



# Quasi-Lagrangian observations of cloud transitions during the initial phase of marine cold air outbreaks in the Arctic – Part 2: Vertical cloud structure

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**Abstract.** The aim of this work is to study the vertical distribution of microphysical cloud properties, in particular the thermodynamic phase partitioning and the cloud droplet size, in low-level mixed-phase clouds during marine cold air outbreaks in the Arctic. For this purpose, high resolution observations of the initial phase of a strong marine cold air outbreak in the Fram Strait collected with the hyperspectral and polarized imaging systems specMACS during the airborne HALO-(AC)<sup>3</sup> campaign are analyzed. Pseudo-vertical profiles of the cloud thermodynamic phase generally showed increasing ice fractions with increasing height and decreasing temperature, except for a geometrically thin layer at the cloud top, which was more liquid-dominated. The measurements indicated that ice formation occurred preferentially at the coldest temperatures. In addition, the effective radius of the liquid cloud droplets increased with height, as expected. The observed vertical evolution of the liquid cloud droplets could be successfully modeled by an entraining parcel model. The good agreement between measured and calculated vertical profiles of the cloud droplet effect radius and additional information based on in situ measurements indicated that the influence of collision-coalescence and ice processes, such as riming, the Wegener-Bergeron-Findeisen mechanism, and ice formation through heterogeneous freezing, on the liquid cloud droplets was small for the observed clouds. The presented analyses and data can help to improve the representation of low-level Arctic mixed-phase clouds in models and to further our understanding of these clouds and the related microphysical processes.

## 1 Introduction

Meridional transports of heat and moisture are important components of the Arctic climate system and relevant for Arctic amplification (Wendisch et al., 2021). During marine cold air outbreaks (MCAOs), cold and dry Arctic airmasses are transported southwards from the cold sea ice over the warmer open ocean (Papritz and Spengler, 2017; Fletcher et al., 2016). The large temperature gradients between the cold advected airmasses and the ocean surface generate intense surface fluxes of heat and moisture, which may be responsible for 60 % to 80 % of oceanic heat loss during winter in the Nordic Seas, influencing deep water formation and sea ice dynamics (Papritz and Spengler, 2017; Svingen et al., 2023). Furthermore, the strong temperature contrasts create convection and lead to the formation of low-level clouds (Papritz and Spengler, 2017). The clouds usually first organize into cloud streets aligned with the mean wind direction and transition into cellular structures further downstream due



to precipitation formation and a decoupling of the evolving atmospheric boundary layer (Brümmer, 1999; McCoy et al., 2017; Abel et al., 2017; Pithan et al., 2018; Tornow et al., 2021). MCAOs may be related to polar lows and severe weather events in the mid-latitudes, such as cold extremes or heavy snowfall (Pithan et al., 2018). The Fram Strait is one of the main pathways for MCAOs in the Arctic and this region experiences comparably frequent and intense MCAOs (Papritz and Spengler, 2017; Dahlke et al., 2022). The accurate modeling of the intense air mass transformations during meridional transports into and out of the Arctic is challenging for large-scale and high-resolution models (Sato et al., 2016; Pithan et al., 2016; Tomassini et al., 2017; Field et al., 2017; Wendisch et al., 2021). Models particularly struggle to correctly represent the microphysical evolution of clouds during MCAOs and warm air intrusions (Pithan et al., 2014; McCoy et al., 2015; Tan and Storelvmo, 2019; Field et al., 2014; Abel et al., 2017). As a result, projections of future Arctic climate remain highly uncertain (Smith et al., 2019; Cohen et al., 2020; Block et al., 2020).

The clouds that form during MCAOs are typically mixed-phase clouds and have a distinct vertical structure. A geometrically thin layer with supercooled liquid water is typically observed at the cloud top. Ice crystals form from this supercooled liquid layer through heterogeneous nucleation and sediment downwards (Morrison et al., 2012). The ice crystals in mixed-phase clouds can rapidly grow at the expense of liquid cloud droplets through the Wegener-Bergeron-Findeisen (WBF) mechanism (Wegener, 1911; Bergeron, 1935; Findeisen, 1938). However, Arctic mixed-phase clouds were observed to be very persistent with average lifetimes of 12 hours and occasionally up to several days (Shupe et al., 2006; Morrison et al., 2012). The partitioning and the spatial distribution of the cloud thermodynamic phase are important quantities since the spatial distribution of the supercooled liquid water droplets and ice crystals affects, for example, the efficiency of the WBF mechanism (Korolev et al., 2017; Korolev and Milbrandt, 2022) and therefore cloud cover and cloud lifetime (Pithan et al., 2014). In addition, the thermodynamic phase determines the radiative effect of the cloud (Choi et al., 2014; Matus and L'Ecuyer, 2017). The accurate modeling of mixed-phase clouds and their microphysics is challenging for climate and general circulation models (Morrison et al., 2012; Pithan et al., 2014; Komurcu et al., 2014; Cesana et al., 2015, 2022). Models of different scales struggle, in particular, to correctly represent cloud thermodynamic phase partitioning and the vertical distribution of cloud liquid water (Inoue et al., 2021; Kretzschmar et al., 2019, 2020). Observational data is needed to provide constraints to models (Pithan et al., 2018). The typical spatial scales of inhomogeneities in Arctic clouds are on the order of a few hundred meters (Schäfer et al., 2017, 2018). These scales require high-spatial resolution measurements to be resolved. Especially, information of the vertical distribution of cloud microphysical properties is needed.

The vertical cloud structure can, in general, be analyzed using active remote sensing measurements. Vertical information about the cloud microphysical properties can, however, also be derived from passive imaging. Rosenfeld and Lensky (1998) and Lensky and Rosenfeld (2006) combined two-dimensional fields of the effective radius of liquid cloud droplets and the cloud top temperature derived from passive satellite observations to create pseudo-vertical profiles of the droplet radius in convective clouds. This method assumes that the droplet effective radius is conserved for a given temperature and that the cloud top properties of different clouds at different evolution stages observed in a single snapshot are similar to those of an individual evolving cloud. The method was validated based on observational data as well as model data (Lensky and Rosenfeld,



2006; Zhang et al., 2011). It was first developed for pure liquid water clouds, but later also applied to deep convective clouds, which contain cloud ice (Freud et al., 2008).

60 This work is based on measurements of the specMACS instrument collected during the airborne HALO-(AC)<sup>3</sup> field campaign, which was conducted in March and April 2022 and focused on airmass transformations during meridional transports into and out of the Arctic (Wendisch et al., 2024; Ehrlich et al., 2025). During HALO-(AC)<sup>3</sup>, the German High Altitude and LOnG range research aircraft (HALO, Krautstrunk and Giez, 2012), containing remote sensing instrumentation, operated together with the Polar 5 and Polar 6 aircraft (Wesche et al., 2016), performing further remote sensing and in situ measurements.  
65 The measurements were conducted using a quasi-Lagrangian flight strategy, which allows for studying cloud evolution during MCAOs. The hyperspectral and polarized imaging system specMACS (Ewald et al., 2016; Weber et al., 2024) was installed in a downward-looking perspective on board HALO and provides high-spatial resolution information about macrophysical and microphysical properties of clouds, including cloud thermodynamic phase partitioning and the effective radius of liquid cloud droplets (Ewald et al., 2016; Weber et al., 2024).

