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.

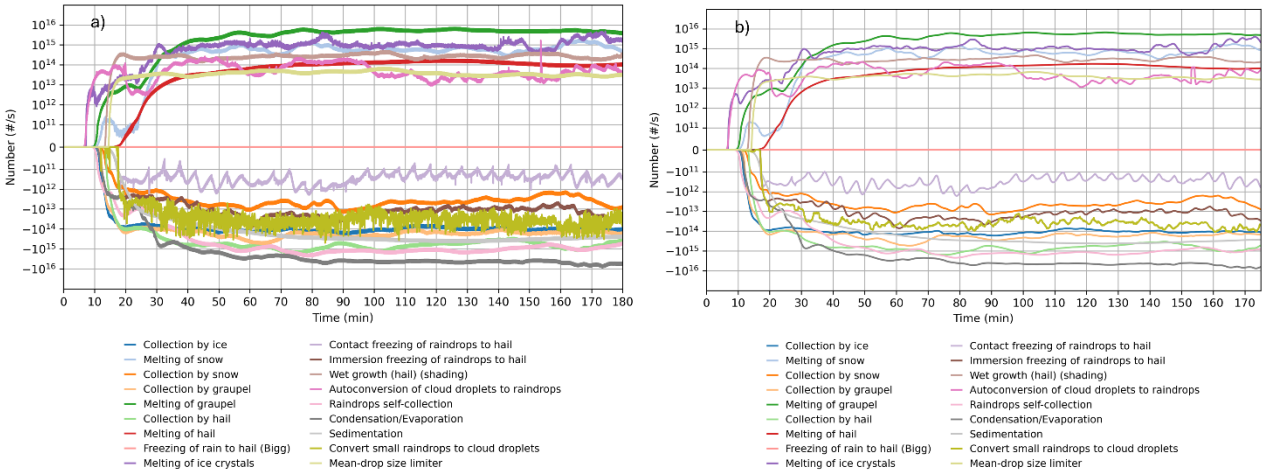


Figure 1. The time series of source/sink terms for the total number of raindrops in the domain for RHSS. Different microphysical processes are depicted with different colors indicated in the figure's legend at the bottom. The model data (a) and their 1-minute averages (b) are depicted.

- 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.

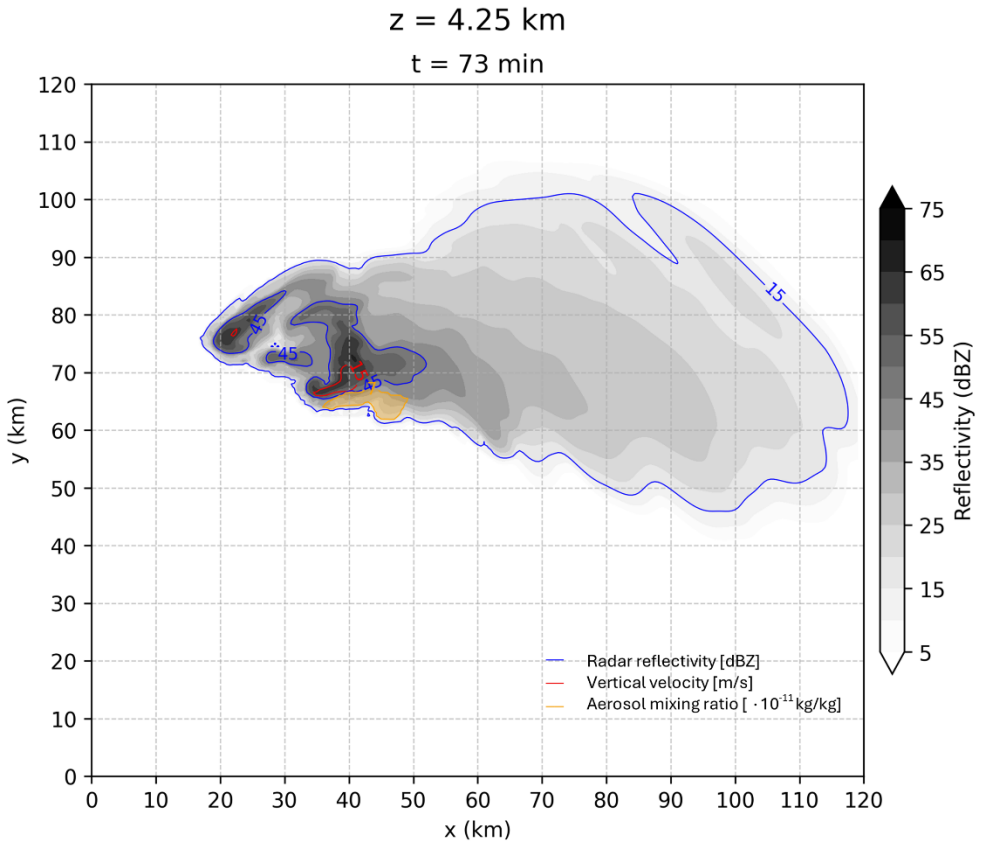


Figure 2. Horizontal cross-section of the radar reflectivity (grey shading). The isolines of radar reflectivity, vertical velocity, and aerosol mixing ratio in the air are depicted in blue, red, and yellow, respectively.

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.

