Response to the reviewers on the manuscript (egusphere 2026-2416): "Origin and evolution of satellite-observed cirrus clouds using Lagrangian microphysical modeling - Part 1: Method and case studies" by Saiprakash et al.

The authors thank the reviewers for their careful reviews of our manuscript and their helpful comments and suggestions. All comments are addressed point by point below, with the comment in black, our response in blue, and the corresponding revisions to the manuscript in red. All changes of the original manuscript are marked in the revised version.

General note on title revision: Following a referee suggestion on Part 2, the title of the paper series has been slightly revised. For consistency between the two companion papers, the revised title has also been adopted for Part 1:

"Origin and evolution of satellite-observed cirrus clouds using Lagrangian bulk microphysical modeling - Part 1: Method and case studies."

Reviewer #1

General Comments:

The article introduced the DC-Ice framework, which combines satellite observations with Lagrangian parcel modeling including ice microphysics. It allows a more natural approach to characterizing cirrus origin and evolution than analyzing only Eulerian snapshots, which lack the history of ice formation, growth, and exposure to environmental conditions. The Chemical Lagrangian Model of the Stratosphere with ice microphysics is used for back-trajectory calculations from the satellite observation point. Three distinct case studies from mid-latitudes (frontal slow updraft cirrus, fast updraft cirrus, and orographic cirrus) are presented to demonstrate the capabilities of this approach. Ice nucleation mechanism, ice crystal origin, and cloud age were analyzed in detail. The results also highlight the importance of small-scale fluctuations in temperature on ice formation and cirrus evolution.

The proposed Lagrangian approach is interesting and logical for cirrus evolution, considering the critical role of history in ice crystal evolution. The manuscript has the potential to be a nice contribution to ACP. However, some improvement in presentation style is needed. It was challenging to follow the discussion of several multi-panel figures. Some of the information and related discussion are not very critical for the main points. I request that the authors simplify some of the result discussion (make it more concise) and move some of the supporting panels/plots to the supplement to avoid distraction. Moreover, caution should be exercised when considering closed/adiabatic Lagrangian parcels for analysis. Cloud parcels experience significant mixing with each other and with the local environment. These small spatiotemporal scale mixing/variabilities are highly important for individual crystal formation, growth, and overall cloud evolution, especially considering the long trajectory timescale under consideration. The current approach neglects these aspects, which could lead to spurious results/conclusions. The authors should clearly discuss why it may or may not be a problem for the cirrus evolution. Also, I didn't see any discussion of ice crystal shapes/habits or how that's factored into the process rates (like deposition, radiation, sedimentation, etc.). They also play a critical role in controlling cirrus lifetime and should be clearly addressed.

We thank the referee for the positive assessment of the proposed framework and for their constructive suggestions. The presentation of the multi-panel figures and the associated discussion may indeed be overwhelming to the readers and could be simplified to improve the manuscript clarity. Accordingly, we have revised Sect. 3.1.2 by shortening the results discussion and reducing the number of panels in the corresponding figure to highlight the key findings. The complete multi-panel figure has been moved to the Supplement to retain the additional information. The revised figure is shown below as an example of these changes.

