A comprehensive in-situ and remote sensing data set collected during the HALO–$(\mathcal{AC})^3$ aircraft campaign

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Abstract.

The HALO–$(\mathcal{AC})^3$ aircraft campaign was carried out in March and April 2022 over the Norwegian and Greenland Seas, the Fram Strait, and the central Arctic Ocean. Three research aircraft, the High Altitude and Long Range Research Aircraft (HALO), Polar 5, and Polar 6, performed 54 partly coordinated research flights on 23 flight days over areas of open ocean, the marginal sea ice zone (MIZ), and the central Arctic sea ice. The general objective of the research flights was to quantify the evolution of air mass properties during moist and warm air intrusions (WAIs) and cold air outbreaks (CAOs). To ~~gain~~ obtain a comprehensive data set, the three aircraft ~~followed~~ operated following different strategies. HALO was equipped with active

and passive remote sensing instruments and dropsondes to cover the regional evolution of cloud and thermodynamic processes. Polar 5 carried a similar remote sensing payload as HALO, and Polar 6 was instrumented with in-situ cloud, aerosol, and trace gas instruments focusing on the initial air mass transformation close to the MIZ. The processed, calibrated, and validated data are published in the World Data Center PANGAEA as instrument-separated data subsets and listed in aircraft-separated collections for HALO (Ehrlich et al., 2024a), Polar 5 (Mech et al., 2024a), and Polar 6 (Herber et al., 2024). A detailed overview of the available data sets is provided here. Furthermore, the campaign-specific instrument setup, the data processing ~~, and data~~ and quality are summarized. Based on measurements conducted during a specific CAO, it is shown that the scientific analysis of the HALO–$(\mathcal{AC})^3$ data benefits from the coordinated operation of the three aircraft.

1 Introduction

The Arctic currently experiences a strong warming that exceeds global warming by a factor of two to four (Rantanen et al., 2022). In addition to the remarkable sea ice retreat, the enhanced Arctic warming represents one of the most obvious results of Arctic-specific processes and feedback mechanisms causing significant climate changes in the Arctic that are widely referred to as Arctic amplification (Serreze et al., 2009). The effects and consequences of Arctic amplification are extensively discussed in literature (e.g., Wendisch et al., 2023a). However, especially the role of clouds and air mass transports into and out of the Arctic, and related transformation processes are still poorly understood. Therefore, in spring 2022 ~~a major observational initiative,~~ the HALO–$(\mathcal{AC})^3$ campaign ~~,~~ was conducted (Wendisch et al., 2021, 2024). HALO–$(\mathcal{AC})^3$ combined ~~airborne~~aircraft-based, balloon-borne, and ground-based measurements aiming to provide detailed observations of thermodynamic, cloud, aerosol, trace gas, and surface properties as they change during the meridional air mass transports. Furthermore, the collected data will be compared to simulations conducted with numerical Arctic weather and climate models.

The focus area of ~~interest of~~ HALO–$(\mathcal{AC})^3$ was the North Atlantic corridor of the Fram Strait between Greenland and Svalbard also referred to as North Atlantic pathway, which is a major entrance/exit gate for air masses moving North or South between mid and high latitudes ~~also referred to as North Atlantic pathway~~ (Mewes and Jacobi, 2019; Dahlke et al., 2022; Papritz et al., 2022). In this region, warm and moist mid-latitude air masses are pushed frequently northwards into the sea ice-covered central Arctic (Pithan et al., 2018; Liang et al., 2023). Cold air masses moving southwards regularly form cold air outbreaks (CAOs) over the open ocean (Dahlke et al., 2022). Due to the seasonally relatively stable sea ice edge in the Fram Strait and the permanent measurements collected on Svalbard, in particular at Ny-Ålesund research stations, this region has become a hot spot of Arctic research.

A series of airborne, ship, and ground-based campaigns, such as ASTAR, ~~ACLOUD~~ASCOS, ACLOUD, PAMARCMiP, ~~AFLUX, MOSAiC-ACA, PAMARCMiP, ASCOS,~~ Arctic Ocean, ~~COMBLE, NASCENT(Wendisch et al., 2019; Mech et al., 2022a; Tjerns~~ ~~,~~AFLUX, NASCENT, MOSAiC-ACA, COMBLE[1] (Tjernström et al., 2014; Wendisch et al., 2019; Vüllers et al., 2021; Mech et al., 2022a , have provided valuable data to enhance our understanding of the Arctic climate system and ~~improve numerical models~~

[1] ASTAR: Arctic Study of Tropospheric Aerosol, Clouds and Radiation, ASCOS: The Arctic Summer Cloud Ocean Study, ACLOUD: Arctic Cloud Observations Using airborne measurements during polar Day, PAMARCMiP: Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project, AFLUX: Airborne measurements of radiative and turbulent Fluxes in the cloudy atmospheric boundary layer, NASCENT: Ny-Ålesund Aerosol Cloud