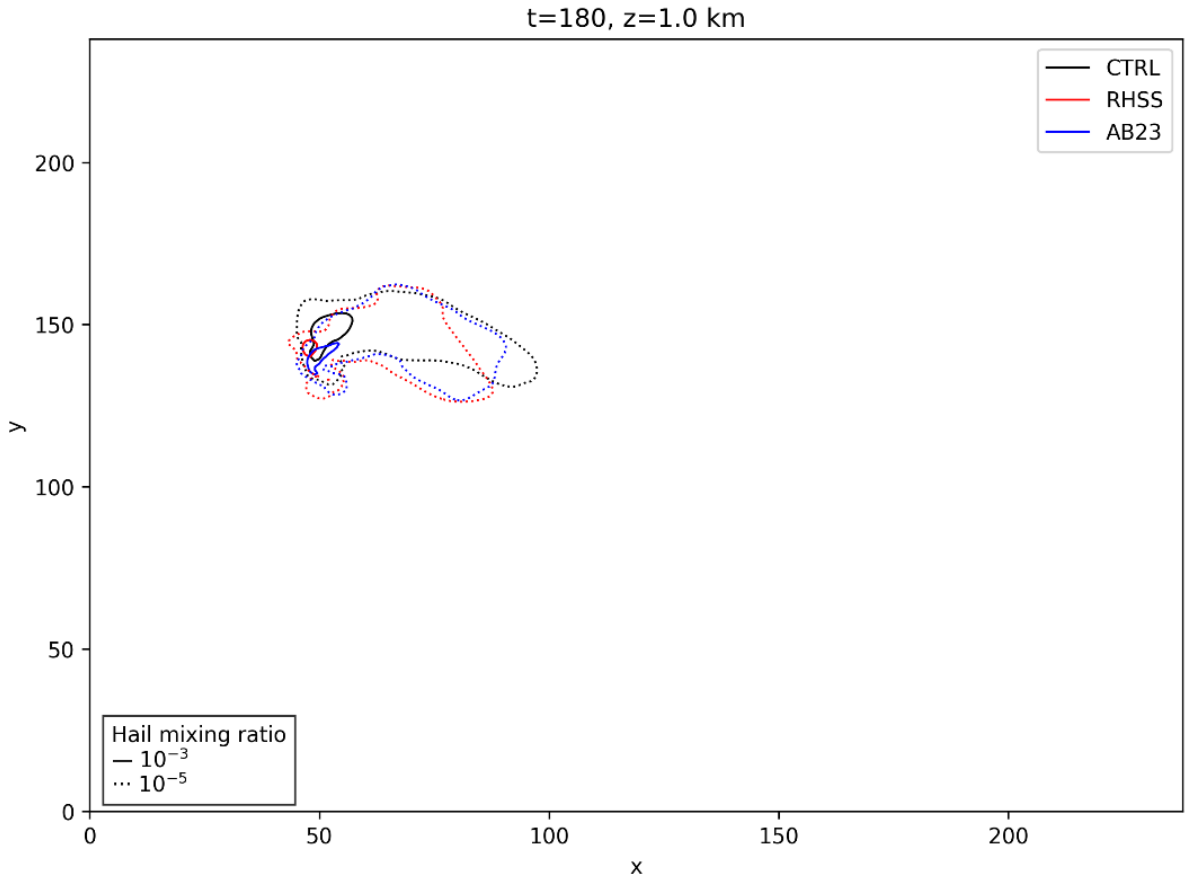


Figure 3. Horizontal cross-section of the hail mixing ratio ($kgkg^{-1}$). The isolines for CTRL, RHSS, and AB23 are depicted in black, red, and blue, respectively. Contour of mixing ratio of 10^{-3} is depicted in solid lines, while 10^{-5} is depicted in dotted lines. The figure shows the mixing ratio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

Response to Referee #2

This study investigates the impacts of two cloud-seeding strategies for hail mitigation using a 3D numerical simulation of a supercell storm, employing advanced three-moment microphysics and mostly explicit aerosol representation. Three simulations are performed: a control experiment without seeding and two experiments in which aerosol particles acting as ice nuclei are introduced to emulate the effects of silver iodide seeding. The authors provide a comprehensive analysis of the resulting changes in hydrometeor mass and numbers, as well as the associated microphysical process rates.

The results indicate that both seeding approaches modify hail characteristics, leading to reductions in hail kinetic energy and the surface area exposed to damaging hail. In contrast, the total hail mass and accumulated hail precipitation remain largely unchanged. These findings suggest that the proposed seeding strategies may reduce the damage potential of hail without substantially suppressing hail production itself. Furthermore, the differences between the two seeding approaches are relatively small, implying that the specific seeding strategy may be less important than the overall introduction of ice-nucleating particles.

The paper provides a detailed and generally well-written analysis of the conducted simulations and addresses the highly relevant topic of weather modification. However, the manuscript is overly long in its current form, and the presentation of the results does not always clearly reflect the main findings of the study. In particular, some statements may overemphasize conclusions that are not directly supported by the analyses presented. I therefore recommend that the following major issues be addressed before the manuscript can be considered for publication.

