Environmental conditions in the North Atlantic sector of the Arctic during the HALO–(AC)^3 campaign

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Abstract.

~~The~~ Centered around the High Altitude and Long Range (HALO) research aircraft and the collaborative research project on Arctic Amplification (AC)^3, the airborne field campaign HALO–(AC)^3 took place from 07 March to 12 April ~~2022 and was designed~~ 2022. Its major goal was to observe the transformation of air masses during their meridional transport in the North Atlantic sector of the Arctic. We evaluate the meteorological and sea ice conditions during the campaign based on the European Centre for Medium–Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5), satellite data, and atmospheric soundings with respect to climatology ~~and describe special synoptic events~~. HALO–(AC)^3 started with a warm period (11–20 March) where strong southerly winds prevailed that caused moist and warm air intrusions (MWAIs). Two MWAIs were detected as Atmospheric Rivers (ARs). Compared to the ERA5 climatology (1979–2022), record breaking vertically integrated poleward heat and moisture fluxes averaged over ~~75.0–81.5° N~~ the Fram Strait latitudes were found. ~~The related~~ These warm and moist air masses ~~reached the central Arctic, causing the~~ caused the highest rainfall rates over the sea ice northwest of Svalbard ~~recorded~~ since the beginning of the ERA5 climatology. ~~Subsequently, the cold period of HALO–(AC)^3 started~~ During the subsequent cold period, starting after the passage of a ~~Shapiro–Keyser~~ strong cyclone on 21 March ~~when the wind regime turned to northerlies, advecting~~ , northerly winds advected colder air into the Fram Strait. ~~Until 08 April, marine~~ Marine cold air outbreaks (MCAOs) prevailed ~~, including two strong MCAO events on 21–26 March and 01–02 April. In between,~~ until 08 April, interrupted by short periods of aged subpolar warm air ~~was advected to the Fram Strait with northeasterly and easterly winds~~. On average, the entire campaign period was warmer than the ~~climatology, especially~~ climatological mean due to the ~~exceptionally strong ARs during the warm period~~ strong influence of the ARs. In the Fram Strait, the sea ice concentration (SIC) was ~~within the~~ well within the climatological variability, staying within the 10–90th percentiles ~~of the climatology~~ over

20 the entire campaign duration. ~~During~~ However, during the warm period, ~~SIC was strongly reduced and an untypically large polynya for this season~~ an atypically large polynya opened north of Svalbard. ~~During the cold period, the polynya was closed again and above average SICs were found. We~~ For potential future studies, we describe the environmental conditions of ~~a Polar Low~~ and ~~far north reaching cirrus~~ in detail, ~~which will be subjects of research using HALO's remote sensing suite in the future. We also present the perspective on the~~ the most significant weather events (ARs, MCAOs, Polar Low, and Arctic

25 cirrus) during HALO–(AC)^3 ~~weather conditions from the research site~~ in detail. Comparing atmospheric conditions over the Fram Strait with Ny–Ålesund ~~, where orographic effects caused by the Svalbard archipelago and temporal shifts of atmospheric signals due to the propagation of synoptic systems~~ (Svalbard), temporal shifts up to one day have been identified. The temporal shift and orographic effects must be taken into account ~~. Overall, our~~ when combining airborne HALO–(AC)^3 measurements with ground based observations at Ny–Ålesund. Compared to previous airborne field campaigns focusing on the evolution

30 of (mixed–phase) clouds, a larger variety of MCAO conditions were observed during HALO–(AC)^3. Our study may serve as basis for future analyses of the data collected during ~~HALO–(AC)^3 and to compare synoptic conditions with other field campaigns~~ the campaign.

1 Introduction

The Arctic experiences a drastic temperature increase almost 4 times stronger compared to the rest of the globe (Rantanen et al., 2022). This enhanced warming is known as Arctic Amplification and is caused by several feedback mechanisms (Serreze et al., 2009; Screen and Simmonds, 2010; Serreze and Barry, 2011). While the contribution of some feedback mechanisms to Arctic Amplification can be regarded as scientific consensus ~~(i.e., sea ice–albedo feedback, Serreze et al., 2009)~~ (e.g., sea ice–albedo feedback, Serreze et al., 2009), others are not yet sufficiently explored and their contribution is uncertain ~~(i.e., influence of clouds, lapse rate feedback, linkages between Arctic and mid–latitudes, Wendisch et al., 2023)~~(e.g., influence of clouds, . As the Arctic warms faster than the mid–latitudes, the meridional temperature gradient decreases in most heights of the troposphere, likely resulting in a weaker jet stream ~~with enhanced~~ and possibly enhancing the tendency to meander ~~(more southward and nor~~ . ~~Consequently, the frequency~~ (Francis and Vavrus, 2015). A more meandering jet would result in an increasing number of poleward moist and warm air intrusions (MWAIs) and southward cold air outbreaks (CAOs)~~is expected to increase (Pithan et al., 2018; Mewes a~~ ~~.~~. However, the tropical upper troposphere warms while the Arctic lower stratosphere cools, enhancing meridional temperature gradients at higher altitudes (Lee et al., 2019; Stendel et al., 2021). The frequency of meridional transport through the North Atlantic has increased during the last decades while it stayed constant or even decreased in other regions (Mewes and Jacobi, 2019) . You et al. (2022) found a positive trend in the frequency and duration of atmospheric blocking over the Barents Sea especially in winter. ~~As blocking situations are associated with meandering jets, both frequency and duration of MWAIs reaching the Arctic through the North Atlantic sector are increasing~~, supporting the statement of an enhanced North Atlantic pathway for meridional transport.

MWAIs frequently transport large amounts of heat and moisture into the Arctic through the Atlantic sector (Woods and Caballero, 2016). When the warm air ~~glides onto the cold Arctic dome~~is pushed upwards over cold Arctic air masses, deep cloud systems including mixed–phase clouds ~~form.~~ may form. During MWAIs, cirrus clouds, whose radiative effect is not well explored over sea ice (Hong and Liu, 2015; Marsing et al., 2023), can be formed or advected to the Arctic. Woods et al. (2013) and Woods and Caballero (2016) stress that intense MWAIs have a large effect on the downward terrestrial radiation at the surface, contributing to the warming of the Arctic. Such MWAIs precondition the sea ice for the melting season, resulting in lower sea ice extent at the end of the summer (Kapsch et al., 2013, 2019). Numerical models still struggle to accurately represent the mixed–phase clouds and the transformation processes of the air masses ~~well~~ (Pithan et al., 2014; Cohen et al., 2020). MWAIs can often be linked with filamentary bands of ~~extreme~~ strong moisture transport, known as Atmospheric Rivers ~~(Newell et al., 1992). Atmospheric Rivers (ARs)~~(ARs, Newell et al., 1992). ARs are responsible for over 90 % of the poleward moisture transport across the mid–latitudes and are frequently accompanied by ~~extreme~~ strong winds and precipitation (Nash et al., 2018). ~~In the Arctic, ARs~~ While the precipitation can cause snow accumulation ~~, as well as the opposite, melting of snow and sea ice due to enhanced~~ during ARs in the Arctic, the enhanced emission of downward terrestrial radiation ~~from the clouds~~ by the clouds can lead to melting of snow and sea ice (Neff et al., 2014; Komatsu et al., 2018; Mattingly et al., 2018, 2020; Bresson et al., 2022; Viceto et al., 2022). In a warming climate, ARs are expected to shift polewards and intensify due to the increased moisture load (Ma et al., 2020).

CAOs are often responsible for severe weather events in the high– and mid–latitudes and mainly occur in winter and spring (Fletcher et al., 2016; Pithan et al., 2018). Here, we focus on marine CAOs (MCAOs) where cold and dry air is advected southwards from the sea ice to the ice–free (open) ocean. Over the open ocean, the strong temperature contrast between the surface and the lower tropospheric air leads to intense fluxes of sensible and latent heat, responsible for 60–80 % of the oceanic heat losses in that region (Papritz and Spengler, 2017). This heat and moisture transfer into the atmosphere destabilizes the boundary layer and leads to the formation of cloud streets, which later develop into open cells. This cloud evolution is not well represented in models but an important feature (Pithan et al., 2018). MCAOs can also cause the formation of Arctic mesoscale cyclones (Polar Lows, Rasmussen and Turner, 2003; Zahn and von Storch, 2008), which may locally lead to heavy precipitation and strong winds. The formation processes of Polar Lows and their relation to MCAOs are still not fully understood, partly due to the sparsity of measurements in the Arctic (Moreno-Ibáñez et al., 2021).

So far, observations of air mass transformations in the Arctic have mostly been conducted from a fixed local position (Eulerian view). Only a few aircraft based samplings of air mass properties over a limited regional area have been reported (e.g., Wendisch et al., 2019; Mech et al., 2022). To observe air mass transformation processes along their meridional pathway in a Eulerian view, multiple stations that are aligned with the wind direction would be needed. Therefore, Pithan et al. (2018) proposed a quasi–Lagrange approach following air masses to and from the Arctic, which motivated the field campaign HALO–(AC)[3] within the Transregional Collaborative Research Center TRR 172 (TRR 172) "Arctic Amplification: Climate Relevant Atmospheric and Surface Processes and Feedback Mechanisms (AC)[3]". The campaign was designed to obtain quasi–Lagrange observational data of air mass transformations during MWAIs and MCAOs to gain process understanding and evaluate the performance of weather and climate models (Wendisch et al., 2021).

During HALO–(AC)[3], extensive remote sensing and in situ measurements of surface, cloud and thermodynamic properties have been performed between the Norwegian Sea and the North Pole from 11 March to 12 April 2022 with three research aircraft (HALO, Polar 5, and Polar 6). The High Altitude and LOng-range research aircraft (HALO) operated by the German Aerospace Center (DLR, Ziereis and Gläßer, 2006; Stevens et al., 2019) is a modified Gulfstream G550, which has a sufficient operating range (9000 km in altitudes up to 15 km) for quasi–Lagrange air mass observations and was based in Kiruna during HALO–(AC)[3]. For HALO–(AC)[3], it was equipped with a similar instrumental payload as during the EUREC4A campaign (Stevens et al., 2019; Konow et al., 2021). Polar 5 and Polar 6 (P5 and P6) were based in Longyearbyen and operated by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI, Wesche et al., 2016) in a similar coordinated way as during the ACLOUD campaign (Wendisch et al., 2019).

~~In this study , we focus on the analysis of the~~ This study focuses on the environmental conditions during HALO–(AC)³ and their climatological context to serve as comprehensive reference in future studies. After ~~presenting the data~~ introducing the data basis and methods in Sect. 2, we describe the synoptic development during two dominating periods ~~and the classification of certain synoptic events based on meteorological parameters~~ in Sect. 3.1. We also provide a view on the conditions ~~from~~ at Ny–Ålesund (Sect. 3.2), where future studies will use the extensive measurements from the French–German Atmospheric Observatory AWIPEV. Sea ice conditions in the North Atlantic sector of the Arctic are presented in Sect. 3.3. We further analyse the origin and strength of the MWAIs and ARs (Sect. 4.1), the conditions during the MCAO periods (Sect. 4.2), the formation and environmental characteristics of the Polar Low (Sect. 4.3), and Arctic cirrus clouds (Sect. 4.4), before concluding our study in Sect. 5.

2 Data and Methods

Geographical coordinates for measurement regions as displayed in Fig. 1. Note that the northern part of the northern region in the central Arctic is extended to the west. Northern region Central region Southern region Northern limit in deg N 89.3 (84.5) 81.5 75.0 Southern limit in deg N 81.5 75.0 70.6 Western limit in deg E -54.0 (-9.0) -9.0 0.0 Eastern limit in deg E 30.0 16.0 23.0

2.1 Study domain

As the research flights during HALO–(AC)[3] were conducted in the Norwegian, Greenland, and Barents Seas, the Fram Strait, and central ArcticOcean in early spring, we also confined our analysis to this region. Both region and season for this campaign were selected because the largest fraction of MWAIs enters the Arctic through the North Atlantic during winter and early spring flight tracks cover the North Atlantic sector of the Arctic, the major pathway of MWAIs (Johansson et al., 2017; You et al., 2022). Based on the flight tracks, illustrated in Fig. 1, we selected three domains for which averages of several meteorological variables were calculated in this study. Table A1 summarizes the our synoptic analysis as shown in Fig. 1. The exact geographical coordinates of the domains are listed in Appendix A, Table A1. From north to south the domains are referred to as northern region (central Arctic north of Svalbard and Greenland), central region (Fram Strait and Greenland Sea), and southern region (Greenland and Norwegian Seas between Svalbard and Norway). A particular focus lies on the central regionas most flights were carried out in this domain. Within the central region, flight activities of P5 and P6 remained within 500 km of the northwestern coast of Svalbard due to their limited operating range. HALO covered the entire pathway of MWAIs and MCAOs between Greenland, Svalbard and Norway up to the central Arctic. , where measurements were performed with all three aircraft.

2.2 ~~Measurements~~ Atmospheric conditions observed from HALO and at Ny–Ålesund

HALO is equipped with a dropsonde launch system (Airborne Vertical Atmospheric Profiling System, Hock and Franklin, 1999) and RD94 dropsondes were used to obtain Vertical profiles of temperature, relative humidity, and pressure with an accuracy of 0.2 K, 2 %, and 0.4 hPa, respectively, between the aircraft flight altitude and the surface (Vaisala, a; George et al., 2021). Wind profiles are derived from the temporal change of the dropsonde's position measured by the GPS receiver.

Measurements gathered pressure and wind were recorded with RD94 dropsondes launched from HALO (Hock and Franklin, 1999; George and radiosondes launched at the Atmospheric Observatory of the French–German AWIPEV research base in Ny–Ålesund (Svalbard, 78.92° N, 11.92° E) provide an additional view on the environmental conditions during HALO–(AC)[3] in the central region. At AWIPEV, ground based meteorological measurements (Maturilli et al., 2013; Maturilli, 2020a) are complemented by vertical profiles of wind, temperature, pressure, and relative humidity from daily radiosondes (Maturilli and Kayser, 2016, 2017; Maturilli . The currently used Vaisala RS41 radiosondes have uncertainties of temperature, pressure, and relative humidity measurements of 0.2–0.4 K, 0.6–1.0 hPa, and 3–4 %, respectively (Vaisala, b). During the campaign period, the launch frequency of the radiosondes was increased to) every 6 hours . From these vertical (Vaisala RS41, Maturilli, 2020b). From the radiosonde
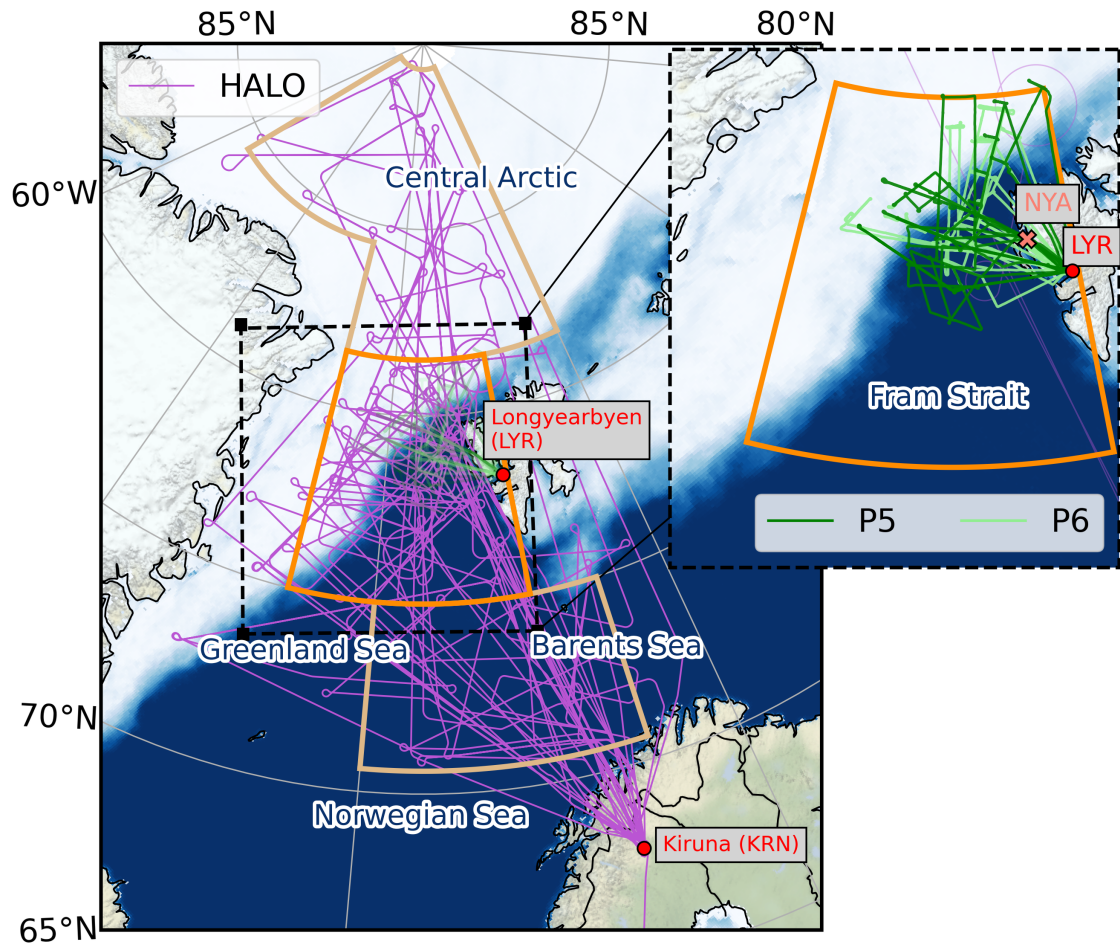
Figure 1. Flight tracks of HALO (purple), as well as P5 and P6 (dark and light green, zoomed domain in the right panel) during HALO–(AC)³. For orientation, the mean sea ice concentration from 07 March to 12 April 2022 based on AMSR2 satellite data (Spreen et al., 2008) is showed as filled contours. The three ~~main~~ measurement ~~regions~~ domains (southern region, central region, and northern region) are marked as yellow and orange boxes. The central region is highlighted. The orange label NYA in the zoomed domain marks the location of Ny–Ålesund.

profiles, we identified the thermal tropopause according to the WMO definition as the lowest level at which the temperature lapse rate falls below $2\,\mathrm{K\,km^{-1}}$ and does not exceed this value for the next $2\,\mathrm{km}$. The integrated water vapour (IWV) was calculated from profiles of air pressure and specific humidity, which was derived from the temperature and relative humidity measurements. ~~In addition to the radiosonde data~~ Ground based meteorological measurements gathered at AWIPEV provide an additional view on the environmental conditions during HALO–(AC)³ in the central region (Maturilli et al., 2013; Maturilli, 2020a). Additionally, we used data from the CL–51 ceilometer ~~(Maturilli and Ebell, 2018; Maturilli, 2022)~~ to assess the cloud conditions at Ny–Ålesund (Maturilli and Ebell, 2018; Maturilli, 2022).

