Comment:

The authors present a numerical analysis of the potential for cloud seeding to mitigate the rainfall from an extreme historical MCS event in Japan. The paper is interesting and well-written and I think is suitable for publication with moderate revisions that would help strengthen the novelty of the study and to highlight an addition (in my opinion, important) limitation and direction for future work. I also have a few minor grammar suggestions. I doubt I caught all the grammar mistakes, which anyway are so small and infrequent that they do not detract from the quality of the work.

Response:

We thank the reviewer for this positive and encouraging evaluation of our manuscript. We appreciate the reviewer's assessment that the study is interesting, well written, and suitable for publication. We are also grateful for the constructive suggestions aimed at strengthening the novelty of the work and for highlighting an important limitation and direction for future research.

In response, we have revised the manuscript to better clarify these aspects and to explicitly acknowledge the additional limitation and future research needs. We have also carefully addressed the minor grammatical suggestions provided by the reviewer and conducted an overall review of the manuscript to further improve clarity and readability.

In our responses, the additional text introduced in the revised manuscript is indicated in red.

Comment:

My concern regarding novelty stems from the fact that very little information is provided on numerical cloud seeding studies, particularly those aimed at rainfall mitigation and those based in Japan. This lack of information on previous work made it impossible for anyone who isn't themselves familiar with the literature to understand how much was new about the present study. That said, the introduction section is already lengthy. Therefore, I recommend creating a new section entitled "Background" or something like that, following the introduction, that can provide further details on methods and findings of a few key previous studies, which will help frame the current work. Some points now provided in the introduction may perhaps be moved into that background section as well.

Response:

Thank you for your useful comment. Following this suggestion, we added a new section entitled **“Background”** as Section 2. In this section, we review previous numerical studies of cloud seeding and overseeding, with particular emphasis on studies aimed at rainfall mitigation and those conducted in Japan, and summarize their key methodologies and findings. To improve the clarity and focus of the manuscript, several discussions on overseeding that were originally included in the Introduction have been moved to the new Background section. As a result, the Introduction has been streamlined to better highlight the motivation and objectives of the present study, while the Background section provides the necessary context to clarify the novelty and positioning of our work. The following shows the content of the new Background section. Section 2.1 was moved from the Introduction, and Section 2.2 was newly added to review previous studies and clarify the motivation for the present study.

2 Background

2.1 Concept of overseeding

The concept of overseeding was succinctly outlined in the textbooks of Mason (1971) and Rogers and Yau (1989) and nicely summarized in Durant et al. (2008), describing a scenario in which introducing an excessive quantity of ice nuclei leads to the formation of a large number of small ice crystals in convective clouds containing supercooled water droplets. Such seeding practice is categorized as glaciogenic seeding (Hashimoto et al., 2015). Under such conditions, the competition for available moisture within the cloud becomes intense, inhibiting the growth of individual ice crystals to sizes sufficient for precipitation. When the concentration of artificially generated ice crystals significantly exceeds natural levels, the rapid increase in the number of simultaneously growing precipitation particles can result in a substantial reduction in their growth rates due to moisture depletion. Furthermore, the freezing of supercooled water releases latent heat, which strengthens the updraft and thereby reduces the sedimentation velocity of precipitation particles. Consequently, these processes would lead to a decrease in the size and sedimentation velocity of precipitation particles at the location of the overseeding, which may temporarily suppress precipitation from the seeded cloud layer. Precipitation particles with reduced growth rates are likely advected downstream by upper-level wind and eventually fall as precipitation in the downstream region (i.e., redistributing rainfall over a broader area). Such a dispersal mechanism has the potential to mitigate the localization of intense precipitation. The aforementioned concept of overseeding has also been discussed in recent studies (Koloskov et al., 2010; Murakami, 2015; Korneev et al., 2022; Abshaev et al., 2022), leading to growing interest in its potential for disaster risk reduction.

2.2 Numerical overseeding studies in Japan

Although numerical investigations of cloud overseeding generally remain limited, a series of recent studies in Japan have suggested its potential to influence peak rainfall intensity during heavy rainfall events. Early studies using mesoscale atmospheric models showed that excessively increasing ice nucleus number concentrations within MCSs can reduce maximum rainfall intensity and the spatial extent of heavy rainfall (Suzuki et al., 2012; Onaka and Suzuki, 2014). In these studies, overseeding was typically represented by artificially multiplying the ice nucleus number concentration by large factors within cloud microphysics schemes.