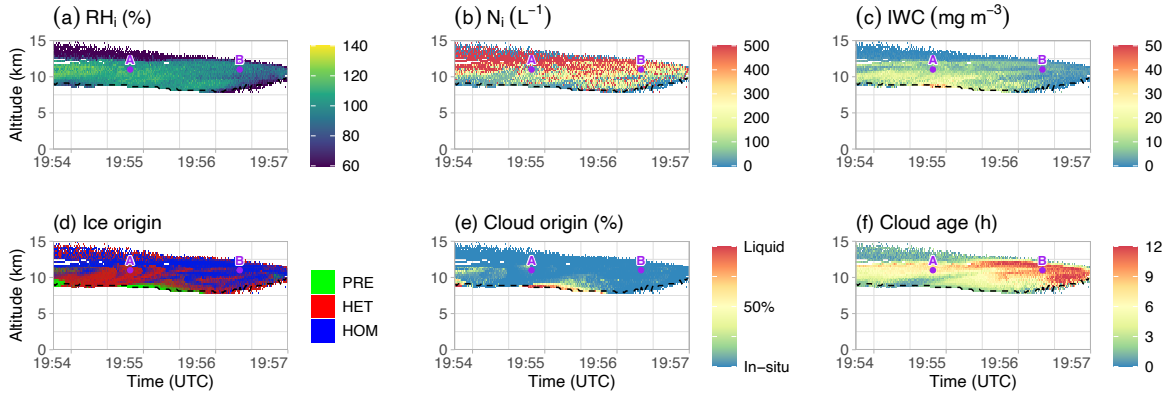


Figure R1. *Revised Fig. 4 for the slow updraft case study (03 February 2010): Vertical profiles of* ***(a)*** *relative humdity with respect to ice (RH_i),* ***(b)*** *ice number concentration (N_i),* ***(c)*** *ice water content (IWC), and* ***(d–f)*** *origin-based metrics from DC-Ice along the selected satellite overpass. The 238 K temperature threshold is indicated by the dashed black line. The purple dots indicate Parcels A and B.*

Sect. 2 has been revised to provide a clearer description of the methodology, including an improved schematic of the DC-Ice framework and additional clarifications regarding the model setup and microphysical representation.

We agree that the closed parcel assumption and the neglect of inter-parcel mixing represent a limitation of the present setup, which, however, applies mainly at the edges of the clouds where entrainment and detrainment occur. Mixing within clouds occurs most frequently in regions with stronger wind shear than is the case in larger-scale cirrus clouds with relatively weak updrafts, for example, in mixed-phase clouds or in cirrus clouds located near the jet stream (Emig et al., 2025). This can be seen from previous Lagrangian analyses of warm conveyor belt ascent, indicating that the importance of mixing depends on the dynamical environment, with moisture losses associated with turbulent mixing occurring primarily during the lower altitude part of the ascent (Schwenk and Miltenberger, 2024). More directly, previous CLaMS-Ice simulations incorporating temperature fluctuations and a pseudo-mixing term to account for changes in the total water budget showed that these processes did not substantially alter the overall distributions of ice mass mixing ratio and N_i (Sullivan et al., 2022). These findings suggest that the influence of mixing on cirrus microphysics is not necessarily dominant under most atmospheric conditions. In addition, the relatively short trajectory duration used in this study also may help limit the impact of possible inter-parcel mixing. Nevertheless, accounting explicitly for inter-parcel mixing is currently a work in progress.

To clarify this point, the following sentence has been added to Sect. 2.2.1:

"It should be noted that inter-parcel mixing is not explicitly addressed in the model, as previous studies have shown that changes in the total water budget do not substantially alter the overall distributions of ice mass mixing ratio and N_i (Sullivan et al., 2022). In addition, the relatively short trajectory duration may help limit a possible impact of inter-parcel mixing, although mixing may still occur under strong wind shear conditions."

Furthermore, the discussion of model limitations has been expanded in Sect. 6 as follows:

"Potential limitations of the DC-Ice framework arise from assumptions in its dynamical and microphysical treatment of air parcels and could constitute the focus of future improvements. The closed-parcel assumption does not explicitly account for inter-parcel mixing. However, previous CLaMS-Ice simulations incorporating temperature fluctuations and a pseudo-mixing term showed that these processes did not substantially alter the overall distributions of ice mass mixing ratio and N_i (Sullivan et al., 2022)."

Regarding the treatment of ice crystal habit and shape, additional details have been included in Sect. 2.2.2. CLaMS-Ice uses a two-moment bulk microphysical representation and does not explicitly predict the evolution of individual ice crystal habit, shape, or particle density. This simplified treatment may influence depositional growth, vapour depletion, sedimentation, and cirrus lifetime. However, since ice crystal shapes are relatively simple in cirrus clouds at very cold temperatures, with many particles being quasi-spherical (Heymsfield, 2010; Wolf et al., 2018, Fig. R2), the impact of this simplification is less significant than in mixed-phase clouds. A prognostic treatment of ice crystal habit remains beyond the scope of the present study and is noted as a direction for future model development in Sect. 6.