Major comments

- **Conclusions on hail suppression:** Figures 6 and 20 clearly show that neither the total hail mass nor the accumulated hail precipitation changes substantially between the control and the seeding experiments. Is this outcome consistent with the authors' initial hypotheses and the intended objectives of the respective seeding methodologies? Based on the presented results, the primary effect appears to be a reduction in hail size and hail kinetic energy, which could potentially lessen crop damage, rather than a reduction in the overall amount of hail produced. This distinction should be emphasized more clearly throughout the manuscript, particularly in the abstract and conclusions. As currently written, some statements may give the impression that hail suppression was achieved, whereas the results suggest a modification of hail characteristics and associated damage potential rather than a decrease in total hail occurrence or mass.

Regarding the physical results, Fig. 6 shows the time series of the total mass and number of hydrometeor classes in the entire domain using a logarithmic y-axis. On this scale, the increase in the total number of hailstones in the seeding experiments reaches approximately 10% (e.g. at the 110-min mark), which is a non-negligible change. In contrast, the effect of seeding on the total hail mass is less clear, fluctuating between higher and lower values compared with the CTRL experiment. Similarly, the decrease in the total cumulative hail precipitation (Fig. 20) is 26% for RHSS and 14% for the AB23 methodology. These results are consistent with the beneficial competition hypothesis, which asserts that a larger number of smaller hailstones will

be produced, thereby yielding smaller and potentially less damaging hailstones at the surface. In theory, a more numerous population of smaller hailstones should enhance melting during their descent, consequently increasing the total accumulated rainfall. Although we do not observe such an increase in Fig. 20, it is important to note that raindrops and hailstones coexist within the same region of the cloud. By injecting glaciogenic material into this zone, the system is partially deprived of available liquid water, an effect that influences both raindrops and hailstones simultaneously. Explaining the exact mechanisms behind this rainfall decrease requires a more detailed future study of these highly non-linear microphysical interactions.

Furthermore, in the revised version of the manuscript, we have thoroughly edited the text to state clearly that the objective of this weather modification strategy is not necessarily the total elimination of hail mass, but rather the reduction of individual hailstone sizes to mitigate damage potential.

- **Length of the manuscript:** With 23 Figures and a long appendix, the manuscript is quite lengthy. Consider shortening some text and figures. For instance, the difference figures such as Fig,. 19 are hard to read and do not add significant new information. I strongly suggest revising each figure and reevaluating if new information is shown to support the key findings of the paper or which figures are redundant.

The authors agree that the manuscript is lengthy and that shortening it will significantly improve its readability and clarity. Following the recommendations of both referees, we have thoroughly re-evaluated the necessity of each graphic. To address this, we integrated all three experiments into a single figure. This modification allowed us to eliminate the appendix, simplifying the revised manuscript by removing 14 pages and 16 figures in total, while simultaneously facilitating a direct comparison between the two methodologies.

- **Effectiveness for hail crop damage reduction:** A key result highlighted in the abstract is that the study "indicates that both strategies effectively reduce hail-induced crop damage." However, the impact on hail-induced crop damage is not directly investigated in this work. Rather, the potential reduction in crop damage is discussed as part of the rationale for selecting and evaluating the cloud-seeding strategies. To avoid giving readers the impression that crop damage was explicitly assessed, the abstract should clarify that this conclusion is inferred from the intended objectives of the seeding strategies rather than from a direct analysis of hail impacts on agriculture.

We thank Referee #2 for this comment and fully agree that the language should be conservative and precise throughout the manuscript. In the revised version, we have explicitly adapted the Abstract and relevant sections to clarify that we did not investigate crop damage directly, but instead used hail kinetic energy at ground level as a standard physical proxy for crop damage potential.

- **Introduction:** The physical process of how cloud seeding works in the context of hail suppression is not explained clearly. It would be very useful to explain this in the introduction of the paper. In addition, it would be helpful if the authors would state an overall aim and the more specific research questions that are subject of this paper in the introduction.

This is an excellent suggestion. We agree that adding a clear description of the hypothesized microphysical mechanisms, along with their broader effects on cloud properties and products, will significantly enhance the clarity of the study.

In the revised version of the manuscript, we have updated the Introduction to describe in details how glaciogenic seeding functions in the context of hail mitigation. Furthermore, we have clearly explained the overall aim of the study and formulated specific research questions at the end of this section to guide the reader through our scientific objectives.

- **Limitations and implications of this study:** In the context of relevance for policy makers, it seems important to properly indicate the limitations and caveats of this study such that it becomes clear which questions need to be addressed before weather modification technologies like hail suppression can effectively be implemented. I suggest adding a brief discussion of some limitations of this study, including the fact that this study focuses on the effects of a single supercell rather than any effects on a larger surrounding. What could be potential impacts of the analyzed cloud seeding methodologies on weather systems and the environmental air in vicinity to the seeding? Are there potential effects beyond the three hours of the simulation period? How could the results of this study be combined with physical experiments or observational data (e.g. data that related the listed hail properties more to crop damage)? Would it be feasible to conduct similar experiments for a larger domain at a lower horizontal resolution or is the aerosol scheme too computationally expensive for that and not suitable for lower resolutions (e.g. km-scale)? Can the authors think of any other follow up studies that would make these results more generalizable?

The limitations of this approach arise from both numerical constraints and uncertainties, as well as from the fact that this is an idealized case study. These limitations are discussed in detail in the Discussion section.