2.3 Satellite observations of sea ice

We focused on sea ice concentration (SIC), i.e., the percentage of a satellite pixel (grid cell in ERA5) covered by sea ice, derived from satellite measurements to describe the sea ice conditions during HALO–(AC)^3. In general, we separated observations for areas with and without sea ice (latter is also termed open water) through the threshold of 15 % SIC. ~~Starting with the launch of the Numbus–7 satellite in 1978,~~ Satellite based passive microwave radiometers ~~from space~~ provide a long–term observation of sea ice (Spreen and Kern, 2016). ~~To put SIC during HALO–(AC)^3 into a climatological context~~ Here, we used the OSI SAF Global Sea Ice Concentration Climate Data Record (SIC CDR v2.0), namely the product OSI–450 from 1979 to 2015, and the complementary Interim Climate Data Record OSI–430–b from 2016 onwards (OSI SAF, 2017; Copernicus Climate Change Service (C3S), 2020). ~~It~~ The product is based on ~~satellite microwave data from a series of instruments: SMMR (1979–1987), SSM/I (1987–2008), and SSMIS (2006–today). The dynamic hybrid algorithm~~ low–frequency passive microwave satellite data and is described in Lavergne et al. (2019) ~~and it processes frequency channels at 19 and 37~~. The datasets are available daily with a grid spacing of 25 km×25 km.

To study the evolution of SIC during HALO–(AC)^3 at a higher spatial resolution, we used the merged MODIS–AMSR2 SIC dataset, available daily at 1 km resolution. ~~It is based on passive microwave (AMSR2 sensor on GCOM–W1 (JAXA)) and thermal infrared (MODIS sensor on AQUA (NASA)) satellite data. The merged~~ The merged MODIS–AMSR2 product (Ludwig et al., 2020) takes advantage of the high spatial resolution of thermal infrared ~~, where SIC computed from temperature anomalies~~ (Drüe and Heinemann, 2004), and of the independence of cloud cover of microwaves ~~. SIC is computed from polarization differences at 89 GHz between open ocean and sea ice (ASI algorithm, Spreen et al., 2008).~~ (Spreen et al., 2008).

2.4 Reanalysis data

~~For the analysis of the~~ To analyse the weather development, we used the ERA5 reanalysis from the European Centre for Medium–Range Weather Forecasts (ECMWF) ~~, which has~~. ERA5 offers hourly data output since 1950 with a horizontal resolution of 31 km ~~with~~ and 137 vertical model levels ~~and offers hourly data output from 1950 until present (Hersbach et al., 2018a, b, 2020). Climatological comparisons are based on the years 1979–2022 to cover the inter–annual variability of atmospheric conditions, unless specified differently. In the following, we describe the processing of~~ (Hersbach et al., 2018a, b, 2020). ERA5 ~~data and derivation of indices calculated for our analysis.~~

2.4.1 ~~Basic meteorological parameters~~

~~Daily means of basic meteorological variables, such as the mean sea level pressure, 2 m air temperature, 10 m wind speed, IWV, total daily precipitation (in liquid and frozen form), were calculated and averaged for each of the three measurement regions for the description of the synoptic evolution~~ represents clouds and precipitation in the Arctic better than other reanalyses (Graham et al., 2019a; Avila-Diaz et al., 2021). Additionally, ERA5 features a higher vertical resolution than other reanalyses, which leads to more accurate wind fields and, thus, to improved water vapour transport estimates (Graham et al., 2019b). However, ERA5 shows higher warm biases over sea ice of near surface temperatures than other reanalyses due to the

misrepresentation of the stable stratification (Wang et al., 2019; Yu et al., 2021). During HALO–(AC)[3], dropsonde measurements launched from HALO were assimilated into ERA5. The climatological comparisons presented here are based on the years 1979–2022 unless specified differently. Grid points with a land fraction ~~≥ 0 were excluded . We respected the increasing data point density with increasing latitudes (due to the 0.25° × 0.25° grid) by computing regional averages~~ > 0 have been excluded from our analysis according to the ERA5 land–sea–mask. Domain averages of the regularly gridded ERA5 quantities were calculated as area averages weighted by the cosine of ~~latitudes. Additionally, we computed averages of vertically integrated meridional heat (IHT_north) and moisture flux (IVT_north) over the ocean grid points of the central region latitudesfor information about the time and location of MWAIs.~~ the latitude to respect the increasing data point density with increasing latitudes. In the following, we describe the processing of ERA5 data and derivation of indices calculated for our analysis.

~~We assessed the weather conditions during HALO–(AC)[3] with respect to the climatological reference period with anomalies of temperature at 850 hPa and 2 m height, 500 hPa geopotential height, and IWV. Evaluating the temperature anomalies at these two levels reveals the vertical extent of the temperature anomalies in the lower troposphere. We computed means over the climatology years of these variables for three (sub–)periods of HALO–(AC)[3]: 11–20 March, 21 March–12 April, 07 March–12 April. We obtained the anomalies by subtracting the long–term means from the mean of the respective time period in 2022 so that positive (negative) values correspond to anomalies above (below) the long–term mean.~~

2.4.1 Detection of Atmospheric Rivers and moist and warm air intrusions

~~The northward component of vertically integrated water vapour transport (IVT_north) is used to detect periods of increased poleward water vapour transport. Woods and Caballero (2016) defined~~ Woods and Caballero (2016) detect moist air intrusions into the Arctic ~~using~~ when the vertically integrated meridional moisture flux (IVT_north) at 70° N ~~above certain threshold~~ (exceeds $200 \, \mathrm{Tg} \, \mathrm{d}^{-1} \, \mathrm{deg}^{-1}$ ($60.6 \, \mathrm{kg} \, \mathrm{m}^{-1} \, \mathrm{s}^{-1}$) over a duration of at least 1.5 days and a zonal extent of at least 9°. ~~Here~~For our purpose, we adapted this ~~definition to our campaign site~~ detection and defined MWAIs with positive daily means of IVT_north averaged over the central region. An MWAI is considered weak ~~when this variable does not exceed~~ (strong) when IVT_north is below (equal or above) $100 \, \mathrm{kg} \, \mathrm{m}^{-1} \, \mathrm{s}^{-1}$. ~~Values above this threshold suggest strong MWAI conditions.~~Additionally, we computed the ~~climatological mean, as well as the~~ temporal mean, 25–75th and 10–90th percentiles over the climatology ~~years for each day.~~

period. In this study, ARs were identified with a global algorithm by Guan and Waliser (2015) in its revised version (Guan et al., 2018)~~. IVT must exceed the 85th percentile of the season and grid cell, and must reach an absolute value of 100 kg m⁻¹ s⁻¹, while fulfilling geometrical requirements (length > 2000 km, length to width ratio of > 2, IVT direction within 45° of the detected AR axis). To account for the~~, adapted to the lower moisture content ~~in the polar atmosphere, the absolute IVT threshold is reduced to 50 kg m⁻¹ s⁻¹. In case a detected AR at the 85th percentile threshold does not fulfill other requirements (e.g., related to its structure or geometry), higher IVT thresholds are successively tested (85–95th in steps of 2.5). This procedure ensures detection of an AR that is embedded in a wide area of enhanced moisture transport with respect to the local climatology~~of the Arctic (Lauer et al., 2023).

2.4.2 Marine cold air outbreak index

A key feature of MCAOs are strong temperature decreases with increasing height especially in the lower troposphere over open ocean. This forms the basis for the MCAO index M to identify them and to quantify their strength. The MCAO index M was calculated following Papritz and Spengler (2017) and Dahlke et al. (2022):

$$M = \theta_{\mathrm{SKT}} - \theta_{850} \tag{1}$$

with θ_{SKT} (θ_{850}) as the potential skin temperature (potential temperature at $850\,\mathrm{hPa}$). Grid points with skin temperatures below $271.5\,\mathrm{K}$ (i.e., over sea ice) were excluded from further processing as in Dahlke et al. (2022). We averaged over the central region and computed the climatology as for IVT$_{\mathrm{north}}$.

Following Papritz and Spengler (2017), MCAO conditions are present when $M > 0\,\mathrm{K}$ and its strength can be classified as weak ($0\,\mathrm{K} < M \le 4\,\mathrm{K}$), moderate ($4\,\mathrm{K} < M \le 8\,\mathrm{K}$), strong ($8\,\mathrm{K} < M \le 12\,\mathrm{K}$) or very strong ($M > 12\,\mathrm{K}$).

2.4.3 Lower tropospheric parameters for marine cold air outbreak analysis

For a detailed analysis of the MCAO conditions over the campaign (Sect. 4.2), we used hourly ERA5 data of wind, temperature, and relative humidity at 850, 925, and $1000\,\mathrm{hPa}$, as well as cloud cover, precipitation and surface turbulent heat fluxes (sensible and latent). All variables were temporally averaged over 6 hour intervals and spatially averaged over the central region. Cloud cover was confined to open water surfaces only as ERA5 tends to overestimate especially low–level cloud cover over sea ice (Di Biagio et al., 2021). Details can be found in Appendix A.

2.4.4 Environmental conditions of Polar Lows

We analyse the environment for Polar Low formation with a set of conditions (C1–C6) suggested by Radovan et al. (2019) and Terpstra et al. (2016) in a 200 km radius around the Polar Low's centre (pressure minimum): C1: sea surface temperature (SST) − 500 hPa temperature, C2: SST − 2 m temperature, C3: mean lapse rate below 850 hPa, $C4_i$: mean relative humidity below
250   950 hPa, $C4_{ii}$: mean relative humidity between 850 and 950 hPa, C5: 10 m wind speed (here, gust), C6: 500 hPa geopotential height anomaly.

~~Condition C1 is a measure of the convection potential as it evaluates the mean temperature gradient between the surface and the mid-troposphere. Large differences between the 2 temperature and the SST (C2) promote strong sensible heat fluxes, stressing the air–sea interaction. Condition~~ Condition C3 is evaluated as the vertical mean of the vertical potential temperature
255   gradient $\partial\theta/\partial z$ ~~(with θ as potential temperature and z as height)~~ between the surface and the 850 hPa pressure level. ~~Positive values of C3 represent an increase of potential temperature with height. At least conditionally unstable conditions (unstable (stable) for moisture–saturated (unsaturated) air parcels) should be present ($\partial\theta/\partial z \leq 3\,\mathrm{K\,km^{-1}}$). The relative humidity conditions $C4_i$ and $C4_{ii}$ are an important measure for the availability of moisture for latent heat release, a major energy source of a Polar Low. Maximum 10 m wind speed (C5) is an indicator of the Polar Low's strength. The geopotential height condition (C6) is~~
260   ~~selected to ensure the presence of an upper level trough~~The meaning of each condition is summarized in Appendix A.

For conditions C1–C4, the 75th percentile, for C5, the maximum, and for C6, the mean ~~in a 200 km radius around the Polar Low's centre~~ were computed. Wahl et al. (2017) found that scales of multiples of the grid cell spacing are required to realistically represent the energy spectrum of a wind field. We decided to use the maximum 10 m wind gust instead of mean wind to get a better estimate of the near–surface wind field of this small–scale phenomenon that might be hidden due to the
265   coarse resolution of ERA5. The climatology of the 500 hPa geopotential height for C6 consists of all days of April between 1979 and 2022 for each grid point within the 200 km radius. Subsequently, the geopotential height anomaly was computed as the difference between the conditions during HALO–(AC)³ and the climatology, and C6 was obtained by averaging over the 200 km circle. ~~Table 1 summarizes the conditions and their thresholds (Rasmussen and Turner, 2003; Zahn and von Storch, 2008; Radovan .~~

270   Furthermore, we calculated vorticity from 10 dropsonde measurements taken within 1 hour arranged on a circular pattern. Following Lenschow et al. (2007) and Bony and Stevens (2019), we assumed horizontal variations in the wind field to be linear and expanded the wind vector with ~~taylor~~ Taylor expansion around the centre of the circle ~~. The wind vector v can be expressed as~~

$$v = v_0 + \frac{\partial v}{\partial \vartheta} + \frac{\partial v}{\partial \phi}$$

275   ~~for spherical coordinates ϑ and ϕ and the average wind velocity vector of all dropsondes v_0. By performing least–squares regression, the horizontal gradients $\frac{\partial v}{\partial \vartheta}$ and $\frac{\partial v}{\partial \phi}$ were obtained to calculate the relative vorticity~~

$$\zeta = \frac{1}{r\sin\vartheta_0}\left(\frac{\partial v}{\partial \phi} - \frac{\partial u \sin\vartheta}{\partial \vartheta}\right).$$

in spherical coordinates.

2.4.5 Trajectory calculations

Trajectory calculations were performed using LAGRANTO (Sprenger and Wernli, 2015) and wind fields from ERA5 ~~(Hersbach et al., 2020)~~ ~~retrieved on native resolution ($0.25° \times 0.25°$, 1 hour, 137 model levels)~~. To assess the origin of sampled cirrus air masses, 72 hour back–trajectories for the northernmost sections of the flights on 11 and 12 April were computed. Trajectories were initialized at the pressure levels 350–550 hPa in 50 hPa steps, where the single–layer cirrus had been observed by HALO ~~.~~ (Sect. 4.4). Furthermore, 72 hour back– and 48 hour forward–trajectories were computed to identify the pathways of the MWAIs (ARs) on 13 and 15 March (Appendix C). These trajectories were initialized along the 77.5° N latitude with 1° zonal spacing between 20° W and 13° E at 18:00 UTC on the respective days at the pressure levels 700, 850, and 925 hPa.

~~Criteria to evaluate environmental conditions of a Polar Low in a 200 km radius around its centre according to Radovan et al. (2019) . Condition Meaning How evaluated Threshold C1 Sea surface temperature — 500 temperature 75th percentile ≥ 43 K C2 Sea surface temperature — 2 temperature 75th percentile ≥ 6 K C3 Mean lapse rate below 850 75th percentile ≤ 3 K km^{-1} C4$_{\text{i}}$ Mean relative humidity below 950 75th percentile $\geq 75\%$ C4$_{\text{ii}}$ Mean relative humidity between 850 and 950 75th percentile $\geq 82\%$ C5 10 wind gust maximum ≥ 15 m s^{-1} C6 500 geopotential height anomaly mean ≤ -160 gpm~~

3 Meteorological and sea ice conditions during HALO–(AC)^3

3.1 Analysis and identification of synoptic events

In this section, we characterize weather events during HALO–(AC)^3 and assess their strength ~~with~~ in the climatological context.
At first, we separate the campaign into two major periods based on IVT$_{north}$ and the MCAO index (M) in the central region ~~in~~ (see Fig. 2). The campaign started with a warm and humid period with positive IVT$_{north}$ and negative values of M, coinciding with enhanced static stability, from 11 to 20 March 2022. The warm period was followed by a cold and dry period from 21 March to 12 April 2022, where IVT$_{north}$ (M) was almost exclusively negative (positive).

Within the warm and cold periods, we classified a large variety of weather events based on IVT$_{north}$ and M, the large scale pressure constellation, and regional averages of ~~basic~~ meteorological variables from ERA5 (Fig. 3 and 4). ~~IHT$_{north}$ and~~ In Fig. 5, we show latitude–averages of IVT$_{north}$ ~~, averaged~~ and the vertically integrated meridional heat flux IHT$_{north}$ over the central region ~~latitudes, were used~~ to spatially and temporally localize meridional heat and moisture transport corresponding with MWAIs and MCAOs ~~(Fig. 5). For the warm, cold, and the entire HALO–(AC)^3 period, we present~~. Negative values of IHT$_{north}$ and IVT$_{north}$ indicate southward fluxes. To put the weather conditions into climatological context, anomalies of temperature at 850 hPa and 2 m above the surface, geopotential height at 500 hPa, and IWV ~~with respect to the climatology (Fig. 6) .~~ were computed for the warm, cold and the entire campaign period. Positive (negative) anomalies correspond to values above (below) the long–term mean. Evaluating the temperature anomalies at these two levels reveals the vertical extent of the temperature anomalies in the lower troposphere.

3.1.1 Warm period

~~We start our analysis on 07 March to capture the initial conditions of HALO–(AC)^3. Before the warm period started, southerly and southwesterly winds dominated over the southern and central regions (07–09 March 2022, Fig. 3d). The~~ During the warm period, the corresponding general circulation pattern was ~~initially~~ characterized by a high surface pressure system extending from the North Sea to Baltic Sea and Scandinavia ~~.~~ (Fig. 4a, b). The surface high was connected to a ridge in the 500 hPa geopotential height. Low surface pressure and low 500 hPa geopotential height were located over Greenland and the North Atlantic. ~~A weak MWAI (IVT$_{north}$ < 100 kg m^{-1} s^{-1}) associated with the southwesterly flow barely reached the central region on 08–09 March (Fig. 3a). No signal~~ This pressure constellation resulted in a consistent southerly and southwesterly flow with only a few short–lived interruptions in the three measurement regions. The interruptions can be seen ~~in the central Arctic regarding temperature and IWV increases during that time (Fig. 3c, e). Subsequently, on 10–11 March, a weak high pressure system at the surface and ridge in the 500 hPa geopotential height temporarily caused northerly winds between two lows over the Fram Strait. The brief interruption of the southerly flow is reflected in the 2 m temperature drop (~~ as near–surface temperature drops and wind direction change (e.g., 11 March, Fig. 3c ~~) on 10–11 March~~, d).

~~At the beginning of the warm period (~~On 11–13 ~~March), the high pressure ridge over Scandinavia intensified~~ and ~~established~~ 15–16 March, the pressure gradients between Greenland and Scandinavia were intensified and blocking (Omega Block) was established over most of Europe. Intense MWAIs are connected to blocking situations over the eastern border of a large
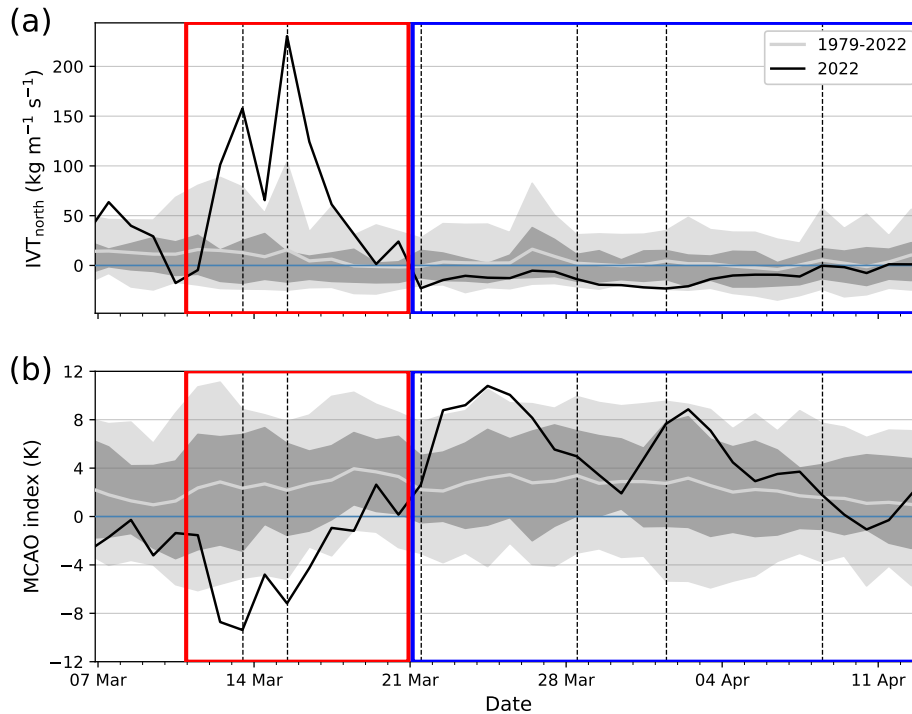
Figure 2. Daily means of (a) northwards component of integrated water vapour transport (IVT_{north}), (b) Marine Cold Air Outbreak (MCAO) index (M) based on ERA5 and averaged over the central region for HALO–(AC)[3] (black line). ~~Daily values of the climatological~~ The mean~~(1979–2022, grey line),~~ as well as the 10–90th and 25–75th percentiles of the climatology (1979–2022) are illustrated as grey line, light and dark grey ~~shading~~shadings. The red (blue) box indicates the warm (cold) period dominated by MWAIs (MCAOs). Vertical dashed black lines mark the days shown in Fig. 4.

