The reviewer's comments are in black, and responses are in blue.

The manuscript discusses a cloud seeding case study used for investigating the effect of turbulence on the dispersion of the seeding plume, the ice nucleation, ice crystal growth, and subsequent precipitation formation. It employs idealized WRF LESs to quantify the effect of turbulence. The authors provide a nice overview of the case study and their methods. Their findings are interesting for the scientific community focusing on mixed-phase clouds. In general, the manuscript is well written using clear language and the figures are well done. I do have comments regarding study setup and scientific conclusions. After addressing them, I recommend the manuscript for publication.

Reply: We appreciate your insightful comments. The paper has been revised accordingly and has been improved. Please see our point-by-point response below.

Major comments:

Throughout the manuscript, different time scales are discussed (e.g., glaciation time and turbulent mixing). In lines 34-37, the complex interplay of cloud seeding effects, dynamics, and microphysics is mentioned. It would be helpful if the authors can spend more time on that, as this is at the heart of their study. How are dynamics and turbulence separated? The idealized simulations employ a horizontal resolution of 100m. Is this enough to resolve the largest eddies? How does the definition of turbulence influence the interpretation of the results? The authors often talk about complete cloud glaciation, but what does that mean? The seeding plume has no LWC anymore? What is the definition of that?

Reply: We appreciate your comment. In lines 34-37, the statement points out that if one wants to see an unambiguous seeding signature, the seeding-induced cloud phase change should be faster than the changes in natural variability (caused by either dynamics or microphysics). This is added to the paper. Actually, the whole paper is about this, focusing on cloud glaciation after seeding and the impacts of turbulence. For the case presented here, both the enhanced AgI amount and turbulence accelerate the phase change (liquid to ice), and it is faster than the changes in natural variability, so the seeding signature is unambiguous. Dynamics includes both turbulence and that has larger scales; in this study, we focus on turbulence, and the updrafts and downdrafts are only forced by turbulence. The idealized simulation with a resolution of 100 m can resolve eddies larger than 600 m, it is sufficient to reveal the influence on the seeding effect based on our analysis in the paper. The impacts of smaller eddies on ice growth and seeding effects need to be further investigated in the future. This information is added to the paper. Complete glaciation means the liquid water in cloud regions that are affected by seeding is completely consumed by ice growth, resulting in the LWC approaching zero. This happens when the liquid water consumption by ice growth is faster than liquid water formation by dynamic forcing or liquid water supply from areas outside of the seeding region by turbulent mixing.

The case study description should be extended by more numbers already in the text. The authors say the seeding area was characterized by high RHs, from Figure 1a it looks like 50-60%, which in my opinion is not high. It is further stated that the cloud is decoupled form the surface, 500m, and with a cloud top temperature of-16°C. Where is this information coming from? From Figure 2 I can only see that the radar reflectivity is low, i.e., that most likely it was non precipitating. The authors should avoid using the jet colormap (Figure 1, continuous or discretized) given the known issues with using that colormap (this goes for all figures having that colormap). I further cannot see the -16°C cloud top temperature given the scale only goes to -14.5 in Figure 1d. What is the reason for choosing such a large range given that most of the observed temperatures were in-between-14 and -12°C. In Figure 1, is the pink area in a and b corresponding to the view in c and d? If not, it could help to do it that way.

Reply: We appreciate your comment. The RH in Fig. 1 is from the reanalysis data, it may not reveal the actual RH in clouds, but it is evident that the RH at 850hPa is relatively higher in the flight areas, while the RH is low at higher levels. The information about the cloud is from the sounding measurement (Fig. 3), this has been added to the revised paper. The jet colormap is changed to viridis. The cloud top temperature is from the sounding measurement (Fig. 3a and b), this is added in the text. The color range in Fig. 1d is revised accordingly. Yes, the pink areas in Fig. 1a and b correspond to the views presented in Fig. 2c and d, which include the actual seeding trajectory.

How do the authors define NOSEED and SEED areas? Why wasn't a simulation with no seeding used as a reference for no seeding effect? This is important to know, especially when the authors talk about the change in precipitation.

