

Responses to reviewer comments on the revised manuscript “Interacting effects of droplet number and ice formation processes on mixed-phase cold-air outbreak clouds”

We thank both reviewers for their time and effort in reviewing our responses and the revised manuscript. Detailed responses to each comment from the Reviewer #1 are shown below.

Line numbers and section numbers may change in the revised manuscript, so line numbers correspond to the original manuscript when referring to that, and they refer to the latest revised manuscript when referring to changes made.

Response to comments by Reviewer #1

Reviewer comment (1)	II. 321-323: To my best knowledge this might be the first case where TWP increases under greater N_{inp} (e.g., via higher N^{15}_{INP} or E_{HM}). Looking at previous LES studies using ranging N_{inp} (e.g., Tornow et al., 2021, Wu et al., 2022, Juliano et al., 2026), these studies also find an IWP increase and a LWP decrease – but in those studies the LWP decrease was stronger compared to the IWP increase, uniquely resulting in an overall TWP decrease. There are several things to consider for the authors: (1) Could this be a model-specific behavior? COMBLE-MIP (Juliano et al., 2026) focusses on one specific case and illustrates the strong diversity across models regarding their LWP and IWP changes under ice. (2) Are these special conditions? That is, are other studies looking at CAO cases where WBF is less dominant, for example due to generally higher RH_w? (3) Could other processes be at play? Ideally, the authors provide a quantitative measure of WBF strength to show that it explains TWP change. In my opinion, the authors should thoroughly address such questions in their discussion (point 1 and 2), and even expand their analysis (point 3).
Our response:	As the three questions are associated with the TWP responses to the perturbation of ice formation processes, we address them together below for clarity. Note that some figures referenced in the response below correspond to figures in the cited papers and are highlighted in blue to distinguish them from figures in the revised manuscript and in this response. Our study is not the first to report an increase in TWP associated with stronger ice formation. The result (Figure 4c) from Wu <i>et al.</i> (2025) shows that after approximately 15 hours since ice edge, the TWP from a high ice concentration simulation (ice25) is higher than the one from a low ice concentration simulation (ice01), while the highest TWP is from the lowest number concentration at earlier stages. This is similar to what we have

found in this study, that is the TWP reduces with stronger ice formation processes in the Sc region, while increase in the Cu region. Although Lee *et al.* (2021) examined midlatitude mixed-phase stratocumulus rather than marine CAO clouds, they likewise found that increasing INP enhanced depositional growth and increased TWP (Figure 9).

Our IWP and LWP responses to a higher ice number concentration in the Sc region are also similar to the results from Tornow *et al.* (2021), but the IWP in the Cu region in their study (Figure 2d) becomes much less sensitive to ice number concentration, which is different from our IWP responses in the Cu region. The study by Juliano *et al.* (2026) suggests that models show diverse responses to switching from liquid-only to mixed-phase setup, which is consistent with the reviewer. We agree that the parametrisations and treatment of cloud processes in different models may lead to different responses and sensitivities to ice formation processes. We have now expanded on this in the Discussion and Conclusions section; please see the “New text” section below for the added content.

The WBF process is not represented as a separate prognostic process in our model configuration because condensation is treated within the bimodal cloud scheme. Therefore, we cannot provide a quantitative measure of WBF strength here, but we can estimate its role by looking at RH (relative humidity) to ice and RH to liquid in the Cu region from the control simulation, shown in Figure R1. One thing we would like to highlight here is that ice growth by vapour deposition does not necessarily imply WBF. In addition to vapour supplied by evaporating cloud droplets, ice particles can also grow from ambient water vapour. Between 1 and 2 km ASL (above sea-level) where most of the cloud occurs, given an approximately 5% supersaturation to ice and a mean specific humidity of about 0.002 kg kg^{-1} , the introduction of more ice can increase the total water path by up to approximately 100 g m^{-2} for a cloud layer with 1 km thickness. As shown by the central 90% intervals of RHs, all three thermodynamic regimes described by Korolev (2007), including simultaneous liquid and ice growth, WBF-favourable conditions, and simultaneous evaporation/sublimation, occur within the Cu region. This suggests that the Cu region in our case is thermodynamically heterogeneous rather than uniformly WBF-dominated, and therefore the net cloud response reflects the combined effects of various local processes.

