Clouds and precipitation in the initial phase of marine cold air outbreaks as observed by airborne remote sensing

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Abstract. Marine cold air outbreaks (MCAOs) strongly affect the Arctic water cycle and, thus, climate through large-scale air mass transformations. The description of air mass transformations is still challenging, partly because previous observations do not resolve fine scales, particularly for the initial development of an MCAO, and lack information about the thermodynamical evolution starting over sea ice and continuing over open ocean and associated cloud microphysical properties. Therefore, we focus on the crucial initial development within the first 200 km over open water for two case studies in April 2022 during the HALO-(AC)³ campaign. The two events, just three days apart, belong to a particularly long-lasting MCAO and occurred under relatively similar thermodynamic conditions. Even though both events were stronger than the climatological 75th percentile of that period, the first event was characterized by colder air masses from the central Arctic which led to an MCAO index twice as high compared to the second event.

The evolution and structure were assessed by flight legs crossing Fram Strait multiple times at the same location, sampling perpendicularly to the cloud streets. Airborne remote sensing and in situ measurements were used to build statistical descriptions of the boundary layer, dynamics, clouds, and precipitation. For this purpose, we established a novel approach based solely on radar reflectivity measurements to detect roll circulation that forms cloud streets. The two cases exhibit different properties of clouds, riming, and roll circulations though the width of the roll circulation is similar. For the stronger event, cloud tops are higher, more liquid-topped clouds exist, the liquid water path, mean radar reflectivity, precipitation rate, and precipitation occurrence have increased, and riming is active. The variability of rime mass has the same horizontal scale as the roll circulation, implying the importance of roll circulation on cloud microphysics and precipitation.

Boundary layer and cloud properties evolve with distance over open water, as seen by, e.g., cloud top height rising. In general, cloud streets form after traveling 15 km over open water. After 20 km, this formation enhances cloud cover to just below 100 %. After around 30 km, precipitation forms though for the weaker event the development of precipitation is shifted to larger distances. Within our analysis, we developed statistical descriptions of various parameters (i) within the roll circulation and (ii) as a function of distance over open water. These detailed cloud metrics are particularly well suited for the evaluation of cloud-resolving models close to the sea ice edge to evaluate their representation of dynamics and microphysics.

1 Introduction

Marine cold air outbreaks (MCAOs) are strong air mass transformations. During Arctic MCAOs, cold and dry air flows from the ice-covered central Arctic southward over the open ocean. There, cloud streets form that are well visible in satellite images and transform to cellular convection downstream under extreme surface heat fluxes (Brümmer, 1996). Especially over open ocean, cloud streets have important implications on the radiative surface energy budget due to their high albedo induced by liquid cloud tops (Geerts et al., 2022). Moreover, their long lifetimes affect precipitation evolution and characteristics (Abel et al., 2017) and, thus, the Arctic water cycle. Arctic MCAOs can also strongly influence the weather in the mid-latitudes (Turner and Marshall, 2011).

The Arctic is a hot spot with respect to climate change, most pronounced by strong surface temperature increases and sea ice decline (Wendisch et al., 2023). Dahlke et al. (2022) also showed significant shifts in the occurrence of MCAOs, i.e., decreases in early winter and increases in late winter. These shifts are possibly caused by changes in synoptic circulation patterns and feedback mechanisms involving the retreating sea ice. How MCAO characteristics will develop in the future will require improved modeling capabilities (Geerts et al., 2022), and a better process understanding of these air mass transformations, including cloud phase changes (Pithan et al., 2018). To resolve the meso-scale cloud organization in MCAOs, large-eddy simulations (LES) are required. Yet, especially the transition between organizational states is difficult to model as initial conditions, turbulence, cloud microphysics, and large-scale flow interact. Furthermore, small-scale surface heterogeneity in the marginal sea ice zone (MIZ) are important for the formation of rolls (Gryschka et al., 2014) whereby the exposure of air to open water in the MIZ plays an important role (Spensberger and Spengler, 2021). LES studies also highlight the importance of mixed-phase microphysical processes in preconditioning the transition of cloud organization (Abel et al., 2017; Tornow et al., 2021). Model settings like the employed ice microphysical scheme and model resolution affect the timing of transformation that differs between the models, e.g., when the ice phase is permitted (de Roode et al., 2019). Meanwhile, a higher resolution evokes roll convection at smaller distances to the sea ice edge and increases precipitation amount (Spensberger and Spengler, 2021). So far, no consensus has been reached and progress is delayed by the lack of observations to confront models.

First airborne in situ measurements during the Convection and Turbulence (KonTur) experiment (Markson, 1975; Brummer et al., 1982; Brümmer et al., 1985), ARKTIS '88 (Brümmer et al., 1992), '91, and '93 (Brümmer, 1999), and Marginal Ice Zone Experiment (MIZEX; Walter and Overland, 1984) investigated the meso-scale roll convection inside the atmospheric boundary layer (ABL) that is strengthened by thermal instability when air flows from the sea ice over the open water (Atkinson and Wu Zhang, 1996). Brümmer (1996) and Müller et al. (1999) showed how the ABL was modified as a function of distance from the sea ice within the first 300 km under the influence of strong surface heat fluxes from open water. While cloud reflectance measurements by satellites have provided important insights into the geometrical appearance of MCAOs since their beginning, recent studies such as Murray-Watson et al. (2023), Wu and Ovchinnikov (2022), and Tornow et al. (2023) quantitatively studied cloud development in a quasi-Lagrangian way. Using back trajectories, they investigated cloud properties derived by the Moderate Resolution

Imaging Spectroradiometer (MODIS) as a function of time since the air passed the sea ice edge. Liquid water path (LWP) and cloud top height (CTH) increase within the first 10 hours, with the strongest increase in the initial MCAO phase, i.e., the first couple of hours. Further, they demonstrate that MCAO strength affects the development until 30 h after the air left the ice edge. However, due to retrieval limitations, they only considered liquid-dominated clouds and no information on vertical structure and precipitation is available. ~~The~~ Based on CloudSat observations, Mateling et al. (2023) demonstrate the important role of snowfall ~~by MCAOs , producing~~ from MCAOs which produce the majority of snowfall in the North Atlantic~~, was shown by Mateling et al. (2023) using Cloudsat radar observations. However, Cloudsat~~. Yet, CloudSat sampling is limited by its blind zone of 1 km (Maahn et al., 2014; Schirmacher et al., 2023) and it is unclear whether differences to model precipitation ~~(von Lerber et al., 2022)~~ result from model deficits or instrument limitation (von Lerber et al., 2022).

In summary, there is a clear need for high-resolution cloud observations within ~~MCAO, which~~ MCAOs. These are typically only available from ground-based remote sensing measurements at supersites. Therefore, the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) in 2021/2022 (Geerts et al., 2022) established two ground stations at Andenes and Bear Island, Norway, ~~which provided~~ providing important insights into cloud properties (Mages et al., 2022; Lackner et al., 2023) and ~~supported~~ supporting model evaluation (Geerts et al., 2022). ~~However, As~~ these stations were located about 1000 km away from the sea ice edge~~. Thus~~, only open and closed cellular convection~~but no cloud streetshave been~~, but not cloud streets, were observed.

In this study, we exploit detailed cloud observations taken during the initial MCAO phase close to the ice edge, where rapid development of mixed-phase clouds occurred. We use airborne remote sensing observations that target model evaluation in a statistical sense and suggest suitable metrics for this. The measurements were performed during the HALO-(AC)[3] campaign (Wendisch et al., 2024) that took place over the Fram Strait where MCAOs occur frequently (Dahlke et al., 2022; Mateling et al., 2023; Papritz et al., 2015). We focus on a major MCAO event that remained active for more than two weeks (Walbröl et al., 2024). Within this period of northerly flow, ~~just three days apart,~~ two dedicated research flights were performed just three days apart, equipped with active and passive remote sensing instrumentation. The environmental ~~situations~~ conditions during the flights ~~have many commonalities but~~ were similar but contained slightly different flavors, ~~in particular~~ particularly with respect to the cloud properties. Strait flight tracks crossed cloud streets ~~perpendicular~~ multiple times perpendicularly to their elongated orientation ~~multiple times~~ to perform high-resolution measurements of cloud and precipitation properties which are not possible from satellite, e.g., see LWP observations by MODIS (Fig. 1c, d). The data cover a fetch, ~~i.e.,~~ that is the distance the air traveled over open water prior to the measurement, of up to about 150 km. From these unique measurements, we aim to answer the following questions:

I. What are the differences between the environmental conditions on both flight days, and what are their implications on cloud development?

II. Can we identify characteristic changes in cloud and precipitation properties perpendicular to cloud street orientation, i.e., within the roll circulation?

III. How do roll circulation, cloud, and precipitation properties evolve with fetch in the initial MCAO phase, e.g., up to travel times of four hours?
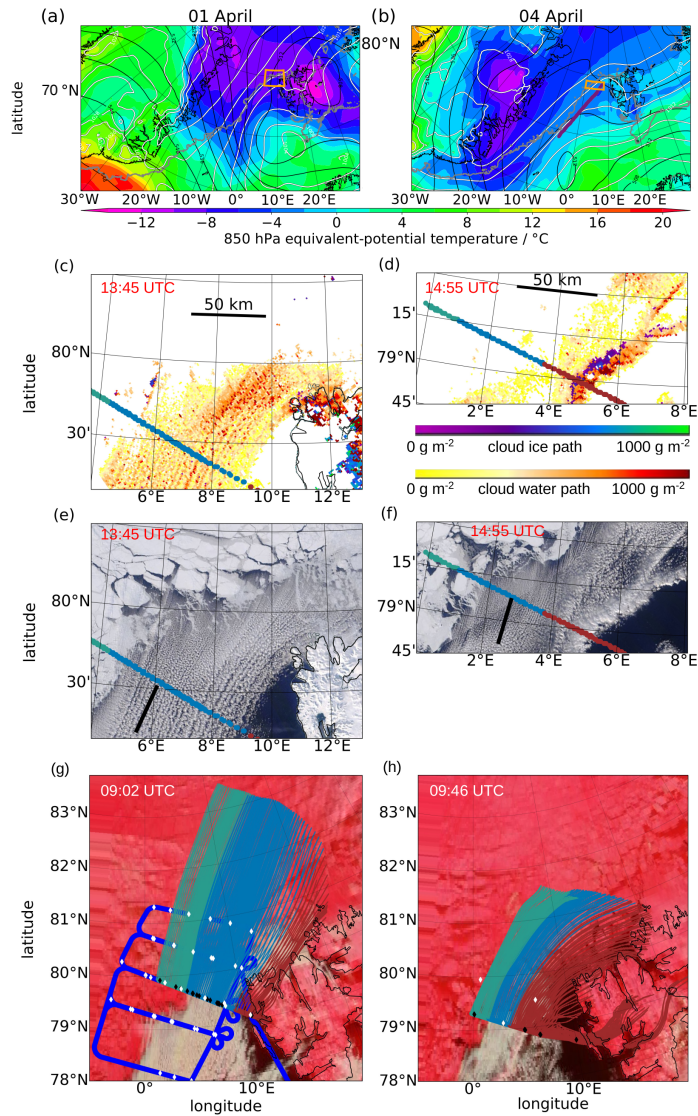
Figure 1. Overview of 01 (left) and 04 April 2022 (right). (a, b) Maps of mean sea level pressure (white contours), 500 hPa geopotential height (black contours), and 850 hPa equivalent-potential temperature (shading) from ERA5 at 12:00 UTC with 15 % sea ice concentration (gray dots), the flight area (orange) shown in c-h, and the convergence line (purple) on 04 April. (c,d) Total cloud water path (Nasa Worldview, 2023a; 1 km resolution) and (e,f) corrected reflectance (Nasa Worldview, 2023b; 500 m resolution) of MODIS Terra on 01 April (13:45 UTC) and 04 April (14:15 UTC). Thick colored dots show P5 track, categorized by the measurement regime (Table 1). Black lines represent the orientation of the cloud streets. (g,h) 12-hour near-surface back trajectories for the P5 measurement locations (colored lines), dropsonde locations (diamonds) of *P5* (black) and *HALO* (white), and the flight path of *HALO* on 01 April 2022 (blue line). Background image from Visible Infrared Imaging Radiometer Suite (VIIRS) (Nasa Worldview, 2023c) at 09:02 UTC on 01 April and 09:46 UTC on 04 April.

