Reply to referee #2

We thank Referee #2 for reviewing the manuscript and the valuable comments and suggestions which we address below. The responses to the referee comments are given in blue italic letters.

General

This manuscript analyzes observations and retrievals of cloud macrophysical and microphysical properties during the HALO-(AC)³ field campaign, focusing on their temporal and spatial variations. One case out of six is used to demonstrate detailed cloud evolution, while the statistical analysis shows the spread and general tendencies across all six cases. The presented dataset is valuable for improving our understanding of MCAO cloud structures and their evolution.

However, the selection of the demonstration case needs stronger justification. In addition, when comparing the aircraft-based findings with previous studies, especially satellite-based analyses, the manuscript should provide clearer explanations for why the results differ. Simply stating that satellite resolution is coarse or retrieval uncertainty is high is not sufficient to explain contrasting trends.

I also find that the statistical analysis section does not add much new information beyond what is already shown in the case study, except for illustrating the spread among cases. Based on these concerns, I recommend returning the manuscript to the authors for major revision before it can be considered for publication in ACP.

Major Comments

1. Case selection (Section 3.1)

Please justify the choice of the 20220401 case as the main demonstration of cloud macrophysical and microphysical evolution. Based on Figure 1, this case does not appear to be the most representative of a classic MCAO. In this case, cloud streets are oriented roughly parallel to the ice edge, implying continuous advection of fresh cold air from the ice to the open ocean. As a result, cloud properties are persistently influenced by cold, dry air.

A more typical MCAO would involve cold air flowing off the ice edge and clouds forming with roll structures oriented roughly perpendicular to the ice edge (e.g., 20220329). While the 20220401 case may still provide useful insights, its findings may lack generality. This might explain why the cloud fraction evolution in this case differs from the statistical behavior reported in Murray-Watson et al. (2023). In your Figure 5, the 20220401 case appears to be the only one with nearly constant cloud fraction during the first several hours, and it also has the shortest flight time over open ocean.

The MCAO observed on 20220401 was the strongest MCAO sampled during HALO-(AC)³. Based on the MCAO index, it was a typical event for this region and time of the year (Walbröl et al., 2024). The flight was selected because there was a clear northerly flow on that day with air masses originating from the central Arctic. In contrast, the other observed MCAOs were much more influenced by the topography of Svalbard or showed more complicated, rather circular backward trajectories. In addition, collocated in situ measurements are available for the flight on that day and a large number of dropsondes was released. This was not the case for the other flights. Other studies also investigated specifically the research flight on 20220401 and we wanted to contribute to a complete picture of the MCAO observed on that day. Therefore, we also selected this flight for a more detailed case study. In addition, the second part of this work in Weber et al. (2025a) discusses the vertical cloud structure on that day using the collocated in situ measurements. We agree that the cloud streets are not entirely perpendicular to the sea ice edge, which might influence the cloud evolution

compared to a MCAO with the mean wind direction aligned entirely perpendicular to the sea ice edge, and added this information to the discussion of the results. However, the conditions were typical for a MCAO in this region during that time of the year, as discussed by Walbröl et al. (2024) and Kirbus et al. (2024). We added more details about the case selection to Sect. 3:

"The event on 2022-04-01 was the strongest MCAO sampled during HALO-(AC)[3]. In contrast to the other MCAO flights, the backward trajectories showed a clear northerly flow from the central Arctic towards the South without a significant influence of the topography of the island of Svalbard. In addition, collocated in situ measurements were collected on this day. Several studies have already analyzed data from the research flight on 2022-04-01. Kirbus et al. (2024) studied the thermodynamic evolution during this MCAO, based on dropsonde measurements during HALO-(AC)[3]. In addition, Schirmacher et al. (2024) investigated the roll convection regime using radar observations. In the following, the temporal and spatial evolution of macrophysical and microphysical cloud properties, including cloud top height, cloud thermodynamic phase, and cloud droplet size, derived from passive remote sensing with specMACS will be presented and discussed. This complements existing studies about the MCAO observed on 2022-04-01 and contributes towards a complete picture of this case. The second part of this work (Weber et al., 2025a) additionally analyzes the vertical cloud structure observed on this day, exploiting the collocated remote sensing and in situ observations and building upon the results presented in the following."

2. Comparison with previous studies

Both the case study and the statistical analysis are compared with previous work, especially Murray-Watson et al. (2023, hereafter MW23). However, it is not a fair comparison to contrast a single case with a statistical composite from many cases, particularly when the selected case is not a typical MCAO example.

For cloud fraction, you attribute differences between your results and MW23 to instrument resolution (L212–215). It is not clear how resolution alone would systematically change cloud fraction estimates and the temporal/spatial trend, and this needs clearer explanation. Later, you note that stronger MCAOs tend to have higher cloud fractions, consistent with MW23.

For cloud particle size, MW23 found smaller sizes for stronger MCAOs, which is opposite to your result. You attribute this partly to satellite retrieval uncertainties, but it is unclear why such uncertainties would specifically lead to smaller effective radii in stronger MCAOs. Wouldn't retrieval uncertainty affect strong and weak MCAO cases similarly? This point needs more careful physical and methodological explanation.

