

Responses to reviewer comments on the 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 manuscript. Their insightful comments have greatly helped us improve the scientific quality of our manuscript.

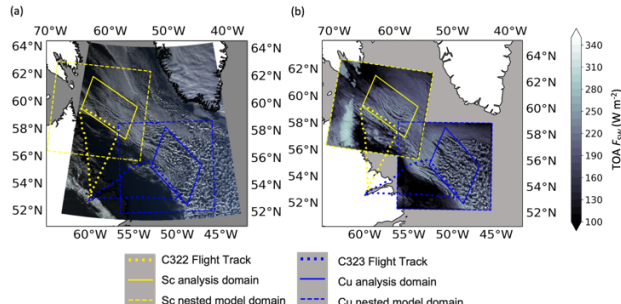
Detailed responses to each comment are shown below.

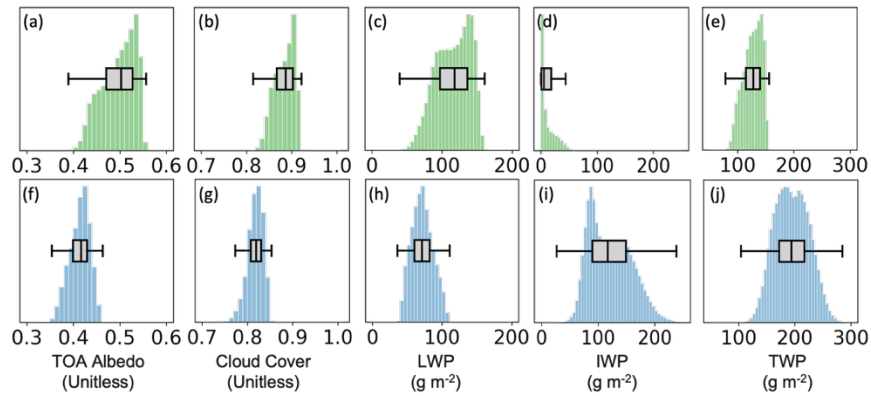
Line numbers and section numbers may change in the revised manuscript, so line numbers correspond to the original manuscript when referring to that, and they refer to the revised manuscript when referring to changes made.

Changes made besides the response to reviewer comments are documented after our responses to reviewer comments.

Response to comments by Reviewer 1

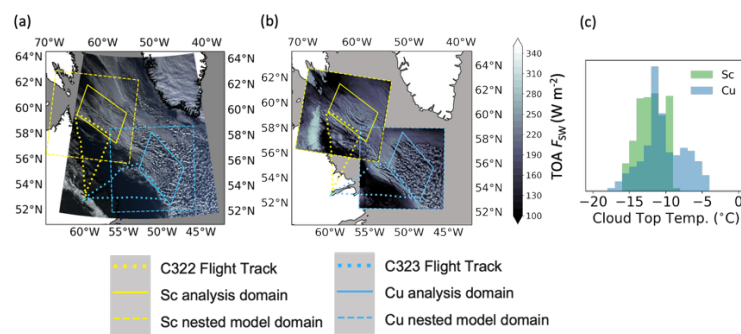
Reviewer comment (1)	21 – I wonder if there are any other studies that could be cited here?
Our response:	We cited Korolev et al. (2017) because it provides a comprehensive review of mixed-phase clouds. The statement here describes a well-established characteristic of mixed-phase clouds that has been examined in many previous studies. Rather than attempting to cite all relevant studies, we have added references related to the Wegener–Bergeron–Findeisen (WBF) process, which is the best-known microphysical processes in mixed-phase clouds, and the textbook from Pruppacher and Klett (1996), in addition to the review from Korolev et al. (2017).
Old text:	<i>L19-L21: “In these mixed-phase clouds, liquid and ice hydrometeors exist at the same time, and the radiative properties of these clouds are strongly controlled by the characteristics and interactions of these hydrometeors at the microphysical scale (Korolev et al., 2017).”</i>
New text:	<i>L19-L22: “In these mixed-phase clouds, liquid and ice hydrometeors exist at the same time, and the radiative properties of these clouds are strongly controlled by the characteristics and interactions of these hydrometeors at the microphysical scale (Wegener, 1911; Bergeron, 1935; Findeisen, 1938; Findeisen and Findeisen, 1943; Pruppacher and Klett, 1996; Korolev et al., 2017).”</i>
Reviewer comment (2)	54-59 Please also include Elsaesser et al. (2025) here.
Our response:	We have now added the work from Elsaesser <i>et al.</i> (2025) into the corresponding paragraph.

Old text	<p>L57-L59: <i>“...constraining model parametric uncertainties with observations (Johnson et al., 2020; Regayre et al., 2023) and identifying the potential existence of structural deficiencies in climate models (Regayre et al., 2023; Prévost et al., 2025).”</i></p>
New text	<p>L58-L61: <i>“...constraining model parametric uncertainties with observations (Johnson et al., 2020; Regayre et al., 2023), identifying the potential existence of structural deficiencies (Regayre et al., 2023; Prévost et al., 2025) and parameter calibration (Elsaesser et al., 2025) in climate models.”</i></p>
Reviewer comment (3)	<p>Sec. 2.1 I wonder if the author could list cloud-top temperature (CTT) here (e.g., from a typical configuration). Assuming that CTT varies across configurations (e.g., I would expect stronger ice processes to produce lower/warmer cloud-tops, thereby preventing themselves) and if not too much work, perhaps CTT could even be added to Fig. 6?</p>
Our response:	<p>We have added distributions of cloud top temperature (CTT) from control simulations of the two domains in Figure 1(c). Please note that we also changed the colour of C323 track and boundaries of the Cu regions in Figure 1, following the suggestion from Reviewer #2.</p> <p>We agree with the reviewer that the variation and dependency of CTT to the perturbation of these parameters are interesting to investigate. Therefore, we have added distributions of CTT from 1 million model variants in Figure 6, distributions of CTT changes from multiple OAT tests in Figure 9, paired-projections for both domains in Figure F4 in Appendix F, and results from the global sensitivity analysis of CTT in Figure G1 in Appendix G. Please refer to the “New text” box below for the new Figure 1, Figure 6, and added content in the main context. Please refer to tracked changes for the new Figure 9, Figure F4 and Figure G1 as they are too big to shown in this document.</p> <p>Please also note that the output time for CTT is different from the time for the other variables. CTT is not a direct output from the UM model and requires further processing using 3-D cloud field (e.g., mass mixing ratio of all five cloud hydrometeors). We only output specific time points for these 3-D fields to compare with in-situ observations in a subsequent work. Such choice on the output time points was to save storage space from PPE simulations.</p>
Old text:	 <p>(a) (b)</p> <p>Legend:</p> <ul style="list-style-type: none"> C322 Flight Track Sc analysis domain Sc nested model domain C323 Flight Track Cu analysis domain Cu nested model domain <p>TOA F_{sun} ($W m^{-2}$)</p>



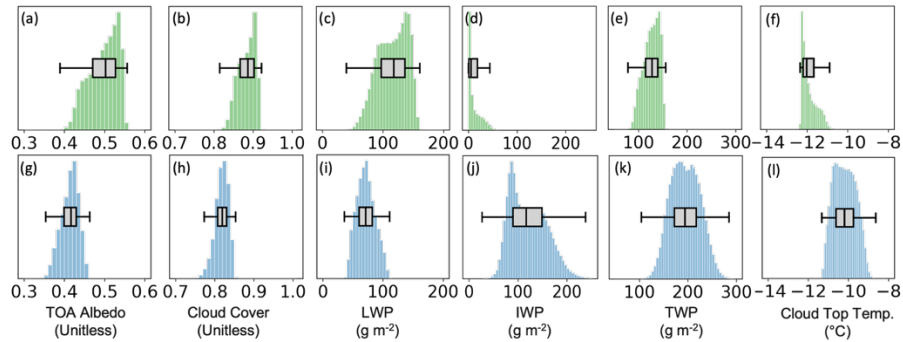
New text:

The new Figure 1 is shown below with the updated caption.



