Response to Reviewer #1

We sincerely thank Reviewer #1 for the constructive and insightful feedback. We appreciate the recognition of the conceptual advance provided by the GCCN-ISP mechanism, and we address each suggestion below (black text: reviewer's comments, blue text: our response, orange text: manuscript revisions):

Comment 1 (Line 102 and elsewhere): "'saturated' should be changed to 'saturation'

Response: Corrected. And we have revised the manuscript to replace all incorrect uses of "saturated vapor pressure" with "saturation vapor pressure" to ensure consistency and accuracy.

Comment 2 (Lines 124–125): "You mention no new water supplied by turbulent mixing. First, you mean by updrafts. Second, you should discuss the implications of having updrafts on your model calculations."

Response: We thank the reviewer for this helpful comment and have revised the manuscript accordingly.

In atmospheric clouds, the evolution of cloud droplet size is influenced by two key factors: (1) the ambient water vapor pressure, which controls the vapor availability for condensation or deposition, and (2) the equilibrium saturation vapor pressure over the droplet surface, which depends on droplet size, curvature, and composition (via the solute effect).

Vertical motion (updrafts) affects the ambient vapor pressure by inducing adiabatic cooling and enhancing supersaturation (G.Abade et al., 2024; M.Guti'errez et al., 2023). Such updrafts can slow the Wegener–Bergeron–Findeisen (WBF) process by supplying moisture and sustaining supersaturation, thereby delaying the depletion of supercooled droplets (G.Abade et al., 2024; A.Khain, M. Pinsky and A. Korolev., 2021; A. Korolev and I. Mazin., 2003). Vertical motion determines the ambient water vapor pressure, thereby affecting the activation of cloud droplets and the rate of primary ice formation. This dynamical factor operates independently from the solute effect of cloud condensation nuclei (CCN), which modifies the equilibrium properties of individual droplets. In contrast, the solute effect in our study, acts by lowering the equilibrium saturation vapor pressure over supercooled droplets, thereby changing the thermodynamic balance point. It can allow liquid droplets to persist even when the environment would otherwise favor ice growth. In this way, both updrafts and solute effects can extend the lifetime of mixed-phase clouds—but via distinct physical mechanisms.

This distinction motivates our modeling choice: by neglecting vertical motion, we isolate the solute effect as an internal microphysical process, enabling a clear quantification of its standalone contribution to droplet–ice vapor competition. We have added the following discussion:

Line 129 "As mentioned earlier, in this equation, there is no new water supplied by turbulent mixing, meaning that updrafts are not considered. In atmospheric clouds, the evolution of cloud droplet size is governed by two key factors: (1) the ambient water vapor pressure, which determines the vapor availability for condensation or deposition, and (2) the equilibrium saturation vapor pressure over the droplet surface, which is influenced by droplet size, curvature, and composition (via the solute effect). Updrafts affect cloud microphysics by cooling air parcels and enhancing supersaturation, thereby suppressing the WBF process and delaying ice growth (G.Abade et al., 2024; M.Guti'errez et al., 2023; M. Pinsky and A. Korolev., 2021). In contrast, the solute effect reduces the surface saturation vapor pressure, directly influencing whether supercooled droplets can persist. This study intentionally excludes vertical motion to isolate the microphysical contribution of the solute effect to droplet–ice vapor competition."

Comment 3 (Line 125): "'decreases at a rate' should be changed to 'changes at a rate as follows'"

Response: We have revised the sentence to “changes at a rate as follows” to allow both increases and decreases of supersaturation, depending on the conditions.

Comment 4 (Line 125): “Mention that S is dependent upon the droplet/ice particle size distributions and vertical velocity.”

Response: We have revised the text to explicitly state that the supersaturation is influenced by both droplet and ice particle size distributions, as well as vertical velocity, which together determine the rates of vapor condensation and deposition. As our response in Comment 2, the discussion of the vertical motion effects has been added to the revised manuscript.

Comment 5 (Lines 127–128): “It also changes due to S. You assume that S decreases.”

Response: We agree and correct it in the text.

Comment 6 (Lines 177–186): “What if vertical velocities of let’s say 10, 50 and 100 cm/s are assumed?”

Response: Thank you for this suggestion. As noted in our response to Comment 2, we intentionally neglect vertical motion in our model to isolate the microphysical role of solute effects on the droplet–ice vapor balance. Including vertical velocity would modify the ambient water vapor pressure and enhance supersaturation, thereby influencing the rate of droplet activation and primary ice formation.

Previous studies have investigated this aspect in detail. For example, Lu et al. (2012) show that with increasing vertical velocity the droplet number concentration increases while the relative dispersion decreases. Specifically, the study by J. Bühl, P. Seifert, R. Engelmann and A. Ansmann. (2019) demonstrates that increasing the standard deviation of vertical velocity from 0.1 to 1.0 m/s leads to a two-fold increase in the mass flux of ice water in clouds with cloud-top temperatures below −12°C.

We acknowledge its importance while emphasizing that the goal of our work is to provide a theoretical baseline under specific conditions. We agree that applying prescribed updrafts (e.g., 10–100 cm/s) in future model extensions will help quantify how solute effects and dynamic forcing interact.

Comment 7 (Line 225): “What you mean here is the curvature effect.”

Response: We have revised the manuscript to explicitly name the curvature effect (Kelvin effect), which influences the equilibrium RH of droplets depending on size.

Line 239: The saturation vapor pressure increases for smaller droplets due to the curvature effect (also known as the Kelvin effect), which enhances evaporation from highly curved droplet surfaces.