The paper is organized as follows: First, we introduce the airborne measurements and data (Sect. 2). Second, we describe the methodology that we developed to assign the fetch to each measurement using back trajectory calculations (Sect. 3.1); and the identification algorithm to detect roll circulations from cloud radar measurements (Sect. 3.2). Section 4 describes boundary layer and cloud development during the two flights (Sect. 4.1), characterizes cloud properties within roll circulation (Sect. 4.3) and the development along fetch (4.4). Finally, Sect. 5 concludes on the questions raised above and discusses pathways for future model evaluation.

2 Data

Airborne measurements from the HALO-(AC)[3] campaign (Wendisch et al., 2021) manifest the backbone of this study. During this campaign, the High Altitude and LOng-range research aircraft (*HALO*; Ziereis and Gläßer, 2006), the research aircraft *Polar 5* (*P5*) and *Polar 6* (*P6*; Wesche et al., 2016) operated in the North Atlantic sector of the Arctic at altitudes around 10 km, 3 km, and below 3 km, respectively. This analysis mostly focuses on radar, radiometer, lidar, and dropsonde measurements from *P5* that probed MCAO events in their early phase. Dropsonde measurements from *HALO* and in situ observations from *P6* further support the analyses. We limit the analyses to measurements taken over ocean and restrict the remote sensing measurements to straight flight segments that exceed a flight altitude of 2 km to observe clouds from aloft. The focus is on two *P5* flights, namely on 01 April 2022 (Fig. 1a) and 04 April 2022 (Fig. 1b). To investigate roll circulation, the flight paths crossed the cloud streets perpendicularly. *P5* probed along the same path back and forth, yielding 6 legs on 01 April (09:08–14:20 UTC) and 4 legs on 04 April (10:06–14:22 UTC).

2.1 Synoptic overview of cases

On 01 and 04 April, the large-scale constellation of a high-pressure system over Greenland and a low-pressure system over Siberia led to advection of cold air from the central Arctic over the open ocean (Fig. 1a, b) and to cloud street formation (Fig. 1e, f). On 01 April, the center of the cold air at 850 hPa was located over Svalbard. A local near-surface low-pressure system southwest of Svalbard resulted in a near-surface north-easterly flow. With height, the flow turned northerly as indicated by the 500 hPa geopotential (Fig. 1a). On 04 April, contrarily, the cold air at 850 hPa height was shifted more to the west, and the flow at all heights aligned parallel to the sea ice edge over Fram Strait (Fig. 1b). The easterly flow forced air to ascend over Svalbard, thereby causing a lee effect. Therefore, a larger cloud-free region west of the island appeared, and a convergence line parallel to the ice edge at the transition to the cloudy regime formed (Fig. 1f). However, note that the flow within our study area might deviate from the large-scale condition. On both days, the MCAO index was stronger than the 75th percentile of the climatology from 1979 to 2022 (Walbröl et al., 2024). While the synoptic conditions are similar for both cases, differences in flow directions led to different MCAO strengths which in turn precondition the evolution over water.

2.2 Airborne instrumentation

Dropsondes: Vaisala Dropsondes RD94 were launched from *P5* and *HALO*. From *P5*, 18 and 14 sondes were launched on 01 and 04 April, respectively. They provide vertical profiles of potential temperature (θ; accuracy=0.2 K), relative humidity (2 %), pressure (0.4 hPa), and horizontal wind components derived from GPS recordings (Vaisala, 2010; George et al., 2021).

Airborne Mobile Aerosol Lidar (AMALi): AMALi onboard *P5* measures profiles of backscattered intensities at 532 nm (parallel and perpendicular polarized) and 355 nm (not polarized; Stachlewska et al., 2010). The lidar measurements are processed with a vertical resolution of 7.5 m and temporal resolution of 1 s. Lidar backscatter is highly sensitive to hydrometeors, especially to liquid, which, in our case, is always super-cooled. Cloud top height (CTH) is obtained for every profile that has consecutive heights with backscatter coefficients exceeding one of cloud-free sections by a factor of five. The CTH is the maximum altitude of these consecutive heights. Further details can be found in Mech et al. (2022a) and Schirmacher et al. (2023).

Microwave Radar/radiometer for Arctic Clouds (MiRAC): The active component of the downward-looking airborne MiRAC (Mech et al., 2019) onboard *P5* consists of a frequency-modulated continuous wave (FMCW) radar that operates at 94 GHz. Additionally, a passive channel 89 GHz accompanies the active measurements. Both measurements are taken with a 25° backward inclination of the instruments. While the vertically resolved radar measurements are reconstructed to nadir measurements, the passive measurements are taken on a slanted path. MiRAC measures every second corresponding to a horizontal resolution of the equivalent radar reflectivity (Ze) of about 85 m at ground in flight direction for typical cruise altitudes of 3 km height and ground speeds of 80 m s^{-1}. The radar measurements are quality controlled and corrected for surface clutter and aircraft attitude (Mech et al., 2019). Sensitivity and vertical resolution of the cloud radar depend on the chirp settings. During HALO-(AC)[3], the detection limit for the most distant ranges from *P5* of 3 km was around -45 dBZ and the vertical resolution was 4.5 m close to the aircraft and at most 13.5 m (Mech et al., 2022a). The processing interpolated the vertical resolution to 5 m over the whole profile. A blind zone of 150 m above ground is omitted due to ground clutter (Schirmacher et al., 2023). The accuracy of Ze is about 0.5 dBZ. Attenuation by water vapor (<1 dBZ) and clouds (~0.6 dBZ) can potentially reduce this accuracy (Schirmacher et al., 2023).

Cloud top height is also derived from the radar profiles and corresponds to the height of the uppermost radar reflectivity signal above noise level. Comparing this height with CTH derived from lidar allows us to assess the supercooled liquid layer thickness (LLT). Here, we exploit the fact that the lidar is more sensitive to particle amount (liquid), whereas the radar is more sensitive to particle size, i.e., ice particles (Ruiz-Donoso et al., 2020). Due to limited vertical resolution of the instruments and resulting uncertainties in CTH, the CTH of the lidar has to exceed the CTH of the radar by at least 10 m for a profile to be defined as liquid topped and thus mixed-phase. For the calculation of hydrometeor depth (D), we take the difference between lidar CTH and the lowest radar signal within a continuous cloud layer. However, if a minor gap in the cloud profile occurs, i.e. the vertical distance between two layers is smaller than 50 m, we define only one layer from the lower cloud bottom to the upper cloud top.

We define profiles containing a Ze value higher than -5 dBZ (Schirmacher et al., 2023) in the lowest 500 m (Shupe et al., 2008) as precipitating. Using the Ze-S relation for three bullet rosettes (Kulie and Bennartz, 2009), this value corresponds to a snowfall rate (S) of 0.07 mm h^{-1}. This relation is also used to analyze S close to the ground at 150 m. Note that these S estimates are inaccurate since Z-S relations highly depend on ice habits, which are very variable within cloud streets (Maherndl et al., 2023; Moser et al., 2023).

The passive channel observes brightness temperatures (TB) which are primarily influenced by the emission of liquid clouds and the surface. Differences in TB between clear-sky and cloudy situations are used to retrieve LWP over the ocean via a regression approach (Ruiz-Donoso et al., 2020). Due to the unknown emissivity of sea ice, LWP is only derived over open ocean. Depending on atmospheric conditions, the maximum uncertainty is below 30 g m^{-2} (Ruiz-Donoso et al., 2020). While radar reflectivities are corrected to nadir profiles, TB and, thus, LWP measurements are measured along a slanted path (Mech et al., 2022a). As visible in the lidar backscatter and its strong attenuation close to cloud top, we assume that most liquid resides in the uppermost few hundred meters of the cloud, which is in accordance with Shupe et al. (2008). Therefore, LWP lags behind the radar observations in time. Based on geometric considerations, we shift the LWP measurements assuming a daily average CTH for cloud streets. Since this average differs for both days, we shift the LWP measurements by different time periods, i.e., 16 and 19 s on 01 and 04 April, respectively, which results in an estimated maximum error of 4 s. As a result, a good agreement between LWP peaks and profiles of high Ze is observed.

In situ probes: The *P6* was equipped with three in situ probes, namely the Cloud Droplet Probe (CDP; Lance et al., 2010), Cloud Imaging Probe (CIP; Baumgardner et al., 2011) and Precipitation Imaging Probe (PIP; Baumgardner et al., 2011). The CDP is a forward-scattering optical spectrometer that measures small cloud particles (2.8–50 μm). Larger cloud particles are observed by the CIP (15–960 μm) and PIP (103 μm–6.4 mm) which record shadow images of the cloud particles as particles pass through the sampling area (Moser et al., 2023). Rimed mass is calculated from images of the fractal particle shapes, as well as the continuous particle size distribution derived from combining CDP, CIP, and PIP observations. CIP and PIP data are processed similarly to previous campaigns (Mech et al., 2022a).

Collocation: On both days, *P5* (remote sensing) and *P6* (in situ) were closely collocated. In the riming analyses, we use a data subset during which both aircraft flew on straight paths with a time difference between the collocated measurements of less than 5 min, a spatial distance between both platforms below 5 km, and a flight altitude of *P6* between 0.15 and 1.3 km. Thereby, we reduce the error caused by sampling different air masses with *P5* and *P6*; and caused by sampling air masses with varying microphysical properties due to changing *P6* locations within the cloud vertical extent. On 01 April, 3971 seconds of collocated observations cover longitudes between 4.5 and 6.5°E corresponding to 25–165 km of fetch. On 04 April, only 845 seconds of observations are collocated, located between 1.5 and 4.5°E and covering fetches between 55 and 165 km, and mostly at around 80 km. On 01 April, seven collocated data segments exist with gaps of less than 5 s. These segments cover 39 min at 60–140 km fetch with most measurements concentrated around 7°E longitude.

