Ice aggregation in Arctic shallow mixed-phase clouds: enhanced by dendritic growth and absent close to the melting level

Giovanni Chellini[1], Rosa Gierens[1], and Stefan Kneifel[1]

[1]University of Cologne

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Abstract

Shallow mixed-phase clouds (MPCs) occur extensively in the Arctic, and are known to play a key role for the energy budget. While their characteristic structure is nowadays well understood, the significance of different precipitation-formation processes, such as aggregation and riming, is still unclear. Using a 3-year dataset of vertically-pointing W-band cloud radar and K-band Micro Rain Radar (MRR) observations from Ny-Ålesund, Svalbard, we statistically assess the relevance of aggregation in Arctic low-level MPCs. Combining radar observations with thermodynamic profiling, we find that larger snowflakes (mass median diameter above 1 mm) are predominantly produced in shallow MPCs whose mixed-phase layer is at temperatures between -15 and -10°C. This coincides with the temperature regime known for favoring aggregation due to growth and subsequent mechanical entanglement of dendritic crystals. Doppler velocity information confirms that these signatures are likely due to enhanced ice particle growth by aggregation. Signatures indicative of enhanced aggregation are however not distributed uniformly across the cloud deck, and only observed in limited regions, suggesting a link with dynamical effects. Low Doppler velocity values further indicate that significant riming of large particles is unlikely at temperatures below -5°C. Surprisingly, we find no evidence of enhanced aggregation at temperatures above -5°C, as is typically observed in deeper cloud systems. Possible reasons are discussed, likely connected to the ice habits that form above -10°C, increased riming, and lack of already aggregated particles precipitating from higher altitudes.

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Ice aggregation in Arctic shallow mixed-phase clouds: enhanced by dendritic growth and absent close to the melting level

G. Chellini[1], R. Gierens[1], and S. Kneifel[1]

[1]Institute for Geophysics and Meteorology, University of Cologne, Cologne, Germany

Key Points:

- Arctic shallow MPCs produce large ice aggregates predominantly at dendritic-growth temperatures
- The typically observed enhanced aggregation zone close to 0°C is absent in Arctic shallow MPCs
- Enhanced aggregation due to dendritic growth occurs intermittently in limited regions of the MPC

Corresponding author: Giovanni Chellini, g.chellini@uni-koeln.de

Abstract

Shallow mixed-phase clouds (MPCs) occur extensively in the Arctic, and are known to play a key role for the energy budget. While their characteristic structure is nowadays well understood, the significance of different precipitation-formation processes, such as aggregation and riming, is still unclear.

Using a 3-year dataset of vertically-pointing W-band cloud radar and K-band Micro Rain Radar (MRR) observations from Ny-Ålesund, Svalbard, we statistically assess the relevance of aggregation in Arctic low-level MPCs. Combining radar observations with thermodynamic profiling, we find that larger snowflakes (mass median diameter above 1 mm) are predominantly produced in shallow MPCs whose mixed-phase layer is at temperatures between -15 and -10°C. This coincides with the temperature regime known for favoring aggregation due to growth and subsequent mechanical entanglement of dendritic crystals. Doppler velocity information confirms that these signatures are likely due to enhanced ice particle growth by aggregation. Signatures indicative of enhanced aggregation are however not distributed uniformly across the cloud deck, and only observed in limited regions, suggesting a link with dynamical effects. Low Doppler velocity values further indicate that significant riming of large particles is unlikely at temperatures below -5°C.

Surprisingly, we find no evidence of enhanced aggregation at temperatures above -5°C, as is typically observed in deeper cloud systems. Possible reasons are discussed, likely connected to the ice habits that form above -10°C, increased riming, and lack of already aggregated particles precipitating from higher altitudes.

Plain Language Summary

Shallow mixed-phase clouds (MPCs), i.e. shallow clouds containing both liquid droplets and ice crystals, form frequently in the Arctic region. Their characteristic structure -consisting of one or multiple liquid layers at sub-zero temperatures, from which ice crystals form and precipitate- is nowadays well understood. However, the processes that lead to the growth of ice crystals into snow have been overlooked.

Using a 3-year dataset of radar observations from Ny-Ålesund, in Svalbard, Norway, we are able to identify situations when the ice particle growth is dominated by aggregation of several individual crystals. Combining radar observations with temperature information, we find that larger snowflakes are only produced in MPCs if their liquid portion is at temperatures between -15 and -10°C. This coincides with the temperature regime known for favoring aggregation due to growth and subsequent entanglement of branched crystals.

Surprisingly, we find no evidence of enhanced ice aggregation at temperatures above -5°C, as is typically observed in deeper cloud systems. Possible reasons are discussed, likely connected to the ice crystal shapes that develop above -10°C, increased liquid droplet production, and lack of already aggregated particles precipitating from higher altitudes.

1 Introduction

Shallow mixed-phase clouds (MPCs) are ubiquitous in the Arctic. They have been shown to occur widely and frequently (e.g., Morrison et al., 2012; Mioche et al., 2015) and to persist typically for several hours (de Boer et al., 2009; Shupe, 2011), with some recorded cases lasting up to several days (e.g., Zuidema et al., 2005). They are further known to introduce, on average, a strong positive surface radiative forcing (Shupe & Intrieri, 2004; Serreze & Barry, 2011; Matus & L'Ecuyer, 2017; Tan & Storelvmo, 2019). Arctic shallow MPCs display a characteristic structure with one or multiple shallow liquid layers close to cloud top, from which ice particles form and precipitate (Shupe et al.,

2006b). Their persistence is due to a complex interplay of several processes (Morrison et al., 2012), and they have been found to occur under a variety of conditions, including both stable and unstable stratification, and under a wide spectrum of aerosol concentrations (Jackson et al., 2012; Sotiropoulou et al., 2014; Kalesse, de Boer, et al., 2016; Young et al., 2016; Gierens et al., 2020). Intense cloud-top radiative cooling caused by the supercooled liquid close to cloud top drives buoyant production of turbulence in the cloud layer, which, in turn, drives condensation and maintains the liquid layer (Solomon et al., 2011).

The frequent formation of precipitation in Arctic mixed-phase clouds has been demonstrated by several studies, as far back as Rangno and Hobbs (2001) and Harrington and Olsson (2001). More recently, Silber, Fridlind, et al. (2021) observed that more than 85% of clouds containing supercooled liquid above Utqiaġvik, Alaska, precipitate continuously. Precipitation from MPCs, especially when deposited to the surface, withdraws moisture and ice nuclei from the MPC (Morrison et al., 2012; Solomon et al., 2014, 2015). Lower cloud fractions and faster dissipation have been suggested for Arctic stratocumuli that develop precipitation (Harrington & Olsson, 2001; Simpfendoerfer et al., 2019). It can then be expected that in addition to cloud lifetime, precipitation further affects the phase and radiative characteristics of the MPC (Harrington & Olsson, 2001; Avramov & Harrington, 2010; Solomon et al., 2015; Tan & Storelvmo, 2019; Eirund et al., 2019; Proske et al., 2021). Tan and Storelvmo (2019) have shown that in the Community Earth System Model (CESM) Arctic amplification increases the larger the ice particles in Arctic MPCs are, because of a stronger cloud-phase feedback. Furthermore, Proske et al. (2021) argue that, out of all microphysical processes, aggregation is the dominant mechanism affecting ice water path and cloud radiative effects, and therefore has the largest need to be represented correctly in climate models. Gaining process-level understanding of precipitation formation in Arctic shallow MPCs is thus necessary for an accurate representation of these clouds. In particular, the role of individual ice-growth processes, such as aggregation and riming, in the formation of precipitation in Arctic low-level MPCs is still unclear.

In-situ observations of ice particles in Arctic shallow MPCs reported in literature vary largely: pristine ice crystals, aggregates, and rimed particles have all been observed (McFarquhar et al., 2007; Avramov et al., 2011; Mioche et al., 2017; Wendisch et al., 2019). McFarquhar et al. (2007) reported observing mostly irregular and rimed branched crystals at cloud base, from in-situ aircraft observations at Utqiaġvik, Alaska. At the same site Avramov et al. (2011) observed dendrites and large aggregates. Mioche et al. (2017) compiled in-situ observations from several aircraft campaigns above the Greenland and Norwegian seas, reporting large fractions of rimed or irregular ice particles. Fitch and Garrett (2022) reported, based on long-term ground-based in-situ observations, that, at Oliktok Point, Alaska, 65% of all frozen precipitation displays some degree of riming, even with observed liquid water path of less than 50 g/m^2.

In this study we investigate the significance of different ice-growth processes, with a focus on aggregation, for precipitation formation in Arctic MPCs, using a long-term dataset of vertically-pointing dual-frequency (K- and W-band) radar observations, from the high-Arctic site of Ny-Ålesund, Svalbard, Norway. Radar observations obtained at different wavelengths can be combined in order to derive mean particle size of the hydrometeor population based on their differential scattering properties (Battaglia et al., 2020). The dual-wavelength ratio (DWR), i.e. the ratio of equivalent radar reflectivity factors at two separate frequencies, increases when particles grow in size and transition from the Rayleigh scattering regime into the non-Rayleigh scattering regime (e.g., Hogan et al., 2000; Liao et al., 2005). When combined with in-cloud temperature and filtering for intense riming using vertical Doppler velocity information, DWR information has been used to derive the typical temperature regions favoring aggregation for mid-latitude clouds by e.g. Dias Neto et al. (2019) and Barrett et al. (2019). These authors observed a first

noticeable increase in DWR at Ka- and W-band to occur in the temperature interval from -15 to -10°C, consistently with early cloud chamber studies (e.g., Kobayashi, 1957). Said temperature region is part of the often-called dendritic-growth zone (DGZ), where several plate-like particle habits are preferentially growing, including dendrites. The DGZ extends from -20 to -10°C, with enhanced depositional growth between -18 and -12°C (Takahashi et al., 1991; Takahashi, 2014). The dendrites' large cross-sectional area and ability to mechanically entangle their branches favor a rapid formation of aggregates (Pruppacher & Klett, 2012; Connolly et al., 2012). A second enhanced aggregation zone close to 0°C is often observed as well, revealed by a further increase in DWRs at several frequency combinations (W-, Ka-, Ku-, and X-band) (Chase et al., 2018; Dias Neto et al., 2019; Tridon et al., 2019). Close to the melting level the presence of a quasi-liquid layer on the ice particles (Fletcher, 1962; Slater & Michaelides, 2019) is thought to favor intense aggregation (Fabry & Zawadzki, 1995).