“Figure 1. Flight tracks (dotted line), nested model domains (dashed squares) and model analysis domains (solid rectangles) for Sc region (yellow) and Cu region (blue) on 24 October 2022 over the Labrador Sea: (a) the RGB satellite imagery created using bands 1 (620-670 nm), 3(459-479 nm) and 4 (545-565 nm) from MODIS (Moderate Resolution Imaging Spectroradiometer) Level 1B Calibrated Radiances Product (Collection 6.1) (MODIS Characterization Support Team (MCST), 2017) onboard the Aqua satellite, (b) the SW (shortwave) reflectance at the top-of-the-atmosphere from the control simulations. The selected model time is the same as the satellite retrieval time at 17:00 UTC and the model output fields are instantaneous. Cloud top temperatures in the two analysis domains are shown in (c). The cloud top temperatures were derived using the air temperature at the highest model level in a column, with a cloudy grid defined using total cloud water content $\geq 10^{-6} \text{ kg kg}^{-1}$. The model output time for CTT in the Sc region is 14:00 UTC and is 19:00 UTC in the Cu region for the corresponding times of flights. The temperature profiles were evaluated in our previous work (Huang et al., 2025).”

The new Figure 6 is shown below with the updated caption.



“Figure 6. Distributions of cloud variables from 1 million combinations of parameter values for (a,g) all-sky TOA albedo (unitless), (b,h) cloud cover (unitless), (c,i) all-sky LWP (g m^{-2}); (d,j) all-sky IWP (g m^{-2}), (e,k) TWP (g m^{-2}) which is the sum of LWP and IWP, and (f,l) cloud top temperature ($^{\circ}\text{C}$). Separate distributions are shown for the Sc (top row) and Cu (bottom row) regions.”

L286-L290:

“Cloud top temperature (CTT) is derived from the air temperature at the highest model level in a column with total cloud water content $\geq 10^{-6} \text{ kg kg}^{-1}$. The model output is taken at 14:00 UTC for the Sc region and 19:00 UTC for the Cu region, corresponding to the times of the M-Phase C322 and C323 flights respectively. An evaluation of modelled air temperature against aircraft measurements can be found in Huang et al. (2025).”

L294-L296:

“...in the Sc region...and CTT from -12.3°C to -11.2°C .”

L296-L298:

“In the cu region,...and CTT from -11.0°C to -9.3°C .”

L301-L302:

“Paired projections for cloud cover,... and CTT are shown in Appendix F.”

L337-L344:

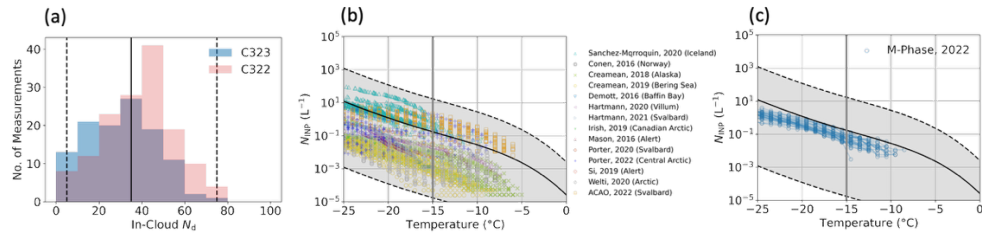
“In this CAO case, CTT is strongly controlled by N_d in both regions, with stronger effects from N_{INP}^{-15} and mpof in the Cu region. SIP processes have limited influences on CTT in both regions. A reduction in N_d or an increase in N_{INP}^{-15} leads to a lower CTT, and hence a shallower vertical development of clouds. Both the reduction of N_d and the increase of N_{INP}^{-15} INP can lead to an enhancement of precipitation, as shown in our previous work (Huang et al., 2025) for this CAO case. This response of CTT to the change of precipitation is consistent with previous work from Tornow et al. (2021) on CAO clouds, which show that enhancement of precipitation can stabilise the boundary layer during CAO event and lead to less vertical development of clouds. The limited cloud vertical development from a high N_{INP}^{-15} can also prevent the effects of converting liquid to ice, as the INP concentration is temperature-dependent.”

L410-L416:

“Similar to the other variables discussed above, parameter interactions are also identified here for CTT, particularly in the Cu region. Across different parts of the parameter space, an increase in N_d can reduce CTT from about -0.5°C to nearly -2°C in the Cu region. An increase in N_{INP}^{-15} can lead to an

	<p><i>increase in CTT ranging from nearly 0 °C to about +1.5 °C. This dependence of individual parameter sensitivities on other parameters indicates that these parameters also jointly affect cloud vertical development in CAO clouds and may therefore influence cloud field evolution, such as the transition from stratocumulus to cumulus. It is therefore important to explore the full parameter space when assessing the effects of aerosols and ice-production processes on cloud evolution during CAO events.”</i></p>
<p>Reviewer comment (4)</p>	<p>Sec. 2.2.2 If aerosol was considered here, it would affect both N_d and N_{inp}; it is unclear if the chosen dynamic ranges for N_d and N_{inp} correspond well? I wonder if the authors could briefly quantify and explain.</p>
<p>Our response:</p>	<p>The primary sources of INPs are not necessarily the primary sources of CCN, and given we are still actively working to understand what aerosol species act as INPs (and the mechanisms), the two will not necessarily scale with aerosol. As a result, changes in aerosol concentration do not necessarily produce the same response in CCN and INP concentrations. In addition, aerosols were used only in the global model to derive a temperature-dependent INP parameterisation for the regional model. The global and regional model simulations were performed separately, and aerosols were not considered for N_d and N_{INP} in the regional model.</p> <p>We understand the reviewer's concern that the perturbed range of N_d is much smaller than that N_{INP}. However, the choice reflects the fact that their sources of information are very different (before having in-situ measurements from the M-Phase aircraft campaign), and our aim was to examine cloud responses within those corresponding ranges.</p> <p>For N_d, the variability comes from the natural variability of CCN during a CAO event. We tested how cloud properties respond to the observed range of N_d in this event based on N_d calculated using satellite retrievals, which has now been added to Figure 3(a) in the revised manuscript. The range of N_d from satellite agrees well with the observed N_d from the M-Phase aircraft measurements.</p> <p>For N_{INP}, cloud-relevant INP concentrations are very difficult to constrain without <i>in-situ observations</i>. Without measurements for this specific case, we would have needed to rely on sparse observations from high-latitude regions of the Northern Hemisphere (Figure 1b). The perturbed range of N_{INP} was therefore chosen to reflect the uncertainty implied by those available measurements before the M-Phase aircraft campaign.</p> <p>We have now added content to expand the choice of the perturbed range and to clarify the role of aerosols in the global model and in the regional model in the revised manuscript. We have also modified the discussion on the role of aerosols in the revised Discussion and Conclusions.</p>

Old text:



L129-L130:

“We did not select the bigger range as in Huang et al. (2025) because the N_d at coarser resolution can be obtained from satellite retrievals (e.g., Grosvenor et al. (2018)), which is not the major source of uncertainties considered for this case in N_d .”