2.3 Satellite and reanalysis data

For the sea ice concentration (SIC), we use a daily product that merges satellite observations from MODIS and the second Advanced Microwave Scanning Radiometer (AMSR2) at 1 km horizontal resolution (Ludwig et al., 2020). For the analysis, we interpolate the data to a 0.05° x 0.05° latitude/longitude grid. Sea surface temperatures (SST) are obtained from the Arctic Ocean - Sea and Ice Surface Temperature product based ~~upon~~ on observations from the Metop–A Advanced Very High Resolution Radiometer (AVHRR). The daily product (Copernicus Marine Service, 2023) has a spatial resolution of 0.05° and covers surface temperatures of ocean, sea ice, and MIZ. Using satellite SST and dropsonde temperature measurements ~~above~~ over open water (Fig. 1g, h, black and white dots), we calculate the MCAO index from the difference between the potential temperature (θ) at ~~the~~ sea surface and 850 hPa altitude. Generally, the MCAO index is positive during a MCAO and describes its strength (Papritz et al., 2015; Kolstad, 2017). Over ocean, we ~~moreover calculated~~ use the Coupled Ocean-Atmosphere Response Experiment (COARE) bulk air-sea flux algorithm (Fairall et al., 2003) to additionally calculate surface heat fluxes from ~~the~~ satellite SST data and dropsonde observations at 10 m height~~based on the Coupled Ocean-Atmosphere Response Experiment (COARE) bulk air-sea flux algorithm (Fairall et al., 2003)~~.

The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis product version 5 (ERA5; Hersbach et al., 2020) is used to analyze the large-scale environmental conditions and to compute back trajectories using Lagranto (Sprenger and Wernli, 2015). ERA5's temporal, horizontal, and vertical resolution is one hour, 31 km, and 137 model levels from the surface up to the top of the atmosphere, respectively (Kirbus et al., 2023). Note, that most HALO dropsondes have been assimilated in ERA5, leading to an improved performance for our study cases.

3 Analysis and identification approaches

In the following, we describe two approaches we established for analyzing ~~airborne measurements. The firstconcerns~~ the airborne measurements: first, the quantification of ~~the~~ fetch assigned to each measurement (Sect. 3.1)~~. Second, we present~~; second, a novel method to identify roll circulation from airborne radar reflectivities only (Sect. 3.2).

3.1 Trajectory calculations and fetch

During MCAOs, the warm ocean alters thermodynamic ~~conditions of airmasses within the ABL, which were~~ ABL conditions of air masses initially formed in the central Arctic ~~, by~~ through turbulent surface heat and moisture fluxes (e.g., Brümmer, 1996) whenever SIC is below 100 %. We aim to quantify this influence of open water on ABL development. Since it is impossible to calculate integrated surface fluxes along the trajectories with our data, we derive the fetch for each airborne measurement. We follow Spensberger and Spengler (2021) and ~~also~~ account for open water over the MIZ ~~and~~ as well as leads in the ice. For flows unaffected by land masses, travel time over open water and fetch can be linearly converted and are both valid to study. The correlation coefficient between travel time and fetch is 0.99 for all $P5$ measurements that are not influenced by land masses,

Table 1. Categorization of *P5* airborne data.

day	description	color	location
01 April	influence by Svalbard	red	longitude>9.08°E
01 April	prior to cloud streets	green	fetch<15 km
01 April	cloud streets	blue	remaining data
04 April	influence by Svalbard and convergence line	red	longitude>3.7°E
04 April	prior to cloud streets	green	longitude<1.7°E
04 April	cloud streets	blue	remaining data

and -0.5 for measurements influenced by Svalbard. ~~Therefore~~Thus, the latter data have been removed from the analysis (see below).

We need to know the air masses' previous path to calculate fetch for each measurement. ~~For this purpose~~Therefore, we compute near-surface Lagrangian back trajectories using Lagranto (Sprenger and Wernli, 2015) with ERA5 wind fields as input. Specifically, we calculate back trajectories for the previous 12 hours for every flight minute, and assign them to the observations within each minute. The trajectories originate at the horizontal location of *P5* and at 1000 hPa height corresponding to roughly 300 m above the surface. To investigate the influence of the surface on the air masses, we take a near-surface starting point for the trajectories. Similar to Spensberger and Spengler (2021), we calculate the fetch for every back trajectory by integrating the ratio of open water obtained from MODIS-AMSR2 SIC data (Sect. 2.3) along the back trajectory paths over the previous 12 h until measurement time (0 h):

$$fetch = \int_{s(12h)}^{s(0h)} (1 - SIC(s))ds \tag{1}$$

Note that due to the resolution of ERA, neighboring trajectories are rather similar (Fig. 1g, h). Differences in fetches between two neighboring trajectories mainly come from differences in SIC along the trajectories. The median of the relative change between two adjacent fetches is 9.6 %.

To ~~concentrate~~ focus on cloud street characteristics during ~~undisturbed~~ MCAO conditions, we limit the analysis to ~~data~~ air masses that did not pass Svalbard at any time, and that are not affected by the convergence line on 04 April (Table 1; Fig. 1c–h, non-red dots). The remaining measurements are classified ~~to be~~as either 'cloud streets' (Fig. 1c–h, blue) if radar reflectivities appear regularly~~or~~, or else as 'prior to cloud streets' (Fig. 1c–h, green). The latter category includes samples taken over and close to sea ice that have fetches less than 15 km on 01 April and longitudes smaller than 1.7°E on 04 April (fetches of about 17 km; Table 1). On 04 April, longitude instead of fetch is used for classification ~~because~~as cloud streets over open ocean and cloud-free conditions over sea ice ~~have both~~ both have fetches of 17 km. Note that fetch includes contributions from the MIZ (80 % <SIC~~>~~< 100 %) and open water.
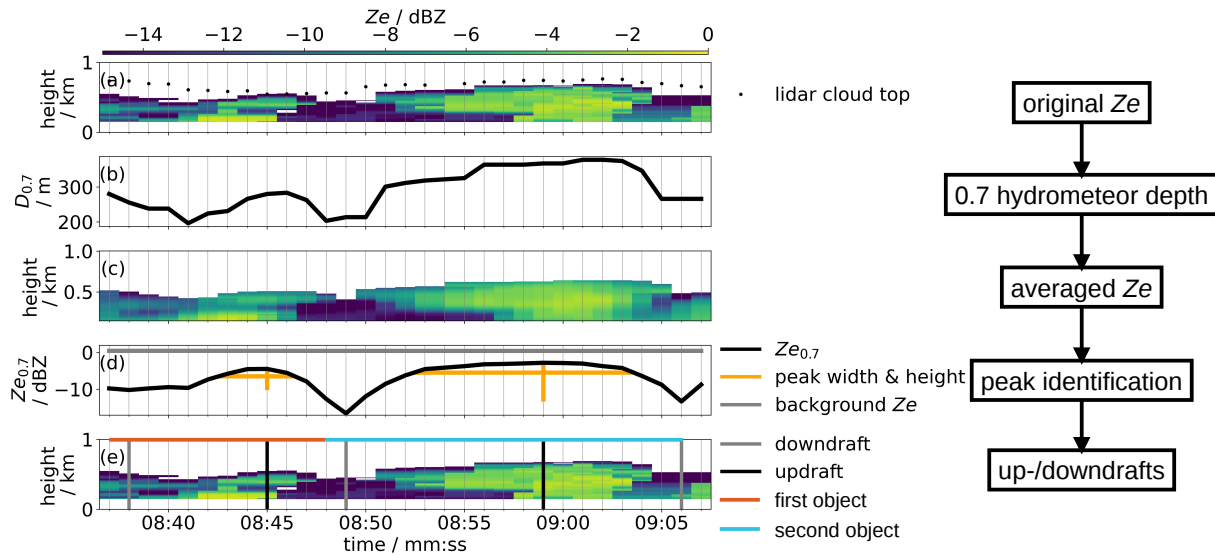
Figure 2. Visualization of roll cloud circulation identification. Time series (30 s) of the equivalent radar reflectivity Ze profiles measured by MiRAC starting at 10:08:37 UTC on 01 April (a), 0.7 of hydrometeor depth ($D_{0.7}$, b), Ze smoothed in space and time (c), smoothed Ze at $D_{0.7}$ (d, black) with its peak width and height (d, orange) and the background Ze (d, gray). The original Ze observations (same as in a), detected up- (black) and downdrafts (gray), and circulation objects (blue, red) are shown in (e). For comparison, the ~~the~~ cloud top height observed by the ~~lidar~~ AMALi lidar is displayed (a, black dots). The shown time period covers fetches from 73 to 80 km and corresponds to a flight distance of 7 km.

3.2 Roll circulation identification

245 To identify roll ~~circulations~~ circulation from radar measurements, we must rely on indirect information. Previous studies applied spectral ~~analysis~~ analyses to observations of the three wind components, temperature, mixing ratio, and radiative fluxes (Brümmer et al., 1985, 1992; Brümmer, 1999; Walter and Overland, 1984). While vertical velocity cannot be extracted from the airborne Doppler measurements (Mech et al., 2022a), we exploit the fact that ~~due to the vertical motion,~~ cloud particles form to the largest extent at the location of the strongest updraft due to vertical motion. Here, frequent saturation with respect

250 to ice ~~and thus~~ occurs, facilitating the formation of cloud droplets and growth of both liquid and ice particles ~~occurs~~ (Korolev and Field, 2008). In order to account for potential influences by dry entrainment at cloud top (Klingebiel et al., 2015) or ~~precipitation (Morrison et al., 2012)~~ occurrence of precipitation (Morrison et al., 2012), we only consider measurements at the height of 0.7 of the hydrometeor depth (D; ~~See~~ Sect. 2.2) for the identification of roll circulation. By using the radar reflectivity at this height ($Ze_{0.7}$), we target the largest ice particles within the ~~profiles~~ profile, and minimize the influence of dry air

255 entrainment/supercooled liquid water droplets at cloud top ~~and~~ as well as precipitation at the bottom of D. ~~See~~ We refer the reader to Appendix A for ~~a discussion about~~ further discussion on the height selection ~~and~~ including a sensitivity analysis.

$Ze_{0.7}$ serves as a proxy for vertical velocity. We assume that maxima in $Ze_{0.7}$ represent updraft regions while minima in $Ze_{0.7}$ represent downdraft regions of the roll circulation. For cloud-free areas, we define the downdraft in the area's center. The workflow of the circulation detection is summarized in Fig. 2. Appendix A summarizes further details including Table A1 for a sensitivity analysis. Among different configurations, we selected the detection algorithm with the best ratio between determining peaks and ignoring noise. This automated peak detection depends only on the large-scale condition and, thus, might not determine every maximum of $Ze_{0.7}$ considered by the human eye.

We only apply the detection algorithm to the 'cloud street' regime as roll convection is invisible to the radar as long as no significant amount of hydrometeors is present. According to our definition, the maximum updraft (maximum $Ze_{0.7}$) is not necessarily centered between the two detected edges of our roll circulation object. The wavelength of the circulation λ is the distance between two identified adjacent downdrafts. The meso-scale circulation is described by the aspect ratio AR, that is the ratio between λ and CTH at the updraft position. In total, we identified 356 and 112 cloud circulation objects in the 'cloud street' regime on 01 and 04 April, respectively.

4 Variability of thermodynamic conditions and cloud street properties

In the following, we first investigate the boundary layer conditions (Sect. 4.1) and the preconditioning by riming (Sect. 4.2). We then statistically analyze cloud morphological and microphysical properties within the roll circulation object within the 'cloud street' regime (Sect. 4.3), followed by an assessment of cloud and precipitation properties as a function of fetch within the first 170 km (4 h) of the MCAO development (Sect. 4.4).