70 This work builds upon Weber et al. (2025a), who investigated the temporal and spatial evolution of macrophysical and microphysical cloud properties during MCAOs using specMACS measurements during HALO-(AC)<sup>3</sup>. The objective of this work is to extend the analyses by Weber et al. (2025a) and study the vertical distribution of microphysical cloud properties, in particular the thermodynamic phase partitioning and the cloud droplet size, in low-level Arctic mixed-phase clouds and its evolution during MCAOs. To this end, measurements of microphysical cloud properties from specMACS are combined  
75 with cloud top temperature measurements from the thermal imager on board HALO and cloud top height measurements from specMACS to construct pseudo-vertical profiles, following the method by Rosenfeld and Lensky (1998) and Lensky and Rosenfeld (2006). Specifically, the vertical distribution and the temperature dependence of the cloud thermodynamic phase as well as their evolution with time are analyzed for the strong cold air outbreak observed on 2022-04-01 in the Fram Strait. In addition, the vertical distribution and evolution of the cloud droplet effective radius on this day is investigated. Furthermore,  
80 we test the ability of a simple parcel to describe the observed vertical profiles of the droplet effective radius and study the influence of cloud ice on the supercooled liquid water droplets. This work aims to provide observational constraints to models, which struggle to accurately represent mixed-phase clouds, their thermodynamic phase partitioning, the vertical distribution of cloud liquid water, and evolution during MCAOs. In addition, the presented analyses can help to further our understanding of Arctic mixed-phase clouds and the associated microphysical processes.

85 This paper is structured as follows. The applied data and methods are introduced in Sect. 2. The results of the analyses are presented in Sect. 3 and discussed in Sect. 4, before the findings are summarized in Sect. 5.

## 2 Data and methods

### 2.1 Measurement data

In this work, measurements of the spectrometer of the Munich Aerosol Cloud Scanner (specMACS, Ewald et al., 2016; Weber  
90 et al., 2024) during the airborne HALO-(AC)<sup>3</sup> measurement campaign in the Arctic are applied (Wendisch et al., 2024; Ehrlich



et al., 2025). In particular, data from the research flight on 2022-04-01 in the Fram Strait are analyzed. The HALO flight on that day sampled the initial phase of a MCAO following a quasi-Lagrangian flight strategy (Wendisch et al., 2024), and was coordinated with the Polar 5 and Polar 6 aircraft. specMACS consists of two hyperspectral cameras sensitive to the visible and near-infrared and the shortwave infrared wavelength range, so-called VNIR and SWIR, and two 2D RGB polarization-resolving cameras, which are installed in a downward-looking perspective on board HALO. This work applies measurements of the SWIR spectrometer, which covers the wavelength range between 1000 nm and 2500 nm wavelength and has a field of view of  $35.3^\circ$  in across-track direction, and the polarization-resolving cameras, which have a maximum combined field of view of  $91^\circ \times 117^\circ$  in along-track and across-track direction. The specMACS measurements provide high-spatial resolution information about cloud macro- and microphysical properties with spatial resolutions between 10 m and 100 m for typical flight altitudes, depending on the retrieved quantity.

The cloud top height is derived from measurements of the polarization-resolving cameras with the stereographic retrieval by Kölling et al. (2019). The effective radius of liquid cloud droplets is retrieved using the multi-angle polarimetric cloudbow retrieval by Pörtge et al. (2023). Information about the cloud thermodynamic phase is obtained with two different methods. First, the ice index, as defined by Ehrlich et al. (2008) and Ruiz-Donoso et al. (2020), is calculated from the measurements of the SWIR. This index is based on spectral absorption differences between liquid water and ice in the near-infrared wavelength range and provides qualitative information about the cloud thermodynamic phase. Values below 20 correspond to a liquid water cloud, whereas larger values indicate a mixed-phase cloud (Ehrlich et al., 2009). Second, a quantitative ice fraction was retrieved from the measurements of the polarization-resolving cameras using the polarimetric phase partitioning retrieval by Weber et al. (2025b). The ice fraction is defined as the ratio of the ice optical thickness to the total cloud optical thickness. In general, the results of the polarized retrieval for the cloudbow angular range using the IDEFAX forward operator for the green color channel are shown, and only observations with saturated polarization signals are considered because they provide the smallest uncertainties (Weber et al., 2025b). For the analyses in Sect. 3.1, however, data of the ice fraction derived from the more uncertain slope angular range had to be used, since the observation geometry did not allow for applying measurements in the cloudbow angular range. Further information about the retrieval can be found in Weber et al. (2025b).

Since the measurements of specMACS are based on passive remote sensing, they are representative for the cloud top. The spectral measurements used to determine the ice index originate from deeper cloud layers than the polarization measurements applied to retrieve the ice fraction and the effective radius of liquid cloud droplets, because the polarization signal is dominated by single scattering. Similar to Weber et al. (2025a), measurements above sea ice with sea ice concentrations larger than 80 % were excluded from the analyses to reduce additional uncertainties due to the influence of the (unknown) surface and misclassification of clouds and sea ice with the brightness-based cloud mask.

In addition to the specMACS observations, measurements of other instruments on board HALO and collocated in situ measurements collected by the Polar 6 aircraft were applied to further characterize the observed clouds. Information about cloud top temperature is available from the thermal imager VELOX (Schäfer et al., 2022) on board HALO, which measures brightness temperatures at six different wavelength channels between  $7.7\mu\text{m}$  and  $12\mu\text{m}$  and has a similar field of view and spatial resolution as the spectrometers of specMACS. Here, the brightness temperatures measured by the first broadband



channel (covering the wavelength range between 7.7 $\mu\text{m}$  and 12 $\mu\text{m}$ ) were used. For measurements in the Arctic, with low water vapor content in the atmosphere, the measurements of this channel are representative for the cloud top. Measurements of the lidar backscatter ratio and aerosol depolarization by the WALES lidar (Wirth et al., 2009) and the radar reflectivity measured by the HAMP 35 GHz cloud radar (Mech et al., 2014) on board HALO provide vertical information about the observed clouds.

130 Furthermore, dropsonde measurements of the air temperature, the pressure, and the relative humidity were gathered. In addition to the measurements from the various instruments on board HALO, collocated in situ observations by the Polar 6 aircraft were used. The different scattering and optical array probes installed on board Polar 6 measure the particle number size distribution, from which the cloud droplet and ice crystal number concentrations and the effective radius and diameter of liquid cloud droplets and ice crystals can be computed as described in Moser et al. (2023) and Ehrlich et al. (2025). The combined particle

135 number size distributions measured by the Cloud Droplet Probe, Cloud Imaging Probe, and Precipitation Imaging Probe were integrated over size for particles smaller than 50 $\mu\text{m}$  diameter, assuming these particles to be liquid, to calculate the cloud droplet number concentration and over particles larger than 50 $\mu\text{m}$  diameter to obtain the ice crystal number concentration (Moser et al., 2023).

As in Weber et al. (2025a), the measurements and retrieval results were combined with backward trajectories to assign every

140 measurement the time the air mass has traveled southwards since passing the ice edge.

## 2.2 Parcel model

The parcel model predicts vertical profiles of the liquid water content of a pure liquid water cloud due to the lifting of an air parcel. The cloud droplet number concentration is assumed to be vertically constant and the actual liquid water content is linearly related to the adiabatic liquid water content through the adiabaticity  $f_{\text{ad}}$ , which accounts for entrainment (Brenquier

145 et al., 2000; Grosvenor et al., 2018). According to this model, vertical profiles of the effective radius of liquid cloud droplets can be computed with (Grosvenor et al., 2018; Brenquier et al., 2000)

$$r_{\text{eff}} = \left( \frac{3}{4\pi\rho_w} \right)^{1/3} (f_{\text{ad}}C_w)^{1/3} (kN_d)^{-1/3} h^{1/3}. \quad (1)$$

Here,  $\rho_w$  is the density of liquid water and  $h = z - z_{\text{base}}$  is the height above the cloud base height.  $k$  is the factor converting volume mean radii to effective radii, with  $k = 0.8$  a typical value for maritime clouds (Martin et al., 1994; Pawlowska and

