Investigating the development of clouds within marine cold air outbreaks: Response to Reviewers

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We thank the reviewers for their care in reading our manuscript, all of their suggestions have been carefully considered and our responses are attached below. Please note that the line numbers referenced below when discussing where edits have been made correspond to the diff manuscript.

1 Response to Reviewer 1

l. 11 - recommend rephrasing as trajectories are not stable.

We have removed the reference to these trajectories being "more stable" at line 12.

l. 18-21 - I understand what you're trying to communicate in those two sentences, but they seem somewhat detached, so I recommend rearranging/rephrasing.

We have rearranged he sentences to make the paragraph clearer at line 22. The final sentence now reads as: "These results also highlight the need for information about present-day aerosol sources at the ice edge to correctly model cloud development."

l. 29-31 - because studies on the effect of clouds on sea ice cover find indications of additional feedbacks and effects, I recommend adding "for example" before "a decrease in cloud reflectivity ..."

Thank you for the suggested, we have changed line 30 accordingly.

l. 51-52 - this sentence is not clear. Stratification of the lower BL creates convective conditions? Do you mean that the cloud effectively forms a secondary BL (in addition to the now-decoupled mixed layer), which can support the formation of convective clouds because the coupled BL is now shallower? In any case, a reference is required here.

The sentence has been rephrased for clarity at line 53, and a reference has been added. Essentially, the cooling of the sub-cloud layer moves that layer to a more convective state, which, with the moistening due to the evaporation of the drizzle, promotes the formation of cumuliform clouds (Stevens et al., 1998).

The sentence now reads as "This cooling creates instability near the surface, which, in conjuction with the moistening effect, is favourable to the formation of cumuliform clouds (Stevens et al., 1998)".

l. 51 - define "This"

This comment has been addressed in the above response.

Fig. 1 - coordinates are pixelated. We apologise for the degraded quality of the image - it has been updated, and new labels have been added for clairty.

l. 59 - add "generally" after "aerosol concentration"

Line 62 has been amended accordingly.

l. 66-67 - This sentence is somewhat repetitive of l. 55-56.

The sentence at line 71 has been shortened to avoid repetitiveness.

l. 68 - higher –> high and l. 69 - remove 'liquid'

Line 73 has been amended.

l. 70-75 - sentence too complex. Recommend breaking it in two.

The sentence has been altered (line 78). The sentence now reads as: The radiative properties of supercooled liquid clouds - which are prevalent in the Arctic (Shupe, 2011; Cesana et al., 2012) - in a changing climate are of particular interest. The Arctic region is warming at a much faster rate than in lower latitudes (**?**), and leading to the ability to establish more industries and shipping routes as sea ice is lost.

l. 71 - recommend concern –> interest This comment has been addressed above. **l. 71 - recommend adding Shupe, 2011.**

The reference has been added at line 78 (see above).

l. 96 - above –> north of

This has been changed in line 104.

l. 108 – to my knowledge, eq. 1 originates in Wood and Hartmann (2006). Please also provide a reference for eq. 2.

We appreciate pointing out this reference. We have added it added at line 117, and included other references for Equation 2.

l. 133 - rho –> rho_w

This has been fixed in line 122.

l. 114 - Q here is not the scattering efficiency but the extinction efficiency

This has been corrected in line 124.

119-124 - I doubt that 263 K and MODIS ice fraction retrievals really remove ice (or even most of it). You can say that ice occurrence is less likely and that you are focusing on liquid-dominated clouds, which is still somewhat vague. As you already noted, it is challenging to detect phase with a passive instrument.

We appreciate your points regarding the challenges of removing (or limiting) ice clouds in this dataset. We have rephrased the paragraph to state that we are looking at liquid-dominated clouds, and have included a reference on the efficacy of the MODIS phase discrimination algorithm (which compares relatively favourably with CALIOP). The sentence now reads as:

Although the MODIS optical property phase algorithm typically performs well in comparison to active sensors (Marchant et al., 2016), it is still unlikely that this filtering entirely removes ice clouds from the dataset.

123 - the results of de Boer et al., 2009 refer to mass and don't claim that these clouds are ice-free, as you also demonstrate in Fig. 2. Recommend rephrasing this sentence accordingly.

