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Measurement report: Intercomparison of cloud spectrometers and a holographic probe during the ACTRIS sub-zero in-cloud Campaign at Sonnblick Observatory

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Abstract

This study presents results from the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) Cloud In Situ European Centre for Cloud Ambient Intercomparison campaign, a ground-based intercomparison of cloud spectrometers conducted at the Sonnblick Observatory (3,106 m a.s.l.) from 21 November to 3 December 2022. Seven instruments measuring cloud microphysical properties were deployed, including three Fog Monitors, three Cloud Droplet Analyzers, and an open-path Single Particle Holographic Imaging probe (ICEMET), which served as the reference instrument. The campaign evaluated cloud droplet number concentration, median volume diameter, effective diameter, liquid water content, and droplet size distributions under sub-zero conditions. Significant sampling losses were observed in vertically oriented instruments compared with ICEMET, particularly for cloud droplets with median volume diameters of 10–15 µm. Cloud droplet number concentration and liquid water content were the most affected parameters, whereas median volume diameter and effective diameter remained comparatively robust. Horizontally aligned instruments showed improved agreement with ICEMET, highlighting the importance of wind-aligned sampling geometry. Despite these losses, all spectrometers demonstrated strong consistency in derived sizing parameters, indicating that droplet size structure can be reliably retrieved under a range of deployment configurations. In contrast, liquid water content showed larger discrepancies, highlighting the need for correction methods accounting for sampling losses of larger droplets. Our results provide practical guidelines for instrument deployment, demonstrate the influence of inlet design on measurement quality, emphasize the value of multi-instrument intercomparisons, and support efforts to harmonize ground-based cloud microphysical observations within the ACTRIS framework.

1. Introduction

Clouds remain among the critical components of climate modeling, carrying significant uncertainties that impact our ability to predict climate change (Morrison et al., 2020; IPCC, 2021). Key cloud properties, such as albedo, precipitation rate, and lifetime, are linked to cloud microphysics and cloud chemical composition (e.g., Komppula et al., 2005; Chang et al., 2019; Motos et al., 2023). The characterization of cloud droplet size distribution (*DSD*) is crucial for identifying and characterizing clouds, their microphysical attributes (Rosenfeld and Ulbrich, 2003; Pruppacher and Klett, 2010) and their temporal evolution (Albrecht, 1989; Liu et al., 1995; Small et al., 2009; Van Laar et al., 2019). DSD measurements also provide insights into cloud dynamics and their role in the Earth's climate system, offering data for refining climate models and improving predictive capabilities (Guichard and Couvrex, 2017; Morrison et al., 2020). *In situ* measurements of clouds are important for advancing our understanding of aerosol-cloud interactions (Dusek et al., 2006; Asmi et al., 2011; Bellouin et al., 2019). In this context, *in situ* observation of cloud microphysical parameters remains challenging due to limitations in measurement techniques and varying environmental conditions (e.g., Spiegel et al., 2012; Guyot et al., 2015; Baumgardner et al., 2017; Doulgeris et al., 2020).

Several efforts have been made to address challenges in measuring cloud properties (e.g., Spiegel et al., 2012; Guyot et al., 2015; Lloyd et al., 2018; Chang et al., 2019; Doulgeris et al., 2022; Luebke et al., 2022). The methods to observe cloud microphysical properties are categorized into three different types of optical probes based on different working principles: the Gerber particulate volume monitor (PVM) probe (Gerber, 1984, 1991), the cloud holographic imaging probes (e.g., Baumgardner et al.,2017), and the cloud spectrometers (e.g., Doulgeris et al., 2023). PVM probes use optical measurements to determine the liquid water content (LWC) of individual droplets. The measurement generates a voltage, which is converted to *LWC* using calibrated values determined using a disk supplied with the instrument. The value of *LWC* is provided in grams of condensed liquid water per cubic meter of air (g m^{-3}), while the effective radius (Re) measures the average size of the cloud droplet population, in µm. Cloud holographic imaging probes capture images from individual objects using methods of shadowgraphy or holography (e.g., Raupach et al., 2006; Henneberger et al., 2013; Kaikkonen et al., 2020: Fuchs

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et al., 2025). Holography can generally be divided into the generation of holograms and the numerical retrieval of single-particle information from the holograms. Cloud spectrometers provide the cloud *DSD*, from which cloud droplet number concentration (N_c), *LWC*, median volume diameter (*MVD*) and effective diameter (*ED*) can be derived. Typically, the cloud spectrometers are calibrated for size measurements but not for number concentration measurements. Therefore, cloud spectrometers may be affected by sampling efficiency as a function of droplet size and are more sensitive to environmental and installation conditions. However, cloud spectrometers are essential since they are the only method to directly measure DSD. To accurately quantify cloud microphysical properties, existing cloud spectrometers should be validated and intercompared to address potential biases and uncertainties. A variety of cloud spectrometers have already been evaluated and intercompared in different environmental conditions (e.g., Gerber, 1999; Burnet and Brenguier, 1999, 2002; Spiegel et al., 2012; Guyot et al., 2015; Baumgardner et al., 2017; Doulgeris et al., 2020; Tiitta et al., 2022). These experiments revealed that cloud spectrometers could be used to observe surface clouds; however, their ability to measure clouds is strongly dependent on local conditions, requires continuous monitoring, and needs further evaluation, especially in sub-zero conditions.

At the European level, the ACTRIS project (Aerosols, Clouds, and Trace Gases Research Infrastructure Network; http://www.actris.net/) aims to improve and harmonize observations of in-situ cloud properties through a network of ground-based stations equipped with advanced atmospheric probing instrumentation for clouds. The European Centre for Cloud Ambient Intercomparison (ECCINT) plays a key role in integrating essential cloud probes, including measurements for *LWC* and *MVD*. Understanding LWC is critical for predicting the formation of cloud types and is intricately linked to three other fundamental cloud microphysical variables: *MVD*, N_c, and *DSD*. ECCINT operates in collaboration with cloud *in situ* National Facilities across Europe, ensuring the provision of high-quality datasets to support ACTRIS.

In this study, we present results from the first ECCINT Intercomparison Campaign, a community effort with the objective to test and compare the performance of multiple ground-based cloud spectrometers operating simultaneously under natural cloud conditions at the high-altitude Sonnblick Observatory. Thus, the performance of six cloud spectrometers and one open-path cloud holographic imaging probe was compared and evaluated over 16 days in November and December 2022. The measurement site and instrument description can be found in Sections 2.1 and 2.2. Subsequently, in Section 2.3, we present the procedure followed during data analysis and the campaign strategy. In Section 3, we present the intercomparison of the instruments and how they were influenced by meteorological parameters and their installation setup. Finally, in Section 4, we summarize our main results and conclusions, highlight limitations of each setup and provide recommendations for the deployment of cloud spectrometers in future studies and ongoing developments within the ACTRIS framework.

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2. Methods

2.1 Measurement site description

ECCINT took place at Mt. Hoher Sonnblick (3106 m a. s. l.) within the Sonnblick Observatory (12°57′ E, 47°03′ N), designated as a Global Atmospheric Watch station (GeoSphere Austria, 2025a). The observatory metadata were obtained from the Dynamic Ecological Information Management System, (GeoSphere Austria, 2025b). The observatory is a high-alpine site characterized by its remote location and minimal local emissions. It resides within a protected national park zone, where environmental regulations are strict and helicopter overflights are restricted. Extensive glacier fields lie to the east and south, while a steep escarpment descends approximately 800 m to the northeast. The elevated position of the observatory allows for frequent immersion in clouds, making it an ideal location for ground-based *in situ* cloud measurements under natural and relatively undisturbed conditions.