4.1 ABL conditioning

First, we investigate how much the ABL conditions differ between the cases, including possible drivers. The influence of the ocean on the ABL through surface sensible and latent heat fluxes is more pronounced on 01 than 04 April (Fig. 3e, f). Dropsondes show maxima of 450 (225) $\mathrm{W\,m^{-2}}$ for sensible (latent) heat fluxes, respectively. Over the MIZ, fluxes decrease, and the ratio changes to a higher contribution of the sensible heat flux due to less evaporation over sea ice as also found by Li et al. (2020). Along the whole flight track, ERA5 shows that the sensible heat flux decreases much faster with distance from the sea ice edge on 04 than 01 April (Fig. 3e, f), even though oceanic conditions here represented by SST are similar (Fig. 3a, b). This indicates that the atmospheric conditions differ between the cases, which is especially confirmed for temperature by differences in MCAO fields (Fig. 3c, d). The MCAO index averaged over all dropsondes launched from $P5$ is stronger on 01 than 04 April (8.6 K versus 4.6 K, Table 2). Note that although dropsondes were launched further away from sea ice on 01 April, ERA5 fields show roughly the same factor of two differences over both flight tracks. In accordance with Seethala et al. (2021), fluxes and MCAO indices from ERA5 generally

Table 2. Conditions during 01 and 04 April. BLH and CTH stand for atmospheric boundary layer height, i.e., the inversion height of potential temperature, and cloud top height, respectively.

parameter	source	01 April	04 April
MCAO index	dropsondes	8.6 K	4.6 K
cloud street orientation	MODIS	10°N	5°N
cloud street wavelength	MODIS	2 km	1 km
temperature at cloud top	dropsondes	<-20°C	-20 to -10°C
median cloud street CTH	radar	700 m	300 m
interquartile range of cloud street CTH	radar	530–790 m	250–375 m
BLH trend	dropsondes	$4.5\,\mathrm{m\,km^{-1}}$	$2.9\,\mathrm{m\,km^{-1}}$
mixing ratio trend within 100 km fetch	dropsondes	< doubling	> doubling
driver of wind shear	dropsondes	wind direction	wind speed
cloud street profiles with precipitation	radar	67 %	35 %
cloud street profiles with liquid-topped clouds	radar and lidar	86 %	71 %

correspond to dropsonde estimates, except over sea ice where ERA5 seems to overestimate the fluxes. ~~However, the dropsondes resolve finer~~ Finer spatial structures in both parameters are resolved in the dropsondes.

290 ~~The cloud condition~~ Cloud conditions on 01 April ~~is~~ are characterized by cloud streets ~~with an orientation of~~ oriented by about 10° to the ~~north~~ North (Fig. 1e, black line) and a wavelength of about 2 km with shorter distances between the separated streets close to sea ice. Note that this information is retrieved from MODIS sensors (bands 1, 3, and 4) that have a spatial resolution of at least 500 m. ~~Close to the sea ice edge, the near-surface air of~~ At the height of the median CTH, here 925 hPa, air subsides within the 'prior to cloud streets' ~~regime shows weak subsidence~~ and 'cloud streets' regime, respectively (Fig. 3g,

295 green and blue track). ~~For the 'cloud street' regime, the air ascends except for~~ Over ocean, subsidence is generally reduced compared to over sea ice. The area of fetches between 75 and 120 km ~~(about~~ around 7°E longitude ~~; blue track) even though~~ ~~SST and MCAO indices increase~~ is characterized by strong subsidence (Fig. 3a, c) ~~. We suggest that this subsidence, which is visible over the whole~~ throughout the entire atmospheric column (not ~~show n)~~ ~~, is provoked by a wave effect induced by Svalbard.~~ shown) despite increasing SST and MCAO indices. This wave-like pattern is likely induced by wave effects

300 originating from Svalbard archipelago (Shestakova et al., 2022).

The thermodynamic state of the ABL is described by mean profiles of dropsondes released from *P5* and *HALO* over sea ice and open water. On 01 April, temperatures are lower than -20°C throughout all altitudes over sea ice (fetch <15 km), and for parts over open water (Fig. 4a). Over sea ice, ~~the surface layers , which are~~ surface layers generally develop an inversion as air is cooled from the ground ~~, and the air above, which is~~ and warmed by subsidence ~~, generally develop an inversion~~ from

305 above. Profiles that were sampled by *HALO* dropsondes over sea ice exhibit a thin (< 250 m deep) ABL. Close to the sea ice edge, the depth of the ABL ~~, which~~ is similar to conditions over closed sea ice (Fig. 4b). The ABL is capped by a low-level jet at 250 m height (Fig. 4e) and has a low water vapor mixing ratio (0.5 g ~~kg⁻¹~~ kg^{-1}; Fig. 4c), ~~is similar to over closed sea ice~~
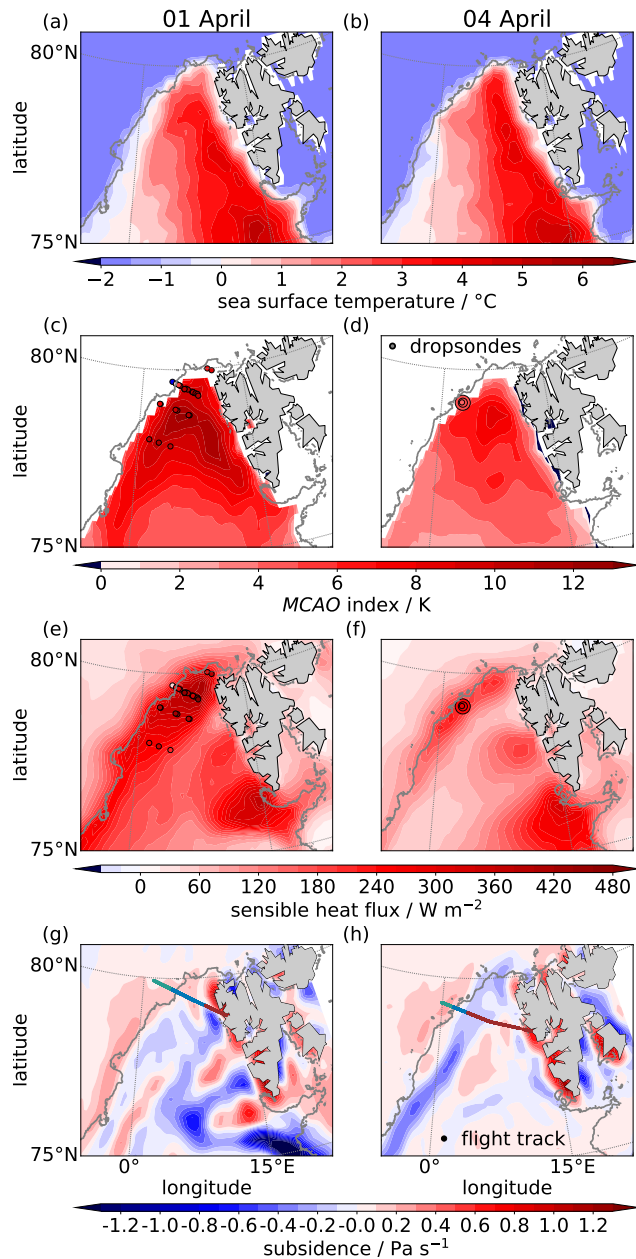
Figure 3. Overview of environmental conditions on 01 April (left) and 04 April (right). Maps of ~~MCAO index~~ sea surface temperature (a, b), ~~sea surface temperature~~ MCAO index (c, d), sensible heat fluxes (e, f), and subsidence at ~~1000~~925 (g) and 975 hPa (~~e, f~~h) from ERA5 reanalysis data. Positive subsidence values indicate downward motion. MCAO indices (c, d) and sensible heat fluxes (e, f) from dropsonde observations are shown as circles~~(a, b)~~. Flight tracks in (~~e~~g) and (~~f~~h) are color-coded according to the measurement categorization (Table 1). The gray lines indicate the 15 % sea ice concentration from ERA5.
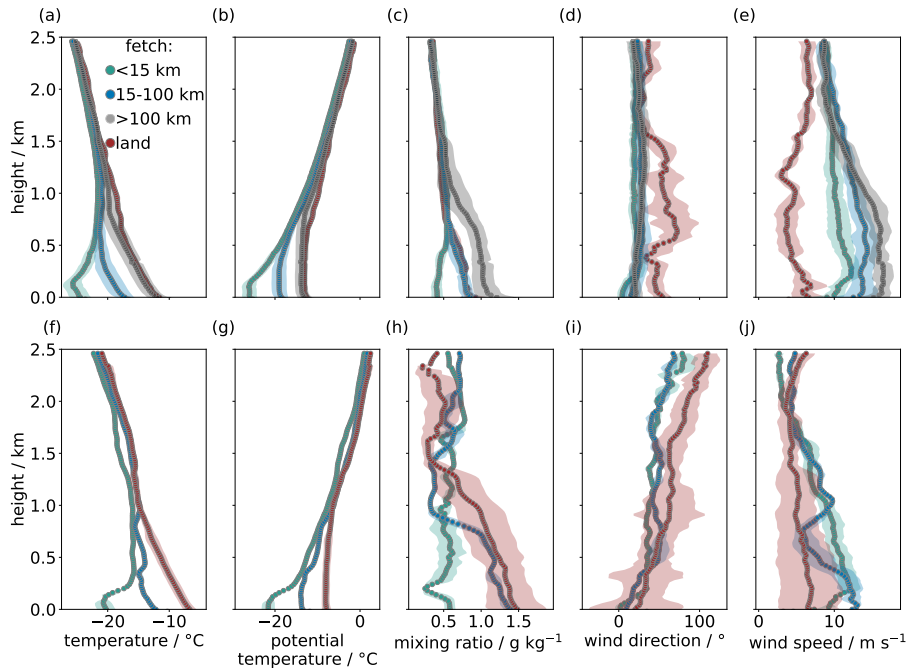
Figure 4. Averaged dropsonde profiles from *HALO* and *P5* of temperature (a, f), potential temperature (b, g), mixing ratio (c, h), wind direction (d, i) and speed (e, j) binned by fetch on 01 April (first row) and 04 April 2022 (second row). The shaded areas represent the standard deviation of each category. The color coding follows the categorization shown in Table 1. On 01 April, the number of dropsondes per category is 27 (<15 km fetch; green), 14 (15-100 km and >100 km fetch; dark and light blue), and 3 (land; red). On 04 April, the number is 3, 4, and 9, respectively.

(Fig. 4b). The mixing ratio indicates the low background vapor concentration of the polar air mass. With 28°, wind direction is constant with height while the near-surface wind ~~comes~~ originates from 0°N regardless of surface properties (Fig. 4d). Over open water, ~~the~~ temperatures and, thus, wind speeds within the neutrally-stratified ABL increase with fetch. The boundary layer height (BLH), ~~i.e.,~~ that is the inversion height of the potential temperature θ, doubles within the first 100 km (Fig. 4b). ~~Also, the mixing~~ Mixing ratio increases with fetch due to strong surface heat fluxes and turbulent mixing of near-surface air.

