REVIEW FOR SUN ET AL.

(egusphere-2025-3620)

This is a modeling study that focuses on Arctic mixed-phase stratus and their sensitivity to different formulations of the immersion freezing mechanism (IMF). Sensitivity simulations are performed with a simplified 1D aerosol-cloud model that investigates a lot of interesting aspects, such as the different impact of using deterministic and CNT IMF schemes on the cloud ice crystal budget and their response to variations in aerosol load, microphysical properties (terminal velocity) and thermodynamic parameters (cloud-cooling and cloud-top entrainment rate). Overall, it is an interesting study that highlights how sensitive is the representation of the complex interactions between primary ice production and thermodynamic/aerosol processes to the choice of IMF parameterization. However my main worries concern whether the findings are truly representative of the Arctic mixed-phase cloud conditions

MAIN COMMENTS:

(A) The case study is constructed using thermodynamic measurements from SHEBA and aerosol inputs from ISDAC and ICEALOT campaigns. While ISDAC and ICEALOT occurred in spring, it is not clarified to which season the SHEBA case corresponds to. The Arctic aerosol composition exhibits seasonal and spatial variability with long-range transport of dust and anthropogenic aerosols peaking in late winter–spring ("Arctic haze") and marine organic/sea-spray sources dominating in summer. This seasonal variability is also reflected in the INP composition/origin (Creamean et al. 2022).

Here, the prescribed dust load appears low, yet multiple observational studies show that dust intrusions into the Arctic can be important during certain periods, often linked to springtime transport from Asian or Saharan sources. Similarly, sea-spray emissions depend on open-water fraction and wind-driven surface conditions, which vary seasonally and geographically. Therefore, a short discussion on how the chosen PSDs and thermodynamic properties align in season and location would be useful, along with clarifications on the Arctic conditions that are represented by this case.

(B) The authors mainly show results related to the activatable INPs and ice crystal number. I think it would be very useful to show results related to activated INPs and compare to the vast literature that has been recently published on Arctic INPs (e.g. Wex et al. 2019, Creamean et al. 2022, etc). I suspect that the CNT formulations might predict INP concentrations that are outside (above) the observed range, suggesting that these two parameterizations are not suitable for Arctic conditions.

(C) I think that the highly idealized nature of these simulations is underdiscussed. Mixed-phase microphysical processes are complex and the impact of processes like WBF, riming and aggregation can largely affect the ice crystal size distribution and eventually the available ice crystal budget. Taking into account these processes could likely change the relative contribution of each IMF parameterization to the ice number and affect their interactions with other processes, like sedimentation. Moreover, there is increasing evidence that secondary ice production (SIP) is important in Arctic stratocumulus. Accounting for SIP can also impact how the ice crystal budget responds to different IMF parameterizations (and whether the choice of IMF remains that important). All these uncertainties should be discussed in the final section. Considering a cloud that is unaffected by these processes suggests limited representativeness of the real Arctic conditions

MINOR COMMENTS:

Line 185: you probably refer to Figure 2. What is the liquid water path range?

Line 216: Here it is mentioned that SSA PSDs are based on measurements above sea, while the SHEBA case corresponds to pack-ice conditions (see main comment A)

Line 218: composite. Figure 1 should be 2

Section 2.3: Are primary ice production and sedimentation the only microphysical processes accounted in the model? This should clearly stated that other important processes are ignored (e.g. WBF, riming, etc) Also are there any aerosol processes accounted for?

Line 278: Could you provide references for dust being negligible in the Arctic? There are many studies that do not support this claim (e.g. Boo et al. 2023; Creamean et al 2022)

Section 2.4: The description of sensitivity simulations is a bit confusing. E.g. CCR=0.3 is listed as sensitivity test, while based on the caption of figure 2, I would assume that the same CCR is applied in the CTRL simulation. If CCR is zero in CTRL simulation then this should be listen Table 4. If green profiles in Figure 2 concern only the sensitivity test and not CTRL case, this should be clearly explained in the caption

Line 285-287: Also it should be explicitly stated that CTRL simulation is run with a single aerosol type

Line 308: also shown in Figure 2(?)

Line 310: clarify that each PSD corresponds to different aerosol type

Line 503: Why organic INPs are more sensitive to temperature changes?

Line 576: black instead of brown

Fig 7 is confusing. There is a light solid brown line in panels a and b, not include in the legend. Also dashed blue line is not visible in panel a

Fig 8 is confusing. Is it the logarithmic scale that inhibits the demonstration of the whole vertical profile?

Lines 663-666: why does this happen?

Lines 737-738: I would rephrase. For example, regarding the need of additional ice production mechanisms, this is not simply a theoretical perception; observations indicate the occurrence of such mechanisms in Arctic clouds. Observing INP recycling of course is not possible. Moreover, please compare the CNT INP predictions to Arctic measurements (see main comment B). This way we might get an idea of whether CNT-like processes can be truly dominant in the Arctic, which is generally known as a low-INP region.

Lines 815-817: You can include an important test by including INP measurements from the literature (again comment B)

REFERENCES

Creamean, J.M., Barry, K., Hill, T.C.J. *et al.* Annual cycle observations of aerosols capable of ice formation in central Arctic clouds. *Nat Commun* 13, 3537 (2022). https://doi.org/10.1038/s41467-022-31182-x

Wex, H., Huang, L., Zhang, W., Hung, H., Traversi, R., Becagli, S., Sheesley, R. J., Moffett, C. E., Barrett, T. E., Bossi, R., Skov, H., Hünerbein, A., Lubitz, J., Löffler, M., Linke, O., Hartmann, M., Herenz, P., and Stratmann, F.: Annual variability of ice-nucleating particle concentrations at different Arctic locations, Atmos. Chem. Phys., 19, 5293–5311, https://doi.org/10.5194/acp-19-5293-2019, 2019.