Accordingly, the following clarification has been added to Sect. 2.2.2:

"However, since ice crystal shapes are relatively simple in cirrus clouds at very cold temperatures, with many particles being quasi-spherical (Heymsfield, 2010; Wolf et al., 2018), the impact of this simplification is less significant than in mixed-phase clouds."

This point has also been further addressed in the discussion of model limitations in Sect. 6:

"The shape of ice crystals, which may affect depositional growth, vapour depletion, particle fall speed and cirrus lifetime, is treated in a simplified manner in the model. This simplification is justified as the ice crystal shapes are relatively simple in cirrus clouds at very cold temperatures, with many particles being quasi-spherical (Heymsfield et al., 2010; Wolf et al., 2018)."

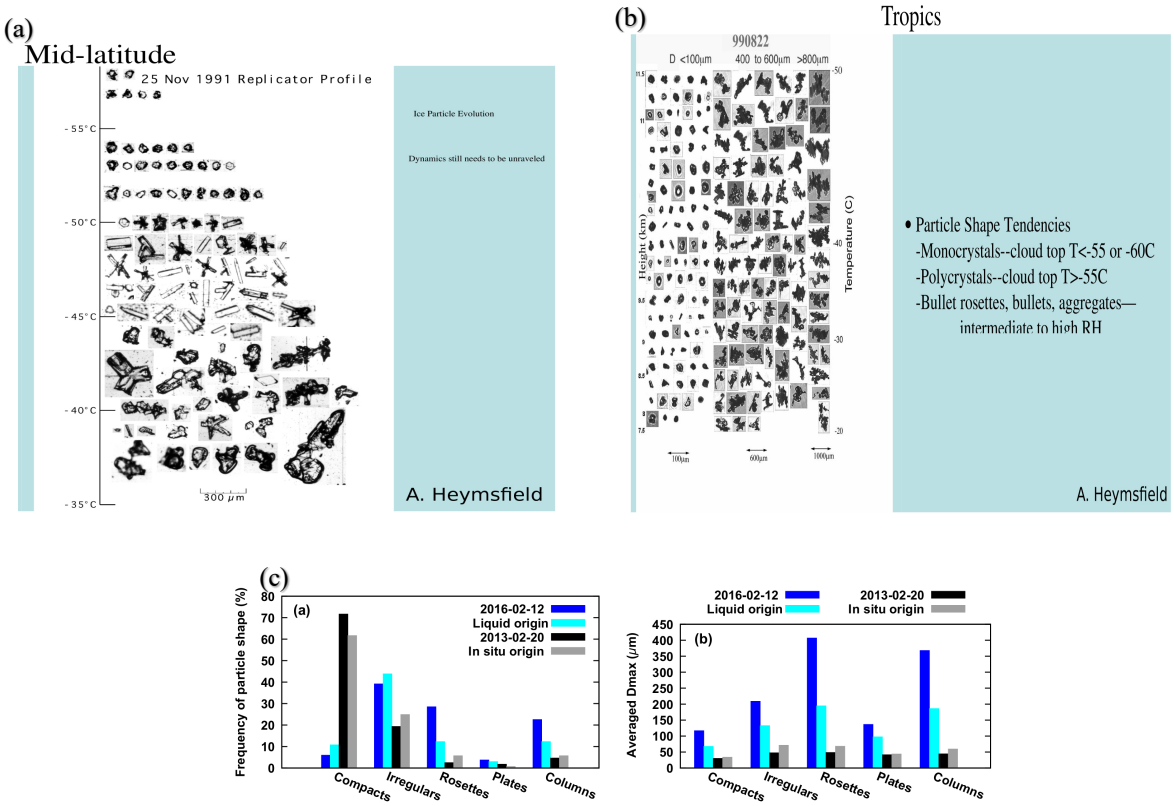


Figure R2*. Ice crystal shapes observed in cirrus clouds: (a) vertical distribution of ice crystal habits in midlatitude cirrus (Heymsfield and Iaquinta, 2000), (b) ice crystal shapes observed in tropical cirrus (Heymsfield et al., 2002), and (c) occurrence of different ice particle shapes in Arctic ice clouds according to cloud origin (Wolf et al., 2018).*

Here are a few other specific comments:

Figure 1 - It may be inaccurate to demonstrate the parcel trajectories as an ice crystal trajectory in this figure. The suggested approach only provides bulk average statistics of the parcel along a large-scale Lagrangian trajectory (not an individual ice crystal trajectory). The current representation is misleading.

