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

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 potential 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.

Reply: We appreciate your insightful comments. The paper has been revised accordingly, and has been improved a lot. In addition, according to reviewer 1's comment, we updated the ice growth model, and all the figures have been updated. Please see our point-by-point response below.

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.

Reply: We appreciate your comment. In the model, the temperature profile is determined by the cloud top temperature and lapse rate. Once the cloud top temperature is given, we can calculate the temperature at different levels. Typically, the lapse rate in a stratiform cloud is 5-6 K/km, we made sensitivity tests using different lapse rates, and an example is shown in Fig. R1. It is seen that the results are quite similar using a lapse rate of 5 and 6 K/km. In this study, we use 5.5 K/km, and a random temperature perturbation varies between -0.1 K and 0.1 K is applied to each level. Sorry for missing the information about temperature, this has been added to the revised paper.

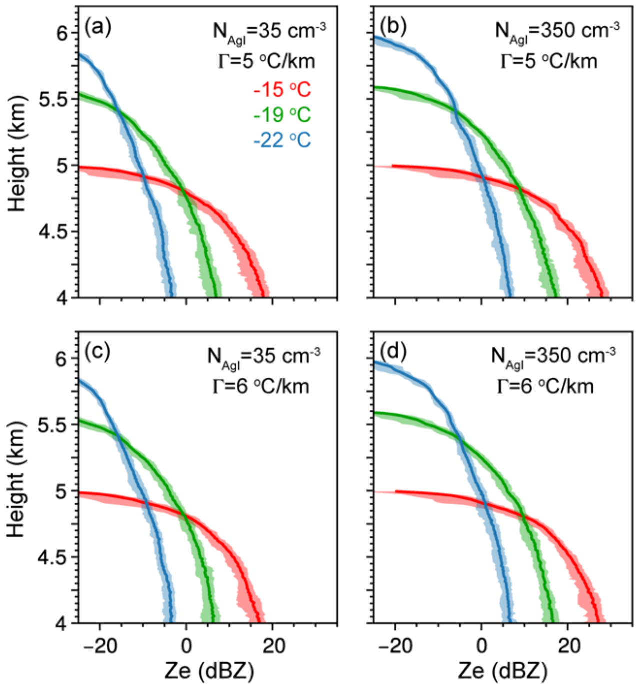

Figure R1. Vertical profiles of Ze from the simulations with a temperature lapse rate of (a and b) 5 K/km, and (c and d) 6 K/km, and an AgI particle concentration of (a and c) 35 cm^{-3}, and (b and d) 350 cm^{-3}.

In the model, we assume there is sufficient liquid water or vapor supply, which means once the liquid water is consumed by ice growth, new liquid water can quickly form due to turbulent mixing or updraft (e.g., orographic lifting). Ice formed in a single timestep (1 s) is too low to consume all the liquid water in clouds, it is the continuous ice nucleation that results in complete glaciation if we assume there is no continuous water supply. Therefore, to test the impact of liquid water content on ice growth, it is necessary to consider both the upper limit of LWC and the time duration for ice growth. We note this is related to Comment 2. Please see the more detailed response below.

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.

Reply: We appreciate your comment. In the model, we assume there is a continuous water supply. We agree that in real cloud this is not always true, and there is an upper limit of LWC. This would certainly affect the ice growth and the Ze profiles. We made several sensitivity tests in the revised manuscript, including different upper limits of LWC (assuming no continuous liquid water formation), different time durations for ice growth, and different AgI particle concentrations for a limited LWC (Fig. R2a-c). It is seen from the figure that for a model time of 90 minutes, the Ze decreases with decreasing LWC. For a given LWC of 0.2 gm^{-3}, ice nucleation and growth in a longer time would consume more liquid water, leading to lower Ze (Fig. 2b), which means the ice formed later on has no sufficient liquid water and vapor to grow. For a given LWC and time duration, more AgI concentration does not mean a larger Ze (Fig. R2c), ice crystals may compete for the limited liquid water and suppress the ice crystal size. In addition, we made sensitivity tests of different turbulent dispersion coefficients and different initial ice particle size distributions (Fig. R2d-f), these are also sources of uncertainties in the model, though the Ze profile is less sensitive to them compared to LWC. This analysis is added in the revised paper, which provides us a better understanding of how the results may vary due to the different environmental conditions.