L141-L144:

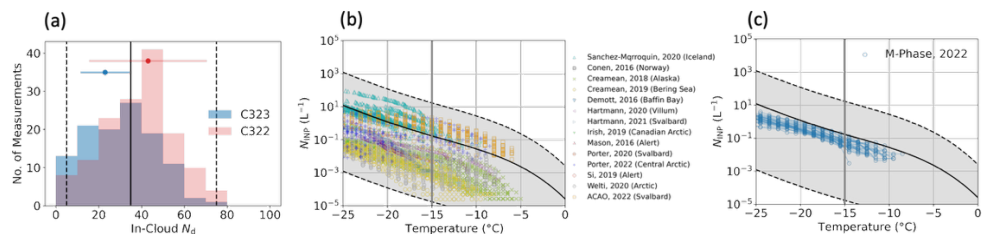
“Such big range of INP concentration (6 orders of magnitude) was selected to represent the uncertainties of INPs to our knowledge without the in-situ measurements of INPs from the aircraft campaign. This is because, unlike N_d , INP concentration cannot be derived from satellite/remote sensing.”

L420-L425:

Our results show that aerosols (which affect N_d and N_{INP}) strongly control mixed-phase cloud radiative properties in the Sc region, but with large uncertainty in the sensitivities depending on other poorly quantified model parameters. Observational constraints can be obtained from satellite retrievals and applied to constrain the N_d part of the parameter space, but measurements of N_{INP} are sparse and difficult to be obtained from satellite, leaving the sensitivity of clouds to N_{INP} difficult to constrain. A high temporal and spatial coverage of INP measurements are therefore needed to constrain the properties and sensitivities of mixed-phase CAO clouds.”

New text:

The new Figure 3 is shown below with the updated caption.



“Figure 3. Comparison between the perturbed range and the measurements: (a) N_d with measured in-cloud N_d from M-Phase C322 and C323 using the CDP (cloud droplet probe) onboard, and N_d (mean \pm one standard deviation) calculated based on retrievals from MODIS instrument onboard the Aqua satellite; ...”

L128-L131:

“... to cover the observed N_d ranges calculated using satellite retrievals from MODIS instrument onboard the Aqua satellite with the method from Grosvenor et al. (2018) (Figure 3a). The satellite-derived N_d ranges agree well with the N_d ranges from the CDP (cloud droplet probe) instrument onboard M-Phase C322 and C323 (Figure 3a).”

L133-L136:

	<p><i>“The range of N_d was chosen to understand how much the variation of N_d in a CAO event affects the cloud properties, which arises from the natural variability of aerosols and limited by the fixed N_d setup. We did not select the bigger range as in Huang et al. (2025) because the domain-mean N_d can be constrained approximately from satellite retrievals (e.g., Grosvenor et al. (2018)).”</i></p> <p><i>L148-L155:</i> <i>“N_{INP} in the regional model setup was directly linked to the number concentration of ice crystals produced by heterogenous ice nucleation, assuming that one INP produces one ice crystal. No aerosols were included for the INP concentration in the regional model. Therefore, when perturbing N_d and N_{INP} in this study, we are effectively directly changing cloud hydrometeor concentrations rather explicitly modelling the interaction between evolving aerosol fields and clouds. We chose to not use aerosol-interactive N_d and N_{INP} in this study to reduce the complexity of interpretation over the multi-dimensional parameter space and the computational resources required for running a large number of simulations for PPEs. However, there are several limitations of such a choice (e.g., missing potential feedbacks with aerosol processing) which are further discussed in the Discussion and Conclusions.”</i></p> <p><i>L160-L164:</i> <i>“Such a large range of INP concentration (six orders of magnitude) was selected to represent the range of possible INPs based on our knowledge prior to the in-situ measurements of INPs from the aircraft campaign. This is because, unlike N_d, the INP concentration cannot be constrained using satellite retrievals or other remote-sensing observations. The ranges for N_d and N_{INP} were therefore based on different sources of information available before the aircraft campaign. The aim was to examine how these natural ranges in these two quantities interactively affect CAO clouds.”</i></p> <p><i>L464-L473:</i> <i>“Our results show that, for this CAO case, N_d and N_{INP} strongly control the radiative properties of mixed-phase clouds in the Sc region, but with large uncertainty in the sensitivities depending on other poorly quantified model parameters. The strong sensitivity of this CAO case to changes in N_d highlights the importance of accurately representing and treating CCN in models in order to better simulate mixed-phase CAO clouds. Our results also show that cloud sensitivities to N_d can depend on N_{INP}^{-15}. Because measurements of INP concentrations are sparse and cannot be obtained from satellite retrievals or other remote-sensing observations, the sensitivity of clouds to CCN can remain difficult to constrain without knowing INP concentrations. Improved temporal and spatial coverage of INP measurements is therefore also needed to better constrain the properties and sensitivities of mixed-phase CAO clouds, together with improved representation of INPs in atmospheric and climate models.”</i></p>
<p>Reviewer comment (5)</p>	<p>Fig. 6 I'm surprised by the large cloud cover in the Cu regime. How do the authors define cloud cover?</p>
<p>Our response:</p>	<p>The cloud cover is derived using cloud fractions at individual model levels, assuming maximum-random overlap of cloud layers in a column. The cloud</p>

	<p>fractions are from the bimodal cloud scheme (Weverberg et al., 2021a, b) in our model setup.</p> <p>Shallow cumulus can occupy a substantial fraction of a grid box at certain model levels. Therefore, the cloud cover derived using this approach can be high. However, our model is able to capture the decreasing of cloud cover from stratocumulus to cumulus regions. As the aim of this study is to understand how cloud cover and other model variables respond to parameter perturbations, we consider this definition to be appropriate for the purpose of this study.</p> <p>We have also added a short description on the definition of cloud cover in the same sentence where the cloud scheme is introduced.</p> <p>References:</p> <p>Weverberg, K. V., Morcrette, C. J., and Boutle, I.: A Bimodal Diagnostic Cloud Fraction Parameterization. Part II: Evaluation and Resolution Sensitivity, <i>Monthly Weather Review</i>, 149, 859 – 878, https://doi.org/10.1175/MWR-D-20-0230.1, 2021a.</p> <p>Weverberg, K. V., Morcrette, C. J., Boutle, I., Furtado, K., and Field, P. R.: A Bimodal Diagnostic Cloud Fraction Parameterization. Part 920 I: Motivating Analysis and Scheme Description, <i>Monthly Weather Review</i>, 149, 841 – 857, https://doi.org/10.1175/MWR-D-20-0224.1, 2021b.</p>
Old text:	<p>L90-L93: <i>“The cloud parameterization in the nested model was from the Bimodal Cloud scheme (Weverberg et al., 2021b, a), and the radiative processes were from SOCRATES (Suite Of Community Radiative Transfer codes based on Edwards and Slingo) (Manners et al., 2023). Mass mixing ratio and number concentration of ice hydrometeors were both considered when calculating the single-scattering albedo of ice in SOCRATES (Baran et al., 2025).”</i></p>
New text:	<p>L92-L98: <i>“The cloud parameterization in the nested model was from the bimodal cloud scheme (Weverberg et al., 2021b, a). This approach uses subgrid turbulent kinetic energy to diagnose the subgrid humidity distribution and hence cloudy fraction. The cloud cover was derived using cloud fractions in a column with the maximum-random overlap assumption. The radiative processes were from SOCRATES (Suite Of Community Radiative Transfer codes based on Edwards and Slingo) (Manners et al., 2023), and mass mixing ratio and number concentration of ice hydrometeors were both considered when calculating the single-scattering albedo of ice in SOCRATES (Baran et al., 2025).”</i></p>
Reviewer comment (6)	<p>Fig. 7/8 Is the small sensitivity of mpof in Sc-dominated regimes connected to the large cloud fraction (as well as small IWP)?</p>
Our response:	<p>Yes, the IWP and ice cloud fraction are small in the Sc-dominated region, while the liquid cloud fraction is high. How much liquid and ice interacts in a model grid box is not just determined by mpof, but also the liquid and ice</p>