Thanks for this helpful comment. Our initial aim with Fig. 1 was to highlight that CLaMS-Ice tracks the microphysical evolution of cirrus parcels, but we agree that the current version gave the impression that it happens at the individual crystal level rather than for bulk properties. The Fig. 1 schematic has been improved accordingly to avoid this misleading interpretation, as shown in Fig. R3 below.

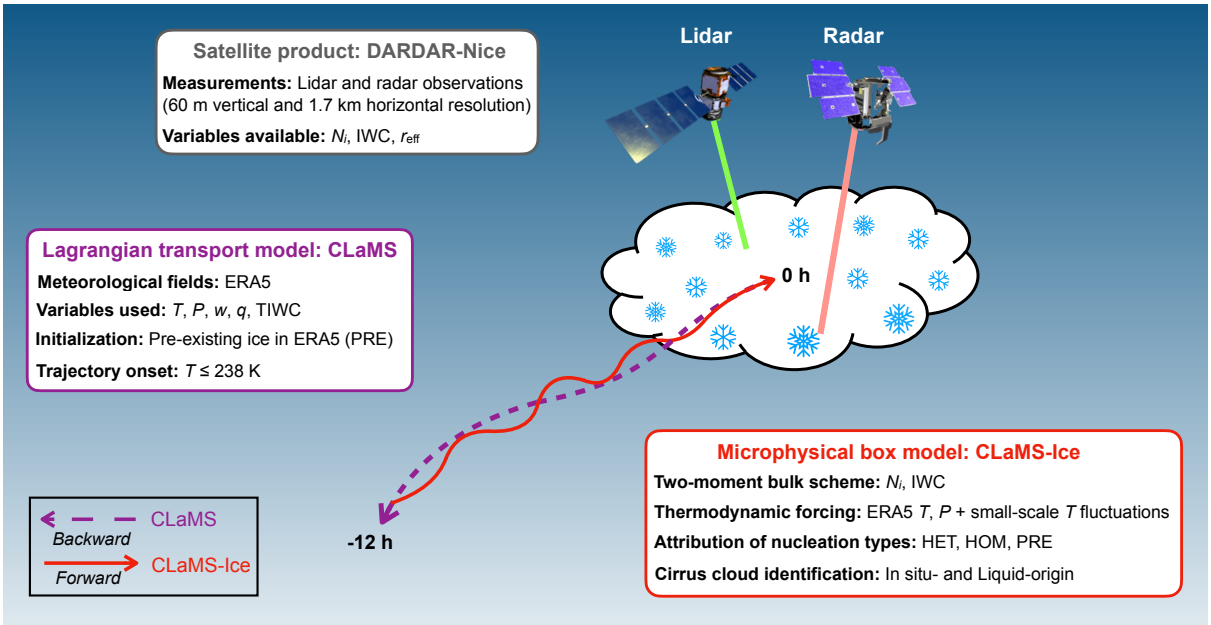


Figure R3*. Revised Fig. 1 of the manuscript, illustrating the DC-Ice framework.*

L127 - Please explicitly state which nucleation parameterizations are used here.

We have added a more complete description to the manuscript.

"The model incorporates homogeneous ice nucleation of aqueous aerosol particles (Koop et al., 2000) and heterogeneous ice nucleation, where prescribed INPs nucleate ice once the heterogeneous freezing threshold is reached (Spichtinger and Gierens, 2009b), as well as depositional growth of ice crystals, sublimation, and sedimentation (Spichtinger and Cziczo, 2010), with respective parameters (e.g., critical supersaturation, INP concentration, and sedimentation rate) specified during initialization."