On 04 April, the MODIS image shows cloud streets with an orientation of 5° to the ~~north~~ North (Fig. 1f, black line), and a wavelength of about 1 km. ~~The air mass ascends at~~ Compared to conditions on 01 April, the air mass at CTH (975 hPa) ascends for fetches larger than 60 km ~~, i.e., larger fetches compared to 01 April~~ (Fig. 3h). A wave effect is notable within the region affected by the lee effect but not for the analyzed data west of the convergence line. Warmer temperatures on 04 April reveal a difference in air mass between both days: all temperatures below 2 km height ~~lie~~ range within -20 to -10°C (Fig. 4f)~~and~~. Free tropospheric θ ~~of the free troposphere is on average~~ is higher by about 5 K ~~higher~~ on average compared to 01 April (Fig. 4b, g). Furthermore, ~~the~~ mixing ratio of the polar air mass is slightly higher at all heights (Fig. 4c, h). ~~Even~~ Flow conditions differ compared to 01 April even though a low-level jet also exists at 200 m over sea ice ~~as before~~ (Fig. 4j)~~, flow~~
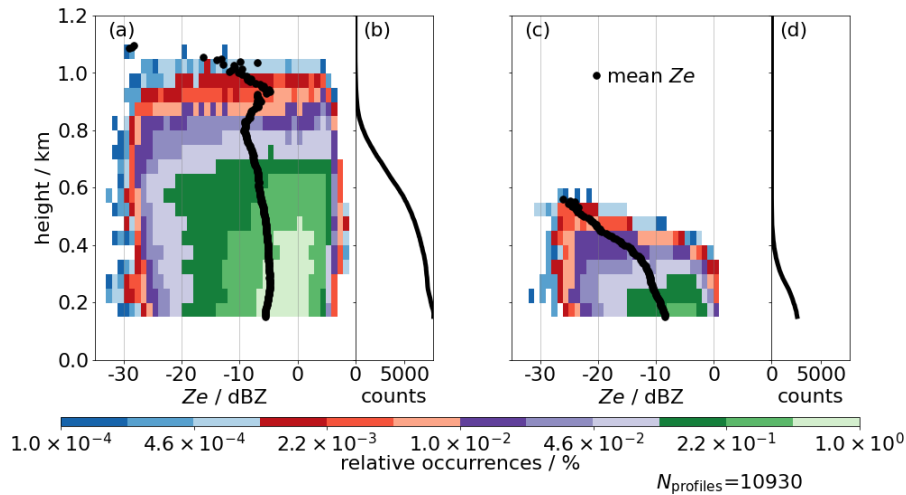
Figure 5. Contoured frequency by altitude diagram (a, c) and absolute counts per altitude (b, d) for all radar reflectivities (Ze) obtained by MiRAC in the 'cloud street' regime on 01 April (a, b) and 04 April (c, d). Moreover, each averaged Ze profile (black dots), and the total number of profiles (N_profiles) is displayed.

~~conditions differ compared to 01 April~~. A directional shear from northerly ~~wind~~ winds at the surface to westerly ~~wind~~ winds occurs at all heights, ~~which~~ and is strongest at BLH (Fig. 4i). Although *HALO* dropsondes cannot detect a BLH in the central Arctic (81.3–87.0°N) as it is likely too shallow (not shown), the capping inversion is stronger over the sea ice close to its edge~~is stronger~~. On 04 April, this inversion weakens less with fetch compared to 01 April due to a layer of warm air above BLH.

325 Together with about half as high ERA5 surface fluxes on 04 April (Fig. 3e, f), this results in a much weaker BLH increase rate averaged over all fetches (Table 2), and a reduction of wind speeds by $5\,\mathrm{m\,s^{-1}}$.

On both days, the radar profiles in the 'cloud street' regime frequently (93 %) exhibit clouds. The contoured frequency by altitude diagrams (Fig. 5) ~~reveals~~ reveal the different cloud and precipitation characteristics of cloud streets between the days~~: especially,~~. CTH is twice as high on 01 ~~than~~ as on 04 April, respectively. Furthermore, ~~the~~ mean Ze ~~profile~~ (black

330 dots) is ~~larger~~ higher at all heights. On 01 April, values larger than -5 dBZ ~~, which are~~ associated with the onset of snowfall ~~,~~ occur at all heights. The shorter the fetch on 01 April, the stronger is the decrease in the mean Ze profile close to the surface (not shown). Thus, near-surface ice particles might experience stronger sublimation on 01 April when the mixing ratio is comparably small~~and~~, and the relative humidity with respect to ice is below 100 % (not shown). On 04 April, Ze rarely exceeds -5 dBZ even below 500 m, reducing the frequency of precipitation compared to 01 April (Table 2). Moreover, mean

335 Ze increases towards the surface, indicating the ongoing growth process of ice particles. On both days, most cloud streets are liquid-topped (Table 2)~~, which mainly have~~. Liquid-topped cloud streets are mainly characterized by a higher CTH ~~than~~ compared to non-liquid-topped clouds (not shown).

In summary, the MCAO case on 01 April is by a factor of two stronger than 04 April due to colder and drier air masses (Table 2). On both days, wind shear occurs ~~by~~ in wind speed changes on 01~~and direction~~, and directional changes on 04 April,
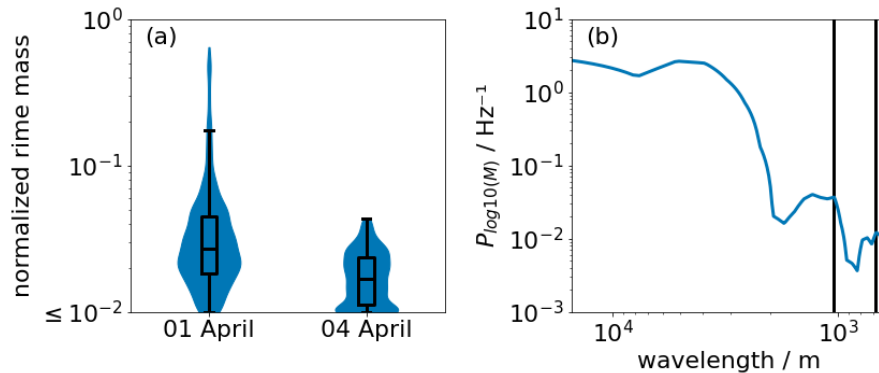
Figure 6. Left: Violin and box plot of the normalized rime mass (M) obtained by the in situ method for collocated flight data of cloud streets on 01 and 04 April. Right: Corresponding power spectrum of M on 01 April with black lines marking important local maxima of the spectrum.

respectively. Contradicting the MCAO index, air subsides close to the surface in the 'cloud street' regime at fetches around 100 km on 01 April due to a wave effect caused by Svalbard.

4.2 Preconditioning by riming

Ice growth affects the boundary layer evolution during MCAOs in several ways, e.g., by reducing cloud liquid water and triggering early and light precipitation, which then in turn cools and moistens the air below the cloud (Tornow et al., 2021). ~~To~~ We evaluate the strength and variability of riming to investigate whether riming preconditions cloud microphysics~~and precipitation characteristics are~~, and whether it impacts precipitation characteristics already in the initial state of MCAO evolution~~, we evaluate the strength and variability of riming. In doing so, we~~. We use a subset of in situ and remote sensing data ~~within the 'cloud street' regime~~ during which *P5* and *P6* were collocated within the 'cloud street' regime (Sect. 2). To determine the degree of riming, we calculate the normalized rime mass (M) defined as the rime mass divided by the mass of the size-equivalent spherical graupel particle. Following Maherndl et al. (2024), two methods are applied. The combined method uses the closure of in situ particle size distributions and Ze simulations obtained from running averages of in situ particle size distributions over 30 s. The in situ method relates M to in situ particle shape measurements only. The results of both retrievals are comparable. However, since the collocation of *P5* and *P6* measurements might be inaccurate, we only show results from the in situ method for which no matching is necessary. Note that our definition of updrafts might bias the following findings.

Considering particles with $M > 10^{-2}$ as rimed, more rimed particles exist on 01 April (97 %) than on 04 April (80 %), respectively. The median M of $10^{-1.6}$ on 01 April and $10^{-1.8}$ on 04 April (Fig. 6a) clearly reveals that riming is only significantly active in cloud streets on 01 April. In particular, normalized rime masses of $M > 10^{-1}$ only exist on 01 April. On this day, cloud top temperatures are colder than or at the low end of temperatures within the dendritic-growth zone (DGZ;

−20 to −10°C. Hence, conditions are too cold for aggregation to be dominant (Chellini et al., 2022). On 04 April, contrarily, riming is not significant because cloud top temperatures lie within the DGZ, fostering aggregation.

The spatial variability of riming is investigated by linearly detrended and mean-centered power spectra of M obtained during seven collocated segments (Sect. 2). Edge effects are minimized by applying a Hann window for smoothing. Due to the units of variance, the power spectrum increases automatically for smaller wavelengths. The averaged power spectrum of M peaks at about 0.7 and 1.1 km (Fig. 6b). These values roughly correspond to the wavelength λ of cloud streets as seen in the MODIS images (Fig. 1; also see Sect. 4.4 below) and as derived from the roll circulation analyses below. For 01 April, we, hence, infer that riming is mainly present within the updraft regions of cloud streets. A more detailed comparison with λ of the roll circulation detected by the remote sensing measurements is performed in Sect. 4.4. We further analyze the effect of active riming, present on 01 April, on cloud microphysics in the following sections.

4.3 Impact of roll circulation on cloud and precipitation properties

Our measurement strategy across cloud streets allows us to detect individual roll circulation objects (Sect. 3.2). For the following statistical assessment, we refer to 'clouds' as objects that have at least five successive radar measurements, resulting in 344 and 109 objects on 01 and 04 April, respectively. First, we investigate the location of their updraft center ($Ze_{0.7}$) within the cloud. As explained before, these objects are not necessarily symmetric. However, most clouds form centered around the updraft of the circulation. Around 50 % of the time, maxima of $Ze_{0.7}$ occur within the central tercile of the cloud, and only rarely within the tercile closest to the lateral cloud boundary (7 %).

To characterize how dynamics within roll circulations affect cloud and precipitation properties, circulation objects are composited for their relative distance to $Ze_{0.7}$ (Fig. 7). More precisely, we group cloud properties into three regions according to their distance from the maximum updraft region ($Ze_{0.7}$): the central updraft region, the region close to a cloud boundary, and the region in between.