2.2 Instrumentation

During the campaign, three different types of cloud spectrometers were installed and tested: three fog monitors (FM; model 120; Droplet Measurement Technologies Inc.), three cloud droplet analyzers (CDA; Palas GmbH), and one holographic imaging probe (ICEMET; Kaikkonen et al., (2020)). An overview of instrumentation is summarized in Table 1. All instruments were installed on the southeastern terrace of the observatory (Fig. 1), to ensure the exposure to unimpeded airflow and optimal sampling conditions for the best possible and accurate measurements. Additionally, the station was equipped with instruments to continuously measure meteorological parameters in accordance with WMO standards. Below, we briefly introduce the instruments and describe their installation setups.

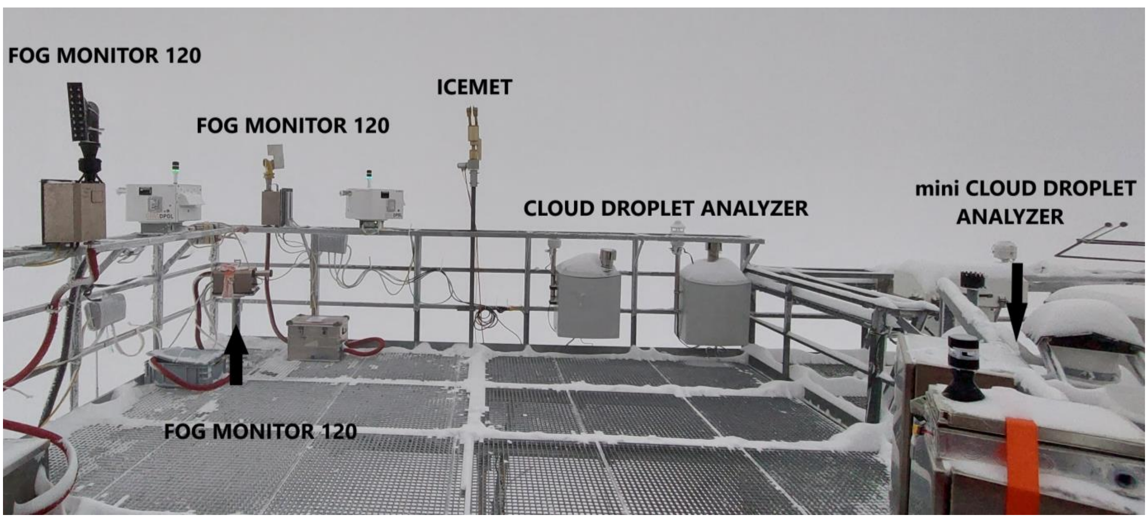

Figure 1. Overview of the cloud spectrometers and probe deployed on the Sonnblick Observatory platform during the campaign. Shown are: three Fog Monitors 120 (FM-120), two Cloud Droplet Analyzers (CDA), one Mini Cloud Droplet Analyzer (mCDA), and the Single Particle Holographic Imaging Probe (ICEMET).

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2.2.1. The Fog Monitors

The FM-120 is a forward-scattering optical spectrometer designed to measure cloud particle number concentration and size distribution. It covers a size range of 3–50 µm, divided into 30 bins at 1-µm intervals from 3 to 14 µm, and 2-µm intervals from 14 to 50 µm. When a particle passes through a 658 nm laser beam, the forward scattered (4–12°) laser light is detected, allowing the instrument to convert the scattered light intensity from individual particles into an optical scattering cross-section using light Mie scattering principles (Bohren and Huffman, 1983). The sizing calculation assumes that the particles are perfectly spherical pure water with a refractive index of 1.33 (Harvey et al., 1998). The instrument also integrates over the size bins to provide liquid water content and effective droplet diameter, among other parameters. The details of the FM-120 operation can be found in the Droplet Measurement Technologies (2009) manual.

For the FM-120, two types of inlets are available from the manufacturer: a simple horn inlet for use in both horizontal and vertical positions and a vertical swivel inlet for sampling in the wind direction. During the campaign, different inlet configurations were tested to address issues encountered under sub-zero conditions. Three Fog Monitors (FM-120) were installed at the station, originally from: The Institute of Chemical Process Fundamentals of the Czech Academy of Sciences (FM_CAS), The Finnish Meteorological Institute (FM_FMI), and The Institute for Atmospheric and Climate Sciences of Zurich (FM_ETH). All FM-120 measured at a temporal resolution of 1 s.

The FM_CAS was placed vertically and initially was operating with the swivel inlet but faced clogging issues due to ice accumulation. For this reason, the use of alternative inlet configurations was tested on site. These included a polyethylene terephthalate (PET) bottle inlet with multiple holes to prevent ice buildup (Fig. S1) and a bucket inlet attached to the horn inlet, which proved effective in preventing ice accumulation and allowed uninterrupted sampling (Fig S2). The first PET bottle inlet version had 4 holes, each pointing to a different direction. The measurements using this inlet version ran overnight without freezing the inlet, but with riming decreasing the size of the holes considerably. Thus, as a next step, the number of holes was increased to 8. Also, this inlet version required periodic cleaning as rime started growing on the holes. Finally, to overcome the need for cleaning every couple of hours, a bucket inlet made of polypropylene (PP) attached to the horn inlet with four metal binders was made. The lower edge of the bucket was located just under the upper edge of the horn inlet, allowing an undisturbed flow, but at the same time preventing the ice deposition on the inner inlet walls (Fig. S2). The possible rime growth on the bucket inlet was not influencing the measurement even in the sub-zero dense cloud conditions. The FM_CAS windows and Pitot tube were cleaned before the campaign. Calibration was conducted as suggested in the instrument manual, using precision glass beads. These beads, with a diameter of 32.5 ± 1.2 µm and composed of soda lime glass with a refractive index of 1.52, were injected into the sample area via compressed air.

The FM_ETH was also installed vertically and measured at a one-second temporal resolution. It experienced similar operational challenges to FM_CAS, especially related to inlet freezing and pump clogging. Three inlet designs were tested: a rotating inlet aligned with the wind and two custom waterproof inlets with different window sizes (Fig. S3). Only the larger-window waterproof inlet remained functional under ice-accreting conditions. Further testing is necessary to validate its long-term reliability under extreme weather. Factory calibration was conducted by the manufacturer before the campaign.

Unlike the other two FM-120s, the FM_FMI was installed horizontally and remained relatively unaffected by ice clogging, requiring minimal adjustments to the inlet configuration. It was fixed to face the main wind direction, which is around 220° at Sonnblick. Calibration was performed using glass before and after the measurement campaign.

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2.2.2. The Cloud droplet analyzers

Three CDAs were installed at the station: one from FMI (CDA_FMI), one from the company Palas (CDA_Palas), and the third one was a prototype mini cloud droplet analyser (mCDA) also operated by FMI.

The CDA (Palas GmbH) is a high-resolution optical aerosol spectrometer specifically designed for measuring the size distribution and number concentration of cloud aerosols and droplets (Doulgeris et al., 2025). The system can measure the size of the cloud droplets while also determining the water content of the air. It uses an optical aerosol sensor that utilizes Lorenz-Mie scattered light analysis of single particles to determine their size (Doulgeris et al., 2025, CDA manual). Each particle passes through an optically differentiated measurement volume that is uniformly illuminated with a polychromatic LED light source. As particles move through this volume, they generate scattered light impulses, which are detected at an angle between 85° to 95°. The number of scattered light pulses is used to determine the particle count, while the amplitude of the measured scattered light pulse serves as a measure of the particle diameter. The CDA can measure a size range approximately from 0.2 µm to 100 µm, depending on the settings. A volume flow rate of 5.0 l/min is maintained. During this campaign, CDA_FMI covered a size range from 0.4 to 94 µm using 38 bins, while CDA_Palas covered a size range from 1 to 42 µm using 52 bins (water equivalent size range). The inlet of CDA_FMI had a total sampling length of 10 cm, whereas the inlet of CDA_Palas was longer (13 cm). The calibration of CDAs was done before and after the campaign using MonoDust 1500, which is dust with a specified and known particle size. CDA_FMI measured at a ten-second temporal resolution, while CDA_Pallas measured at a two-minute temporal resolution. Both CDAs were equipped with Sigma head inlets to prevent ice deposition on the inner walls. However, the influence of the Sigma inlet design will be revisited in the discussion.