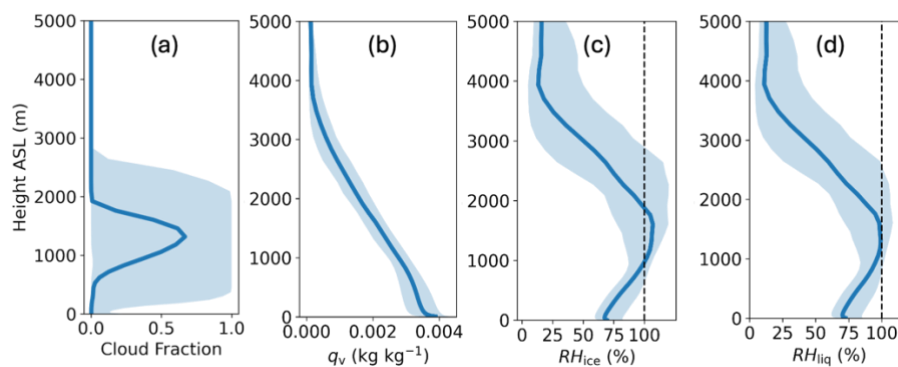


Figure R1. (a) Bulk cloud fraction, (b) specific humidity (q_v), (c) relative humidity to ice (RH_{ice}) and (d) relative humidity to liquid (RH_{liq}) in the Cu

region. The solid blue line represents the median value, and the shaded region represents the central 90% interval (5% percentile to 95% percentile).

Other processes can also contribute to the TWP responses as a result of stronger ice formation processes in the Cu region. In addition to stronger deposition of water vapour, a higher ice number concentration may also reduce the snow autoconversion efficiency, the size and the falling speed of ice hydrometeors, hence leading to less removal of cloud water through frozen rain process and increasing IWP and TWP. This effect is more evident in the Cu region where precipitation is much stronger compared to the Sc region, as shown in Figure 7 of our previous work (Huang *et al.* 2025). We have now added this in the Results section. Analysing or even emulating process rates would provide further insight into these mechanisms, but such diagnostics are highly state-dependent and require careful treatment and processing, which is beyond the scope of this work on the purpose of revealing interactions between parameters. We therefore recommend this as a potential future work.

To the best of our knowledge, we are not aware of CAO study that has specifically investigated on a condition when WBF is less dominant. However, as different responses of TWP to ice formation processes are seen in different regions even in the same case presented in our work, we expect the balance between various processes to be case- and regime-dependent. The positive TWP response reported here should not be regarded as universal response to increasing ice formation, but rather as a response under the environmental conditions examined in this study. We have expanded the Discussion and Conclusions section to include a discussion on this.

References:

Huang, X., Field, P. R., Murray, B. J., Grosvenor, D. P., van den Heuvel, F., and Carslaw, K. S.: Different responses of cold-air outbreak clouds to aerosol and ice production depending on cloud temperature, *Atmospheric Chemistry and Physics*, 25, 11363–11406, <https://doi.org/10.5194/acp-25-11363-2025>, 2025.

Juliano, T. W., et al.: The Cold-Air Outbreaks in the Marine Boundary Layer Experiment model–observation intercomparison project (COMBLE-MIP), Part I: Model specification, observational constraints, and preliminary findings, *EGUsphere*, 2026, 1-53, <https://doi.org/10.5194/egusphere-2026-1237>, 2026

Korolev, A.: Limitations of the Wegener–Bergeron–Findeisen mechanism in the evolution of mixed-phase clouds, *J. Atmos. Sci.*, 64, 3372–3375, <https://doi.org/10.1175/JAS4035.1>, 2007.

Lee, S. S., Ha, K.-J., Manoj, M. G., Kamruzzaman, M., Kim, H., Utsumi, N., Zheng, Y., Kim, B.-G., Jung, C. H., Um, J., Guo, J., Choi, K. O., and Kim, G.-U.: Midlatitude mixed-phase stratocumulus clouds and their interactions with aerosols: how ice processes affect microphysical, dynamic, and thermodynamic development in those clouds and