On 01 April, the medians of several parameters show consistent behavior although the variability, expressed by the interquartile distance, is high: CTH increases by 9 % from the cloud boundary to the location of the maximum updraft (Fig. 7a). In line with liquid formation within updrafts, LWP increases by 22 % (Fig. 7e). The mean of Ze over each profile (82 %; Fig. 7g) and S (42 %; Fig. 7i) increases, supporting the assumption of enhanced ice production in updrafts. In contrast, a decrease of LLT (32 %; Fig. 7c) by 20 m can be seen, which exceeds the uncertainty of 10 m. We speculate that, here, updrafts carry ice particles to higher cloud regions. If so, the mixed-phase region would expand at the expense of the liquid layer and would enhance riming (Fig. 4.2). Potential riming occurrence would increase ice particle size, Ze, and S in updrafts. The observed slight LWP increase in updrafts (Fig. 7e, f) could indicate that, in our study, condensation is more favored than depletion of liquid.
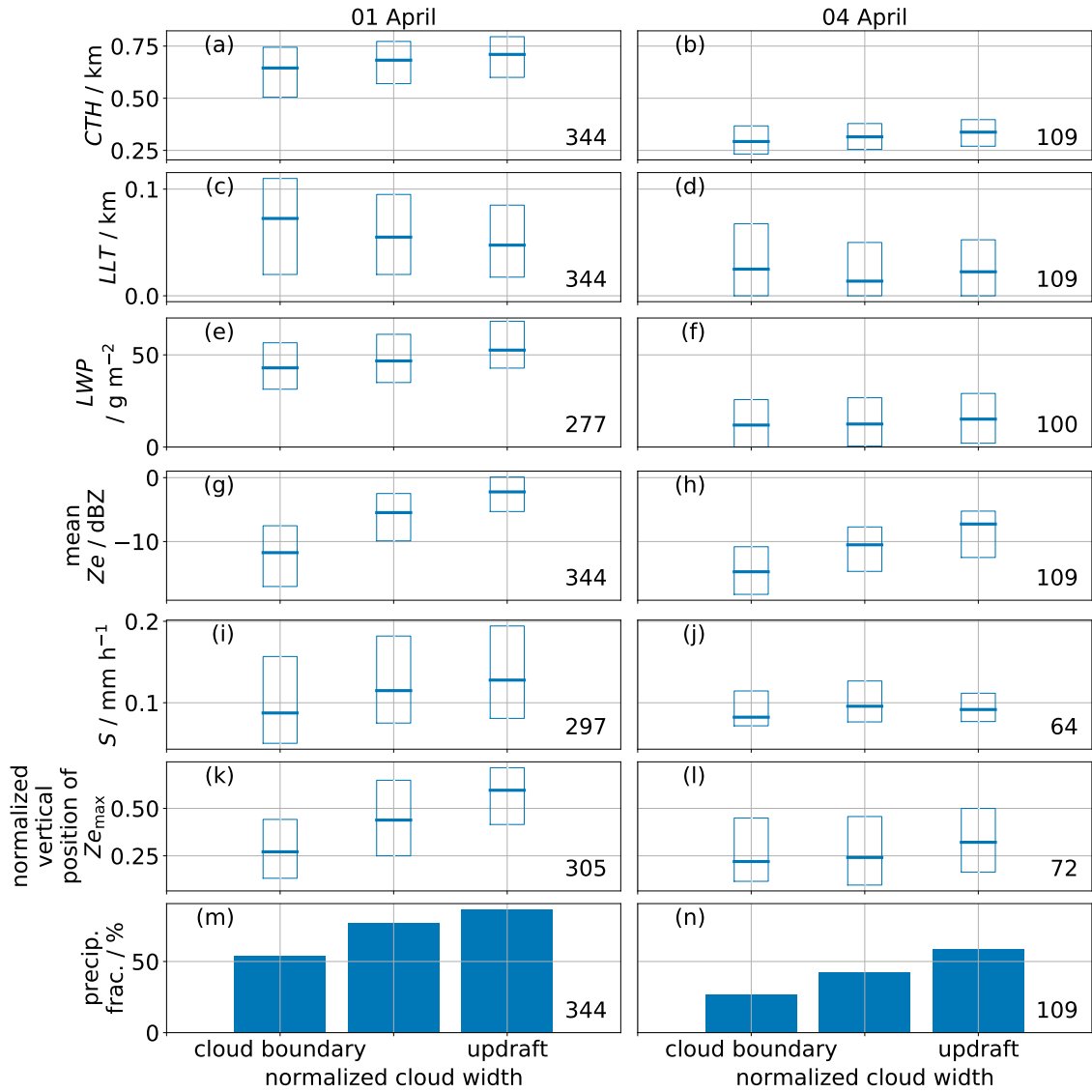
Figure 7. Average composites of cloud and precipitation properties within the normalized distance between lateral cloud boundary and updraft (max $Ze_{0.7}$) for circulation objects within the cloud street regime on 01 April (left column) and 04 April (right column): cloud top height (CTH; a, b), supercooled liquid layer thickness (LLT; c, d), liquid water path (LWP; e, f), mean radar reflectivity (Ze) over each profile (~~f,~~ g, ~~h~~), snowfall rate at 150 m (S; ~~h,~~ i, ~~j~~), vertical position of the maximum Ze for each profile normalized by the hydrometeor depth (~~j,~~ k, ~~l~~), and fraction of precipitating profiles (precip. frac.; ~~l,~~ m, ~~n~~). The median (horizontal line) and lower and upper quartile (box edges) are displayed at the boundary of the clouds, the updraft position, and in between. The total number of objects is given for every parameter separately.

Strong riming events might explain the frequently high extremes of S. Precipitation events do not only intensify at updraft locations, but also occur more frequently than at cloud boundary (87 compared to 55 % of the profiles, Fig. 7). On 01 April, we expect that most ice occurs at 0.6 of the hydrometeor depth for updraft positions as indicated by $Ze_{\max}$ (Fig. 7k). Large rimed particles close to cloud top might lift the height compared to the cloud boundary, where most ice is located within the lowest third of the hydrometeor depth.

On 04 April, the absolute increase of CTH (Fig. 7b) and mean Ze (Fig. 7h) within the clouds is about half of that on 01 April. Moreover, S (Fig. 7j) and LLT (Fig. 7d) stay constant within the clouds. In all three categories, the normalized height at which ice occurrence is highest is similar to cloud boundary conditions on 01 April (Fig. 7l). The smaller MCAO strength on 04 April seems to weaken the updraft motion and might, thus, suppress the rise of CTH and the lifting of ice into the liquid layer in updrafts. In updrafts, this might prevent riming, likely hampering an increase in S and mean Ze, as well as a lifting of the level with highest ice occurrence. While the absolute precipitation fraction is lower than on 01 April, e.g., reduced by 50 % at cloud boundary, the relative increase of precipitation fraction from object center to boundary is similar (30 percentage points).

4.4 Development along fetch

To investigate how the open water surface affects roll circulation and cloud properties, we analyze their evolution over all observed fetches (Fig. 8). The most prominent characteristic of an MCAO event is the rise in BLH driven by the strong heat fluxes as air flows over the relatively warm ocean. Already in the MIZ, evaporation and convection lead to the appearance of initial, still unorganized clouds in the 'prior to cloud street' regime, although horizontal cloud cover is low (Fig. 8g). Within the 'cloud street' regime, cloud cover increases rapidly and exceeds 90% for fetches beyond 30 km. The comparison of BLH, derived from dropsondes, and closely located airborne measurements shows that CTH is generally only 8.5 m lower than BLH, which indicates that we can use CTH as a proxy for BLH. On both days, CTH increases steadily with fetch (Fig. 8a). Both median CTH and CTH growth rate are reduced by more than half on 04 April compared to conditions on 01 April. A potential reason for this reduction might be a reduced buoyancy in the ABL, and warm air being advected above the boundary layer. Future modeling experiments could test this hypothesis, including lee effects on air mass development caused by the Svalbard archipelago. Interestingly, on 01 April, the linear increase of CTH levels at around 100 km fetch (2.5 h travel time). This area of fetch corresponds to an area of increased subsidence (see Fig. 3), capping cloud development. On 04 April, CTH
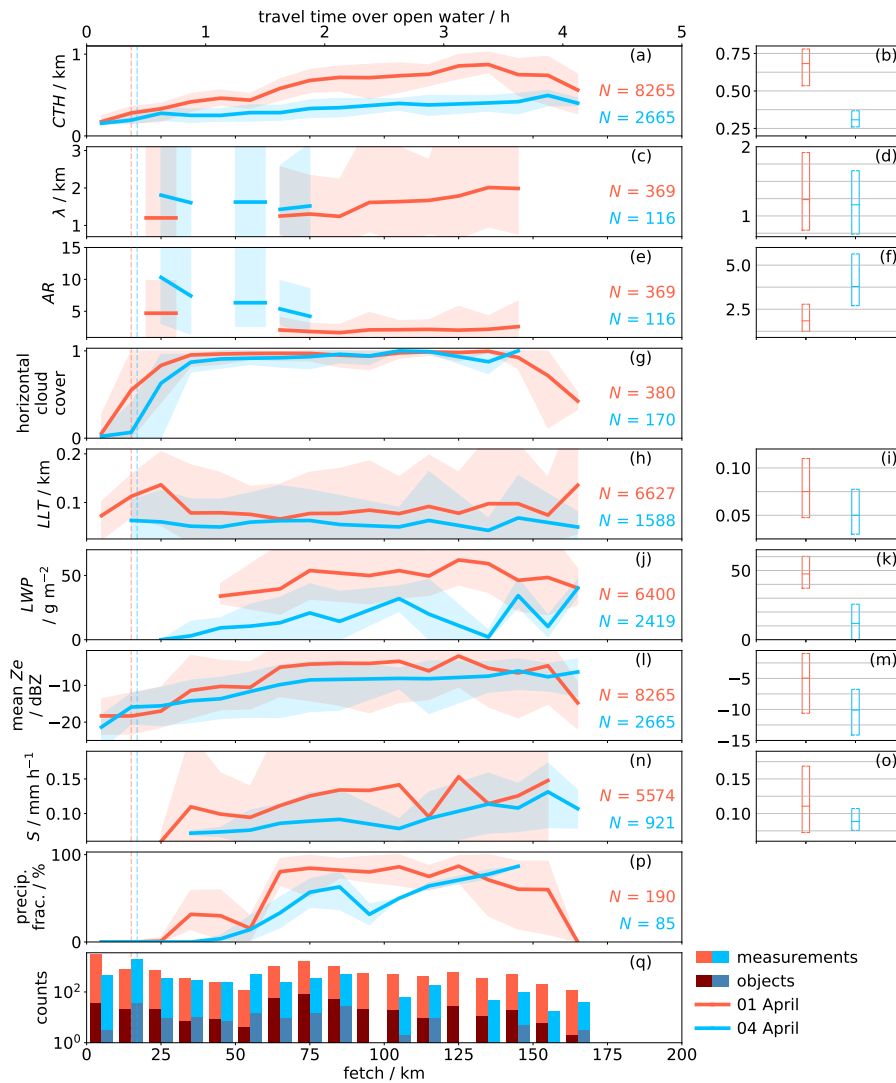
Figure 8. Left: Development of circulation, cloud, and precipitation characteristics with fetch on 01 (red) and 04 April (blue): cloud top height (CTH; a, b), wavelength of the circulation (λ; c, d), aspect ratio of the circulation (AR; e, f), horizontal cloud cover (g), liquid layer thickness (LLT; h, i), liquid water path (LWP; j, k), mean radar reflectivity over each profile (mean Ze; l, m), snowfall rate at 150 m height (S; n, o), precipitation fraction (p), and amount (q) of measured profiles (colored) and identified cloud circulations (gray) per fetch bin. LLT, LWP, and S statistics are only calculated when cloud/precipitation occurs. Lines and shades represent mean values and the 5th and 95th percentile, respectively. The vertical dashed lines indicate the regime change from 'prior to cloud streets' to 'cloud streets' (Sect. 3.1). Right: Boxplots show each distribution's median and interquartile range within the 'cloud street' regime. The total amount of measurements (N) is given for each parameter and day.

~~effect caused by Svalbard. Even though ERA5 reanalysis with its coarse resolution shows a rising air mass at these fetches (Fig.~~, cloud cover, and precipitation fraction decrease rapidly beyond fetches of 140 ~~8), we suggest that the air mass subsides and suppresses cloud development.~~ km. Corresponding trajectories are geographically close to trajectories excluded from the analysis due to land mass influences. We speculate that the Svalbard lee effect gains importance and increasingly suppresses cloud and precipitation formation despite coarse ERA5 subsidence values indicating rising air masses.