	<p>cloud fractions. Therefore, perturbing mpof has limited influence in the Sc-dominated region.</p> <p>We have briefly expanded on this in the revised manuscript.</p>
Old text:	<p><i>L283-L285:</i> <i>“The increasing effect from mpof in Cu region than the Sc region comes from an increasing ice formation in Cu clouds when the cloud top deepens and more mixing between ice and liquid hydrometeors.”</i></p>
New text:	<p><i>L310-L314:</i> <i>“The increasing effect from mpof in the Cu region compared to in the Sc region comes from increasing ice formation in Cu clouds when the cloud top deepens and more mixing between ice and liquid hydrometeors. The effects from mpof in the Sc region are also limited by a large liquid cloud fraction with little ice cloud fraction, as the extent to which liquid and ice interacts in a model grid box is not just determined by mpof alone but also cloud fraction.”</i></p>
Reviewer comment (7)	<p>Fig. 9 How should the reader interpret a greater TWP in the Cu-dominated regime under increased E_{HM}? While a LWP reduction make sense to me, I’m surprised to see an even stronger IWP increase.</p>
Our response:	<p>The increase in IWP can exceed the decrease in LWP because the change of IWP in clouds is not only from the direct conversation of liquid to ice, but also from more vapour deposited to ice compared to liquid.</p> <p>At subzero temperatures, the saturation vapour pressure over ice is lower than that over liquid. For example, at -10 °C, the saturation vapour pressure over ice (approx. 260 Pa) is about 9% less than the saturation vapour pressure over liquid (approx. 286Pa). The increase in IWP therefore reflects not only the freezing of existing liquid water, but also more vapour deposition onto ice compared to liquid.</p> <p>We have added a brief explanation of this mechanism in Section 3.2 of the revised manuscript. We did not include this discussion in Section 3.3, where Figure 9 is presented, because Section 3.3 focuses on parameter interactions, whereas Section 3.2 focuses on the responses of cloud properties and is therefore a more appropriate location for this explanation.</p>
Old text:	N/A
New text:	<p><i>L321-L323:</i> <i>“When ice formation processes are stronger (e.g., a higher N_{INP}^{-15} or E_{HM}), the reduction in cloud liquid is less than the increase in cloud ice, leading to a net increase of total water path (Figure F3). This is because the increase of IWP is not only from the direct conversion of liquid to ice, but also a stronger vapour deposition onto ice compared to liquid at the same temperature.”</i></p>
Reviewer comment (8)	<p>I. 342 “shown ... show “</p>

Our response:	“Shown” has been removed to improve the readability of this sentence.
Old text:	<i>L342-L343: “The response surfaces shown in the previous section show that the sensitivity of cloud properties to a change in a parameter depends strongly on the setting of the other parameters.”</i>
New text:	<i>L381-L382: “The response surfaces in the previous section show that the sensitivity of cloud properties to a change in a parameter depends strongly on the setting of the other parameters.”</i>

Response to comments by Reviewer 2

<p>Reviewer comment (1)</p>	<p>One of my main concerns is the author's selection of cloud droplet number concentration (N_d) and ice-nucleating particles (INPs) as the perturbed parameters. The selection of N_d instead of CCN, while simultaneously selecting INP concentrations, is physically difficult to justify. INPs are a subset of aerosols with strong ice-nucleating ability and are generally associated with way larger uncertainties than CCN. The authors state that aerosol-derived N_d is not used to avoid additional uncertainties, but this reasoning appears inconsistent given that the study includes the much more uncertain INP parameter. If INP variability is considered acceptable within the emulator framework, then CCN should be also included rather than fixed-N_d profile. The omission of CCN effects through a prescribed N_d should be more carefully justified. I am particularly concerned because, in real CAO environments, N_d is strongly controlled by aerosol aging processes and activation to CCNs. Also, CCN will have competition of water vapors with INPs in mixed-phase cloud, hence affects INPs response as well. Treating N_d as an independent tunable parameter, rather than linking it to aerosol activation, may bias the INP response and the interpretation of the relative importance of microphysical sensitivities.</p>
<p>Our response:</p>	<p>A key line here is "If INP variability is considered acceptable within the emulator framework, then CCN should be also included rather than fixed-N_d profile." There seems to be a misunderstanding here. To be clear, we define N_d directly, rather than linking droplet activation to an evolving aerosol field. Similarly, we parameterise N_{INP} as a function of temperature only and so it is not dependent on the model aerosol concentrations. Primary ice concentration is then set to be equal to N_{INP} and hence it is defined by a quantity that does not evolve through the CAO, and so is on a comparable basis to N_d.</p> <p>We chose to do this in part to reduce complexity and aid the interpretation of the results, and also in part for a pragmatic reason. The pragmatic reason is that at present we have no means of allowing an INP spectrum to evolve with time, so no possibility of modelling INP-cloud interactions in a meaningful manner. Understanding the two-way interaction of aerosol with mixed-phase clouds is in its infancy, but nevertheless, the way we have constructed our modelling study allows us to understand the interacting effects of variables when N_d and N_{INP} are held constant as cloud evolves.</p> <p>We agree with the reviewer that excluding aerosol-interactive CCN and INP in the model might affect the relative importance of microphysical sensitivities (although this is theoretical and not based on evidence). Therefore, we have added discussion on the limitations of this setup in the revised manuscript. Please see the content in the "New text" below for our changes to the manuscript.</p>
<p>Old text:</p>	<p>L132-L137:</p>