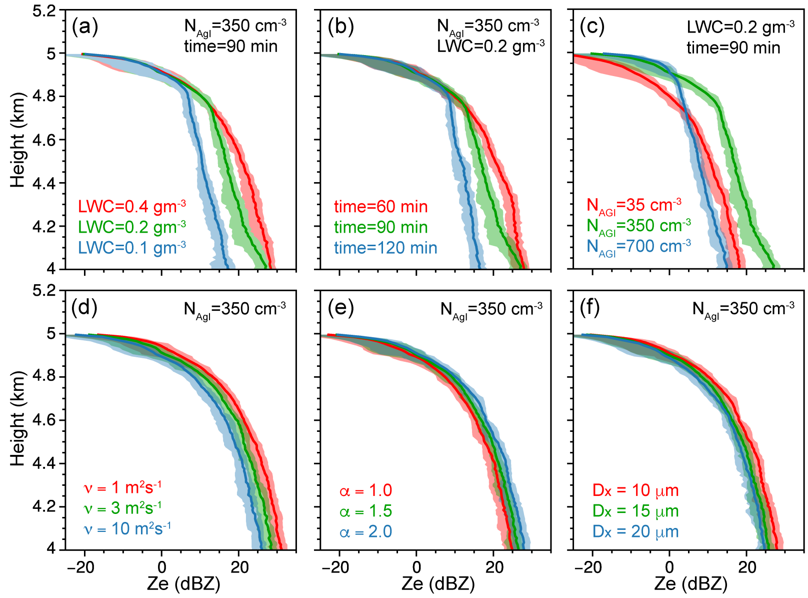

Figure R2. Vertical profiles of Ze simulation using different (a) upper limits of LWC, (b) time durations for ice growth, (c) AgI particle concentrations with limited LWC, (d) turbulence dispersion coefficients, and (e, d) coefficients in the initial ice particle size distributions.

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.

Reply: We appreciate your comment. Yes, we agree, in precipitating clouds, the presence of natural ice would likely diminish the detectability of the seeding signature. We do not consider the interaction between the seeded ice and natural ice, and we do not consider the competition for liquid water between the seeded and natural ice. In the paper, as we stated, we assume there is sufficient liquid water and vapor supply, therefore, there is enough liquid water for the growth of both natural ice and seeded ice crystals. Aggregation between natural and seeded ice is expected to further enhance the ice crystal size, which is favorable for seeding signature detection. Therefore, if there is a source for continuous water supply (e.g., orographic lifting), this method is probably valid for precipitating clouds. At least we provide a lower limit of AgI concentration that is needed to detect unambiguous seeding signatures. More AgI may be needed if considering the interaction between natural and seeded ice crystals. We acknowledge that the validation of this model and parametrization in precipitating clouds needs further validation in the future, this discussion is added in the abstract, Section 4, and conclusions.

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.

Reply: We appreciate your comment. In the revised paper, we compare the 1D model with the 3D model using 2 cases, a shallow cloud (same as the case in the original manuscript), and a deeper one. The sounding data is originally based on the shallow case (solid line in Fig. R3). To model the deeper case, we modify the temperature and vapor mixing ratio data (dashed line in Fig. R3). The deeper case has a cloud depth of 2 km, seeding is performed at -21 °C. In the shallow case, seeding is performed at -15 °C. The other model configurations are the same as the original manuscript. We acknowledge that this model and the parameterizations need more validation in the future, especially using observational datasets such as Cloudlab (Henneberger et al., 2023).