The mCDA prototype, developed by Palas GmbH, has the same fundamental measurement principles as the full sized CDA. Its sensor operates based on optical light scattering by individual particles, allowing for comprehensive analysis of cloud aerosols. The mCDA prototype holds a size range from 0.67 to 90 µm, with 256 size channels in 10 second temporal resolution. The instrument's flow rate is controlled at 2.8 l/min, optimizing particle sampling efficiency, while its LED light source ensures consistent illumination for accurate particle detection. Continuous monitoring and inspection on the instrument were conducted to ensure the absence of inlet clogging. Since it is a prototype, to ensure data quality, only measurements obtained during periods of confirmed stable operation were used in the analysis.

2.2.3 The Single Particle Holographic Imaging ICEMET

The single particle holographic imaging method typically measures particles ranging from 5 to 200 µm, and the device can measure particles up to 1 mm in diameter. For the Sonnblick dataset, the size range was restricted to 5–70 µm to effectively differentiate ice crystals from LWC and MVD data. The ICEMET uses a 5.6 mm laser diode (Ushio Opto Semiconductors) operating at 660 nm wavelength as the point light source and a Sony IMX264 grayscale image sensor with resolution 2048×2048 of 3.45 µm size pixels and a maximum frame rate of 35 frames s^{-1} (fps). A more detailed description of the ICEMET-Server hologram analysis software can be found in Molkoselkä et al. (2021). A detailed assessment of potential particle losses in the ICEMET sampling system, including the influence of isokinetic sampling factors, is provided in Juttula et al., 2022.The sampling speed typically operates at 0.27 cm^3/s or equivalently 16 cm^3/min (as implemented at the Sonnblick Observatory), depending on the wind speed. The anti-icing system is powered at 500W, operating at a voltage of 48VDC.

The ICEMET sensor was positioned on a 2-meter tall, 60 mm diameter pole atop the measurement platform. Its power supply was internally installed within the station. Data acquisition was managed by an external laptop running ICEMET-sensor software, responsible for preprocessing holograms and transmitting them

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over the measuring stations' WiFi to a server at Oulu University. The server, a GPU-equipped desktop PC, conducted hologram analysis, encompassing reconstruction, particle segmentation, autofocus, generation of binary images and storage of single particle data into a database. Additionally, it filtered data according to preset configurations to derive time-series of LWC and MVD data. The presented DSD data was acquired from the single particle datasets within the database utilizing Python scripts, operated manually for extraction. The recorded holograms were reconstructed using the method described by Kaikkonen et al., (2020) and Molkoselkä et al. (2021) using the ICEMET-Server-software version 1.6.0 (Molkoselkä, 2020).

Table 1. Overview of the cloud spectrometers used during the ECCINT-INT01 campaign.

instrument	Measurement size range	number of bins	inlet orientation	sampling frequency [Hz]
FM 120_CAS	3–50 µm	30	vertical	1
FM 120_FMI	3–50 µm	30	horizontal, fixed to one direction	1
FM 120_ETH	3–50 µm	30	vertical	1
CDA_FMI	0.40- 94 µm	38	vertical	0.1
CDA_Palas	1-42 µm	52	vertical	0.008
mCDA*	0.67 -90 µm	256	vertical	0.1
ICEMET	5-70 µm	65	horizontal, following the wind direction	1

* .. prototype

2.2.4 Meteorological instrumentation

Standard meteorological parameters were continuously monitored at the Sonnblick Observatory using the PWD 52 weather sensor (VAISALA) and the FT 42 wind sensor (Forest Technologies Systems). The PWD 52 weather sensor was installed on a 3-meter tower 5 m west from the measurement terrace and provided measurements of temperature, relative humidity, air pressure, precipitation, and visibility. The FT 42 wind sensor was installed next to the area of the cloud spectrometers. It has a crucial role in monitoring local wind dynamics, providing high-resolution measurements of wind speed and direction.

2.3 Data handling and processing

All cloud spectrometers measured the cloud size distribution, which was used to derive key cloud microphysical properties. Specifically, the PADS 4 software was used for the data acquisition of the FM (Droplet Measurement Technologies Manual, 2009), and provided the number concentration (cm^{-3}), the liquid water content ($g\ cm^{-3}$), the median volume diameter (µm), and the effective diameter (µm). For consistency, the same equations were used to derive these parameters from the CDA and mCDA. All data were averaged to a 1-minute resolution, except CDA Palas, which was already set to 2-minute averages by the manufacturer.

Uncertainties related to the cloud spectrometers typically relate to coincidence, dead-time losses and variations in velocity ratio (Guyot et al., 2015) for number concentrations above 500 cm^{-3}. During the campaign, observed N_c were mostly below 250 cm^{-3}, so these effects were considered minimal for this study. The expected sampling losses for FM are approximately 5% for 20 µm droplets, 20% for 40 µm droplets, and 40% for 50 µm droplets, as reported by Spiegel et al. (2012). These losses are primarily due to non-ideal and non-isokinetic sampling conditions, where the air flow was neither perfectly aligned with the instrument sample path nor consistent in speed. A small number of duplicates (< 5 data points) were found in the ICEMET sensor data, which

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were corrected manually. The hologram data was post-processed, and all particles identified from the hologram were stored in a database, described by the following main parameters: Equivalent Diameter (diameter of a sphere/disk with the same projected area), 3D position of the particle, Circularity of the object (Heywood circularity, relation of area to the perimeter, for a perfect circle = 1, for others > 1), Dynamic range (maximum and minimum values of the reconstructed sub-window where the particle was found). Small hex-shaped ice crystals and round ice particles were not yet reliably filtered from the Liquid Water Content (LWC) data using the Circularity (+size, dynamic range). The impact on *LWC/MVD/ED* was very small on the measurement result due to the small number of ice crystals compared to droplets, but it results in a slight overestimation of LWC in mixed-phase clouds.

Specific criteria with a combination of meteorological and instrument-based parameters, were adopted to identify cloud presence at the station. A visibility below 1000 m was used as the threshold for in-cloud conditions, while a limit of 3000 m was applied for cloud-edge cases to retain all *in situ* cloud data. In addition to visibility, relative humidity (*RH*) above 85% was connected to cloud presence at the station, and the cloud spectrometers should have a concentration > 1 #/cm^3 for a size range > 1 µm. Future campaigns would also need to define these parameters separately, as they depend on location and instrument setup.

All cloud spectrometer data went through quality control, with each team responsible for flagging any anomalies. During the campaign, a common issue encountered by most cloud spectrometers was riming of supercooled cloud droplets, which led to instrument inlet freezing and affected measurement accuracy. The flagged issues included icing or hoar frost in the intake (typically associated with near-zero dynamic pressure), as well as independent cases of pump switching or higher dynamic pressure, invalid dynamic pressure readings, and other mechanical problems. For the ICEMET sensor, no invalid data resulting from sensor icing or contamination of the sensor windows was found. In contrast, both FM_CAS and FM_ETH faced challenges with inlet clogging. As described in Section 2.2.1, the initially planned rotating inlet quickly proved unsuitable for sub-zero conditions, often clogging within a few hours. Alternative inlets were tested, but many measurements during the first cloud event were flagged due to the heavy snowfall. Based on this experience, we recommend not using either the rotating or standard horn inlets in vertical orientation under freezing cloud conditions without sufficient heating. These configurations are prone to ice accumulation and may compromise data quality during extended sub-zero operations. The use of strong heating should be cautiously considered because it could possibly lead to potential local evaporation of hydrometeors in the sampling line.