	interactions?, Atmospheric Chemistry and Physics, 21, 16843–16868, https://doi.org/10.5194/acp-21-16843-2021, 2021. Tornow, F., Ackerman, A. S., and Fridlind, A. M.: Preconditioning of overcast-to-broken cloud transitions by riming in marine cold air outbreaks, Atmospheric Chemistry and Physics, 21, 12049–12067, https://doi.org/10.5194/acp-21-12049-2021, 2021. Wu, P., Ovchinnikov, M., Xiao, H., Lackner, C. P., Geerts, B., Tornow, F., and Elsaesser, G.: Effect of ice number concentration on the evolution of boundary layer clouds during Arctic marine cold-air outbreaks, Journal of geophysical Research: Atmospheres, 130, e2024JD041282, https://doi.org/10.1029/2024JD041282, 2025.
Old text:	L321-L323: <i>“When ice formation processes are stronger in the Cu region (e.g., a higher N_{INP}^{-15} or E_{HM}), the reduction in cloud liquid is smaller than the increase in cloud ice, leading to a net increase in total water path (Figure F3). This is because the increase in IWP results not only from the direct conversion of liquid to ice, but also from stronger vapour deposition onto ice than onto liquid at the same temperature.”</i>
New text:	L327-L335: <i>“When ice formation processes are stronger in the Cu region (e.g., with a higher N_{INP}^{-15} or E_{HM}), the reduction in cloud liquid is smaller than the increase in cloud ice, leading to a net increase in TWP (Figure F3). This is because the increase in IWP results not only from the direct conversion of liquid to ice, but also from stronger vapour deposition onto ice than onto liquid at the same temperature. In addition, a higher ice number concentration can reduce snow autoconversion efficiency and decrease the size and fall speed of ice hydrometeors, thereby reducing cloud-water removal through frozen precipitation and increasing IWP and TWP. This effect is more pronounced in the Cu region, where precipitation is substantially stronger than in the Sc region. Analysing the relevant process rates would provide further insight into these mechanisms, but this is beyond the scope of the present study. We therefore recommend that future work investigate the joint effects of these processes on TWP responses across different cloud regimes and CAO conditions.”</i> L498-L512: <i>“Opposite responses of TWP to stronger ice formation processes (e.g., a higher N_{INP}^{-15} or E_{HM}) are observed in the two regions, with particularly large variations in the Cu region. Stronger ice formation reduces TWP in the Sc region but increases TWP in the Cu region. Wu et al. (2025) similarly showed that a simulation with a high ice number concentration produced a higher TWP than one with a low ice number concentration approximately 15 hours after the ice edge, although the simulation with the lowest ice number concentration produced the highest TWP at earlier stages. Lee et al. (2021) focused on mid-latitude mixed-phase stratocumulus and also found that increasing INP concentrations enhanced depositional growth and increased TWP. Our IWP and LWP responses to a higher ice number concentration in the Sc region are also comparable to those reported by Tornow et al. (2021). However, the IWP</i>

	<i>in their Cu region was much less sensitive to ice number concentration than that found in our study. Juliano et al. (2026) showed that models exhibit diverse LWP and IWP responses when switching from liquid-only to mixed-phase configurations. We therefore suggest that differences in the parameterisation and treatment of cloud processes among models may contribute to their differing sensitivities of cloud water paths to ice formation. Given that the TWP response to ice formation processes differs even between regions within the same case examined here, we expect the balance among processes to be both case- and regime-dependent. The positive TWP response identified in this study should therefore not be interpreted as a universal response to increased ice formation.”</i>
Reviewer comment (2)	II. 88ff. Given that above studies used interactive surface fluxes, it would be important to clarify if surface fluxes were fixed in this study. Currently there is no information provided.
Our response:	The sea surface temperature and surface fluxes are fixed in our model setup. We have now added this information in the revised manuscript.
Old text	N/A
New text	L109-L110: <i>“The model is set to the atmosphere-only configuration with prescribed sea surface temperature (SST) and fixed surface fluxes. The mean SST in the Sc region is 277.5 K and is 280.5 K in the Cu region.”</i>
Reviewer comment (3)	II. 88ff Given that different ice habits may result in differently strong WBF process rates (Avramov and Harrington, 2010), the authors should clarify which habit was assumed for cloud ice.
Our response:	We have now added a brief description of cloud ice and snow habits in the Methods section.
Old text:	L120: “Figure 2 shows the main processes in CASIM with...”
New text:	L120: <i>“Figure 2 shows the five hydrometeors and the main processes in CASIM with...”</i> L125-128: <i>“In CASIM, cloud ice is represented as a spherical particle ($m \propto D^3$, where m is mass and D is diameter of a hydrometeor) and snow is represented as aggregate particles ($m \propto D^2$) based on findings from Cotton et al. (2013) (Field et al., 2023). Details for terminal fall speed, mass-dimension and shape of the particle size distribution of each hydrometeor in CASIM can be found in Table A1 in Field et al. (2023) and the calculation of the ventilation coefficient is presented in Equation A23 in Field et al. (2023).”</i>