(e.g., McCusker et al., 2023)to validate and improve numerical Arctic weather models (e.g., Kretzschmar et al., 2020; McCusker et al., 20
. However, most of the previous airborne aircraft campaigns in the Fram Strait were limited to smaller areas due to restricted flight ranges of the involved planes, or were focused on atmospheric processes over open ocean, e.g., the downstream development of CAOs (Vüllers et al., 2021). Observations from ships such as MOSAiC (Shupe et al., 2022) provide longer term measurements in the Arctic sea ice but are mostly restricted to the local scale. The permanent research stations at the ground are often affected by specific influenced by orographic effects and not always representative for the Arctic Ocean (Gierens et al., 2020). Therefore, the HALO–$(\mathcal{AC})^3$ aircraft campaign was designed to combine different aircraft platforms and aiming for observations in applying a quasi-Lagrangian approach.

To characterize the process of air mass transformation air mass transformations and to quantify their consequences, measurements of thermodynamic parameters, cloud and aerosol particles properties, trace gas concentrations, and the radiative energy budget are most of specific relevant. Especially close to the sea ice edge, these transformations can be fast (Murray-Watson et al., 2023; Kirbus et al., 2024) requiring small-scale observations (Murray-Watson et al., 2023; Kirbus et al., 2024; Schi
. Therefore, three research aircraft equipped with state-of-the-art instrumentation were involved in HALO–$(\mathcal{AC})^3$ to sample atmospheric parameters on different spatial scales and during different stages of air mass transformation (Wendisch et al., 2024).

The observations cover major strong warm air intrusions (WAIs) injecting warm and moist air into the central Arctic. Multiple cold air outbreaks (CAOs) were characterized in their initial stage close to the sea ice edge with the Polar by the instrumentation on Polar 5 and Polar 6 research aircraft and 6. Partly, the Polar aircraft were flown in a quasi-Lagrangian perspective jointly with HALO. This approach allows to quantify the air mass transformations by deriving changes of thermodynamic profiles, large scale subsidence, and cloud properties over a period of 24 hours. Individual events of high latitude Arctic cirrus and the formation of a polar low are included in the data set. These synoptic events, the general meteorological conditions, and the sea ice distribution during HALO–$(\mathcal{AC})^3$ are summarized and compared to the long-term climatology by Walbröl et al. (2024). They found that two WAI events were associated with an extraordinary strong moisture transport that led to record-breaking near-surface air temperatures and precipitation rates in Svalbard. Although these WAI events were followed by one of the longest CAO event on record, the entire campaign period was warmer than the climatological mean.

The collected airborne aircraft-based data set includes a multitude of in-situ and remote sensing instruments and provides measurements of basic thermodynamic quantities, the radiative energy budget and as well as cloud, aerosol, and trace gas properties. The aim of this paper is to give an overview of the available data sets of the airborne aircraft-based measurements, their accessibility, and potential uncertainties that have to be considered when using the data. In Section 2 the general setup and an overview of the HALO–$(\mathcal{AC})^3$ aircraft activities are summarized. The data sets and their availability are described in Sections 3 and 4. To highlight the potential of merging the data of the different aircraft, Section 5 outlines examples of combined data analysis on the basis of one case study.

Experiment, MOSAiC-ACA: Multidisciplinary drifting Observatory for the Study of Arctic Climate - Airborne observations in the Central Arctic, COMBLE: Cold-Air Outbreaks in the Marine Boundary Layer Experiment

2 HALO–(AC)^3 aircraft campaign

2.1 General setup

HALO–(AC)^3 was designed as a concerted effort combining airborne, ground-based, and balloon-borne observations in the area around Svalbard and in the central Arctic. For the aircraft campaign in March and April 2022, the German High Altitude and Long Range Research Aircraft (HALO) operated by the German Aerospace Center (DLR, Krautstrunk and Giez, 2012) was equipped with a comprehensive suite of active and passive remote sensing instruments and dropsondes (Stevens et al., 2019). Based in Kiruna, northern Sweden, HALO with its extended flight range covered one of the major sectors of WAIs and CAOs (Mewes and Jacobi, 2019; Liang et al., 2023) and followed air masses into the central Arctic close to the north pole (8000 km range in altitudes up to 13 km). The Polar 5 (remote sensing) and Polar 6 (in-situ) aircraft of the Alfred Wegener Institute (AWI, Wesche et al., 2016) probed the lower troposphere out of Longyearbyen, Svalbard (1500 km range in altitudes up to 4km). Both Polar aircraft mostly operated in the Fram Strait with a focus on the local transitions at the sea ice edge. Several coordinated flights between the three aircraft were conducted with Polar 6 sampling in-situ aerosol, cloud, and precipitation particles within the boundary layer, Polar 5 observing clouds and precipitation from above roughly at 3 km altitude, and HALO providing the large scale view and following air masses during one single and along successive flights with a quasi-Lagrangian flight strategy.