Here, we obtain 3-year statistics of DWR in Arctic shallow MPCs, by combining radar observations from a W-band cloud radar and a K-band precipitation radar, the Micro Rain Radar 2 (MRR-2). We further combine radar observations with thermodynamic retrievals from a co-located microwave radiometer. This publication is thus structured as follows: essential theoretical aspects of dual-wavelength radar observations are explained in section 2, the instruments and further techniques used are described in section 3, results are shown and discussed in section 4, and finally the main conclusions and questions raised by this study are summarized in section 5.

2 Background: dual-wavelength radar approach

The equivalent radar reflectivity factor Z_e (hereafter called reflectivity) for an ensemble of scatterers in the measurement volume is defined as:

$$Z_e = \frac{\lambda^4}{\pi^5}||K_W||^{-2}\int_0^\infty N(\sigma_b)\sigma_b(\lambda)d\sigma_b, \tag{1}$$

where λ is the transmitted signal wavelength, $||K_W||^2$ is the dielectric constant of liquid water, σ_b is the backscattering cross-section of the individual scatterers, and $N(\sigma_b)$ the number distribution across the scatterer population (Fabry, 2018). Z_e thus depends on both size (through σ_b) and concentration of particles (through $N(\sigma_b)$), in addition to habit, phase, and orientation, and does not provide unequivocal information on particle size. Following the definition of Z_e, values measured at two wavelengths are equal if scattering from all particles and at both wavelengths can be approximated by Rayleigh scattering. If the particles increase in size, they first start to deviate from Rayleigh scattering at the shorter wavelength: this leads to a smaller Z_e at the shorter wavelength compared to the longer one, where more particles are still in the Rayleigh scattering regime (Battaglia et al., 2020). As a result, quantities combining Z_e values at both wavelengths can be related to the characteristic size of the underlying particle size distribution (Hogan et al., 2000; Matrosov et al., 2005; Liao et al., 2005; Szyrmer & Zawadzki, 2014; Tridon & Battaglia, 2015; Kneifel et al., 2016).

The most commonly used variable to quantify differential scattering of the radar beams at two separate wavelengths is the Dual-Wavelength Ratio (DWR, sometimes named Dual-Frequency Ratio, DFR), defined as:

$$DWR_{\lambda_1,\lambda_2} = \frac{Z_{e,\lambda_1}}{Z_{e,\lambda_2}}, \tag{2}$$

where Z_{e,λ_i} are the equivalent reflectivity factors in linear units and λ_1 is commonly chosen to be larger than λ_2. With this convention DWR = 0 dB if particles scatter according to the Rayleigh regime at both wavelengths and if their $||K_W||^2$ (Eq. 1) are identical or have been corrected for. DWR values increase as particles transition into non-Rayleigh

scattering at the shorter wavelength, then reach a saturation value as non-Rayleigh scattering is reached at both wavelengths. As a result, the DWR can be used as a proxy for the mean size of the sampled particle population (Hogan et al., 2000; Liao et al., 2005; Kneifel et al., 2016). The relation between DWR and particle size is, however, not univocal, and further depends on the particle shape and density (e.g., Matrosov et al., 2019) as well as on the particle size distribution (PSD) shape (Mason et al., 2019). Using the scattering database of Ori et al. (2021) and dendrite aggregates as well as a simple inverse exponential PSD, we find for example a DWR_{K-W} of 3 (6, 9) dB to correspond to a mass median diameter of 1.5 (2.4, 3.7) mm, respectively. The maximum DWR value for such modeled dendrite aggregates is 11.4 dB, obtained for a mass median diameter of 8.1 mm, while the saturation DWR value is 9.4 dB. The full dependency of DWR on mass median diameter for different particle types is shown in Appendix A.

3 Datasets and methods

3.1 Measurement site

The observations analyzed in this study were carried out at the observatory of the Arctic research base AWIPEV in Ny-Ålesund, Svalbard. Ny-Ålesund is located at 79°N, in the region where Arctic amplification is the most intense (e.g., Dahlke & Maturilli, 2017). The site is located 13 m above sea level close to the coast of the Kongsfjorden, a fjord with surrounding mountains with altitudes of 500 to 1000 m. Similar to other locations in the Arctic, the lower troposphere above Ny-Ålesund is often stably stratified. Temperature and humidity inversions have been found in respectively 75 and 84% of the daily radiosondes launched between 1993 and 2014 (Maturilli & Kayser, 2017). Mean monthly values of surface air temperature have been observed to range between 5.8°C in July and -12.0°C in March (Maturilli et al., 2013) and average yearly precipitation has been measured to be 564 mm/year with a large standard deviation of 444 mm/year, in the 2012-2019 period (Mori et al., 2021). Furthermore, remote sensing observations of clouds at this location have already been analyzed in depth by previous studies, such as Nomokonova, Ebell, et al. (2019), Vassel et al. (2019), Nomokonova et al. (2020), Gierens et al. (2020), and Ebell et al. (2020).

While clouds in general occur at the site 60-80% of the time (Shupe, 2011; Maturilli & Ebell, 2018; Nomokonova, Ebell, et al., 2019), Nomokonova, Ebell, et al. (2019) observed a frequency of occurrence of 20.6% for single-layer MPCs (with no restriction on cloud depth or cloud-top height). They report an average LWP of 66 g/m^2, and average IWP of 164 g/m^2 for this cloud type. Gierens et al. (2020) estimated the occurrence of low-level MPCs lasting more than 1 hour to be 23%, with average LWP and IWP values of 35 and 12 g/m^2, respectively. Frequency of occurrence, LWP and IWP values from these two studies are similar to those observed during the Surface Heat Budget of the Arctic Ocean (SHEBA) campaign (Shupe et al., 2006a), at Iqaluit, Alaska (de Boer et al., 2009; Zhao & Wang, 2010), and at Eureka, Nunavut, Canada (de Boer et al., 2009). The height of the liquid base of low-level MPCs ranges typically between 0.54 to 1.0 km, which is at or above the height of the surrounding mountaintops (Gierens et al., 2020).

3.2 Radar systems

In this study, we calculate DWRs (K- and W-band) of MPCs based on continuous zenith-pointing radar observations available from September 2017 to October 2018, and from June 2019 to February 2021. The W-band observations are obtained with 94-GHz frequency-modulated continuous wave (FMCW) Doppler cloud radars (RPG-FMCW-94-SP, manufactured by Radiometer Physics GmbH (RPG); Küchler et al. (2017)). Observations from two slightly different RPG-FMCW-94-SP radar systems have been combined: during the first time period, observations were collected with the MiRAC-A (Mech et al., 2019) which has a slightly larger beamwidth than the JOYRAD-94 (Küchler et

	JOYRAD-94	MiRAC-A	MRR-2
Central frequency	94.0 GHz	94.0 GHz	24.23 GHz
Time res.	2-3 s	2-3 s	60 s
Integration time	0.5-0.6 s	0.5-0.6 s	60 s
Range res.	4-5.3 m	3.2-7.5 m	30 m
Min. range	100 m	100 m	30 m
Max. range	12 km	12 km	960 m
Sensitivity at 100 m	-62 dBZ	-64 dBZ	-13 dBZ
Sensitivity at 900 m	-50 dBZ	-50 dBZ	-6 dBZ
Beam width (half power)	0.5°	0.85°	1.5°

Table 1. Selected technical specifications of the three radar systems used in this study: two cloud radars, JOYRAD-94 and MiRAC-A, and a precipitation radar, MRR-2. Further information on the instruments can be found, respectively, in Küchler et al. (2017), Mech et al. (2019), and Klugmann et al. (1996).

al., 2017) used from June 2019 onwards. Both systems collected data with a temporal resolution of 2-3 s and vertical resolutions between 3-8 m depending on the range region (for technical details of the radars see Table 1, Küchler et al. (2017), and Gierens (2021)). The measurements were set up with a minimum and maximum range of 100 m and 12 km, respectively.

The W-band observations are complemented by observations from a K-band (24 GHz), zenith-pointing, FMCW Doppler Micro Rain Radar (MRR-2, Metek GmbH; Klugmann et al. (1996)). Due to its economic and light-weight design it has been frequently used to study snowfall in mountainous (Cha et al., 2009; Kneifel et al., 2011) and polar regions (Grazioli et al., 2017; Durán-Alarcón et al., 2019), evaluate satellite products (Maahn et al., 2014; Souverijns et al., 2018) and model performance (Scarchilli et al., 2020). We use the processing method developed by Maahn and Kollias (2012), which is fine-tuned for observations of frozen hydrometeors. The resolution in time (60 s) and range (30 m) is much coarser than the W-band cloud radars. Its average sensitivity for this measurement set up ranges between -13 and -6 dBZ, depending on range. Said sensitivity was calculated as the mean average noise level times 1.2, as that is the lowest threshold for spectral reflectivity values to be considered signal in the processing routine by Maahn and Kollias (2012).

In order to calculate DWRs, we averaged the W-band data to the MRR resolution. Note that during the study period the MRR was set up to measure with a maximum range of 960 m. Calculated DWRs are therefore only available from the lowest W-band range gate (100 m) up to this height. Mean Doppler Velocity (MDV) is taken from the W-band cloud radars.