325 basin (here, North Atlantic), redirecting cyclones northward as the typical eastward propagation is blocked (Woods et al., 2013). Consequently, warm and moist air masses originating from the North Atlantic were transported towards our three main measurement areas, driven by several low pressure systems that formed between Iceland and eastern Greenland.

~~Besides the before mentioned weak MWAI event, we identified a much stronger~~ We identified a strong MWAI event during the first week of the campaign (Fig. 3a) with area–averaged IVT_{north} up to $160\,kg\,m^{-1}\,s^{-1}$ ~~.~~(Fig. 2a). The event was detected

330 as AR and passed through the measurement regions on 12–13 March ~~. It was connected with a more pronounced and narrow meridional flow due to the intensified pressure contrast between Scandinavia and Greenland~~ (Fig. 4a). ~~Exceptionally warm and moist air masses were transported from the British Isles over the Fram Strait towards the North Pole. As a result, equivalent potential temperature values at 850 hPa in the northern region were elevated by up to 30 K compared to later parts of the campaign (Fig. 4a). In the same region~~In the northern region, IWV reached ~~the maximum value of the campaign with an

335 area–average above~~ its campaign maximum ($8\,kg\,m^{-2}$) on 13 March and declined afterwards ~~(Fig. 3e). The~~ while the 2 m
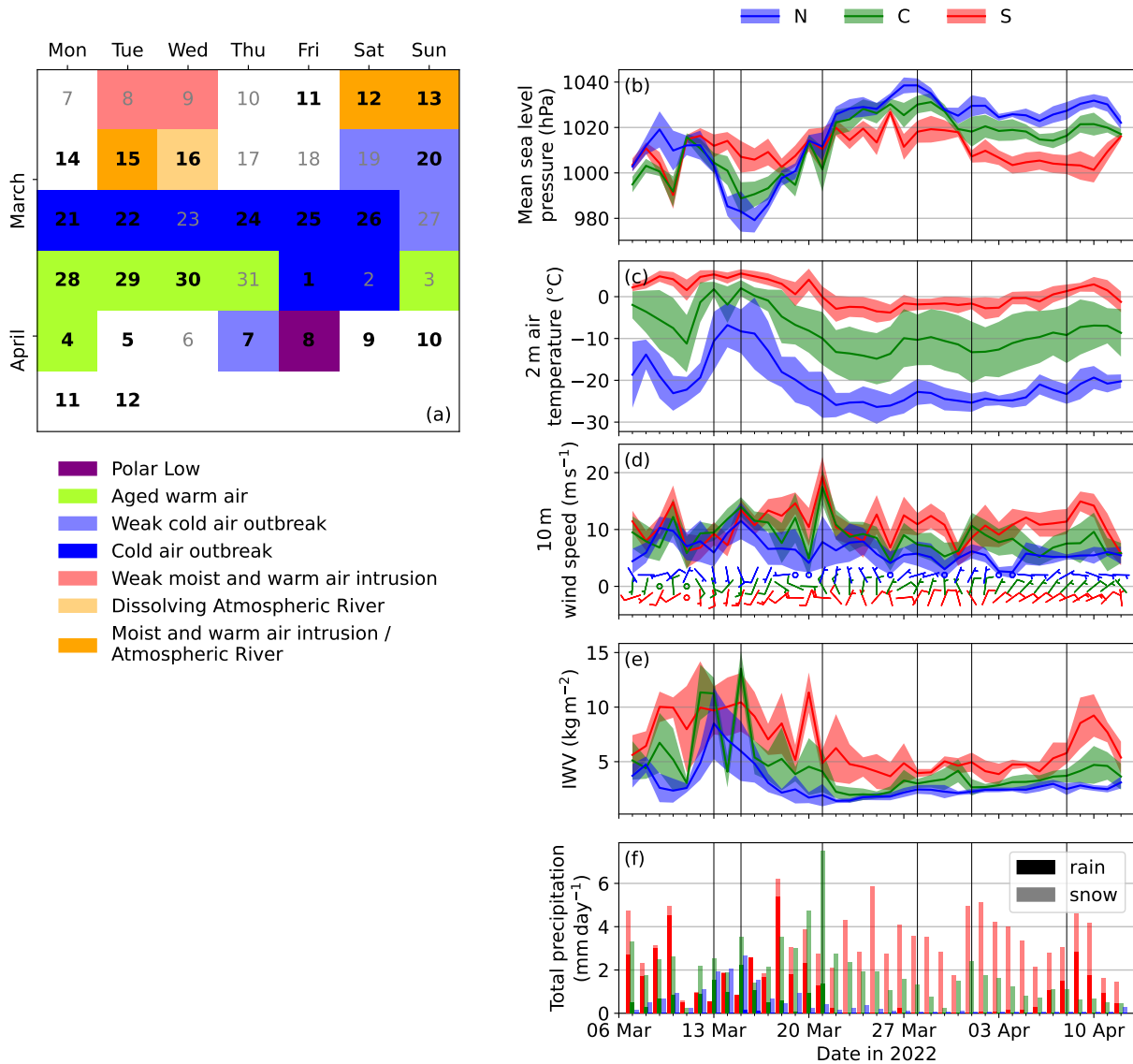
Figure 3. Left column: (a) Calendar of March and April 2022 showing the categorized and colour-coded weather conditions. Bold font indicates days when research flights were performed. Right column: Regional averages (lines) and standard deviation (shading) of ERA5 based time series of (b) mean sea level pressure, (c) 2 m temperature, (d) 10 m wind (lines indicate speed, barbs indicate direction and speed), (e) integrated water vapour (IWV), and (f) daily accumulated precipitation, separated into rain (no transparency) and snow (partly transparent). Regional averages are performed for the southern (S, red), central (C, green), and northern (N, blue) region shown in Fig. 1. Vertical black lines indicate days shown in Fig. 4.

temperature in the northern region continued to increase until the following day.

(Fig. 3d, e).

A second AR followed on 15 and 16 March (Fig. 3a), which had a more distinct confluent tropospheric southwesterly flow between the Greenland low and the Scandinavian high (Fig. 4b). In the central Arctic Ocean, the strongest warming occurred on 16 March and resulted in the highest 2 m temperature in March averaged over all ERA5 grid points north of 80° N (latitude–weighted) since 1979 (not shown). Simultaneously, the latitude–averaged IHT_{north} and IVT_{north} exceeded the previous maxima from 1996 ($9.44 \cdot 10^{10}\,\mathrm{W\,m^{-1}}$ vs. $9.32 \cdot 10^{10}\,\mathrm{W\,m^{-1}}$, and $388\,\mathrm{kg\,m^{-1}\,s^{-1}}$ vs. $384\,\mathrm{kg\,m^{-1}\,s^{-1}}$, Fig. 5). In some parts of the northern region, near–surface temperatures were above freezing and even liquid precipitation was documented over the sea ice (Fig. 3c, f, analysed in greater detail in Sect. 4.1). The AR on 15–16 March also caused the highest daily precipitation of the northern region over the campaign period. In the central region, the area–averaged 2 m temperature was above freezing and a high fraction of rainfall to the total daily precipitation was found.

After the AR, much drier but still relatively warm air followed, leading to a strong reduction in IVT_{north} and a slight reduction in IHT_{north} (Fig. 5). As a surface based high pressure system formed over Greenland, the large–scale pressure constellation started to change. However, at upper

levels, low geopotential persisted, promoting the formation of a strong low pressure system near Iceland on 20 March. The low quickly propagated towards the northeast and was characterized by rapid deepening ($> 25\,\mathrm{hPa}$ core pressure decrease in 24 hours) and a frontal structure representative of a Shapiro–Keyser cyclone (Shapiro and Keyser, 1990). ~~Unlike the Norwegian cyclone model, its warm front keeps circling around the centre, forming a warm core, instead of being caught up by the cold front (known as occlusion).~~ On the eastern flank of the Shapiro–Keyser cyclone, IHT_{north} and IVT_{north} ~~were similarly high~~ indicate similarly strong fluxes as on 12 March (Fig. 5). ~~However, as the moisture transport sufficiently dissipated before reaching the southern or central region, we did not classify this as an AR. Because of the low amount of heat in the cold air to the west of the Shapiro–Keyser cyclone, strongly negative IHT_{north} was absent.~~

In the climatological perspective, the prevailing pressure gradient between Scandinavia and Greenland ~~, is~~ reflected in the extremely strong gradient of the $500\,\mathrm{hPa}$ geopotential height anomalies ($> 10\,\mathrm{gpdm}$ over Scandinavia, $< -10\,\mathrm{gpdm}$ over Greenland, Fig. 6h) ~~, and~~ was responsible for the associated warming. Moreover, we found positive temperature anomalies at $850\,\mathrm{hPa}$ of more than $7\,\mathrm{K}$ over the Fram Strait and up to $9\,\mathrm{K}$ over Scandinavia and around Franz Josef Land ~~over the warm period (~~(northeast of Svalbard, Fig. 6b). At $2\,\mathrm{m}$, the warming was amplified to more than $16\,\mathrm{K}$ above climatology over Franz Josef Land and more than $10\,\mathrm{K}$ over the Greenland Sea and Fram Strait (Fig. 6e). The bottom–amplified warming is consistent to the findings of Woods and Caballero (2016), confirming the reduction of the Arctic boundary layer inversion strength through intense MWAIs. Additionally, the high amounts of moisture carried by the ARs resulted in positive IWV anomalies of more than $2\,\mathrm{kg\,m^{-2}}$ over the southern, central, and parts of the northern region (up to $4\,\mathrm{kg\,m^{-2}}$ in the Norwegian and Greenland Seas, Fig. 6k).

3.1.2 Cold period

~~The intense~~ On 21 March 2022, the Shapiro–Keyser cyclone, together with a strong high pressure system over Greenland, marked a turning point in the ~~dominating weather conditions over all measurement areas at the beginning of the third campaign week (21–27 March 2022). Due to anomalously high pressure over Greenland (even exceeding the 90th percentile on some days between 21 and 31 March, not shown), a strong~~ circulation pattern (Fig. 4c). Compared to the warm period, the zonal pressure gradient ~~resulted over the Fram Strait, which caused northerly winds~~ across the North Atlantic has been inverted. The resulting northerly winds caused negative IHT_{north} and IVT_{north} after the cyclone passed (Fig. 3d and 5). Although the sign of the pressure gradient remained until the end of the campaign (12 April), the position and strength of the synoptic– and meso–scale circulations changed over time. ~~Figure 4c shows the position of the low pressure system and the advection of the cold air masses for 21 March.~~ As Kolstad et al. (2009) showed, there is a connection between such a circulation pattern and the onset of MCAOs in that region.

~~With the high amounts of water vapour circled around the cyclone's centre, we found the strongest southward latitude–averaged IVT_{north} on the cyclone's western flank ($-90\,\mathrm{kg\,m^{-1}\,s^{-1}}$, Fig. 5b). As the cyclone stayed over the Barents Sea while being filled up, it got access to cold, dry air from the sea ice covered Arctic Ocean, causing a quick reduction of absolute IVT_{north} values. The negative IHT_{north} and northerly winds associated with the cold air advection (Fig. 5a and 3d) favoured the development of an MCAO period. Convective cloud streets emerged over the Fram Strait as cold Arctic air masses were transported over~~
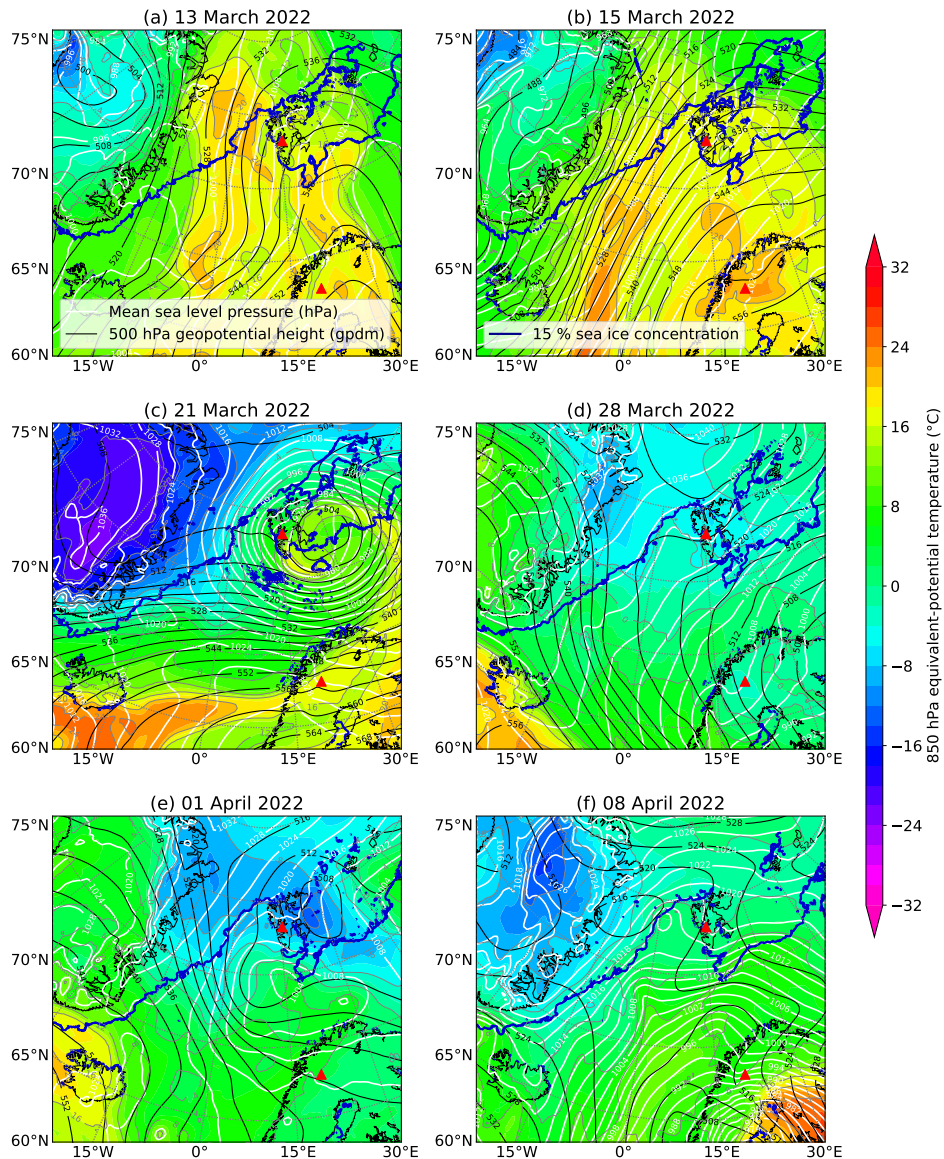
Figure 4. Maps of mean sea level pressure (white contour lines), $500\,\mathrm{hPa}$ geopotential height (black contour lines), and $850\,\mathrm{hPa}$ equivalent–potential temperature (shading and grey contours) from ERA5 data for representative days of the main weather conditions at 12 UTC. 13 March (a) and 15 March (b) represent the moist and warm air intrusions with AR characteristics, (c) shows the Shapiro–Keyser cyclone on 21 March that marked the beginning of the cold air outbreak period, 28 March (d) and 01 April (e) represent the persistent northeasterlies with varying cold air advection strength, and (f) features the Polar Low west of Svalbard on 08 April. The $15\,\%$ sea ice concentration from AMSR2 (Spreen et al., 2008) is displayed as blue contour line.
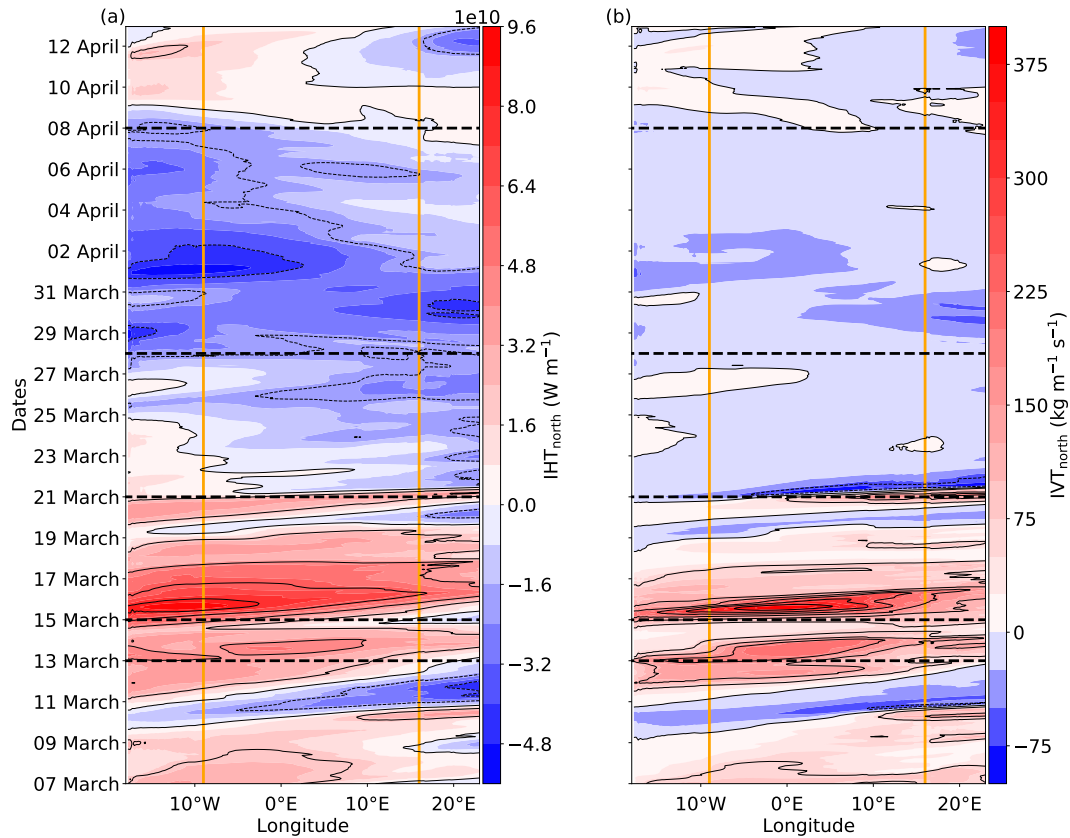
Figure 5. Hovmöller diagram of hourly vertically integrated meridional fluxes of (a) heat (IHT$_{north}$), and (b) moisture (IVT$_{north}$) during HALO–(AC)^3, averaged over the central region latitudes. Positive (negative) values indicate northward (southward) fluxes. Orange vertical lines indicate the longitude boundaries of the central region. Important synoptic events shown in Fig. 4 are marked by horizontal dashed lines. Data is based on ERA5.

405 ~~the relatively warm ocean.~~ In all three measurement regions, the area–averaged 2 m temperature ~~including standard deviation~~ remained below 0 °C ~~in the third campaign week~~ until 07 April (Fig. 3c).

As the Shapiro–Keyser cyclone stayed over the Barents Sea while dissipating, IWV dropped to the lowest area–averaged values in the northern region (1.4–2.4 kg m^{-2}, Fig. 3e). ~~The moderate to strong MCAO conditions (5 K < M < 10 K) lasted for~~ Two strong MCAO events were observed during the cold period. The first one lasted for almost the entire third campaign week

410 ~~, partly exceeding~~ with a maximum M of 10 K, which exceeded the 90th percentile of the climatology (~~see~~ Fig. 2b). ~~Towards the end of the week, the MCAOs~~ The second MCAO event occurred on 01–02 April and exceeded the 75th percentile with M up to 9 K. This event showed the minimum latitude–averaged IHT$_{north}$ of the campaign ($-5.32 \cdot 10^{10}$ W m^{-1}, Fig. 5) and did not reach the 0.02th percentile of the climatology.