During the HALO-(AC)^3 campaign period, an intensive atmospheric measurements program extending the permanent observations was conducted at the research base AWIPEV at Ny-Ålesund/Svalbard (78° 55' N, 11° 55' E, Neuber, 2006) jointly operated by AWI and the French Polar Institute Paul-Émile Victor (IPEV). The tethered balloon BELUGA (Balloon-born moduLar Utility for pro linG the lower Atmosphere, Egerer et al., 2019; Lonardi et al., 2024) was launched to collect vertical profile data in the atmospheric boundary layer and the lower free troposphere from the ground to about 1 km height with sophisticated turbulence, radiation, and aerosol particle instrumentation (e.g., Pilz et al., 2023). An overview of the balloon-born observations conducted during HALO–(AC)^3 is given by Lonardi et al. (2024). During March and April 2022, the frequency of the regular radiosonde launches at AWIPEV was increased to six-hourly intervals (Maturilli, 2022a, b). These data are published by Maturilli (2022a, b). A long-term data set of ground-based cloud remote sensing observations at AWIPEV is published by Chellini et al. (2023). To link the airborne measurements with the observations at AWIPEV, Polar 5 and Polar 6 regularly passed over the site during the outbound or inbound flights.

In parallel to HALO-(AC)^3, the ISotopic Links to Atmospheric water's Sources (ISLAS) (ISLAS, Sodemann, 2018) campaign and the airborne field campaign Arctic Cold Air Outbreak (ACAO) (ACAO, Raif et al., 2024) were performed. For ISLAS, the ATR-42 research aircraft operated by SAFIRE (french: Service des Avions Français Instrumentés pour la Recherche en Environnement, Lamorthe et al., 2016) was deployed with in-situ cloud, aerosol, and trace gas probes and remote sensing instruments. ACAO used the BAE-146 operated by the Facility for Airborne Atmospheric Measurements (FAAM) to measure cloud, aerosol and atmospheric quantities. Both aircraft were stationed in Kiruna and mostly operated in low altitudes between Svalbard and Northern Scandinavia. To combine the efforts, HALO, ATR-42, and BAE-146 were coordinated in four flights.

Figure 1. Distribution of the ight tracks of all aircraft, Polar 5 and Polar 6 (red), and HALO (blue) during HALO-(AC)^3. The sea ice cover corresponds to the middle of the campaign period 30 March 2022. The yellow line indicates the standard ight leg.

2.2 Overview of ight activities

An overview of all HALO-(AC)^3 research ight activities ights including information on the coordination and dropsondes is provided in Table 1, the ight tracks are illustrated in Fig. 1. In total, HALO performed 17 research ights (RFs), while Polar 5 and Polar 6 conducted 13 ights each. Nine HALO ights were coordinated with Polar 5 and/or Polar 6. For close spatial and temporal coordination of the three aircraft, a standard leg (SL) between two way points xed waypoints (79 24' N, 7 37' E and 79 56' N, 1 31' E) was de ned and repeatedly implemented in the ight planning. This straight SL connects areas of open ocean to the East and the dense sea ice further west. Most of the time, the SL crossed the mai direction of air mass advection in the boundary layer (2) (Walbröl et al., 2024) and, therefore, allowed for detailed sampling of

Table 1. Overview of HALO-(AC)^3 research flights including the research flight (RF) number and information on the coordination of HALO with the Polar 5 (P5), Polar 6 (P6), BAE-146, and ATR-42 aircraft. Flights covering the standard leg (SL) and overpasses of Polar 5 over AWIPEV station in Ny-Ålesund (NyÅ) are indicated. The number of successfully launched dropsondes from Polar 5 and HALO is given. For HALO dropsondes, the number of launches used in the Global Telecommunication System (GTS) data assimilation is specified in brackets.

Day	Research flight (RF)			Coordination	Standard	AWIPEV	Dropsondes from	
	HALO	Polar 5	Polar 6	HALO perspective	Leg		P5	HALO (GTS)
12.03.2022	02	-	-				-	20
13.03.2022	03	-	-				-	21
14.03.2022	04	-	-				-	9
15.03.2022	05	-	-				-	25 (3)
16.03.2022	06	-	-	BAE-146			-	23 (19)
20.03.2022	07	01	01	P5, P6		NyÅ	12	17 (13)
21.03.2022	08	-	-	BAE-146			-	13 (13)
22.03.2022	-	02,03	02			NyÅ	12	-
24.03.2022	-	-	03				-	-
25.03.2022	-	04	-			NyÅ	5	-
26.03.2022	-	-	04				-	-
28.03.2022	09	05	05	P5, P6	SL	NyÅ	15	16 (16)
29.03.2022	10	06,07	06	P5, P6, ATR-42, BAE-146		NyÅ	5	18 (10)
30.03.2022	11	08	07	P5, P6, ATR-42, BAE-146		NyÅ	15	32 (32)
01.04.2022	12	09	08	P5, P6	SL	NyÅ	18	41 (41)
04.04.2022	13	10	09	P5, P6	SL		14	13 (11)
05.04.2022	-	11	10		SL		10	-
07.04.2022	14	12	-	P5	SL	NyÅ	17	15 (10)
08.04.2022	15	-	11	P6			-	21 (5)
09.04.2022	-	-	12				-	-
10.04.2022	16	13	13	P5, P6	SL		18	22 (21)
11.04.2022	17	-	-		SL		-	7 (6)
12.04.2022	18	-	-				-	17 (16)