On the other hand, as rightly pointed out by Referee #2, this study focuses exclusively on the effects of seeding on supercell cloud properties and products, but not on the broader surrounding environment and weather systems. Examining Fig. 4 (of the manuscript), we see that approximately 54% of the total injected AP mass remains uncollected for the RHSS case after 3 h and 65% for the AB23 case. Given this, and the fact that the APs are submicron in size, meaning they have negligible terminal velocities, they are removed from the atmosphere almost exclusively by precipitation (wet deposition). In other words, the uncollected APs, which may represent a significant fraction of the injected mass, can remain in the atmosphere for a long time and inadvertently influence the microphysical processes of other weather systems. These downwind effects of seeding require further investigation. Studies investigating the impact of AgI on either human health or the environment have shown no significant effects on either (WMO, 2025).

Regarding the connection of this study with observational data, there are several possible approaches. The most direct signal could be obtained from radar data. Radar could be used to identify microphysical changes within the seeding zone caused by phase changes and subsequent processes such as particle growth. Radar data, as well as hailpad data, could also be used to verify the model results for hailstone diameter and its spatial distribution. This discussion is included in the revised version of the manuscript.

Although the aerosol scheme is quite computationally expensive, simulations over a larger domain could be performed at a coarser resolution (e.g., kilometer scale) or even at 100 m resolution by utilizing HPC facilities. The current obstacle to applying the relatively complex seeding methodology used in this study to broader and more realistic scenarios is the development of a cloud cell tracking algorithm capable of identifying individual cells, tracking

them, and applying the proposed seeding methodology to each of them separately. As a proof of concept, we previously initialized convection in the ARPS model using output data from the NMMB (Janjic and Black 2007; Janjic 2005) weather prediction model and high-resolution topography, but with much simpler seeding criteria. We plan to improve this approach in future work.

As mentioned before, in this work we investigated the effects of glaciogenic seeding on a single supercell cloud in an idealized environment. The most obvious next step toward making these results more generalizable would be to employ an ensemble modeling approach, such as that described in Papaevangelou et al. (2025). Using the same setup with, for example, 10 ensemble members, ideally for several different soundings, would greatly increase the statistical significance of the results. Our currently available computational resources do not allow us to perform such simulations. As a reference, the three experiments conducted for this study required approximately 30 days to complete. However, access to more powerful computing resources would make this research feasible, and we plan to pursue it in future work.

- **Connecting the results with the respective seeding cycles:** I think it would be very useful to **indicate the seeding cycles in all time series figures** to make better sense of how the aerosol mass changes in each hydrometeor class in response to the seeding. Based on the presented results, do the authors think that timing of the seeding would have a large effect? Given that the two methodologies give similar results, I wonder if a main conclusion of this paper is also that the microphysical effects are not too strongly dependent on when and where the seeding is conducted, as so on as it targets the major convective region of the cloud. Would you agree?

We thank Referee #2 again for the constructive suggestion to include indicators of individual seeding cycles on the time series figures, as this makes it easier to investigate the most direct microphysical signals of seeding. This has been included in the revised version of the manuscript.

To address your point regarding how the timing of seeding affects the overall microphysical dependence on when and where seeding is conducted, we are planning to perform a sensitivity study in the near future. We will vary the location, timing of the cycles, mass of the reagent, etc., to assess the dependence of microphysical hailfall characteristics on these parameters. This, together with the ensemble approach already mentioned, are definitely the next steps in our research.

Based on the present results, the timing, seeding zone, and aerosol concentration appear to play an important role in the overall effectiveness. While both methodologies yield comparable broad trends in terms of general cloud behavior, the quantitative outcomes at the surface differ substantially. For instance, as shown in Fig. 20, the total cumulative hail precipitation decreases by 26% for the RHSS methodology compared with 14% for the AB23 approach. Furthermore, the reduction in hail kinetic energy at the ground (Table 4 of the manuscript) also exhibits a strong dependence on these parameters. This notable discrepancy suggests that the microphysical effects and the resulting damage mitigation potential are likely sensitive to when, where, and with what concentration the seeding is conducted, even if both strategies successfully target the major convective region of the cloud.

Detailed comments

L. 16: Remove "very explicit" because it is a bit subjective and hard to understand what exactly this means. This occurs at multiple locations throughout the manuscript (e.g."highly explicit"). I suggest being more conservative with those words and instead explain how aerosols are treated and how this is different from more conventional aerosol schemes.

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

L. 50: To which extent are the risks associated with field experiments also a reason why numerical simulations are used as the primary tool to investigate cloud seeding effects?

Every method chosen to study a phenomenon has its pros and cons. Although field experiments can provide the most direct answers to unanswered questions regarding cloud seeding, there are several reasons to use numerical models for this purpose.

Replicability: In the field, no two storms are the same, whereas numerical models are the only frameworks that allow these phenomena to be simulated repeatedly (control, seeding, etc.) under the same environmental conditions to study the influence of a specific process. Due to natural variability, field studies require a relatively large number of randomized cloud-seeding events to obtain a statistical signal of cloud seeding. On the other hand, statistical studies rarely explain how cloud seeding affects the microphysical structure of the cloud and the mechanisms of potential precipitation modification; instead, they focus on whether it affects a process and to what extent. Detailed studies that aim to directly measure the impact of glaciogenic material on cloud characteristics are usually very expensive and logistically challenging. Examples of projects that have achieved excellent results in recent years are the SNOWIE (Tessendorf et al., 2019) and CLOUDLAB (Henneberger et al., 2023) projects. However, both of these projects focus on non-convective orographic clouds and, to the best of the authors' knowledge, no similar studies have been conducted for convective clouds.