Reply: We appreciate your comment. SEED and NOSEED are defined as the areas affected and unaffected by the seeding plumes at each moment, respectively. This information is added to the paper. In this study, the field measurement had seeding performed, and we primarily focus on the impact of turbulence on the cloud seeding effect, so we use the simulation with actual AgI amount as the Control. Since the seeding signature is unambiguous, analysis between SEED and NOSEED areas inherently provides the necessary contrast between seeding and no seeding simulations.

A short description on the natural ice nucleation in the model should be done. What parameterization is active at these temperatures and how strong is the freezing to be expected? This should also be discussed in relation to the observed case, where basically no ice nucleation (low radar reflectivity) was observed. So, is it relevant to turn on ice nucleation in the model? This is also of importance to the discussion about the effect of turbulence on ice nucleation.

Reply: We appreciate your comment. We use the default natural ice nucleation parameterizations in the fast SBM scheme, including deposition and condensation nucleation, contact nucleation (Meyers et al., 1992), and immersion freezing (Bigg, 1953). The ice concentration generated from natural ice nucleation can be found in Fig. 8a (black contours), which is an order of magnitude lower than the ice concentration induced by seeding. Given that the cloud in the case is liquid, the natural ice nucleation was intentionally turned off in the simulation to compare with observation for model evaluation. However, turning on the natural ice nucleation in the subsequent experiments was primarily to better understand how turbulence affects natural ice generation and growth. After the turbulence is enhanced, the natural ice concentration is enhanced by about 2 times (black contours in Fig. 8d and j).

Radar reflectivity and cloud thickness in the model simulations: Figure 5 shows a rather thin liquid cloud layer with strong seeding signals. I wonder what changed in the radar reflectivity in Figure 7 as there is a stronger signal in the seeding, but also from the background cloud? Also is the cloud thickening from 2:30 to 3:00 in Figure 7? I am further confused by the signal of LWC (cloud water mixing ratio) in Figure 8 as it appears to be more widespread than in Figure 5 (over more vertical levels). Am I confusing here something? A difference plot with a reference simulation (no seeding) could also be helpful to disentangle turbulence induced by the seeding plume and from the environment.

Reply: We appreciate your comment. The Control experiment without natural ice nucleation is shown in Fig. 5, which conforms to the actual conditions of the case. Fig. 7 includes all experiments listed in Table 1, where the background radar reflectivity is the result of natural ice nucleation. The cloud is not thickening, and the changes in radar reflectivity indicate the falling snow (below the cloud base). In Fig. 8, the vertical axis for LWC is presented on the right side (1.3-1.9 km height). We are sorry for the misunderstanding. It is now clarified in the figure caption.

Precipitation: The results are presented in a nice way, but I am missing a proper discussion on the significance of the simulations (i.e., uncertainty) and especially the scale is omitted in the text. The figures show a scale of 0.1 μm h^{-1} of changes in precipitation? Also here the computation of the differences in SEED and NOSEED should be made clear (see comment above). Figure 11: the boxes seem to be of different sizes and I am wondering what the numbers in the text really tell me given that the colors show the precipitation and not total water volume.

Reply: We appreciate your comment. Yes, the precipitation rate variation presented in Fig. 10a is in μm h^{-1} because the precipitation was quite weak in this study due to the strong sublimation above the surface (Fig. 7). This is true in observation as almost no surface precipitation was detected after seeding. The calculation methodology for Fig. 10 is described as follows: 1) Identify precipitation regions for SEED and NOSEED at each moment based on cumulative precipitation characteristics; 2) Computing the average precipitation for both regions; 3) Calculating the differences in precipitation rates and cumulative precipitation between SEED and NOSEED areas at each moment.