air masses crossing the sea ice edge. Four HALO flights were coordinated with the ATR-42 and/or BAE-146 aircraft providing additional in-situ cloud observations. For all research flights, individual flight reports were compiled by the team of participants and are published by Ehrlich et al. (2024). These reports summarize the general objective of the research flights, motivate the flight pattern in combination with the current synoptic weather conditions, and provide notes by the instrument operators,

Figure 2. Classi cation of ight times over speci c surface types separated for all aircraft individually.

quick-looks, and images from the ights. To identify how the ights were affected by the general meteorological and sea ice conditions during HALO–(AC)^3, the reader is referred to (Walbröl et al., 2024).

In total, the measurement time of HALO amounts to 143 hours covering a distance of 143,000 km. Polar 5 and Polar 6 operated for about 53 hours and 64 hours, respectively. Due to the lower ight speed of the Polar 5 and 6 aircraft, this corresponds to a distance of 36,000 km for each aircraft. The spatial distribution of measurements is illustrated in Fig. 1 and shows a focus of measurements around the sea ice edge in the Fram Strait. This mostly results from Polar 5 and Polar 6 ~~, but also from~~ ights and the intense coordination with HALO in this region. The SL features the highest density of measurement, it was own in collocation during ve ights. The ights covered different surface conditions, including snow-covered land, open ocean, closed sea ice, and the MIZ as summarized for each aircraft in Fig. 2. The classi cation uses satellite observations of sea ice concentrations provided by the Advanced Microwave Scanning Radiometer (AMSR-II, Spreen et al., 2008). The de nition of the MIZ follows the common thresholds of sea ice concentration between 15 % and 80 % (Strong et al., 2017). With above 50 % of the ight time, open ocean is the dominant surface type observed by the three aircraft. Due to the longer endurance, HALO covered a higher fraction of observations over sea ice (30 % of total ight time) than Polar 5 and Polar 6 (20 %). The MIZ was sampled more intensively with Polar 5 and Polar 6. A similar amount of ight time of Polar 5 and Polar 6 was spent over land to coordinate with the columnar observations performed at AWIPEV in Ny-Ålesund. Vertically, the ight altitudes of all three aircraft were well separated. HALO stayed mostly at 9-13 km altitude for remote sensing measurements, while Polar 5 also conducted remote sensing observations at 3 km altitude. To quantify the surface energy budget, Polar 5 measured in low altitude close to the surface during two ights. Polar 6 frequently changed altitude mostly in the atmospheric boundary layer between 0.1 km and 2 km, and regularly (once a ight) pro led the atmosphere up to 4 km altitude.

2.3 Instrumentation

HALO–(AC)^3 made use of the experience operating collected by the author team in the past when Polar 5, Polar 6, and HALO were applied for atmospheric research and adapted the instrumentation from previous campaigns. HALO was set up for cloud and atmospheric remote sensing observations from high altitudes and in-situ sampling of basic atmospheric parameters by dropsondes. The instrumentation onboard of HALO is listed in Table 2. It is identical to the cloud observatory instrument package applied in a series of missions such as the Next Generation Remote Sensing for Validation Studies (NARVAL) observations and the Elucidating the role of cloud–circulation coupling in climate (EUREC^{4}A) campaign (Stevens et al., 2019; Konow et al., 2021).

On Polar 5 and Polar 6, separate payloads for remote sensing (Polar 5) and in-situ measurements (Polar 6) were installed in a similar configuration as operated during ACLOUD (Ehrlich et al., 2019). The instruments on board of Polar 5 and Polar 6 are listed in Table 3, including the main measured quantities and references providing detailed descriptions of the instruments and their uncertainties. Basic measurements of meteorological parameters and the radiative energy budget were conducted on both aircraft. The remote sensing (Polar 5) and cloud microphysical instruments (Polar 6) were operated almost identical setup as used during the AFLUX and MOSAiC-ACA campaigns (Mech et al., 2022a). For HALO–(AC)^3, the cloud microphysical devices was were extended by a Cloud Probe with Polarization Detection (BCPD, Beswick et al., 2014). One major change of the Polar 6 instrumentation compared to Ehrlich et al. (2019) was in the aerosol particle microphysical instrumentation. The second ultra-high sensitivity aerosol spectrometer (UHSAS) was replaced by the High-volume flow aERosol particle filter sAmpler (HERA), a Mobility Particle Size Spectrometer (MPSS), and a miniature Cloud Condensation Nuclei Counter (mCCNC).