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3. Results and Discussion

A total of six natural cloud events were observed at the station during this period where temperatures ranged from -13.0 to -4.2°C, with an average temperature of -10.1°C (standard deviation 1.6°C), and the average wind speed was 7.2 ms^{-1} (standard deviation 2.6 ms^{-1}). The dominant wind direction was approximately 113.0°, although winds and clouds were observed from various directions. The diversity of wind directions and frequent cloud events provided us with a strong basis for evaluating challenges and instrument performance under cloud in situ field deployment.

The ICEMET probe provided the most extensive in-cloud, quality-controlled data coverage over the campaign period. In contrast, FM_ETH showed the lowest coverage, largely because it was used to test different inlet configurations. The differences in data coverage are due to both the operational ability of each instrument and the challenges of sampling in sub-zero conditions. To evaluate the behaviour and performance of the ground-based instruments under natural cloud conditions, the ICEMET was used as the reference instrument. As an open-path imaging instrument, ICEMET operates without obstruction from ice, making it an ideal baseline offering both high coverage and minimal sampling issues. The other instruments were divided into two groups: the first group consisted of fog monitors (FM_CAS, FM_FMI, FM_ETH), while the second group included the CDAs (CDA_FMI, CDA_Palas and the mCDA).

3.1 Evaluation of derived parameters from cloud spectrometers

3.1.1 Fog Monitor sampling losses

In this section, we focus on the measurements conducted by the three FM deployed on the station's roof. To standardize the size range between FMs and ICEMET, the first two bins of the FM were removed. Consequently, we utilized the following size ranges: FM-120 from 5 to 50 µm and ICEMET from 5 to 70 µm.

To estimate potential losses of cloud droplet counts from each FM, N_c was used as a benchmark parameter. Each FM-120 was compared to ICEMET throughout the entire identified cloud period at the station (Figure 2). Significant underestimation of N_c was observed in the vertically mounted instruments (FM_CAS: slope of 0.44; FM _ETH: slope of 0.18, Fig. 2). The size of the cloud droplets was the most influential factor affecting sampling efficiency. These discrepancies are higher for MVD larger than 10 µm, with estimated losses reaching a factor of ~ 2.5 for FM_CAS and a factor of ~ 4 for FM_ETH. This phenomenon is related to the vertical orientation of the inlets, resulting in detection consistently at a 90° angle relative to the sampling angle, which is considered unfavourable for cloud spectrometers (Guyot et al., 2016; Doulgeris et al., 2020). Additionally, for N_c exceeding 75 #/cm^3, both FM_CAS and FM_ETH losses could reach 50 %, even for smaller cloud droplets (MVD < 10 µm). This behaviour was not related to wind speed and temperature (Fig. S4, S5) and is attributed to the differences in instrument inlets/mounting orientation tested during the campaign. The FM comparison shows that sampling geometry alone can substantially influence measured cloud droplet concentrations under field conditions.

In contrast, the FM_FMI, which was installed horizontally but fixed to one wind direction, showed the best agreement with ICEMET (slope of 0.62, Fig. 2). As expected, favourable conditions were observed when the FM-120 was facing the wind direction. When the wind direction was not favourable to FM_FMI, the size of the cloud droplets remained a significant factor and potential losses reached a factor of ~ 2 for MVD larger than 10 µm. This confirms the importance of inlet orientation relative to wind in minimizing sampling losses.

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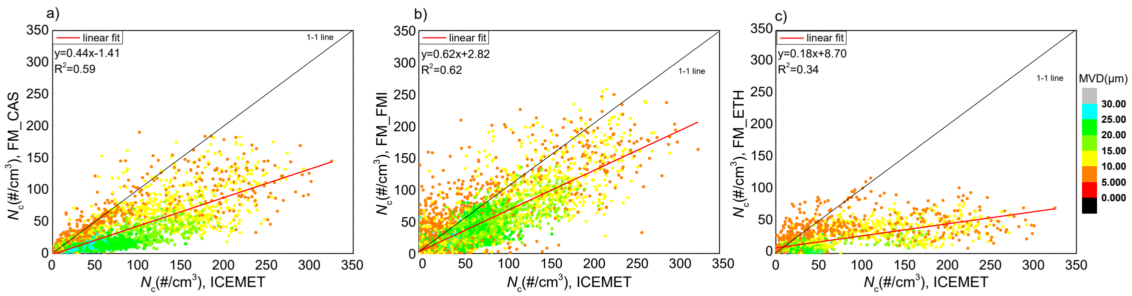

Figure 2. Comparison of 1-minute averaged number concentration (N_c) measured by (a) FM_CAS, (b) FM_FMI, (c) FM_ETH with respect to ICEMET over the whole campaign period. Data points are color-coded by median volume diameter (MVD, µm) derived from ICEMET. The black line indicates the 1:1 reference line, while the red line shows the linear regression fit.

3.1.2 Fog Monitor sizing equivalent parameters and liquid water content

This section focuses on examining the ability of FMs to derive sizing equivalent parameters, MVD and ED and the LWC. Both sizing equivalent parameters exhibited consistent agreement across the three FMs and showed strong correlation with ICEMET, with R^2 for MVD ranging from 0.77 to 0.82, and the slope between 0.78 and 0.85 (Figure 3). Similar values were observed for ED (Figure S8). The best agreement was observed for MVD < 10 µm, corresponding to FMs' minimal losses. Notably, even when N_c was significantly underestimated (even by a factor of 10 for MVD > 10 µm, Fig.2) the derived MVD and ED values remained consistently close to ICEMET across most of the observed size spectrum. Data points in the 5–10 µm and 10–15 µm range align closely with the 1:1 line, indicating strong agreement. For 15–20 µm droplets, agreement remains good but with increasing scatter. In the 20–30 µm range, a small flattening of the slope becomes visible, suggesting that FM may slightly underestimate MVD at the higher end of their sizing range. For cloud droplets >30 µm (occurring less frequently under typical Sonnblick conditions), scatter increases, and a clear underestimation is visible. This behaviour suggests that while cloud droplet losses affect N_c, the shape and peak of the size distribution are preserved well enough to maintain reliable MVD and ED values, especially in the dominant size range (<20 µm).

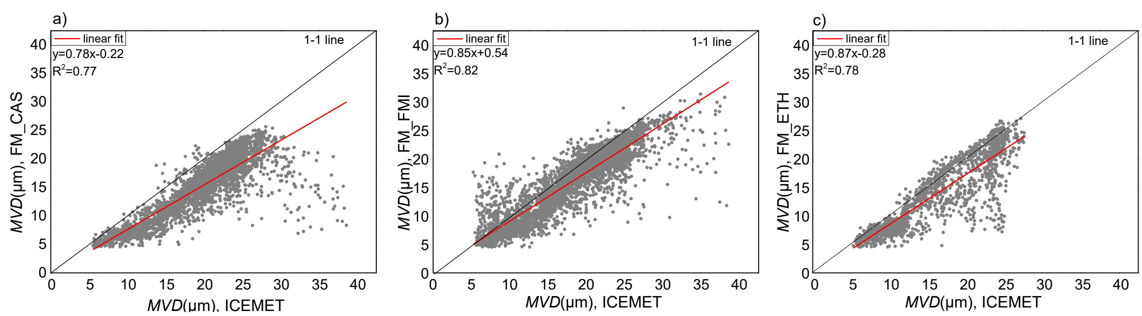

Figure 3. Comparison of 1-minute median volume diameter (MVD) measured by (a) FM_CAS, (b) FM_FMI, (c) FM_ETH with respect to ICEMET over the whole campaign period. The black line shows the 1:1 reference; the red line shows the linear regression fit.