Financial reasons: Field campaigns involve complex reagent delivery systems such as rocket pads or airplanes, remote measurements (radars, lidars, etc.), as well as in situ measurements (UAVs, radiosondes, dropsondes, airplanes, etc.), all of which are much more expensive than numerical simulations.

Safety and logistical reasons: Any type of observation related to convective clouds brings its own safety concerns and logistical challenges, especially when the aim is to understand fine microphysical processes.

L. 62: Can you clarify whether in this study, the cloud seeding strategy that was simulated was aimed at suppressing rainfall or forcing rainfall? In general, it would be useful to contrast these two concepts (precipitation suppression vs. enhancement) in the introduction and make clear what the difference is in terms of which clouds seeds are chosen.

We thank Referee #2 for bringing this detail to our attention. In this study, we focused exclusively on hail mitigation and the impact of seeding material on hailfall; therefore, precipitation enhancement and suppression are outside the scope of this work. Although the two seeding methods resulted in a slight decrease in the total precipitated mass (Fig. 6 of the manuscript), this decrease was not the primary objective of the simulated methods. Following your suggestion, we added a brief clarification of these different weather modification techniques in the revised version of the manuscript.

L. 80-82: It is not entirely clear how the assessment of hail crop damage relates to cloud seeding. Did Ursu et al. (2025) analyze the impact of hail on crop damage or were they also able to investigate the effectiveness of cloud seeding through this method? If so, how?

In the work of Ursu et al. (2025), the authors calculated hail kinetic energy using radar data and overlaid it on changes in satellite-derived NDVI (the Normalized Difference Vegetation Index), a widely used indicator of vegetation health. They established a threshold of 300 J m^{-2} to delineate potentially affected areas. No cloud seeding was mentioned in this paper, but we used their results as a benchmark for hail-induced crop damage potential.

L. 86-90: I would move this paragraph to the introduction because it still describes the overall scientific challenge that is addressed in this paper.

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

L. 113: Do you mean that you are conducting a storm-following simulation in which the domain moves along with the storm such that the storm center stays in the center of the domain? Please clarify this and consider moving this sentence after the description of the domain setup, since it appears to be unrelated to the sentences before that focus on the aerosol types rather than on the model domain.

Yes, we conducted a storm-following simulation, although we used a very simple method. Due to a strong mid-level wind, the storm was propagating relatively quickly, at about 14 m s^{-1}. For a 3 h simulation, a much larger domain would be needed; therefore, constrained by available computational power, we chose a smaller domain that moves at 14 ms^{-1} due north and 3 ms^{-1} due east so that the storm center (main updraft) remains near the center of the domain. We did not use any algorithms to calculate the storm center but instead estimated the storm movement and simply advected the whole domain in this way.

We also agree with the suggestion to move this sentence after the description of the domain setup, and this will be implemented in the revised version of the manuscript.

L. 116: When are the large and the small timesteps used respectively? Is the used model a model that uses adaptive timesteps?

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.

L. 121: Please add a reference to the sounding if it is a well-known one. In addition, please clarify if the sounding is an artificial one or if this is a sounding from real observations.

To initialize the supercell storm in the ARPS model, we used observed radiosonde data obtained at Ft. Sill, Oklahoma, at 1500 on 20 May 1977. The sounding represents a modified composite constructed from real observations taken at Fort Sill and Elmore City on May 20. 1977. This composite merges the lower-level thermodynamic data from Fort Sill with upper-level data from Elmore City, combined with a smoothed composite hodograph to realistically capture the pre-storm environment. This is now clarified in the revised version of the manuscript. This data is freely available as part of the ARPS model package (https://arps.caps.ou.edu/arpsdown.html). As a reference, we point to the following papers:

Klemp, J. B., Wilhelmson, R. B., and Ray, P. S.: Observed and numerically simulated structure of a mature supercell thunderstorm, J. Atmos. Sci., 38, 1558–1580, 1981

Klemp, J. B. and Rotunno, R.: A study of the tornadic region within a supercell thunderstorm, J. Atmos. Sci., 40, 359–377, 1983.

Brandes, E. A.: Finestructure of the Del City–Edmond tornadic mesocirculation, Mon. Weather Rev., 109, 635–647, 1981.

L. 136: Please explain the term "beneficial competition".

The term “beneficial competition” refers to the hypothesis that introducing a large number of INs into a hail embryo formation zone (EFZ) will produce more numerous hailstones, which compete for the available supercooled water and ultimately grow to smaller sizes (American Society of Civil Engineers, 2015; Abshaev et al., 2006; Papaevangelou, 2025). The explanation is implemented in the revised manuscript.

L. 211: Why is a northward movement anomalous?

Since Referee #1 raised a similar point, we provide a consistent explanation below:

As illustrated in the hodograph (right panel in Fig. 2) and indicated by the arrow, this specific supercell propagated almost directly northward. In the Northern Hemisphere, these types of convective storms typically move from west to east; therefore, the term “anomalous” specifically refers to this atypical storm-motion direction.