Table 2: Overview of the instrumentation of HALO and the measured quantities that are part of the database. λ is wavelength, ν is frequency, T is air temperature, and p is atmospheric pressure. RH is relative humidity, FOV is field of view.

Instrument	Measured Quantities, Range, and Sampling Frequency	Reference
Meteorology		
BAHAMAS	T, p, RH, Wind Vector, 10 Hz	Krautstrunk and Giez (2012); Giez et al.
Dropsondes	Vertical profile of T, p, RH, 2Hz, Vertical profile of Horizontal Wind Vectors Vector, 4Hz	Vaisala (2020)
Radiative Energy Budget		
BACARDI Pyranometer	Solar Irradiance (Upward, Downward, Broadband $= 0.2$ – $3.6\,\mu$m), 10Hz	Ehrlich et al. (2023)
BACARDI Pyrgeometer	Terrestrial Irradiance (Up- and Downward, Broadband $= 4.5$ – $42.0\,\mu$m), 10Hz	Ehrlich et al. (2023)
SMART	Spectral Irradiance (Downward $= 0.32$ – $2.1\,\mu$m), 1Hz	Wolf et al. (2019)

Remote Sensing		
WALES	Backscatter Coef cient (= 532 nm), 1 Hz	Wirth et al. (2009)
	Particle Linear Depolarization (= 532 nm), 1 Hz	
	Water Vapor Molecular Density (at = 935 nm), 12 s	
HAMP Active	Radar Re ectivity Factor, Doppler Spectra, = 35 GHz, 1 Hz	Mech et al. (2014)
HAMP Passive	Brightness Temperature, 25 Channels, 22 :24 190:81 GHz, Nadir, 1 Hz	Mech et al. (2014)
specMACS	Spectral Radiance (Upward, Swath = 32.7 35:5 , = 0 :4 2:5 µm), 30 Hz	Ewald et al. (2016)
	Polarized Radiance, RGB Color Channels, 2D elds 9 11 17 , 8 Hz	Weber et al. (2024)
VELOX	Spectral Brightness Temperature, 6 Channels, 7 :7 12 m,	Schäfer et al. (2022)
	2D Fields 35.5 x 28.7 , 635 x 507 pixels, 10 Hz	
KT-19	Brightness Temperature (Upward nadir, 9 :6 11:5 µm), 20 Hz	Schäfer et al. (2022)

Table 3: Overview of the instrumentation of Polar 5 and Polar 6 and the measured quantities that are part of the data ba is wavelength, is frequency, T is air temperature, and p is atmospheric pressure. RH is relative humidity, FOV is eld of view, PNSD is the particle number size distribution, rBC refractory black carbon, SS is the level of supersaturation, and D_p symbolizes the particle diameter.

Aircraft	Instrument	Measured Quantities, Range, and Sampling Frequency	Reference
Meteorology			
P5&P6	Nose Boom	T , p, RH, Wind Vector, 100 Hz	Hartmann et al. (2019) Tetzlaff et al. (2015)
P5	Dropsondes	Vertical pro le of T , p, RH, 2 Hz, Vertical pro le of Horizontal Wind Vector, 4 Hz	Vaisala (2020)
Radiative Energy Budget			
P5&P6	Pyranometer	Solar Irradiance (Up- and Downward, Broadband = 0 :2 3:6 µm), 20 Hz	Ehrlich and Wendisch (2015) Philipona et al. (1995)
P5&P6	Pyrgeometer	Terrestrial Irradiance (Up- and Downward, Broadband = 4 :5 42:0 µm), 20 Hz	Ehrlich and Wendisch (2015) Philipona et al. (1995)
P5	SMART	Spectral Irradiance (Up- and Downward, 0 :4 1:8 µm), 2 Hz Spectral Radiance (Upward, FOV = 2,1 = 0 :4 1:0 µm), 2 Hz	Bierwirth et al. (2009)
Remote Sensing			
P5	AISA Eagle/Hawk	Spectral Radiance (Upward, Swath = 36 = 0 :4 2:5 µm), 20-30 Hz	Schäfer et al. (2013)
P5&P6	Fish-Eye Camera	Spectral Radiance (Lower Hemisphere, RGB Channels), 4-6 s	Carlsen et al. (2020)
P5	AMALi	Particle Backscattering Coef cient (= 355 ; 532 nm), Cloud Top Height,	Stachlewska et al. (2010)