These findings suggest that MVD and ED derived from FM instruments can generally be reliable without strict filtering, even during periods of partial sampling loss. However, when interpreting the data, one needs to

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be aware of potential biases, particularly for droplets larger than 10 µm, where aspiration losses may influence sizing accuracy. Overall, the results demonstrate that FM instruments can capture statistically meaningful cloud sizing properties even when they face losses in N_c. Overall, N_c was the most affected parameter, whereas MVD and ED remained comparatively robust.

In addition, LWC is far more sensitive to droplet count and the shape of the size distribution. Campaign variations in meteorological conditions often introduce uncertainties, particularly for larger droplets prone to losses, in surface-based cloud spectrometer measurements (e.g., Spiegel et al., 2012; Guyot et al., 2015; Doulgeris et al., 2020). Therefore, we limited the LWC comparison to wind isoaxial conditions (when the FM_FMI was aligned with the wind ±30°), which represents the most favourable scenario. Despite favourable alignment and relatively consistent N_c values, agreement between FM_FMI and ICEMET derived LWC under wind iso-axial conditions remained limited (slope = 0.25, R^2 = 0.41, Figure 4). This highlights the sensitivity of LWC estimation, particularly for fog monitors, even under ideal conditions, indicating systematic underestimation. Moreover, it suggests potential discrepancies in the measured size distributions. Notably, the most significant disparities occurred for MVD>10 µm and N_c values exceeding 50 cloud droplets/cm^3. These conditions lead to a significant underestimation of LWC. The results show that while fog monitors are reliable for sizing statistics, their LWC output is highly sensitive to sampling configuration and should therefore be interpreted with caution.

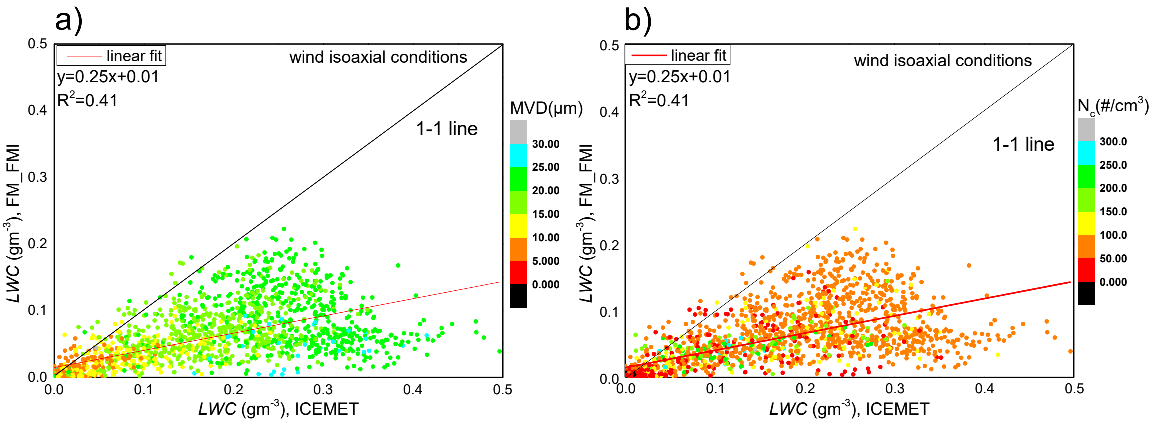

Figure 4. Comparison of Liquid Water Content (LWC) between FM_FMI and ICEMET under wind isoaxial conditions in relation to (a) MVD, (b) number concentration (N_c).

3.1.3 CDA sampling losses

As with the FM, all data were averaged to one-minute resolution (except for CDA_Palas, which operated at two-minute interval). It is important to note that mCDA, as a prototype, experienced several functionality issues and had significantly lower data coverage compared to the other CDAs. To maintain consistency in size ranges across all instruments, we excluded the first 18 bins from CDA_FMI, the first 22 bins from CDA_Palas and the first 120 bins from mCDA. The final size ranges used in the analysis were as follows: CDA_FMI from 5 to 50 µm, CDA_Palas from 5 to 40.7 µm, mCDA from 4.86 to 90 µm, and ICEMET from 5 to 70 µm.

To estimate possible losses in cloud droplet counts for each CDA, N_c was used again as the benchmark parameter. Each CDA was compared to ICEMET for the entire duration of cloud cover at the station. Unlike FM, all CDAs sampled vertically, maintaining a constant 90° angle relative to the wind. As a result, there was no wind direction that was favorable, and once again, cloud droplet size was identified as the dominant factor influencing sampling losses. Significant discrepancies were observed between CDA_FMI and CDA_Palas when compared with

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ICEMET (slopes between 0.12 and 0.21, and R^2 from 0.34 to 0.47, Figure 5). mCDA showed better agreement (slope of 0.53 with R^2 = 0.73) likely due to its shorter inlet length, which reduces inertial losses. For MVD < 10 µm, cloud droplet losses were relatively small, while for MVD > 10 µm, losses increased up to a factor of 25 for CDA and up to a factor of 4 for mCDA. These results confirm that vertical orientation and inlet configuration (specifically the sigma type inlet design) significantly influence sampling efficiency in CDAs, especially for larger cloud droplets, and highlight the need for improved inlet design optimization for ground-based deployment.

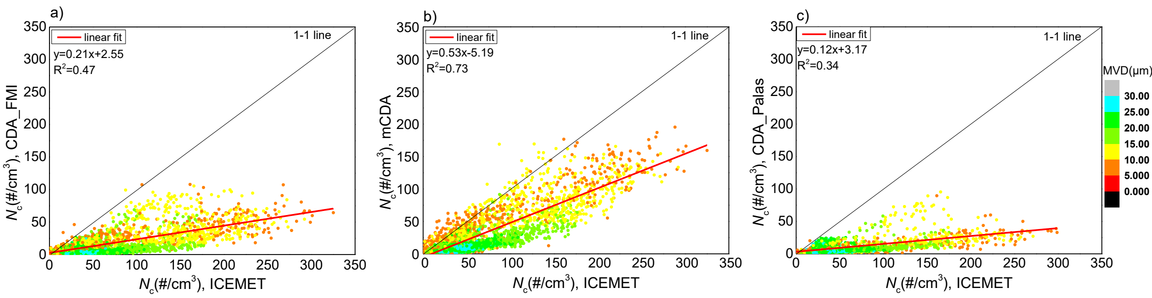

Figure 5. Comparison of number concentration (N_c) between ICEMET and (a) CDA_FMI, (b) mCDA, and (c) CDA_Palas. Points are color-coded by ICEMET-derived median volume diameter (MVD). The black line represents the 1:1 ratio; the red line shows the linear regression.