The boxes indicate the approximate SEED areas; they are different between the left and right panels. The numbers in the text present the changes in cumulative precipitation volume within the SEED areas of the four experiments, which are calculated by comparing the average cumulative precipitation inside and outside of the boxes. It is seen from Fig. 11 that the precipitation changes induced by seeding and enhanced turbulence are quite clear; it is unlikely that model uncertainties can explain such a significant precipitation change. However, we agree that the model uncertainty can affect the magnitude of precipitation changes, such as that from the microphysics scheme and the unresolved smaller turbulent eddies. This discussion is added in Section 4.

Minor comments:

Line 17: the acronym LESs does not have to be introduced as it is not used in the abstract.

Reply: We appreciate your comment. The acronym LESs has been removed from the abstract.

Line 18: “the model can reasonably capture”- is there a word missing? reasonably well?

Reply: We appreciate your comment. “the model can reasonably capture” is changed to “the model can reasonably well capture”.

Line 29: “similar crystal structure” to “similar molecular lattice structure”

Reply: We appreciate your comment. “similar crystal structure” has been changed to “similar molecular lattice structure”.

Line 30: Here the onset freezing temperature for AgI should be stated and also other references, such as Marcolli et al., 2016 and Chen et al., 2024 should be included.

Reply: We appreciate your comment. The onset freezing temperature of AgI particles (-4 °C for AgI particles in 0.1 μm, and -8 °C for AgI particles in 1 μm) is added in the text. The references are added.

Line 41: What is the result of complete cloud glaciation? The decrease in cloud top and complete cloud clearing? Again here the definition of complete cloud glaciation is needed. I further do not understand the second part of the sentence, is the mixing consuming water or is it producing more through cloud droplet formation / growth?

Reply: We appreciate your comment. Complete glaciation means the liquid water in cloud regions that are affected by seeding is completely consumed by ice growth. “Mixing” here means “turbulent mixing”, which indicates supercooled water in adjacent areas can mix into the glaciated cloud areas, leading to a mixed-phase state. Sorry for any misunderstanding. The sentence has been revised to: *“It is a result of complete glaciation in seeding areas, which means the liquid water consumption by ice growth is faster than liquid water formation by dynamic forcing or liquid water supply from areas outside of the seeding region by turbulent mixing. This leads to the liquid water content (LWC) approaching zero”*

Line 59: definition of plains should be stated earlier, as it is already used before in the introduction and in the abstract.

Reply: We appreciate your comment. The definition of plains has been added at line 45: *“decrease in cloud top has been reported in several studies in which seeding experiments were conducted over flat land (plains)”*

Line 63: The formula by Korolev and Mazin is later used, maybe this can be pointed out here, otherwise this reads as a rather random information. This also can be said for the next sentence, regarding the findings by Korolev and Field (2008). What are the authors trying to convey with this information? How is this relevant for their study?

Reply: We appreciate your comment. The sentence has been revised to: *“Korolev and Mazin (2003) proposed a formula (shown later in Section 3.4)…”*. Korolev and Field (2008) showed that turbulence is the key process to maintain the cloud in a long-lived mixed-phase state. This is relevant to this study because we aim to investigate whether turbulence can keep the cloud in a mixed-phase state after seeding or not.

Line 68: the introduction of LWC is good and should be used throughout the manuscript (instead of liquid water and cloud water mixing ratio). This way, it is consistent and will help ease the understanding.

Reply: We appreciate your comment. “LWC” has been appropriately applied in the revised paper.

Line 70: Does “suppress this through cloud top entrainment” refer to ice growth or / and precipitation?

Reply: We appreciate your comment. “suppress this through cloud top entrainment” refers to “suppress ice growth through cloud top entrainment”. This has been revised in the paper.

Line 79: I think it is valid to conduct the study over flat lands, but the authors say it is also relevant to mountainous terrain. Here, more justification for this interpretation would be great.

Reply: We appreciate your comment. Relevant justification for this interpretation has been added to the paper. Turbulence also plays a vital role in particle dispersion and ice growth in orographic clouds (Xue et al., 2014; Chu et al., 2018; Jing et al., 2016)

Line 91: already here the cloud type (i.e., stratiform) can be defined.