150 Brenquier, 2000). The condensation rate  $C_w$  depends on temperature and pressure and is computed from the dropsonde measurements with the formula given in Grosvenor et al. (2018). The adiabaticity  $f_{\text{ad}}$  accounts for the reduction of the condensation rate through entrainment. A detailed discussion of uncertainties and assumptions of the adiabatic cloud model can be found in Grosvenor et al. (2018). Here, the adiabaticity was computed with an entrainment model to further account for variations of the entrainment with height (de Rooy et al., 2013):

$$155 \quad f_{\text{ad}} = \exp(-\epsilon h), \quad (2)$$

with  $\epsilon = 1 \text{ km}^{-1}$ , which is a typical value for cumuliform clouds. The cloud base height of the liquid water cloud  $z_{\text{base}}$  was derived from dropsonde data and the cloud heights from the stereographic, respectively, cloudbow retrieval of specMACS as



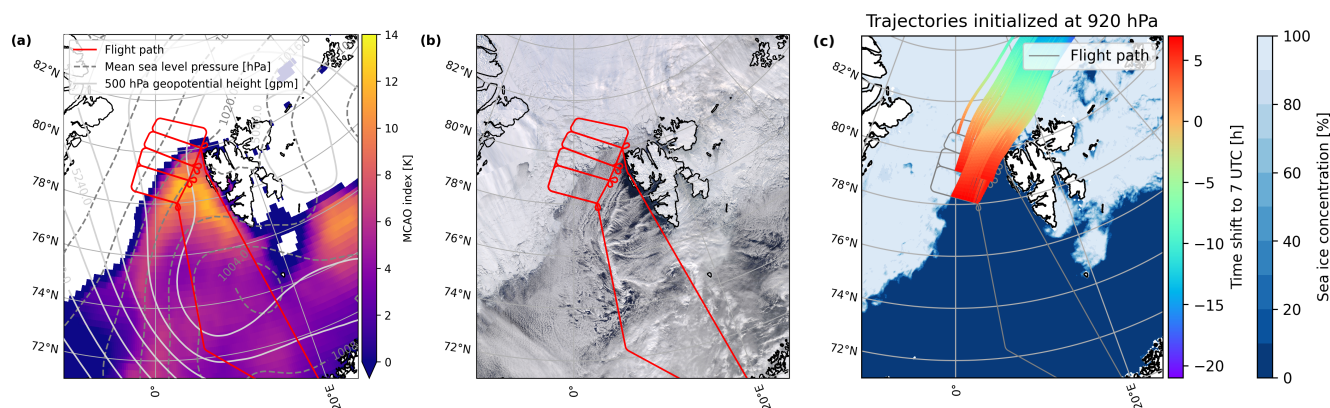
described below, and increases with time above open ocean as the boundary layer develops. Concerning the dropsonde data, the cloud base height was defined as the height where the relative humidity with respect to liquid water first exceeded 99 %. For the specMACS measurements, the minimum height of the measurements, where an effective radius was determined with the cloudbow retrieval was used. A relation for the cloud base height as a function of time above open ocean was obtained by fitting a linear curve through the cloud base heights obtained from the dropsondes and specMACS. This relation is used to compute the effective radius for different times above open ocean. The cloud droplet number concentration  $N_d$  was derived from in situ measurements of the P6 aircraft, which performed collocated measurements with HALO on 2022-04-01, as described above. A more detailed discussion and analysis of the cloud droplet number concentration measurements is given in Sect. 3.2.

### 2.3 Case overview and synoptic situation

This section gives an overview of the research flight conducted by HALO on 2022-04-01, which is analyzed in detail in this work. The flight on 2022-04-01 targeted the Fram Strait region, where a MCAO was observed on that day, and was coordinated with the Polar 5 and Polar 6 aircraft. Figure 1 shows the MCAO index in panel (a), the MODIS satellite image in panel (b), and the backward trajectories together with the AMSR2-MODIS sea ice concentration in panel (c). The flight track is superimposed in red and contours of the mean sea level pressure and the geopotential height at 500 hPa from ERA5 data are displayed in panel (a). The MCAO index is a measure for the strength of the MCAO. It was computed from the potential skin temperature at the surface and the potential temperature at a pressure of 850 hPa using ERA5 data (Hersbach et al., 2023a, b) following Fletcher et al. (2016):

$$M_{\text{CAO}} = \theta_{\text{skin}} - \theta_{850\text{hPa}}. \quad (3)$$

According to Papritz and Spengler (2017) and Dahlke et al. (2022), the event observed on this day with average MCAO indices of around 8 K in the Fram Strait region can be classified as a moderate to strong MCAO. It appears to be a typical event for this region during that time of the year (Kirbus et al., 2024). The synoptic situation was characterized by a high-pressure system over Greenland and the Central Arctic and a low-pressure system above Scandinavia, the Barents Sea, and Russia. This led, together with a local low pressure system south of Svalbard, to a northerly flow in the Fram Strait as indicated by the backward trajectories in panel (c). The satellite image in Fig. 1b shows cloud streets extending southwards from the ice edge. In addition, there are local effects due to the topography of Svalbard visible with several convergence lines and cloud-free regions southwest of the island. The flight pattern targeted the initial phase of the MCAO following the quasi-Lagrangian sampling approach with flight legs oriented perpendicular to and along the wind direction (Wendisch et al., 2024). This quasi-Lagrangian observation strategy allows to study the evolution of thermodynamic and cloud properties observed during the MCAO. The temporal and spatial evolution of cloud macro- and microphysical properties during this research flight was already analyzed in Weber et al. (2025a). In the following, the evolution of the vertical cloud structure will be studied.



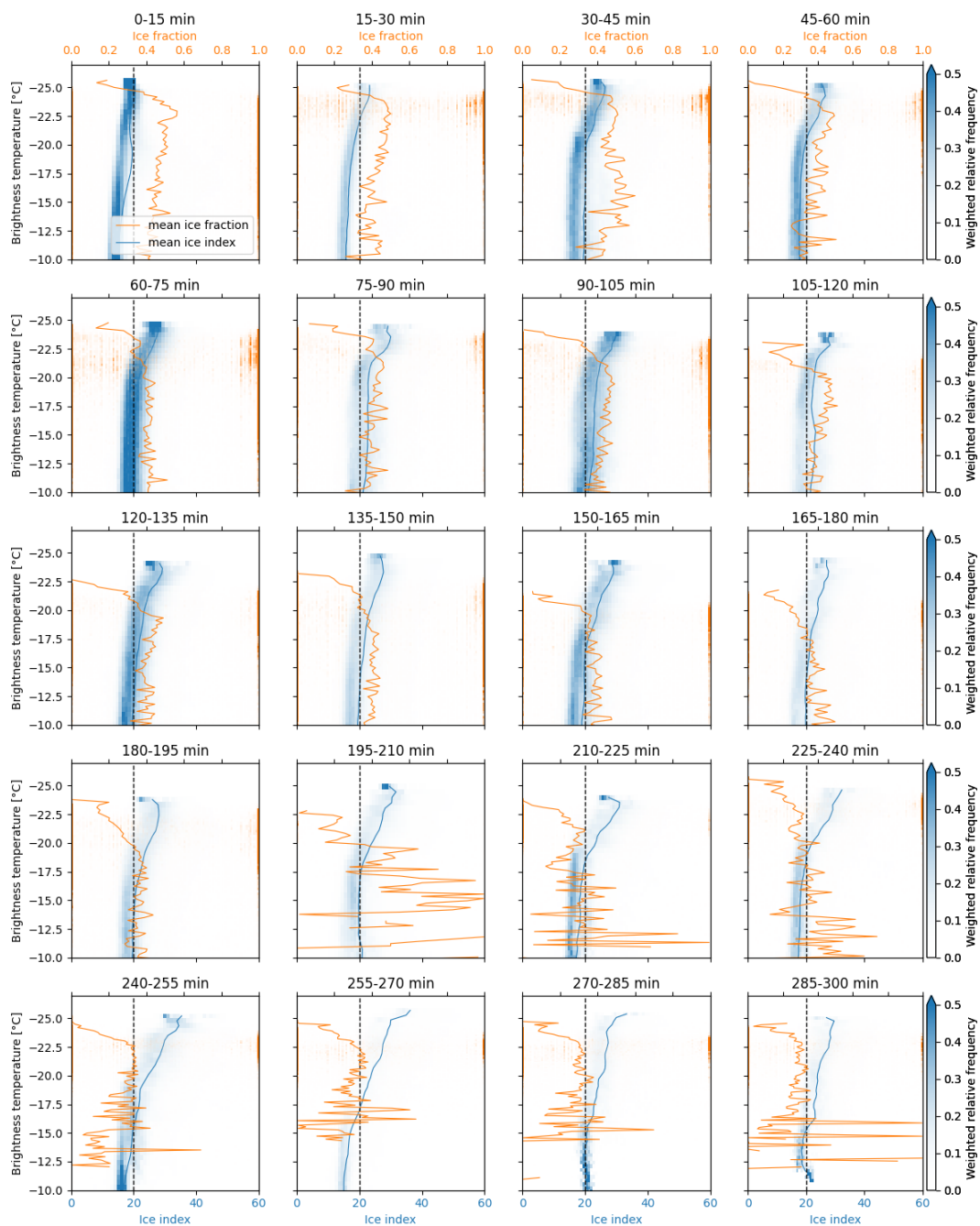
**Figure 1.** MCAO index from ERA5 data (Hersbach et al., 2023a, b) (a), MODIS satellite image (Corrected Reflectance (True Color)) from NASA Worldview (<https://worldview.earthdata.nasa.gov/>) (b), and backward trajectories along the flight track together with AMSR2-MODIS sea ice concentration (Ludwig et al., 2020) (c) for the flight on 2022-04-01. The red lines indicate the flight track. In addition, the mean sea level pressure and geopotential height at 500 hPa from ERA5 are shown as gray dashed and solid lines, respectively, in panel (a). For better visibility, only every 20th backward trajectory is shown in panel (c). The color coding displays the time along the trajectories.