Subsequent studies further examined the dependence of rainfall mitigation on cloud developmental stage and seeding strategy. Yokoyama et al. (2015) demonstrated that seeding during the early stage of cloud development was more effective than seeding during the mature stage, as early-stage seeding weakened vertical updrafts, leading to reductions in peak rainfall intensity. More recently, Nozaki et al. (2024) showed that the effectiveness of cloud seeding strongly depends on seeding location, timing, and environmental conditions, with both mitigation and enhancement of rainfall occurring under different configurations. In addition, studies exploring more targeted seeding strategies, such as pinpoint seeding, have suggested that focusing seeding on strong updraft regions may enhance mitigation efficiency (Yagi et al., 2017; Sano et al., 2024). These studies reported reductions in peak rainfall intensity on the order of 10–30% under favorable conditions and underscored the importance of seeding geometry and vertical placement.

Despite these advances, systematic comparisons of key seeding parameters, including seeding altitude, horizontal extent, and vertical thickness, remain limited, and their influence on the effectiveness of cloud seeding has not been fully clarified. Moreover, the physical mechanisms by which overseeding modifies microphysical growth pathways and interacts with mesoscale dynamics—particularly the downstream redistribution of precipitation in organized convective systems such as MCSs—remain insufficiently understood. These limitations motivate the present study, which aims to provide a more systematic and process-oriented assessment of rainfall responses to cloud overseeding.

*All the references were cited in the original manuscript.

Comment:

My other major concern is the lack of mention of what I see as the biggest limitation of the work and one of the biggest questions that needs to be answered if such approaches are ever to be operationalized. The authors examine the effects of cloud seeding directly into the storm area. In an operational context, this is akin to knowing exactly where the storm will take place. MCSs are notoriously difficult to forecast, particularly with respect to precise timing and location. Therefore, it seems unrealistic that such seeding could be accomplished in so localized a way. Instead, one would presumably need, with some multi-hour lead time, a prediction that a larger region is likely to develop an MCS somewhere within it, and seeding is done throughout the region. It is easy to imagine several things as a consequence of this: 1) the amount of AgI or other material needed could increase by orders of magnitude, and 2) the likelihood that some adverse outcome occurs due to rainfall being shifted spatially, rather than mitigated entirely, will increase, perhaps substantially. I suggest that the authors consider follow-up work that examines seeding, perhaps at lower concentrations, over larger areas, rather than just the storm location, to examine this effect. It may also be wise to perform ensemble simulations using some perturbation approach to better understand how stochastic the result may be.

Response:

Thank you for raising this important point regarding operational feasibility. We agree that prescribing seeding directly within the storm region implicitly assumes accurate knowledge of the timing and location of MCS development, which is challenging in practice. In the present study, we intentionally adopted a retrospective, mechanism-oriented design because our primary objective is to examine whether the hypothesized overseeding processes occur and to clarify their underlying physical mechanisms, rather than to assess real-time operational implementation. To achieve this objective, it is necessary to conduct experiments under well-understood conditions, such as known locations of deep convection and the presence of supercooled liquid water, where the proposed physical mechanisms can be robustly evaluated.

Nevertheless, we fully agree that careful consideration of operational implementation is essential for assessing the practical applicability of the proposed approach. Demonstrating practical feasibility, however, would require a comprehensive assessment of the current forecasting environment in Japan, including the accuracy of MCS predictions, observational constraints such as data availability and latency, and the ability to determine/flight appropriate seeding extent and timing under forecast uncertainty. Japan has a dense observation network, including ground precipitation radar, which may be useful to judge the seeding practice. Additional analysis design for assessing the practical feasibility should reflect such forecast environment accurately, while these are inherently case and location specific. We believe that such additional analyses are beyond the scope of the present mechanism-focused study. We would like to explicitly address these issues as limitations and identify them as important topics for future research.

To incorporate the points discussed above into the manuscript, we introduced a new subsection entitled “4.3 Limitations and implications for operationalization” and added the following paragraph:

Second, consideration of practical feasibility from an operational perspective is lacking. The present study prescribes cloud seeding within regions where deep convection and supercooled liquid water are known to exist, based on retrospective simulations. This design was intentionally adopted to prioritize the examination of whether the hypothesized overseeding processes occur and to clarify their underlying physical mechanisms under well-understood conditions, rather than to assess real-time operational implementation. From an operational perspective, however, careful consideration of practical feasibility is essential. Demonstrating such feasibility would first require a comprehensive assessment of the current forecasting environment in Japan, including the accuracy of MCS predictions, observational constraints such as data availability and latency, and the capability to determine appropriate seeding extent and timing under forecast uncertainty. At the same time, designing analyses to assess operational feasibility must accurately reflect these forecasting and observational conditions and is inherently case- and location-specific. Because such comprehensive assessments extend beyond the scope of the present mechanism-focused study, these operational considerations are explicitly identified here as limitations and are left as important topics for future research.

The limitations originally discussed in Section 5 (“Concluding Remarks”) were relocated to the newly introduced section, resulting in the removal of Section 5.

Minor comments:

Throughout: “downwind” is likely better than “downstream” for atmospheric work

Response:

Thank you for your suggestions.

