Review for "Cloud environment controls the precipitation response to liquid propane (LP) seeding: an ice nucleation parameterization for LP seeding and idealized simulations " by Chen et al., EGUSphere

Summary

This study presents a comprehensive analysis of liquid propane (LP) acting as a cloud seeding agent. The authors implement two ice-forming parameterizations based on laboratory experiments for LP and evaluate LP's precipitation enhancement efficiency in an idealized 2D modeling framework using WRF. The simulations vary in their topography (two idealized mountain heights), environmental conditions (adapted input sounding profiles) and seeding rates. Across all simulations it became apparent that the environmental conditions control the precipitation enhancement, in the simulations associated with an increase except for the case of warmer environment. The highest efficiency is achieved for high availabilities of supercooled liquid water and low natural precipitation production.

The authors identified a research gap, that with increasing efforts to increase precipitation becomes more urgent to investigate. The manuscript provides an important step to close this gap. The manuscript is well-written and logically constructed, but I have several comments that should be addressed before it can be considered for publication.

Major comments

- **Precise language:** I marked below where the authors remain ambiguous or imprecise in their language describing and interpreting their results. I recommend to amend this because it impedes the understandability and interpretation of the manuscript difficult. I might have missed more instances of this, so I caution the authors to double-check their descriptions and interpretations.
- **Comparison to AgI:** LP should have the advantage of producing ice crystals at temperatures closer to 0 °C making it complementary to AgI, as the authors note; however, a direct comparison is missing and I would suggest that the authors set up a corresponding AgI case study to have a direct comparison (at least for a subset of the simulations). Or they find a different also quantitative way of comparing the two seeding agents. Given that Xue et al., 2013a,b conducted the study for 2D and 3D, I would appreciate a discussion on what the expected changes are performing 3D simulations compared to the here conducted 2D simulations (e.g., dispersion of LP, ...).

Minor comments

- Line 14ff: Can you quantify the height of the mountain also in the abstract, because high and low are quite ambiguous. Along the same lines, how much is a 'mild' reduction and how do you quantify 'most efficient.'
- Line 16: "Snow enhancement dominates the net total precipitation increase", is this true for both cases?
- Line 26: "cloud temperatures" to "temperatures" because it is clear that the SLW is within the cloud.
- Line 29: Can you be more quantitative with regard to AgI being "relatively inefficient at the warmer end of this range". What do you classify as warmer end? I think it would be beneficial to show comparable freezing curves of AgI to LP. A reference missing is Miller et al., 2025, ACP. The notion of "relatively warm environments" is repeated in the same sentence, and should be defined. I would also like to see a clear definition in Line 60, because up to now it remains fairly ambiguous.
- Line 32: Do you have a reference for the high production of ice crystals from LP as well as for the California and Utah studies?
- Line 37: This imprecise term of high ice crystal number concentration is used again here, where at least some number should be given. Also for "liquefied propane" the introduced abbreviation of LP should be used.
- Line 38: What are the habits of the rapidly frozen cloud droplets? Initially they will be spheres, but immediately grow to their shape given the temperature and ice supersaturation. What is here the surprising finding? A similar finding is reported in Line 58. What ice crystal habit is expected?
- Line 41: "the release of LP as a fine mist causes rapid vaporization" is a repetition of the sentence in Line 31.
- Line 45: I am not sure if I would say that -40 °C is well below homogeneous freezing of -38 °C. Do only cloud droplets freeze or would also solution droplets freeze?

- Line 46: Marcolli et al., 2016 (and Miller et al., 2025) shows that the freezing temperature of AgI goes up to $-5\,°\mathrm{C}$.
- Line 72: What do the authors refer to with "warmer climates"? Is it regions with warmer climates, again in what sense? Or is it a future state? Also I am missing here references to these increased activities.
- Line 72: I also believe the manuscript would benefit from a clear (short) description on the microphysical pathway of cloud seeding, which will also make the phrase "winter precipitation" clearer. Currently, throughout the manuscript, these terms are used without much explanation.
- Line 83: Please also cite work outside of your research group, as there have been numerous studies investigating cloud seeding as a form of precipitation enhancement.
- Line 95: The last sentence of the introduction is repetitive (to the sentence in Line 89) and not needed.
- Section 2.1 Model configuration: are there any spin-up effects in this 2D setup? How is the turbulence parameterized if the PBL scheme is turned off? Am I correct in understanding the cloud microphysics scheme is more like a 1.5 moment scheme, with ice and rain being the only ones with prognostic number tracers?
- Line 114: The analysis region does not only include the downstream region down from the generator? How was this region chosen? Similarly, how was the investigated time window chosen?
- Figure 1: I am assuming that the advection comes from the left side of the figure/mountain. Maybe an additional remark (and arrow in the figure) could help.
- Line 123: "silver iodide" was already used by its acronym.
- Line 128: instead of introducing the two laboratory studies in the introduction, I would do it here (as it is now, and remove it in the introduction).
- Line 132: With the temperature expression in the equation, temperature finally enters with °C into the equation. Is this correct?
- Figure 2: I believe for the discussion on the efficacy of LP a comparison of AgI freezing parameterization should be done.
- Line 169: How were the $6\,\mathrm{gallons}\,\mathrm{h}^{-1}$ defined?
- Line 179: What is the threshold to define the subfreezing cells?
- Line 183: Why is the time at $14\,\mathrm{h}$ chosen? Especially, given that the first figure in Section 3.1 shows a timestep at $12.5\,\mathrm{h}$, i.e., right at the end of seeding. What time step is chosen for the computed values in Table 2? Is there a reason why precipitation is not given as a rate, such as $\mathrm{mm}\,\mathrm{h}^{-1}$ but only in mm?
- Line 184: Precipitation volume is defined via the rain category in the microphysics scheme? I would say precipitation enhancement is best characterized by the precipitation reaching the ground, or is there a better reason to use the volume? This is not sufficiently well justified in the text.
- Figure 4: Instead of using the naming convention of the model variables (e.g., qcloud, qice), it could be more reader-friendly to just define them as cloud mixing ratio, etc. Am I correct in seeing no graupel contour lines in the figure? I am wondering if a quantitative table (or direct reference in the manuscript) would help because the single quantities are quite hard to distinguish in the figure. To increase visibility, the vertical axis could be cut at $2500\,\mathrm{m}$ while keeping the same figure size.
- Line 209: what does the numerical value of $7.3 \times 10^3\,\mathrm{m}^3$ correspond to? And in table the relative change is $0.22\,\%$ and not $0.3\,\%$?
- Line 211: "produce" to "produceS"
- Line 217: I believe to have a better understanding of the impact of different environmental temperatures, values of temperature and SLW at the height of the generator should be given. Currently, the reader needs to rely on the vague description of warmer seeding temperatures without having a feeling of how much warmer that is. The temperatures can be qualitatively read from Figure 4, but a table would be useful here. This way, the efficiency of LP could be better understood. Moreover, an estimate number concentration based on AgI freezing could be given to provide more arguments why LP is more efficient at "warmer" temperatures.

