

Reply to referee #1

We thank Referee #1 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.

This study by Weber et al. investigates the vertical distribution of microphysical cloud properties and its evolution during the early stage of a marine cloud air outbreak observed during the HALO-(AC)³ measurement campaign. The manuscript is interesting to read, well aligned with the scope of the journal, and presents clear results and conclusions that are highly relevant and useful to the community investigating mixed-phase clouds and their evolution during marine cold air outbreaks. Overall, the manuscript is well written and well structured.

I recommend this paper for publication after a minor revision. Below there is a list of comments for the authors to consider.

Comments:

Line 113: “had to used” change to “had to be used”

Changed as suggested.

Line 139: I think it is good to add here that “the backward trajectories were computed from ERA5 wind fields using Lagranto”, so that readers do not need to consult Weber et al.(2025a) to obtain this information.

Changed as suggested.

Section 3.1: The discussion about the ice fraction shown in Figure 2 (Section 3.1) is focused on the mean values. However, there is a large spread in the values of the ice fraction (from 0 to 1) for a given brightness temperature. Can the authors comment on this feature? Is it possible to give some estimation regarding the cloud ice characteristics (i.e. number concentration, size or effective radius) when the ice fraction is 1. It is mentioned that there is a four orders of magnitude difference between the measured ice and cloud droplet number concentrations. I was wondering whether this difference is reduced when the ice fraction is 1.

Thank you very much for this comment. We agree that it would be very interesting to give some estimation regarding the cloud ice characteristics for specific specMACS measurements.

Unfortunately, we cannot derive ice crystal number concentrations and sizes from the specMACS measurements. In principle, the ice crystal effective radius can be derived from measurements of the spectrometers using a bispectral retrieval. However, bispectral retrievals only exist for either liquid water clouds or ice clouds and not for mixed-phase clouds. Applying a bispectral retrieval for ice clouds to mixed-phase clouds would yield huge uncertainties due to the influence of liquid cloud droplets in addition to the uncertainty of the necessary ice crystal habit assumption. Information about ice crystal number concentration and crystal size is only available from the collocated in situ measurements. Here, however, we cannot directly relate in situ measurements to individual specMACS measurements but only compare the measurements statistically. There was a collocation between the different research aircraft with two direct overflights above open ocean, but the in situ measurements would have had to be taken at the same time at the same horizontal location and at the correct altitude close to cloud top for a direct comparison.

The in situ measurements of the ice crystal effective radius, in general, showed a large variability between about 15 to 150 μm with mean values around 120 μm and a tendency towards larger sizes at lower altitudes. The ice crystal number concentration according to the in situ observations varied between about 0 to 0.1 cm^{-3} with a mean of about 0.02 cm^{-3} , whereas the observed cloud droplet

number concentrations were in the range of 50 to 180 cm⁻³, as shown in Fig. 6. So, even if the difference between the cloud droplet and ice crystal number concentrations is reduced, the observed range of values indicates that the absolute difference remained large.

Part of the large variability of the ice fraction can also be explained by the large retrieval uncertainties. In general, smaller ice fractions were observed in the centers of the clouds and higher ice fractions close to one at the cloud edges. On the one hand, this can be expected as the measurements at the cloud sides correspond to lower altitudes. On the other hand, the ice fractions applied in the analyses in Sect. 3.1 were retrieved using the slope angular range. This angular range is less sensitive to the ice fraction and, in addition, more strongly affected by 3D radiative effects than the cloudbow angular range. As a result, the distribution of the derived ice fractions from the slope angular range shows a tendency towards a bimodal structure with higher frequency of the ice fractions close to 0 and close to 1. For more details to the retrieval uncertainties and configurations please refer to Weber et al. (2025b). Unfortunately, the observation geometry did not allow to combine measurements in the more certain cloudbow angular range with the VELOX measurements. So, the observed spread can be related to both physical reasons as well as retrieval uncertainties.