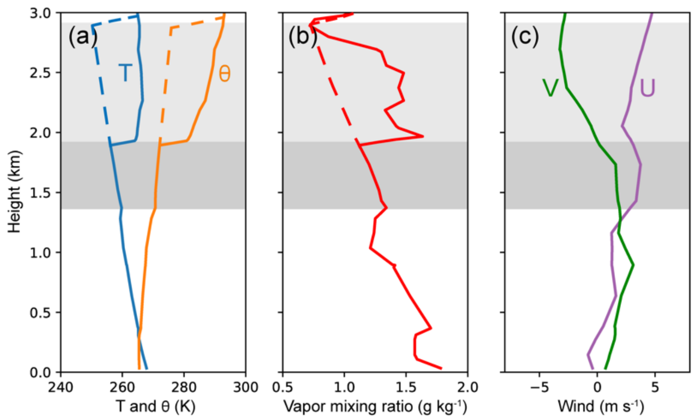

Figure R3. The initial profiles of (a) temperature and potential temperature, (b) vapor mixing ratio, and (c) U and V components of the wind field. The solid lines indicate the original data used for the shallow cloud, and the dashed lines indicate the modified data used for the deep case. The dark-shaded area (1.3km – 1.9 km) indicates the shallow cloud layer and the light-shaded area (1.3 km - 2.9 km) indicates the deep cloud layer.

Figure R4 shows the modelled Ze, and IWC. It is seen that the Ze and IWC are much greater for the shallow case (Fig. R4a-d) than the deeper one (Fig. R4e-h), because seeding is conducted at -15 °C for the shallow case, while at -21 °C for the deeper case.

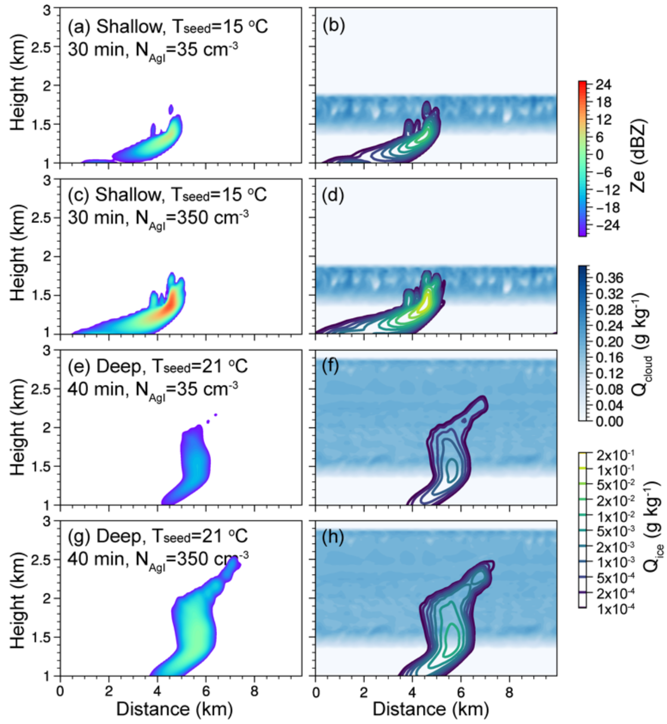

Figure R4. Cross sections of Ze (rainbow shading), liquid water mixing ratio (blue shading), and ice mixing ratio (contoured) were obtained from 3D LES simulations for (a-d) the shallow cloud, and (e-h) the deeper case.

Statistically, the 1D model is consistent with the 3D model. Although there are inevitable differences (a few dBZ). Here, we would like to point out there was a mistake (incorrect height data) when plotting the 3D model results in Fig. 6. In the new version, we found the 1D model and 3D model shows similar vertical variation (Fig. R5).