	<p><i>“The INP concentrations over the Labrador Sea region were derived based on a new $n_s(T)$ (active site density) parameterization for soil dusts (Appendix A), to account for the biogenic component associated with the dust (Herbert et al., 2025). The dust concentrations from a global model over the Labrador Sea region during the M-Phase aircraft campaign period were used with the above soil dust parameterization to derive the temperature-dependent INP concentration perturbed in this study. Appendix B shows the details of the global model and the INP concentration in the control simulation which agrees well with INP measurements from the M-Phase aircraft campaign as in Figure 3c.”</i></p> <p><i>L452: “We also made some simplifications to the cloud microphysics processes (e.g. no spatial variation of N_d and N_{INP})...”</i></p>
<p>New text:</p>	<p><i>L138-L155: “INP concentration (N_{INP}) was perturbed by scaling a temperature-dependent INP parameterization as shown in Figure 3b and 3c. The temperature-dependent INP parameterisation over the Labrador Sea region was derived based on $n_s(T)$ (active site density) parameterizations for sea-spray aerosols (McCluskey et al., 2018) and soil dusts (see Appendix A) that accounts for the biogenic component associated with the dust (Herbert et al., 2025). The sea-spray aerosol and dust concentrations from a separate global model over the Labrador Sea region during the M-Phase aircraft campaign period were used with the above parameterizations to derive the temperature-dependent INP parameterisation in this study. The global model used for the aerosol concentrations was performed with a global configuration of the UM (Brown et al., 2012a) version 12.1 which includes Global Atmosphere version 8.0 and Global Land model version 9.0 (Willett et al., 2020). Appendix B shows the details of the global model and the INP concentration in the control simulation, which agrees well with INP measurements from the M-Phase aircraft campaign as in Figure 3c.</i></p> <p><i>N_{INP} in the regional model setup was directly linked to the number concentration of ice crystals produced by heterogenous ice nucleation, assuming that one INP produces one ice crystal. No aerosols were included for the INP concentration in the regional model. Therefore, when perturbing N_d and N_{INP} in this study, we are effectively directly changing cloud hydrometeor concentrations rather than explicitly modelling the interaction between evolving aerosol fields and clouds. We chose to not use aerosol-interactive N_d and N_{INP} in this study to reduce the complexity of interpretation over the multi-dimensional parameter space and the computational resources required for running a large number of simulations for PPEs. However, there are several limitations of such choice (e.g., missing potential feedback with aerosol processing) which are further discussed in the Discussion and Conclusions.”</i></p> <p><i>L506-L517: “In this first PPE study of a high-resolution regional model of mixed-phase clouds, we have made several simplifying assumptions in</i></p>

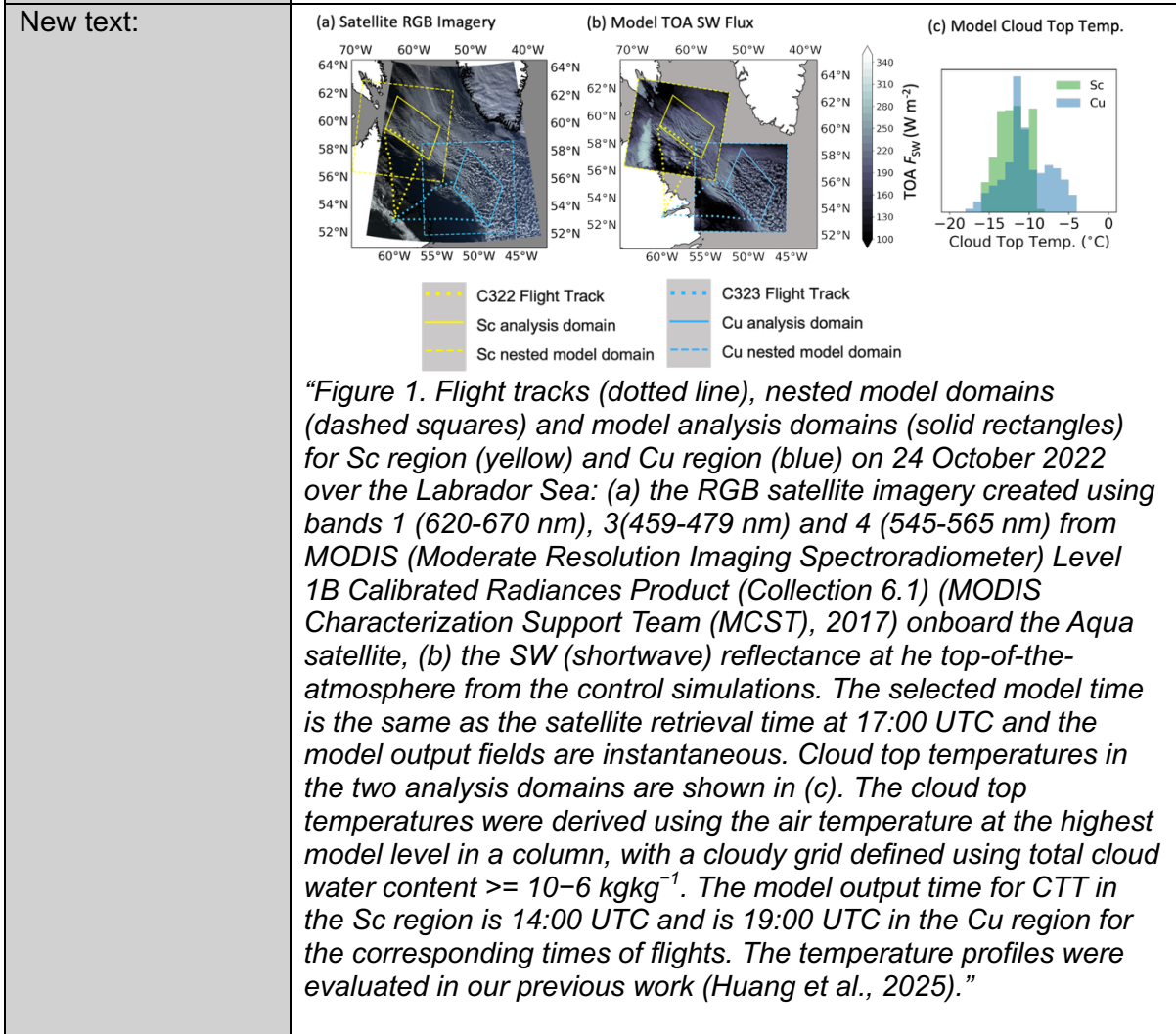
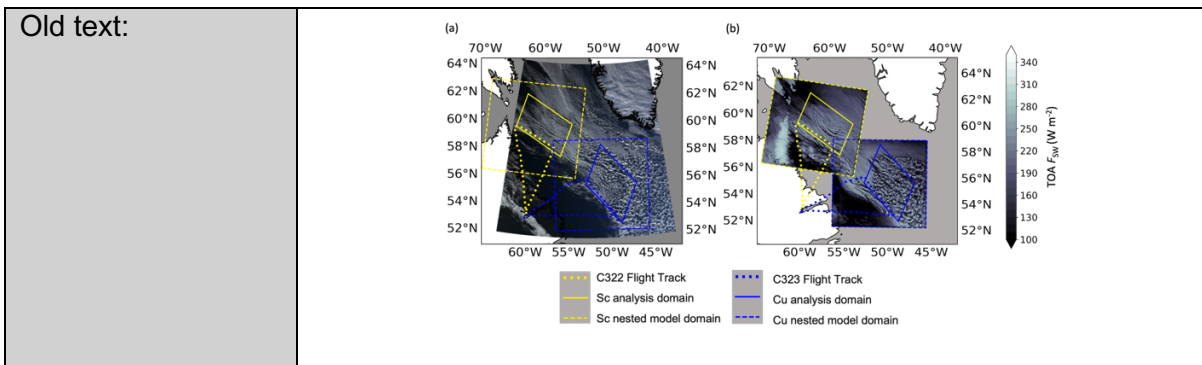
	<p><i>the cloud microphysics processes, including the use of fixed N_d and temperature-dependent N_{INP}, rather than aerosol-interactive CCN and INP. This choice was made to reduce the complexity of the model result interpretation and to have a direct understanding of N_d and N_{INP} interactions which is the main objective of this study. However, this approach omits several potentially important processes, including interactions of aerosols and cloud hydrometeors, feedbacks associated with aerosol and in-cloud processing of CCN and INP, and the influence of different aerosol sources. These processes could alter the sensitivities of CAO clouds to aerosols and to other microphysical parameters. Future work should therefore include aerosol-interactive CCN and INP in order to provide a more complete representation of aerosol effects and their interactions in mixed-phase CAO clouds.”</i></p>
<p>Reviewer comment (2)</p>	<p>My second concern comes from the sparsity of the sampling in the 6-D parameter space. The PPE uses 66 ensemble members, which is reasonable, but 66 samples in a six-dimensional nonlinear parameter space may still be sparse, especially given the strong parameter interactions and equifinality demonstrated in the manuscript. This raises questions about the robustness of the emulator, particularly near the boundaries of the parameter space where extrapolation risks may be larger. I therefore suggest that the authors conduct a convergence test to evaluate the stability of the emulator results. In addition, a more explicit discussion of emulator uncertainty quantification and potential extrapolation errors in the manuscript would be helpful.</p>
<p>Our response:</p>	<p>We have now added discussion of emulator uncertainty quantification in Appendix C with a convergence test.</p> <p>Please note that it is not feasible to perform a traditional convergency test (comparing emulators trained on multiple PPEs of different sizes, each generated independently with the Latin hypercube sampling method) using our model setup. This is because such a test requires many more simulations and each of them is very computational expensive. Instead, the convergency test we performed were designed based on the existing 66 training points. We selected a different number of training points from these 66 points and tested the trained emulator against the test data.</p> <p>There's no traditional extrapolation error in our study as all the data generated from emulators are within the boundaries of the parameter space. But we agree with the reviewer that the uncertainties near the boundaries of the parameter space can be high. Therefore, we have limited our analysis and conclusions away from the boundaries in the original manuscript (e.g., keep the starting points, higher and lower end of parameter perturbation in the multiple OAT test away from the boundary values of each parameter), as well as intentionally making the control value of some variables away from the boundaries using boundary values much bigger/smaller than the actual uncertain ranges (e.g., E_{HM} and E_{BR}).</p>