Standard operational guidelines for both seeding methodologies determine the location of the seeding zone based on the assumption that supercells move eastward, with the primary inflow layer located on their southern flank. Consequently, both operational manuals specify that seeding should be conducted on the right side relative to the storm’s direction of motion. If these manual guidelines were followed strictly for the simulated storm, seeding would be incorrectly executed on the eastern side of the system, completely missing the actual hail embryo formation zone (EFZ).

L. 211-213: I am slightly confused by the identification of the seeding zone. From the method description, it seemed that both cloud seeding methodologies have specified criteria to identify the seeding zone. So why do the authors choose to further restrict this to the main updraft region in the cloud? Or in other words, would the criteria listed in tables 2 and 3 not automatically result in a seeding zone close to the maximum updraft?

The criteria listed in Tables 2 and 3 represent threshold values for the start of seeding and a way to determine the intensity/type of convective cloud. The manuals for both methods contain instructions that serve more as general guidelines for a radar operator than strict rules for determining seeding zone boundaries. With respect to the location (Fig. 1 of the manuscript) of the zone, radar reflectivity provides radial boundaries for the seeding zone (45 and 15 dBZ for RHSS, and 35 and 1 dBZ for AB23). On the other hand, no azimuthal boundaries are strictly specified. Without further restrictions of criteria, for a developed cloud, seeding is performed far away from the main updraft (still within radar reflectivity thresholds), which is clearly

outside EFZ. For this reason, we decided to restrict seeding to within 10 km of the main updraft. Figure 4 of this document shows that without this restriction the seeding zone would expand much farther to the east (x = 115 km).

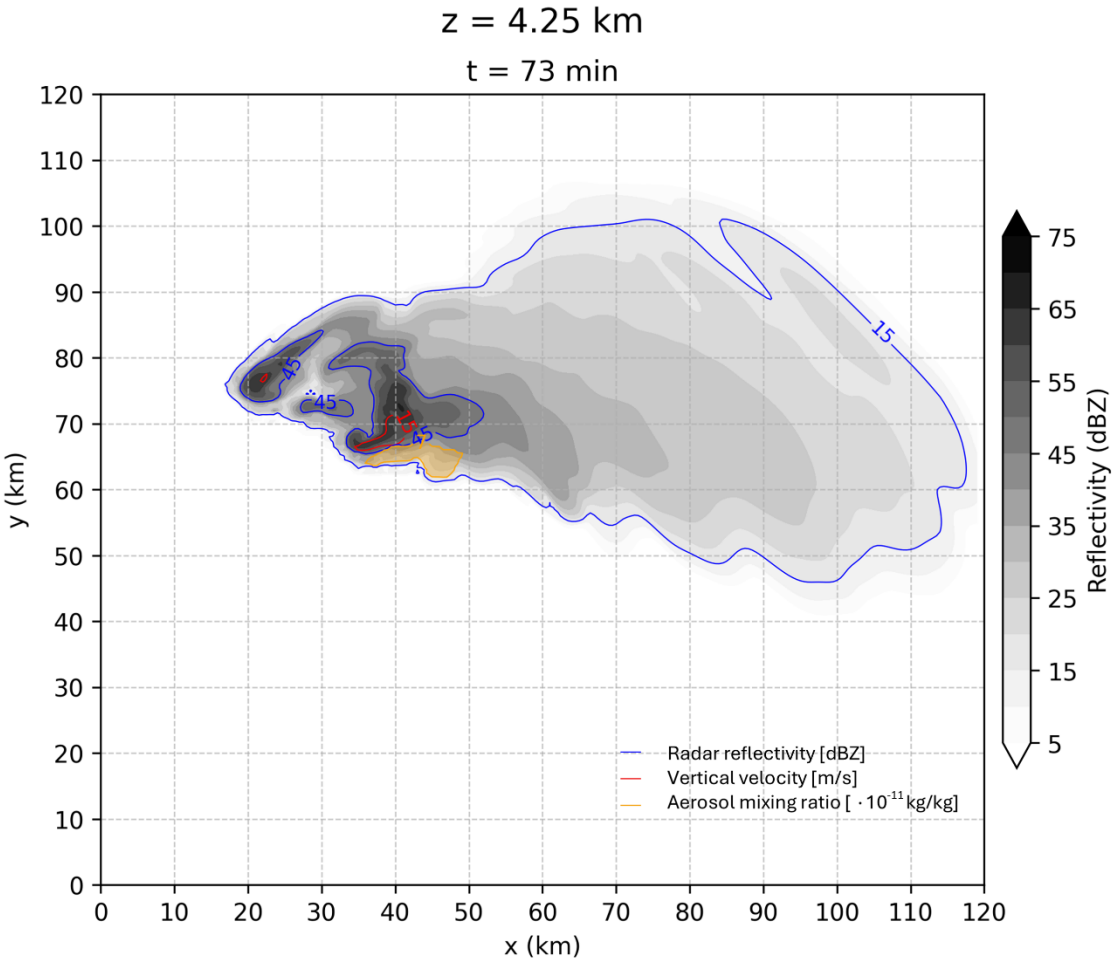


Figure 4. Horizontal cross-section of the radar reflectivity (grey shading). The isolines of radar reflectivity, vertical velocity, and aerosol mixing ratio in the air are depicted in blue, red, and yellow, respectively.

L. 224-245 and Fig. 2: Consider moving this paragraph and figure to the method section because this explains the chosen sounding to initiate the supercell rather than presenting results that are relevant for the cloud seeding related science questions.