Downstream is now replaced with downwind throughout the manuscript.

We replaced Figure 2(a) with the one below to clearly indicate the wind direction and clarify the downwind direction.

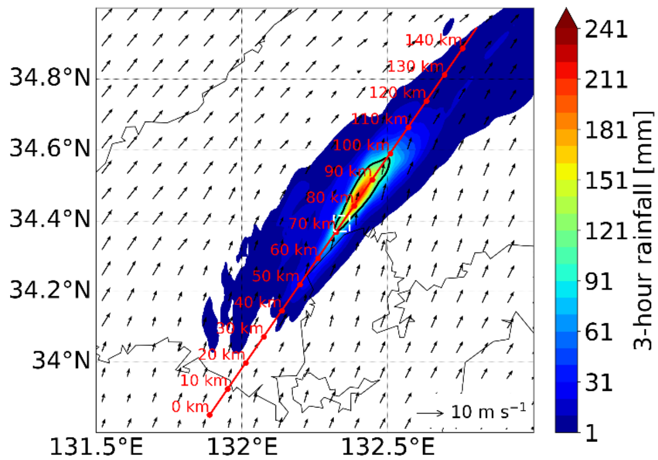

Figure 2. (a) WRF-simulated 3-hr accumulated rainfall with the path for vertical cross sections (red line and points), horizontal extent of cloud seeding (white dashed square), heavy rainfall region (>100 mm in 3 hours; black outline), and 850 hPa wind vectors at 16:20 UTC on August 19, 2014.

L17 and 18; delete “s” from “altitudes” and “areas”

Response:

Addressed.

L25: “… decrease as the maximum reduction…” is awkward wording

Response:

The sentence is revised as follows:

The most effective seeding configuration (24 km × 24 km area at 7.2 km) achieved an 11.5% decrease in area-averaged 3-hr accumulated rainfall and a maximum reduction of 32% in 3-hr accumulated rainfall over the heavy rainfall region.

L66 and 69: delete uses of “the” except at the start of line 69

Response:

Addressed.

L70: delete “to date” as it is unnecessary

Response:

Addressed.

L88: change “in” to “on”

Response:

Addressed.

L89: the 100 mm/h is unclear. Is that a peak rate over some short time interval?

Response:

We revised the sentence as follows to clarify the meaning:

[…] exceeding a peak hourly rainfall rate of 100 mm/h […]

L97: delete “s” from convections

Response:

Addressed.

L103: “under a future climate”

Response:

Addressed.

L104: countermeasure is one word

Response:

Revised as “countermeasure”.

Eqn 1: Does beta have a physical meaning? If so, describe it. Also, what is a more typical value in WRF?

Response:

Thank you for your comment.

In the standard WRF implementation of the Morrison double-moment microphysics scheme, the ice nucleus concentration is diagnosed using the Meyers formulation without β, which represents background ice nuclei under natural atmospheric conditions. In this study, β is introduced as an artificial, unitless multiplier to represent an overseeding condition, in which the effective ice nuclei concentration in the mixed-phase region is deliberately increased far beyond typical background levels.

Physically, β does not represent a directly measurable environmental parameter; rather, it serves as a modeling control parameter that enables a strong enhancement of ice nuclei to mimic the effects of intense glaciogenic seeding. By adopting a very large value of β, we ensure a rapid and substantial increase in ice nucleus concentration, allowing us to isolate and examine the microphysical and dynamical response of convective clouds to extreme ice nuclei perturbations.

We have added the following sentences to Section 2.3 to clarify the explanation above:

In WRF v4.1.2, the number of ice nucleus concentration is determined based on the Meyer's formula within the Morrison 2-moment cloud microphysics scheme (Meyers et al., 1992).

$$n_c = \exp\{-2.80 + 0.262 \times (273.15 - T)\} \times \beta \qquad (1)$$

where n_c is the number of ice nucleus concentration per kilogram, T is air temperature in kelvin, and β is a unit less multiplier which is introduced for seeding experiments. In the WRF model, the Meyer's formula triggers the freezing of cloud droplets when the following conditions are met: a cloud water mixing ratio greater than 10^{-14} kg kg^{-1} and an air temperature below –4°C (i.e., deposition freezing). In the present study, β is introduced as an artificial, unitless multiplier to represent an idealized overseeding condition, in which the effective ice nuclei concentration in the mixed-phase region is intentionally increased by several orders of magnitude.

L195 and Table 2: use "design" rather than "flow"

Response:

Replaced “flow” with “design”.

L195: change “was” to “is”

Response:

Addressed.

Figure 4: remind the reader what the thick black polygon indicates

Response:

We have added the following sentence in the caption of Figure 4:

The black outline denotes areas where the 3-hr accumulated rainfall exceeds 100 mm in the CTL run.