3.1.4 Cloud droplet analyzers sizing parameters and liquid water content

In this section, we focus on investigating the derived parameters MVD, ED and LWC for all three CDAs. Overall, the agreement for MVD and ED between CDAs and ICEMET was good (Fig. 6). Specifically, for MVD, R^2 ranged from 0.78 to 0.84, with slopes between 0.43 and 0.52. Similarly, when deriving ED, the R^2 values were 0.81 with a slope of 0.77 for CDA_FMI, 0.80 with a slope of 0.83 for CDA_Palas and 0.77 with a slope of 0.85 for mCDA. Despite the strong overall agreement, differences became visible when investigating performance across droplet size ranges. No significant dependence on wind speed or temperature was observed (Fig. S6, S7). For MVD < 10 µm, all CDAs showed strong agreement with ICEMET, with tight clustering around the 1:1 line. In the 10–20 µm range, the agreement remained good, but a slight flattening of the slope showed some underestimation. For MVD > 20 µm, a more evident difference appeared, with all CDAs underestimating MVD relative to ICEMET. This was most noticeable in CDA_FMI and CDA_Palas, where underestimation increased steadily with droplet size. All three CDAs had positive y-axis intercepts in their MVD comparison with ICEMET. These observations supported the conclusion that the shape and peak position of the droplet size distribution remain relatively stable, even in the presence of significant losses in number concentration. However, biases in the upper size range (>15 µm) are consistently observed and should be considered when interpreting size parameters from vertically sampling CDAs.

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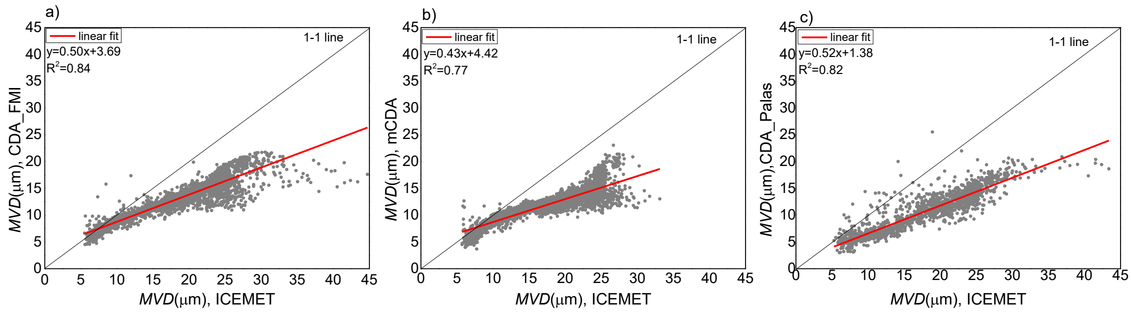

Figure 6. Median volume diameter (MVD) comparison between (a) CDA_FMI, (b) mCDA, (c) CDA_Palas and ICEMET. Black lines represent the 1:1 reference; red lines indicate linear regression fits.

For LWC, among the three instruments, mCDA showed the best performance due to its compact inlet and reduced sampling losses. However, even in this best-case scenario, the accuracy of LWC estimates remained limited, with losses of up to a factor of 4 for MVD > 10 µm. Since LWC depends heavily on both N_c and the shape of the number size distribution, current configurations of CDAs are not sufficient for reliable LWC determination without applying correction procedures. Consequently, LWC derived from ground-based cloud spectrometers should be interpreted with caution, particularly in the presence of larger cloud droplets. In particular, the sigma type inlet of the CDA introduces additional uncertainties, as its geometry enhances the incidence of cloud droplets entering at near 90° angles, conditions under which sampling efficiency is the poorest. This worsens the problem of underestimating large droplets and further complicates the retrieval of accurate LWC values. Further work is needed to improve sampling correction methods if CDAs are to be used for deriving LWC values in ground-based applications.

3.2 Size distribution

3.2.1 Size distribution of the fog monitors

Following the evaluation of the overall performance of the FM, we present the droplet size distribution observed during a cloud event on 25 November 2022. This case was selected because the wind direction was not favourable for FM_FMI, making it a suitable cloud case for investigating losses linked to non-ideal sampling orientation. The cloud event in this case evolved through different stages of cloud droplet sizes, allowing for analysis across different droplet size ranges and number concentrations under comparable meteorological conditions.

Wind speeds averaged around 5 m s^{-1}, and temperature remained nearly constant at −9.5 °C. The mean wind direction was 14.3° (STD 11.6°), corresponding to an approximately 200° deviation from the fixed FM_FMI inlet (Fig. 7). The temporal evolution of the number concentration and sizing parameters demonstrates continuous growth of cloud droplets, corresponding to an increasing number concentration. Once the number concentration reaches its peak, it begins to decline while the sizing parameters continue to increase (Fig. 7). The sizing parameters (MVD and ED) remained consistent across instruments ($R^2 \approx 0.9$), while LWC discrepancies were significant, particularly in vertically oriented FM setups.

To explore how losses vary with droplet size, we selected three time periods representing different stages of cloud development: The early stage (20:15–20:30 UTC) with MVD ≈ 7 µm, the growth phase (21:55–22:20 UTC) with MVD ≈ 12 µm, and the mature stage (23:05–23:20 UTC) with MVD ≈ 15 µm. These periods are shaded in grey in Figure 7 and correspond to size distributions in Figure 8.

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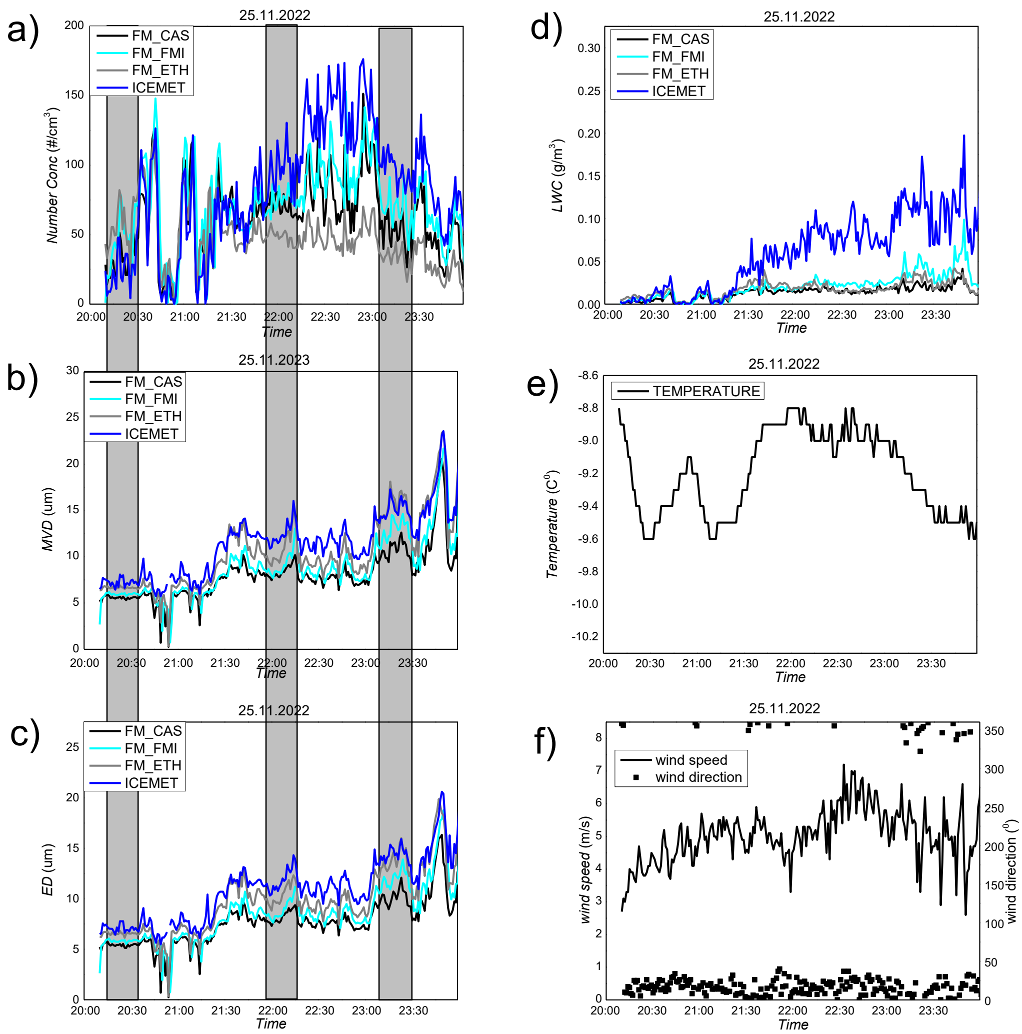

Figure 7. Time series of cloud microphysical properties measured by FMs and ICEMET and meteorological conditions on 25 November 2022 showing (a) number concentration (Nc), (b) median volume diameter (MVD), (c) effective diameter (ED), (d) liquid water content (LWC), (e) temperature and (f) wind speed and direction. Shaded grey areas highlight the three selected time intervals analysed in the size distribution comparison in Figure 8.