### 3 Results

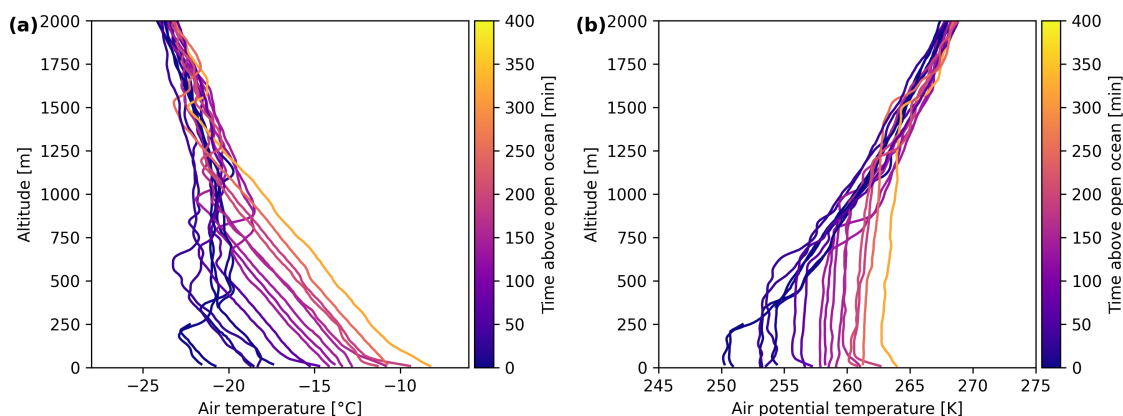
#### 3.1 Temperature dependence and vertical distribution of cloud thermodynamic phase

190 To investigate the temperature dependence and the vertical distribution of the thermodynamic phase partitioning, retrieval results of the ice index and ice fraction from specMACS were combined with measurements of the cloud top temperature from the VELOX instrument, following the method by Rosenfeld and Lensky (1998) and Lensky and Rosenfeld (2006). The measurements from VELOX and specMACS were matched to obtain corresponding cloud top temperature measurements for every ice index, respectively, ice fraction measurement. These data were then used to construct pseudo-vertical profiles of the  
195 cloud phase as a function of temperature.

Figure 2 shows the ice index (blue) and ice fraction (orange) as a function of cloud top temperature. The individual panels correspond to different time ranges above open ocean. This depiction was chosen since the thermodynamic structure of the boundary layer during MCAOs changes with time above open ocean. Vertical profiles of the air temperature and potential temperature measured by dropsondes during the research flight on 2022-04-01 are shown in Fig. 3. The dropsonde data were  
200 combined with trajectory data to assign every measurement a time above open ocean. In general, the temperature decreases with height, and an inversion marks the top of the boundary layer. The altitude of the inversion layer increases with time above open ocean as the boundary layer deepens. In addition, the temperature increases with time. A detailed study of the thermodynamic evolution of the MCAO on 2022-04-01 during HALO-(AC)<sup>3</sup> can be found in Kirbus et al. (2024) and Wendisch et al. (2025).



**Figure 2.** Histograms of ice index (blue) and ice fraction (orange) as a function of the brightness temperature between 7.7  $\mu\text{m}$  and 12  $\mu\text{m}$  (representative for cloud top) for different time ranges above open ocean. The blue and orange solid lines denote the respective mean. The black dashed line indicates the threshold value of the ice index between the liquid water and the mixed phase. The ice fraction was derived with the IDEFAX for the slope angular range.



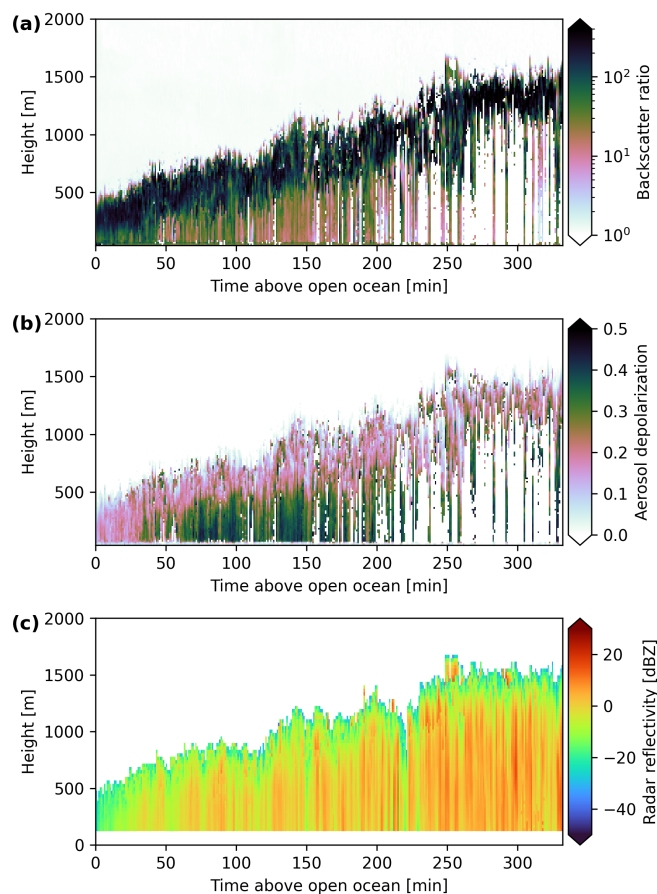
**Figure 3.** Air temperature (a) and potential temperature (b) measured by the dropsondes on 2022-04-01. The colors indicate the time above open ocean at the location of the individual dropsondes.

