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 #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 1 of this document shows that without this restriction the seeding zone would expand much farther to the east (x = 115 km).

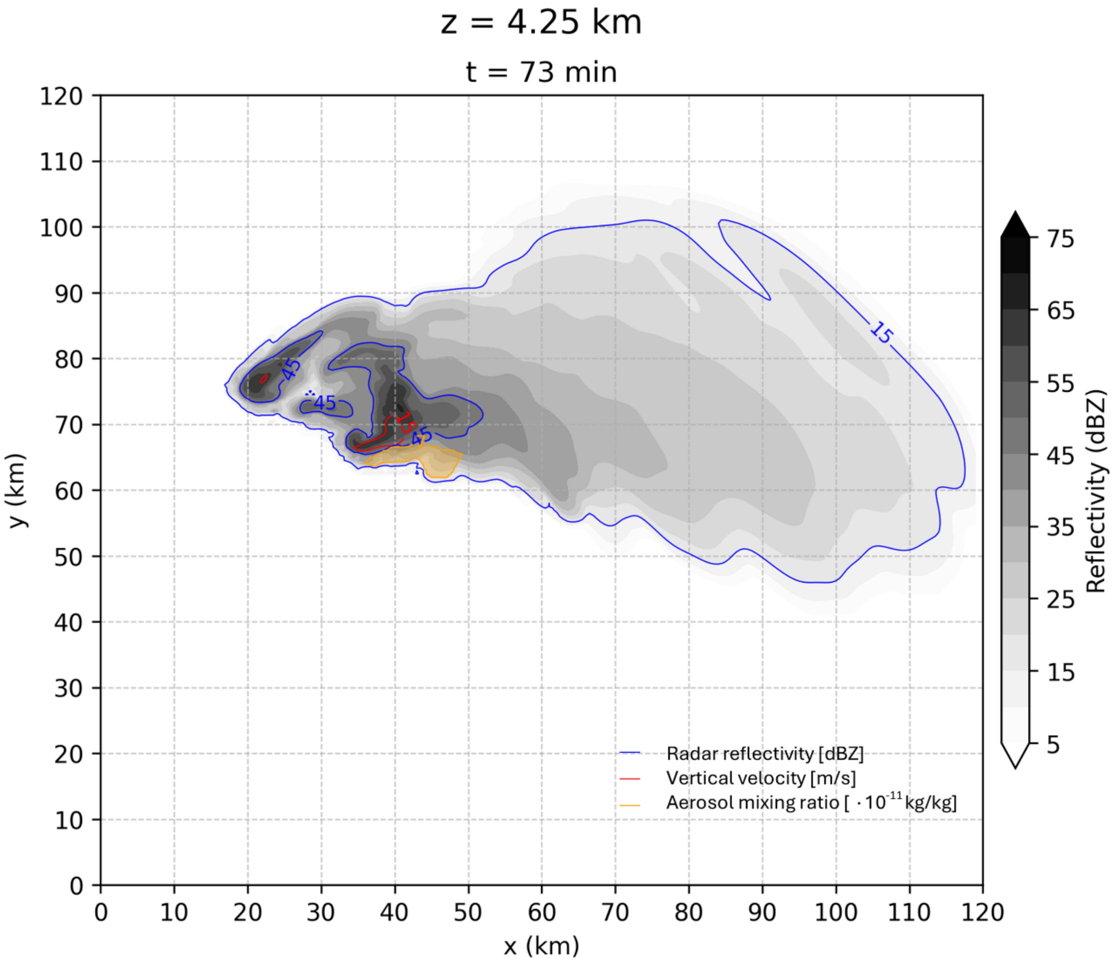

Figure 1. Horizontal cross-section of the radar reflectivity (grey shading). The isolines of radar reflectivity, vertical velocity, and aerosol mixing ratio in the air are depicted in blue, red, and yellow, respectively.

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. 2 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.

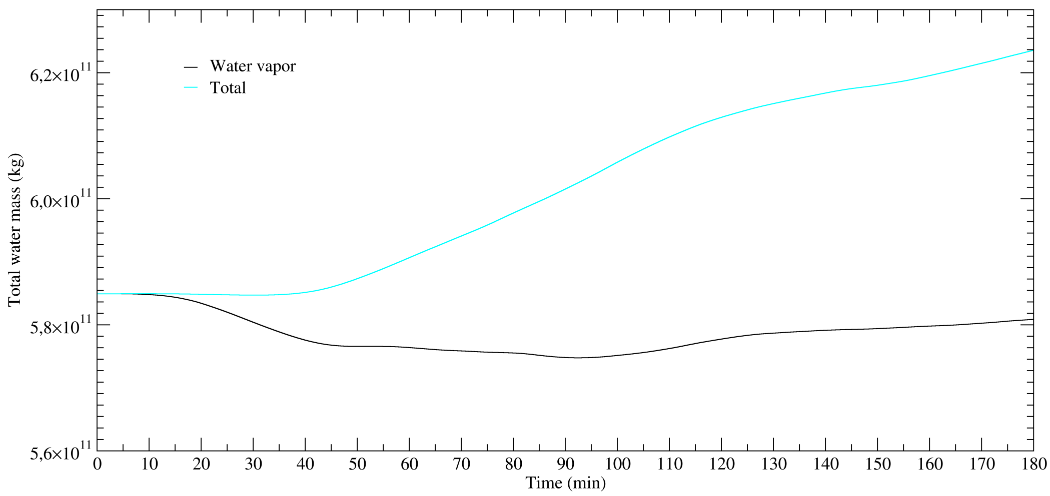

Figure 2. The time series of the total water mass (cyan) and water vapor mass (black) in the entire domain for the CTRL experiment.

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