Responses to reviewer comments on the manuscript "Different responses of cold-air outbreak clouds to aerosol and ice production depending on cloud temperature"

We thank all the reviewers for their time and effort on reviewing our revised manuscript. Please see below for our responses to the reviewers' comments and minor changes made besides the response to reviewer comments.

Response to comments by reviewer 1

Reviewer comment (1)	That said, I still have reservations about the 15 March case study that should be addressed. Specifically, I have reservations about the change in the simulation behaviour around 54W as seen in Figure 5 and beyond. In the revised manuscript it is stated: The model struggles with reproducing the cloud streets in March, and a better representation of the cloud streets requires much higher computational resources with finer grid spacing to conduct the sensitivity test, hence are not further investigated here. Yet the simulations are able to generate fine-scale cloud streets to the east of the 54W line, so I would think the resolution is adequate. Rather I suspect the issue is due to the coarse resolution fields generated by the global model ("N216 ~60 km resolution") coming in through the western boundary at 60W. What is the wind speed along the western boundary? How far would you expect the boundary effects to propagate into the nested domain? Will it reach the sub-domain? Will it reach 54W? Please comment on this directly in the manuscript.
Our response:	We thank the reviewer for raising this question. We realised that the nested model domains for both cases have not been shown in the manuscript, which may lead to misunderstanding of the location of the sub-domains within the nested model domains. The bigger domains shown in Figure 3 and Figure 4 in the manuscript are not the nested model domains, but domains designed based on the availability and coverage of the satellite retrievals and they are smaller than the actual nested model domains. We have now added the maps showing the nested model domains and the subdomains for analysis in a new Appendix (Appendix C in the revised manuscript). The ordering of the appendices after Appendix C has also been updated in the revised manuscript.

	We believe that all the sub-domain for analysis in the March case is sufficiently far from the western boundary of the nested model domain. The boundary effects do not reach the sub-domain or regions around 54W. Please see the new Appendix C for a more detailed discussion and our answers to the reviewer's questions. We have also added the text to explain why the cloud streets are not resolved in the early stratus region in our model in the manuscript. Please see the "New text" below for the added content in the main content and Appendix 1 in the end of this document for the added content in the new Appendix C.
Old text:	*Line 208-Line 210:* "The model struggles with reproducing the cloud streets in March, and a better representation of the cloud streets requires much higher computational resources with finer grid spacing to conduct the sensitivity test, hence are not further investigated here."
New text:	*Line 83-Line 84:* "The nested model domains are shown in Appendix C." *Line 208-Line 214:* "In the March case, the model struggles with reproducing the fine structures of cloud streets to the east of 54 ºW in the sub-domain. This is because the effective horizontal resolution (between 5 times to 10 times of the grid spacing) in our model cannot fully resolve the cloud streets at the beginning of the CAO event. With the clouds moving into the convective region and the boundary layer getting depended (to the west of 54 ºW), the scales of cloud street grow and can then be resolved in the model. A better representation of the cloud streets at the beginning of the CAO event requires higher model resolution (Field et al., 2017a) and therefore much higher computational resources to conduct the sensitivity test, hence are not further investigated here." *Line 227–Line 230:* "The locations of the sub-domains in the nested model domains are shown in Appendix C. The whole sub-domain in the March case and most of the sub-domain (except the small northwestern part) of the October case are sufficiently distant from the boundaries of the nested model domain, hence not affected by the boundary effects from fields entering from the global model. A detailed discussion on the boundary effects is shown in Appendix C." *Added content in Appendix C (shown in Appendix 1 in the end of this document)*