Thank you very much for this comment. We changed the discussions in sections 3.1 to make clearer that 2022-04-01 is a single case study and might therefore differ from the average general statistics in Murray-Watson et al. (2023). In addition, we added more comparisons to other references and more explanations about the observed results and potential reasons for differences between the different works to both sections 3.1 and 3.2. In particular, we adjusted the parts discussing the differences between the observed cloud fractions and cloud droplet effective radii between our work and Murray-Watson et al. (2023). Differences between the instrument resolutions as well as the choice of threshold values can affect the absolute values of the derived cloud fraction. We agree that this applies similarly to weak and strong cold air outbreaks and see, in general, a similar behavior of weak and strong MCAOs as Murray-Watson et al. (2023). An explanation for the observed almost constant cloud fraction on 2022-04-01 compared to the general statistics could, for example, be that this individual case is not entirely representative as mentioned by you. Regarding the cloud droplet radii, there are different potential reasons for differences in the absolute values, including different retrieval methods, sensitivities, and instrument resolutions. The observed differences in the droplet size during strong and weak cold outbreaks which are opposite to the findings of Murray-Watson et

al. (2023) can also have several reasons. First, variations in aerosol concentrations can have a large influence on the cloud droplet size. Second, during HALO-(AC)³, only six MCAOs could be observed, which showed a large variability and occurred in different regions under different synoptic situations. Nevertheless, these six events are not necessarily representative for the general statistics of weak and strong MCAOs. For all changes please see the Latexdiff.

3. Relationship between Sections 3.1 and 3.2

I understand that Section 3.1 presents a detailed case and Section 3.2 presents statistics. However, Section 3.2 does not seem to add much new information beyond Section 3.1, other than showing the large spread across cases. These two sections could potentially be merged, with individual cases discussed in the context of the statistics.

I briefly looked at your Part 2 manuscript on vertical cloud structure. Combining horizontal and vertical structures into a single comprehensive observational paper could be very valuable. As it stands, the current manuscript alone does not seem sufficient as a standalone paper. I will leave it to the authors to decide.

If you prefer to keep this as a separate paper, I suggest adding more discussion of the physical mechanisms behind the observed temporal and spatial evolution. Currently, the manuscript mostly presents observations, with limited interpretation. Alternatively, you could emphasize which of your findings are truly new compared to previous satellite or modeling studies.

The first draft was actually a single paper including the analyses of the temporal and spatial cloud evolution as well as the vertical cloud structure. However, the draft was very long and addressed many different research questions relevant also to slightly different communities. Therefore, we decided to split the draft in to two parts, since shorter papers are usually also easier to read. The second paper got a positive review so far and we would, therefore, like to keep the two separate paper drafts. However, we agree that this paper draft is comparably short. We followed your suggestions and added more discussions, explanations, and interpretations about the observed temporal and spatial evolution throughout the paper and additionally emphasized more which of our findings are new. An explanation, why we show the case study in addition to the statistics is given above in the answer to the first comment. With the statistics, we wanted to go beyond a simple case study and discuss the observed variability as well as differences depending on the MCAO intensity. Studies based on airborne observations often only discuss single case studies. Then, often the question of the representativity and poor statistics is raised. Therefore, we analyzed all available data. For all changes please see the Latexdiff.

Minor Comments

L50: can you elaborate briefly on why true Lagrangian observations are challenging.

We added a brief explanation: "In the Arctic, no geostationary satellite data is available and aircraft move much faster than the observed airmass."

L78: "aircraft" -> "aircrafts."

Changed as suggested.

L105: The full name of the instrument should be given at its first appearance.

Changed as suggested.

Figure 2: What does "WGS84" on the y-axis of the left column mean? Has this been defined?

WGS84 refers to the World Geodetic System 1984 and specifies the reference system defining the Earth's surface and therefore the cloud top height. We included this information for completeness since some studies use ellipsoidal and others geoid heights. We added an explanation: "The cloud top heights are given above the World Geodetic System 1984 (WGS84) ellipsoid."

L208–209: You state that cloud fraction remains almost constant during the first hours. To me, the variability in the first half looks comparable to that in the second half, as seen in Figures 2b and 2e. Please clarify how this conclusion is reached.

The "almost constant" referred to the mean cloud fraction, which remains similar. We agree that the variability is large and also remains almost constant with time. We changed the sentence to: "The average cloud fraction (see Fig. Fig2b and 2e) remained almost constant during the first hours of the observed MCAO, as can also be seen in the RGB images in Fig. 3. The variability of the cloud fraction is high showing values between 0.5 and 0.8 and is also almost constant with time."

L212–215: MW23 presents statistics from many MCAO cases, while you compare their results with a single case. I suggest avoiding direct comparison of one case with statistical composites. Also, while specMACS may provide more accurate cloud identification due to higher resolution, it may also have a narrower field of view than satellites, which could affect cloud fraction estimates.

We changed and extended the comparisons between different studies. Please see our answer to major point 2 above.

Figure 4: There is a distance near the beginning where no data appear in the bottom row, while data are shown in the top row once the aircraft is over open ocean. Please clarify why this occurs.

Both rows show the same measurements, but the upper row displays them as a function of time above open ocean and the bottom row as a function of distance above open ocean. Time and distance were both calculated using the same backward trajectories. However, the wind speed is not necessarily constant along the trajectories which leads to differences between the visualizations in terms of time and distance. In particular, close to the sea ice edge, the surface wind typically increases due to the off-ice acceleration which leads to a "stretching" of the curves at small distances above open ocean compared to small times above open ocean. This information was given in the section before and we extended it to: "The different shapes of the curves describing, e.g., the evolution of the cloud top height during the first kilometers above open ocean compared to the first minutes above open ocean in Fig. 2 and similar figures in the following sections can be explained by changing wind speeds due to the off-ice acceleration at the sea ice edge."