In the early stage, all instruments size distribution agreed well, particularly for droplets <10 µm, where sampling losses are minimal and and concentrations over 0.1 #/ccm were measured in each size bin. (Fig. 8a). In the growth and mature stages (Fig. 8b, c), ICEMET and FM_ETH showed a shift in the size distribution toward larger cloud droplets, while FM generally underestimated concentrations in the size range from 10 to 15 µm compared to ICEMET. These losses become more pronounced above ~10 µm since inertial and gravitational effects dominate, particularly for vertically sampling instruments. Horizontally aligned instrument that follows the wind direction

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(ICEMET) measured higher concentrations in the larger droplet bins, confirming earlier findings that sampling angle is a key factor influencing instrument performance.

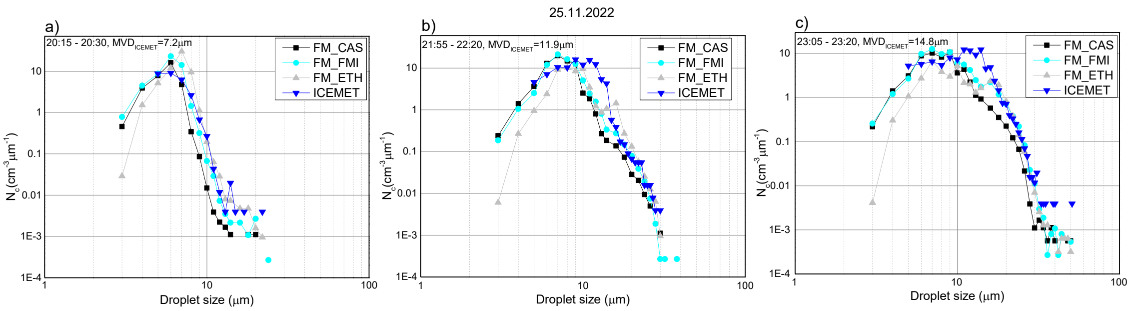

Figure 8. Size distribution of cloud droplets measured by three FM and ICEMET during three stages of a cloud event on 25 November 2022. Panels show droplet number size distributions (dN/dlogDp, #/cm^{-3}) for: (a) 20:15–20:30 UTC, MVD = 7.2 µm; (b) 20:55–22:20 UTC, MVD = 11.9 µm; and (c) 23:05–23:20 UTC, MVD = 14.8 µm.

These observations confirmed that FM underestimate cloud droplets from 10 to 15 µm, particularly when wind direction is not aligned with the inlet. As expected, this has a direct impact on derived LWC which is sensitive to large droplet contributions. Importantly, this case demonstrates that sampling losses are not uniform across the distribution but instead are size-specific. This is a crucial consideration for interpreting and correcting ground-based cloud spectrometer data. While previous sections demonstrated that MVD and ED can be reliably derived even under partial under sampling, the present analysis highlights that losses are not uniform across the distribution. As a result, while summary sizing parameters remain statistically robust, caution is warranted when interpreting the full-size distribution from such data. In such cases, the application of correction factors, particularly those accounting for inlet geometry and flow alignment (Spiegel et al., 2012) is recommended to improve the representativeness of the measured spectra and derived LWC.

3.2.2 Size distribution of Cloud Droplet Analyzers

Following the general characterization of FM performance, we present a representative case study to investigate the behaviour of the CDAs focusing on their cloud DSD measurements. The case from 30 November 2022 was selected because it represented a liquid cloud layer with well-defined periods of droplet growth and decay. This was a period during which ICEMET measured MVD >12 µm, a range in which the CDAs previously showed increased sampling losses. This example allowed us a detailed investigation of the limitations of cloud DSD measurements across different CDA designs under different microphysical conditions, particularly in the larger cloud droplets, where sampling losses and biases were expected.

Two 15-minute periods were selected for detailed comparison of size distributions: 13:15–13:30 UTC, during a peak in droplet size and concentration, and 15:00–15:15 UTC, when cloud droplet sizes were smaller (Fig. 9, grey shading). All instruments show the same temporal evolution, though ICEMET consistently reported higher values for both N_c and LWC.

At 13:15–13:30 UTC, ICEMET and mCDA measured the largest range of droplet sizes, including substantially higher concentrations of droplets >10 µm, whereas CDA_Palas measured much lower values in this size range (Fig. 10). ICEMET and mCDA reported concentrations of droplets >10 µm that were approximately 3 to 10 times higher than those measured by CDA_Palas, depending on droplet size bin. The lower concentrations reported by CDA_Palas, particularly for droplets >10 µm, are likely associated with enhanced sampling losses

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related to its inlet design and vertical sampling configuration. In addition, a shift in the size distribution is observed, suggesting that these sampling effects may also influence the droplet size spectrum. This indicates that sampling effects influence not only droplet concentrations but also the shape of the size distribution, particularly in the larger droplet range. This discrepancy is consistent with earlier findings of cloud droplets >10 µm under sampling in vertically oriented instruments with longer inlets. By contrast, at 15:00–15:15 UTC, all instruments observed a shift in the distribution toward smaller droplet sizes, with a more consistent representation of the cloud droplets <10 µm across instruments. This highlights that discrepancies increase with droplet size, indicating that sampling losses are not uniform across the size spectrum.

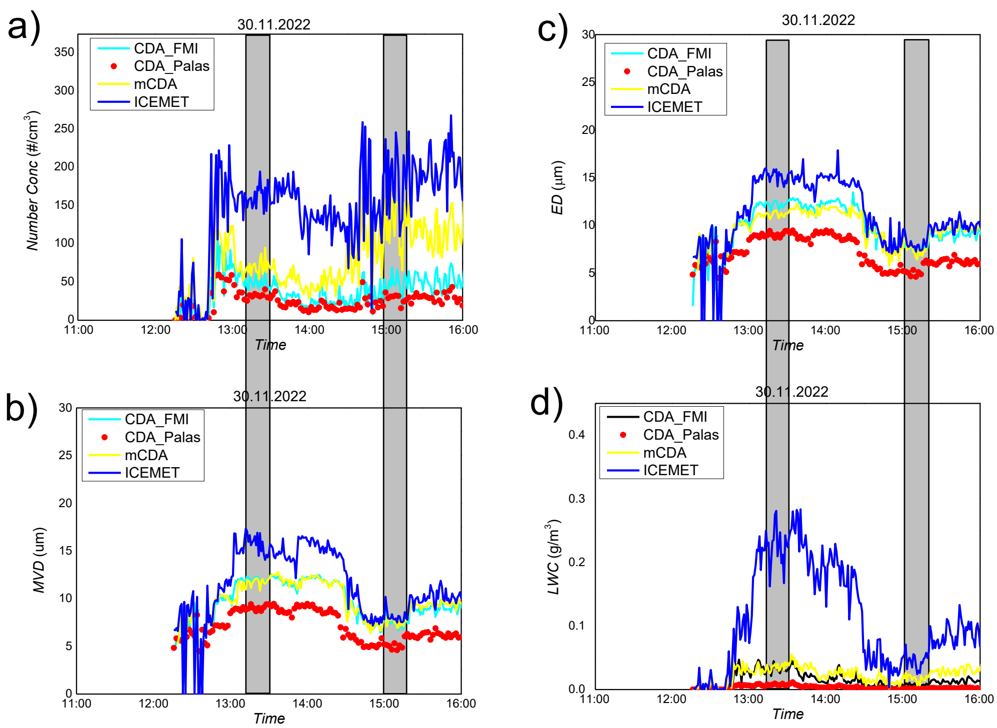

Figure 9. Time series of (a) number concentration (Nc, # cm^{-3}), (b) median volume diameter (MVD, µm), (c) effective diameter (ED, µm), and (d) liquid water content (LWC, g m^{-3}) on 30 November 2022, derived from four instruments: CDA_FMI, CDA_Palas, mCDA and ICEMET. Grey shaded areas indicate the time intervals selected for the droplet size distribution comparison in Figure 10.