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

L. 264: In l. 113, it was indicated that the model domain moves along with the storm. Does the anvil grow so large that it leaves the domain nevertheless?

Yes, this is correct. Although the moving domain successfully keeps the main updraft and primary precipitation region near the center, the anvil grows significantly due to strong upper-level winds and begins to exit the domain boundaries around the 1-hour mark. However, this part of the cloud is not relevant to the formation of hail embryos or the resulting hailfall characteristics; therefore, its impact on the main conclusions of this work is negligible.

L. 291: What does this imply? Would a higher aerosol number in the non-precipitating hydrometeor classes mean that one of the methods is more effective because that is what you want to achieve?

We thank the Referee for drawing attention to this important detail. First, this behavior arises because smaller aerosol particles (APs) are collected more efficiently than larger ones due to Brownian diffusion and electrostatic scavenging (Vučković et al., 2025b). Consequently, this leads to a more pronounced difference between the two methodologies in terms of the total number of collected APs compared to their total mass. However, a higher aerosol number within non-precipitating hydrometeor classes does not automatically guarantee a more effective hail mitigation strategy. Whether a collected AP will successfully activate as an ice nucleus (IN) and initiate the ice phase depends heavily on local temperature, supersaturation, and its specific diameter. By examining Figs. 4 and 5 alone, we cannot fully trace the dynamic trajectories and microphysical pathways of these aerosols to determine their ultimate impact on the storm. For instance, if an aerosol is scavenged by an ice crystal and rapidly advected to a higher altitude, it is effectively 'lost' for hail mitigation purposes, as it cannot activate as a fresh IN. Conversely, an aerosol collected by a cloud droplet that subsequently freezes and acts as an artificial embryo directly supports the seeding objective. Figs. 4 and 5 cannot distinguish between these two scenarios, much less the numerous other complex pathways that APs might follow. Since the two simulated methodologies utilize completely different seeding zones, the transport and routing of APs differ significantly. For this reason, we argue that the aerosol number concentration in non-precipitating hydrometeor classes cannot serve as a standalone indicator of seeding effectiveness.

Instead, true effectiveness is determined by the complex interplay between the spatial-temporal delivery of APs and their resulting concentration in the EFZ. For example, while the direct injection in the RHSS method provides high local AP concentrations that trigger aggressive competition and reduce domain-wide total kinetic energy, the broader, continuous seeding in the AB23 method may be better to prevent "missed windows" in seeding. Consequently, AB23 achieves a more pronounced reduction in areas exposed to highest kinetic energy. Ultimately, this suggests that while AP concentration dictates the overall energy suppression, a steady, well-timed supply is critical for mitigating the most destructive, large-diameter hail events. This disscusion is added to revised menuscript.

L. 305: remove: “due to the large number of figures”

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

Fig. 6: Water vapor is shown in the figure but not mentioned in the text. Why is the total water vapor of the domain constant throughout time? Should that not vary as hydrometeors form? Also, what is the cyan line: total of all hydrometeors? Why is that line constant when most hydrometeors vary over two orders of magnitude throughout the lifetime of the supercell?

First, the cyan line in Fig. 6a represents the total water mass in the domain (all hydrometeors plus water vapor). It may appear that these two lines do not change over time because the y-axis is logarithmic, so changes at higher values are less apparent. In Fig. 5 of this document, a linear y-axis is used for the mass of hydrometeors (black line) and total water mass (cyan line).

Both the formation of hydrometeors and vapor advection through the domain boundaries affect the total mass of water vapor.

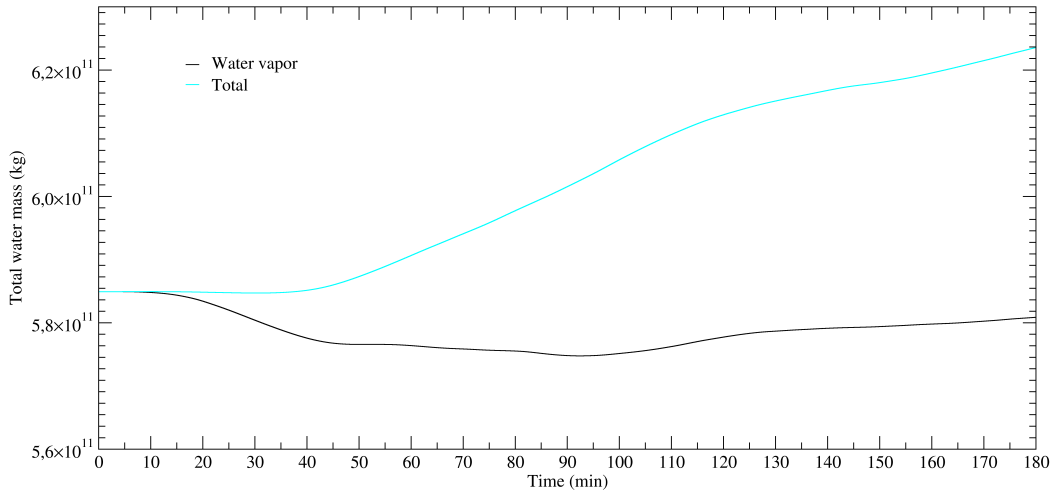


Figure 5. The time series of the total water mass (cyan) and water vapor mass (black) in the entire domain for the CTRL experiment.