Between the two strong MCAO events and after the second one, the MCAO conditions weakened (decreasing ~~MCAO index~~ M) in the western Fram Strait due to ~~increasing pressure~~ decreasing pressure gradients and calming winds, which turned more towards easterlies ~~.~~

~~The fourth week of the campaign (28 March – 03 April) was predominantly marked by a northeasterly and easterly flow (~~ (Fig. 3d). ~~While a high pressure system was still located over Greenland, a new anticyclone formed over the central Arctic and a low pressure complex developed over northwestern Russia (see Fig. 4d) . The latter two systems advected~~ Especially in the central region, the near–surface temperature increase (Fig. 3c) indicated the advection of relatively warm air ~~masses from different subpolar regions (partly through~~ from several subpolar regions across the central Arctic ~~) to the measurement areas. On their way north, the air masses were cooled over the sea ice covered Arctic Ocean. We classified this event as an~~ . We classified these events as aged warm air ~~period~~ periods (Fig. 3a) during which we observed mainly three recurring patterns. First, the easterly winds ~~over Svalbard~~ resulted in cloud–free areas ~~west of the island due to lee effects~~ in the lee of Svalbard. Second, converging winds over the central Fram Strait led to increased convective cloud formation. Third, some cloud streets developed ~~in a narrow band over the Fram Strait in the westernmost ice–free area~~ over the western Fram Strait due to a less disturbed off–ice flow. Both position and intensity of these patterns varied from day to day. ~~Southward advection of~~ On 05–06 April, the relatively warm air ~~led to stronger southward heat and moisture fluxes (more negative IHT_{north} and IVT_{north}) between 27 March and 03 April compared to the week before (Fig. 5a). Averaged over the central region, IVT_{north} was partly below the 25th percentile (Fig. 2a).~~

~~Another strong MCAO event (M up to 9 K, exceeding the 75th percentile) occurred on 01–02 April, associated with a weak cyclone that formed at the southern edge of Svalbard ahead of a trough in the 500 hPa geopotential (Fig. 4e). Temporarily, it advected slightly colder air masses with more intense northerly winds compared to the days before (Fig. 3d). The intensified northerly winds resulted in the strongest southward latitude–averaged heat flux of the campaign (Fig. 5a). With a value of $-5.32 \cdot 10^{10}$ W m^{-1}, it is the 99.8^{th} percentile of the southward latitude–averaged heat flux climatology.~~

~~In the first half of the fifth campaign week (04–10 April), the weather conditions in the measurement areas were similar to the previous week. The large system of low 500 geopotential, which was responsible for the strong MCAO on 01–02 April, moved to northern Scandinavia and intensified. As a result, the main wind direction turned slightly more towards easterlies in the southern and central region. Consequently, the off–ice flow over the Fram Strait, and the southward heat and moisture fluxes weakened (IHT_{north} and IVT_{north} closer to 0, Fig. 5), reducing the MCAO activity. Gradually, 2 m temperatures and IWV increased over all three measurement regions (Fig. 3c, e)~~ was still present in the measurement regions, but the advection was weaker due to reduced horizontal pressure gradients. Therefore, we did not attribute these days to one of the weather classes defined in Fig. 3.

~~An upper–level trough reached the Fram Strait from the east on~~ On 07 April, ~~which led to~~ another weak MCAO (Fig. ~~3a and~~ 2b) ~~. Moreover,~~ and the positive vorticity of ~~the trough together with the MCAO~~ an upper–level trough reaching Fram Strait promoted the formation of a mesoscale cyclone with features of a Polar Low (Fig. 4f, details in Sect. 4.3). ~~The Polar Low caused slightly positive latitude–averaged IHT_{north} as warm air was advected northward from the North Atlantic in the eastern Fram Strait, ending a period of consistently negative meridional heat fluxes (Fig. 5a).~~ In the following two days, the Polar Low

moved to the northwest and dissipated over the sea ice northeast of Greenland.

In parallel, a low pressure complex over Scandinavia advected warm and moist air from Siberia towards the Norwegian Sea. This air mass caused an increase of IWV above $10\,\mathrm{kg\,m^{-2}}$ over parts of the southern region (Fig. 3e) and was advected northwards with a southerly upper–level flow in the following days (10–12 April). The elevated moist air led to the formation of cirrus clouds over the western Fram Strait (see Sect. 4.4).

Overall, the period of pronounced MCAO activity lasting from 21 March to 12 April much better reflects the typical state of the central region than the preceeding warm period. Climatologically, the entire campaign period is characterized by weak MCAO conditions (M between 1 and 3 K). With a duration of 5–6 days, the first HALO–(AC)[3] MCAO period (21–26 March) was slightly longer than the mean duration of MCAO events (3–4 days, Terpstra et al., 2021). During the cold period, the 500 hPa geopotential height anomalies were negative over Scandinavia and northwestern Russia (coinciding with low surface pressure), and positive over the central Arctic and Greenland (coinciding with high surface pressure, Fig. 6i). The persistence of the northerly winds due to this anomalous pressure constellation explains the longevity of the MCAO conditions. Negative temperature anomalies at 2 m and at 850 hPa were most prominent in the central Fram Strait, Norwegian Sea and parts of the Greenland Sea, which were affected by the cold air advection (Fig. 6c, f). Reduced IWV compared to the climatology overlaps well with the negative 850 hPa temperature anomalies (Fig. 6l). Positive temperature anomalies at 850 hPa were restricted to regions that were not affected by cold air advection (central Arctic, eastern Barents Sea). Interestingly, the central Arctic Ocean showed negative temperature anomalies at 2 m and positive anomalies at 850 hPa, suggesting enhanced static stability compared to the climatological mean (Fig. 6c, f). This area also shows slightly positive subsidence anomalies at 850 hPa (not shown). In contrast, the static stability is reduced in the area between Svalbard and Franz Josef Land positive anomalies at the surface negative anomalies at 850 hPa.

3.1.3 Climatological assessment of the full HALO–(AC)^3 period

The 2 m temperature anomalies for the entire HALO–(AC)^3 period (07 March–12 April) were positive in most regions shown in Fig. 6d. Only in the central Fram Strait and north of Greenland negative 2 m temperature anomalies down to -1.2 K and -2.4 K, respectively, were found, coinciding with the regions of strongest negative 2 m temperature anomalies during the cold period. Slightly positive 2 m temperature anomalies over the sea ice in the western Fram Strait indicate that the extremely positive anomalies of > 8 K during the warm period were not completely balanced by negative anomalies during the longer cold period (Fig. 6d–f). Temperature anomalies at 850 hPa were positive in all regions shown in Fig. 6. The strongest anomalies with 2–3.5 K were found over the central Arctic Ocean and northern Barents Sea, coinciding with the regions of positive 850 hPa temperature anomalies during the cold period (Fig. 6a, c). Positive temperature anomalies combined with high surface pressure over Scandinavia (central Arctic) in the warm (cold) period resulted in overall positive 500 hPa geopotential height anomalies over these regions (Fig. 6g). The lowest 500 hPa geopotential height anomalies were located over the east coast of Greenland, where low geopotential also remained during the first part of the cold period.

Over the central region, we found small northward heat fluxes ($\mathrm{IHT_{north}}$ of $5.4 \cdot 10^8 \, \mathrm{W \, m^{-1}}$) and moisture fluxes ($\mathrm{IVT_{north}}$ of $18 \, \mathrm{kg \, m^{-1} \, s^{-1}}$). Consequently, the thermal energy input into the Arctic through this pathway was slightly positive and the brief but intense MWAIs / ARs overcompensated the long MCAO period. In previous years, $\mathrm{IHT_{north}}$ and $\mathrm{IVT_{north}}$ were often smaller or even negative over the campaign days and the central region.

3.2 Ny–Ålesund

The extensive remote sensing observations at Ny-Ålesund may complement the airborne observations during HALO–(AC)^3. However, Ny-Ålesund is located at the eastern edge of the central region and measurements may be influenced by the local orography. Based on the temperature profiles (Fig. 7a), the atmospheric conditions at Ny–Ålesund can also be divided into a warm (11–21 March) and a colder period (22 March–12 April). Compared to the full central region, this indicates a temporal shift of one day.

The warm air advection related to the first AR led to an increase of 2 m temperature from about $-14\,^\circ\mathrm{C}$ to $+2\,^\circ\mathrm{C}$ within 19 hours (meteorological tower measurements, not shown). Vertical advection of heat and moisture lifted the tropopause to 12.9 km (measured by the 12 UTC radiosonde on 12 March, Fig. 7a).
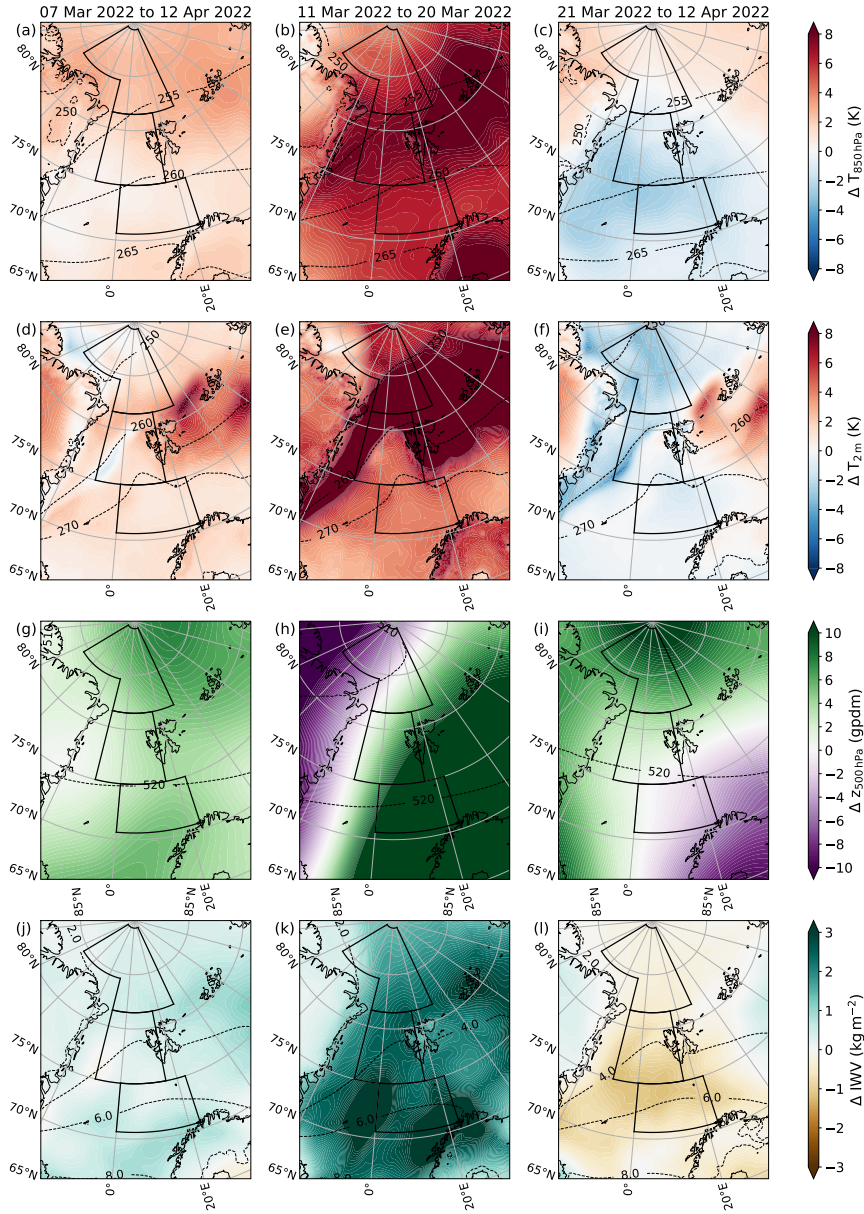
Figure 6. Anomaly maps of (a–c) temperature at 850 hPa ($\Delta T_{850\,\text{hPa}}$), (d–f) 2 m temperature ($\Delta T_{2\,\text{m}}$), (g–i) geopotential height at 500 hPa ($\Delta z_{500\,\text{hPa}}$), and (j–l) vertically integrated water vapour (ΔIWV) based on ERA5 for the entire campaign, the warm, and the cold period in the left, middle, and right column. The coloured contours show the long--term mean subtracted from the mean of the time period in 2022 so that positive (negative) values correspond to anomalies above (below) the long-term mean. The dashed black isolines describe the long—term climatology in each panel. The three measurement regions (shown in Fig. 1) are illustrated as black boxes.

~~were observed on these days (IWV of $14.5\,\mathrm{kg\,m^{-2}}$ on 15 March at 18 UTC, Fig. 7b).~~ The $2\,\mathrm{m}$ temperature remained above freezing for five days and even reached a new ~~record high temperature for all days of~~ maximum for March on 15 March ($5.5\,^{\circ}\mathrm{C}$). On this day, also the highest IWV was observed ($14.5\,\mathrm{kg\,m^{-2}}$, Fig. 7b).

The warm period was characterized by constant low–level cloud cover over Ny–Ålesund detected by the ceilometer, interrupted only by a few hours of high–level cloud occurrence in connection with a high pressure ridge passing the site in the night of 14–15 March (not shown). The situation changed during the course of 17 March, when the cloud deck started to dissolve and the $2\,\mathrm{m}$ temperature dropped below $0\,^{\circ}\mathrm{C}$.

The influence of the Shapiro–Keyser cyclone (see Sect. 3.1) delayed the beginning of the cold period over Svalbard compared to the central region by about one day. Northerly winds corresponding to the MCAO period led to extremely dry conditions with IWV down to $1.1\,\mathrm{kg\,m^{-2}}$ (closest grid point in ERA5 with land–fraction < 0.25: $1.5\,\mathrm{kg\,m^{-2}}$) on 24 March at 06 UTC (Fig. 7b)~~, which~~. This IWV is below the 3rd percentile of all radiosondes between 07 March and 12 April 1993–2022 (Maturilli and Kayser, 2016, 2017; Maturilli, 2020b). At Ny–Ålesund, the MCAO conditions ~~between 23 and 29 March~~ on 23–30 March, and on 01–05 April were mostly associated with clear sky and $2\,\mathrm{m}$ temperatures below ~~$-15\,^{\circ}\mathrm{C}$~~ $-12\,^{\circ}\mathrm{C}$. Aged warm air reached Ny–Ålesund on ~~28~~ 28–29 March with more humidity, ~~increasing IWV up~~ with slightly higher temperatures and IWV increasing to $4\,\mathrm{kg\,m^{-2}}$. ~~After the subsequent stronger MCAO on 01–02 April, clear sky conditions due to orographic lee effects (foehn) associated with the calm easterly winds persisted until 05 April.~~

~~Generally, the Ny–Ålesund observations provide a ground based view on the atmospheric events that occurred in the Svalbard region during HALO–(AC)³. Because of orographic effects especially in~~ Especially during the cold period, ~~the perspective of~~ cloud conditions at Ny–Ålesund ~~is~~ are not representative for the ~~entire central region , and much less for the southern and northern regions~~ central region because of lee effects as visible on MODIS images (e.g., NASA Worldview, not shown). Additionally, the temporal delay related to the propagation of synoptic systems ~~from other areas to Ny–Ålesund~~ during the warm period must be kept in mind when ~~considering other observations from~~ combining Ny–Ålesund ~~in relation to~~ with HALO–(AC)³ ~~in future studies~~ observations.

3.3 Sea ice conditions

The different synoptic patterns ~~changed~~ affected the sea ice conditions in the measurement areas. In Fig. 8a–c, we present the spatial distribution of SIC ~~for three selected time periods. We selected~~ before (09–11 March~~,~~) and during (14–16 ~~March, and 10–12 April 2022 to show SIC before and during the MWAIs~~ March) the MWAIs, as well as after the MCAO period (10–12 April). SIC was $> 90\,\%$ in almost the entire northern region in the first period (Fig. 8a). In the central region, ~~this was true for about~~ the sea ice covered 30–40 % of the area with a southwest–northeast oriented ~~sea ice edge, approximately from the lower left to the upper right corner of the box~~ edge. The southern region was almost completely ice–free over the entire campaign duration (Fig. 8a–c). A time series of SIC for the central region compared to the climatology is shown in Fig. 8d.

The MWAI / AR events on 12–13 and 15 March ~~showed a clear impact on the sea ice due to a~~ caused a reduction of SIC in the northwestern part of the central region, resulting in the lowest values of the entire campaign period (Fig. 8b~~). Averaged over the central region, SIC reached its minimum for the campaign duration, which is~~, d). SIC was below the climatological
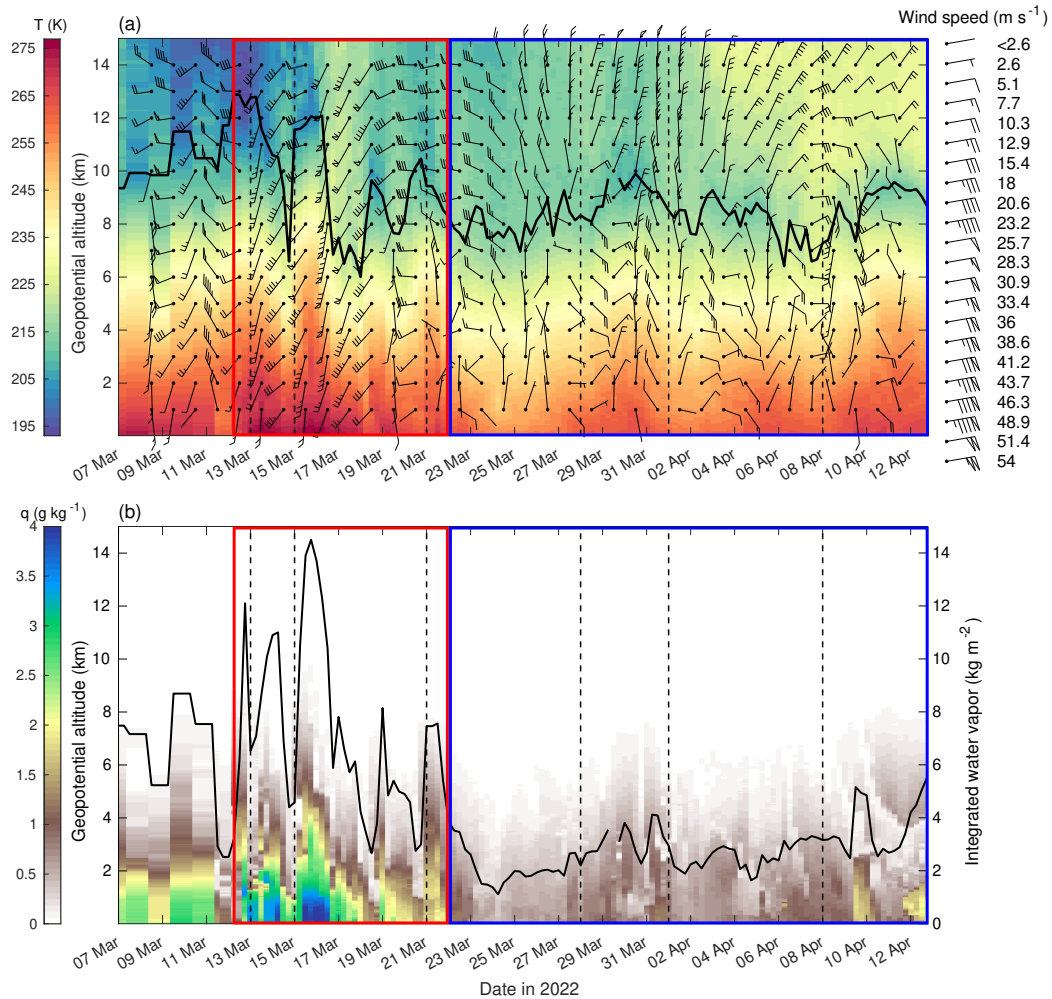
Figure 7. Time series of Ny–Ålesund radiosondes of (a) temperature profiles (shading), height of thermal tropopause (black line), and wind barbs in selected levels, and (b) specific humidity profiles (shading) and resulting IWV (black line, right axis). Vertical dashed black lines indicate the days shown in Fig. 4. The red (blue) box indicates the shifted warm (cold) period.

mean but within the 10–90th ~~quantiles~~ percentiles. Furthermore, an unusually large polynya opened from north of Svalbard to Franz Josef Land, which resulted in the below–average static stability during the cold period in this region (Fig. 8~~d~~b). We assume that ice dynamics related to strong winds caused the SIC decrease, but ice melt cannot be excluded as well because temperatures were above freezing and liquid precipitation was observed over sea ice. Rapid ice melt has been attributed to warm air advections and induced increases of heat flux in summer (Tjernström et al., 2015; Woods and Caballero, 2016). ~~After the two AR events, an unusually large polynya opened from north of Svalbard to Franz Josef Land (Fig. 8b).~~ Although the liquid precipitation on snow alters the signal of the microwave radiometry and might have increased the uncertainty of the

550

SIC product (Stroeve et al., 2022; Rückert et al., 2023), that SIC reduction was obvious in visual satellite images as well (e.g., NASA Worldview, not shown).