During the first hour above open ocean, high diabatic heating rates exceeding  $6 \text{ K h}^{-1}$  and moistening rates larger than  
205  $0.3 \text{ g kg}^{-1} \text{ h}^{-1}$  were observed at the surface. The heat and moisture are increasingly mixed upward as the time above open ocean increases and the boundary layer develops.

During the first 15 min after passing the ice edge, the ice index is below the threshold value of 20 for all temperatures, which indicates a liquid water cloud. At later times, the ice index is still almost constant with temperature except for the coldest part, where it increases with decreasing temperature and crosses the threshold value from the liquid water into the  
210 mixed-phase regime. This indicates that ice formation happens preferentially at the coldest temperatures. This is reasonable as several studies based on in situ measurements have shown that the relative fraction of ice increases with decreasing temperature (Korolev et al., 2017). With time, the transition from the liquid water to the mixed phase shifts to higher temperatures, and the ice indices at the coldest temperatures further increase. This could be explained by ice, which is continuously formed at the coldest temperatures at the cloud top and sediments downwards. Consequently, the relative fraction of ice increases and liquid  
215 water might additionally be depleted through riming or the WBF mechanism.

The ice fraction derived with the polarimetric retrieval is mostly constant or slightly increasing with decreasing temperature, similar to the ice index. However, a strong decrease of the ice fraction with decreasing temperature can be observed at the lowest temperatures. This indicates that there is a very thin, more liquid-dominated layer at the cloud top, which is not detected by the spectral retrieval used for determining the ice index. The spectral retrieval is sensitive to deeper altitudes within the cloud  
220 than the polarized retrieval, and the polarized retrieval is more sensitive to liquid water. At longer times above open ocean in the last two rows of Fig. 2, the retrieved ice fraction becomes variable and uncertain due to increasing solar zenith angles and a decreasing number of data points.

Similar to the profiles of the ice index and ice fraction as a function of temperature, pseudo-vertical profiles of both quantities as a function of height can be constructed. The resulting plots are not shown here, since the temperature typically decreases  
225 with height and the results of both analyses are similar (see Fig. 3). The ice index and ice fraction both increased with height,



**Figure 4.** Lidar and radar measurements as a function of time above open ocean on 2022-04-01. (a) Lidar backscatter ratio. (b) Aerosol depolarization. (c) Radar reflectivity. The depolarisation data was filtered for cloud data only, with backscatter ratios larger than 10.

in agreement with the temperature dependence. At the very top, the ice fraction generally showed a strong and sharp decrease, which was also partly captured in the vertical profiles of the ice index. However, this decrease was less pronounced for the ice index. This confirms the existence of a geometrically thin, more liquid-dominated mixed-phase layer compared to the altitudes directly below at cloud top. The supercooled liquid layer had a geometrical thickness of about 100 to 200 m.

230 Additional vertical information is obtained from active remote sensing measurements. The lidar and radar measurements on board HALO were combined with backward trajectories to create composites as a function of time above open ocean. To this end, the data were sorted into one minute bins and all measurements of a certain time bin were averaged. Figure 4 shows the corresponding results for the lidar backscatter ratio (first row), aerosol depolarization (second row) and radar reflectivity (third row). The cloud top height in both, lidar and radar data, shows an increase with time, similar to the measurements of  
235 specMACS discussed in Weber et al. (2025a). At cloud top, the lidar backscatter ratio is high and the depolarization is close to zero, indicating spherical particles. As the lidar is particularly sensitive to small liquid cloud droplets with a high number



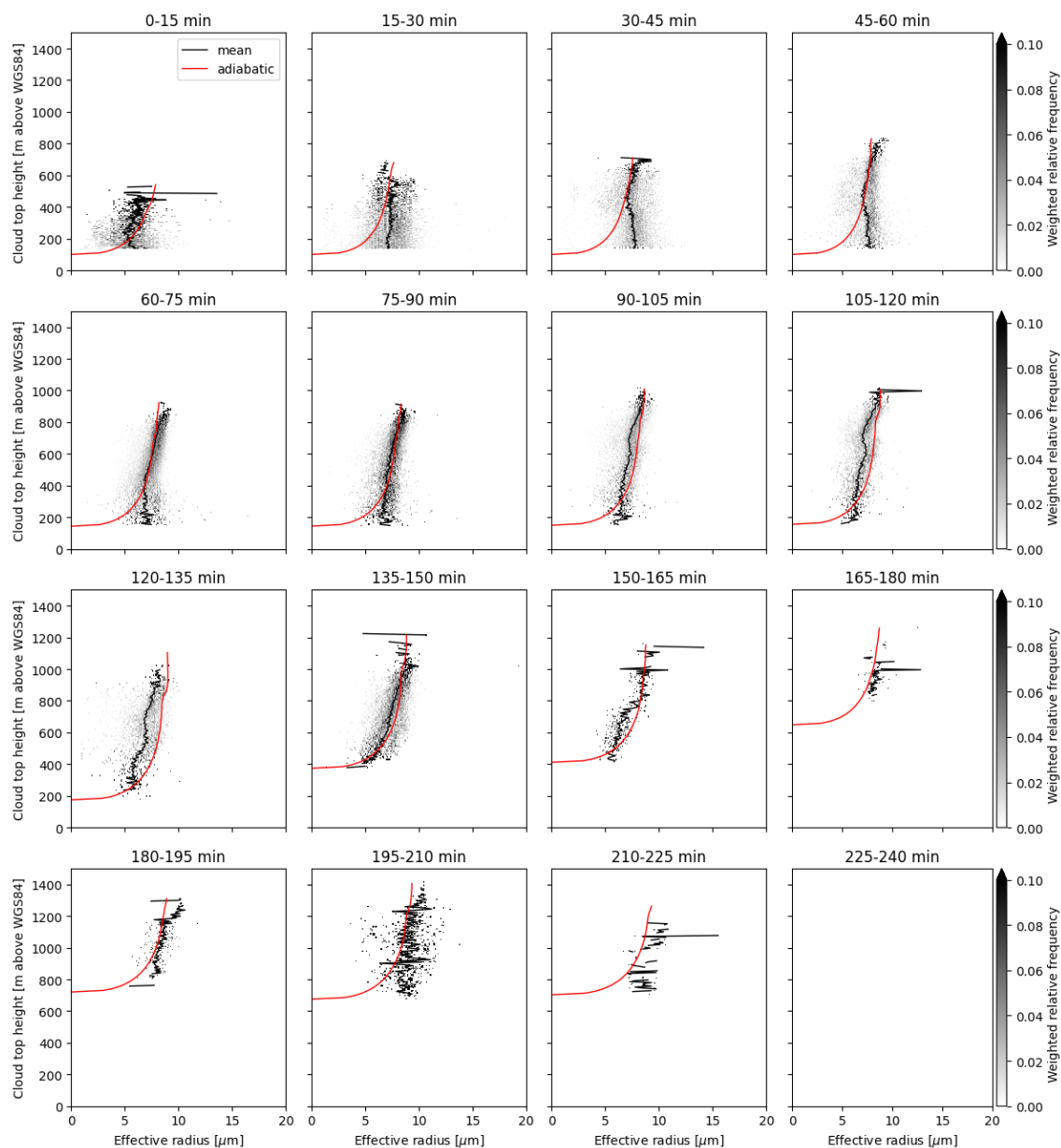
concentration, this hints at the presence of supercooled liquid water in this layer. The radar reflectivity increases with time and from cloud top towards the surface, as the radar signal is dominated by the larger ice crystals. These sediment downwards and grow further during their descent. After about 30 to 45 min above open ocean, the radar reflectivity exceeds the threshold value of  $-5$  dBZ for precipitation (Schirmacher et al., 2024). Moreover, the high radar reflectivities at high altitudes indicate the presence of ice close to cloud top. An increasing radar reflectivity with decreasing height is not a contraction to the observed increasing ice fraction with increasing height and decreasing temperature. The radar reflectivity is very sensitive to the size of the ice crystals, which increases with decreasing height as the larger ice crystals sediment and further grow during their descent, and to a lesser degree influenced by the number concentration. In contrast, the ice fraction is a quantitative optical measure which reflects the optical thickness of both phases and depends on the sizes and number concentrations of cloud liquid water and cloud ice.

