Title: Estimating the concentration of silver iodide needed to detect unambiguous signatures of glaciogenic cloud seeding

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Recommendation: Accept with major revisions

Yang et al. (2024) examines the optimal AgI concentrations for cloud seeding to produce detectable radar signatures in mixed phase stratiform clouds. Using a 1D ice growth model with an AgI nucleation parameterization, the authors conducted 1000 simulations to explore how factors like temperature, pressure, and seeding height influence the reflectivity response/detectability. Findings indicate that seeding is most effective around -15°C, which requires the least AgI for detectable signatures, while seeding at colder or warmer temperatures demands higher concentrations of supercooled water for the same response. Although the 1D model captures key ice growth characteristics, it simplifies cloud dynamics and assumes uniform conditions, limiting applicability. Comparisons with 3D LES simulations highlight these limitations near the seeding level. The parameterization offers a tool for estimating poretnail airborne AgI seeding contribution but is less applicable to ground based seeding which is more dependent on different dispersion mechanisms. Although I think the manuscript is novel in showing optimal conditions for the detectability of seeding given varying seeding material amounts and is well written with few grammatical errors, I do have several suggestions that would help improve the quality of the manuscript.

General Comments:

The paper needs to clearly specify the vertical temperature profile used throughout the study and how this profile relates to the assumed background liquid water content (LWC). The background LWC in the analysis is estimated by assuming an adiabatic cloud, but the details of this assumption are not fully explained. I suggest including a figure showing the temperature profile and corresponding LWC for all 1D simulations earlier in the study to help the reader understand the background conditions and the baseline environment in which the seeding effects are modeled.

Clouds in real-world conditions rarely exhibit perfectly adiabatic liquid water content profiles. It is important for the authors to clearly state that the assumption of an adiabatic profile represents a theoretical upper limit of liquid water content available for seeding. If clouds contain less supercooled liquid water, it is likely that more AgI would be required to achieve comparable seeding effects. To address this, the paper would benefit from a brief sensitivity analysis that explores how variations in background SLW content impact the amount of AgI needed to produce similar reflectivity enhancements. Such an analysis would provide a more realistic comparison and better represent the variability found in natural cloud conditions.

The study assumes that all clouds examined were initially composed entirely of supercooled liquid water with no background ice crystals. This assumption significantly impacts the interpretation of the seeding effects, as introducing ice crystals in an ice-free environment is likely to produce substantial changes in reflectivity and ice water content. In natural mixed-phase clouds, where ice crystals already exist, the reflectivity changes resulting from seeding may be much more subtle due to the higher baseline of ice content. Therefore, the large reflectivity increases reported in this study could be partially attributed to the idealized initial conditions rather than the inherent efficacy of seeding under more typical, mixed-phase cloud conditions. This raises questions about the generalizability of the findings to real-world scenarios, where the presence of natural ice would likely diminish the detectability of the seeding signature. The authors need to explicitly state this assumption especially in the abstract and conclusions and add a statement at the end on its implications for the interpretation of their results. This is especially true for Section four, where the study attempts to translate the impact of adding additional AgI in a completely supercooled cloud to scenarios with background natural IWC and likely (but unknown) variable supercooled liquid water conditions. The authors need to explicitly state their justification at the beginning of the section (there is some justification at the end) on why they can make this translation to clouds with natural background ice populations.

The paper's conclusions heavily rely on a single comparison with 3D LES data, which raises concerns about the robustness and generalizability of the findings in Sec. 3.2. The 1D simulations appear to involve seeding in a deeper orographic cloud (up to 6 km) over several kilometers, whereas the LES comparison is conducted on a much shallower stratiform cloud, only about 600 m thick, at a single temperature. This discrepancy in cloud depth and structure between the 1D and 3D simulations could significantly influence the modeled seeding effects, particularly in terms of ice growth dynamics, particle fall speeds, and reflectivity changes. Additionally, the thermodynamic environments likely differ between the 1D model runs and the LES simulation, including variations in temperature, moisture profiles, and turbulence intensity, which are critical factors influencing ice nucleation and growth. Without a detailed comparison of these environmental differences, the validity of using the LES as a representative or benchmark for the 1D results is questionable. The paper would benefit from a more thorough examination of how these thermodynamic discrepancies might affect the outcomes to ensure the conclusions are not overly reliant on a single, potentially unrepresentative LES case.

The study attributes reflectivity enhancement primarily to particle growth, but it does not adequately disentangle the contributions from nucleation or increased particle growth versus dispersion effects. A deeper analysis into how much of the observed reflectivity increase due to ice crystal growth, changes in particle size distribution, or enhanced dispersion of particles within the 1D model would provide a clearer understanding of the seeding impacts. This would be nice to show for a single simulation run. Such analysis would clarify the main drivers of reflectivity enhancement and guide more targeted seeding strategies.

Specific Comments:

Line 126: Was scavenging of AgI by nucleation accounted for by the 1D model? That one was of the parameterizations in Xue et al. 2013a.

Line 126: This would be an appropriate place to discuss seeding strategy, which was limited in the manuscript. Did seeding occur at the specified temperature height? How long did seeding occur? Was it for the entire period of the 1D simulation?

Line 135: Suggest rewording the second half of the sentence: "Radiative cooling at cloud top reduces stability resulting in weak vertical motions at cloud top that may also enhance supersaturation.

Line 146: Should this be temperature and supersaturation dependent?

Line 182: Suggest rewording to: terminal fall velocity.

Sec. 2.2: What was the vertical temperature profile used in this analysis? Was it consistent for all 1000 simulation runs?

Sec 2.2: A statement needs to be added to this section that the 1D model does not incorporate aggregation or secondary ice production mechanisms, such as rime-splintering or Hallett-Mossop processes, which can significantly alter ice particle size distributions and radar reflectivity. By not including these processes, the model may underestimate the reflectivity in conditions where aggregation is a dominant growth mechanism, or in clouds with abundant SLW or high ice crystal concentrations as a result of SIP.

A statement also needs to be added clarifying that nucleated particles that form at a given level are either columnar or plate-like depending on background temperature and remain that way as they descend to the surface.

Sec. 2.4: A statement needs to be added to this section discussing the uncertainties when making radar reflectivity calculations using the assumption of Rayleigh scattering, which is valid for larger particles and longer wavelengths but may not hold at shorter wavelengths (e.g., W-band radar) where reflectivity becomes more sensitive to particle concentration rather than size. This assumption could limit the parameterization's applicability across different radar systems used in cloud seeding operations. A similar statement can be found in the conclusions.

Fig. 2: Why are there mean layers where particles consistently see decreases in IWC and Z_e, if particles are growing with depth? How random is the turbulent kinematic diffusion between the different runs? Are their changes in LWC as a result of variations in the temperature profile under the assumption that the cloud is adiabatic? A figure showing initial conditions would be useful to add at the beginning of the analysis.

Fig 2: A panel showing total number concentration for each distribution would be helpful to the reader to determine how many ice crystals are contributing to *IWC* and Z_e at a given height.

Fig. 6: Note in the caption that you are only comparing the -15°C simulation with these LES results in the figure caption.

Figure 7: I found Fig. 7 difficult to interpret because there are four parameters. Could it be broken into a three panel plots showing temperature vs AgI, temperature vs height, and then AgI vs height with reflectivity shaded as a function of reflectivity enhancement. That may make it easier to interpret.

Line 272: Suggest removing the sentence starting with “Long-term remote sensing measurements”. It seems out of place and doesn’t add anything to the discussion without showing additional data.

Line 433: This assumption needs to be clearly stated at the beginning of this section.