We appreciate you pointing this out to us, and have altered the sentence to:

Additionally, only pixels with a cloud top temperature above 263 K are included; in situ measurements in the Arctic have shown that these clouds typically have very high liquid water fractions (de Boer et al., 2009).

l. 125 - provide a reference for CALIOP

References have been added for CALIOP and CloudSat at line 137.

Fig. 2 caption - 'Liquid' should be 'Warm' per the legend.

Thank you for noticing this, the caption has been fixed.

l. 150-151 - this sentence is somewhat repetitive - recommend combining it with the final sentence of the previous paragraph.

The sentences have been altered, and now read as: "However, MODIS struggles to retrieve cloud properties over sea ice (e.g. Chan and Comiso, 2013), the strict filtering of sea ice applied in this work helps to prevent potential cloud misclassification."

l. 150 - see 2.2 –> see Section 2.2

This has been amended in line 163.

SLP can often be below 1000 hPa around cyclones over the North Atlantic, for example. In these cases, the 1000 hPa ERA5 data is wonky. How common are these cases in your dataset and what is the impact (if any) on the results?

We found that in about 14% of cases, the mean sea level pressure (from ERA5 data) in the region is below 1000 hPa. We analysed these cases separately from the rest of the dataset, and found that the general patterns observed in the paper were still clear and there was minimal impact on the results. As a result, we have not altered the main text.

l. 154-155 - what are the statistics of cloud top pressure justifying the use of the 750 hPa pressure level? I know that you present CTP later on in the manuscript but as a reader, this can be confusing as it is non-chronological.

The rationale was that this to ensure the data were taken from above the cloud top. However, the data in the supplementary have been changed to be the humidity at 800 hPa, as this is closer to the cloud but still above the average cloud - as can be seen in Figures 5, 6 and 7, the typical cloud embedded in an outbreak is below 800 hPa. The pattern higher (lower) humidity for weaker (stronger) events still holds. The text at line 168 has been updated and the rationale explained.

l. 158 – The MCAO acronym now refers to both the index and the event itself, so one of these definitions requires a different acronym.

"M" is now used to define the MCAO index and MCAO is left to refer to the events thoughout the manuscript.

l. 170 - I don't understand Fig. 4 and what it represents. If the white areas are mainly regions with no data (a value of 0) as they exceed the range, then color it differently than white. Also, I recommend introducing Fig. 4 right after the following paragraph in which you explain the trajectory calculation.

Figure 4 has been updated with the aim of improving the clarity. The values of zero have been kept as their original color to help illustrate the TSI method - that all values on the map are "zero hours since moving off ice" in the advection scheme until they are assigned a non-zero value once they do move off the ice. The bounding box has also been restricted to the area of interest. The paragraph was also moved.

l. 181-182 - So basically you are limiting the analysis to the region from the North Atlantic to the Kara Sea. This should be specified explicitly, and the boundaries should be highlighted in Fig. 5.

Figure 5 has been updated (as with other figures) to only show the region of interest. Line 109 now states the region of interest as the North Atlantic to the Kara Sea.

Fig. 6 - what do the shaded regions represent? Standard deviation? Quartiles?

The shaded regions are the 95% confidence interval for the mean (using bootstrapping). The caption has been changed to include that.

l. 217 - Recommend adding Shupe, 2011

This reference has been added at line 109.

l. 226-229 - This was already discussed extensively in previous MCAO work such as Tornow et al., 2021; 2022.

The text at line 244 has been amended to attribute Tornow et al., 2021, 2022.

l. 233-235 - probably higher than previous MODIS-based studies because of the different data filtering methodologies (excluding highly supercooled clouds).

We thank you for your suggestion, a sentence was added at line 259 to include it.

l. 241-243 - these suggestions regarding airmass origin were recently demonstrated to some extent by Silber and Shupe, 2022.

We thank you for bringing our attention to this reference, it has been added in line 263.

l. 254 - Because the 340 W m-2 value is derived from the solar constant incident onto a disc instead of the full sphere recommend changing: incident solar –> global average incident solar

We have updated the value of the incident solar radiation used to make it more reflective of the region and time of year, and have also used CERES data to obtain a value at just about the cloud top (around 850 mbar). The text has been changed at line 275 where the albedo is used to estimate changes in forcing to reflect this.

l. 258 - are –> is

This has been amended at line 281.

l. 294 - reaching 15 um –> reaching the commonly-used 15 um threshold.