Next, we ~~focus on the circulation characteristics, i.e., wavelength λ and aspect ratio, of~~ examine the dependency of circulation characteristics within the 'cloud street regime' as function of fetch, specifically wavelength (λ) and aspect ratio (AR). Note that bins ~~in~~ of fetch with less than 10 roll circulation objects ~~are not analyzed to avoid results being contaminated by outliers. Thus, data gaps around fetches of~~, e.g., at fetches around 50 km ~~exist~~, are removed as outliers from all following analyses of λ and AR (Fig. 8c, e). ~~Nevertheless, we can see some development with fetch:~~ On 01 April, λ increases ~~on 01 April (Fig. 8c)~~ from roughly 1 to about 2 km at a fetch of 150 km (Fig. 8c), approaching the width of the cloud streets seen by MODIS (2 km; Sect. 4.1). ~~Because the data used for the spectral analysis of riming are distributed over different fetches it seems likely that the peaks at 0.7 and 1.1 km~~ are linked to cloud streets (For fetches larger than 60 km, AR is around 2 and remains rather constant with fetch. As discussed in Sect. 4.2 and Fig. 6)b, the normalized rimed mass M follows a multi-modal power spectrum. Local maxima of 0.7 and 1.1 km, respectively, align with λ, suggesting that riming is enhanced in updraft regions of roll circulation objects. On 04 April, the ~~data~~ measurements only revealed reliable circulation information for fetches smaller than 80 ~~km. For these fetches~~ km. There, λ ~~stays roughly constant~~ does not increase substantially with fetch and aligns with the cloud street width of the MODIS images (1 km; Sect.4.1).

~~The data gaps also affect the analysis of ARs. In fact the large spread between the 5th and 95th percentile hints at the existence of some outlier. There is some evidence that~~ Yet, spread in λ values is high as roll convection is comparatively weaker at low fetches. This spread propagates to the derived AR ~~decreases with fetch. For fetches larger than~~ distribution which is characterized by a large interquartile range from 2.7 to 5.6. Beyond fetches of 60 km ~~roll circulation is enhanced on 01 April and a constant~~, where convection is stronger, variability is lower and AR ~~of about 2 is observed. This confirms the model by Brown (1972) stating that~~ slightly reduces with fetch. There, observed AR ~~increases when less energy is available~~ nearly doubles compared to conditions on 01 April. Brown (1972) relate larger AR to reduced available energy for convection. ~~Regarding median values,~~ Heat fluxes observed at fetches of 60 km and beyond are indeed reduced on 04 April (Fig. 3e, f). In summary, median λ is similar on both days (around 1.2 km; Fig. 8d), while CTH ~~is roughly~~ on 01 April is increased by a factor of two ~~larger on 01~~ compared to 04 April (Fig. 8b). Consequently, ~~the~~ median AR on 01 April (Fig. 8f) is smaller ~~on 01 April at 1.8~~ than on 04 April ~~at~~ (1.8 and 3.9~~.~~, respectively).

~~To investigate how the exposure to open water influences cloud microphysics, we look at the~~

We further analyze liquid layer thickness LLT (Fig. 8h), LWP (Fig. 8j), mean Ze (Fig. 8l) and S (Fig. 8n) to investigate how the exposure to open water influences cloud microphysics. All parameters ~~, with the exception of~~ except for LLT ~~,~~ show a slight increase with fetch. Median LWP ~~is significantly higher on 01 April with a median of~~ conditions differ substantially on both days as the median LWP reduces from 50 ~~gm^{-2} compared~~ gm^{-2} on 01 April to 10 ~~gm^{-2}~~ gm^{-2} on 04 April~~. While the latter value is below the absolute~~, respectively. While LWP ~~error~~ ranges within the uncertainty limit of 30 g m^{-2} (see Sect.

2.2) for small fetches below 100 km, it steadily increases with fetch and exceeds the uncertainty limit for fetches larger 100 km. The median LLT of 75 (50) m on 01 (04) April, respectively, points at the dominant presence of liquid layer topped mixed-phase clouds. This finding is in agreement with the overall high occurrence of liquid layers of 86% (71%) for the respective days (see Tab. 2). We attribute the constant LLT with fetch to the fact that both liquid (LWP) and ice (approximated by mean Ze) increase simultaneously, which in turn keep the LLT constant.

While the evolution of cloud microphysics with fetch is similar on both days, thermodynamic conditions modify the intensity of the parameters. On 04 April, characterized by overall warmer temperatures, clouds are more shallow. On this day, 90 % of the profiles containing liquid-topped cloud streets have LLT of smaller than 100 m, which is more than on 01 April (70 %). Less supercooled liquid may reduce the amount of liquid-topped cloud profiles (Table 2), LWP (Fig. 8k) and LLT (Fig. 8i). A potential mechanism could be that the warmer temperature, low amount of supercooled liquid, and weak MCAO index prevent riming, reducing snowfall rate and mean Ze. This could potentially explain why snowfall occurs less frequently on 04 April. Moreover, the lack of riming in updrafts would reduce the variability in snowfall rate within each fetch bin. Lacking preconditioning by riming might delay the precipitation onset on 04 April by more than 10 km (Fig. 8p) which starts forming at fetches of 26 and 39 km on 01 and 04 April, respectively.

5 Conclusions

Our study investigates the evolution of thermodynamics, cloud and circulation morphology, cloud microphysics, and precipitation within air masses developing the first 170 km fetch (about 4 hours of travel time) in a long-lasting cold air outbreak in Fram Strait. Airborne remote sensing and in situ observations were performed as part of the HALO-(AC)^3 campaign within two research flights just three days apart. A unique sampling strategy oriented perpendicularly to cloud streets provided the opportunity to statistically quantify finely-resolved macro- and microphysical cloud and circulation properties in the initial MCAO phase. Specifically, two metrics were developed for this purpose. First, we make use of a novel approach to detect roll circulation from vertical radar profiles only which allows the analysis of cloud and precipitation parameters as a function of their position within the roll circulation. Second, we use back trajectories to analyze cloud and circulation development with fetch which allows us to draw a consistent picture of the MCAO development on 01 and 04 April 2022 (Fig. 9). Our findings answer the research questions posed in Sect. 1:

I. What are the differences between the environmental conditions on both flight days, and what are their implications on cloud development?

Both MCAO events feature northerly winds advecting dry and cold air masses to Fram Strait. The event on 01 April is characterized by colder air temperatures, leading to a doubling of MCAO index
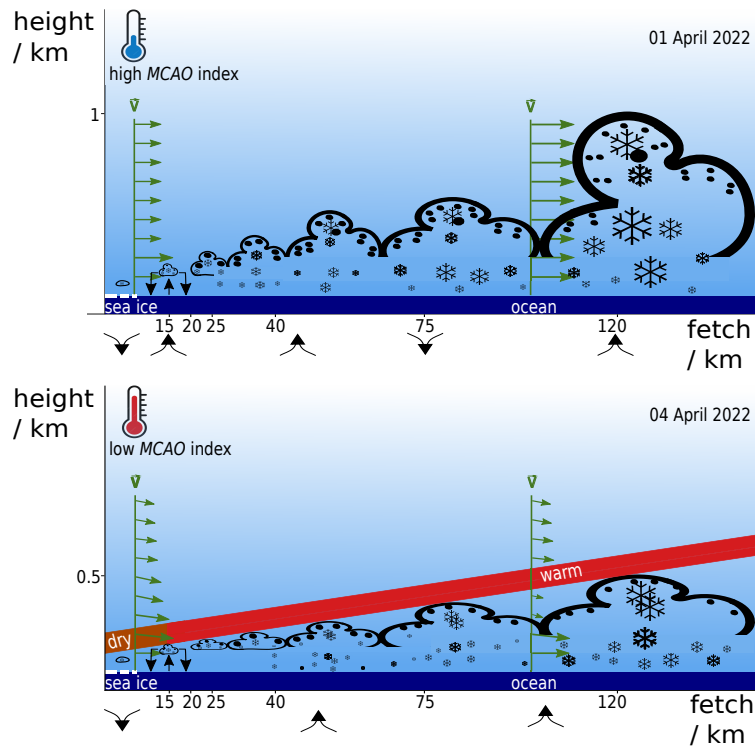
Figure 9. Sketch of the development of roll ~~circulations~~ circulation and microphysics of the associated cloud streets with fetch on 01 April (first row) and 04 April (second row). The arrows at the bottom indicate the direction of the near-surface vertical motion.

and stronger heat fluxes compared to the 04 April case. The more active convection on 01 April ~~compared to 04 April~~ deepens the boundary layer ~~, causing~~ which causes higher cloud top heights that are well aligned with the boundary layer height. A rough scaling ~~with a~~ factor of two ~~can be assumed for all parameters~~ is observed in fluxes, MCAO index, CTH and LWP between both days. ~~One also has to note that the island of Svalbard influences the flow . This provoked~~ Svalbard archipelago influenced the flow on both days, provoking a wave effect in the lee of Svalbard on 01 April with subsiding air masses ~~and thus~~ leading to reduced cloud top heights at 75 to 100 km fetch. On 04 April, lee effects caused an even stronger cloud-free zone west of the island, which led to a convergence zone and was not considered in the analysis.

The difference in cloud top height between lidar and radar is used to ~~diagnose the liquid layer thickness LLT, which indicates the presence of~~ detect the presence and derive the thickness of a supercooled-liquid layer at cloud top. Supercooled-liquid layer topped mixed-phase clouds ~~for~~ occurred 86% ~~(and~~ 71% ~~)~~ of the time on 01 ~~(and~~ 04 ~~) April~~ April, respectively. With respect to cloud microphysics, the most prominent difference between both days is that riming is only significantly active during the cold and strong MCAO case on 01 April. This day also features a higher amount of supercooled liquid water with median ~~liquid water paths~~ LWP of roughly $50\,\mathrm{g\,m^{-2}}$. Riming influences LLT, radar reflectivities, precipitation

onset, and strength by producing larger ice particles. Regarding median properties, cloud liquid layer thickness, liquid water path, and snowfall rate are again roughly a factor of two lower for the weaker MCAO on 04 April.

510 II. Can we identify characteristic changes in cloud and precipitation properties perpendicular to cloud street orientation, i.e., within the roll circulation?

Yes, several hundred roll circulation objects were identified using cloud radar measurements performed on multiple legs perpendicular to cloud street orientation. A composite analysis of these objects reveals that on 01 April, several parameters show consistent trends from the updraft region towards cloud boundaries, while on 04 April, only ~~increased~~

515 radar reflectivity and ~~precipitation can be found in the~~ cloud top height increase slightly in the respective updraft region. ~~We hypothesize~~ On 01 April, our data reveal the same frequency of the normalized rimed mass and updrafts within clouds. Thus, we speculate that the presence of significant riming on 01 April leads to ~~increases in liquid water path,~~ the observed increases in snowfall rate, ~~and the height~~ increases the height with most ice towards the updraft center~~while the~~, and impacts the observed LLT ~~decreases because updrafts lift ice particles~~ decrease towards the updraft as ice

520 particles might be lifted into the pure liquid layer. Our statistical analysis of ~~mean~~ median cloud characteristics within the roll circulation and their variability (Fig. 7) could be used to test the performance of cloud parameterizations and better understand riming effects.

III. How do roll circulation, cloud, and precipitation properties evolve with fetch in the initial MCAO phase, e.g., up to travel times of ~~4~~ four hours?

