Responses to Reviewer 2 and the Editor

We thank both reviewers and the editor for taking time to read the manuscript and provide excellent feedback. The reviewer's comments are in black, responses in blue, and modified text in revised manuscript in *red*.

1 Response to Reviewer 2

1.1 General Comments

The readability of the paper has clearly improved with the reorganization of the sections and addition of new figures. Here just a few technical comments:

We appreciate positive feed back on improved manusciprt.

1.2 Technical comments

T1. Line 82: there is a "?" corresponding to a missing reference.

The tracked changes file has an issue with the reference, however, the revised manuscript itself has no issue.

T2 Line 106: Value for large... – The value for large...

Modified accordingly.

T3: The numbering for subsection 2.2.1 appears twice, first for "In-situ measurement data of aerosols and ice" and second for "Remote sensing data".

In the manuscript, there is no issue, however, this problem is found in the tracked changes file. Subsection 2.2.2 "Remote sensing data" follows subsection 2.2.1 I "In-situ measurement data of aerosols and ice"

T4 Line 343: In relation to the term "recycled ice crystals", I understand the explanation given in the comments, but then what is recycled are not the ice crystals but the mineral dust particles acting as INPs that can participate again in new nucleation events and form new ice crystals. By "recycled ice crystals" I would imagine ice that is transported with the downdrafts along the edge of the cloud and then close to the base is reintroduced into the cloud with an updraft, but that didn't fully sublimate. Would this be correct?

Yes you have understood correctly. Recycled ice crystals specifically mean ice crystals that did not completely sublimate in the downdrafts (where sub-saturation is present). We have replaced "recycled" with a clarifying sentence in the following way:

"Rising convective cells originate near the base of the CONV layer, where newly nucleated and ice crystals that survive sublimation in downdrafts are re-entrained into supersaturated updrafts, increasing IWC through depositional growth."

T5 Line 445: "gives some confidence in the model"– If the authors agree, I would recommend to write "gives confidence in the model", since "some confidence" sounds rather weak.

We agree. Modified accordingly.

"Given the model ICNC is found within this range, it gives confidence in the model."

T6 Caption Fig. 15: "the five simulation" – "the five simulations"

Modified accordingly.

T7 Table A1: missing TP – Tropopause"

Added TP - Tropopause to the Table A1.

