Response to Editor Comments on "Impacts of Environmental Conditions and Ice Nuclei Recycling on Arctic Mixed-Phase Cloud Properties"

Response to Editor:

We first want to thank the editor for taking the time to review our manuscript, and for helping guide the peer review process for this manuscript as a whole. We sincerely appreciate it.

Editor comments:

Please use the terms "INP" (ice nucleating particle) and "INPs" (ice nucleating particles) throughout the manuscript, as these are now the most widely accepted and commonly used terms within the ice nucleation community (see Vali et al., 2015).

Vali, G., DeMott, P. J., Möhler, O., and Whale, T. F.: Technical Note: A proposal for ice nucleation terminology, Atmospheric Chemistry and Physics, 15, 10263–10270, https://doi.org/10.5194/acp-15-10263-2015, 2015.

We agree with this suggestion, and have changed our use of "IN" in the text and figures to "INP." We have however kept the simulation names (INFLUX, DRY_INFLUX, HIGHIN) as is.

I also suggest to use the past tense when describing your simulations and results, as they represent work that has already been completed.

We have changed our description in "Methods" to use past tense, except where describing aspects of the model itself (as opposed to the simulation).

Lines 96-156: As we ~~are~~ were interested in examining the behavior of ice crystals under vapor deposition with little impact from collisional processes, we chose to simulate a single-layer precipitating mixed-phase Arctic stratocumulus cloud observed on 26 April 2008 during Flight 31 of the Indirect and Semi-Direct Aerosol Campaign (ISDAC, McFarquhar et al. (2011)). This cloud was observed both by ground-level remote sensing instruments and in situ aircraft observations. Observations of this day indicated that the majority of ice crystals were pristine, with little indications of riming or aggregation (Jackson, 2012). Additionally, the single-layer nature of the cloud ~~precludes~~ precluded seeder-feeder effects and ~~reduces~~ reduced the chances of ice-ice collisions.Drizzle was also absent, indicating a lack of collisional growth among cloud droplets (Ovchinnikov et al., 2014). Therefore, droplet collisional growth, riming, aggregation, and secondary ice production were disabled in our simulations. This particular cloud has been examined extensively by other modeling studies, making it a good case to simulate as our results can be compared with those of previous work (Ahola et al., 2020; Das et al., 2025; Fu and Xue, 2017; Paukert and Hoose, 2014; Raatikainen et al., 2022; Savre and Ekman, 2015; Sulia and Kumjian, 2017).

Initial environmental conditions ~~are~~ were identical to those used in Ovchinnikov et al. (2014) and depicted here in Skew-T format in Figure 1. The boundary layer ~~is~~ was initially decoupled from the surface, as evidenced by the stable lapse rate between the surface and 400 m. Between 400–650 m, there ~~is~~ was a well-mixed (dry adiabatic) layer, while between 650 and 820 m, the atmosphere ~~follows~~ followed a moist adiabatic lapse rate. We also ~~initialize~~ Initialized all simulations with condensate following an adiabatic LWP profile between 650–820 m (not shown). The maximum initial value of liquid water mixing ratio ~~is~~ was 0.163 g kg^{-1} at 820 m. Zonal wind ~~is~~ was initially set to −7 m s−1 throughout the domain, while meridional wind ~~varies~~ varied linearly with height from −2 m s−1 at the surface to 4.735 m s−1 at 2250 m (here, negative values for zonal and meridional wind indicate easterly and northerly winds, respectively). Initial temperatures ~~are~~ were approximately −8.7 ◦C at

the surface, between −13 ◦C and −15 ◦C within the cloud, and −10.5◦C at the maximum of the above-cloud inversion. All simulations ~~use~~ used 10 meter vertical and 20 meter horizontal grid spacing, with 144 vertical levels and 64 grid points in each horizontal dimension. Horizontal boundaries ~~are~~ were periodic, with a rigid model top at 1.44 km. Simulations ~~are~~ were run with a 0.5 second timestep for 8 hours. Subgridscale turbulence ~~is~~ was parameterized with a 1.5 order TKE-based closure, while radiation ~~is~~ was parameterized using a Liquid Water Content (LWC)-profile approach as in Ovchinnikov et al. (2014). Surface energy fluxes ~~are~~ were neglected as in Ovchinnikov et al. (2014). Initial CCN number mixing ratio ~~is~~ was 200 mg^{-1} (~267 cm^{-3} at the lowest model level) and initial ~~IN~~ INP number concentration ~~is~~ was 1 L^{-1}. To reduce computation time, we only ~~add~~ added SDs up to 1200 m of altitude.