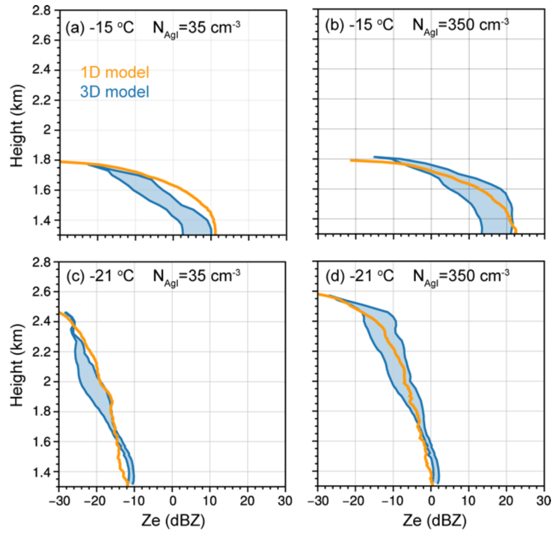

Figure R5. The vertical profiles of Ze simulated using the 1D and 3D models with an AgI particle concentration of (a, c) 35 cm^{-3}, and (b, d) 350 cm^{-3} for the (a, b) shallow and (c, d) deep cases, respectively. The left and right boundaries of the blue shaded area indicate the 95th percentile and the maximum Ze from the 3D model, respectively.

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.
Reply: We appreciate your comment. In the revised paper, we made sensitivity tests for different turbulent dispersion coefficients, different coefficients in the ice particle size distribution function, different upper limits of LWC, and different time durations for ice growth. These results are present in Fig. R2, and please see the description for this figure in our reply to comment 2. This figure and related text are added to the revised manuscript.

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.
Reply: Yes, we follow Xue et al., 2013a, the fraction of the total AgI particles that are scavenged by cloud droplets is parameterized based on Caro et al. (2024).

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?
Reply: We appreciate your comment. The seeding strategy is added accordingly. For each run, seeding is performed at a given temperature height, which is randomly selected in the 2500 experiments (1000 in the original paper). Seeding only takes place at the beginning of each run, but ice nucleation by AgI particles keeps occurring. The total AgI particle decreases due to ice nucleation in every time step (1s).

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.

Reply: The sentence is reworded to "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?

Reply: Yes, it is temperature and supersaturation dependent, this is revised in the paper.

Line 182: Suggest rewording to: terminal fall velocity.

Reply: "terminal velocity" is changed 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?

Reply: We appreciate your comment. In the model, the temperature profile is determined by the cloud top temperature and lapse rate. Once the cloud top temperature is given, we can calculate the temperature at different levels. Typically, the lapse rate in a stratiform cloud is 5-6 K/km, we made sensitivity tests using different lapse rates, and an example is shown in Fig. R1. It is seen that the results are quite similar using a lapse rate of 5 and 6 K/km. In this study, we use 5.5 K/km, and a random temperature perturbation varies between -0.1 K and 0.1 K is applied to each level.

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.

Reply: We appreciate your comment. The statement is added to the paper: *"The 1D model does not incorporate aggregation or secondary ice production mechanisms, such as the rime-splintering process and shattering of freezing drops, 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.

Reply: We appreciate your comment. The statement is added to the paper: *"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.

Reply: We appreciate your comment. In fact, we have this discussion in the last section of the paper. According to your suggestion, we add this discussion to Section 2.4.

Fig. 2: Why are there mean layers where particles consistently see decreases in IWC and Ze, 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.

Reply: We appreciate your comment. The vertical variation of IWC is because the ice concentration varies with height. Ice crystal concertation is determined by ice nucleation rate, so it is related to turbulence. However, we made a mistake in generating the random numbers of turbulence. This is corrected in the code and the figure is updated (Fig. R6), in the updated figure, we still see a slight variation of IWC, determined by the variation of ice concentration.