We added a discussion about this to Sect. 3.1: “In general, the variability of the retrieved ice fractions is large. The horizontal distribution of the retrieved ice fractions (not shown) showed generally smaller ice fractions at the cloud centers and larger ice fractions towards the lower cloud sides. In addition, small-scale variability could be observed. Part of the large spread of the ice fraction, including values close to 0 and 1 in Fig. 2, however, has to be related to retrieval uncertainties, which have been characterized in detail in Weber et al. (2025b).”

Line 241: “contraction” change to “contradiction”?

Changed as suggested.

Line 268: “combing” change to “combining”

Changed as suggested.

Figure 5: What is WGS84 (in the y-axis label)?

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.”

Section 3.2: In this section, the order in which the results are presented feels somewhat strange to me. After introducing Figure 5 and describing the main features of the measured profiles of the effective radius of liquid cloud droplets, line 264 states that the measured and modelled profiles shown in Figure 5 will be compared. However, the discussion then shifts to explaining the results shown in Figure 6, before finally returning to the comparison of the profiles in Figure 5 at the end of the section. I personally didn’t like very much these transitions between Figures 5 and 6.

I think it would be better to briefly state at the beginning of the section that the goal is to analyze and compare the vertical and temporal evolution of the effective radius of liquid cloud droplets based on measurements and parcel model calculations. Then you can clarify that the parcel model calculations require knowledge of the cloud droplet number concentration. In consequence you want to introduce first the results shown in Figure 6, followed later by the description and comparison of the profiles in Figure 5.

Thank you very much for this suggestion. We tried to restructure the section to make it easier to follow. Please see the latexdiff for all changes.

Line 273: Are these decoupled clouds associated to the synoptic situation and possibly forming before the air mass is advected over the ocean, or are they related with some other local atmospheric conditions?

These clouds are observed in the marginal sea ice zone. Cloud formation starts as soon as small fractions of open ocean exist at the still sea ice dominated surface. Above sea ice, longwave radiative cooling at the surface causes a temperature inversion. As soon as the clouds reach the open ocean, the turbulence induced by the strong surface warming causes a coupling of the boundary layer and the clouds. We added this information:

“Cloud formation starts as soon as small fractions of open ocean exist in the marginal sea ice zone. Above sea ice, longwave radiative cooling at the surface causes a temperature inversion. The turbulence induced by the warm open ocean surface then leads to a coupling of the boundary layer and the associated clouds.”

Line 345: “Collision and coalescence is relevant” change to “Collision and coalescence are relevant”

Changed as suggested.

Lines 435-439: Can the authors comment on whether the results and conclusions presented in these lines are likely to be specific to this case or representative of cold air outbreaks in general? Related to this, are there previous studies on cold air outbreaks that have reported results and reached conclusions that are consistent with, or in contrast to, those presented here?

The presented analyses and conclusions are based on a single case study and in general, large differences in the evolution of clouds during MCAOs can be observed. According to the MCAO index climatology, the MCAO observed on 2022-04-01 in the Fram Strait was a typical event for the region during the time of the year, but it is not necessarily representative of MCAOs in general. To the best of our knowledge, the parcel model was for the first time applied to Arctic mixed-phase clouds in this work and there is only a limited number of studies investigating the cloud thermodynamic phase during MCAOs. The results agree with our current theory and understanding of mixed-phase clouds and a previous study by Seppala et al. (2025) observed a phase-stable MCAO regime with high and relatively constant fractions of liquid water clouds over a long period of time. The observed MCAO on 2022-04-01 might also fall into this category. We added a discussion about this to the conclusion:

“The findings of this work are based on a single case study. According to the MCAO index climatology, the observed MCAO on 2022-04-01 in the Fram Strait was a typical event for the region during the time of the year (Walbröl et al., 2024; Kirbus et al., 2024). However, the variability between the cloud evolution during the different observed MCAOs during HALO-(AC)³ was large (e.g., Weber et al., 2025a) and the case on 2022-04-01 is, therefore, not necessarily representative of the evolution of clouds during MCAOs in general. At the same time, a previous study based on satellite observations observed a “phase-stable” MCAO regime with high and relatively constant fractions of liquid water clouds over a long period of time Seppala et al. (2025). The MCAO on 2022-04-01 in the Fram Strait might be classified as one of these events.”