Old text	N/A
New text	<p>L257-L259: <i>“Appendix C describes and discusses the emulator performance from the kernel selection and testing steps, as well as the dependency of the RMSE on the different numbers of training points.”</i></p> <p>As the newly added content in Appendix C is too long to attach here, please refer to tracked changes for the added uncertainty quantification and convergence test in Appendix C in the revised manuscript.</p>
Reviewer comment (3)	<p>Finally, while the authors acknowledge case specificity, many conclusions are framed in broader terms regarding mixed-phase CAO clouds and aerosol–cloud interactions. Given the strong dependence of mixed-phase cloud processes on thermodynamic structure, aerosol regime, and synoptic conditions, I suggest that the authors more explicitly frame their conclusions as case-specific and discuss how different aerosol forcing and environmental conditions (such as continental versus marine environments), could alter the inferred parameter sensitivities.</p>
Our response:	<p>We have now highlighted the case-specificity and CAO-specificity in several places additional to the ones in the original manuscript, especially when describing the responses of cloud properties from parameter perturbations and the relative importance of parameters.</p> <p>Discussion on how environmental conditions could alter the parameter sensitivities is also expanded in the Discussion and Conclusions of the revised manuscript. As our work focused on CAO clouds and we framed our conclusions to CAO clouds which are generally in marine environments, we did not include the discussion on continental versus marine environments as suggested by the reviewer.</p>
Old text:	<p>L275-L278: <i>“Using the paired-projections, we are able to qualitatively identify key parameters controlling the cloud properties over the parameter space.”</i></p> <p>L286: <i>“All three SIP parameters have a relatively weak effect on TOA albedo and LWP in both Sc and Cu regions, even though...”</i></p> <p>L371-L372: <i>“For example, changes in SIP parameters can cause either increases or decreases in cloud cover...”</i></p> <p>L405: <i>“An increase in N_{INP}^{-15} leads to a reduction in TOA albedo and LWP in the Sc region, which is consistent with...”</i></p> <p>L438:</p>

	<p><i>“The influence of mpof is more prominent in the Cu region...”</i></p> <p>L461: <i>“... factors controlling mixed-phase cloud properties”</i></p>
<p>New text:</p>	<p>Please note that we include several minor changes here. To enhance readability, we have underlined the newly added phrases in these minor changes.</p> <p>L304-L305: <i>“Using the paired-projections, we are able to qualitatively identify key parameters controlling the cloud properties over the parameter space <u>in this CAO event.</u>”</i></p> <p>L315: <i>“All three SIP parameters have a relatively weak effect on TOA albedo and LWP in both Sc and Cu regions <u>in this case</u>, even though...”</i></p> <p>L417-L418: <i>“For example, changes in SIP parameters <u>in this case</u> can cause either increases or decreases in cloud cover...”</i></p> <p>L451: <i>“An increase in N_{INP}^{-15} leads to a reduction in TOA albedo and LWP in the Sc region <u>in this case</u>, which is consistent with...”</i></p> <p>L486: <i>“The influence of mixed-phase overlap factor (mpof) <u>in this case</u> is more prominent in the Cu...”</i></p> <p>L498-L505: <i>“The sensitivity of mixed-phase CAO clouds to the parameters investigated here may be substantially different in a different CAO event. For example, in previous work we showed that the sensitivities of mixed-phase CAO clouds to change in INP concentration can differ in both magnitude and sign between warm and cold CAO cases (Huang et al., 2025). Previous studies have shown that CAO cloud properties depend strongly on environmental conditions (Fletcher et al., 2016b; McCoy et al., 2017; Wu and Ovchinnikov, 2022; Murray-Watson et al., 2023), including factors such as CAO strength and wind conditions. This environmental dependence is likely to modify CAO cloud sensitivities to the parameters examined here. Future work should therefore investigate how different environmental conditions influence CAO clouds and how those influences interact with key cloud microphysical parameters.</i></p> <p>L519: <i>“...factors controlling mixed-phase <u>CAO</u> cloud properties.”</i></p>
<p>Reviewer comment (4)</p>	<p>Page4 L109: in the manuscript, the author only considered dust as INPs. However, more and more studies have reported that sea-salt aerosols can also act as effective INPs, particularly in marine</p>