We ~~do~~ did not permit ice formation at the start of the simulation, but rather ~~restrict~~ restricted it to occur beginning one hour after the start of the simulation. This ~~is~~ was done to permit a radiatively driven cloud circulation and STBL to begin to form without competition from ice crystals for water vapor. After one hour, SDs containing ~~IN~~ INP which are in liquid-supersaturated conditions were allowed to to undergo probabilistic immersion freezing. The probability of a given SD freezing ~~is~~ was calculated using a parameterization based on the behavior of SNOWMAX bacteria (Wex et al., 2015). SNOWMAX bacteria become active INP at approximately −5 ◦C and maintain approximately the same ice nucleating activity between −10 and −20 ◦C. Because temperatures within the cloud during this case ~~are~~ were between −13 and −15 ◦C, the use of a SNOWMAX parameterization for ice nucleating activity therefore ~~ensures~~ ensured that most ~~IN~~ INP-containing particles ~~freeze~~ froze within only a couple of timesteps after they ~~enter~~ entered liquid-supersaturated conditions. Once a particle has nucleated, its SD type ~~is~~ was instantly set to "ice" rather than "liquid". The ice nucleation parameterization used in this study ~~takes~~ took no account of the amount of ~~IN~~ INP contained within an SD, but rather ~~uses~~ used a simple “~~IN~~ INP/No ~~IN~~ INP” binary classification for SDs. Future modeling work will explore the sensitivity of cloud microphysical evolution to different species or sizes of ~~IN~~ INP as described in Fu and Xue (2017).

To test the sensitivity of particle growth and cloud properties to both environmental conditions and microphysical parameterization, we present results from seven simulations. Initially, these were a CONTROL case using the same initial atmospheric profile as that used in Ovchinnikov et al. (2014), a DRY case in which the water vapor mixing ratio above 825 m was reduced from 1.2 to 0.8 g kg^{-1}, a WEAKINV case in which the inversion strength was reduced from 3.5 K to 1.5 K, and a DRY_WEAKINV case combining the weaker inversion strength of WEAKINV and the reduced above-cloud water vapor mixing ratio of DRY. Note that in WEAKINV, above-cloud water vapor mixing ratio is unchanged, meaning that the above-cloud relative humidity ~~increases~~ increased relative to CONTROL due to the reduced inversion strength.

During the course of our analysis, we also discovered that depletion of ~~IN~~ INP through particle sedimentation was an important factor in controlling both ice and liquid growth rates in all simulations. To examine the impact of perfectly-efficient ~~IN~~ INP recycling on cloud microphysical and boundary-layer evolution, we ran an additional two simulations, one with CONTROL environmental conditions and one with DRY conditions, in which any particle which reached the surface was re-injected into the below-cloud boundary layer as a dry CCN/~~IN~~ INP particle. Note that in this manuscript, the "efficiency" of ~~IN~~ INP recycling refers to the fraction of ice crystals which return their ~~IN~~ INP to the boundary layer through sublimation rather than precipitate to the surface. "Perfectly efficient" ~~IN~~ INP recycling thus indicates that all ~~IN~~ INP are returned to the boundary layer, rather than removed through precipitation. These simulations are denoted as INFLUX and DRY_INFLUX. We should emphasize that the INFLUX and DRY_INFLUX simulations ~~are~~ were not meant to represent a specific process such as surface emission of INP. Rather, they ~~serve~~ served as a counterfactual to the CONTROL and DRY simulations, allowing us to disentangle the effects of free-tropospheric thermodynamics from INP recycling on the cloud microphysical properties.

To assess the sensitivity of cloud properties to increased free-tropospheric ~~IN~~ INP number concentration, we conducted a simulation, HIGHIN, in which initial ~~IN~~ INP number concentrations above the inversion layer ~~are~~ were increased by a factor of 5.6 (reflecting the high-~~IN~~ INP conditions in Hiranuma et al. (2013)). The results of HIGHIN are discussed very briefly in section 3.2.

However, for describing modeling results and conclusions, it is common to use present tense (Georgakaki et al., 2022; Qu et al., 2022; Solomon et al., 2015; Sotiropoulo et al., 2021). As such, we would prefer to keep our results and discussion in present tense.

We have also corrected our acknowledgements to use the initial of the editor and one anonymous reviewer, rather than their full names, as helpfully suggested by the editorial staff.

References:

Georgakaki, P., Sotiropoulou, G., Vignon, É., Billault-Roux, A.-C., Berne, A., and Nenes, A.: Secondary ice production processes in wintertime alpine mixed-phase clouds, Atmos. Chem. Phys., 22, 1965–1988, https://doi.org/10.5194/acp-22-1965-2022, 2022.

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