Comment 8 (Section 4.1): “How is the growth of the ice particles considered? That is, things like ventilation coefficient, particle mass, etc.”

Response: Thank you for pointing this out. In our model, we do not explicitly calculate the growth rate of ice particles, as the focus is on the phase transition from supercooled liquid to ice rather than on the detailed microphysics of ice growth. We do not include the ventilation coefficient, particle mass, or other factors that influence the precise growth rate of ice particles. These processes, such as riming or aggregation, depend on microphysical details beyond the scope of this study. We intend to capture the onset and general behavior of freezing, rather than to quantitatively model the full evolution of ice particle size.We have clarified this modeling choice in Section 4.1:

Line 234: “Ice particle growth is treated through vapor deposition under a temperature-dependent saturation vapor pressure over ice. Detailed growth processes, such as the effect of the ventilation coefficient and mass transfer, are not included, as the focus here is on the phase transition rather than the rate of ice growth.”

Comment 9 (Line 271): “Particle size distribution. How about the ice particle size distribution, which is interesting and relevant. Also, effective diameter usually considers both the liquid and ice phase together.”

Response: In this study, we focus on the size distribution of supercooled liquid droplets, and the effective radius calculated refers exclusively to the liquid phase. Following the classification criteria used in AFLUX measurements and previous studies (e.g., Brown and Francis, 1995), particles smaller than 50 μm are assumed to be droplets, while those larger than 50 μm are classified as ice.

We have now clarified this point in the manuscript by explicitly stating that the calculated effective radius corresponds only to the droplet mode, not the combined liquid–ice population.

Line 203 “According to AFLUX observations, particles >50 μm are classified as ice (Brown and Francis, 1995). Therefore, the effective particle radius calculated in this study refers specifically to the supercooled liquid droplets (<50 μm).”

Comment 10: “What are the implications of the proposed process?”

Response: We thank the reviewer for this important question. Many current models assume CCNs are primarily small particles (<1 μm), which tends to result in rapid ice growth via the WBF process and an underestimation of cloud liquid water content and lifetime. Our study highlights that the presence of giant CCN can enhance local vapor depletion around large droplets, thus prolonging liquid water persistence. This finding may help explain the observed longevity of mixed-phase clouds in the Arctic and underscores the need to incorporate GCCN-ISP into atmospheric models to improve simulation of cloud phase partitioning and climate feedbacks.

Line 400 ”Finally, we emphasize the broader climatic relevance of the GCCN-ISP mechanism. The persistence of supercooled liquid water affects the radiative properties and lifetime of mixed-phase clouds. Suppressing the WBF process via solute effects could extend cloud persistence, potentially altering cloud radiative forcing and Arctic amplification. This mechanism also highlights the need to better represent giant CCN and their solute effects in models, as current schemes tend to underestimate their influence on phase partitioning. Although the present study does not explicitly quantify such impacts, we hope to explore these implications in future work by coupling the GCCN-ISP framework with climate models.”

References:

G. Abade et al. "Persistent mixed-phase states in adiabatic cloud parcels under idealised conditions." Quarterly Journal of the Royal Meteorological Society, 150 (2024): 3450 - 3474. https://doi.org/10.1002/qj.4775.

M. Guti'errez et al. "Steady-state supersaturation distributions for clouds under turbulent forcing." Journal of the Atmospheric Sciences (2023). https://doi.org/10.1175/jas-d-23-0155.1.

A. Khain, M. Pinsky and A. Korolev. "Combined effect of the Weber-Bergeron-Findeisen mechanism and large eddies on microphysics of mixed-phase stratiform clouds." Journal of the Atmospheric Sciences (2021). https://doi.org/10.1175/jas-d-20-0269.1.

A. Korolev and I. Mazin. "Supersaturation of Water Vapor in Clouds." Journal of the Atmospheric Sciences, 60 (2003): 2957-2974. https://doi.org/10.1175/15200469(2003)060<2957:SOWVIC>2.0.CO;2.

J. Bühl, P. Seifert, R. Engelmann and A. Ansmann. "Impact of vertical air motions on ice formation rate in mixed-phase cloud layers." npj Climate and Atmospheric Science, 2 (2019): 1-5. https://doi.org/10.1038/s41612-019-0092-6.

Lu, C., Y. Liu, S. Niu, and A. M. Vogelmann (2012), Observed impacts of vertical velocity on cloud microphysics and implications for aerosol indirect effects, Geophys. Res. Lett., 39, L21808, doi:10.1029/2012GL053599.

E. Ávila, R. Pereyra, N. Castellano and C. Saunders. "Ventilation coefficients for cylindrical collectors growing by riming as a function of the cloud droplet spectra." Atmospheric Research, 57 (2001): 139-150. https://doi.org/10.1016/S0169-8095(01)00067-9.

Wusheng Ji and Pao K. Wang. "Ventilation coefficients for falling ice crystals in the atmosphere at low-intermediate Reynolds numbers." Journal of the Atmospheric Sciences, 56 (1999): 829-836. https://doi.org/10.1175/1520-0469(1999)056<0829:VCFFIC>2.0.CO;2.

Brown, P. R. A., and P. N. Francis, 1995: Improved Measurements of the Ice Water Content in Cirrus Using a Total-Water Probe. J. Atmos. Oceanic Technol., 12, 410–414, https://doi.org/10.1175/1520-0426(1995)012<0410:IMOTIW>2.0.CO;2.