Line 319 has been altered, and is also addressed in a comment below discussing N_d development.

l. 267-270 - That is a nice method. Is resampling performed with or without repetition?
Also, please provide the number of samples in each subset here and elsewhere (e.g., in figures).
Also, by "dividing the AOD distribution" do you refer to the AOD time series? This is not clear.

The resampling is done without repetition.

The number of samples for each dataset are shown in Table 1 below, and have been added to Figures 6, 7, 8 and 9 in the main text.

As for the method, it is the AOD distribution at each time step for the composites which is divided into bins - line 288 has been updated to improve clarity. The text now reads:

"As aerosol concentration is also known to affect cloud development (Section 4.3), the data are resampled such that the AOD distributions are equal for the strong and weak MCAO composites for each time step (following **?**). The resampling method involves dividing the AOD distribution at each time step into bins for strong and weak trajectories and randomly sampling the

Dataset	Number of Pixels	Figure (main text)
All MCAO	568,829	6
Non-MCAO	3,185,523	6
Towards	3,122,213	6
Strong MCAO	117,900	7
Weak MCAO	153,624	7
High AOD	205,766	8
Low AOD	188,349	8

bin of the trajectory with more points in it until it matches the trajectory with fewer points (as illustrated in Figure 1 of **?**). This is repeated for each time step."

l. 300 - more unstable –> less stable

The text has been rephrased at lines 227, 328 and 411.

l. 302 - Figure 6 –> Figure 7. Also note that cloud depth is implicit here, so you should note that this is indicated in the figure.

Line 330 has been changed to note that cloud depth is implicit with cloud top height.

l. 303-305 - what is then the source for the steepest Nd decline before 15 h? Just drying entrainment? Nd is assumed to be constant with height here, so this is not just a cloud-top effect. Perhaps this is the ice effect you discuss towards the end, which is more likely at the lower CCT closer to the ice edge.

There are several factors which could explain the rapid N_d decline. One is the drying entrainment drying, which would be expected to be more intense in the strong MCAO events. Entrainment also mixes in cleaner air to the cloud layer, reducing the CCN concentration (Tornow et al., 2022). The boundary layer also deepens in the stronger events, which reduces the N_d concentration. Precipitation is also key - although the mean droplet size is smaller than the typical precipitation threshold (Figure 7 e in the main text), there are still a significant number of precipitating droplets. Figure X below shows the fraction of pixels in each aggregated 25km x 25km grid box which are above 15 um. It can be seen that early in the trajectories, at least 30% of droplets are precipitating, which contributes to the N_d decline. Riming due to the presence of ice would accelerate this (Tornow et al., 2021). The text at lines 316-321 have been updated to include more of this discussion.

l. 330 - define INP and CCN

Definitions for INP and CCN are now included earlier in the text (lines 71-72) at their first mention.

l. 331-332 - right, but please provide a reference for this sentence.

An appropriate citation has now been added at line 364.

l. 332 - simply –> qualitatively, l. 404 - since this is the future we are dealing with, I would use a weaker verb here such as insinuate, for example., l. 412 - emit as black bodies –> have an emissivity near unity.

These edits have been made at line 364, 439 and 448.

l. 420 - Recommend adding a reference to the MOSAiC overview paper (Shupe et al., 2022)

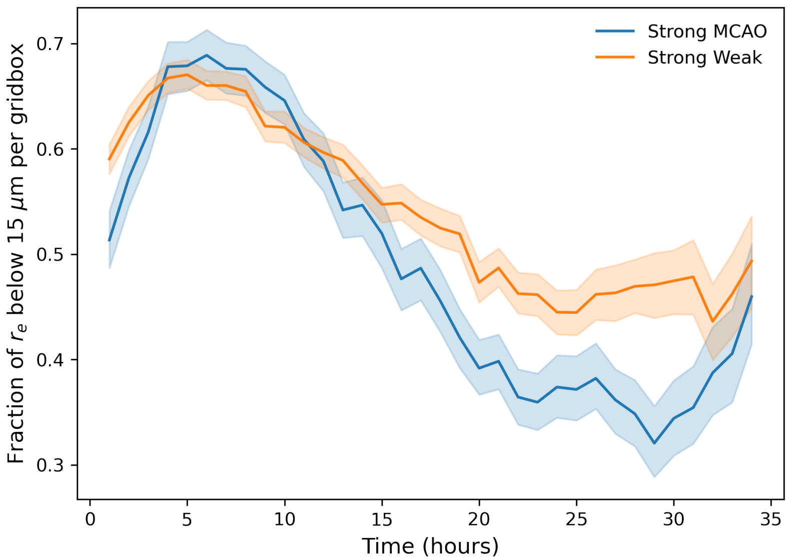

Figure 1. Fraction of 1 km pixels for each 25 km x 25 km which have retrieved droplet effective radius below the precipitation threshold (15 um).