After the AR events, the sea ice conditions recovered and the polynya closed again (Fig. 8c, d) mostly due to sea ice transport from the central Arctic. This southward transport can be attributed to the winds during the high MCAO activity between 21 March and 07 April.

For most of the campaign period, the average SIC in the central region was above the climatological mean (Fig. 8d).

A map of SIC anomalies compared to the climatological mean is illustrated in Fig. 8e. Southwest of 75° N and 0° E as well as northeast and southeast of Svalbard, SIC anomalies were negative. In contrast, a positive SIC anomaly was found in the central and western Fram Strait, which overlaps well with the negative 2 m temperature anomalies shown in Fig. 6d, f. The west coast of Svalbard ice in the climatology but was completely ice–free during HALO–(AC)[3]. In the northern and southern regions, the mean SIC for the entire campaign period did not differ more than 5 % from the climatological mean.

Note that uncertainties in the marginal ice zone are especially large due to weather related filters and as a result of temporal and spatial interpolations. This mainly affects the central region where the estimated uncertainties of the SIC product (total standard uncertainty) can reach up to 40 % at the ice edge, mostly due to smearing uncertainty (gridding of the swaths, i.e., areas imaged on the surface, from several daily overflights), and different satellite footprints at different frequency channels.
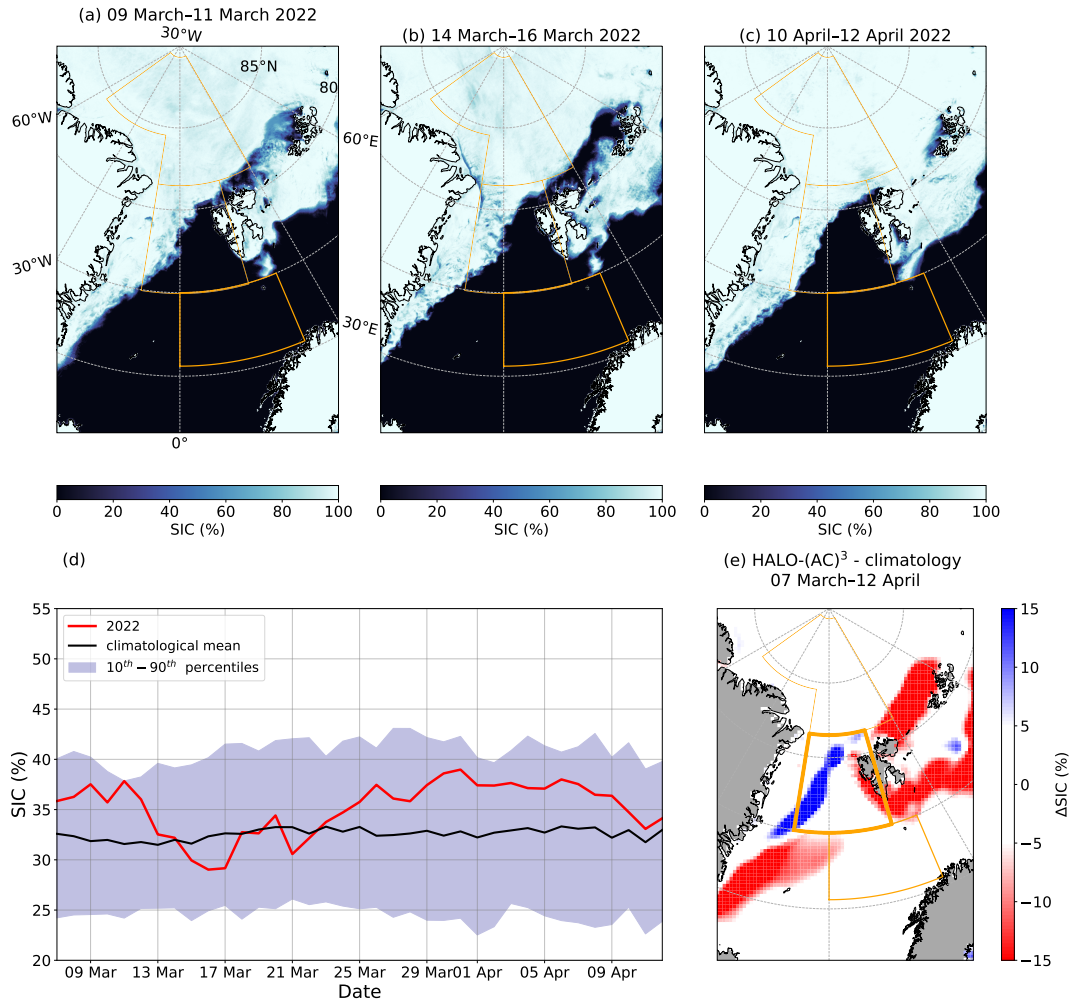
Figure 8. Average sea ice concentration (SIC) ~~for two three–day time periods during~~ from the ~~HALO–~~MODIS-AMSR2 product at 1 km grid resolution for (~~AC)³ campaign: (~~a) 09–11 March (prior to the first AR event), (b) 14–16 March (during the second AR event), (c) 10–12 April (at the end of the campaign). Data is from the MODIS-AMSR2 product at 1 km grid resolution. (d): SIC time series averaged over the central region for ~~HALO–(AC)³~~ the campaign period, as well as the mean, and 10–90th percentiles of the 1979–2022 climatology. (e): ~~Time–averaged~~ SIC anomalies from the climatological mean averaged over the entire campaign period. Note that ~~here~~ only differences larger 5 % are considered due to the uncertainties of the satellite product in the marginal ice zone. Data for (d) and (e) is from the OSI–SAF sea ice concentration climate data record~~Copyright © 2018 EUMETSAT~~.

4 Specific events during HALO–(AC)³

4.1 Warm air intrusions and Atmospheric Rivers

580 The ~~first two campaign weeks were~~ warm period was characterized by four independent AR events (12–13 March, 14 March, 15 March, and 20 March) that were at least partly sampled by research aircraft in the three measurement regions. Back trajectory analyses with LAGRANTO (Sect. 2.4.5) revealed that the air masses of the 12–13 March event (Fig. B1a) originated from mid–latitude regions of the North Atlantic and from central Europe (Fig. C1a). For the second AR event on 15 March (Fig. B1b), the air masses originated almost exclusively from the western part of the mid–latitude North Atlantic (Fig. C1b). ~~Maximum IVT~~
585 ~~(meridional and zonal) exceeded $400\,\mathrm{kg\,m^{-1}\,s^{-1}}$ between 13~~ We neglect the ARs on 14 and ~~16 March in the central region (see Appendix B, Fig. B1).~~

~~Apart from these major MWAIs in conjunction with ARs , two more remarkable events of moisture transport were identified. The first one was associated with the Shapiro–Keyser cyclone (Sect. 3.1) and approached our region of interest on~~ 20 March ~~with a maximum IVT exceeding $500\,\mathrm{kg\,m^{-1}\,s^{-1}}$. The Shapiro–Keyser cyclone, however, steered the AR away from the sea~~
590 ~~ice edge to the southeast of Svalbard and dissipated sufficiently before entering the southern or central region. The second moisture transport event , associated with the low pressure complex over Scandinavia from 08 to~~ as they did not enter the central region, but either propagated northwards to the west of it or dissipated before reaching it. The moist air advection event on 10 April ~~, was confined to the southern region and much more zonally oriented but~~ (Fig. C1c) was too weak to be ~~detected as AR~~ identified as AR, but was relevant for the formation of cirrus clouds over sea ice.

595 We compare the strength of AR events during HALO–(AC)³ by analysing them with respect to the relation between IVT and latitude over the North Atlantic and Arctic Ocean (50–90° N, 60° W–40° E) (Fig. 9). Note that a different region was selected to extend the view on the North Atlantic, one of the major pathways of ARs (Guan and Waliser, 2017; Nash et al., 2018). Along their northward propagation, ARs generally decline in intensity. If otherwise ARs start to form in the Arctic, their moisture supply is reduced so that their intensification is limited (Papritz et al., 2021). Therefore the number of strong AR
600 events decreases meridionally ~~.~~ (Fig. 9).

North of 70.6° N (southern boundary of the southern region), only few ARs exceed an IVT of $250\,\mathrm{kg\,m^{-1}\,s^{-1}}$ when averaged over the detected AR area (Fig. 9). In the climatology, the majority has mean values around $150\,\mathrm{kg\,m^{-1}\,s^{-1}}$. The AR events on 12–13, and 15 March represent strong cases in terms of mean IVT for all time steps as they lie outside the 25th percentile in latitude–IVT space (Fig. 9). On 15 March at 18 UTC, the AR averaged IVT even exceeded the 10th percentile while being
605 centered at 76° N. While the AR centre from the event on 12–13 March was located most northerly before it dissipated, the AR from 15 March was characterized by the most intense moisture transport with mean IVT of around $250\,\mathrm{kg\,m^{-1}\,s^{-1}}$ when centered at 70° N, decreasing to $200\,\mathrm{kg\,m^{-1}\,s^{-1}}$ at 75° N. Maximum IVT (meridional and zonal) slightly exceeded $400\,\mathrm{kg\,m^{-1}\,s^{-1}}$ between 13 and 16 March in the central region (see Appendix B, Fig. B1). HALO's dropsonde measurements showed a maximum IVT of $490\,\mathrm{kg\,m^{-1}\,s^{-1}}$ on 15 March, suggesting that ERA5 underestimates the moisture flux. As these
610 AR events had meridionally elongated structures, the outflow region reached up to the central Arctic while their centres were

located at 70–78° N (Fig. 9). During their poleward propagation, the moisture transport decreased so that they no longer fulfilled the detection requirements.

The AR events in the warm period were associated with anomalous amounts of precipitation. In Fig. 10, we show the hourly averaged precipitation rate from 11 to 20 March 2022 as well as for the ~~same days of the climatology . Further, the fraction of the precipitation rate in 2022 to that in the climatology is illustrated~~climatology of these days. Along the east coast of Greenland, the total precipitation and snowfall rate partly exceeded $1\,\mathrm{mm\,h^{-1}}$ (Fig. 10a, d), around six times higher compared to climatology (Fig. 10c, f). Over the North Atlantic, Fram Strait, and central Arctic Ocean, total precipitation and snowfall rates exceeded the climatology by a factor of 3. ~~In parts of the Norwegian and Barents Seas, total precipitation and snowfall rates were below the climatological mean.~~ Record breaking rainfall rates were found northwest of Svalbard, exceeding the climatology up to a factor of 36 (Fig. 10i). However, the actual rainfall rate in this area was below $0.25\,\mathrm{mm\,h^{-1}}$ and the high deviation is caused by even lower rainfall rates in the climatology. Liquid precipitation over sea ice was also observed by the cloud radar onboard HALO during research flights.

In summary, the ARs observed during HALO–(AC)[3] featured uncommonly high AR–averaged IVT values, higher than $90\,\%$ of all ARs in the climatology. Additionally, record breaking rainfall rates occurred over the sea ice northwest of Svalbard.

4.2 Marine cold air outbreaks

The cold period included several MCAO events (21 March–07 April), which are analysed in detail specifically for the central region. Figure 11 shows the time series of atmospheric conditions as described in Sect. 2.4.3. To highlight the conditions in the MCAOs' source region, we also include the temporal evolution of the parameters averaged over the ~~northern region (without extension to the west)~~ eastern part of the northern region in Appendix D (Fig. D1). The corresponding temporal development over the southern region is shown in Fig. D2 in Appendix D.

After the Shapiro–Keyser cyclone, which caused multi–layered clouds and intense snowfall on 21 March at the west coast of Svalbard (Fig. 11d–g), MCAO conditions were established. From 22 to 26 March, the contribution of convective to total snowfall increased over open water and mid– and high–level cloud cover decreased. Over sea ice, the total snowfall was low and almost exclusively stratiform. Liquid precipitation was not present except for 21 March. Low–level cloud cover remained high until 07 April, reflecting the presence of the atmospheric boundary layer clouds typically associated with MCAOs (Fig. 11d). ~~However, some parts of the open water regions of the central region were not fully covered by low–level clouds as the 5 % percentile was mostly between 0.2–0.4.~~

The strong MCAO events (21–26 March and 01–02 April) were characterized by the strongest northerly lower tropospheric winds and high values of domain–averaged turbulent fluxes of sensible and latent heat flux (Fig. 11a, h). The maximum values of sensible and latent heat coincided with the highest wind speeds and low temperatures (21–22 March, Fig. 11a, b, h). Note that over the southern region the sensible heat fluxes were slightly lower, whereas, on average, latent heat fluxes were higher than over the central region (Fig. D2). ~~One possible explanation is that the lower tropospheric air temperature~~ Near–surface air temperatures increased towards the south~~. Hence,~~, resulting in smaller sensible heat fluxes ~~would become smaller while the while~~ latent heat fluxes ~~would increase~~ were increased due to a rising saturation water vapour pressure at the air–sea interface
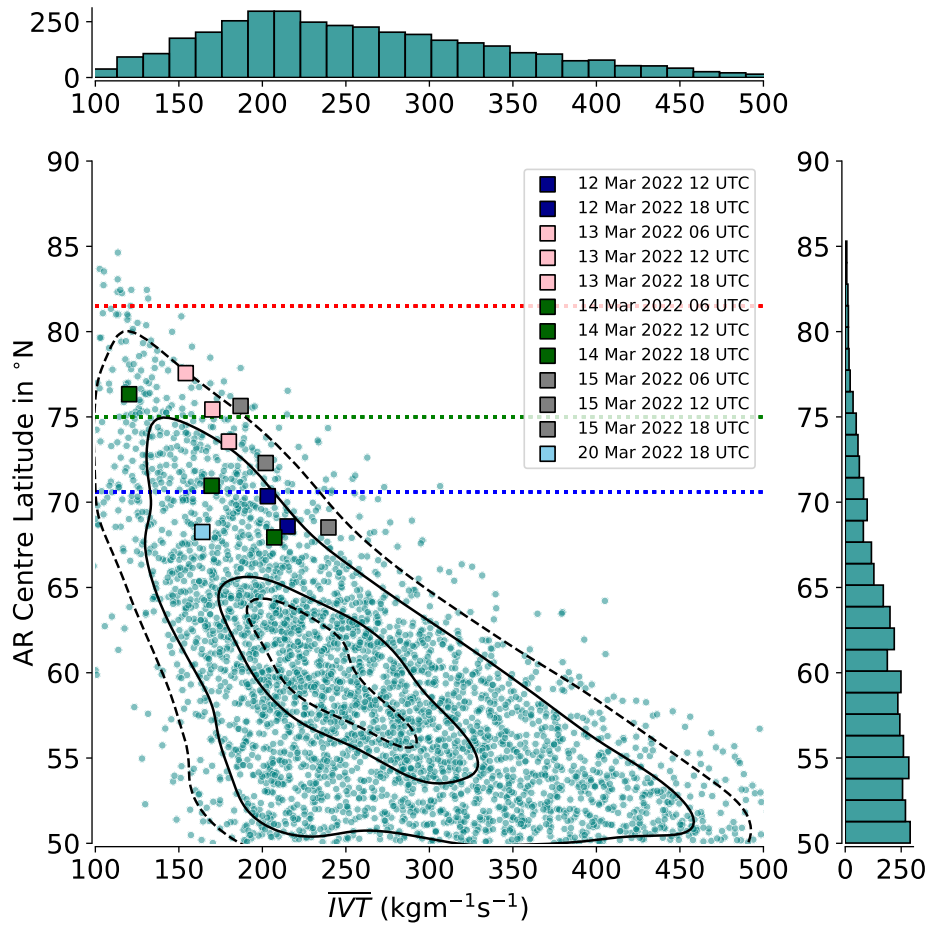
Figure 9. Six hourly climatological (1979–2022) distribution of central latitudes of Atmospheric Rivers (ARs) as a function of mean AR IVT using an ERA5 based AR catalogue modified from Guan and Waliser (2015). Cases categorized as ARs during HALO–(AC)[3] are illustrated by coloured boxes for 06, 12, and 18 UTC of respective flight days. Black (dashed) lines indicate the 25th and 75th (10th and 90th) percentiles of a kernel density estimation to visualize the shape of the histogram. Horizontal dotted ~~grey~~ lines indicate the latitude boundaries of the three measurement regions (~~Table A1~~Fig. 1) in the same colours as in Fig. 3.

645 (e.g., Hartmann et al., 1997). We found that larger differences between the specific humidity of the air and specific humidity at saturation in the southern compared to the central region were responsible for the increased latent heat fluxes (not shown).