2 Response to the Editor

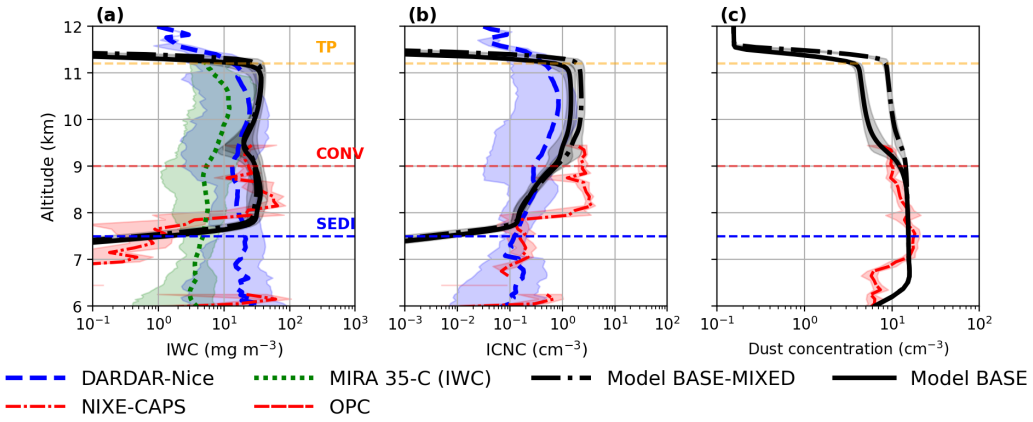
2.1 General Comments

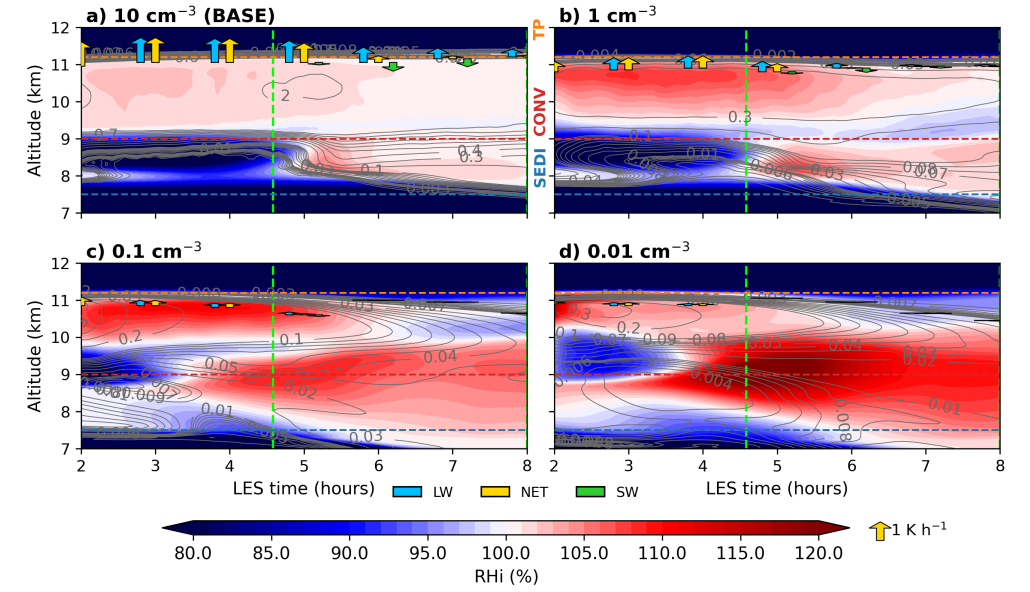
Congratulations on the updated paper. It reads much better and is much clearer now. I especially like the added process analysis (Fig. 2 in your answer/Fig. 12 in the revised manuscript). As a last step, I would like you to take care of the following minor revisions:

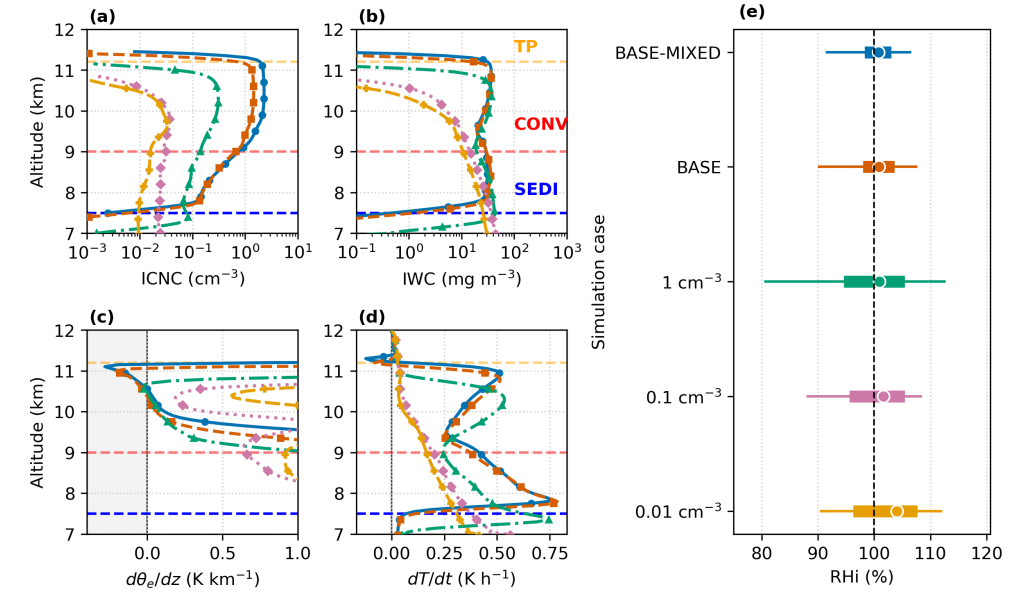
We thank the editor for constructive feed back.

Comment 1: Re-check the axis and labels of your figures. Fig. 9 and Fig. 15, the legend is quite small; in Fig. 13 the arrows are very hard to see.

Increased sizes for axis, labels and legend text of Figs 9 and 15. Increased arrow sizes in Fig. 13. Modified figures are shown below in manuscript order (Figs. 9, 13, 15).







Simulation case (layer-mean N_D, C_D)

- BASE-MIXED ($N_D = 16$ cm^{-3}, $C_D = 57$ μg m^{-3})
- BASE ($N_D = 6.7$ cm^{-3}, $C_D = 24$ μg m^{-3})
- 1 cm^{-3} ($N_D = 0.76$ cm^{-3}, $C_D = 2.7$ μg m^{-3})
- 0.1 cm^{-3} ($N_D = 0.16$ cm^{-3}, $C_D = 0.57$ μg m^{-3})
- 0.01 cm^{-3} ($N_D = 0.016$ cm^{-3}, $C_D = 0.057$ μg m^{-3})

Comment 2: The Conclusions can be improved and made stronger - I would recommend to order it around the major findings of your study (the mineral dust availability can influence the dynamical organization of cirrus (radiative-dynamical feedbacks), not just ice formation; the persistence of your dusty cirrus depends on coupled microphysical and radiative processes (with a focus on the coupled, so not only radiative interactions); the ice nucleation scheme matters) and then add some context to it (your model, the observations = your case...). Or to explicitly add your major findings a bit more clearly after the summary that you have.