- Line 219: “unseeded precipitation response” is the natural precipitation? I would recommend to keep the same phrase for consistency and clarity.
- Line 220: Is this the same information as in Line 208? To be consistent with Table 2, the ‘relative response’ should be called ‘relative impact’?
- Figure 10: I have difficulties in fully interpreting the volumetric values. This is connected to my comment to Line 184. Why was the volume chosen and not a more intuitive quantity?
- Table 2: Why are the efficiencies of the doubled seeding concentrations consistently lower than for the 1x seeding concentration? This is also in contradiction to Sect. 3.4.
- Line 233: Did the authors expect a spatially uniform increase in precipitation? If so, why?
- Line 235: Total enhancement over what time? From Figure 6 I actually need to do the integration to find that the largest enhancement came from Cold and Dry. Here again numerical values would help, unless these are the values used in Table 2.
- Figure 6: I find it difficult to read this figure and I was wondering if a bar plot showing the different contributions could be more helpful because, e.g., in the Default case the lines for CTRL and SEED overlap. Also the marker for the position of the generator is barely visible and should be plotted on top of the axis (and not cut off). If the authors want to stick with the current presentation, please use clearer markings and differentiation points. Also please avoid the combination of red and green for color-vision-deficiency friendliness (this goes for all upcoming figures). Also this figure could either be combined with Figure 7 for direct comparison or to the difference plot, Figure 8. Or even all figures from 6 to 9 could be combined into one for easier comparison. Figure 7 could benefit from a log scale, because the terms from rain and snow are so dominant, that the graupel contribution is barely visible.
- Line 263: What is a “mild” reduction?
- Line 264: I do not believe the authors can draw any conclusions about “detailed microphysical causes” because no process rates are shown. Or what is understood by these detailed microphysical causes?
- Line 266: “Natural rain development” should be natural precipitation?
- Line 267: Where is the efficient graupel enhancement visible? How is it efficient?
- Line 270: the sentence starting from “... because the ice generated by” does not make sense to me. Why would the ice fall out if graupel forms? What is the mechanism here? Also the following sentence is not logical to me. Could the authors please clarify?
- Line 275: “Due to snow falls...” I do not understand this. In Figure 9 the changes in snow and graupel are not so strongly separated in space.
- Line 278: “predominant” to dominated?
- Line 286: Is aggregation truly a fast response timescale? It requires a certain size of ice crystals and also then the snow falls down less quickly than rain, for example.
- Line 287: The lagged response in rain and graupel is not surprising given that it takes time for the cloud to form these hydrometeors. I am wondering here, if the separation of ice and snow in the cloud microphysics scheme has an impact on the discussion of the results. Thinking of snow, rain, and graupel as sedimenting particles, all of them need time to grow, so why is the snow production so much faster? Is it truly the aggregation only?
- Line 291: what is an “efficient-rain environment”? also in Line 297 and Line 339
- Line 297: Is it a redistribution of precipitation? Why did you assume it was a numerical artifact?
- Line 300: What is the mechanism of snow production to compensate local rain reduction? Where does the water go?
- Line 302: I am not sure that I understand the sentence for doubling the LP rate. In Table 2 all values are slightly smaller than for 1x seeding. What is the reason for this?

- Line 305: Does the scaling rule not hold for the Warm case because the parameterizations are ill-defined at these temperatures? Here the seeding temperature would be helpful. Where actually does the temperature dependence in the measurements come from?
- Figure 11: please do not use yellow in the figures and avoid red and green, as mentioned above. The figure could also benefit from row titles.
- Line 346: Are HV73 and K82 the only laboratory measurements of LP? The authors argue that this is a practical range, but I am not sure this is fully valid, because if it is the only two measurements, than this is just given.
- Line 260: In what way would it help to have a size distribution representation in the parameterization? For homogeneous freezing this should not matter?
- Line 369: Any reference to the Idaho Liquid Propane Experiment?
- Line 371: Why does the parameterization need to be refined with respect to aggregation, riming, and fallout? After ice nucleation, the cloud microphysical processes in the microphysics scheme should take care of that?