During the weak MCAOs and aged warm air periods, northeasterly winds dominated (Fig. 11a). Compared to strong MCAO conditions, sensible heat fluxes were reduced by a factor of 2 while latent heat fluxes decreased to a lesser extent. Between 27–30 March and 03–05 April, when aged warm air was advected to the central region, precipitation decreased as the air

650 mass dried and temperatures increased (Fig. 11b, c, g). Also, foehn effects due to the easterly winds over Svalbard might have contributed to drier and warmer conditions over parts of the Fram Strait as this effect can influence the atmospheric conditions
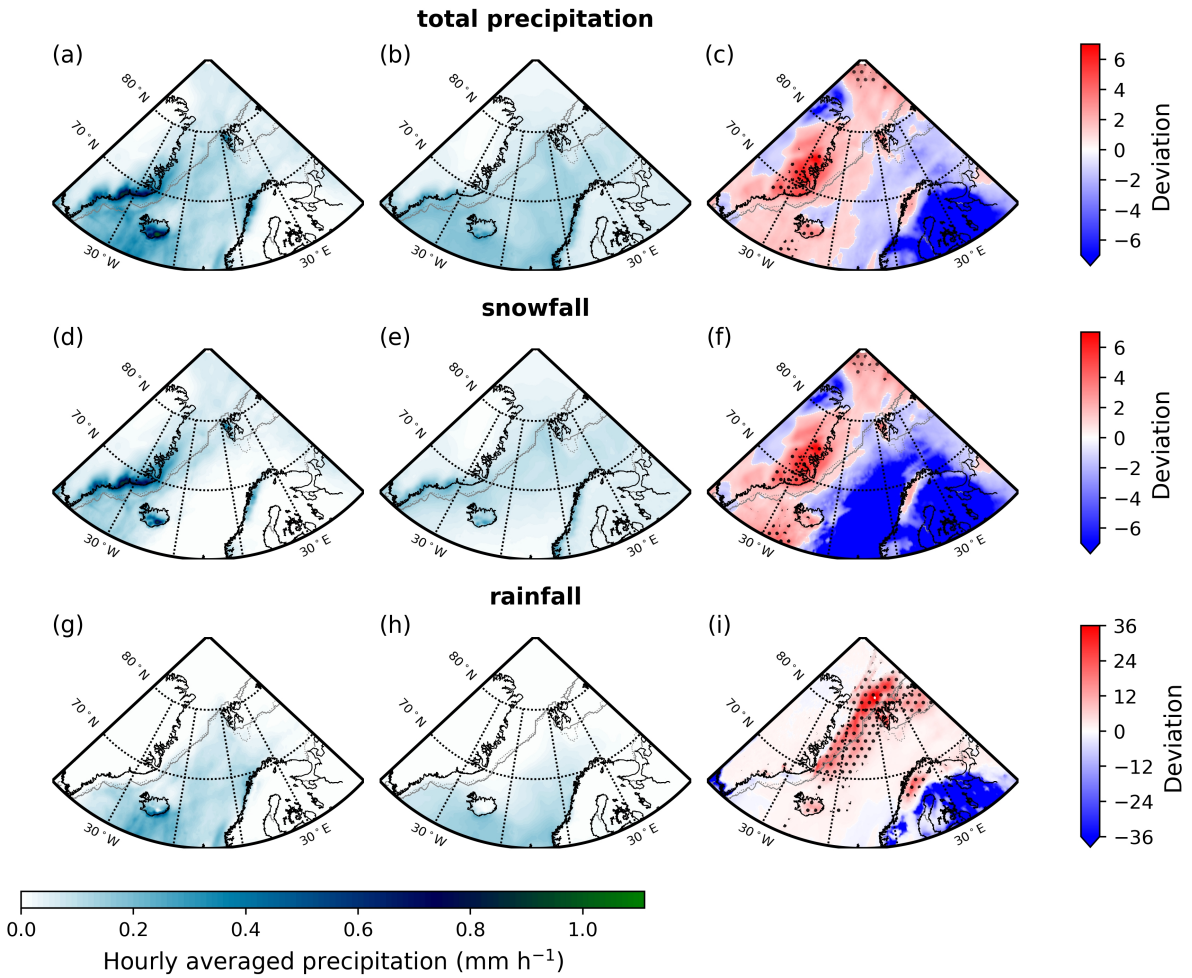
Figure 10. Hourly averaged precipitation, snowfall and rain rate ($\mathrm{mm\,h^{-1}}$) derived from ERA5 for (a, d, g) 11–20 March 2022, and (b, e, h) the climatology. In (c, f, i), we show the deviation from the climatology. Note that the rainfall over sea ice is barely visible in both (g) and (h). Positive deviations of precipitation rates are illustrated as the fraction of the average rate in 2022 to the rate of the climatology while negative deviations are given as its inverse.

more than $100\,\mathrm{km}$ off the coast (Shestakova et al., 2022). The eastern parts of the central region close to Svalbard were not fully covered by low–level clouds as the $5\,\%$ percentile was mostly between 0.2–0.4. For the first aged warm air period, the southward advection of the air masses from the sea ice covered ocean took about one day. This can be seen when comparing the temporal evolution of the lower tropospheric temperature and relative humidity over the northern and central regions (~~e.g.~~ i.e., low relative humidity from 29 to 30 March, Fig. D1a–c vs. 11a–c).

From 05 April on, the mean wind speed decreased and turned to northeast. Hence, more convergent regions developed in the lee of Svalbard with a rather diffuse low–level cloud structure (not shown). These converging winds in combination with a
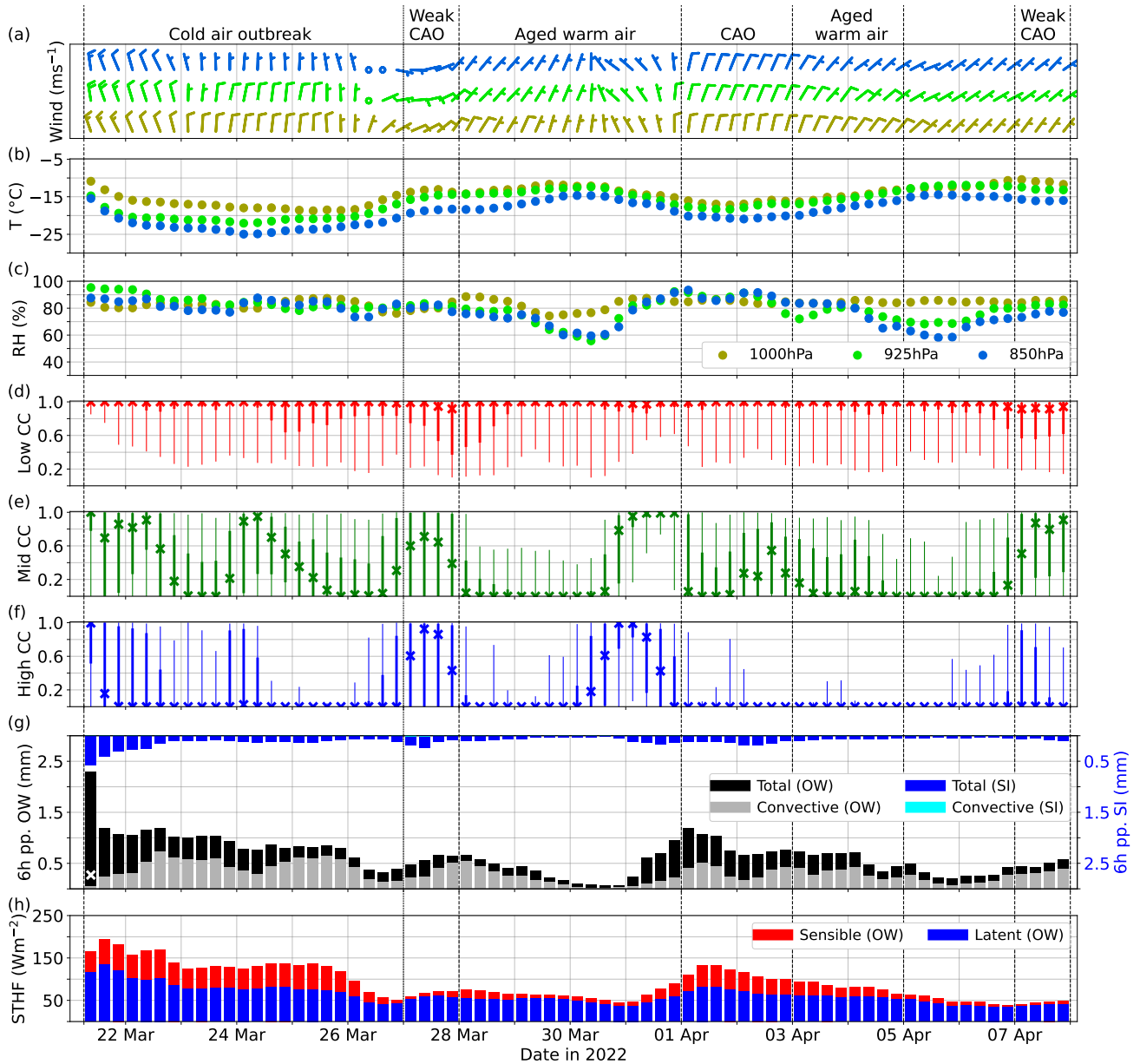
Figure 11. Temporal evolution of (a) wind, (b) air temperature (T), and (c) relative humidity (RH) on the 1000, 925, and 850 hPa pressure levels, and of (d) low–, (e) mid–, and (f) high–level cloud cover (CC), (g) precipitation, and (h) surface turbulent heat fluxes (STHF, upward is positive) over the central region for 21 March – 07 April 2022 derived from ERA5. For cloud cover, we show the median, the 25 and 75th percentiles, and the 5 and 95th percentiles of a 6 hour interval over open–water surfaces only as crosses, thick vertical lines, and thin vertical lines, respectively. In (g), we display area–averaged values of the accumulated 6 hour snowfall distinguished between convective and total precipitation, and open water (OW) and sea ice (SI). White crosses show the accumulated mean rainfall with more than $0.05\,\mathrm{mm}\,(6\,\mathrm{h})^{-1}$.

weak MCAO promoted the formation of a ~~mesoscale cyclone~~ Polar Low in the following days, which is explained in greater detail in the next section.

~~During HALO–(AC)³~~ Hence, different wind regimes ~~and strengths of MCAOs were observed . MCAO strength lied partly outside the 90ᵗʰ percentile, partly well within the interquartile range of the climatology. Wind regimes ranged from northwest to northeast with different intensity.~~ ranging from northwest to northeast and MCAO strengths were observed during HALO–(AC)[3]. The large variety of MCAO conditions provides great opportunities for detailed cloud evolution and air mass transformation studies.

4.3 Polar low

The Polar Low formed on 07 April close to the west coast of Svalbard at a baroclinic zone where cold air transported by ~~north to~~ northeasterly winds converged with warmer North Atlantic air from south to southeasterly winds ~~on 07 April, forming a baroclinic zone~~. During the development phase of the Polar Low, the mean sea level pressure showed closed isobars from 08 April ~~2022~~ 00 UTC on (Fig. 4f). We examine ~~which environmental conditions for the Polar Low formation set by Radovan et al. (2019) were fulfilled. The conditions~~ whether the environmental conditions C1–C6 ~~explained in~~ (see Sect. 2.4.4 ~~and Table 1 are checked~~) were fulfilled in a 200 km radius around the ~~mean sea level~~ pressure minimum of the Polar Low at that time (Fig. 12):

The vertical temperature gradient conditions C1 and C2 are fulfilled with $44\,\mathrm{K}$ and $8.5\,\mathrm{K}$, respectively, while the lapse rate condition (C3) was not fulfilled with $4.2\,\mathrm{K\,km^{-1}}$. Conditions $C4_i$ and $C4_{ii}$, which are a measure for the availability of moisture for latent heat release, exceed the thresholds of $75\,\%$ and $82\,\%$ with $92.7\,\%$ and $93.9\,\%$. Near surface wind gusts reached $16.6\,\mathrm{m\,s^{-1}}$ during the development phase of the Polar Low (00 UTC) ~~, which was sufficient to fulfill condition C5. They~~ and increased to $18.8\,\mathrm{m\,s^{-1}}$ 9 hours later ~~when the Polar Low was in its~~ at the mature stage. In both stages, condition C5 was fulfilled. If we considered the maximum of the 10 m wind speed instead of the gust from ERA5 ~~in the 200 km circle~~, the condition would not have been fulfilled. However, using the Copernicus Arctic Regional Reanalysis (CARRA) from ECMWF with a $2.5\,\mathrm{km} \times 2.5\,\mathrm{km}$ resolution, we ~~fond~~ found maximum wind speeds of more than $16\,\mathrm{m\,s^{-1}}$ ($19\,\mathrm{m\,s^{-1}}$) at 00 UTC (09 UTC). The trough connected to the Polar Low was not sufficiently strong with respect to the climatology as the geopotential height anomaly (C6) was only $-80\,\mathrm{gpm}$. Anomalously high geopotential around Svalbard and the central Arctic during that time might have obscured the strength of the trough, resulting in the failure of condition C6.

Some of the conditions had a large regional variability within the 200 km circle. Condition C2 ranged from below the threshold of $6\,\mathrm{K}$ in the southern part of the Polar Low to $10\,\mathrm{K}$ in the northern half. As the northwestern part of the circle ~~lied~~ lay over sea ice, the vertically averaged lower tropospheric lapse rate (C3) indicated stable stratification and reached values up to $10\,\mathrm{K\,km^{-1}}$. These high values of the lapse rate dominated the computation of the 75ᵗʰ percentile although the lapse rate was below the threshold in most parts of the circle.

At the mature stage (08 April 06–09 UTC), the region of maximum $\mathrm{SST} - T_{500\,\mathrm{hPa}}$ difference coincided well with the observed convective clouds during the research flight with HALO in the eastern part of the Polar Low (see Appendix E, Fig. E1). It also overlapped with the maximum precipitation rate ~~indicated by ERA5 with~~ ($1.2\,\mathrm{mm\,h^{-1}}$ ~~(not shown) . Wind gusts~~

Table 1. Criteria to evaluate environmental conditions of a Polar Low in a 200 km radius around its pressure minimum according to Radovan et al. (2019). An "X" in the right column indicates that the condition is fulfilled.

Condition	Meaning	How evaluated	Threshold	Fulfilled
C1	Sea surface temperature $-$ 500 hPa temperature	75th percentile	≥ 43 K	X
C2	Sea surface temperature $-$ 2 m temperature	75th percentile	≥ 6 K	X
C3	Mean lapse rate below 850 hPa	75th percentile	≤ 3 K km^{-1}	
C4$_i$	Mean relative humidity below 950 hPa	75th percentile	$\geq 75\%$	X
C4$_{ii}$	Mean relative humidity between 850 and 950 hPa	75th percentile	$\geq 82\%$	X
C5	10 m wind gust	maximum	≥ 15 m s^{-1}	X
C6	500 hPa geopotential height anomaly	mean	≤ -160 gpm	

~~peaked at 18.8 m s^{-1} and were therefore stronger than during the development phase. ERA5 data also show updrafts of~~ and strongest updrafts (-1.75 Pa s^{-1} at 850 hPa ~~in the northeastern half of the Polar Low (northwest to southeast) and slight~~
695 ~~descending motion in the centre~~) indicated by ERA5 (not shown). It is likely that higher precipitation rates and updrafts occurred that were smoothed out by the relatively coarse ERA5 data.

Dropsonde measurements between 06:55 and 07:53 UTC show high values of relative vorticity in the lowest 2 km and above 6 km, indicating cyclonic rotation. When averaging ERA5 vorticity over the grid points closest to the dropsonde positions, we find a disagreement to the dropsonde measurements below and good agreement above 4 km height. While the lower
700 tropospheric relative vorticity is related to the Polar Low, the upper tropospheric value is associated with the trough in the geopotential height. The disagreement between ERA5 and the dropsondes could be due to a misrepresentation of the Polar Low's wind field in the reanalysis or due to spatio–temporal mismatches of its position. Measured relative vorticity at 850 hPa (1.5 km height) was about $3.5 \cdot 10^{-5}$ s^{-1} and therefore did not exceed the threshold suggested by Stoll (2022) ($> 20 \cdot 10^{-5}$ s^{-1}). However, the flight track ~~did not perfectly align~~ was not perfectly aligned with the Polar Low's centre ~~and~~ but extended too far
705 to the south and east ~~of the Polar Low~~ where the mean sea level pressure isobars do not suggest a closed circulation (Fig. 13b). Negative relative vorticity to the east of the Polar Low, which is related to lee effects, also influenced the calculation from the dropsonde measurements. ERA5 data shows a maximum of $22 \cdot 10^{-5}$ s^{-1} at 850 hPa within the Polar Low on 08 April at 09 UTC.

As soon as the Polar Low drifted over sea ice, it started to dissipate due to the loss of atmospheric instability and strongly
710 reduced upward sensible and latent heat fluxes. The Polar Low observed during HALO–(AC)[3] fulfilled four of the six conditions (see Table 1). However, Polar Lows can also form without fulfilling all conditions. ~~According to~~ Considering the climatology of Polar Lows in Zahn and von Storch (2008), which covers the years 1949–2005, our Polar Low was located unusually far in the north. Also Radovan et al. (2019) investigated 33 Polar Lows with the Arctic System Reanalysis, of which 32 were centered further to the south than our case. Despite its northerly position, the 10 m wind speed of our Polar Low was
715 larger than the average over the 33 Polar Lows investigated in their study.
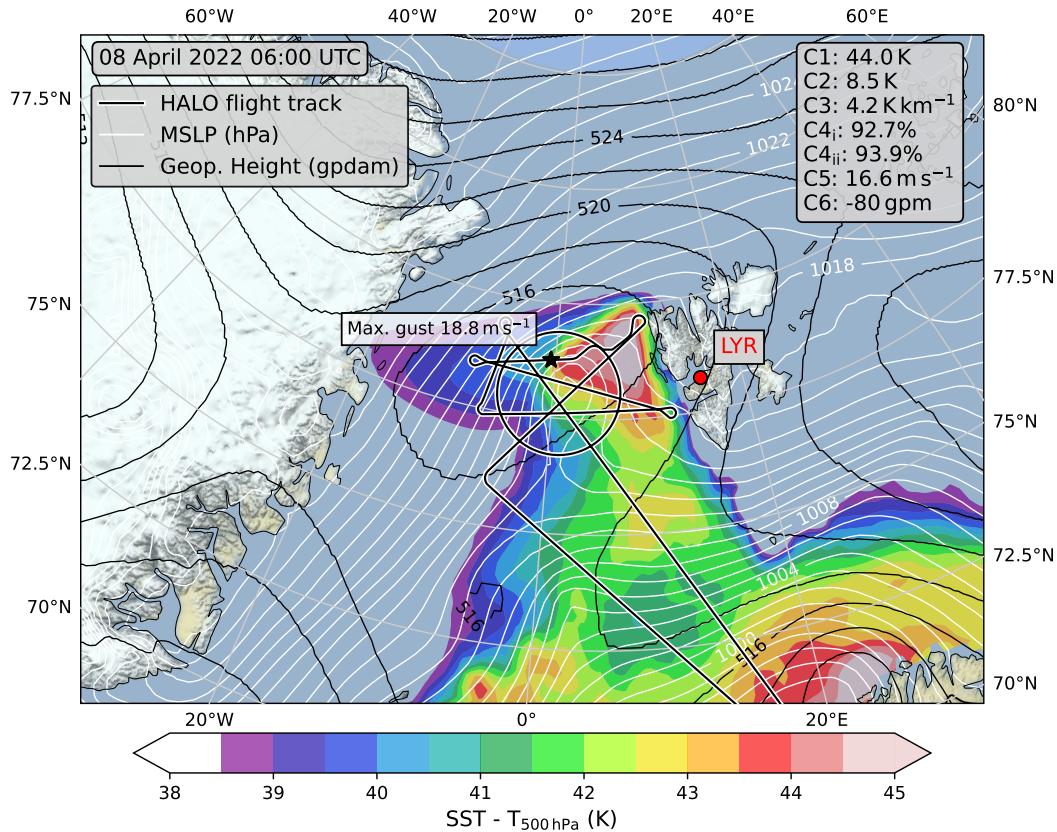
Figure 12. Mean sea level pressure (MSLP, white contour lines), 500 hPa geopotential height (black contour lines), and the difference between sea surface temperature (SST) and 500 hPa temperature during the mature stage of the Polar Low on 08 April 2022 06:00 UTC. Additionally, the maximum 10 m wind gust at 09:00 UTC (black star and text label) and the HALO flight track (black line with white outline) are included. The Polar Low conditions C1 ($SST - 500$ hPa temperature), C2 ($SST - T_{2m}$), C3 (vertical mean of the vertical potential temperature gradient below 850 hPa), C4 (i: mean relative humidity below 950 hPa, ii: mean relative humidity between 850 and 950 hPa), C5 (maximum 10 m wind speed), and C6 (500 hPa geopotential height anomaly) analysed by Radovan et al. (2019) are given for 08 April 2022 00:00 UTC. Data is based on ERA5.