L127- More information about the deposition growth model is needed, e.g., whether it uses spherical ice or tracks the shape/habit evolution; how are different habits or morphology represented? Also, how are all this information coupled with sedimentation, radiation, and aggregation?

The model does not explicitly track ice crystal habit or shape evolution; instead, depositional growth is represented in a two-moment bulk framework following Spichtinger and Gierens (2009a), based on the vapour-density difference between the ambient air and the ice crystal surface, with kinetic and ventilation corrections. Shape effects are represented only in a simplified way through the capacitance factor. The resulting mass and number tendencies are coupled to the other microphysical processes, including sublimation, and sedimentation, through the prognostic bulk quantities. Radiation is not interactively coupled in the present CLaMS-Ice simulations. We have updated the text to clarify these points.

"Depositional growth is calculated from the vapour-density difference between the ambient air and the ice crystal surface, including kinetic and ventilation corrections. Ice crystal shape and habit evolution are not explicitly tracked, with shape effects represented in a simplified manner through the capacitance factor (Spichtinger and Gierens, 2009a). However, since ice crystal

shapes are relatively simple in cirrus clouds at very cold temperatures, with many particles being quasi-spherical (Heymsfield, 2010; Wolf et al., 2018) , the impact of this simplification is less significant than in mixed-phase clouds. These microphysical processes are coupled through their contributions to the prognostic bulk ice mass and number concentrations. Radiation is not interactively coupled in the present simulations."

L134-135 - The initial temperature, humidity, aerosols, etc. might also be highly variable at small scales. But the authors did not consider such variability. It could be crucial for how the trajectory samples evolve. The authors should consider running the Lagrangian parcel calculations for a range of initial conditions around the mean ERA5 data.

We agree that variability in the initial thermodynamic and aerosol conditions can influence parcel evolution. This question is tackled by our methodology via the ensemble approach, where each of the 10 members undergo different temperature fluctuations along the parcel lifetime and their initial drawn INP concentration also differ (the value is taken randomly from a defined log-normal distribution with a geometric mean of 0.01 cm^{-3}, which is used to define the initial INP distribution from which an N_{INP} value is sampled at the start of each trajectory). Furthermore, to address related uncertainties associated with our environmental assumptions, Part 2 of this series (Saiprakash et al 2026) investigates several sensitivity tests, including the amplitude of small-scale temperature fluctuations, INP concentrations, heterogeneous freezing threshold, sedimentation treatment, and trajectory duration. Previous CLaMS-Ice sensitivity work by Costa (2017) showed that average reanalysis-based initialization can provide reasonable agreement at larger scales, while localized case study simulations may remain sensitive to microphysical input parameters such as water vapour and INP concentration. This is now made more explicit by adding in text.

"The initial mean INP concentration N_{INP}, representing the prescribed background environmental INP concentration for heterogeneous nucleation (Kanji et al., 2017). A log-normal distribution with a geometric mean of 0.01 cm^{-3} is used to represent variability in the initial INP concentrations, from which a value is randomly sampled at the start of each trajectory."

"Variability in the initial thermodynamic and aerosol conditions is represented through the ensemble approach, in which members experience different temperature fluctuations along the parcel lifetime, and their sampled initial INP concentrations differ between trajectories. The influence of key model parameters and associated uncertainties is further examined through sensitivity analyses in Part 2 (Saiprakash et al., 2026)."

L143-145 - More information is needed on how these fluctuations are modeled; for example, does it use an approach based on Lagrangian stochastic differential equations (e.g., a Langevin-type model)? If so, what is the timescale and magnitude of the forcing (fixed or varying over time)?

The manuscript has been revised to provide more detail on the implementation of the small-scale temperature fluctuations.