Reviewer comment (2)	One small query for Figure 5, is the figure for a specific time or for the duration of the simulation? I think it's the later, but it would be best to state this explicitly.
Our response:	The times for plots in Figure 5 and figures in Appendix E (originally Appendix D in the previous manuscript) are for a specific time of each case. This choice is to make sure the consistency with the other plots (corresponding to the CERES measurement times). We have now added the specific time for each case in the corresponding plots.
Old text:	N/A
New text:	*The content below are added to the captions of Figures 5, E1 and E1:* "The time points selected are 16:45 UTC for the March case and 17:00 UTC for the October case, which are consistent with the corresponding CERES measurement times."
Reviewer comment (3)	Figure 1 legend: 2022 instead of 2024
Our response:	We are sorry that the reviewer's two typo corrections from the first peer-review report were missed in our previous responses. Both changes have been made.
Old text:	"Figure 1. The UK Met Office surface analysis charts at 1200 UTC on (a) 15 March 2024 and (b) 24 October 2024."
New text:	"Figure 1. The UK Met Office surface analysis charts at 1200 UTC on (a) 15 March 2022 and (b) 24 October 2022."
Reviewer comment (4)	Figure 8 legend: 24 October
Our response:	Corrected. Please note that this was corrected in the previous manuscript and therefore is not shown in the tracked change for the revised manuscript here from this round of review.
Old text:	"… on 15 October, …"
New text:	"… on 15 March 2022, …"

Response to comments by reviewer 3

Reviewer comment (1)	While perhaps not strictly necessary, in my view it is good practice to give the product names and versions numbers of the datasets used, and I encourage the authors to add such to the section on data availability.
Our response:	We have now added missing product names and version numbers of the datasets used in the data availability section, as well as adding the missing version numbers in the Method section and Appendix D (the original Appendix C for the previous manuscript).
Old text:	*Line 544-Line 549:* “MODIS data including the RGB imagery and in-cloud cloud water path can be found from https://modis.gsfc.nasa.gov/. All-sky liquid water path from AMSR-2 can be found from https://www.remss.com/missions/amsr/. Shortwave and longwave radiation flux at the top-of-the-atmosphere can be found from https://ceres.larc.nasa.gov/data/. CALIPSO temperature and IWC can be found from https://www-calipso.larc.nasa.gov/products/. The INP concentrations can be found from https://doi.org/10.5281/zenodo.14781199. Observations during the M-Phase aircraft campaign can be found from https://catalogue.ceda.ac.uk/uuid/2040b17716fd49f2ac8b0b35c773d609/ on the CEDA Archive. Model data used in this work is available at https://doi.org/10.5281/zenodo.14536461.“
New text:	*data availability (Line 552-Line 566):* “The satellite data products used in this study include: MODIS Level 1B Calibrated Radiances Product (Collection 6.1) onboard the Aqua satellite for RSB composites with bands 1,3 and 4 (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MYD021KM) with geolocation data from the Geolocation 1km (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MYD03); MODIS Atmosphere Level 2 Cloud Production (Collection 6.1) onboard the Aqua satellite for cloud water path, cloud cover and cloud-top temperature (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MYD06_L2); CERES SSF Level 2 product (Edition 4A) onboard the Aqua satellite for TOA shortwave flux and longwave flux (https://ceres.larc.nasa.gov/data/); columnar cloud liquid water (version 8.2) for all-sky liquid water path from AMSR-2 onboard GCOM-W (https://www.remss.com/missions/amsr/); Temperature from Level-2 1km Cloud Layer Data (version 4-51, https://asdc.larc.nasa.gov/project/CALIPSO/CAL_LID_L2_01kmCLay-Standard-V4-51_V4-51) and ice water content from Level-2 5km Cloud Profile Data (version4-51, https://asdc.larc.nasa.gov/project/CALIPSO/CAL_LID_L2_05kmCPro-Standard-V4-51_V4-51) from CALIPSO. The ERA5 data used include the surface skin and surface pressure from ERA5

	hourly data on single levels (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels), and temperature and pressure at 800 hPa from ERA5 hourly data on pressure levels (https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels). The INP data from the MPhase aircraft campaign were obtained from: https://zenodo.org/records/14781199. The measurements during the MPhase aircraft campaign can be obtained from https://catalogue.ceda.ac.uk/uuid/6d7971a92d154bb29af3167dfb6f5a7e/. The model data used for analysis can be found from https://zenodo.org/records/14536461. “ *Method (Line 175-Line 182):* Several changes made to add version numbers for the satellite products. *Appendix D (Line 615-Line 616):* Several changes made to add version numbers for the satellite products.

Minor changes made besides the response to reviewer comments

Description of change	Added the missing “financial support” section.
Old text:	N/A
New text:	*Financial support:* “The M-Phase aircraft campaign was supported by the Natural Environment Research Council (NERC) as part of the CloudSense programme (M-Phase: NE/T00648X/1 and NE/T006463/1). XH was supported by the SENSE - Centre for Satellite Data in Environmental Science CDT (Centre for Doctoral Training) (NE/T00939X/1) with a CASE studentship from the UK Met Office.”