4.4 Arctic cirrus over sea ice

The sequence of HALO flights between 10 – 12 April ~~2022~~ aimed to characterize a pronounced field of Arctic cirrus, which entered the central Arctic through the Fram Strait and was finally located close to the North Pole. The initial synoptic state of this period was dominated by a low pressure system, which was centered over Scandinavia on 09 April, advecting warm and moist air westwards (see Sect. 3.1). Along approximately the 5° W meridian the westward flow converged with a cold air mass that formed over the Greenland ice sheet and flowed eastwards into the Fram Strait. Due to the convergence, a strong

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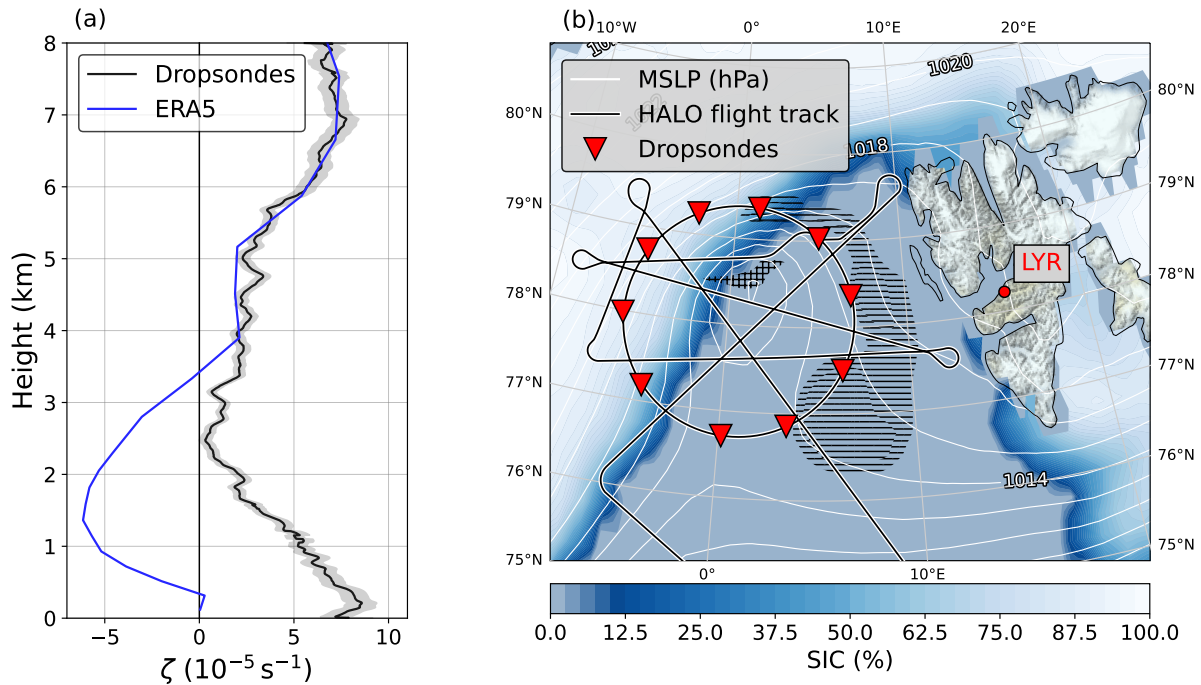
Figure 13. (a) Relative vorticity ζ computed from 10 dropsondes (black) and as model output from ERA5 averaged over the grid points nearest to the dropsondes (blue). (b) Location of the dropsondes (red triangles) launched from HALO while flying in a circle around the Polar Low. ERA5 based mean sea level pressure (white contour lines) and sea ice concentration (coloured filled contours) is shown for 08 April 2022 09 UTC. The HALO flight track is displayed as black line with white outline. Horizontal (horizontal and vertical) hatching indicates areas where ERA5 based 850 hPa relative vorticity is below $-10 \cdot 10^{-5}\,\mathrm{s}^{-1}$ (above $20 \cdot 10^{-5}\,\mathrm{s}^{-1}$).

vertical wind shear developed south of Greenland with low–level northeasterly winds and southeasterly winds at levels above 700 hPa along the east coast of Greenland. The southerly upper–level flow generated a poleward moisture transport, which was accompanied by cirrus and mid–level clouds west of Svalbard and north of Greenland. This upper–level flow continued during the sequence of three research flights conducted by HALO and roughly connected the air masses sampled during the three consecutive days.

The trajectories of the air masses sampled on 11–12 April are shown in Fig. 14a, c. While on 11 April two branches, one southerly and one easterly, merged into the area of observations, the trajectories of 12 April first followed the westward moist air transport south of Svalbard and then turned northwards into the central Arctic. Figure 14b and d ~~show~~ illustrate the relative humidity over ice from all dropsondes launched in the central Arctic during the HALO flights on 11–12 April. The mean profile shows an enhanced moisture layer between 4 km and 8 km. This layer is associated with higher wind speeds up to 25 m s^{-1} and a shift in wind direction from ~~a~~ an easterly flow in the lower 3 km to a southerly flow in the upper troposphere. Below 4 km altitude, the air mass was rather dry with relative humidity below 50 %. In these lower altitudes, the stable cold and dry

air mass in the central Arctic was supported by the outflow of cold and dry air from northern Greenland and prohibited the formation of clouds below the cirrus. The airborne measurements during this constellation of isolated, widespread cirrus over the sea ice in the central Arctic are well suited to investigate the evolution and radiative effect of Arctic cirrus over sea ice, ~~which is not well explored and~~ of which only few observations exist ~~(Hong and Liu, 2015; Marsing et al., 2023)~~.

5 Conclusions

In this study, we described the weather and sea ice conditions during the HALO–(AC)^3 aircraft campaign carried out from 07 March to 12 April 2022 in the North Atlantic sector of the Arctic. ~~Our analysis focused on the three different~~ The analysis is based on the ERA5 reanalysis, dropsondes, satellite based sea ice products, and atmospheric measurements at Ny–Ålesund. We focus on three measurement regions of the campaign: the sea ice covered Arctic Ocean north of Svalbard and Greenland (northern region), the Fram Strait (central region), and the Greenland and Norwegian Seas between Svalbard and Scandinavia (southern region). ~~Descriptions of the weather pattern were based on the ERA5 reanalysis and climatological context was~~ The climatological context is given with respect to the years 1979–2022. ~~Ny–Ålesund radiosondes and near–surface measurements allowed us to compare the conditions in the flight regions to those at the AWIPEV research base. We described the sea ice concentration (SIC) during HALO–(AC)^3 with a high resolution satellite product combining infrared and microwave observations. Climatological context of the SIC was presented with microwave satellite observations only.~~

~~The~~ Based on the vertically integrated meridional water vapour transport (IVT$_{north}$) and the MCAO index M, the campaign was separated into a warm period (11–20 March), and a cold period (21 March–12 April). ~~Vertically integrated meridional water vapour transport (IVT~~During the warm (cold) phase, IVT$_{north}$ ~~) and the MCAO index M averaged over the central region were used to classify the events of HALO–(AC)^3 with highly~~ was positive (negative) ~~IVT$_{north}$ and~~ while M was negative (positive)~~M during the warm (cold) phase. Within the respective periods, IVT$_{north}$ and MCAO index M exceeded the 90th percentile of the climatology on five and four consecutive days, ,~~ respectively.

The ~~campaign started with~~ warm period at the beginning of the campaign was characterized by a consistent southerly flow, which led to a strong MWAI on 12–13 March that was detected as an Atmospheric River (AR) and reached the central Arctic. It was followed by an even stronger AR on 15–16 March. Compared to the climatology, both ARs denoted higher IVT and were centered further in the north than 75 % (partly, 90 %) of all ARs in the North Atlantic pathway within the ERA5 climatology. During the AR on 15–16 March, we found new ~~records~~ maxima of vertically integrated meridional heat and water vapour fluxes (IHT$_{north}$ and IVT$_{north}$) ~~when averaged over~~ for the central region latitudes. The ~~heat and moisture transport of the warm period, dominated by the~~ radiosondes at Ny–Ålesund detected unusually high tropopause altitudes up to 12.9 km. Although the MWAIs were relatively short–lived~~MWAIs / ARs, even surpassed the long period of southward transport during the~~, they caused a campaign average northward transport of heat and moisture, overcompensating the southward transport of the much longer cold period. We therefore stress the importance of MWAIs for the energy exchange between the mid–latitudes and the Arctic. Averaged over the warm period, ~~record breaking~~ new maximum rainfall rates were found over the sea ice northwest
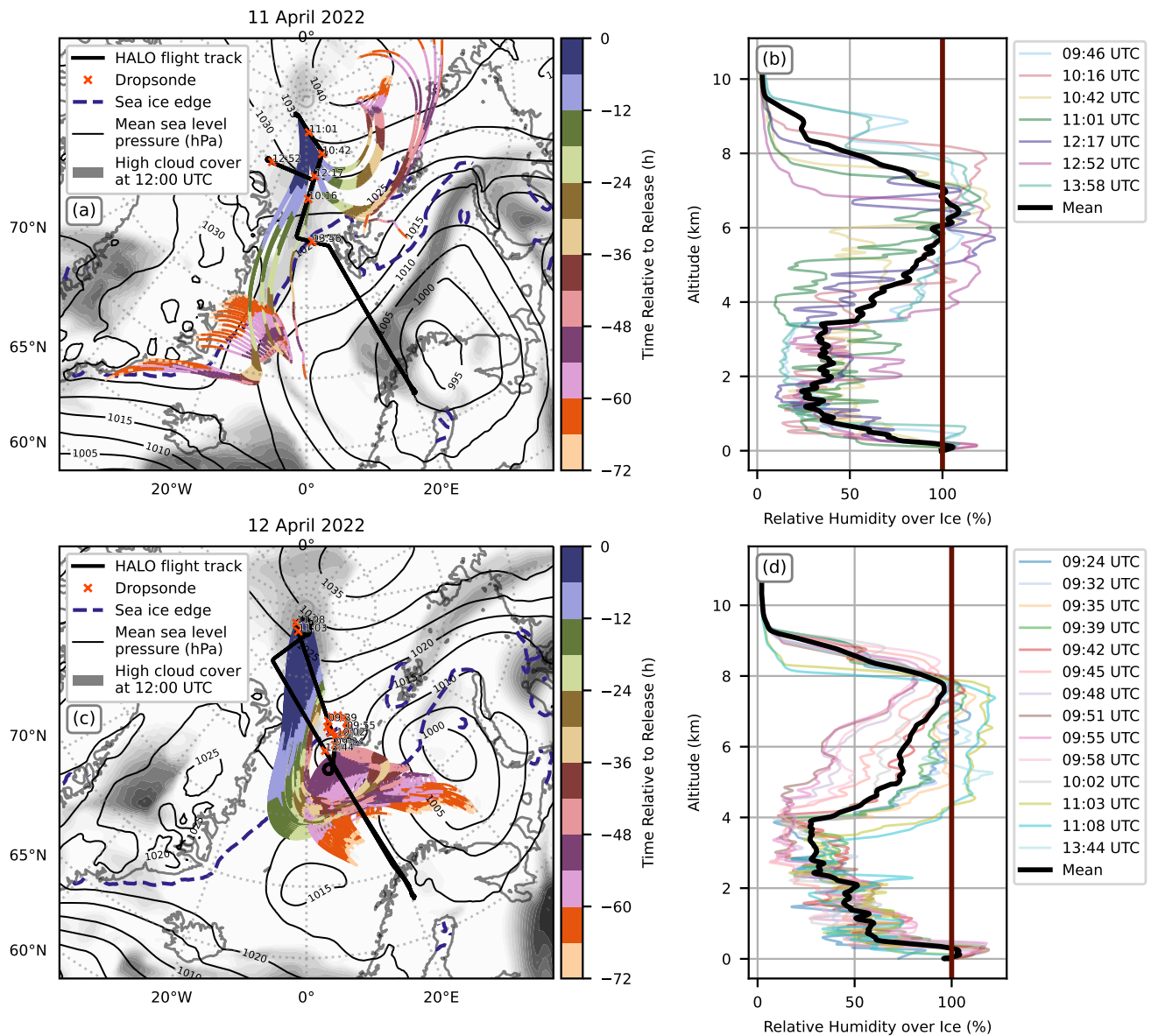
Figure 14. (a, c) Three day back trajectories of air masses in which cirrus were sampled on 11 and 12 April 2022. All trajectories are based on ERA5 reanalysis and end at the HALO flight track in cirrus level between 350 and 550 hPa. Surface pressure (thin black lines) and cloud cover (black shading) above 550 hPa from ERA5 are shown for 12 UTC at both days. The thick black line indicates the HALO flight track, and red crosses the location of dropsonde releases. In (b, d) we show the average profile and all individual profiles of relative humidity over ice measured during the two flights by dropsondes.

of Svalbard, exceeding the climatology by a factor of 36. Not only is the intensity remarkable, but also the occurrence of rain over sea ice at this time of the year.

The cold period was initialized after the passage of a strong cyclone over Svalbard on 21 March, when a northerly flow was established in the central region. We identified two strong MCAO periods (21–26 March and 01–02 April), where M partly exceeded the 90th percentile. The strong MCAOs were associated with high upward fluxes of sensible and latent heat in the unstable atmospheric boundary layer, which stress the interaction between the warm ocean and cold atmosphere. The ocean–atmosphere interactions in the boundary layer resulted in the typical high fraction of low–level cloud cover (cloud streets) and convective precipitation. After each strong MCAO period, aged warm air was advected to the measurement regions by a weaker northeasterly flow. During the aged warm air period, precipitation faded in the central region due to warming and drying. West of Svalbard, cloud–free conditions prevailed because of orographic lee effects (foehn).

After a weak MCAO, a Polar Low formed in the Fram Strait on 07 April. We confirmed that four out of six criteria for Polar Low development were fulfilled by inspecting the environmental conditions. With the help of dropsondes launched along a circle, we found strong rotation confined to the lowest 2 km despite negative relative vorticity in the eastern part related to lee effects. The Polar Low was located unusually far in the north. At the end of the cold period (10–12 April), warm and moist air was advected by a Scandinavian Low towards the southern region and diverted northwards through the Fram Strait. The high altitude southerly winds transported cirrus clouds over the sea ice with cold and dry air from the Greenland ice sheet below. This combination resulted in an isolated humidity layer including Arctic cirrus in the absence of low– and mid–level clouds.

With respect to the climatology, the entire campaign was slightly warmer considering both 2 m and 850 hPa temperatures, except for the central Fram Strait and north of Greenland. Here, 2 m temperature anomalies were negative.

In the central region, SICs were within the 10–90th percentiles of the climatology during the entire campaign period. The AR events caused remarkable reductions of SIC in the Fram Strait and northeast of Svalbard due to dynamical forcing by wind and ocean, and possibly melt. Afterwards during the MCAO period, temperatures stayed below the freezing point and northerly winds increased SIC above the climatological mean in those regions. Only around Svalbard and at its southeastern coast, SICs were lower than the climatological mean values. We identified a strip of positive SIC anomaly in the central and western Fram Strait, which coincides well with negative 2 m temperature anomalies.

~~Upper atmospheric~~ Atmospheric soundings and near–surface measurements at Ny–Ålesund generally represent the weather conditions ~~observed in the HALO–(AC)³ flight area~~ of the central region well, when ~~considering the temporal difference respecting the temporal delay~~ of up to 1 day due to the propagation of synoptic systems ~~.~~ during the warm period. However, during the cold period, lee effects at the coast of Svalbard cause cloud conditions that are only representative for the eastern part of the central region. The additional measurements at the AWIPEV can be implemented into the data analysis of HALO–$(AC)^3$ and provide a long–term climatological context to the airborne measurements. ~~The radiosondes detected unusually high tropopause altitudes up to 12.9 km during the warm period and extremely dry conditions during the first strong MCAO period with IWV below the 3rd percentile (1.1 kg m⁻²).~~

Compared to previous aircraft campaigns in the Arctic within $(AC)^3$ that focused on the evolution of (mixed–phase) clouds (ACLOUD; AFLUX and MOSAiC–ACA, Wendisch et al., 2019; Mech et al., 2022), we observed a larger variety of MCAO conditions during HALO–$(AC)^3$. The long phase of MCAOs with varying strength and different wind regimes provides opportunities for detailed MCAO studies making use of the airborne measurements. Also the sea ice edge was closer to Svalbard than during AFLUX (March–April 2019) so that ocean–ice transects could be performed more easily. We captured several MWAIs / ARs with unusual or even record breaking strength. With regard to the changing climate when exchanges between the mid–latitudes and the Arctic become more frequent and ARs are expected to shift poleward, the campaign provides a unique opportunity to study stronger than average MWAIs / ARs. We conclude that the weather conditions were well suited to achieve the objectives of the HALO–$(AC)^3$ campaign.

Code and data availability. All codes used for the analyses presented in this study have been uploaded to GITHUB and connected with ZENODO for public access (*in preparation*). Sea ice concentration climatology data is found on OSI SAF (2017) and Copernicus Climate Change Service (C3S) (2020). The high resolution sea ice concentration dataset used for 07 March–12 April 2022 is based on the product from the Institute of Environmental Physics, University of Bremen. The data is available at https://seaice.uni-bremen.de/data/modis_amsr2. ERA5 data on single and pressure levels can be accessed through Hersbach et al. (2018b) and Hersbach et al. (2018a). Ny–Ålesund radiosondes and ceilometer data have been published on PANGAEA (Maturilli and Kayser, 2016, 2017; Maturilli, 2020b, 2022). Near–surface meteorology data from Ny–Ålesund is available on PANGAEA as well (Maturilli, 2020a). Dropsonde data from used in this study can be found on ZENODO (*in preparation*).

Table A1. Geographical coordinates for measurement regions as displayed in Fig. 1. Note that the northern part of the northern region in the central Arctic is extended to the west.

	Northern region	Northern region extension	Central region	Southern region
Northern limit in deg N	84.5	89.3	81.5	75.0
Southern limit in deg N	81.5	84.5	75.0	70.6
Western limit in deg E	-9.0	-54.0	-9.0	0.0
Eastern limit in deg E	30.0	30.0	16.0	23.0

Appendix A: Methodology details

This part of the appendix includes additional details regarding the methods described in Sect. 2 that go beyond the necessary information to understand the study but help to reproduce the results.

For an exact computation of the regional averages over the southern, central and northern regions, we provide the geographical coordinates of the domains' boundaries in Table A1.

Here, we describe the processing of variables to analyse the MCAO conditions (Sect. 2.4.3) in greater detail for reproducibility. Turbulent flux data was confined to open water surfaces because our focus is on the intensity of the upward fluxes (positive sign) over open water during the MCAOs. We used the mean values over 1 hour at each grid point instead of the instantaneous values (Hersbach et al., 2020). For low, medium and high–level cloud cover, we computed the median value including 5, 25, 75, and 95th percentiles. Precipitation data was accumulated over 6 hour intervals and grouped into open water and sea ice covered surfaces. Snowfall is further separated into its large–scale and convective parts. The latter is defined in ERA5 as the frozen precipitation resulting from the convection scheme and thus from subgrid–scale convection. Total precipitation is then the sum of the convective and the large–scale part (Hersbach et al., 2020).