Reply: We appreciate your comment. The cloud type (stratiform) has been added to this sentence.

Line 156: Where is the sounding coming from? Is this a real observation? Or did the authors prescribe an artificial profile (also fine)?

Reply: We appreciate your comment. The sounding comes from real observation. This information has been added to the paper.

Figure 3: Can you add the RH profile, such that the conditions are more easy to grasp? Especially when you talk about dry intrusions from above, this could be helpful instead of having to do the calculations oneself.

Reply: We appreciate your comment. The RH profile has been added to the Fig. 3.

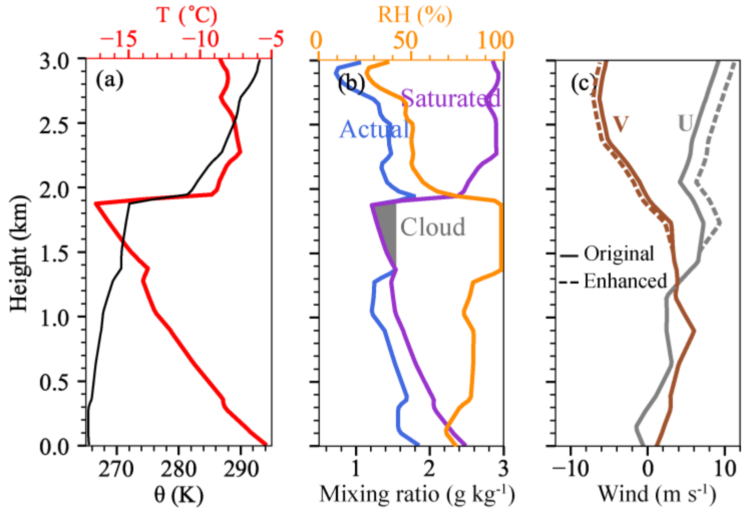

Fig. R1. The initial vertical profiles of (a) temperature and potential temperature, (b) actual vapor mixing ratio, saturation vapor mixing ratio relative to water and relative humidity, and (c) original and enhanced U and V components. The grey shaded area in (b) indicates the initial liquid water mixing ratio.

Line 203: What is the resolution of the radar?

Reply: The range resolution is 250 m; this information is added to the paper.

Line 206: A reference to Omanovic et al., 2024 should be done, given that they reported a similar result with too slow WBF process.

Reply: We appreciate your comment. The reference has been added to the paper.

Omanovic, N., Ferrachat, S., Fuchs, C., Henneberger, J., Miller, A. J., Ohneiser, K., Ramelli, F., Seifert, P., Spirig, R., Zhang, H., & Lohmann, U. Evaluating the Wegener–Bergeron–Findeisen process in ICON in large eddy mode with in situ observations from the CLOUDLAB project. Atmospheric Chemistry and Physics, 24(11), 6825–6844. https://doi.org/10.5194/acp-24-6825-2024, 2024.

Line 241: “scales of seeding plumes”? Do you mean the vertical extent? The spread?

Reply: Yes, it means horizontal spread. This is revised in the paper.

Line 260: What do you mean by similar variations? In terms of magnitude? Pattern?

Reply: The similar variations mean the variation pattern. The relevant sentence has been modified.

Line 265: I believe difference plots between the simulations would help here the discussion, as the difference can be quite subtle and I cannot follow the discussion of the authors on the changes.

Reply: We appreciate your comment. Since we also want to compare the temporal variations between SEED and NOSEED areas (the color-filled and black contours in Fig. R2), we prefer to keep the original pattern. To address your comment, we change the colormap to better show the differences among the panels. Although you mentioned the possible issues about jet (or rainbow) colormap, we tested several different colormaps and this reveals the differences best.