3.2.1 Radar calibration evaluation

Since the aim of our analysis is gaining information on particle size based on DWR calculated from Z_e at K- and W-band, evaluating the calibration (especially in a relative sense) of all radar systems involved is necessary. The radar calibration constant might change, e.g. due to drifts, which can lead to biases in the measured Z_e. In our analy-

MRR-2 yearly JJAS offsets (dB)	-0.81, -1.33, -1.57, -1.88, -1.91
MiRAC-A monthly offsets (dB)	2.75, 3.25, 3.75, 2.25, 4.75, 2.25, 2.75, 2.75, 1.25, 0.75, 0.75, 1.25, 2.75
JOYRAD-94 monthly offsets (dB)	1.75, -0.25, -0.25, -0.25, 0.75, 1.25, 2.25, 2.25, 1.75, 0.75, 0.75, 5.25, 0.25, -0.25, -0.25, 1.25, -0.25, 3.25, 1.75, 1.25, 1.25

Table 2. Calibration offsets obtained for the three radar systems used in the study. The offsets indicated for the MRR-2 were obtained yearly for the period from June to September. Monthly offsets for the remaining months were obtained by linear interpolation of the indicated values. Offsets indicated for JOYRAD-94 and MiRAC-A were calculated monthly. Offsets are reported in chronological order.

sis, we obtained calibration offsets for the MRR following a widely used disdrometer-based approach (e.g., Dias Neto et al., 2019; Myagkov et al., 2020). The W-band radars were instead calibrated using a DWR-based approach, requiring that the DWR distribution has its mode at 0 dB. All the derived offsets are reported in Table 2.

At the AWIPEV site a Parsivel disdrometer (Löffler-Mang & Joss, 2000) is installed, and data are available for the whole study period. Parsivel measures volume-equivalent sizes and fall speeds of particles that fall through its laser beam. It thus provides particle size distributions, and fall speed distributions for the particle population. A critical assessment of its performance can be found in Battaglia et al. (2010). The disdrometer-based calibration method consists in forward simulating Z_e values from drop size distribution observed by Parsivel during rain events. The simulated reflectivities were then compared with the observed ones, taken from the range gate between 120 and 150 m. We selected the rain events based on the following criteria:

- Disdrometer detects liquid precipitation. If frozen precipitation is detected all liquid within 10 minutes is ignored.
- Only data from June through September are used, and only when surface temperature (from nearby weather station) is greater than 5°C, in order to exclude misclassified frozen or partially melted precipitation.
- Disdrometer data are only used if rain rate ≥ 0.1 mm/h following the approach by Williams et al. (2005). Additionally only measurements containing at least 25 samples per minute are used. Both criteria are required in order for the disdrometer measurements to be representative of the drop population.
- Drop size distributions (DSDs) from Parsivel must contain particles larger than 1 mm. This criterion was determined following Myagkov et al. (2020), so that evaporation of the drops between the chosen range gate and the ground doesn't affect the forward simulated Z_e values.
- Events are required to last at least one hour, with gaps allowed for a total of one sixth of the duration of the event.

Reflectivity values were based on the observed DSDs, and forward simulated with the T-matrix method (Waterman, 1965; Leinonen, 2014), using a drop shape model from Thurai et al. (2007). Following Huang et al. (2008), the drops were assumed to have Gaussian distributed canting angles, with 0° mean value and a 10° standard deviation. Attenuation due to liquid was simulated as well, and was subtracted from the forward simulated reflectivity values. All Z_e values below -10 dBZ and above 25 dBZ were excluded. It should be noted that we did not compare time series of observed and simulated Z_e but

rather compared the Z_e distribution of the total rainfall event. This mitigates the issue of time delays between Z_e observed at the lowest radar range gate and the surface observations. A single median reflectivity value was then obtained for all events in each June-through-September period, for both the observations and the forward simulation. In each period the Z_e offset was obtained by subtracting the two median values. In the periods from October to May, monthly Z_e offset values were calculated by linearly interpolating the obtained values. In the months from October 2020 to February 2021 the same offset obtained during the June-through-September period in 2020 was used.

We attempted to apply the same disdrometer-based approach to the calibration of the W-band radars, but we observed a strong dependence of the calculated offset values on the accumulated precipitation during the events. We hypothesize that this is due to deterioration of the coating of the radomes, leading to some of the rain water being absorbed by the radome, thus causing increasing attenuation of the signal. Although this phenomenon is not an issue for snowfall observations, it hampers the applicability of the disdrometer-based method to the W-band radars. For the MRR, we did not observe any attenuating effect due to wet antenna. Unlike the W-band radar, the MRR is not covered by a radome. Due to this reason we used the MRR as our reference and estimated the offsets of the W-band radars using a DWR-based approach in light snowfall. Although the MRR is quite limited in its maximum range, this approach using light snowfall is overall similar to relative calibration methods applied to cloud radars in low-reflectivity ice clouds (Dias Neto et al., 2019; Tridon et al., 2020). The relative offset estimated with this approach uses the fact that, for observations of Rayleigh-scattering frozen hydrometeors only, the DWR distribution has its mode at 0 dB. The radar measurements used for this calibration were selected with the following criteria:

- Signal corresponds to ice-only clouds, based on the Cloudnet target classification (see section 3.3).
- Z_e from MRR is between -5 and 0 dBZ, to ensure the presence of mostly Rayleigh scatterers in the radar volume.
- If Parsivel detects liquid precipitation, all echoes within 10 minutes are ignored.

Monthly DWR distributions for observations satisfying these conditions were then obtained, and the mode of the distribution was taken as monthly Z_e offset. The bins used to calculate the distributions are 0.5 dB wide. We estimated the uncertainty associated with this calibration approach by taking the left standard deviation of the monthly DWR distributions with respect to the mode. The root mean square value of such monthly uncertainties is 2.1 dB.

3.3 Temperature soundings and hydrometeor classification

Many microphysical processes are known to be strongly dependent on temperature (e.g., Pruppacher & Klett, 2012), we thus investigate the dependence of DWR statistics on in-cloud temperature, as well as cloud-top and cloud-base temperature. Additional information on cloud phase is also needed, to properly identify MPC events. For these reasons we use temperature profiles retrieved from a HATPRO (Humidity And Temperature PROfiler; Rose et al. (2005), Nomokonova, Ritter, and Ebell (2019)) microwave radiometer, and the Cloudnet target classification product (Hogan & O'Connor, 2004; Illingworth et al., 2007). The HATPRO is operated by the Alfred Wegener Institute (AWI) and measures on the same platform as the radar systems. In addition to temperature soundings, HATPRO observations are also used to retrieve liquid water path (LWP). In order to increase the accuracy of temperature profiles especially in the lowest 1 km, the observations at seven channels along the 60 GHz oxygen absorption band are obtained at various elevation angles (Crewell & Lohnert, 2007). In this way, the uncertainty (root mean square error) in temperature even in the presence of temperature inversions reaches a maximum value of 2 K (Gierens et al., 2020). Elevation scans are regularly performed

every 15 to 20 minutes. The profiles are linearly interpolated in time to the same resolution as the MRR (60 s).

Observations from the W-band cloud radar, HATPRO, and a ceilometer (model Vaisala CL51; Maturilli and Ebell (2018)), together with output from the ICOsahedral Nonhydrostatic weather model (ICON; Zängl et al. (2015)), in its global numerical weather prediction mode (ICON-IGLO), are operationally combined into the Cloudnet product (Hogan & O'Connor, 2004; Illingworth et al., 2007). In particular, we use the target classification product which classifies hydrometeors into: cloud droplets, supercooled cloud droplets and cloud ice, as well as drizzle or rain. The presence of liquid at sub-zero temperatures is mainly based on ceilometer observations. The ceilometer signal undergoes far greater attenuation when traversing a liquid layer, compared to an ice layer. This leads to limitations of the Cloudnet product if more than one liquid layer is present, as often the signal is unable to penetrate the lowest liquid layer. We will henceforth use the term *liquid base* to refer to the base of the lowest liquid layer detected by the ceilometer. We will further refer to the portion of the MPC above the liquid base as *mixed-phase layer* (MPL). In this study we use the Cloudnet target classification product to derive the height of the liquid base, and cloud-top height.

3.4 Selection of mixed-phase cloud events

Low-level MPC events were identified following an approach similar to that employed by Gierens et al. (2020). Cloudnet data were first checked for the presence of shallow ice- and liquid-containing clouds, meaning clouds with cloud top below 2500 m, and liquid and ice present at any height below 2500 m. Multiple cloud layers are considered as one if separated by 60 m or less, otherwise only the lowest layer is included in the analysis, and the remaining ones are excluded.

During intense precipitation events snow might accumulate on the ceilometer aperture, thus leading to ceilometer data not being available, and liquid layers not being identified in the Cloudnet target classification. When the ceilometer signal is not available, the presence of liquid is evaluated using the LWP retrievals from HATPRO. In these conditions clouds classified as ice only were also considered mixed-phase when LWP exceeded a threshold of 10 g/m^2. In parts of the analysis DWR at liquid base, and its maximum value below the liquid base are evaluated in each sample. When evaluating this quantity, only the subset of data where the ceilometer signal is available and the liquid base is within the MRR range was used.

MPC-events were then identified by requiring that liquid and ice were present for at least 60 minutes, with gaps allowed for a total of one sixth the total duration of the event. Using this method, we identified a total of 1605 shallow MPC cases, adding up to a total duration of 7592 hours. Out of these, 1042 cases, or 6022 hours, are above MRR sensitivity. Out of all cases (cases detected by the MRR), 23.6 % (25.6 %) were detected in winter, 15.4 % (18.0 %) in spring, 30.2 % (23.0 %) in summer, and 30.8 % (33.4 %) in autumn. In part of the analysis we only focus on MPC events detected by the MRR, and with surface temperature below 0°C: 508 cases satisfy these conditions.