The reference has been added at line 457.

l. 423 – following my comment on l. 119-124, Fig. 2 clearly shows that a significant, though not a big, fraction of clouds here contain ice, so I wouldn't treat these clouds as strictly liquid-phase. You could say liquid-dominated for example.

Throughout the text the phrase "liquid-dominated" has been used instead of implying that these are soley liquid clouds.

427-428 - right, but alternatively, there could also be higher ice concentrations around relatively higher temperatures around -5 C due to SIP.

As a detailed discussion of ice processes is not within the scope of this work, lines 427-428 were removed to avoid confusion.

Also, the lower r_e in stronger events is counterintuitive, because these clouds typically deepen with distance from the ice edge (suggesting greater differences from weaker events in cloud top height and temperature), but you could refer to the cloud top temperature panel to support your argument.

We appreciate you pointing this out to us, we have added a section at lines 339 to noting the counter-intuitive results.

2 Response to Reviewer 2

Figure 2 and other similar styled figures: can you add the description of the shadings to the figure caption?

These shadings represent the 95% confidence interval for the mean - this information has now been included in the figure captions for Figure 2 and 6.

Please provide full name of acronyms, such as DARDAR, SMMR DMSP SSM, ERA5

We thank the reviewer for pointing this out, and we have now added the acronym explanations where appropriate in the Materials and Methods section.

Line 158: MCAO is used to represent the boundary layer stability here, whereas it is short for marine cold-air outbreak before this point. Please use a different terminology for one of them (you used M to represent MCAO index in line 197).

We apologise for the confusion; M is now used to present the MCAO index throughout paper and figures.

Figure 3: are the MCAO index and FRO shown here for all March – October 2008 – 2014 regardless of the selection criteria you described in this section? If so, what does the figure look like from the samples after applying various data filters?

The figures below (which have replaced the Figure 3 in paper) show the results following the data filtering method, as well as subsetting for the region of interest. The overall patterns of the results are the same, but the magnitudes of the MCAO strength and frequency have increased - most likely due to filtering the nighttime data. This figure now replaces the original figure as it is more representative of the results. We thank you for the suggestion.

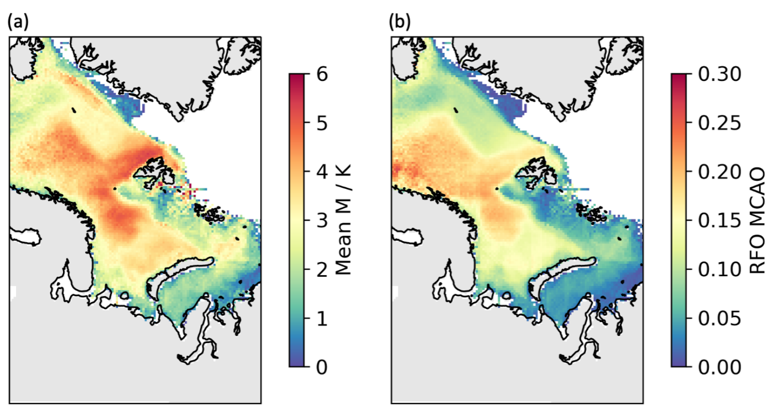

Figure 2. MCAO index (M) calculated from ERA5 data for March-October 2008-2014, filtered to only include MCAO events ($M > 0$) (a) and relative frequency of occurrence for outbreaks (b). Grey represents the land and white represents no data due to sea ice coverage.

Following the previous question, can you show a map of MODIS sample numbers used in the analysis after all the filtering process? You can show that in the response and does not necessarily in the main text.

