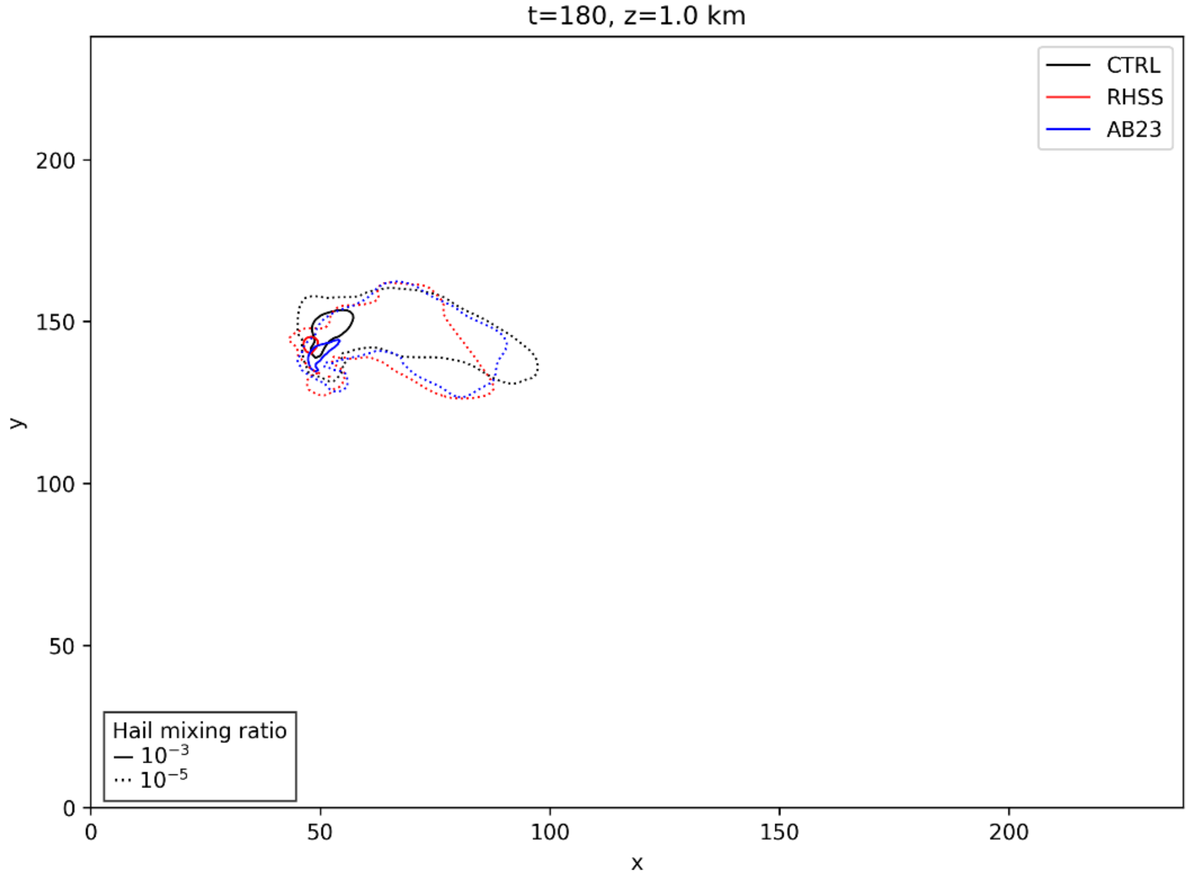

Figure 3. Horizontal cross-section of the hail mixing ratio (kgkg^{-1}). The isolines for CTRL, RHSS, and AB23 are depicted in black, red, and blue, respectively. Contour of mixing ratio of 10^{-3} is depicted in solid lines, while 10^{-5} is depicted in dotted lines. The figure shows the mixing ratio fields at the end of integration (180 min).

- Line 551: the beneficial competition should be mentioned in the introduction.

Thank you for the suggestion. This is implemented in the revised version.

- Discussion section can be combined with the conclusion part.

Thank you for the suggestion. This is implemented in the revised version.

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