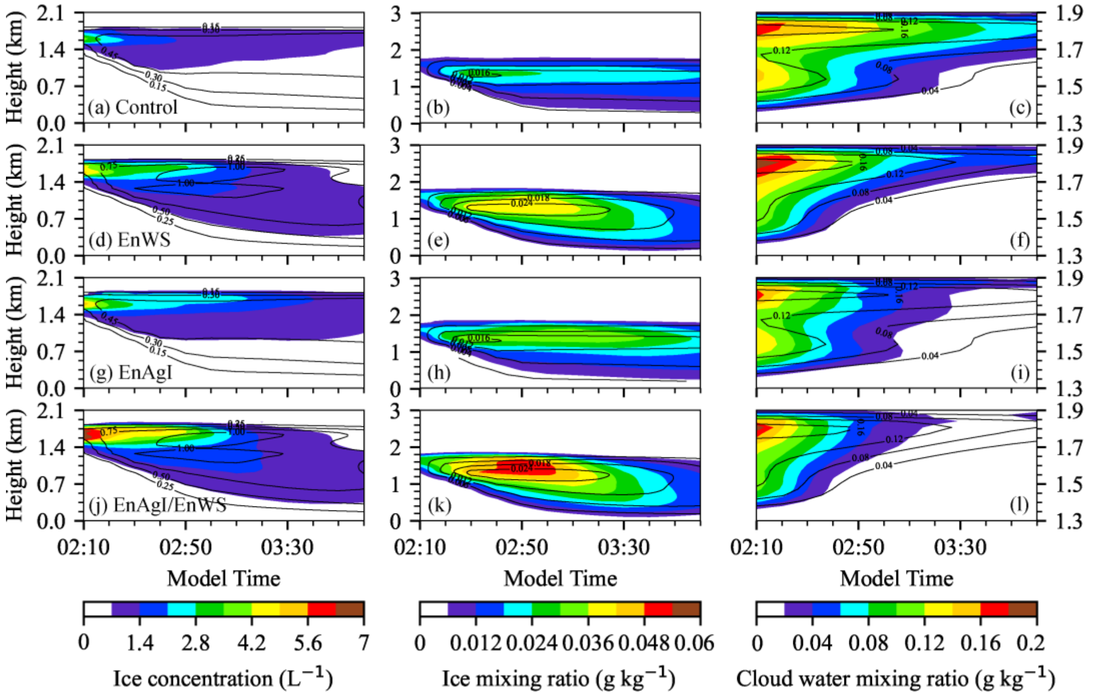

Fig. R2. Time-height diagram of ice concentration (left panels), ice mixing ratio (middle panels), and cloud water mixing ratio (right panels) from the (a-c) Control, (d-f) EnWS, (g-i) EnAgI and (j-l) EnWS/EnAgI experiments. The color-shading applies to the SEED areas, and the black contours are for the NOSEED areas.

Line 275: I understand if you do not want to dive into riming and aggregation, but could you provide more information on that? Maybe an appendix figure? Riming and aggregation should occur especially with these high ice concentrations.

Reply: The riming and aggregation rate are rather minor compared to the diffusional growth rate for such a thin cloud. The magnitudes of riming and aggregation rates are more than 7 orders of magnitudes lower than the diffusional growth rate, which are negligible.

Line 279: I believe there is a word missing before “became lower ...” or what do the authors refer to? The deposition rate?

Reply: We apologize for the lack of clarity in this explanation. It means that the deposition rate became lower. The relevant sentence has been modified.

Line 309: enchantment to enhancement?

Reply: We appreciate your correction. “enchantment” is changed to “enhancement”.

Line 362: I might understand Figure 12 wrong, but enhanced turbulence does not enhance both cloud glaciation and turbulent mixing. I mostly see a reduction in the time for cloud glaciation, while for turbulent mixing this is more difficult to see. Maybe a quantification could be helpful here.

Reply: We appreciate your comment. Stronger turbulence enhances the spread of the seeding plume; therefore, when calculating the characteristic time of mixing, the EnWS and EnAgI/EnWS experiments have larger L (in Eq. 1) than the Control and EnAgI experiments at any moment. The original sentence caused a misunderstanding, it is now changed to *“By comparing the right and left panels in Fig.12, it can be seen that the enhanced turbulence accelerated the cloud glaciation, and the characteristic time of mixing became larger due to the enhanced spread of seeding plume”*.