"These fluctuations are incorporated using the stochastic parametrization of Podglajen et al. (2016), derived from Superpressure balloon measurements during the PreConcordiasi campaign. Random vertical velocity perturbations are generated from white noise following a Laplace distribution with a standard deviation of 0.16 m s^{-1}. These perturbations are integrated with a time step of 200 s to obtain synthetic vertical displacements and their amplitude is scaled by a fluctuation factor f_T based on midlatitude vertical velocities measured during the ML-CIRRUS campaign. After filtering low-frequency components following Podglajen et al. (2016), the resulting displacements are converted into temperature perturbations using the adiabatic relation and added to the ERA5-driven CLaMS temperature."

L146 - Another key shortcoming of this and similar bulk Lagrangian approaches is that they generally neglect inter-parcel mixing. Considering these trajectories represents large-scale evolution, not local parcel trajectories; mixing of parcels with various initial conditions and temporal histories should also be accounted for to achieve a more realistic cloud parcel evolution.

The issue of inter-parcel mixing has been addressed in our response to the general comment above, and additional clarifications have been included in Sects. 2.2.1 and 6 of the revised text.

L147-148 - The sample size of just 10 seems too low, given the expected variability in the temperature field. The authors should demonstrate convergence with the number of samples.

We acknowledge that the ensemble size is an important aspect of the stochastic temperature fluctuation approach. The choice of 10 ensemble members was a compromise between sampling the variability introduced by the stochastic fluctuations and the computational cost of running the full set of CLaMS-Ice simulations for all trajectories and case studies.

To assess the effect of ensemble size, we performed an additional parcel-scale sensitivity test for Parcel A, the representative parcel analysed in Fig. 3, situated at an altitude of 11 km along the CloudSat track at 19:54:49 UTC. We tested smaller ensembles as well as 10, 50, and 100 members. As shown in Fig. R4, temperature and RH_i are relatively stable across ensemble sizes, and IWC shows broadly similar behaviour. However, N_i and the ice origin metric are more sensitive to ensemble size (Figs. R4 and R5), particularly in the timing and relative contribution of homogeneous nucleation, which depends on the peak RH_i reached due to the stochastic temperature fluctuations. In contrast, the cloud origin classification remains relatively insensitive, with the parcel remaining mainly in situ-origin at the overpass. Overall, the origin-based interpretation at the satellite overpass remains broadly consistent across ensemble sizes, which is relevant because these metrics are used primarily as complementary diagnostics for interpreting the satellite observed cloud state.

This indicates that the 10-member ensemble captures the overall thermodynamic evolution, but may under sample rare or intermittent nucleation events. A full rerun of all case studies with larger ensembles was not feasible within the present study because of computational cost. A discussion of this limitation has been added to Sect. 6, noting that larger ensembles would be preferable in future applications.

"The 10-member ensemble, chosen considering computational costs, may undersample rare or intermittent ice nucleation events, suggesting that larger ensembles would allow better statistical sampling of these processes in future global-scale applications of DC-Ice."