4 Results and discussion

A typical shallow MPC event observed from 4 to 6 February 2021 is displayed in Fig. 1. The four panels depict Z_e and MDV from the W-band cloud radar, DWR, and LWP. The figure also shows the height of the liquid base and temperature contours, derived from the ceilometer and HATPRO, respectively. The event depicted in the figure produced precipitation characterized by a wide range of DWR values. In particular, the MPC produced high-DWR showers intermittently throughout its duration, highlighting the presence of large ice particles. These high-DWR showers are alternating with regions

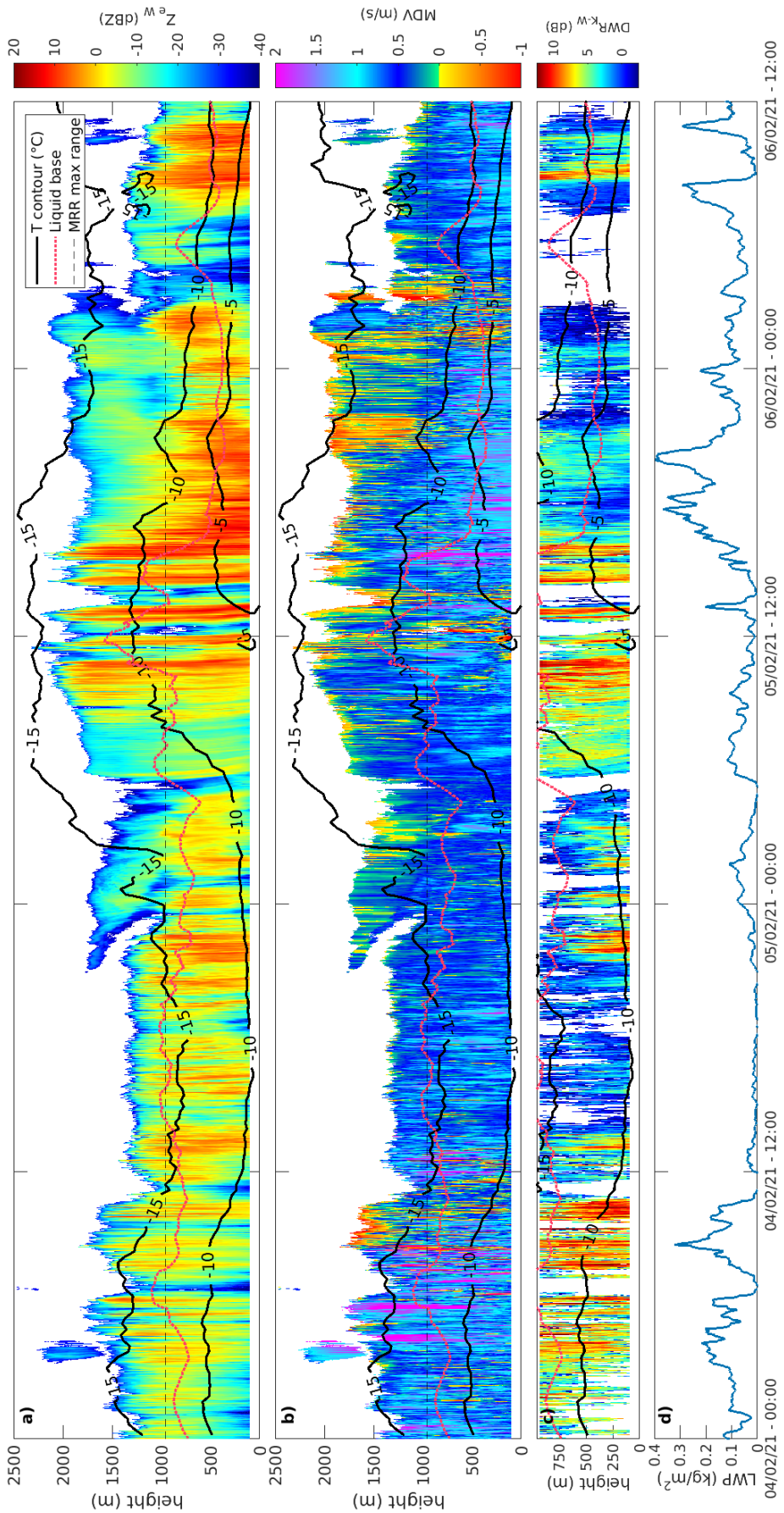

Figure 1. Example of shallow mixed-phase cloud event observed in Ny-Ålesund on 4 to 6 February 2021. Panels a and b display the reflectivity and mean Doppler velocity measured by the W-band cloud radar, respectively. Panel c depicts the Dual-Wavelength Ratio obtained from MRR and cloud radar observations. Panel d displays the LWP, retrieved from HATPRO microwave radiometer observations. In panels a, b, and c, contour lines indicate temperature (black) based on retrievals from HATPRO, and the liquid base height (pink dotted) from the Cloudnet target classification product. The horizontal dashed line in panels a and b indicates the maximum range of the MRR. Times indicated are in UTC.

characterized by lower DWR values, and even periods when the reflectivity was below the sensitivity of the MRR, and thus DWR values were not available. Fig. 1 shows that most high-DWR showers originate from within the mixed-phase layer. Interestingly, high DWR values are not necessarily linked to high reflectivity values, and vice versa.

4.1 Impact of MRR sensitivity and limited maximum range on detected cloud characteristics

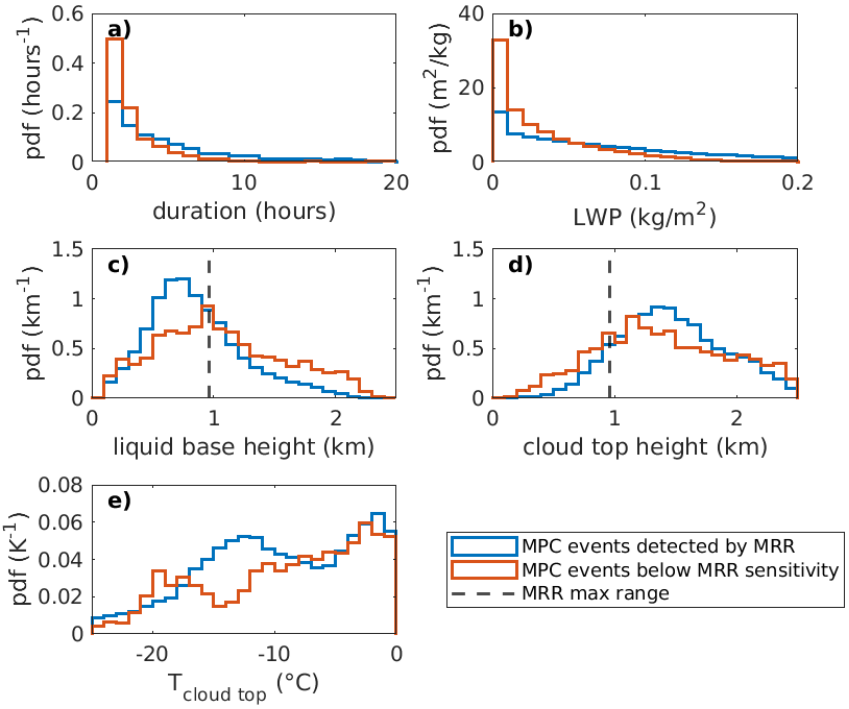

Figure 2. Statistics of mixed-phase cloud characteristics in Ny-Ålesund. Probability density functions (pdfs) are shown for events detected by the MRR, and for events that produced a reflectivity below the sensitivity of the MRR, and thus were only detected by the W-band cloud radar. The parameters shown are MPC event duration (a), liquid water path (LWP; b), liquid-base height (c), cloud-top height (d), and cloud-top temperature (e). The dashed lines in panels c and d indicate the maximum range of the MRR. Bin sizes are respectively: 1 h, 10 g m^{-2}, 100 m, 1°C.

In the following analysis we will focus only on MPC events detected by the MRR. The two limitations of the MRR are its maximum range (960 m), and lower sensitivity compared to the W-band cloud radars. To evaluate the effect of these limitations on the data sampled for the analysis, characteristics of MPCs detected by the MRR, and MPCs detected only by the W-band cloud radar are shown and compared in Fig. 2. Overall, MPCs detected by the MRR tend to last longer (median 4.0 hours) and display slightly higher LWP values (median 69.1 g/m^2) compared to all MPC events (2.9 hours and 55.5 g/m^2 respectively). Fig. 2e further shows that the fraction of MPCs detected by the MRR with cloud-top temperatures between -20 and -10°C (84.8%) is higher than that for MPCs with cloud-top temperatures above -10°C (75.6%). Moreover the number of MPC events with cloud-top T below -20°C is very low (93), and most of these clouds are detected by the MRR (81.5%). While 66.2 % of MPCs detected by the MRR have their liquid base within the instrument's maximum range, only 12.4% have their top within it (Fig. 2c,

d). For this reason the analysis reported in the following sections focuses on precipitation observed at, and below, the liquid base of MPCs. The limited range of the MRR does not appear to introduce a significant bias in the height of the detected cases, as the median cloud-top (liquid-base) height for MPC events detected by the MRR is 1431 m (791 m), while that for all cases is 1420 m (826 m). In summary, while the limited range of the MRR does not affect the height of the detected MPC events, its lower sensitivity leads to the detection of events that produce higher reflectivities. These events appear to be characterized by a longer duration, slightly higher LWP values, and colder cloud-top temperatures.

4.2 Characteristic sizes and fall speeds of precipitating ice particles in the lowest 1 km

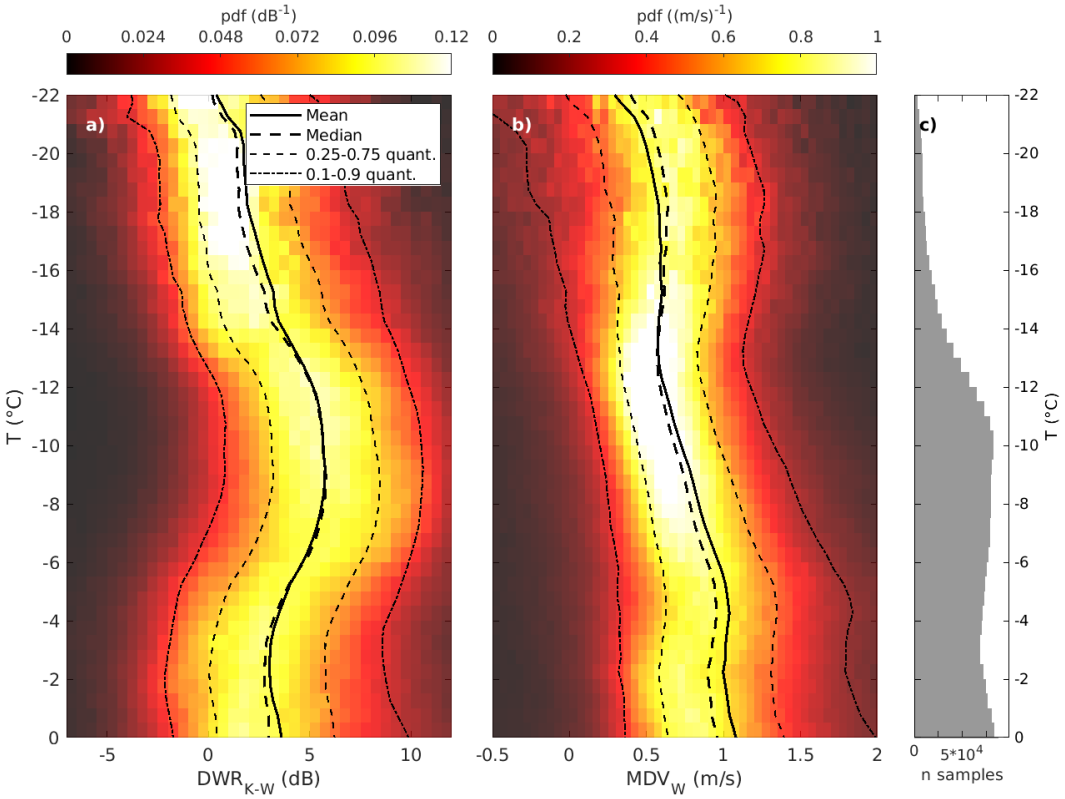

Figure 3. Contoured frequency by temperature diagram (CFTD) of Dual-Wavelength Ratio (DWR; panel a) and Mean Doppler Velocity (MDV; panel b) in the detected mixed-phase cloud events. Panel c displays the number of samples available at each temperature level. MDV values are only included if MRR echoes are available. Bin sizes are: 1 dB, 0.05 m/s, and 0.5 °C.