Appendix 1:

Added content in Appendix C in the revised manuscript

Appendix C: Maps for the nested model domains and the sub-domains for analysis

Figure C1 shows the nested model domains and the sub-domains for analysis of both cases. The sub-domains were chosen to be away from the boundaries of the nested model domains to avoid the boundary effects. In both cases, due to the winds and airmasses from northwest direction, the fields generated from the coarser global model require some time to spin up once entering the nested model domain.

We examined whether the boundary effects can reach the sub-domains by using simple calculations of how long it takes the airmasses to reach the western boundary of each sub-domain, and how long it takes for the boundary layer overturning once the fields entering the nested model domain.

The distances were estimated based on the mean direction of wind. For the March case, the distance between the middle of the western boundary of the nested model domain to the middle of the western boundary of the sub-domain is around 430 km. The mean wind speed from surface to 2 km height above sea level is 13.0 m s^{-1} (46.8 km hr^{-1}). Therefore, it takes around 9 hours for the airmasses to reach the sub-domain in the March case. For the October case, the distance between the northwest point of the nested model domain to the middle of the western boundary of the sub-domain is around 500 km. The mean wind speed from surface to 2 km height above sea level is 16.5 m s-1 (59.4 km hr^{-1}), so it takes around 8.5 hours for the airmasses to reach the sub-domain in the October case.

The timescale for boundary layer overturning in the nested model domain is calculated as L/σ_w, where L is the boundary layer depth (~1000 m at the beginning of the CAO events) and σ_w is the standard deviation of the w component of wind. For the March case, the mean σ_w below 1000 m between the western boundaries of the nested model domain and the sub-domain is around 0.67 ms^{-1}, which results in a 0.4 h overturning timescale. For the October case, the mean σ_w below 1000m between the northwestern end of the nested model domain and the western boundary of the sub-domain is around 0.59 ms^{-1}, resulting in a 0.5 h overturning timescale.

Therefore, the boundary layers for both cases should be well evolved (>10x overturns) by the time the air reaches the sub-domain boundaries used for analysis. Some airmass travelling into northwestern part of the sub-domain may have less time to spin up and be affected by the boundary effects, however we choose to keep this part of the sub-domain for capturing more earlier stage CAO clouds as the clouds broke up into cumulus clouds very soon in the October case.

For the whole sub-domain in the March case and most of the sub-domain (except the small northwestern part) of the October case, the time and distance required for the airmasses to reach the sub-domains are sufficient to avoid the boundary effects propagate into the sub-domain.

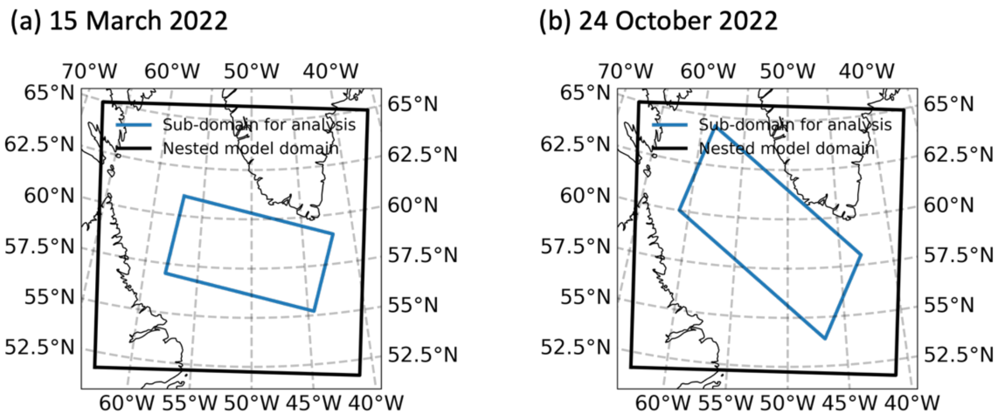

Figure C1. Nested model domains (black) and the selected sub-domains for analysis (blue) for (a) 15 March 2022, (b) 24 October 2022.