The below figure shows the geographic distribution of the number of MODIS samples for each 25 km x 25 km pixel. In comparison with the mean TSI plots, it can be seen that up to about 30 hours into each trajectory, there are several thousand retrievals for each pixel. However, for longer times, there are typically fewer points. This is in part due to the MODIS's polar orbit; at higher latitudes (more likely to be early in the trajectory), there are more overpasses for a given pixel. The low number of samples at very high latitudes is due to this being covered by sea ice for much of the year. All of the pixels shown in this plot have at least a few hundred points.

Line 222: should it be 'decrease at a rate of 1 g m-2 hr-1' or 'change at a rate of -1 g m-2 hr-1'? similar for line 232.

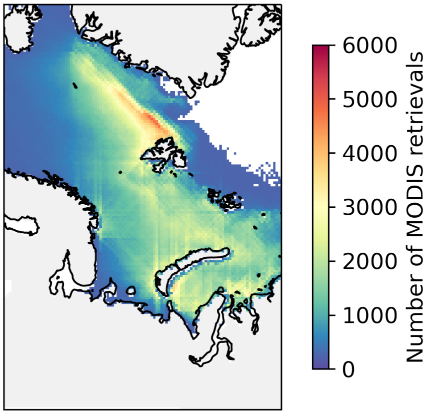

Figure 3. Geographic distribution of MODIS pixels used in the dataset.

Thank you for the observation, and we have amended both lines (239 and 250).

Line 335-336: I am curious how do you resample in the MCAO index space and in the wind speed space at the same time? Do you form the 2-d bins with the MCAO-index and wind-speed and then resample in each 2-d bin?

The resampling for M and then windspeed are done sequentially; first the sampling by M is completed, and then by the wind speed. The M distribution is then checked again to ensure that the populations still have similar distributions. As M and the wind speed are highly correlated, the order of resampling (whether M or wind speed is performed first) does not have a noticable influence on the results.

The text has been changed to make this sequential resampling more clear at line 369.

References

Cesana, G., Kay, J. E., Chepfer, H., English, J. M., and de Boer, G.: Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL053385, 2012.

Chan, M. A. and Comiso, J. C.: Arctic Cloud Characteristics as Derived from MODIS, CALIPSO, and CloudSat, Journal of Climate, 26, 3285 – 3306, https://doi.org/10.1175/JCLI-D-12-00204.1, 2013.

de Boer, G., Eloranta, E. W., and Shupe, M. D.: Arctic Mixed-Phase Stratiform Cloud Properties from Multiple Years of Surface-Based Measurements at Two High-Latitude Locations, Journal of the Atmospheric Sciences, 66, 2874 – 2887, https://doi.org/10.1175/2009JAS3029.1, 2009.

Marchant, B., Platnick, S., Meyer, K., Arnold, G. T., and Riedi, J.: MODIS Collection 6 shortwave-derived cloud phase classification algorithm and comparisons with CALIOP, Atmospheric Measurement Techniques, 9, 1587–1599, https://doi.org/10.5194/amt-9-1587-2016, 2016.

Shupe, M. D.: Clouds at Arctic Atmospheric Observatories. Part II: Thermodynamic Phase Characteristics, Journal of Applied Meteorology and Climatology, 50, 645 – 661, https://doi.org/10.1175/2010JAMC2468.1, 2011.

Stevens, B., Cotton, W. R., Feingold, G., and Moeng, C.-H.: Large-Eddy Simulations of Strongly Precipitating, Shallow, Stratocumulus-Topped Boundary Layers, Journal of the Atmospheric Sciences, 55, 3616 – 3638, https://doi.org/https://doi.org/10.1175/1520-0469(1998)055<3616:LESOSP>2.0.CO;2, 1998.

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, 12 049–12 067, https://doi.org/10.5194/acp-21-12049-2021, 2021.

Tornow, F., Ackerman, A. S., Fridlind, A. M., Cairns, B., Crosbie, E. C., Kirschler, S., Moore, R. H., Painemal, D., Robinson, C. E., Seethala, C., Shook, M. A., Voigt, C., Winstead, E. L., Ziemba, L. D., Zuidema, P., and Sorooshian, A.: Dilution of Boundary Layer Cloud Condensation Nucleus Concentrations by Free Tropospheric Entrainment During Marine Cold Air Outbreaks, Geophysical Research Letters, 49, e2022GL098 444, https://doi.org/https://doi.org/10.1029/2022GL098444, e2022GL098444 2022GL098444, 2022.