		Particle Depolarization (λ = 532 nm), 1 Hz	
P5	MiRAC-A	Radar Reflectivity Factor, Doppler Spectra, λ = 94 GHz, tilted by 25°, 1 Hz	Küchler et al. (2017)
		Brightness Temperature, λ = 89 GHz, tilted by 25°, 1 Hz	Mech et al. (2019)
P5	HATPRO	Brightness Temperature, λ = 7 22.24 31.4 and	Rose et al. (2005)
		λ = 7 51.26 58.00 GHz, Upward nadir, 1-2 Hz	
P5&P6	KT-19	Brightness Temperature (Upward nadir, λ = 9.6 11.5 µm), 20 Hz	Schäfer et al. (2022)
Cloud Microphysical Properties			
P6	2D-S	Cloud PNSD, 2D Particle Images, D_p = 10 1280 µm, 1 Hz	Lawson et al. (2006)
P6	Polar Nephelometer	Non-normalized Volumetric Scattering Phase Function, 1 Hz	Gayet et al. (1997)
		Asymmetry Parameter, Extinction Coefficient, 1 Hz	
P6	CDP	Cloud PNSD, D_p = 3 50 µm, 1 Hz	Lance et al. (2010)
P6	CIP	Cloud PNSD, 2D Particle Images, D_p = 15 960 µm, 1 Hz	Baumgardner et al. (2001)
P6	PIP	Cloud PNSD, 2D Particle Images, D_p = 100 6400 µm, 1 Hz	Baumgardner et al. (2001)
P6	BCPD	Cloud PNSD, D_p = 2 42 µm, Particle Shape, 1 Hz	Lucke et al. (2023)
P6	Nevzorov Probe	LWC, TWC, 1 Hz	Korolev et al. (1998)
Aerosol Microphysical Properties			
P6	CPC TSI-3010	Aerosol and Cloud Residual Number Concentration, D_p > 10 nm, 1 Hz	Mertes et al. (1995)
P6	UHSAS	Aerosol and Cloud Residual PNSD, D_p = 65 nm – 1 µm, 1 Hz	Cai et al. (2008)
P6	Grimm Sky-OPC	Aerosol PNSD, D_p = 250 nm – 5 µm, 6 s	Bundke et al. (2015)
P6	HERA	Aerosol Particle Filter Sampling, INP concentration, 2 – 140	Grawe et al. (2023)
P6	mCCNC	CCN Number Concentration, SS = 0.1 %, 1 Hz	Roberts and Nenes (2005)
P6	MPSS	Aerosol PNSD, D_p = 10 nm – 800 nm, 5 min	Wiedensohler et al. (2012)
Aerosol Chemistry			
P6	ALABAMA	Single Particle Composition (Refractory, Non-Refractory),	
		D_{va} = 230 3000 nm (D_{50}), up to 10 Hz	Clemen et al. (2020)
P6	PSAP	Particle Absorption Coefficient (λ = 565 nm), = 0 5 10^{-6} m^{-1}, 10 s	Bond et al. (1999)
			Mertes et al. (2004)
P6	SP2	rBC Mass/Number Concentration, PNSD, rBC Mass 0.3 290 fg,	Zanatta et al. (2023)
		D_p = 70 675 nm, Single Particle Data	
Trace Gas Chemistry			
P6	Aerolaser AL5002	CO-Concentration, 0 100,000 ppbv, 1 Hz	Gerbig et al. (1999)
P6	Licor 7200	CO_2 Concentration, 0 3000 ppmv, 1 Hz	Burba et al. (2010)
		H_2O Concentration, 0 60 mmol mol^{-1}, 1 Hz	
P6	2BTech O3 Monitor	O_3-Concentration, 0 250 ppmv, 2 s	Johnson et al. (2014)
P6	WVSS-II	H_2O Concentration, 50 40000 ppmv, 1 Hz	Vance et al. (2015)
		Cloud Water Content, 10 2000 mg m^{-3}, 1 Hz	

3 Datasets

All data are published in the World Data Center PANGAEA (Felden et al., 2023) as instrument-separated data subsets and are marked by the tag "HALO-(AC)^3". Three collections of data sets for HALO, Polar 5, and Polar 6 link the data subsets by aircraft for a more structured overview.

- HALO: (Ehrlich et al., 2024a, https://doi.org/10.1594/PANGAEA.968885)
- Polar 5: (Mech et al., 2024a, https://doi.org/10.1594/PANGAEA.968883)
- Polar 6: (Herber et al., 2024, https://doi.org/10.1594/PANGAEA.968884)

All data subsets, separated into the scientific subject, are introduced below. The subsection titles indicate, which aircraft the data sets refer to.