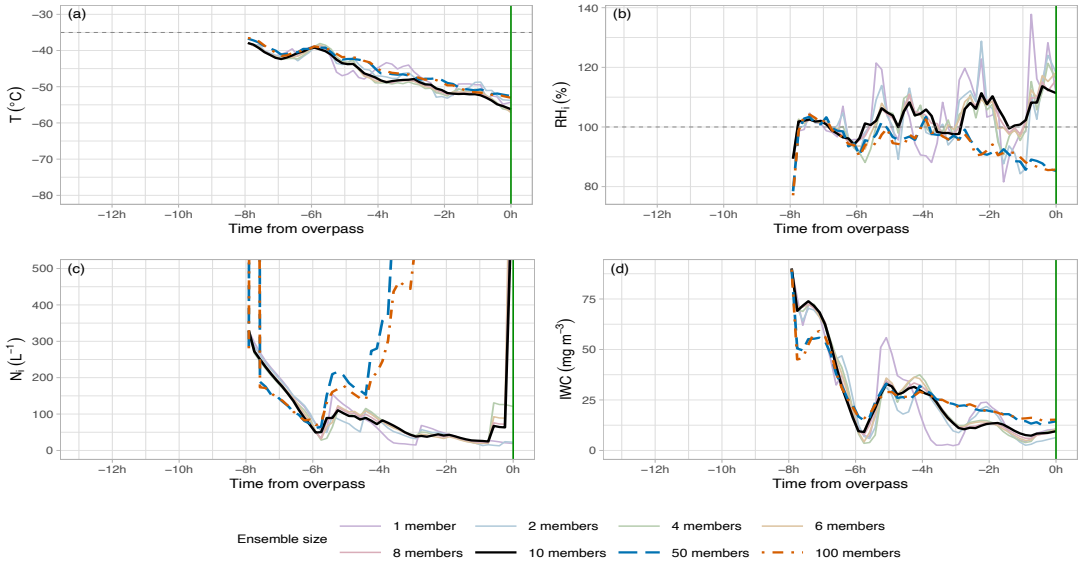


Figure R4. *Ensemble-size sensitivity test for Parcel A, corresponding to the representative parcel analysed in Fig. 3 of the manuscript. The figure compares ensemble sizes from 1 to 100 members for (a) temperature, (b) RH_i, (c) N_i and (d) IWC.*

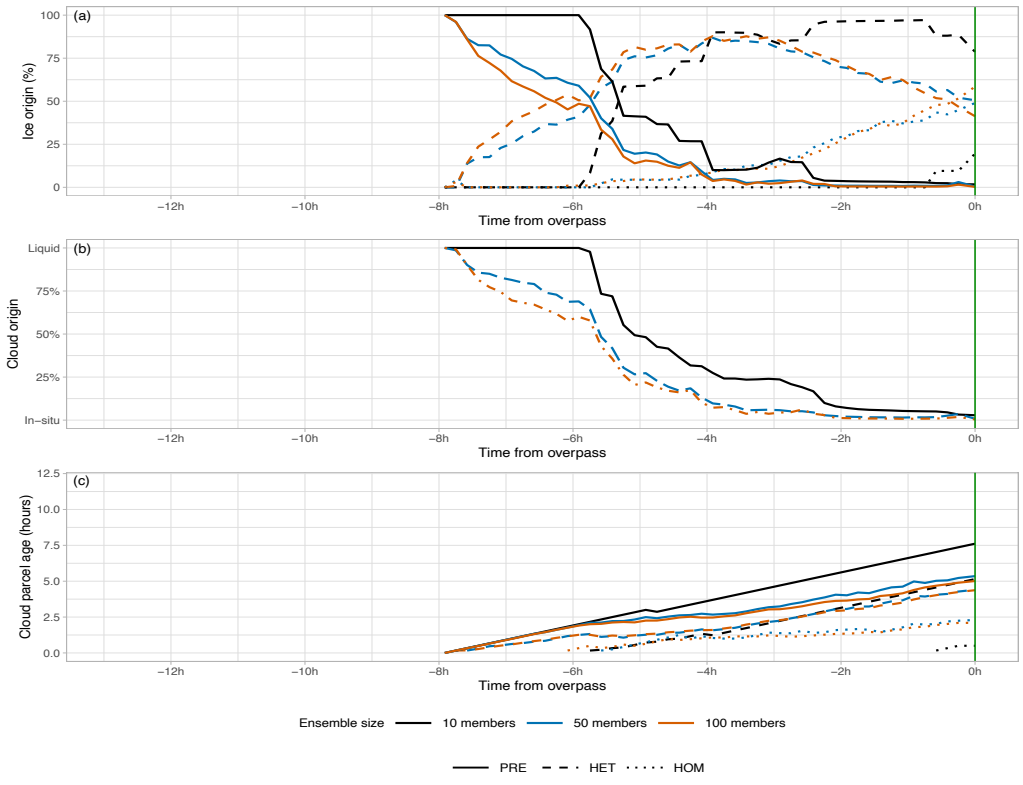


Figure R5. *Same as Fig. R1, but for the origin-based metrics: (a) ice origin, (b) cloud origin, and (c) cloud parcel age, comparing 10, 50, and 100 ensemble members.*

Table 1 – "Initial mean INP concentration" - This must also be highly variable along the long-range trajectories under consideration. Assuming the closed-parcel approach and neglecting the environmental INP concentration variability is not a reasonable approach. It may lead to erroneous conclusions about homogeneous-heterogeneous competition and the fresh homogeneous nucleation phase.