A geometrical thin supercooled layer at cloud top from which ice crystals form and sediment downwards is the expected typical structure of low-level Arctic mixed-phase clouds (e.g. Morrison et al., 2012; Tan et al., 2023; Moser et al., 2025). Both, passive and active remote sensing measurements, qualitatively show this distinct structure.

### 3.2 Vertical evolution of the liquid cloud droplets

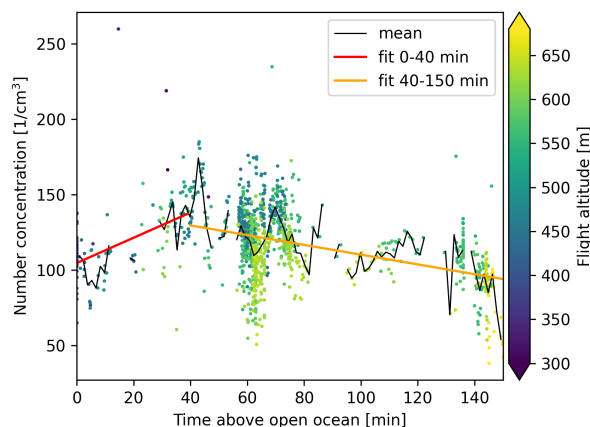
In addition to the vertical distribution of the cloud thermodynamic phase, the vertical evolution of the effective radius of the liquid cloud droplets is analyzed in the following. Pseudo-vertical profiles of the effective radius of liquid cloud droplets are obtained from the measurements similar to Rosenfeld and Lensky (1998) and Lensky and Rosenfeld (2006). To this end, the individual measurements of the effective radius of liquid cloud droplets are combined with the corresponding cloud top heights, yielding a combined pseudo-vertical profile. Figure 5 shows the measured pseudo-vertical profiles of the effective radius of liquid cloud droplets for different time ranges above open ocean in black. In general, the cloud droplet size increases with increasing cloud top height, as is expected. Moreover, the effective radius increases with increasing time above open ocean from initially about  $5 \mu\text{m}$  to maximum values of approximately  $10 \mu\text{m}$  during the observed time range, in agreement with Weber et al. (2025a) and Murray-Watson et al. (2023).

The analyses in the previous section and in Weber et al. (2025a) showed that the liquid water clouds, which form at the very beginning of a MCAO close to the ice edge, rapidly transform into a mixed-phase regime. However, it was not investigated how ice processes influence the cloud liquid water with time and throughout the vertical cloud extent. For example, the WBF mechanism or riming could impact the cloud droplet size and number concentration. To further study these effects, the measured vertical profiles of the effective radius of the liquid cloud droplets are compared to vertical profiles calculated with the parcel model introduced in Sect. 2.2, which does not include ice processes. The input variables for the model are computed from dropsonde measurements, in situ measurements, and measurements of specMACS as explained in Sect. 2.2. The cloud droplet number concentration, needed for the model and obtained from the in situ observations, and its temporal evolution and vertical distribution are further investigated by also combining the measurements with backward trajectories. Differences or agreement between the theoretical and measured profiles provide insights into microphysical processes in the observed mixed-phase clouds and their temporal evolution.



**Figure 5.** Vertical profiles of the effective radius of liquid cloud droplets for different time ranges above open ocean. The black solid line indicates the mean measured effective radius. The red solid lines are vertical profiles calculated using the parcel model (Sect. 2.2).

Figure 6 displays the cloud droplet number concentration as a function of time above open ocean. The color-coding denotes the height of the respective measurements. During the first 40 min above open ocean, the cloud droplet number concentration increases with time. In this time range, the clouds are decoupled from the surface, as indicated by the at least partly increasing potential temperature with height in Fig. 3b (Sotiropoulou et al., 2014; Gierens et al., 2020). Afterwards, the cloud droplet



**Figure 6.** Cloud droplet number concentration as a function of time above open ocean from in situ measurements. The color coding denotes the height of the measurements. The red and orange solid lines are linear fits to the data for times smaller and larger than 40 min, respectively. Only measurements with a LWC larger than  $0.1 \text{ gm}^3$  and with a sea ice concentration smaller than 80 % were used.

275 number concentration decreases with time. Decreasing number concentrations during the initial phase of MCAOs were also  
observed by, e.g., Murray-Watson et al. (2023) and can be explained with entrainment and aerosol scavenging through precipi-  
tation (Abel et al., 2017; Sanchez et al., 2022; Murray-Watson et al., 2023). The increase of the cloud droplet number  
concentration in the beginning is missed in Murray-Watson et al. (2023), potentially due to the much coarser resolution and  
higher uncertainties of the satellite-derived measurements in this study compared to the in situ measurements applied here, but  
280 was also observed by, e.g., Abel et al. (2017).

In addition, the number concentration in Fig. 6 shows only small variations with height. Lower number concentrations are  
measured at higher altitudes, which can for example be explained by the influence of entrainment or by heterogeneous freezing  
of liquid cloud droplets. However, the vertical variations of the number concentration are small compared to the uncertainties of  
the measurements such that the cloud droplet number concentration can be assumed to be approximately constant with height.  
285 A vertically constant number concentration is a required assumption for the adiabatic cloud model and this was also observed  
in other studies such as Brenguier et al. (2000); Painemal and Zuidema (2011) for stratocumulus clouds and by Gerber et al.  
(2008) for small cumulus clouds.

For the parcel model, linear fits were applied separately to times smaller and larger than 40 min to obtain a relation of the  
number concentration as a function of time above open ocean. The orange and red lines in Fig. 6 show the resulting fits. Due  
290 to the limited range of the Polar 6 aircraft, measurements of the number concentration are only available for the first 150 min  
above open ocean. They were extrapolated to larger times using the obtained linear fit. With this, the theoretical vertical profiles  
of the effective radius of liquid cloud droplets were calculated for any time above open ocean.

The theoretical vertical profiles of the effective radius for different time ranges above open ocean are represented by the red  
lines in Figure 5. Large deviations of the measured and calculated profiles are observed in the first row of Fig. 5, especially at



295 lower altitudes. At these times, close to the ice edge, the clouds are decoupled from the surface, as discussed above, and the  
parcel model is not applicable. In addition, the measured and calculated profiles mostly differ at the cloud base. A reason for  
this could be that the lowermost part of the clouds with very small effective radii of the liquid cloud droplets is too optically  
thin to be captured by the measurements, or is geometrically not visible for large viewing angles in combination with high  
cloud fractions. In addition, the initial growth of small liquid cloud droplets at the cloud base is fast and the cloud base height  
300 is difficult to determine, such that small uncertainties have a larger influence. Besides that, there is generally a good agreement  
of the profiles, which indicates that the cloud ice did not significantly impact the cloud liquid water during the observed initial  
phase of the cold air outbreak on 2022-04-01 and that the parcel model is applicable here. The profiles calculated with the parcel  
model were not fitted to the measured pseudo-vertical profiles. Instead, the input variables were computed from measurements  
as described above. Deviations between the parcel model and the direct measurements are explained either by uncertainties of  
305 the input variables, by droplet collision and coalescence, or by ice processes, which are not accounted for in the parcel model.  
These will further be discussed in the following section.