525 ~~Analyzing~~ The analysis of our measurements as a function of fetch shows increasing cloud top height, liquid water path, radar reflectivity, near-surface precipitation rate, horizontal cloud cover, and fraction of precipitating profiles with increasing fetch. Cloud streets form at around 15 km fetch and start precipitating at 25 to 40 km. ~~The~~ We suspect that the later onset of precipitation on 04 April is attributed to the lack of riming ~~. The aspect ratio of the roll circulation decreases with fetch for fetches smaller 50 km and stays constant for larger fetches.~~ in air masses with shorter fetches.

530 The wavelength of the cloud streets λ slightly increases with fetch on 01 April but the variability is rather high. ~~Nevertheless, λ is just barely larger than~~ The detected wavelength of around 1 km within the first 100 km ~~as also~~ of fetch aligns with the local maxima found in the spectral analysis of riming. ~~Such small scales are extremely difficult to resolve from space, highlighting~~ Even though the air-borne derived results here generally coincide with MODIS-derived wavelengths, our analyses highlight the importance of ~~airborne measurements~~ high-resolution airborne measurements to

535 evaluate satellite-derived products.

To answer the two last research questions, we established composite approaches to characterize the roll circulation (Fig. 7) and fetch (Fig. 8). ~~Such~~ These metrics can also be generated from cloud-resolving model output and be used to evaluate ~~their performance to represent~~ the model performance with respect to the representation of microphysics and dynamics in the initial phase of an MCAO. By considering the two cases with similar large-scale synoptic settings but differences with respect to

540 microphysics, e.g., in LWP and riming, ~~insights into the simulation of cloud microphysics could be gained. In particular, it will be~~ microphysical parametrization schemes can be evaluated. It will be particularly interesting to analyze whether ~~such~~ these models successfully reproduce the observed factor of two in scaling found for several parameters between the two cases.

To study the impact of the sharpness of MIZ and flow divergence on cloud evolution, more observations at constant ~~fetches~~ fetch over open water~~and variable fetches~~, and at variable fetch over MIZ near the sea ice edge ~~must~~ should be obtained in

545 the future. Moreover, since the observed cloud top temperatures lie within the dendritic-growth zone, aggregation ~~would be another interesting~~ is an important process to study, ~~which is possible~~ e.g., by dual frequency radar observations (Chellini et al., 2022), in order to understand dominant precipitation-forming microphysical processes.

The Clouds over cOMPlEX environment (COMPEX) campaign planned for spring 2026 northwest of Svalbard will raise the opportunity to better characterize the impact of the marginal sea ice zone (MIZ) on the air mass transformation. Flights

550 within the MIZ and along the ice edge could increase the number of samples. Further, by enhancing our measurement suite with an airborne G-band radar, more information on cloud microphysics can be deduced.

Data availability. Processed radar, in situ, and dropsonde observations obtained during the HALO-(AC)[3] campaign are published by Ehrlich et al. (2024). The retrieved LWP data are currently being prepared for publication on PANGAEA. All airborne data are accessed via the ac3airborne module (Mech et al., 2022b). The merged MODIS-AMSR2 sea ice concentration data are provided by the Institute of

555 Environmental Physics at the University of Bremen (Ludwig and Spreen, 2023). Raw in situ data are stored at the German Aerospace Center and available on request. Back trajectories are calculated from ERA5 reanalysis data (Hersbach et al., 2017, 2020). ERA5 is available on pressure levels (Hersbach et al., 2023a) and single levels (Hersbach et al., 2023b). A Python implementation of the COARE 3.5 bulk air-sea flux algorithm is available at Ludovic et al. (2021). MODIS observations of the total water path can be found under Nasa Worldview (2023a) and of corrected reflectance under Nasa Worldview (2023b). The corrected reflectance observed by VIIRS is available at (Nasa Worldview,

560 2023c).

Appendix A: Peak detection algorithm and ~~sensivity~~ sensitivity

To detect up- and downdrafts, we solely use $Ze_{0.7}$, which are radar reflectivity measurements at the height of 0.7 of the hydrometeor depth (D; ~~See~~ Sect. 2.2). Figure A1 explains the choice of this height (red line). To understand the applied height and Ze thresholds, one has to keep in mind that Ze values larger -5 dBZ (Schirmacher et al., 2023) and below 500 m (Shupe

565 et al., 2008) height are defined as precipitation. At 0.7 of the hydrometeor depth, most largest cloud particles occur, i.e., most maximum Ze per profile exceeding -10 dBZ taken among all non-precipitating values (Fig. A1a, gray line). Most maximum Ze per profile among non-precipitating radar bins occur at cloud bottom (Fig. A1a, black line). Nevertheless, this bottom-near maximum is induced by very small Ze values below -10 dBZ. Since we aim to detect updrafts at the selected height, we take the height where large particles (>-10 dBZ) occur most frequently. Moreover, with 98 %, most precipitation occurs

570 below 0.7 of the hydrometeor depth (Fig. A1b, dashed black line). This finding is not sensitive to the -5 dBZ threshold for precipitation (Fig. A1b, dashed gray line). Dry entrainment and liquid droplets seem rare at 0.7 of the hydrometeor depth since 91 % of the lowest Ze per profile lie above this altitude (Fig. A1b, solid black line). In conclusion, we take Ze at the height of 0.7 of the hydrometeor depth to consider the largest ice particles within the profiles and minimize the influence of dry air entrainment/supercooled liquid water droplets at cloud top and precipitation at the bottom of the hydrometeor depth.
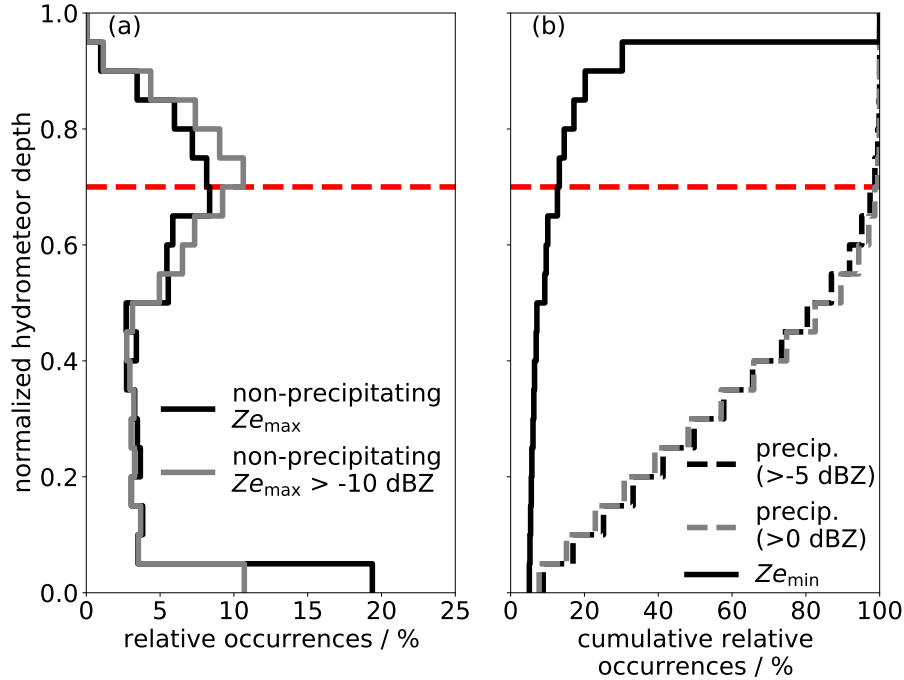
Figure A1. Relative occurrences of Ze_max among non-precipitating hydrometeors (a, black solid) and of non-precipitating Ze_max that exceed -10 dBZ (a, gray solid). Relative occurrence of precipitation defined by Ze values larger -5 dBZ (b, black dashed) and larger 0 dBZ (b, gray dashed), and minimum Ze of each radar profile (b, black solid). The y-axis is the normalized hydrometeor depth (0=base, 1=top). The height that is used to identify roll circulations is indicated by the red line.

To find up- and downdraft regions using $Ze_{0.7}$, we follow this recipe:

   I. Determine 0.7 of D for every profile (Fig. 2b).

  II. Average Ze over 100 m in the vertical to reduce noise.

 III. Smooth Ze by averaging over 3 s to minimize noise detection (Fig. 2c).

 IV. Extract the smoothed $Ze_{0.7}$ at 0.7 of D for each profile, which is the average between 0.65 and 0.75 times D (Fig. 2d, black line).

  V. Derive the large-scale background Ze_back by averaging $Ze_{0.7}$ over 500 s (~ 40 km; Fig. 2d, gray line).

 VI. Determine peaks in $Ze_{0.7}$ using the python package scipy.signal.find_peaks (Virtanen et al., 2020).

       If $Ze_\mathrm{back} \geq 0.67\,\mathrm{mm}^6\,\mathrm{m}^{-3}$, find peaks for $Ze_{0.7}$ with a prominence of at least $0.5\,\mathrm{mm}^6\,\mathrm{m}^{-3}$ (difference between the height of the peak and its lowest contour line; Fig. 2d, vertical orange line) and a width of at least 2.9 samples (about 230 m horizontal distance; Fig. 2d, horizontal orange line). Note that Fig. 2 shows Ze in logarithmic space while peaks are detected in linear space.

       If $Ze_\mathrm{back} < 0.67\,\mathrm{mm}^6\,\mathrm{m}^{-3}$, find peaks for $Ze_{0.7}$ with a prominence of at least $0.1\,\mathrm{mm}^6\,\mathrm{m}^{-3}$ and a width of at least 2.9

samples.

The detected peaks are defined as updrafts (Fig. 2e, vertical black lines) Here, we apply two different thresholds depend-
590 ing on Ze_{back} since the magnitude of the averaged Ze and its peaks generally increase with fetch.

VII. Find the minimum $Ze_{0.7}$ between every two maxima (Fig. 2e, vertical gray line). If conditions between two cloud streets
are cloud-free, we consider the downdraft location at the center of the cloud-free distance.

Table A1. Sensitivity of the steps of the algorithm applied to identify roll circulation objects. Relative changes of the number of objects in
total, number of objects inside the 'cloud street' regime, cloud top height (CTH) of cloud streets, and aspect ratio (AR) of the roll circulation
to the results obtained by the applied configuration after adjusting, i.e., mostly doubling, parameters.

modification	total number of objects	number of objects within 'cloud street' regime	CTH	AR
III: average over 6 s	-17.8 %	-20 %	+24 %	+23 %
IV: 0.6 of hydrometeor depth	-1.8 %	-1 %	0 %	0 %
IV: 0.8 of hydrometeor depth	+3.4 %	0 %	0 %	0 %
VI: width of 5.8 samples	-31.3 %	-37 %	+59 %	+57 %
VI: If $Ze_{\mathrm{back}} \geq 0.67\,\mathrm{mm^6\,m^{-3}}$: prominence of at least $0.2\,\mathrm{mm^6\,m^{-3}}$	-9.8 %	-11 %	+10 %	+11 %
VI: If $Ze_{\mathrm{back}} < 0.67\,\mathrm{mm^6\,m^{-3}}$: prominence of at least $1\,\mathrm{mm^6\,m^{-3}}$	-9.3 %	-10 %	+10 %	+11 %

Author contributions. IS performed the analysis, visualization, and writing and developed the methodology. Together with SS, MK, AE, and SC, the paper was conceptualized, and results were discussed. MM and AE developed the flight strategy for the cloud street investigation. BK calculated the back trajectories. NM collocated the *P5* and *P6* measurements and computed the rime mass fraction. All authors contributed to manuscript revisions.

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