In Fig. 3 we perform long-term statistics of DWR and Mean Doppler Velocity (MDV, taken from W-band cloud radar) as function of temperature, in the detected shallow MPC events. This approach is similar to what has been applied to triple-wavelength observations in mid-latitude clouds by Dias Neto et al. (2019) and Ori et al. (2020). The main difference in our study is that we focus on shallow MPCs and are restricted to the lowest 960 m, as well as clouds that produce large enough Z_e signals to be detected by the MRR. The DWR and MDV statistics in Fig. 3 are displayed as Contoured Frequency by Temperature Diagrams (CFTDs, Yuter and Houze Jr (1995)). Here, DWR and MDV values are matched with temperature (T) retrieved at the same height, and the Figure

displays joint histograms of DWR and T (panel a), and MDV and T (panel b). These histograms are normalized to one at each chosen T level. Note that, unlike many other studies where CFTDs are employed, panels a and b in Fig. 3 should not be interpreted as continuous profiles. Because of the limited depth of shallow MPCs, and the limited range of the MRR, each available profile only spans a portion of the displayed temperature range. The mean temperature difference between the lowest W-band cloud radar range gate (100 m), and the highest MRR range gate (960 m) is 5.2 °C, with 1.8 °C standard deviation. The total number of samples (Fig. 3c) reveals that 90% (95%) of observations occur at temperatures higher than -12.7°C (-15.1°C), with maxima at -10 and 0°C.

Fig. 3 displays that at temperatures below -15°C median DWR values are close to 1 dB, corresponding to median sizes smaller than 1 mm. Median DWR then rapidly increases to 4.1 dB between -15°C and -12°C. These enhanced DWR signals can be found at temperatures as high as -6°C, with a distinct maximum between -12 and -8°C (5.6 dB). At temperatures close to 0°C, the median DWR decreases back to lower values, with a median of 2.7 dB between -5 and 0°C. Similarly, median MDV in Fig. 3b has a relatively constant value of 0.6 m/s between -20 and -12°C, typical for small ice crystals (Kajikawa, 1972; Mitchell, 1996; Barthazy & Schefold, 2006; Heymsfield & Westbrook, 2010), grown most likely by vapor deposition. At the -13°C level where the DWRs increase, we also find the MDVs to increase. Interestingly, while the DWRs seem to remain almost constant between -12°C and -8°C, the MDVs steadily increase, reaching values close to 1 m/s, which is a typical terminal velocity of larger aggregates (Locatelli & Hobbs, 1974; Heymsfield et al., 2007; Brandes et al., 2008; Karrer et al., 2020). A similar behaviour in terms of both DWR and MDV can be noticed in the case study in Fig. 1 as well. Combining DWR and MDV information, together with previous knowledge from mid-latitude clouds, we thus hypothesize that aggregation might play an important role in the formation of the high-DWR hydrometeors we observe between -15 and -5 °C. The region of increasing DWR starting at -15°C is likely associated with intensified aggregation of branched dendritic particles growing in the dendritic-growth zone (DGZ). An increase in DWR associated with enhanced aggregation in the DGZ has been previously observed in mid-latitude clouds (Dias Neto et al., 2019; Barrett et al., 2019; Ori et al., 2020; Lamer et al., 2021; Oue et al., 2021). The presence of high-DWR particles at temperatures above -10°C in Fig. 3a could be simply a result of particles which mainly aggregated in the DGZ and then sedimented to warmer temperatures, while continuing to aggregate.

The low fall velocities observed in Fig. 3a-b at temperatures below -5°C are not indicative of severe riming that could explain the observed DWRs. However, we cannot rule out the possibility of light riming of the larger aggregates, as well as smaller rimed particles as their terminal fall velocities could overlap with the fall velocity of larger, unrimed aggregates. Riming has in fact been observed to occur frequently in Arctic MPCs (McFarquhar et al., 2007; Mioche et al., 2017; Fitch & Garrett, 2022). However, the MDVs from 72.3% (82.7, 91.6%) of the observed echoes are slower than 1.0 m/s (1.2, 1.5 m/s) between -15 and -5°C, which corresponds to a rime mass fraction of 0.31 (0.47, 0.65) according to Kneifel and Moisseev (2020). It further appears unlikely that the DWR increase at -15°C is mainly driven by riming: first, we are not aware of any evidence that riming preferentially occurs at -15°C. Second, in this temperature regime the Wegener-Bergeron-Findeisen process has its maximum (A. V. Korolev & Mazin, 2003) and has been shown to further hamper formation and survival of liquid droplets (Silber, McGlynn, et al., 2021).

Although the DWRs at temperatures warmer than -5°C decrease back to lower values (median of 2.7 dB between -5 and 0°C), the MDVs remain almost constant, close to 1 m/s (median of 1.1 m/s between -5 and 0°C). One potential explanation for this signature could be the higher terminal fall velocity of columns and needle particles, which preferentially grow above -10°C by vapor deposition (e.g., Bailey & Hallett, 2009). They

can reach terminal velocities close to 1 m/s at smaller sizes compared to plate-like particles (Kajikawa, 1972; Mitchell, 1996). Also the presence of supercooled drizzle and potential enhanced riming of smaller ice particles with low DWR could explain the observed behaviour. The likelihood for the formation of drizzle and intensified riming has been found to strongly increase at temperatures closer to the melting level (Cortinas Jr et al., 2004; Zhang et al., 2017; Kneifel & Moisseev, 2020). Overall, the DWR-MDV behaviour found for MPCs at temperatures close to 0°C is significantly different from what is observed at the mid-latitudes. Several studies observed a second and even stronger DWR increase from -5°C towards the melting level (Chase et al., 2018; Dias Neto et al., 2019; Tridon et al., 2019; Ori et al., 2020). Interestingly, we are able to find a similar behaviour also in Ny-Ålesund in cloud systems that are deeper than 2.5 km, as shown in Appendix B. The lack of aggregation close to the melting level in the detected shallow MPC events is further explored in the next section.

4.3 Precipitation formation in the mixed-phase layer

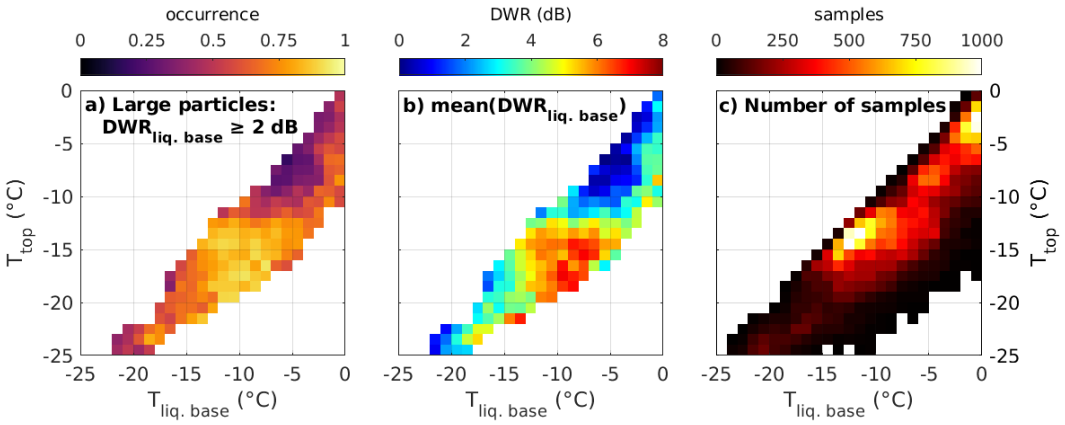

Figure 4. Frequency of occurrence of DWR above 2 dB at liquid base (a), mean DWR at liquid base (b), and number of samples at liquid base (c) as function of cloud-top and liquid-base temperature. In panels a and b bins with less than 60 total samples are ignored. Bins are 1°C wide.

In the previous section, we analyzed DWR values with respect to temperature retrieved at the same height. We can assume that in shallow MPCs the main nucleation and initial depositional growth takes place in the mixed-phase layer (MPL), where on average saturation with respect to liquid water is reached. Therefore, we investigate how much the particles already aggregate in the MPL and how relevant the temperature of the MPL is for the occurrence of larger aggregates in the entire profile.