#### 4 Discussion

In the previous section, pseudo-vertical profiles of the effective radius of liquid cloud droplets were presented. They generally  
showed increasing droplet sizes with increasing height and time above open ocean. In addition, theoretical profiles according to  
310 the parcel model introduced in Sect. 2.2 were calculated and compared to the measurements. This allows on the one hand to test  
the ability of the parcel model to describe the cloud liquid water in the observed mixed-phase clouds and on the other hand to  
study the influence of ice processes. The agreement between the measured and calculated vertical profiles of the cloud droplet  
effective radius in Fig. 5 was generally good, indicating the parcel model realistically represents the cloud liquid water in  
the observed mixed-phase clouds. To support this conclusion, the potential reasons for deviations between the measurements  
315 and the model, including measurement uncertainties, droplet collision-coalescence, and ice processes, are discussed in the  
following.

##### Uncertainties of input variables and model assumptions

First, the uncertainties of the input variables to the model are considered. The measurement uncertainties of the cloud droplet  
number concentration from in situ observations are about 10 % to 30 % (Moser et al., 2023), which corresponds to an uncer-  
320 tainty of the modeled effective radius of about 10 %. In addition, the vertical variation of the number concentration in Fig. 6  
is about 50 %, which could explain deviations between the effective radii of up to 25 %. The cloud base height also has uncer-  
tainties, as it is derived from measurement data, but these uncertainties only shift the computed effective radius profile in the  
vertical direction. Other uncertainties arise from the interpolation between the condensation rates computed from the individ-  
ual dropsondes. However, the condensation rate varies only slightly with temperature and pressure in the observed temperature  
325 range.



Furthermore, an entrainment model (Eq. 2) was applied to compute the effective radius. The effective radius is, in general, only slightly influenced by entrainment (Freud et al., 2008). Variations of the adiabaticity by 10 % in Eq. 1 change the calculated effective radius by less than 4 % for the observed cloud droplet sizes. Nevertheless, the agreement between the measured and calculated vertical profiles of the effective radius varied depending on the chosen value of the adiabaticity. The good agreement  
330 for the applied entrainment model indicates that this model realistically describes entrainment in the observed clouds. However, the adiabaticity could, in principle, also be reduced by other processes than entrainment. In mixed-phase clouds, simultaneously growing liquid cloud droplets and ice crystals compete for the available water vapor. This can lead to a reduced growth of liquid cloud droplets, similar to the influence of entrainment. At least a part of the reduction of the adiabaticity could potentially be attributed to this effect. From the measurements, it is not possible to directly distinguish between the impact of entrainment  
335 and ice crystals competing with the liquid cloud droplets for the available water vapor. However, the observed clouds are still dominated by liquid water, and the ice fraction and ice index are comparably small (see Fig. 2). In addition, the applied entrainment model is a realistic assumption. Thus, entrainment is likely the dominating factor here, but the influence of the ice crystals on the droplet growth introduces an additional uncertainty.

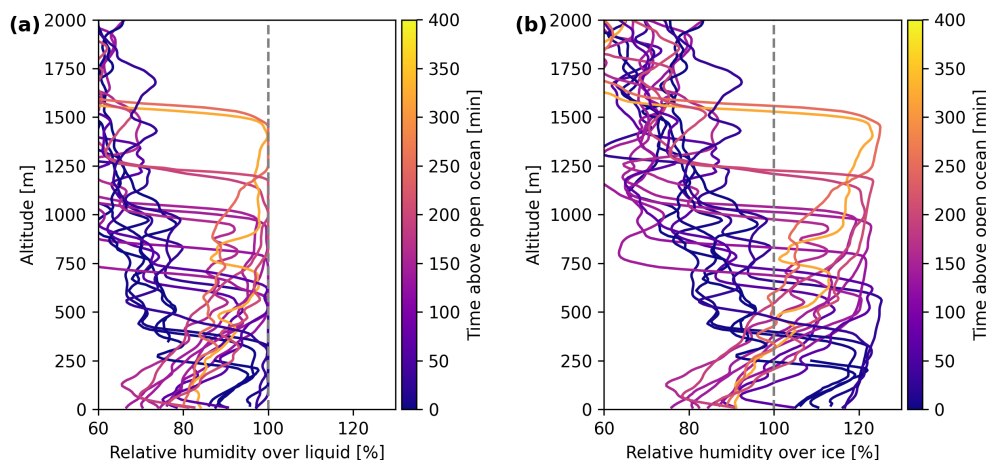
Moreover, the uncertainty of the measured effective radii from the cloudbow retrieval based on an evaluation with synthetic  
340 data is  $-0.2 \pm 1.6 \mu\text{m}$  (Volkmer et al., 2024; Pörtge, 2024). In summary, the uncertainties of the input variables used to model the effective radius and the uncertainties of the measured effective radii can explain the observed differences between the profiles.

### Microphysical processes

Besides measurement uncertainties, microphysical processes, such as droplet collision and coalescence and ice processes, can  
345 lead to deviations of the observed profiles of the effective radius from the parcel model. Collision and coalescence is relevant if the effective radius of liquid cloud droplets exceeds  $14 \mu\text{m}$  (Freud and Rosenfeld, 2012). The observed liquid cloud droplets have maximum effective radii of about  $10 \mu\text{m}$ , which is much smaller than this threshold. Therefore, collision and coalescence can be neglected in the observed clouds.

Another possible explanation for deviations between the parcel model and the observed effective radii is ice processes,  
350 such as ice formation through freezing, ice crystal growth through the WBF, and riming. Ice formation in mixed-phase clouds predominantly happens through heterogeneous freezing of supercooled liquid cloud droplets (de Boer et al., 2011; Cui et al., 2006; Ansmann et al., 2005). Hence, the formation of ice crystals decreases the cloud droplet number concentration. The probability for a supercooled liquid water droplet to freeze increases with increasing droplet size and decreasing temperature, but it also strongly depends on the efficiency of the ice nuclei. The ice crystal number concentration, computed from in situ  
355 measurements of the particle number size distributions from particles larger than  $50 \mu\text{m}$ , amounts to about  $20 \text{L}^{-1}$ , which is four orders of magnitude smaller than the observed cloud droplet number concentration. Hence, the influence of the conversion of liquid water droplets into ice crystals through freezing on the effective radius can be neglected.

A second ice process that can influence the liquid cloud droplets is the WBF mechanism. The WBF mechanism is, however, active only in a distinct regime with supersaturation with respect to ice and subsaturation with respect to liquid water



**Figure 7.** Vertical profiles of the relative humidity with respect to liquid water (a) and ice (b) measured by the dropsondes on 2022-04-01. The colors indicate the time above open ocean of the respective dropsonde. The gray dashed line corresponds to 100 % relative humidity.

360 (Korolev, 2007). Information about the supersaturation during the research flight on 2022-04-01 is available from the dropsondes of HALO and the in situ measurements of the P6 aircraft. Figure 7 displays vertical profiles of the relative humidity above liquid water in panel (a) and above ice in panel (b) measured by the dropsondes. A layer with saturation above liquid water and supersaturation above ice is observed in the upper part for most times, which coincides with regions of high lidar backscatter ratio, indicating the presence of liquid cloud droplets. In this height range, liquid water droplets and ice crystals  
365 grow simultaneously. Close to the cloud top, there is usually a thin layer with supersaturation above ice only, which could be explained by entrainment of dry air. At lower altitudes, only supersaturation above ice is reached. This is the region where the WBF mechanism is active and larger radar reflectivities indicate the presence of ice.