3.1 Measurements of basic aircraft and fundamental meteorological parameters

3.1.1 HALO - Basic aircraft data

The basic aircraft data obtained from instruments mounted on HALO (wind vector, thermodynamic state of the ambient air) were measured with the Basic HALO Measurement and Data System (BAHAMAS, Giez et al., 2021; Krautstrunk and Giez, 2012). For HALO-(AC)^3, all processed data are published with 10 Hz sampling frequency in the HALO data base (Giez et al., 2022, https://halo-db.pa.op.dlr.de/mission/130). The measurements include aircraft location, speed and attitude, the three dimensional (3D) wind vector, air pressure, static air temperature, and humidity. All data were corrected for dynamical effects due to the aircraft movement. The calibration procedure of the wind vector measurements is documented by Giez et al. (2021), the static pressure measurements by Giez et al. (2020). A full uncertainty analysis of all measured quantities in high latitude conditions is provided by Giez et al. (2023). The humidity measurements of BAHAMAS were evaluated in an inter-comparison published by Kaufmann et al. (2018). For users only interested in the position data of HALO, master tracks of longitude, latitude, and altitude derived from the global positioning system (GPS) are published in PANGAEA (Ehrlich et al., 2024b).

3.1.2 Polar 5 / Polar 6 - Basic aircraft data and high frequency nose boom data

Slow and high frequency measurements of wind, air temperature, and humidity were obtained on Polar 5 and Polar 6 from two identical nose boom systems and sensors mounted in a Rosemount housing as described by Mech et al. (2022a). The process datasets for the nose boom measurements are available in ASCII format on PANGAEA in a 1 s resolution (Lüpkes et al., 2024a) and in 1 Hz resolution (Lüpkes et al., 2024b). For users only interested in the position data of the aircraft, master tracks of GPS longitude, latitude, and altitude are published for Polar 5 and Polar 6 (Herber et al., 2022a, b).

The 3D wind vector was derived from Aventech (Aventech Research Inc., Canada) five-hole probes for high frequency pressure measurements combined with accurate position data, which were obtained from a high precision GPS and from an inertial navigation system (INS). Pitch and roll angles were delivered at an accuracy of 0.01° while true heading angles have

an accuracy of 0.4 Finally, horizontal wind components were obtained with an absolute accuracy of 0.2 $m\,s^{-1}$ for straight and level ight sections. Vertical wind was obtained only as the deviation from the average vertical wind. For sections of several kilometers length, an accuracy of about 0.05 $m\,s^{-1}$ of the vertical wind speed relative to the average wind is estimated. Temperature was measured after correcting the adiabatic heating effect of the air by the dynamic pressure at an absolute accuracy of 0.3 K and with a resolution of 0.05 K.

For slow air humidity measurements (frequency of 1 Hz), a Vaisala HMT-333 with a temperature and HUMICAP humidity sensor was mounted in a Rosemount housing. Based on the temperature measurements (uncertainty of 0.1 K), the humidity data were corrected for adiabatic heating and reach an accuracy of 2 %. All data were recorded with a frequency of 100 Hz. Note that the calibration of the 100 Hz data are only valid for straight and level ights, when using these for the calculation of turbulent uxes. The latter are not provided in the dataset. Users who want to calculate uxes with the eddy covariance method should consider only such ight sections where the aircraft was ying in a straight line.

During the HALO-(AC)^3 campaign the sensors mounted at the nose boom showed icing problems. As a result, high resolution data are not available from all ights. Problems concerned especially data from Polar 5, where we cannot provide wind data from nine ights (RFs 08-16) while from Polar 6 wind data are missing from ve ights (RFs 06-08, 12, 16). Icing is clearly marked in the published data.

3.1.3 HALO / Polar 5 - Dropsonde data

Dropsondes were released from HALO and Polar 5 to measure vertical pro les of atmospheric air pressure, temperature, relative humidity, and the horizontal wind vector. HALO exclusively used the Vaisala RD41 dropsondes (Vaisala, 2020), whereas the Polar 5 used the Vaisala RD94 for nine launches and Vaisala RD41 for the rest. Our data processing does not distinguish between the two instrument models. On both aircraft, the Advanced Vertical Atmospheric Pro ling System (AVAPS) was operated for the release and data acquisition of the dropsondes. The spatial coverage of the dropsondes released during HALO–(AC)^3 is mostly well distributed along the ight tracks (Fig. 3). However, due to limitations in ight operations, dropsondes were less frequently released in Danish airspace west of Greenland.

The dropsonde data are provided (George et al., 2024) in the same format as the Joint dropsonde Observations of the Atmosphere in tropical North atlaNtic meso-scale Environments (JOANNE) data set from the EUREC^{4}A campaign (George et al., 2021) and maintain the same de nitions of the data-processing levels from Level-0 to Level-3 as in JOANNE. For processing the dropsondes' raw data (Level-0), the Atmospheric Sounding Processing ENvironment (ASPEN Version 4.0.0, Martin and Suhr, 2024) was used and provides the basic quality controlled data (Level-1). All dropsondes underwent a pre- ight reconditioning to restore the humidity sensors calibration status from drift due to trace-gas pollutants, as also explained in Vömel et al. (2021). The dry bias correction applied in JOANNE was therefore omitted.