References:

Abshaev, M. T., A. M. Abshaev, G. K. Sulakvelidze, I. I. Burtsev, L. M. Fedchenko, B. K. Kuznetsov, A. M. Malkarova, P. A. Nesmeyanov, I. N. Shakirov, and G. F. Shevela. "Development of rocket and artillery technology of hail suppression." *Book of Achievements in Weather Modification». UAE: Abu Dhabi* (2006): 109-127.

Andronache, C.: Diffusion and electric charge contributions to below-cloud wet removal of atmospheric ultrafine aerosol particles. J. Aerosol Sci. 35 (12):1467–82. doi: 10.1016/S0021-8502(04)00290-3 ,2004.

Brandes, E. A.: Finestructure of the Del City–Edmond tornadic mesocirculation, Mon. Weather Rev., 109, 635–647, 1981.

Bryan, G. H., Wyngaard, J. C., & Fritsch, J. M.: Resolution requirements for the simulation of deep moist convection, Monthly Weather Review, *131*(10), 2394-2416, 2003.

DeMott, P. J.: Quantitative descriptions of ice formation mechanisms of silver iodide-type aerosols, Atmos. Res., 38, 63–99, https://doi.org/10.1016/0169-8095(94)00088-U, 1995.

Guichard, F., & Couvreux, F.: A short review of numerical cloud-resolving models. *Tellus A: Dynamic Meteorology and Oceanography*, *69*(1). https://doi.org/10.1080/16000870.2017.1373578, 2017

Henneberger, Jan, Fabiola Ramelli, Robert Spirig, Nadja Omanovic, Anna J. Miller, Christopher Fuchs, Huiying Zhang et al. "Seeding of supercooled low stratus clouds with a UAV to study microphysical ice processes: An introduction to the CLOUDLAB project." *Bulletin of the American Meteorological Society* 104, no. 11 (2023): E1962-E1979.

Janjic, Z. 2005. A Unified Model Approach from Meso to Global Scales. Geophysical Research abstracts 7:24–29.

Janjic, Z, and T L Black. 2007. An ESMF Unified Model for a Broad Range of Spatial and Temporal Scales. Geophysical Research Abstracts 9:2007.

Klemp, J. B., Wilhelmson, R. B., and Ray, P. S.: Observed and numerically simulated structure of a mature supercell thunderstorm, J. Atmos. Sci., 38, 1558–1580, 1981

Klemp, J. B. and Rotunno, R.: A study of the tornadic region within a supercell thunderstorm, J. Atmos. Sci., 40, 359–377, 1983.

Meyers, M.P., DeMott, P.J., Cotton, W.R.: A comparison of seeded and nonseeded orographic cloud simulations with an explicit cloud model. J. Appl. Meteorol. 34, 834–846. http://www.jstor.org/stable/26187222. 1995.

Milbrandt, J. A. and Yau, M. K.: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description, J. Atmos. Sci., 62, 3065–3081, https://doi.org/10.1175/JAS3535., 2005

Papaevangelou, N., Villanueva, D., Eirund, G. K., Chen, J., Dedekind, Z., and Lohmann, U.: Simulations of selective seeding of hailstorms—A summertime case study over Switzerland, J. Appl. Meteorol. Climatol., 64, 1509–1524, 2025.

Papaevangelou, N., Villanueva, D., and Lohmann, U.: Impact of cloud seeding on simulated hailstorms and its dependence on CAPE, wind shear, and tracking thresholds, EGUsphere [preprint], https://doi.org/10.5194/egusphere-20256348, 2026.

Tessendorf, Sarah A., Jeffrey R. French, Katja Friedrich, Bart Geerts, Robert M. Rauber, Roy M. Rasmussen, Lulin Xue et al. "A transformational approach to winter orographic weather modification research: The SNOWIE project." *Bulletin of the American Meteorological Society* 100, no. 1 (2019): 71-92.

Ursu, A., Istrate, V., Jitariu, V., and Lazăr, I. L.: Hail damage detection: Integrating Sentinel-2 images with weather radar hail kinetic energy, Remote Sens., 17, 3850, https://doi.org/10.3390/rs17233850, 2025.

Vučković, V., Vujović, D., and Savić, D.: Influence of electrostatic collection on scavenging of submicron-sized aerosols by cloud droplets and raindrops, Aerosol https://doi.org/10.1080/02786826.2023.2251551, 2023.

Vučković, V., Vujović, D., Savić, D., and Filipović, L.: Impact of electro-collection and ice nucleation on aerosol scavenging, Aerosol Sci. Technol., 59, 1006–1026, 2025a.

Vučković, V., Vujović, D., Savić, D., and Filipović, L.: The effect of electrocollection by ice hydrometeors on the scavenging of submicron-sized aerosol particles, Atmosphere, 16, 1265, https://doi.org/10.3390/atmos16111265, 2025b.

Wang, X., L. Zhang, and M. D. Moran.: Uncertainty assessment of current size-resolved parameterizations for below-cloud particle scavenging by rain. Atmos. Chem. Phys. 10 (12):5685–705. doi: 10.5194/acp-10-5685-2010, 2010.

World Meteorological Organization: WMO statement on weather modification, https://wmo.int/content/wmo-statementweather-modification, last access: 6 July 2026, 2025.