The measured profiles of the effective radius for the time ranges between 90 min and 135 min show some variations of the slope with height and larger deviations from the parcel model in regions where the WBF mechanism could be active.  
370 However, there are only a few dropsonde measurements, which cover only parts of the time ranges, and the in situ data provide only limited vertical information. This makes it difficult to directly relate these deviations to the WBF mechanism, and the deviations are in general small compared to the measurement uncertainties. Moreover, the small ice crystal number concentration measured by the in situ probes indicates that no significant ice multiplication has taken place. Thus, even if the WBF mechanism is active, the measurements suggest that its influence on the effective radius is small. This can be due to  
375 inhomogeneous mixing of the liquid water and ice phase, the small ice crystal number concentration, or a combination of both, which makes the WBF mechanism less effective and limits its impact on the effective radius of the liquid cloud droplets. If highly resolved measurements of the vertical profiles of the cloud droplet number concentration were available, both effects could be distinguished.



Another ice process that can explain deviations between the parcel model and the measured effective radius profiles, especially in regions where the WBF mechanism is not active, is riming. Laboratory measurements indicate that the influence of riming on the cloud droplet size distribution is small (Ávila et al., 2009). According to the theoretically computed collision efficiencies, the liquid cloud droplets must reach a critical size for collisions with ice crystals, depending on the crystal shape (Wang and Ji, 2000). The retrieved effective radii smaller than  $7.5\ \mu\text{m}$  are close to the critical radius for riming, and actually riming was observed during the research flight on 2022-04-01 (Schirmacher et al., 2024; Maherndl et al., 2024). However, the collision probability is small due to the low ice crystal number concentrations. Furthermore, the normalized rime masses computed from in situ and radar measurements by Maherndl et al. (2024) show only light riming with mean values of about 0.03 on this day, which is small.

In summary, there is agreement between the measured vertical profiles of the effective radius of liquid cloud droplets and the applied parcel model within the range given by the measurement uncertainties. Collision and coalescence processes can be neglected in the observed clouds. Ice processes, such as heterogeneous freezing of supercooled liquid cloud droplets, riming, and the WBF mechanism, did not significantly impact the cloud liquid water in the initial phase of this MCAO. The parcel model realistically describes the evolution of the liquid cloud droplets in the observed low-level Arctic mixed-phase clouds, except for cases where the clouds are decoupled from the surface.

### Limitations

Nevertheless, we discuss some limitations of the presented methods and results in the following. In general, the same limitations as in Weber et al. (2025a) apply, including, for example, the issue of the cloud mask in the presence of sea ice and increased measurement uncertainties due to large solar zenith angles in the Arctic. Strictly speaking, the method by Rosenfeld and Lensky (1998) and Lensky and Rosenfeld (2006) to construct pseudo-vertical profiles was only validated for the cloud droplet effective radius. Here, it was also applied to the cloud thermodynamic phase assuming that the thermodynamic phase is also a conserved quantity for a given temperature, similar to the effective radius. A study similar to Lensky and Rosenfeld (2006), based on model data, could be repeated for cloud thermodynamic phase partitioning to investigate the validity of this assumption. For the parcel model, the assumption of vertically constant cloud droplet number concentration is not completely correct, and there are large uncertainties in all the input parameters to the calculated effective radius profiles from the model. In the future, it would be helpful to have vertical profiles measured by the in situ probes. During the research flight analyzed here, measurements were only taken at a limited number of constant flight levels. Accurate and simultaneous measurements of the effective radius of liquid cloud droplets, pressure, temperature, supersaturation, and cloud droplet number concentration in regions with ice supersaturation and liquid water subsaturations where the WBF mechanism is active would allow to further study the effect of the WBF mechanism and even quantify it. Moreover, the observed low-level Arctic mixed-phase clouds were precipitating. In principle, the parcel model is only applicable to non-precipitating clouds. However, here it was applied only to the liquid part of the clouds, whereas the precipitation was in the ice phase.

It is important to note that the definition of the ice fraction can vary significantly across different studies, depending on the measurement techniques and the specific application (Korolev et al., 2017). These differences should be considered when

comparing results from different studies. In this work, the ice fraction refers to an optical ice fraction based on the optical thickness, whereas the ice index provides qualitative information about cloud thermodynamic phase.

## 415 5 Summary

This work investigated the vertical distribution of cloud microphysical properties and its evolution during the initial phase of the marine cold air outbreak observed on 2022-04-01 in the Fram Strait, based on measurements of the hyperspectral and polarized imaging system specMACS during the HALO-(AC)<sup>3</sup> measurement campaign. In particular, the vertical distribution and temperature dependence of the cloud thermodynamic phase and the vertical evolution of the effective radius of liquid cloud droplets were analyzed. To this end, the method by Rosenfeld and Lensky (1998) and Lensky and Rosenfeld (2006) to  
420 construct pseudo-vertical profiles of cloud properties was extended to Arctic mixed-phase clouds.

The initially pure liquid water clouds transitioned to a mixed-phase regime during the first approximately 30 min the air mass spent above open ocean, as also discussed in Weber et al. (2025a). The pseudo-vertical profiles of the ice index and ice fraction, quantifying the cloud thermodynamic phase, generally increased with decreasing temperature, indicating that ice  
425 formation occurred preferentially at the coldest temperatures. In agreement with this, the ice index and ice fraction increased with increasing height, except for a geometrically thin layer at the cloud top, where increasing fractions of supercooled liquid water were observed. This confirmed the existence of a thin, more liquid-dominated layer at the cloud top, as is expected in low-level Arctic mixed-phase clouds. In addition, the measured pseudo-vertical profiles of the effective radius of liquid cloud droplets showed increasing droplet sizes with increasing height, as expected from theory.

430 Furthermore, vertical profiles of the cloud droplet effective radius were calculated using a parcel model and compared to the measured pseudo-vertical profiles to test the ability of the model to describe cloud liquid water in the observed mixed-phase clouds and to study the influence of ice processes on the liquid cloud droplets. Agreement within the uncertainties of the measured and calculated vertical profiles of the effective radius of liquid water droplets was observed, except for short times above open ocean close to the ice edge, when the clouds were still decoupled from the surface and the parcel model is  
435 not applicable. This indicated that ice processes, such as ice formation through heterogeneous freezing of supercooled liquid water droplets, riming, and the Wegener-Bergeron-Findeisen mechanism, did not significantly impact the cloud liquid water during the initial phase of the observed cold air outbreak. Collision and coalescence were not relevant in the observed clouds due to the small droplet sizes. It is concluded that the parcel model, combined with the applied entrainment model, realistically represents liquid water in the observed low-level Arctic mixed-phase clouds. The observations are, in general, in agreement  
440 with our theoretical understanding of Arctic mixed-phase clouds.

The analyses presented in this work provide unique observational data of microphysical properties of low-level Arctic mixed-phase clouds, their vertical distribution, and evolution during a marine cold air outbreak in the Arctic. In particular, the partitioning and vertical distribution of cloud thermodynamic phase and cloud liquid water were investigated, which are not well represented in models and are difficult to measure. These data can help to provide constraints to models to improve



445 the representation of mixed-phase clouds and their evolution during marine cold air outbreaks in the Arctic and to further our understanding of the microphysical processes in these clouds.

*Code and data availability.* The data collected during the HALO-( $\mathcal{A}C$ )<sup>3</sup> campaign are published on PANGAEA (Ehrlich et al., 2025). The measurements of the SWIR camera of specMACS are available at Weber et al. (2024), VELOX measurements at Schäfer et al. (2023), dropsonde measurements at George et al. (2024), in situ observations at Moser et al. (2023), measurements of the HAMP radar at Dorff et al. (2024), the WALES lidar observations at Wirth and Groß (2024), and the backward trajectories for Polar 6 at Kirbus and Wendisch (2024). Retrieval results from specMACS, the HALO backward trajectories, and the analysis codes used in this work can be provided upon request from the corresponding author.

*Author contributions.* AW evaluated all data, performed the analyses, and wrote the manuscript with input from all co-authors. FH had the idea to apply the parcel model. FH and BM provided valuable feedback to the analyses and the outline of the study. All authors contributed to the discussion of the results.

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