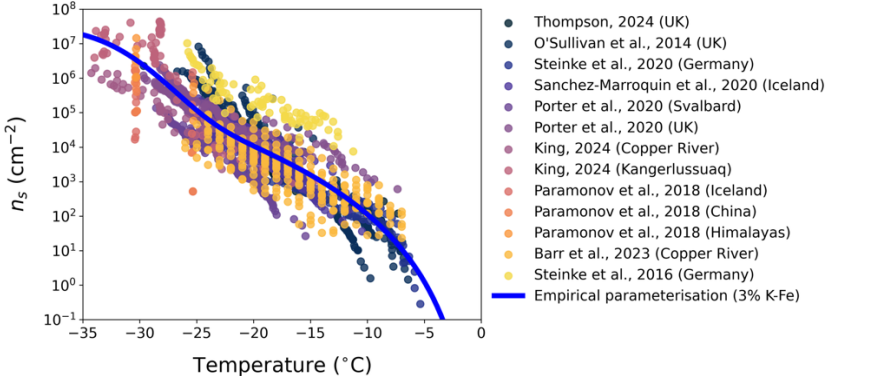
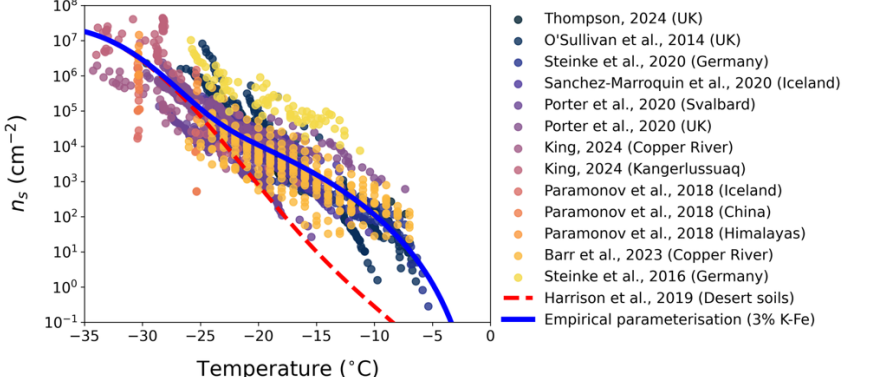
	<p>environments (e.g. Wagner et al., 2021; JV Trueblood et al., 2021). Given that this case is over the Labrador Sea, it would be helpful to discuss the potential contribution of marine (sea-salt) INPs and how excluding them might affect the inferred INP sensitivity. If feasible, I encourage the authors to include an additional sensitivity test (or at least an order-of-magnitude estimate) representing sea-salt INPs, or to justify why dust-only INPs are appropriate for this case.</p>
<p>Our response</p>	<p>The INP parameterisation that we used to represent the temperature-dependent INP concentration includes spatially and temporally collocated contributions from dust and sea spray aerosol (SSA). The latter was erroneously omitted from description in the manuscript. To represent the SSA INPs we applied the parameterisation from McCluskey et al. (2018) that links the surface area of SSA particles to a marine source of INPs. In our region and time of interest the SSA INPs contribute significantly fewer INPs when compared to the dust. This is consistent with previous modelling studies (e.g., Herbert et al., 2025).</p> <p>In the revised manuscript we have amended the text to include a description of how the sea-spray aerosols were included. This includes minor changes to Sect. 2.2.2 and Appendix B. As SSA was already included, the INP parameterization used in this study remains unchanged.</p> <p>References:</p> <p>Herbert, R. J., Sanchez-Marroquin, A., Grosvenor, D. P., Pringle, K. J., Arnold, S. R., Murray, B. J., and Carslaw, K. S.: Gaps in our understanding of ice-nucleating particle sources exposed by global simulation of the UK Earth System Model, <i>Atmospheric Chemistry and Physics</i>, 25, 291–325, https://doi.org/10.5194/acp-25-291-2025, publisher: Copernicus GmbH, 2025.</p> <p>McCluskey, C. S., Ovadnevaite, J., Rinaldi, M., Atkinson, J., Belosi, F., Ceburnis, D., Marullo, S., Hill, T. C. J., Lohmann, U., Kanji, Z. A., O’Dowd, C., Kreidenweis, S. M., and DeMott, P. J.: Marine and Terrestrial Organic Ice-Nucleating Particles in Pristine Marine to Continentally Influenced Northeast Atlantic Air Masses, <i>Journal of Geophysical Research: Atmospheres</i>, 123, 6196–6212, https://doi.org/10.1029/2017JD028033, 2018.</p>
<p>Old text:</p>	<p>L494: <i>“Appendix B: Simulated dust size distributions during M-Phase”</i></p> <p>L501: <i>“...aerosol components (sea salt, sulphate, ...”</i></p> <p>L508-L516: <i>“The simulated dust aerosol size distributions were extracted for a region (62.8°W– 51.6°W, 53.1°N – 60.6°N) and time period (23/10/22 – 5/11/22) consistent with the M-Phase campaign. The dust INP number concentration ($N_{dust-INP}$) is calculated at each temperature T and in each dust size bin i following the singular</i></p>

	<p>description (Murray et al., 2012; DeMott et al., 2015; Vali, 2008) using</p> $N_{dust-INP_i}(T) = N_{dust_i} (1 - e^{n_{s,soil}(T)\pi d^2}) \quad (B1)$ <p>where N_{dust_i} is the dust number concentration in each size bin (L^{-1} of air) and d is the mean diameter of the bin. The bins are summed to obtain the total $N_{dust-INP}$ for each grid box and for each time step (3 hr) of the time series. This is repeated for three model levels (surface, 1 km and 2 km) and a mean taken over the three.”</p>
<p>New text:</p>	<p>L555: “Appendix B: Simulated aerosol size distributions during M-Phase”</p> <p>L557-L558: “... and the marine INP parameterization ($n_{s,SSA}(T)$) from McCluskey et al. (2018) to simulated sea-spray aerosol (SSA) concentrations.”</p> <p>L563-L564: “...aerosol components (SSA, sulphate, ...”</p> <p>L564-L565: “SSA is present in the accumulation and coarse modes.”</p> <p>L571-L580: “The simulated SSA and dust aerosol size distributions were extracted for a region (62.8°W – 51.6°W, 53.1°N –60.6°N) and time period (23/10/22 – 5/11/22) consistent with the M-Phase campaign. The INP number concentration (N_{INP}) is calculated at each temperature T and in each aerosol size bin i following the singular description (Murray et al., 2012; DeMott et al., 2015; Vali, 2008) using</p> $N_{INP_i}(T) = N_{dust_i} (1 - e^{n_{s,soil}(T)\pi d^2}) + N_{SSA_i} (1 - e^{n_{s,SSA}(T)\pi d^2}) \quad (B1)$ <p>where N_{dust_i} and N_{SSA_i} are the dust and SSA number concentrations in each size bin (L^{-1} of air) and d is the mean diameter of the bin. The bins are summed to obtain the total N_{INP} for each grid box and for each time step (3 hr) of the time series. This is repeated for three model levels (surface, 1 km and 2 km) and a mean taken over the three to provide a concentration that is representative of the whole region and altitudes of interest. A polynomial fit to all values of N_{INP} is used to produce a parameterization for $N_{INP,M-Phase}(T)$ which is described by...”</p>
<p>Reviewer comment (5)</p>	<p>Page5 Figure1: change the color blue for C323. The current lines are nearly invisible on printed paper</p>
<p>Our response:</p>	<p>We have now changed the dark blue for C323 in the original Figure 1 to lighter blue in the revised Figure 1. The revised Figure 1 also has one more subplot for cloud top temperatures, following the suggestion from Reviewer #1.</p>



Reviewer comment (6)	Page6 L134: please explicitly write the global model name you used for dust concentration simulation
Our response:	The global model name is now added in the same paragraph.
Old text:	N/A
New text:	L143-L145: “The global model used for the aerosol concentrations was performed with a global configuration of the UM (Brown et al., 2012a) version 12.1 which includes Global Atmosphere version 8.0 and Global Land model version 9.0 (Willett et al., 2020).”