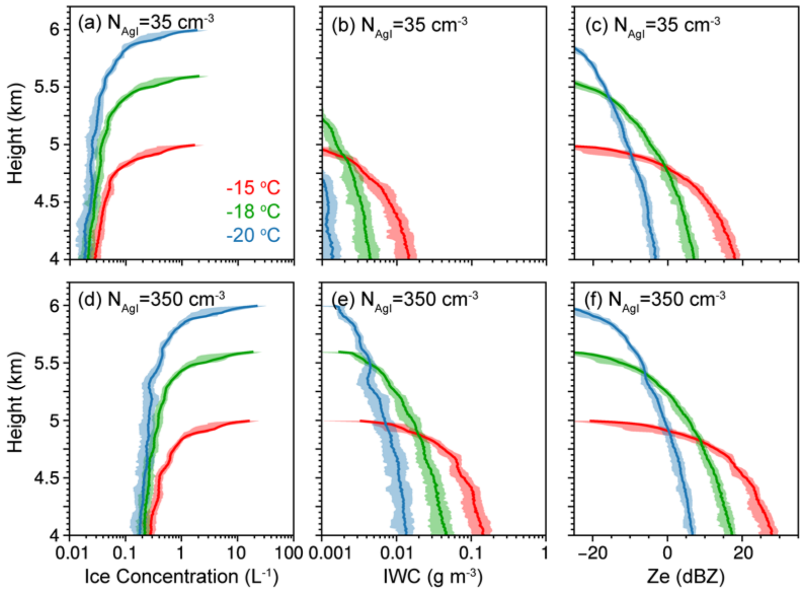

Figure R6. Vertical profiles of (a and d) ice concentration, (b and e) IWC, and (c and f) Ze from the simulations with different seeding temperatures and an AgI particle concentration of (a-c) 35 cm^{-3}, and (d-f) 350 cm^{-3}. The results are obtained based on 10 numerical experiments for each seeding temperature. The shaded area captures the 20th-80th percentile range, and the solid lines are the mean profiles.

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 Ze at a given height.

Reply: We appreciate your comment. Ice concentrations are added to the figure (Fig. R6).

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

Reply: We appreciate your comment. The figure is updated and the caption is revised accordingly.

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.

Reply: We appreciate your comment. We tried to plot the figure according to your suggestion. However, it seems the impact of cloud depth cannot be well revealed. Therefore, we prefer to use the 3D plot.

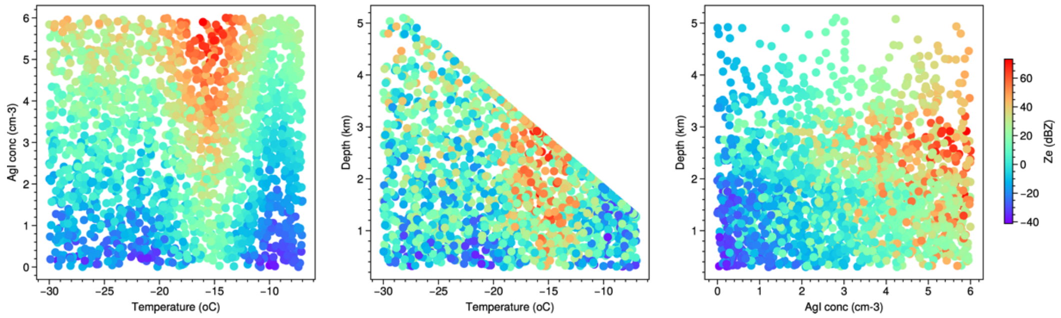

Figure R7. Scatter plots of (a) temperature vs AgI, (b) temperature vs depth, and then (c) AgI concentration vs depth with reflectivity shaded as a function of reflectivity enhancement.

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.

Reply: We appreciate your comment. This sentence is removed in the manuscript.

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

Reply: We appreciate your comment. This assumption is now stated at the beginning of this section, as well as in Section 3.1.