We analyze the DWRs observed at the liquid-base height, and relate it to the cloud-top and liquid-base temperatures in Fig. 4. For a simpler interpretation, in panel a, we group the profiles into small particles (DWR at liquid base lower than 2 dB, corresponding to a mass median diameter of approximately 1.3 mm; see Fig. A1 in Appendix A) and larger particles (DWR at liquid base equal or higher than 2 dB), that are most likely a result of aggregation and/or riming. The threshold of 2 dB was also chosen because of the estimated uncertainty on DWR of 2.1 dB. DWR values higher than 2 dB can thus confidently be attributed to non-Rayleigh scattering by hydrometeors. We also tested slightly different DWR thresholds but did not find a substantial impact on the results (not shown). Fig. 4a thus shows the frequency of occurrence of DWRs at liquid base higher than 2 dB. Panels b and c in the Figure display the mean DWR value at liquid base, and

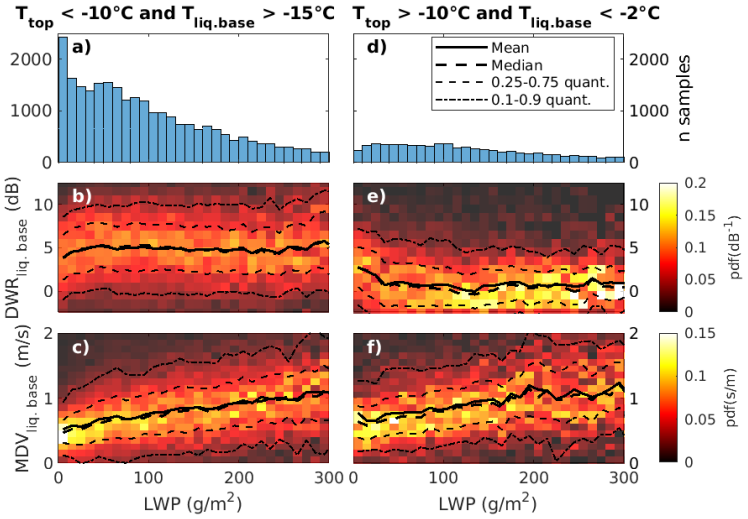

Figure 5. LWP distribution (a, d), and joint DWR-LWP (b, e), and MDV-LWP (c, f) distributions for MPC events in two distinct regimes. Panels a, b and c include MPC events whose mixed-phase layer is at least partly in the temperature interval between -15 and -10°C. Panels d, e and f include MPC events whose mixed-phase layer temperature does not exceed -2°C and does not subceed -10°C. The joint distributions in panels b, c, e and f are normalized to one in each LWP bin. Bin-widths are: 5 g/m^2, 0.5 dB, and 0.05 m/s.

number of available samples, respectively, both as function of liquid-base and cloud-top temperature.

Fig. 4a illustrates that large particles appear to mainly originate from mixed-phase layers with liquid-base temperature higher than -15°C and cloud-top temperature lower than -10°C. In this temperature regime 76.8% of the samples in fact produce particles with DWR of 2 dB or larger. The mean DWR value at liquid base (Fig. 4b) also illustrates that even very thin MPLs on average generate particles with DWRs of 5 dB or higher, if they contain temperatures of -13 to -14°C. Interestingly, this overlaps with the -15.5 to -13.3°C interval, where the laboratory study by Takahashi (2014) observed the maximum growth rate of plate-like crystals. As expected, if the MPL is thicker (larger difference between cloud-top and liquid-base temperature), also the mean DWRs increase, because of the longer time particles can grow by deposition and subsequent aggregation.

Fig. 4b shows that enhanced DWR values can also be found at temperatures outside the DGZ. However, the mean DWR and overall frequency of occurrence is generally much lower than what we observe in the DGZ. Interestingly, for the regions outside the DGZ the MPL also needs to be deeper (i.e., larger temperature difference between cloud top and liquid base) in order to produce enhanced DWRs.

The dependence of DWR and MDV at liquid base on LWP is shown in Fig. 5, for two separate temperature regimes. Enhanced aggregation in the -10 to -15°C temperature region appears to occur already at relatively small LWP values. No substantial change in DWR is found for increasing LWP. This independence can be interpreted as a proof that the observed DWR signature is mainly caused by aggregation rather then riming as the latter would be expected to increase with LWP. However, 5c shows that the MDV observed at the liquid base continuously increases with larger LWP. We suspect, that while riming is not the main mechanism that increases DWR, it is still contributing to the observed increasing particle fall speeds by increasing ice particle density.

The preferential growth of dendrites and the subsequent formation of aggregates in the DGZ is certainly common knowledge in cloud physics (Pruppacher & Klett, 2012) although many details of these processes are still not thoroughly understood. We believe that the signatures found in this study are particularly valuable to better constrain the process of dendritic growth and subsequent aggregation. Unlike in deeper clouds, no particles from above enter the DGZ in the shallow MPCs that are the focus of this study. Instead we can assume that all ice particles are nucleated and grown within the relatively narrow region of the mixed-phase layer. We can further assume that the particles in the MPL grow in conditions which are close to liquid water saturation. This allows to compare and relate our results directly to recent laboratory experiments investigating depositional growth (Takahashi, 2014) or aggregation (Connolly et al., 2012) in the temperature regime of the DGZ.

A number of factors are known to be mainly responsible for the rapid formation of aggregates in the DGZ. Here, if saturation with respect to liquid is reached, supersaturation with respect to ice can reach values up to 14%, depending on temperature (Pruppacher & Klett, 2012), and a maximum of the Wegener-Bergeron-Findeisen (WBF) process is observed (A. Korolev, 2007). Under these conditions, ice particles grow into dendritic shape (Bailey & Hallett, 2009; Pruppacher & Klett, 2012), which is connected to enhanced capacitance (Westbrook et al., 2008; Pruppacher & Klett, 2012) and ventilation coefficients (Takahashi et al., 1991). All these effects together lead to a maximum in the water vapor depositional growth on ice particles in this temperature region (Takahashi, 2014; Takahashi et al., 1991). As already mentioned, Takahashi (2014) found that the depositional growth rate is maximized between -15.5 and -13.3°C (see their Fig. 6). After a growth time of 10 minutes, they observed particles reaching maximum sizes of 1.5-1.8mm with preferentially stellar, dendritic or fern-like habits. This temperature region coincides with the MPL temperatures where we observed the largest DWRs in Fig.4b.

In addition to the very favorable depositional growth conditions, the slower terminal fall velocities of dendrites compared to other shapes with similar mass (e.g., Kajikawa, 1972; Mitchell, 1996) allow them to stay in the supersaturated layer of the cloud for a longer time compared to other ice habits. For example, a 1 mm dendrite falls at 0.3 m/s while the same sized column, which grows for example at temperatures higher than -10°C, has a terminal velocity of 0.8 m/s (Mitchell, 1996). The rapid depositional growth will eventually lead to a sufficiently large diversity of terminal velocities and particles sizes needed for collisions. Moreover, turbulent motions frequently observed in the MPL (e.g., Morrison et al., 2012) can be expected to further enhance the likelihood for particle collisions. Their unique shape allows them to stick to each other by mechanical entanglement of their branches (Pruppacher & Klett, 2012; Connolly et al., 2012).

The question remains, why do we not observe major DWR increases due to particle aggregation close to the melting level in shallow MPCs? Fig. 4 highlights that increases in DWR are indeed observed at the liquid base, when its temperature is between -2 and 0°C. Considering the 2 K uncertainty in the temperature retrievals, we cannot exclude that this signature is caused by melting particles. Even if melting particles are not responsible for the enhanced DWRs, the DWRs found close to 0°C in figures 3 and 4 are still significantly smaller than those observed in previous studies for mid-latitude clouds (Chase et al., 2018; Dias Neto et al., 2019; Tridon et al., 2019; Ori et al., 2020), and in deeper cloud systems in Ny-Ålesund as well (Appendix B).

In general, enhanced aggregation close to the melting level is thought to be caused by the thickening of a quasi-liquid layer (QLL) on the snowflake surface (Fletcher, 1962; Fabry & Zawadzki, 1995; Slater & Michaelides, 2019). This QLL forms on any ice particle, whether being a single crystal, aggregate, or rimed particle, and it increases its aggregation efficiency by enhancing its sticking efficiency. In extreme scenarios, this can lead to the formation of snowflakes several centimeters in size (Lawson et al., 1998). The absence of this second enhanced aggregation zone cannot be explained with a lower ice

number concentration close to the melting level in shallow MPCs: airborne in-situ measurements have shown similar ice number concentrations for MPCs in cases with cloud-top temperature (CTT) between -10 and 0 °C, compared to cases with CTT between -20 and -10°C (Rangno & Hobbs, 2001; Mioche et al., 2017). Furthermore, signatures of secondary ice processes have been observed in Arctic MPCs close to the melting level (Luke et al., 2021).

Although we cannot provide a conclusive answer to this question with our remote sensing observations alone, we discuss possible processes that could lead to the observed lack of aggregation. First, the depositional growth rate above -10°C is at least one order of magnitude smaller than at -15°C (see e.g. Fig. 4 in Takahashi et al. (1991)). Due to the higher terminal fall velocities of columns, needles, and isometric particles, which are often observed in this temperature regime, the time for the particles to grow by deposition is also much shorter than in the DGZ. A more frequent occurrence of riming, which was found in Kneifel and Moisseev (2020) to rapidly increase from -12°C towards 0°C, could further enhance the particles' terminal velocities and limit their residence time in the MPL. Remote sensing observations of single-layer MPCs above Ny-Ålesund have in fact shown a liquid fraction above 0.9 in more than 90% (80%) of the cases, when cloud-top temperature is above -5°C (between -10 and -5°C) (Nomokonova, Ebell, et al., 2019). In contrast, liquid fractions for single-layer MPCs with cloud-top temperatures between -15 and -10°C is below 0.8 in approximately 50% of the cases (Nomokonova, Ebell, et al., 2019). The dependence of DWR and MDV on LWP for MPCs in this temperature regime displayed in Fig. 5e-f is also compatible with increased riming. DWR values are in fact close to 0 dB for LWP values larger than 15 g/m^2, and MDV values tend to increase with increasing LWP.