These findings are consistent with the previous analysis and emphasize the role of inlet design and sampling orientation. The Sigma-type inlets used on CDA_Palas and CDA_FMI, combined with vertical sampling, are likely to enhance inertial and gravitational losses, especially for cloud droplets >10 µm. Although the mCDA also samples vertically, its much shorter inlet may reduce such losses and explain its comparatively better agreement with ICEMET. This supports the hypothesis that inlet length plays a critical role in reducing sampling losses.

This case highlights the importance of investigating bin-to-bin differences when evaluating cloud microphysical properties. While MVD and ED may still be reliably derived due to the stability of the DSD peak, full size distribution agreement, particularly for cloud droplets >10 µm, is more vulnerable to instrumental and sampling related biases. The results highlight the need for careful deployment strategies and suggest that shorter,

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simpler inlets may offer advantages in minimizing losses. Finally, this intercomparison highlights the value of using multiple instruments to assess and harmonize DSD-derived parameters, especially when characterizing droplet populations in different cloud types.

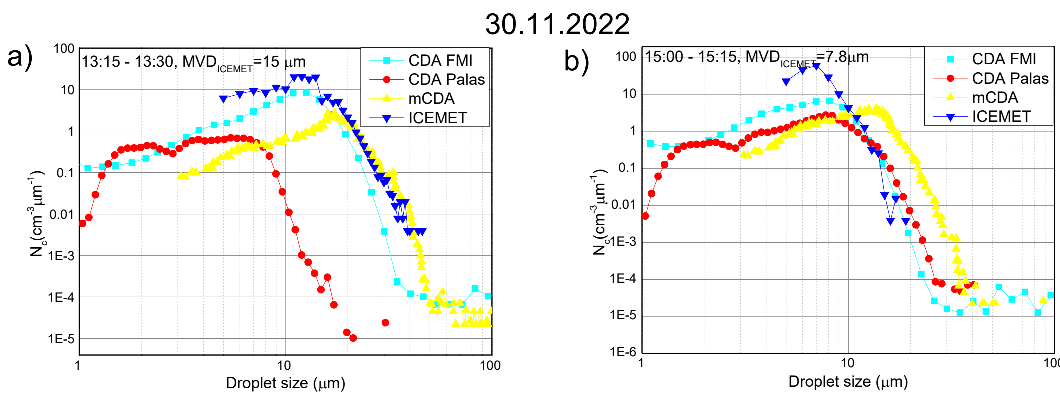

Figure 10. Droplet size distributions measured on 30 November 2022 by four cloud spectrometers: CDA_FMI, CDA_Palas, mCDA and ICEMET during two selected time periods: (a) 13:15–13:30 UTC with MVD_ICEMET ≈ 15 µm and b) 15:00–15:15 UTC with MVD_ICEMET ≈ 7.8 µm.

4. Conclusion

This study presents results from the first European Centre for Cloud Ambient Intercomparison campaign, a coordinated intercomparison effort conducted at the high-alpine Sonnblick Observatory in 2022. Over a 13-day period, we evaluated the performance of six cloud spectrometers, including three Fog Monitors (FMs), three Cloud Droplet Analyzers (CDAs), and one holographic imaging probe (ICEMET), which served as the reference due to its open-path operation and high temporal coverage under sub-zero conditions. The campaign was designed to evaluate instrument performance under realistic environmental conditions and varying inlet configurations, with a particular focus on sampling losses across droplet size ranges, derivation of key sizing parameters (MVD, ED), estimation of liquid water content (LWC), and the characterization of droplet size distributions (DSDs).

Our results highlight the critical influence of inlet orientation and geometry on sampling efficiency. Both FMs and CDAs exhibited significant losses, especially for cloud droplets in the size range from 10 to 15 µm, when operated in vertical configurations. The horizontally oriented FM_FMI, aligned with the prevailing wind, showed the best agreement with ICEMET, highlighting the importance of isoaxial flow conditions. CDAs, all of which sampled vertically through sigma inlets suffered notable losses in cloud droplets >10 µm. However, the mCDA prototype showed improved performance relative to its full-sized counterparts, likely due to its shortened inlet path. Despite sampling losses, all instruments demonstrated strong agreement in derived MVD and ED, indicating that the peak and shape of the size distribution were sufficiently preserved for microphysical characterization. In contrast, N_c and *LWC* were more sensitive to sampling configuration, with *LWC* showing the largest discrepancies across instruments, even under isoaxial flow conditions. These results suggest that LWC estimates from ground-based cloud spectrometers should be interpreted with caution, particularly in the presence of larger cloud droplets. Analysis of *DSD*s revealed systematic under-representation of larger cloud droplets (10–15 µm) in vertically oriented instruments, contributing directly to *LWC* underestimation. This highlights the importance of inlet design and sampling orientation, particularly when interpreting full size distributions.

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To conclude, FM and CDA systems can provide useful sizing information under sub-zero conditions but have clear limitations for N_c and *LWC* measurements. The results emphasize that even well-established probes require site-specific deployment strategies, ongoing evaluation and community-driven intercomparison campaigns to identify and reduce uncertainty. For future studies, we recommend the adoption of horizontal, wind-aligned sampling configurations where feasible, as this orientation consistently reduces droplet losses, particularly for larger cloud droplets. Further evaluation of miniaturized inlet designs, such as that used in the mCDA, may offer promising improvements in reducing inertial and gravitational sampling losses. Additionally, the development of bin-level correction schemes is essential to recover larger cloud droplet concentrations and improve the accuracy of derived parameters such as *LWC*. A stronger emphasis on calibration procedures, particularly for number concentration, is also necessary, as sizing is often well characterized, while particle counting remains a major source of uncertainty across instruments. Finally, continued support for multi-instrument intercomparison efforts, such as those coordinated within the ACTRIS frameworks remain critical for harmonizing measurement practices and advancing the reliability of ground-based cloud microphysical observations. Although no corrections were applied in this study, future work should apply established FM corrections (e.g., Spiegel et al., 2012) and develop corresponding correction factors for CDAs.

By highlighting both strengths and limitations in cloud spectrometers, this work contributes to the broader goal of harmonizing ground-based cloud microphysical measurements and improving the quality of long-term datasets important for aerosol cloud interaction studies.

Data availability

The dataset is available for download at https://doi.org/10.5281/zenodo.21642322 (Doulgeris et al., 2026).

Competing interests

The authors declare that they have no conflict of interest.

Author Contributions

KD led the data analysis and manuscript preparation with contribution from all coauthors. CM and EL designed the study. DB, CM, VK, NZ, CZ. KJ and EL contributed to instrument deployment and data collection during the campaign. All authors contributed to data interpretation and reviewed the manuscript.

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