Level-2 data includes sondes that passed an additional quality control (successful launch and landing detection) and only contain variables that were measured. Both Level-1 and Level-2 data are provided as one le per sounding. Level-3 provides a single NetCDF le, which combines all valid Level-2 soundings from HALO and P5 in a uniform vertical grid-spacing

of 10m. We exclude any Level-4 products here (otherwise present in JOANNE), because of varying sampling strategies of the campaign, which restricts a simpli ed statistical analyses of area-averaged properties such as by George et al. (2023). Nevertheless, the retrieval for estimating the area-averaged properties during HALO-(AC)^3 are detailed in the study by Paulus et al. (2024) and the user is recommended to use the provided Level-3 data for following their estimation.

3.1.4 HALO - Communicating dropsonde data to GTS and assimilation to ECMWF services

Observations by the dropsondes released from HALO were submitted live during the ights via satellite communication to the Global Telecommunication System (GTS) to make the measurements available for data assimilation. On basis of the European Centre for Medium-Range Weather Forecasts' (ECMWF) Integrated Forecasting System (IFS) the assimilated data are evaluated here. Data were sent only for a set of mandatory (main pressure levels) and signi cant levels (local extremes). Thinning and quality control within data assimilation did further reduce data coverage. In total, data of 216 dropsondes were assimilated for 14 analysis times. The number of sondes for each analysis time varies between 4 and 41 sondes. The geographical location of the assimilated data are illustrated in Fig. 3a. There is no tendency to prefer data in sparsely covered high latitudes. Also data from high spatially resolved ight patterns such as from RF12 on 1 April 2022 were assimilated (41 sondes).

The vertical distribution of data availability in the native vertical grid of IFS is shown in Fig. 3b-d individually for wind speed, air temperature, and humidity. The distribution indicates an increased data coverage for the mandatory pressure levels. No air humidity measurements were used in the stratosphere where the accuracy of measurements is low. In the troposphere, the number of assimilated air humidity data is similar to the amount of assimilated air temperature data. In total, 19,131 observations from 216 sondes were assimilated, which distributes to 5,867 temperature observations (from 216 sondes), 4,760 wind observations (from 216 sondes), and 3,744 humidity observations (from 214 sondes).

3.1.5 HALO - Quasi-Lagrangian matches

The HALO-(AC)^3 campaign realized a quasi-Lagrangian ight strategy. As described by Wendisch et al. (2024), air masses were sampled by HALO twice or even more often between two research ights or during one ight. To promote the analysis of the air mass evolution, the locations of these quasi-Lagrangian matches are published in PANGAEA. Kirbus et al. (2024a) summarizes the matches that occurred within one ight day, while matches between two consecutive ight days are listed by Kirbus et al. (2024b). The For a reasonable analysis of air mass transformations, the data sets include only matches with a minimum threshold of one hour between the rst and second sampling. This limits the analysis to HALO ight tracks. The ight tracks of Polar 5 and Polar 6 did not cover such long distances along the trajectories.

Figure 4 illustrates the horizontal and vertical location of quasi-Lagrangian matches that occurred within the research ight number 3 (RF03) performed on 13 March 2022. All locations where the air mass was sampled the rst time (start points) are distributed on the zigzag leg directed northward. On the return ight leg these air masses were sampled a second time (end point). In total, seven quasi-Lagrangian matches (indicated by numbers in Fig. 4) were identi ed.

Figure 3. Geographic locations (a) and altitudes (b-d) of dropsonde measurements of air temperature (b), horizontal wind speed (c) and speci c humidity (d), which are available in the HALO (AC)^3 data set and which were assimilated into GTS.

The matches were derived from trajectory calculations based on the wind elds from the ECMWF reanalysis version 5 (ERA5, Hersbach et al., 2020) and the Lagrangian Analysis Tool (LAGRANTO, Sprenger and Wernli, 2015). ERA5 data has a native temporal resolution of one hour and horizontal resolution of 31 km. For each research ight of HALO, air mass trajectories were initialized in one minute resolution along the ight track via a bi-linear interpolation of the hourly ERA5 elds. To account for the ERA5 temporal and spatial resolution, 30 trajectories were distributed in a circle of 30 km radius around HALO. Vertically, trajectories were initialized at all altitudes below HALO with a 5 hPa resolution to consider wind shear, ascend and descend of air masses (see Wendisch et al., 2024). This is obvious by the distribution of the start/end points in Fig. 4b where the branches of quasi-Lagrangian matches are diffusing and not restricted to a xed vertical column. A quasi-Lagrangian match was registered, when any of the initialized air masses crossed the ight track of HALO at a later time within 30 km horizontal distance. Details on this approach and statistics on the number of quasi-Lagrangian matches are given by Wendisch et al. (2024). An uncertainty analysis is presented by Kirbus et al. (2024). Using different reanalysis data, they showed that the input wind eld does not signi cantly change the trajectories. Dropsonde data, including wind speed and