Thank you for highly constructive feedback. We have now formulated the conclusions section around the key findings in this study and then follow with the model and observation comparison to add context to the results as you suggested. The conclusions read now as follows:

In this study, the conditions governing dusty cirrus persistence were investigated with large-eddy simulation UCLALES-SALSA model using data from ML-CIRRUS campaign flight that sampled these clouds. Previous regional scale model studies have shown that the interaction between mineral dust, humidity, and radiative fluxes is central to dusty cirrus evolution and to their radiative impact, including implications for solar energy production (e.g. Weger et al., 2018; Seifert et al., 2023) while lacking the ability to explain the microphysical aspects controlling dusty cirrus due to the lack of sufficiently high resolution to simulate the convection directly. In this study, these processes were explicitly resolved, which provided a more complete representation of the dynamics and microphysical aspects of the dusty cirrus. Our major findings are given below.

First, mineral dust availability influences not only ice formation but also the dynamical organization and persistence of dusty cirrus. Sensitivity experiments varying the concentration of mineral dust showed that sustained convective cirrus development can occur when mineral dust number and mass concentrations exceed climatological values by approximately one to two orders of magnitude. Persistent cirrus convection can take place even during daytime when dust concentration exceeds a threshold of around $N_D \sim 1$ cm^{-3} (in terms of mass at $C_D \sim 3$ μg m^{-3}). At these concentrations, heterogeneous ice nucleation can maintain a sufficiently high ICNC to sustain strong LW cooling at cloud top, consistent with the mechanisms proposed by Weger et al. (2018) and Seifert et al. (2023). When dust concentrations are lower, ice production weakens, LW radiative cooling becomes insufficient to maintain conditional instability, and the convective organization of the cloud decays.

Second, the persistence of dusty cirrus depends on the interplay between radiative heating and cooling, and large-scale vertical motions. The radiation sensitivity simulations indicate that dusty cirrus is most stable under nighttime conditions, when LW cooling dominates. During the day, the dusty cirrus can still persist under SW heating if dust concentrations remain high enough inside the cirrus. Beyond these radiative effects, large-scale vertical motions can further modulate convective persistence by altering in-cloud relative humidity through adiabatic cooling and warming during ascent and descent, respectively. Especially under strong and long lasting adiabatic warming under vertical descent, convective organization is suppressed effectively.

Third, the choice of DIN parameterization is a major source of uncertainty in simulated dusty cirrus. Hiranuma et al. (2014), Ullrich et al. (2017) and Phillips et al. (2013) schemes produced substantially different ice nucleation efficiencies and vertical distributions of ICNC, which altered the dynamical and radiative evolution of the dusty cirrus. With the Hiranuma et al. (2014) parameterization and dust concentrations comparable to those measured by the OPC, homogeneous freezing made no contribution to ice formation. Homogeneous freezing produced some contribution of ice when dust concentrations were reduced by an order of magnitude, corresponding to a case in which convective development was only weakly sustained but did not collapse under SW heating.

These results highlight the importance of accurately representing heterogeneous ice nucleation on mineral dust under cirrus conditions. Dusty cirrus events may therefore provide useful test bed for evaluating DIN parameterizations against observations, although uncertainties in the observed and simulated ice properties, particularly in the SEDI layer, must also be considered.
Finally, UCLALES-SALSA reproduced key characteristics of observed dusty cirrus, although the degree of agreement varied between cloud properties and vertical layers. Satellite imagery showed similarities in horizontal cloud organization, while cloud radar observations supported the representation of vertical cloud structure and dynamics. For cloud microphysics, agreement in ICNC was strongest in the convectively driven CONV layer between the in-situ observations and model results. In contrast, the comparison in the sedimentation-dominated SEDI layer was less conclusive because of discrepancies between the in-situ and remote sensings observations, as well as the sensitivity of simulated ICNC to sedimentation, vertical transport, and the ERA5-derived large-scale vertical velocity forcing, w_{LS}. Several limitations should be addressed in future work. Because we considered only a single input temperature profile for ice formation, the full temperature range over which dusty cirrus evolution is sustained remains unknown. A more comprehensive assessment would require simulations spanning a wider range of temperature conditions. Improved observational constraints, especially from targeted in-situ campaigns, are therefore needed to reduce uncertainty in the simulation of dusty cirrus systems and their climatic impact.
In summary, this study shows that the persistence of dusty cirrus emerges from coupled feedbacks between mineral dust availability for heterogeneous ice nucleation, radiative heating and cooling, and convective dynamics. The results emphasize that representing these processes in a coupled framework is essential for understanding dusty cirrus evolution and formation. Global climate model studies have yielded contrasting results regarding the impact of INPs on cirrus cloud properties and radiative effects (Beer et al., 2024). These contrasting findings underscore the need to accurately represent the sub-grid-scale processes governing cirrus evolution in global climate models, particularly the interactions between ice microphysics, radiation, and cloud dynamics."

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