Reviewer comment (7)	Page7 L165: please define the variable $N_{iics,xy}$ when first introduced
Our response:	The definition of $N_{iics,xy}$ is now included.
Old text:	L163-L164: <i>“The ice-ice collisional breakup parameterization used in this study follows the temperature dependent-approach in Takahashi et al. (1995) and Sullivan et al. (2018).”</i>
New text:	L183-L185: <i>“The number tendency of ice-ice collisional breakup ($N_{iics, xy}$, where x denotes the colliding hydrometeor and y the hydrometeor being collided with) used in this study follows the temperature-dependent approach in Takahashi et al. (1995) and Sullivan et al. (2018).”</i>
Reviewer comment (8)	Page25 L483-484: It seems to me that you did not demonstrate where the dust source originates in your nested region. Therefore, I am not fully convinced that "purposefully omitting measurements from desert soil sources" is an appropriate choice. I would also suggest presenting the desert dust n_s -T relationship in Figure A1 to show how those dust properties would differ from those examined here.
Our response:	<p>Herbert et al. (2025) demonstrated that a dust parameterization that accounts for a biogenic contribution to its ice-nucleating ability better reproduces observed INP concentrations in all regions (including the northern hemisphere high latitudes) except for regions directly downstream of the Sahara outflow (the Caribbean). We use this as justification for using the new dust INP parameterisation for dust, regardless of its origin.</p> <p>As suggested by the reviewer, we have included the $n_s(T)$ parameterisation for desert soil to the revised Figure A1 (shown in the “New text” box below); this results in a relatively lower efficiency above -20°C, when compared to the new parameterisation. The ability of the new parameterisation to reproduce the measured INP magnitude in Figure 3c for this temperature range provides us with additional confidence that it is appropriate for this region.</p> <p>References:</p> <p>Herbert, R. J., Sanchez-Marroquin, A., Grosvenor, D. P., Pringle, K. J., Arnold, S. R., Murray, B. J., and Carslaw, K. S.: Gaps in our understanding of ice-nucleating particle sources exposed by global simulation of the UK Earth System Model, Atmospheric Chemistry and Physics, 25, 291–325, https://doi.org/10.5194/acp-25-291-2025, publisher: Copernicus GmbH, 2025</p>

<p>Old text:</p>	 <p>Figure A1. Empirical soil-dust parameterization of $n_{s,soil}(T)$. Coloured circles show measurements from laboratory studies (references within figure) that have measured the ice-nucleating activity of soil dust sampled from locations around the world. The solid blue line shows the best fit to the data assuming a K-Fe component (weight percent of 3 %) and a biogenic component described by a power law.</p>
<p>New text:</p>	 <p>“Figure A1. Empirical soil-dust parameterization of $n_{s,soil}(T)$. Coloured circles show measurements from laboratory studies (references within figure) that have measured the ice-nucleating activity of soil dust sampled from locations around the world. The red dashed line shows the parameterization for desert soils from Harrison et al. (2019), whilst the solid blue line shows the best fit to the data assuming a K-Fe component (weight percent of 3 %) and a biogenic component described by a power law.”</p>
<p>Reviewer comment (9)</p>	<p>Page 27 L515: Page 27, L515: Why are only these three levels (surface, 1 km, and 2 km) selected? It would be helpful to clarify the typical upper bound of the cloud top height, how many model levels are located beneath it, and whether these selected levels adequately capture the vertical structure of the INP concentration variation.</p>
<p>Our response:</p>	<p>The three altitudes were used to obtain mean aerosol concentrations that would be representative of the whole region. This captures the range in altitudes where most of the clouds were observed (< 2000 m).</p>

In the control simulations, the median cloud-top height in the Sc region is approximately 1600m above sea level, with a 5th percentile of 1315m and a 95th percentile of 2010m. In this region, 92% of cloud tops are below 2000m. In the Cu region, the median cloud-top height is slightly higher, at approximately 1760m above sea level, with a 5th percentile of 1182m and a 95th percentile of 2642m. In this region, 70% of cloud tops are below 2000m.

Cloud-top height is diagnosed as the height of the highest model level with a total cloud mass mixing ratio $\geq 10^{-6} \text{ kg kg}^{-1}$. Using $10^{-6} \text{ kg kg}^{-1}$ to identify a cloudy model grid box is a relatively loose threshold, and even with this definition, the majority of cloud tops remain below 2000m. We therefore consider it is sufficient to use levels at and below 2000m in this case. Including the model surface level in the mean ensures we are capturing any INPs that are ingested into the cloud base.

The vertical structure of INP concentration is determined solely by temperature in the regional model. The global model and the regional model were performed separately, and the global model was only used for providing a temperature-dependent INP parameterisation (Equation B2) for the regional model. In each PPE simulation, the INP curve remains the same.

A plot of the simulated INP concentration for the three model altitudes is shown below (Figure R1). In the October case, there is only a factor of ~ 2 increase between the surface and 2 km. This demonstrates that there is not a considerable sensitivity to altitude in our simulations, and that using a mean concentration is appropriate.

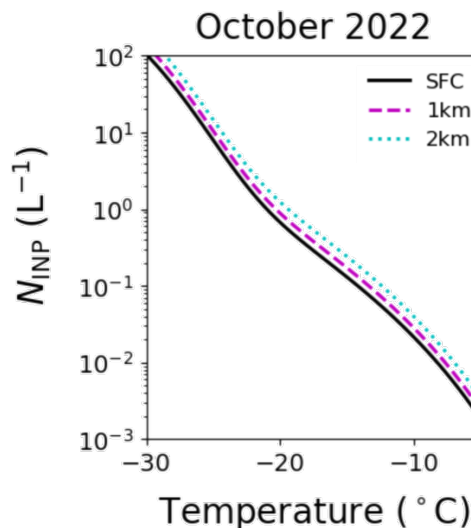


Figure R1. Temperature-dependent INP concentrations using simulated concentrations of sea-spray and dust aerosol from October extracted from three model altitudes (the surface, 1 km, and 2 km).

Old text:

L514-L515:

	<i>“This is repeated for model levels (surface, 1km and 2km) and a mean taken over the three.”</i>
New text:	<i>L578-L579: “This is repeated for three model levels (surface, 1 km and 2 km) and a mean taken over the three to provide a concentration that is representative of the vertical cloud structure in the region (92 % of Sc clouds and 70% of Cu clouds are below 2 km).”</i>

Changes made besides the response to reviewer comments

Description and reasons of change	Change all “parameterization” to “parameterisation” for a consistent spelling of word.
Old text:	There are multiple related changes in the revised manuscript. Please refer to the tracked changes for this minor change.
New text:	There are multiple related changes in the revised manuscript. Please refer to the tracked changes for this minor change.