4.4 Further aggregation below the mixed-phase layer

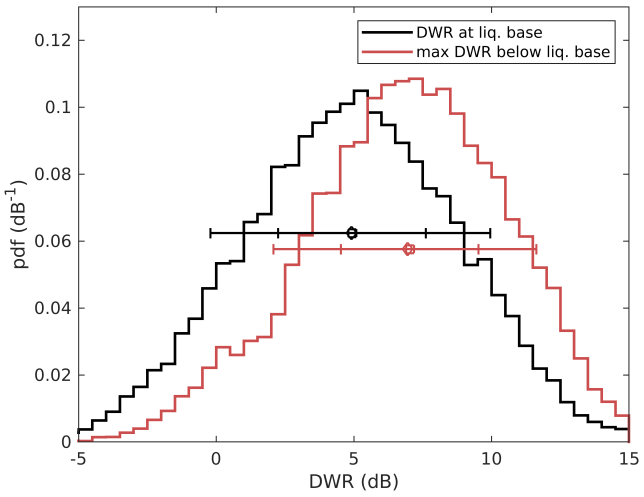

Figure 6. Probability density functions (pdfs) for DWR values at and below the liquid base in shallow MPCs. The black line is relative to values observed at liquid base, while the red line is relative to the maximum DWR value observed in each column below the liquid base. Error bars display 0.1, 0.25, 0.75 and 0.9 quantiles of the two distributions, with diamonds representing the mean values, and squares representing the median values. The data used are only for MPC events with liquid base temperature above -15°C and cloud-top temperature below -10°C. Samples with surface temperature above 0°C are excluded. Bins are 0.5 dB wide.

While the growth of dendritic branches from ice particles is likely to mostly take place in the mixed-phase layer of the MPC, as it requires high supersaturations with respect to ice (Pruppacher & Klett, 2012), aggregation of ice particles can be expected to continue below it. Further increases in DWR below the MPL are in fact observed in the case study shown in Fig. 1, for example on 4 February 2021 between 7 and 11 UTC or between 22 and 24 UTC on the same day. In this section, we evaluate the further DWR increase below the MPL and how strong this increase is in relation to the aggregation signal at the liquid base. We restrict the analysis to profiles where the liquid-base temperatures are above -15°C and the cloud-top temperatures are below -10°C as this is the region where we find the majority of large DWR signatures at liquid base. Connecting processes at different heights in one vertical profile is challenging, as the particles are advected by changing horizontal winds causing often complex fall streaks in the radar time-height display (Kalesse, Szyrmer, et al., 2016; Pfitzenmaier et al., 2017, 2018). In order to avoid these difficulties, we do not directly compare DWR values measured at different heights in the same column. Instead we analyze in Fig. 6 the distributions of DWR values observed at liquid base, and of the maximum DWR values observed below the liquid base in each column. Note that in a given column these two values can be the same, if the maximum DWR is at liquid base: this is observed in 15.3% of the available samples. In order to avoid high-DWR signals originating from melting particles, samples measured when surface temperature was above 0°C are ignored in this analysis.

From Fig. 6 it is clear that aggregation continues to increase mean aggregate size despite the likely sub-saturated air below liquid base (e.g., Shupe et al., 2008). The median (mean) of the largest DWRs observed below the MPL is 7.0 dB (6.9 dB), and is 43% (41%) larger than the median (mean) DWR of 4.9 dB (4.9 dB) at liquid base. Below the liquid base we can attribute most of the DWR increase to aggregation, as riming cannot occur because of the absence of liquid water. The narrower distribution of the maximum DWR below liquid base is due to the fact that the DWRs approach the saturation value, as the particle sizes grow. DWR saturation values for unrimed and lightly rimed aggregates have been estimated in Appendix A to be 10-11 dB for the 24 and 94 GHz combination.

4.5 Persistence of high-DWR signals

Several previous studies demonstrated that Arctic MPCs display a complex horizontal structure, and high spatial variability in terms of dynamics and hydrometeors (Shupe et al., 2008; Schäfer et al., 2018; Eirund et al., 2019; Ruiz-Donoso et al., 2020). It appears therefore interesting to investigate whether the observed high-DWR signatures are restricted to limited regions of the MPC, as observed in Fig. 1, or whether enhanced aggregation tends to occur uniformly across the cloud field.

The vertically-pointing radars used in this study do not resolve the complete horizontal structure of the cloud field but rather observe the variability of clouds that are advected over the measurement site. The observed variability is thus usually a combination of temporal and spatial variability, and spatial variability is only resolved along the wind direction (e.g., Shupe et al., 2008). We estimated the duration of DWR signals exceeding certain thresholds and related them to the total duration of the MPC event (detected by the more sensitive W-band cloud radar, see section 3). The full distribution of this quantity, together with its values for the case study in Fig. 1, is shown in Fig. 7. Note that, unlike the statistics presented in sections 4.2, 4.3 and 4.4, all available samples during MPC events were analyzed, including those with no signal in the MRR data. We'd like to also highlight that the statistics shown in Fig. 7 are sensitive to the definition of MPC event, as this in turn affects the event duration.

For interpreting Fig. 7 it might help to consider first the red curve which represents the distribution of DWRs in relation to the event duration from the case shown

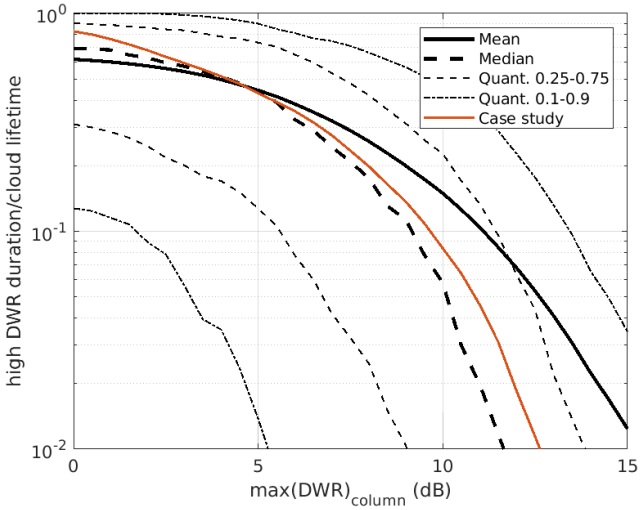

Figure 7. Distributions of the ratio between the duration of high-DWR signals and the total duration of the MPC event. The duration of high-DWR signals is calculated as the total time during an MPC event that the maximum DWR in each column exceeds the value indicated on the x-axis. The curves indicate the mean, median and quantiles of the duration ratio. Only MPC events with the mixed-phase layer at least partly at temperatures between -15 and -10°C are included. The red curve represents the case study observed on 4 to 6 February 2021, illustrated in Fig. 1. Note that the quantity indicated on the y-axis, being a ratio between time intervals, is unitless.

in Fig. 1. We see that cloud regions where the maximum DWR in each column exceeds 5 dB appear for 43.1% of the total MPC duration. Higher DWR values, for example exceeding 8 dB, are only observed for 19.8% of the total duration of the event. The tendency of finding larger DWR values in shorter time periods of the cloud can also be observed when looking at the temporal DWR evolution shown in Fig. 1c. High DWRs in the case study do not display a straight-forward relation with features in the MDV (e.g., upward motions) or the reflectivity field.

Similarly to the case study, 50% of all MPC cases (median line) display DWR values larger than 5 dB for at least 43.8% of the event duration. For larger DWR thresholds, the quantile curves bend relatively quickly to decreasing duration ratios. Again, this result highlights that high-DWR particles appear to form in limited regions of the cloud layer and for a limited amount of time, when compared to the cloud overall extent and duration. In summary, Fig. 7 reveals that 50% of the observed MPCs display DWR values equal or higher than 2 (5, 8) dB for at least 62.5% (43.8%, 17.5%) of the total cloud duration. At the same time, 25% of the observed MPCs display DWR values equal or higher than 2 (5, 8) dB for at least 84.5% (70.2%, 36.1%) of the total cloud duration.

The analysis shown in the previous sections strongly suggests that temperatures compatible with the DGZ are essential in order for MPCs to produce large aggregates. However, their occurrence in limited regions of the MPC indicates that temperature might not be the only driver. Previous studies have shown that dynamical processes are essential in producing ice precipitation in Arctic MPCs, and that precipitation is in turn intertwined with the organization of the stratocumulus deck (Shupe et al., 2008; Eirund et al., 2019). At the same time, aerosol concentrations, surface conditions and surface coupling significantly affect the phase partitioning (Kalesse, de Boer, et al., 2016; Nor-

gren et al., 2018; Solomon et al., 2018; Gierens et al., 2020; Griesche et al., 2021). While we highlighted the relevance of the dendritic-growth zone for the formation of large aggregates in Arctic MPCs, investigating the role of individual processes for the formation of said aggregates is out of the scope of this study.

5 Conclusions and open questions

Using a combination of remote sensing instruments, in particular a 24-GHz precipitation radar and a 94-GHz cloud radar, we evaluated the significance of different ice-growth processes, with a focus on aggregation, for the formation of precipitation in shallow mixed-phase clouds (MPCs) at the high Arctic site of Ny-Ålesund. The combination of equivalent reflectivity factors measured at two radar frequencies into the Dual-Wavelength Ratio (DWR) was used to obtain information on the characteristic size of the particle population. The 3-year statistics of DWR, matched with Mean Doppler Velocity (MDV), thermodynamic retrievals from a microwave radiometer, and phase information from the Cloudnet target classification, provided robust observational constraints for the microphysical processes leading to the formation of precipitation in Arctic shallow MPCs.