In the following, we summarize the meanings of the conditions tested for Polar Low formation (Sect. 2.4.4) for better understanding: Condition C1 is a measure of the convection potential as it evaluates the mean temperature gradient between the surface and the mid–troposphere. Large differences between the $2\,\mathrm{m}$ temperature and the SST (C2) promote strong sensible heat fluxes, stressing the air–sea interaction. Positive values of C3 represent an increase of potential temperature with height. At least conditionally unstable conditions (unstable (stable) for moisture–saturated (unsaturated) air parcels) should be present ($C3 \leq 3\,\mathrm{K\,km^{-1}}$). The relative humidity conditions $C4_i$ and $C4_{ii}$ are an important measure for the availability of moisture for latent heat release, a major energy source of a Polar Low. Maximum $10\,\mathrm{m}$ wind speed (C5) is an indicator of the Polar Low's strength. The geopotential height condition (C6) is selected to ensure the presence of an upper level trough.

Appendix B: Integrated water vapour transport for moist and warm air intrusions

For the MWAIs / ARs on 13 and 15 March, and for the weaker MWAI on 10 April, we show the total IVT in Fig. B1. While the former two events were meridionally aligned, the latter had a rather zonal orientation. The strongest total IVT is found on 850 15 March, exceeding $400\,\mathrm{kg\,m^{-1}\,s^{-1}}$.
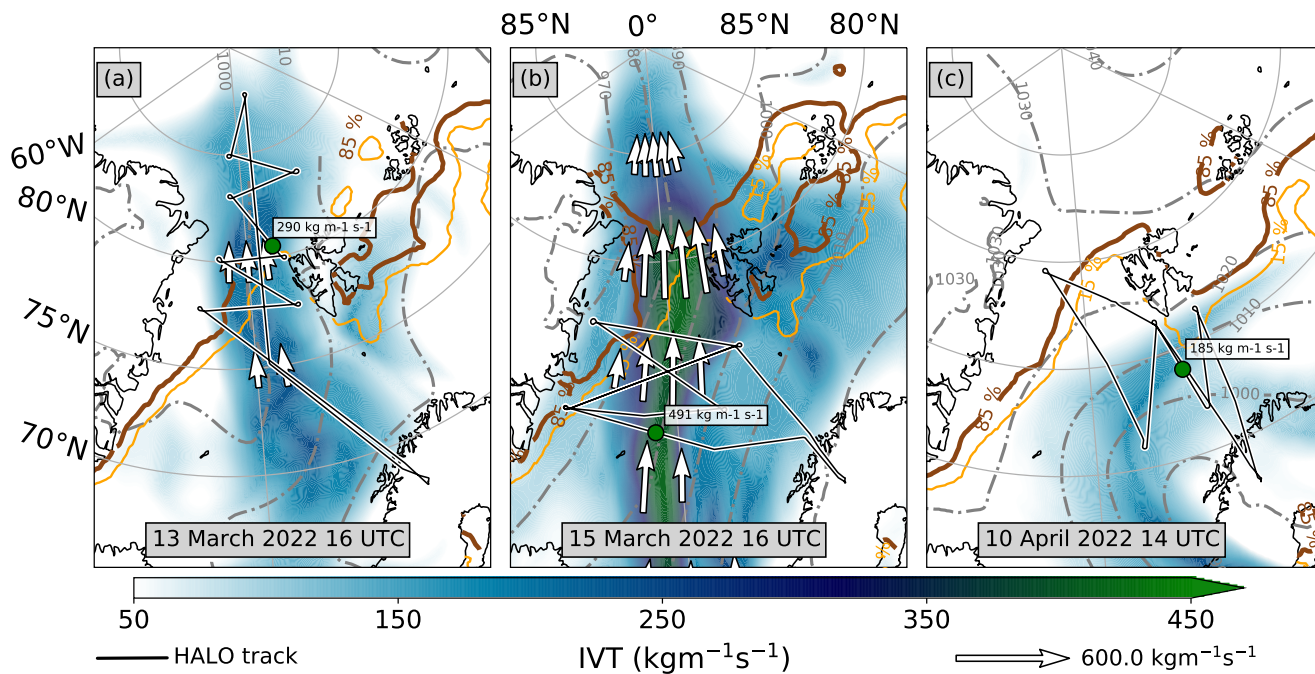
Figure B1. Total integrated water vapour transport (IVT, zonal and meridional component) from ERA5 (colours) and dropsondes (circular marker) for three moist and warm air intrusions / Atmospheric Rivers: (a) 13 March 2022 16 UTC, (b) 15 March 2022 16 UTC, (c) 10 April 2022 14 UTC. Quivers indicating the flow direction and strength, as well as the HALO flight track (black line with white outline) are also included. The orange (brown) line indicate the 15 % (85 %) sea ice concentration isoline. Grey dash–dotted contours show the mean sea level pressure. Data is based on ERA5.

Appendix C: Moist and warm air intrusion trajectories

The general air flow on two selected MWAI / AR days is investigated. Three day back and two day forward trajectories shown in Fig. C1 are initialized on 13 and 15 March each at 18:00 UTC. The trajectories reveal that the air masses of the first MWAI day mainly originated from central Europe and the second case from the North Atlantic. Forward trajectories show that both MWAIs / ARs reached the central Arctic.
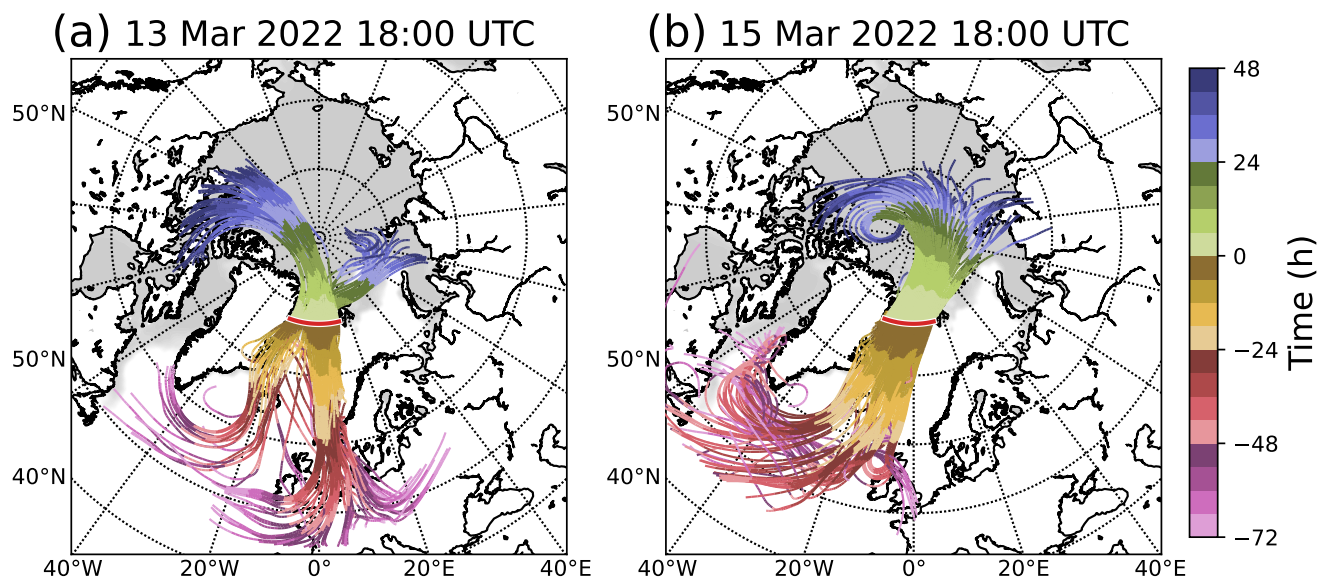
Figure C1. Three day backward and two day forward trajectories of the AR air masses observed in the central region on (a) 13 March 2022 18:00 UTC, and (b) 15 March 2022 18:00 UTC. at altitudes of 700, 850, and 925 hPa. Starting points are placed at $77.5°$ N between $20°$ W and $13°$ E with a zonal spacing of $1°$. Both 72 hour back–trajectories as well as 48 hour forward–trajectories are computed. Grey shading indicates the sea ice concentration from ERA5.

Appendix D: Marine cold air outbreak

Figure D1 shows the ERA5 based temporal evolution of temperature, relative humidity and wind for the ~~northern region.~~ eastern part of the northern region (identical western longitude boundary as the central region). The data has been processed as described in Sect. 2.4.3 and Appendix A. During the stronger MCAOs in the central region with northerly winds, the ~~airmasses~~ air masses originated from the northern region. Due to the low occurrence of northwesterly winds, the western extension of the northern region is not included. For comparison of turbulent fluxes between the central and southern region, we include Fig. D2.
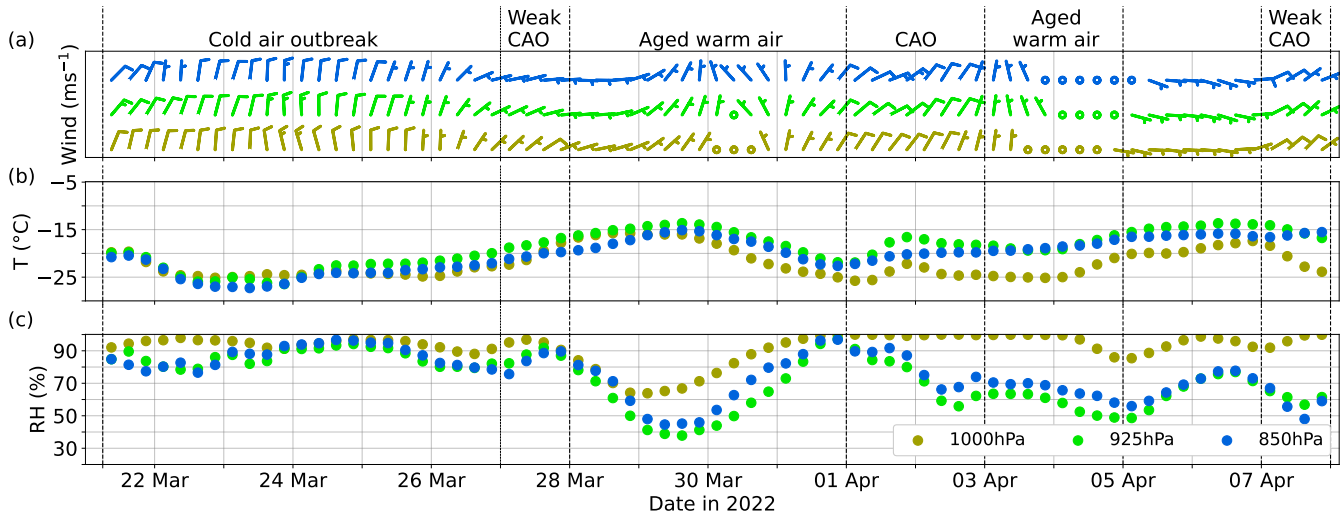
Figure D1. Temporal evolution of (a) wind, (b) air temperature (T), and (c) relative humidity (RH) on the 1000, 925, and 850 hPa pressure levels as in Fig. 11, but for the northern region (without western extension). Data is based on ERA5.
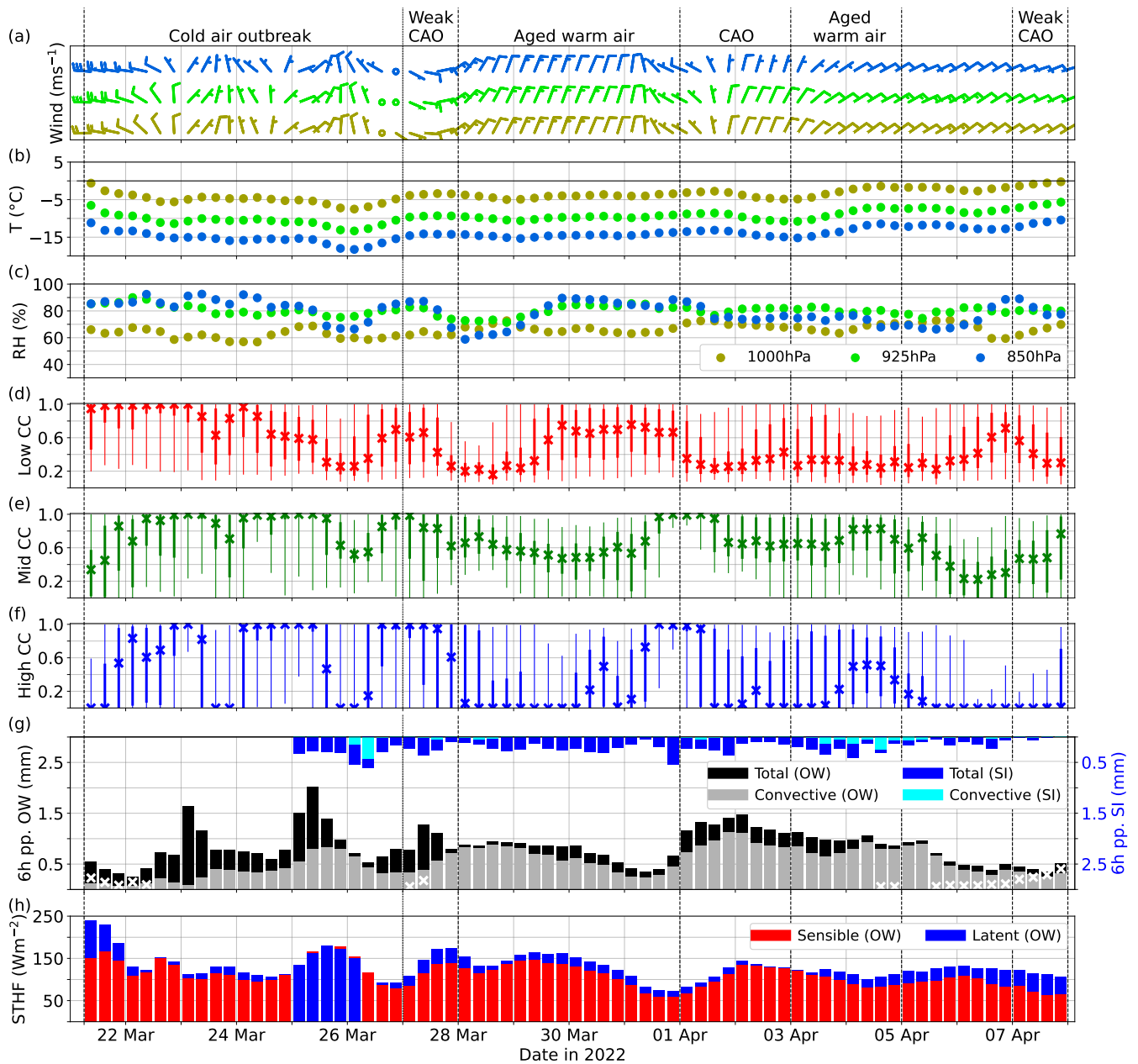
Figure D2. Temporal evolution of (a) wind, (b) air temperature (T), and (c) relative humidity (RH) on the 1000, 925, and 850 hPa pressure levels, and of (d) low–, (e) mid–, and (f) high–level cloud cover (CC), (g) precipitation, and (h) surface turbulent heat fluxes (STHF) as in Fig. 11 but for the southern region. Data is based on ERA5.

Appendix E: Polar Low visual observations

Due to the relatively small extent of a Polar Low, we were able to see the entire structure during the HALO research flight on 08 April 2022. The photo was taken on one of the cross sections through the Polar Low, showing the relatively cloud free centre (eye) and the convective cloud band on its (north–)eastern side (Fig. E1).
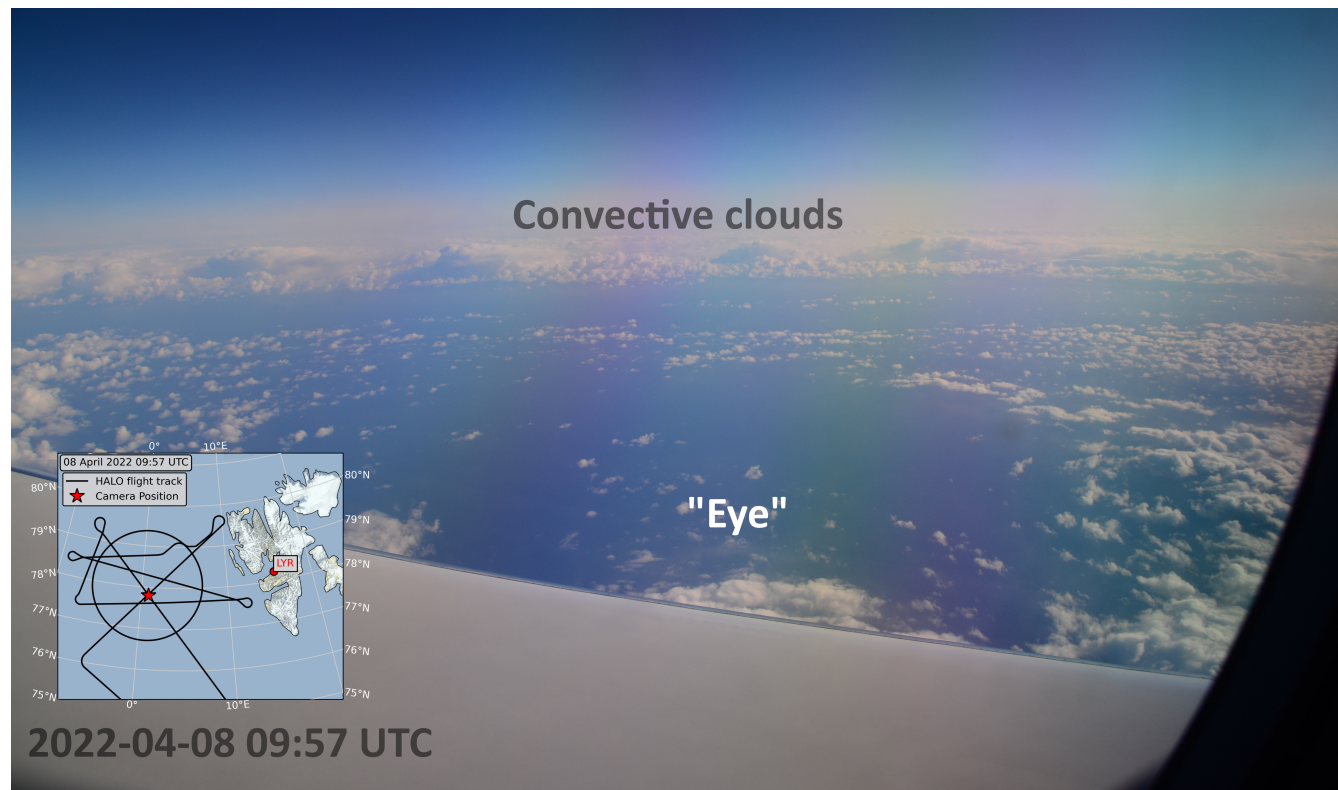
Figure E1. Photo of the Polar Low taken from HALO (portside) on 08 April 2022 at 09:57 UTC. The centre (eye) of the Polar Low can be seen in the foreground while the convective cloud band is visible in the background. The map indicates the flight track (black line) and the position of the aircraft at that time (red star). © Andreas Walbröl

Author contributions. SC, AE, IG, JanM, MW, and AW conceptualized the manuscript. MW and AW formulated the introduction with comments and input from AE, JanM, and SC. HD, BK, ML, NM, MM, JanR, and AW prepared the description of the data and methods chapter. SB, HD, BK, ML, JanM, HM, RN, FP, JohR, JanR, IS, NS, and AW provided visualisations and analysed figures. JohM and AW collected codes from co–authors and made them publicly available. AW is the main author of this manuscript and ensured validation. All co–authors reviewed the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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