We agree that the environmental INP concentration may vary along long-range trajectories and that this can influence the competition between heterogeneous and homogeneous nucleation. In the present CLaMS-Ice setup, a prescribed background INP concentration is used as an initial condition, with individual trajectories initialized using INP concentrations randomly sampled from a log-normal distribution. The subsequent INP budget evolves through the embedding of INPs in ice crystals and their release upon sublimation. However, this uncertainty is partly addressed in Part 2 through sensitivity tests of the prescribed INP concentration and heterogeneous freezing threshold. This has now been clarified in Sect. 2.2.2 of the revised text, with its implications for future model development also acknowledged in Sect. 6.

"The INP concentration is modulated by the sublimation or nucleation of ice particles from in situ-formed and pre-existing ice, while variations in the environmental background INP concentration along the trajectories are not explicitly considered."

"Variations in the environmental background INP concentration along the trajectories could be considered in further model developments, given their possible influence on ice formation pathways."

Figure 3 - Why does the N_i timeseries show significant jumps for individual trajectories? Similarly, INP also has dramatic jumps.

The abrupt changes in N_i primarily result from new ice nucleation events, which cause N_i to rise sharply when the freezing threshold is exceeded, particularly during homogeneous freezing. Similarly, changes in INP concentration can result from INP release upon sublimation of pre-existing ice and INP consumption during heterogeneous nucleation. In the current setup, the CLaMS-Ice output shown in Fig. 3 is recorded at every 10 min, while the microphysical calculations are performed with much shorter adaptive time steps, typically on the order of 0.1–10 s. As a result, rapid microphysical changes occurring between two saved output times can appear abrupt in the plotted trajectories. The text has been updated accordingly.

"However, it is worth noting that the RH_i shown in panel (e) corresponds to instantaneous values recorded at the end of the microphysical calculations, with an output frequency of 10 min. RH_i may be higher between two saved output times, allowing nucleation events to be triggered, but such short-lived peaks are not necessarily captured in the plotted output."

3.1.2 - This section can be shortened significantly by focusing on key aspects of the results. The 12-panel figure is also distracting and can be simplified by removing a few panels and focusing on the main results. It was also hard to go back and forth between Fig. 2 and Fig. 4 to compare the model results with retrievals.

Sect. 3.1.2 has been shortened to focus on the key results, and the corresponding figure has been simplified from 12 to 6 panels to improve readability and facilitate comparison with the satellite retrievals. The complete multi-panel figure has been moved to the Supplement. The revised figure is shown as Fig. R1 in our response to the general comments above.

'WCB' is used only few times. Please consider spelling it everywhere for ease of the general readers.

Changed

Figure 5 - Clearly, CLaMS-Ice does not seem to capture the variability and structure seen in the DARDAR-Nice observation. CLaMS-Ice gives a more uniform field over time, but DARDAR-Nice shows distinct pockets and higher vertical gradients (a separate high concentration region near the top). The authors should briefly discuss the comparison of model results with observations, model shortcomings, and the reasoning behind the model's deviations from observations. Based on the abstract, I assume the model evaluation is discussed in Part II. But some discussion of the model-observation comparison and the model shortcomings are needed here as well.

Thanks for the suggestion and text has been revised accordingly.

"Compared with DARDAR-Nice, the CLaMS-Ice fields also appear smoother and more spatially uniform, suggesting that some localized pockets of enhanced N_i and sharper vertical gradients observed by the satellite are not fully reproduced. This difference may be related to limitations in the ERA5-driven CLaMS trajectories, including the representation of local vertical velocity, humidity variability, and mesoscale cloud displacement (Tompkins et al 2007) as well as the coarser spatial sampling of the backward trajectory starting points compared with the satellite retrieval resolution. Since these factors can affect simulated ice formation and growth, Part 2 further evaluates the model-observation differences through comparisons of DC-Ice outputs with different satellite retrievals and, where available, in situ measurements, together with sensitivity experiments assessing the influence of key model parameters."

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