This study revealed the unique role of the dendritic-growth zone (DGZ) for the formation of precipitable ice particles in Arctic shallow MPCs, together with the absence of enhanced aggregation typically observed close to the melting level in deeper cloud systems. The main findings of this study are as follows:

- Enhanced DWR signatures occurred predominantly in shallow MPCs whose mixed-phase layer was, at least partly, at temperatures between -15 and -10°C. This feature is compatible with similar signatures observed at the mid-latitudes (Dias Neto et al., 2019; Barrett et al., 2019). This signature is typically attributed to enhanced aggregation due to mechanical entanglement of ice particles with dendritic branches, which preferentially grow in this temperature region (Pruppacher & Klett, 2012). In particular, the highest DWR values at the liquid base of the MPC were observed in conjunction with temperatures of -13 to -14°C, in agreement with laboratory studies that reported the highest depositional-growth rates at these temperatures (Takahashi et al., 1991; Takahashi, 2014). While riming likely also plays a role, as confirmed by increasing MDV with LWP, we argue that the growth of the larger ice particles is to be mainly attributed to rapid depositional growth of plate-like particles, and subsequent aggregation. Moreover, the relevance of aggregation in Arctic shallow MPCs in this temperature region is further confirmed by the additional increase in DWR observed below the liquid base, where riming cannot take place.
- While our results demonstrate that mixed-phase layer temperatures compatible with dendritic growth are essential for the formation of large aggregates, these larger hydrometeors are only observed in limited regions of the cloud field. This suggests that dynamical processes might be at play in the formation of these larger aggregates. We reckon that further investigation is needed to understand the link between the growth of dendritic particles and their subsequent aggregation, and dynamics in Arctic low-level MPCs.
- Typically a second enhanced aggregation zone close to 0°C is observed in mid-latitude clouds (Fabry & Zawadzki, 1995; Dias Neto et al., 2019), and in deeper cloud systems in Ny-Ålesund as well. This is usually attributed to the increased sticking efficiency of melting ice particles. The lack of high-DWR signals close to the melting level (-5 to 0°C) in shallow MPCs in Ny-Ålesund suggests that this process is absent in these clouds. Since shallow MPCs span a limited temperature range, particles sedimenting from colder temperatures might be necessary to trigger the enhanced aggregation typically observed. As such, further investigating this tem-

perature regime bears the potential to substantially improve our understanding of aggregation in general, not only limited to shallow MPCs. While we cannot provide a conclusive answer from the remote-sensing perspective, we speculate that specific ice habits and increased riming might contribute to the suppression of aggregation. Ice habits that grow above -10°C typically have faster fall velocities and smaller cross sections than dendrites (Kajikawa, 1972; Mitchell, 1996; Pruppacher & Klett, 2012). Mean Doppler velocity information, together with evidence of increased drizzle production and riming reported in previous studies (Cortinas Jr et al., 2004; Zhang et al., 2017; Nomokonova, Ebell, et al., 2019; Kneifel & Moisseev, 2020), indicates that riming might also be relevant at these temperatures, and might suppress aggregation.

While the multi-frequency and Doppler radar observations presented in this study provided strong observational constraints for the microphysical processes taking place in Arctic shallow MPCs, the range of observational fingerprints can be substantially extended with polarimetric observations. The recent extension of the AWIPEV site with a polarimetric Ka-band radar will allow us to better constrain ice particle concentration and shape in the future. It will further enable us to obtain DWR profiles reaching cloud top, as well as overcome the sensitivity limitations of the MRR. In this regard, dual-frequency cloud radar observations provide the unique opportunity to test and improve the representation of ice-growth processes in numerical models (Ori et al., 2020; Karrer et al., 2021), and this possibility will be in the future explored with the ICOsahedral Non-hydrostatic (ICON) modelling framework (Zängl et al., 2015), in its Large Eddy Model (LEM) version.

Appendix A Examples of DWR dependence on particle size

Fig. A1 illustrates examples of DWR dependence on ice particle shape and size. DWR values were computed using the scattering database developed by Ori et al. (2021). Particle size distribution is assumed to be inverse exponential, and the figure shows the dependency of DWR on the mass median diameter $D0$. The chosen particle types are unrimed dendrite aggregates, unrimed column and dendrite aggregates, and rimed column and dendrite aggregates. Three values for the degree of riming have been chosen, indicated by the Effective LWP (ELWP): 0.1, 0.2 and 0.5 kg/m^2. ELWP is defined as the liquid water path that produces the simulated amount of riming, assuming a riming efficiency of 100 % (Leinonen & Szyrmer, 2015; Leinonen et al., 2018). The Figure shows that DWR is 0 dB when $D0$ is 1 mm for all particle types, it then rapidly increases as $D0$ increases. It then reaches a saturation value between 10 and 11 dB for unrimed and lightly rimed (ELWP = 0.1, 0.2 kg/m^2) aggregates, above 10 mm. The saturation value is higher for higher degrees of riming.

Appendix B DWR signatures in deep cloud systems in Ny-Ålesund

Similarly to Fig. 3, Fig. B1 displays Contoured Frequency by Temperature diagrams (CFTDs) of DWR and MDV. Only cloud systems with cloud-top height higher than 2.5 km were selected for this figure. DWR and MDV values are matched with temperature (T) retrieved at the same height, and the Figure displays joint histograms of DWR and T (panel a), and MDV and T (panel b).

In addition to the typical increase in DWR corresponding to the dendritic-growth zone (Dias Neto et al., 2019; Barrett et al., 2019; Ori et al., 2020; Lamer et al., 2021; Oue et al., 2021), the figure displays a further increase of DWR close to the melting level, which is typically observed at the mid-latitudes (Chase et al., 2018; Dias Neto et al., 2019; Tridon et al., 2019; Ori et al., 2020).

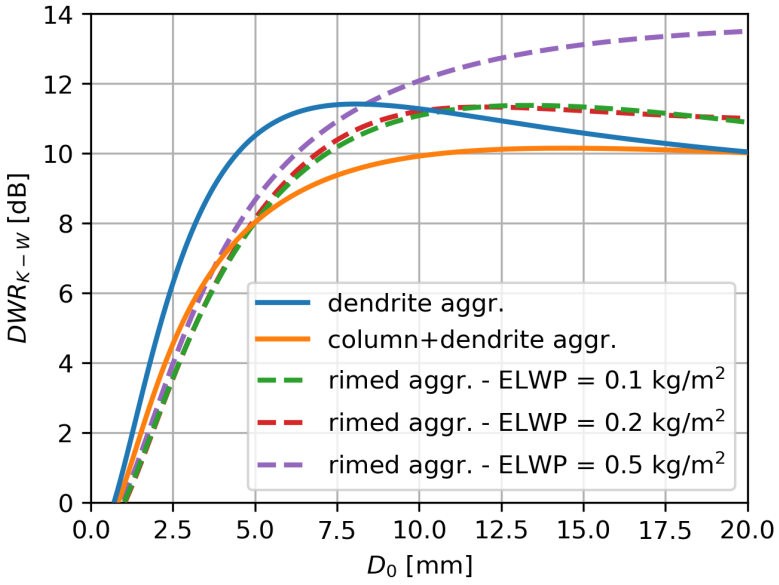

Figure A1. Calculation of DWR at K- (24.2 GHz) and W-band (94.0 GHz) for different ice particle types, as function of the mass median diameter D0, obtained with the scattering database by Ori et al. (2021). The ice particles included are: unrimed dendrite aggregates, unrimed dendrite and column aggregates, and rimed dendrite and column aggregates. The degree of riming for the rimed aggregates is indicated by the effective liquid water path (ELWP, see text for definition).

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Data availability statement

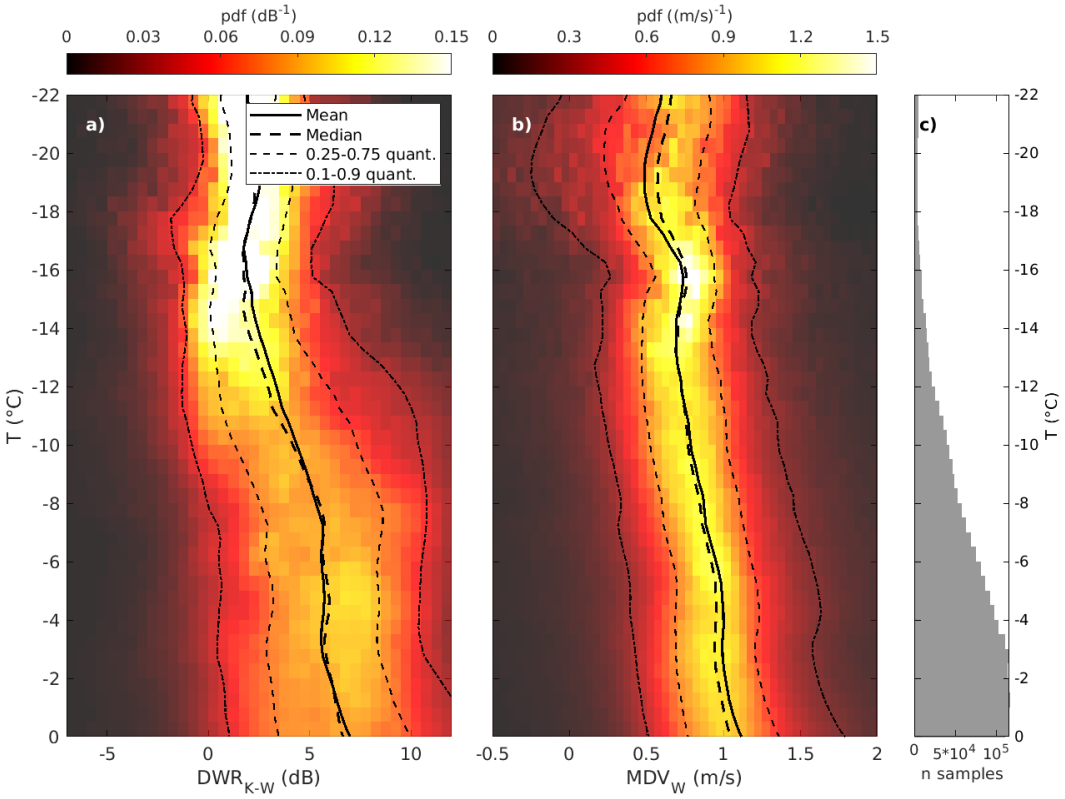

Figure B1. Contoured frequency by temperature diagram (CFTD) of Dual-Wavelength Ratio (DWR) and MDV (Mean Doppler Velocity) in clouds with cloud-top height above 2.5 km. All clouds with cloud-top height above 2.5 km that are detected by the MRR during the study period at sub-zero temperatures are included. Panel c displays the number of samples available at each temperature level. Since MDV is obtained from the W-band cloud radar, MDV values are only included if MRR echoes are available. Bin sizes are: 1 dB, 0.05 m/s, 0.5 °C.

Microwave radiometer retrievals for 2017 and 2018 are available in Nomokonova, Ritter, and Ebell (2019). The Cloudnet target classification product can be downloaded from `https://cloudnet.fmi.fi/`. The processed DWR and MDV data, and the microwave radiometer retrievals for 2019, 2020 and 2021 have been submitted to the PANGAEA archive (`https://pangaea.de`) and will become publicly available during the review process. Although not necessary to reproduce the results reported in this study, the MRR and 94 GHz cloud radar original data will be published in the near future, and will also be uploaded to the PANGAEA archive.

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