Figure 13: How can you have negative condensation rates (evaporation) with vertical velocities larger than w^*? Can you quantify how often you encounter which conditions, i.e., both growing or only ice crystals growing?

Reply: The w^* used in the calculation using Eq. 3 is based on constant temperature and pressure conditions (cloud top), primarily intended to demonstrate the overall distribution of condensation rates when vertical velocities are above or below w^*. However, temperature and pressure within clouds are not constant. In addition, in the model, the simulation of condensation rate does not exactly follow Eq. 3, there are other factors, such as ice shape, that also influence the result. Therefore, there could be a low occurrence of negative condensation rates even when vertical velocities are slightly above w^*. For the Control and EnAgI/EnWS experiments at 03:30 MT, the occurrence of simultaneous liquid and ice growth is 0.21 and 0.04, the occurrence of ice growth only is 0.79 and 0.91, and the occurrence of simultaneous liquid evaporation and ice sublimation is 0 and 0.05, respectively.

Line 397-401: this is one sentence, can you split it up?

Reply: We appreciate your comment. The original sentence has been divided into two separate sentences. *"The case presented here is a well-capped, shallow (~500 m deep) decoupled stratus cloud with a cloud top of -16°C. The results show that stronger shear-driven turbulence can enhance the dispersion of AgI particles and the nucleation and growth of ice crystals."*

Line 414: There are other (older) reference to ice crystal growth across temperatures, please add them.

Reply: The following references are added:

Chen, J.-P. and Lamb, D.: The theoretical basis for the parameterization of ice crystal habits: Growth by vapor deposition, J. Atmos. Sci., 51, 1206–1222, https://doi.org/10.1175/15200469(1994)051<1206:TTBFTP>2.0.CO;2, 1994.

Fukuta, N. and Takahashi, T. The growth of atmospheric ice crystals: A summary of findings in vertical supercooled cloud tunnel studies, J. Atmos. Sci., 56, 1963–1979, https://doi.org/10.1175/15200469(1999)056<1963:TGOAIC>2.0.CO;2, 1999.

Harrington, J. Y., Moyle, A., Hanson, L. E., and Morrison, H.: On Calculating Deposition Coefficients and Aspect-Ratio Evolution in Approximate Models of Ice Crystal Vapor Growth, J. Atmos. Sci., 76, 1609–1625, https://doi.org/10.1175/JAS-D-18-0319.1, 2019.

Line 417: Nimbostratus produce natural precipitation. Why did you choose this cloud type as an example? Is it really ideal to be seeded?

Reply: Deep stratiform clouds, such as nimbostratus, may be suitable for seeding, but it is difficult to detect unambiguous seeding signatures due to natural precipitation. There is supercooled liquid water in these clouds, and some previous studies tried to investigate the seeding effect in these clouds (e.g., Pokharel et al., 2015, Jing et al., 2015). Although observing the seeding effect is different in these clouds, we can still use model simulations to study the impacts of turbulence.

Line 448: What ways do you see to parameterize turbulence in connection to cloud microphysics? Are there open questions in this regards?

Reply: Numerical weather predicting and climate models cannot resolve turbulence, so it is necessary to parameterize the impacts of turbulence on cloud microphysics, but it is challenging. Several studies have tried to develop parameterizations of turbulence-induced droplet collision (e.g., Franklin, 2008), but to our knowledge, there is no parameterization of ice growth affected by turbulence. Recently, we developed an observationally constrained parameterization of liquid-ice mixing inhomogeneity in ice growth for climate model, which is relevant to turbulence, but it has not been published (Yang et al., GRL, in revision).

Franklin, C., A warm rain microphysics parameterization that includes the effect of turbulence. J. Atmos. Sci. 2008, 65, 1795–1816.

Yang, J., et al., Parameterizing the heterogeneous liquid-ice mixing in modelling ice growth through the Wegener-Bergeron-Findeisen process in CAM6, Geophys. Res. Lett. In revision.